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Process Dynamics

The Fundamental Principle of Process Control

Process Dynamics (1)

- All Processes are dynamic
  - i.e. they change with time.
- If a plant were totally static with respect to all it's variables, then control would be easy
- But in reality the dynamics are constantly changing
- We will define the basic terms and show how they relate to process response

This is the most fundamental subject in the course.

It is vital to understand process dynamics to understand process control

This is the REAL difference between process engineers and control engineers. Process engineers think in terms of steady-state conditions (e.g. mass balances across units).

Control engineers think in terms of dynamics as well as steady-state

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Process Dynamics, subjects covered

- Process Response
- Process Gain
- Process Deadtime
- Process Lag
- Order
- Linearity
- Non-self regulating systems
- Plant tests

We will discuss the above

Response is the “response” of a system to a change

Gain, deadtime and lag are used to define the dynamics

Order is a measure of the “complexity” of the process, we will discuss this later.

We will cover each subject in turn

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Process Dynamics (2)

- The change with respect to time of the process variables such as temperature, pressure, flow, composition etc, due to
  - controlled changes e.g. feed rate, temperature, pressure etc
  - uncontrolled changes e.g. ambient temperature, feed composition etc
- Understanding process dynamics is fundamental for achieving good control

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All processes are constantly changing with time.

We will define the basic terms

We will show how these terms relate to the process

We will see how to obtain the dynamics from plant data

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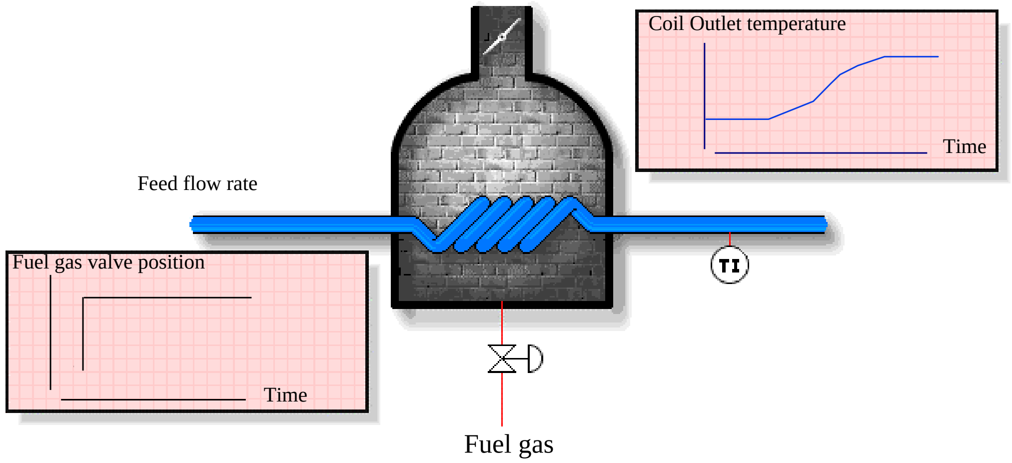
PID open loop tutorial



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Gain is due to the cause and effect. A certain amount of fuel gas affects the temperature of the furnace by a certain amount. This resulting effect is the process gain of the system

When you change the fuel gas, does the COT go up immediately? Why not? Because there is some distance to travel before the change BEGINS to affect the COT. This distance velocity lag is the deadtime.

When the change begins to affect the COT does it shoot up immediately to its final resting value? Why not? Because there is some thermal inertia that the tubes in the furnace have to overcome before they heat up. This causes a LAG in the system. The lag is actually defined as the time to reach 63.2% of the final steady-state value. We will see why this is in a minute.

Characterizing Process Dynamics Response

- Dynamic response of a process can usually be characterized by 3 parameters :
- Process Gain
  - Kp or G and is the Change in the process variable divided by the change in the manipulated variable. Expressed in Engineering units
- Deadtime
  - DT or θ, the time between MV changing and a noticeable change in PV. Expressed in minutes
- Lag
  - T1 or τ Effects the rate at which the PV responds to an MV change. Expressed in minutes

Dynamics arise due to the length of the process path flow

So the 3 parameters are expressed as above

Note that all must be expressed in engineering units

Note that as Deadtime increases, the control problem becomes harder to solve

Lag is time to reach 63.2% of the final value we will see why in the next slide. Note that also as Lag increases, the control problem becomes harder

Laplace Transforms

- Laplace Transforms are simply a mathematical technique which can express equations in the time domain
- This allows straight-forward calculations to be carried out instead of solving complex differential equations
- Format is easily understood
- Best illustrated by some examples

Laplace Format Explained (1)

$$3.5\frac{1}{20s+1}e^{-5s}$$

Process Gain of 3.5

Process lag is 1st order and 20 min

Process Deadtime of 5 min

Laplace Format Explained (2)

Process Lead
of 5 min

$$0.5\frac{5s+1}{(10s+1)(10s+1)}e^{-2s}$$

Process Gain
of 0.5

Process lag is 2nd
order and consists of
2 lags each 10 min long

Process Deadtime
of 2 min

Laplace Format Explained (3)

Process Lead
of 0.5 min

$$20.0\frac{0.5s+1}{100s^2+20s+1}e^{-0s}$$

Process Gain
of 20

Process lag is 2nd
order and consists of
2 lags each 10 min long
(alternative representation)

No Process Deadtime

We will explain Lead during the feedforward section of the course, but basically it gives a different characteristic response.

First order system

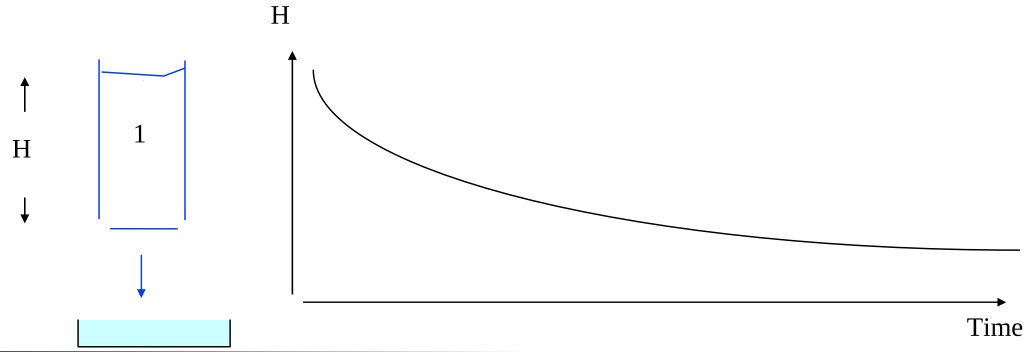
At time, t, h = height of liquid in vessel

$$h = H \exp(-t/\tau)$$

When $t = \tau$

$$h = H.\exp(-1) = 0.368\ H$$

i.e. level has fallen by (1-0.368) = 0.632 H



"bucket chemistry"

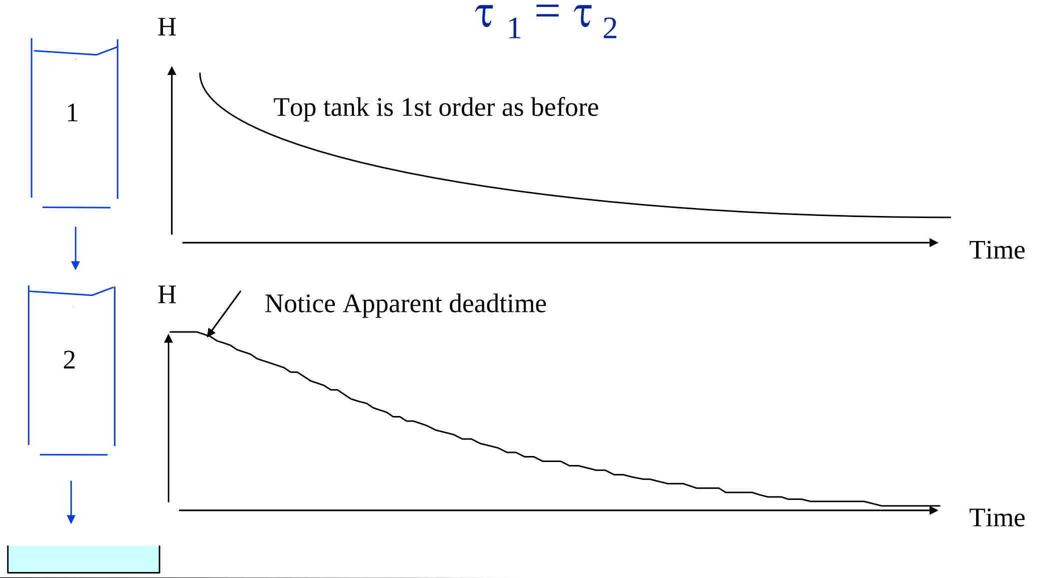
Now we will see why a lag is defined as 63.2% of the final value

Here we have a cylinder emptying and following an exponential decay curve

We can show that the level falls by 0.632 or 63% of it's initial value at time t=T1 because exp(-1) is 0.368 so the level has fallen by 0.632 for a unit step change

In practice the equation is more complex and non-linear, but this approximation is good enough in practice

Second order system of equal time constants, $\tau_1 = \tau_2$



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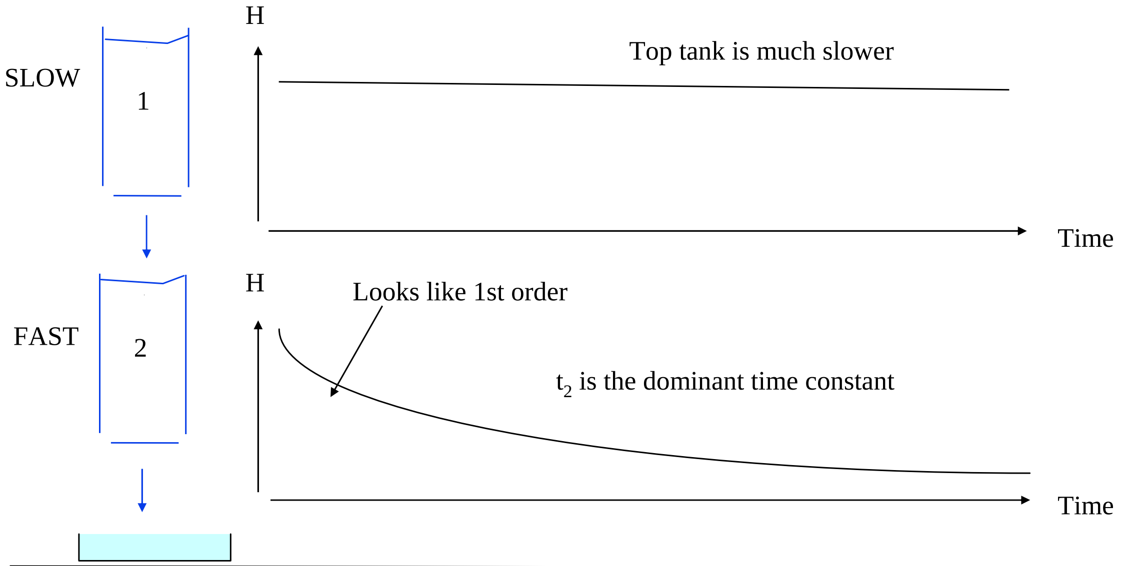
This system of buckets can be useful to explain other phenomena in process control

Now consider 2 cylinders, one emptying into the other. The top tank behaves as before. The lower tank however is slightly buffered by the action of the upper tank and empties more slowly

Do you see the apparent “deadtime” at the start (which is actually due to the combination of the 2 lags)

Second order system $\tau_1 > \tau_2$

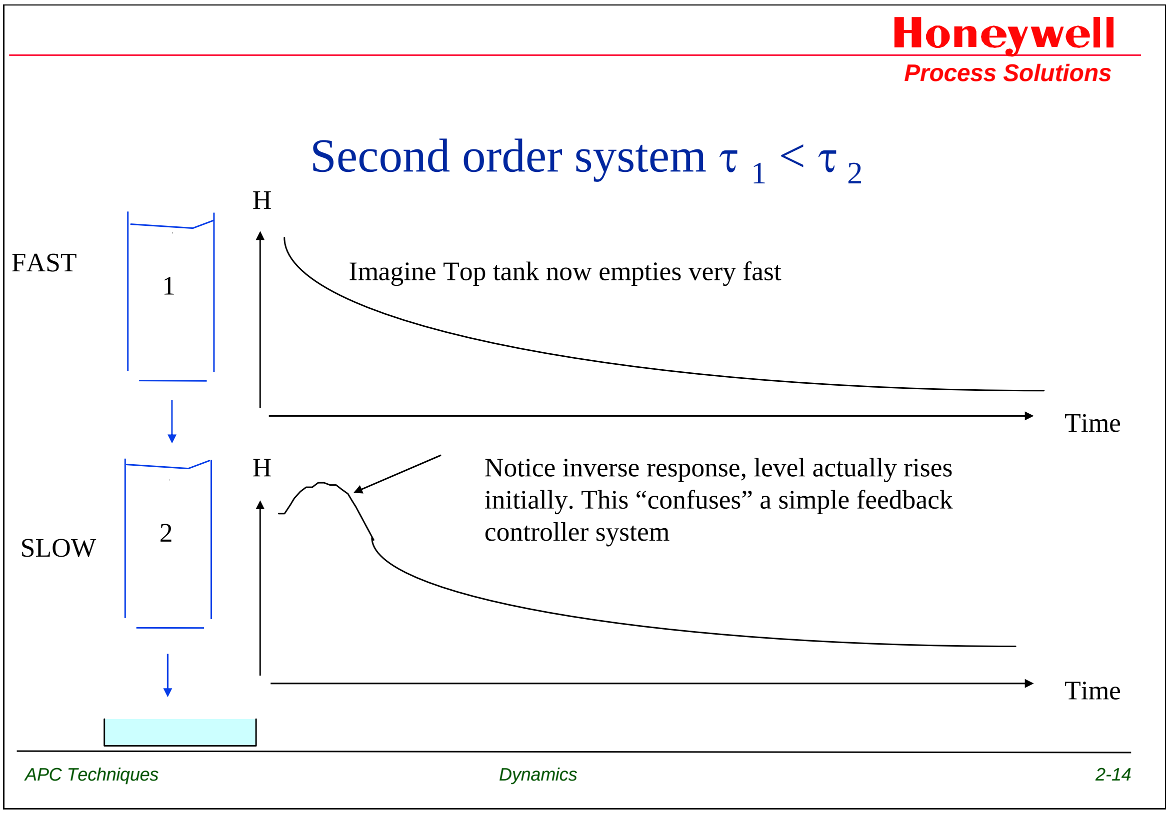


Now consider again the situation of two tanks.

Now the top tank has a big hole and the bottom tank a small hole.

The effect approximates to 1st order dynamics i.e. one lag

Notice that we are now saying that for 2 lags, T1>T2, T1 has little effect

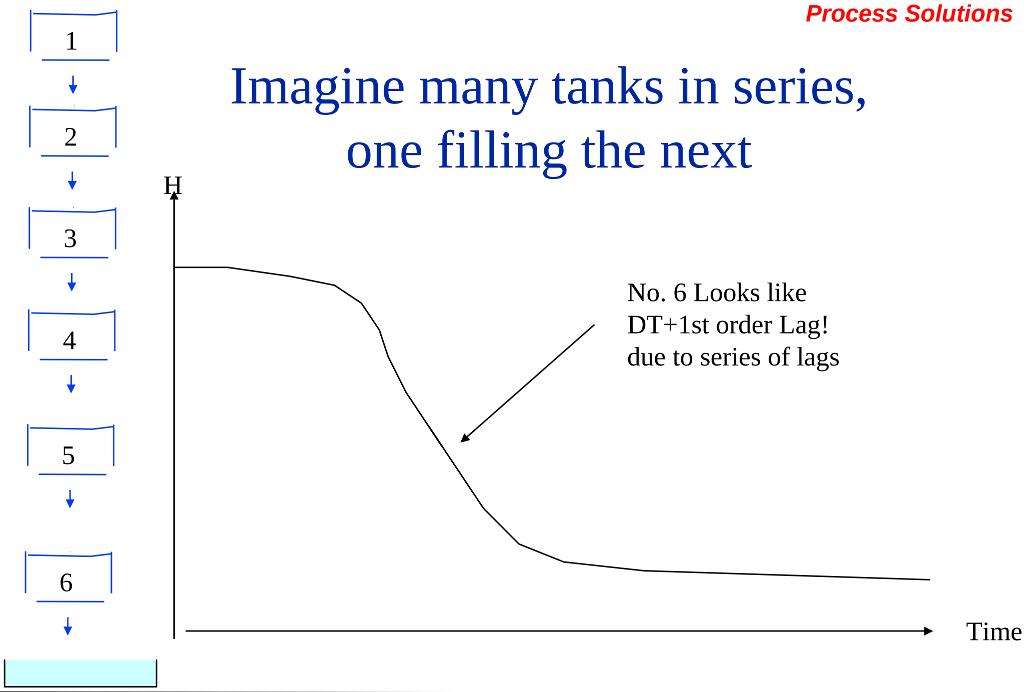


The other scenario is the reverse, the bottom tank is now slow. It gets an initial boost from the top tank that temporarily actually increases the level beyond its initial starting point.

This inverse response actually occurs in real systems in plants e.g. in pressure control systems and gives us problems in tuning.

We will look at this later in more detail in a minute

Imagine many tanks in series, one filling the next



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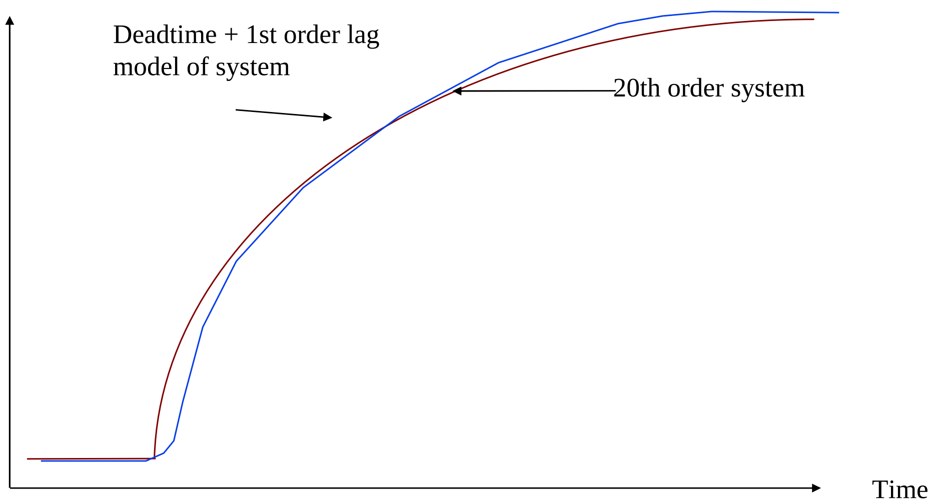
First order model approximation of a 20th order system



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What does a real plant response look like?

Real plants exhibit very high order dynamics (i.e. many lags in series) We can approximate a high order system such as the 20 order one above as a 1st order system with deadtime with a pretty good fit

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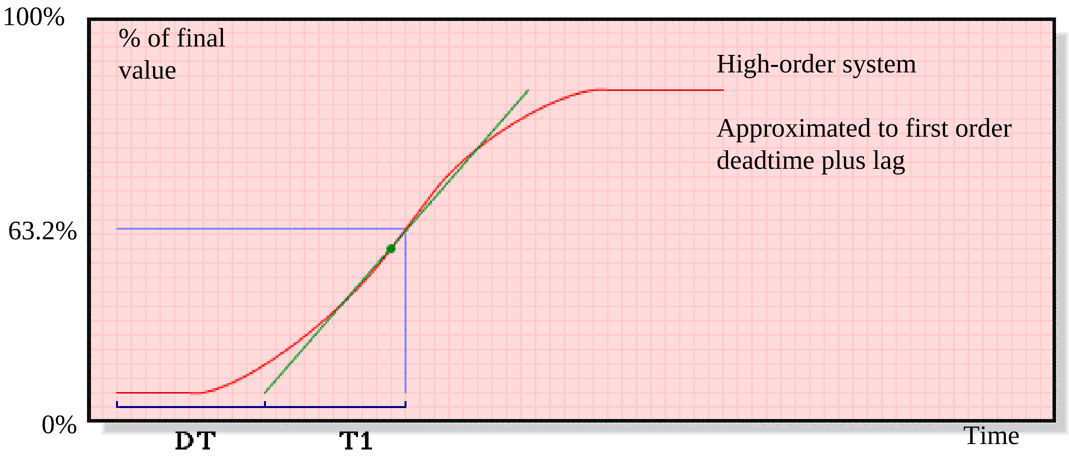
Deriving Process Dynamics



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The dynamics may be derived in two ways

The first is to approximate the curve to one of deadtime and 1st order lag and to draw a tangent at the point of steepest slope. The point of intersection on the X-axis marks the end of the deadtime and start of the lag period

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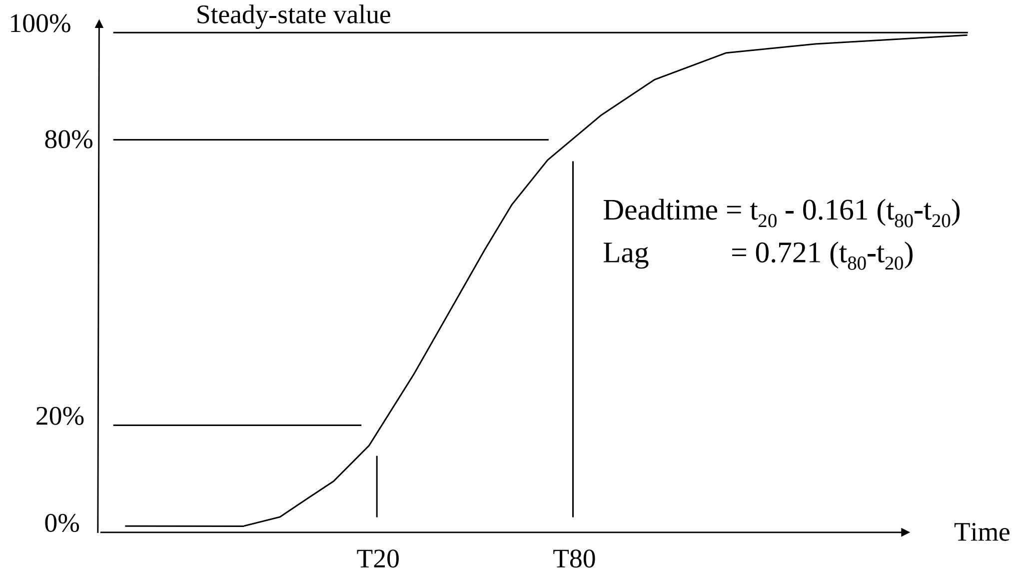
Deriving Process Dynamics with the 20%/80% method



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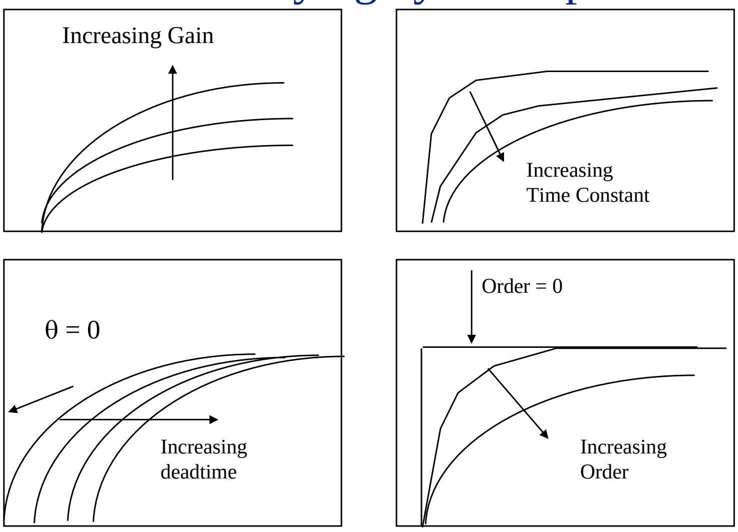
Another and more easy method is the 80/20 method developed by Honeywell Hi-Spec.

It uses a simple empirical formula to calculate the dynamics directly.

Simply measure 20% and 80% of the final value on the Y-axis and then determine the corresponding times. Then use the formula above

Effect of varying dynamic parameters



The above curves show the variation of shape of response with varying dynamics. Be sure you understand why each occurs?

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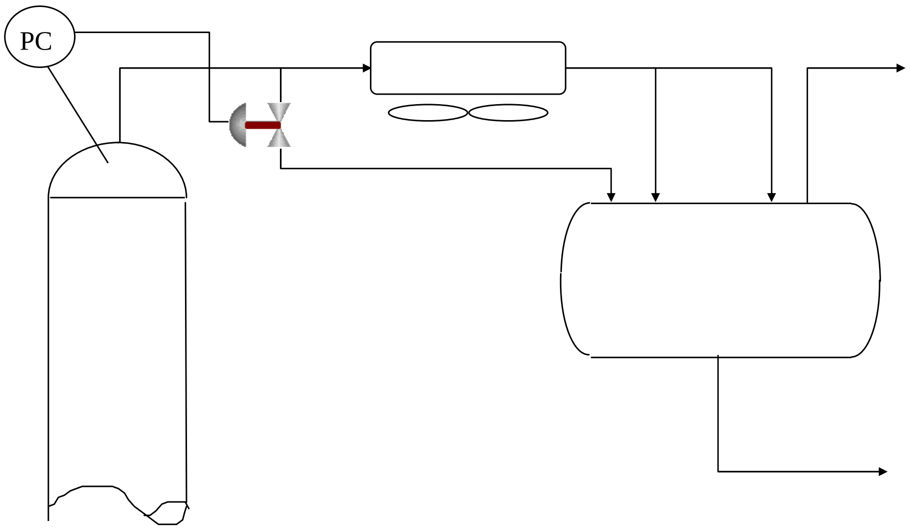
Inverse Response (1)



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Inverse response is the situation where a variable first moves in the opposite direction to that desired for control and then moves back in the correct direction to a final steady-state value

A Distillation Column with hot-bypass provides a good example

We will see how inverse response can occur in practice

1) Pressure controller opens the valve

2) There is less pressure drop across the valve so more flow through the valve and the pressure in the column drops

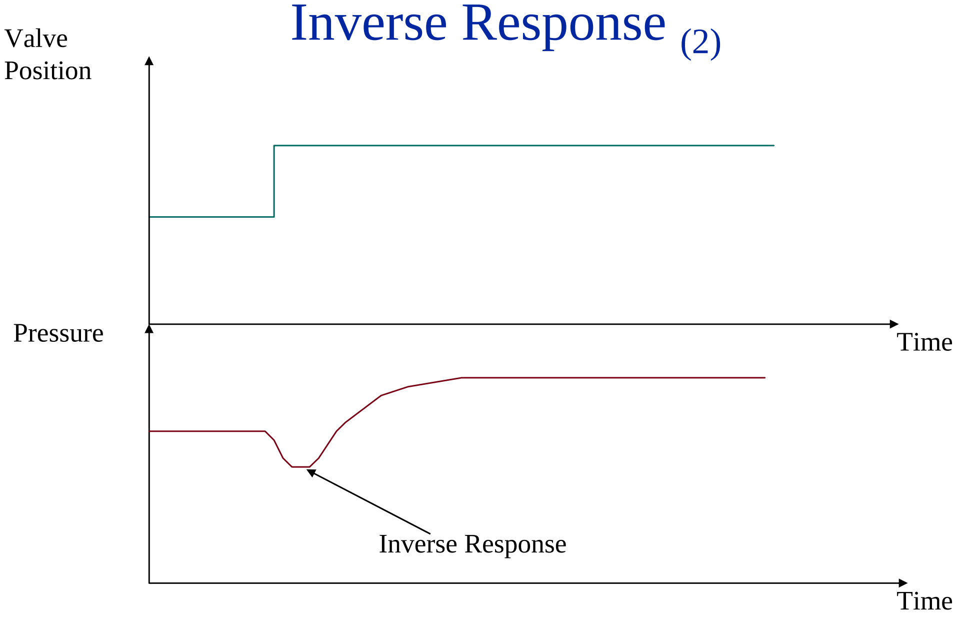
3) Also less flow through the condenser so the duty drops

4) The temperature in the drum slowly starts to rise (more hot gas is bypassed) hence the pressure in the drum rises

5) There is less pressure drop across the valve and the condenser so the column pressure starts to rise

6) The pressure and therefore the temperature continues to rise but this increases the duty in the fin-fans which finally settles out at a new steady-state position

Inverse Response (2)



The trend above shows the inverse response

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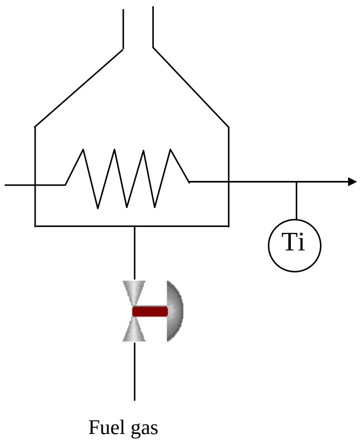
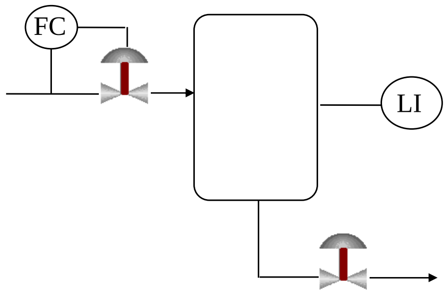
Self-regulating Process



If increase opening of fuel gas control valve, then coil outlet temperature will rise and move to a new steady-state value

Non-Self Regulating Process



If increase opening of outlet valve, then level will fall and continue to fall without reaching a new steady-state value

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A self-regulating system is one that will come to a new steady-state following a disturbance. Most control systems are self-regulating with one notable exception, level control

A non-self regulating system (such as level control) is one that will not reach a new steady-state following a disturbance but will continue in one direction or the other either filling or emptying the vessel. This may make it harder to control

Most control systems ARE self-regulating

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Linearity

- A linear system has a constant process gain
- Most processes in refining, chemicals etc are at least slightly non-linear
- This has implications for controller tuning (need to tune for different conditions)
- Implications for plant tests or step tests
- Some processes are known to be highly non-linear e.g. pH control

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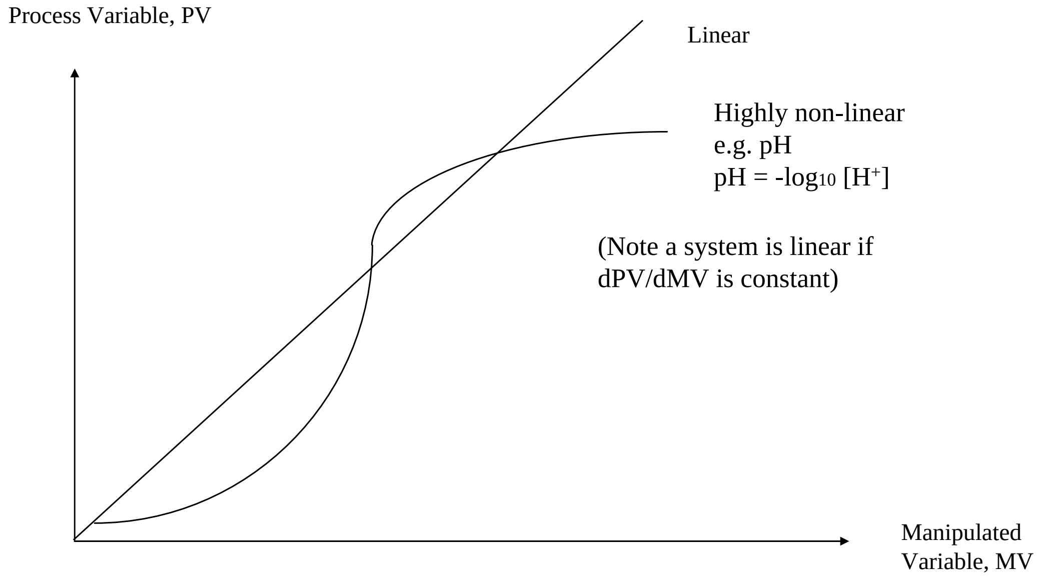
What are the implications for tuning? Use compromise tuning. Need to tune for different conditions since process results in different ways for different changes in MV

What are the implications for plant tests? Do tests in both directions

How can we solve highly non-linear control problems? Need to use some form of adaptive control



This is a typical pH control scenario

Process responds very non-linearly

Control is very difficult using normal methods (PID)

How to solve ? Use adaptive control, or linearize the process by controlling log pH instead of straight pH?

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Plant Tests, Guidelines (1)

- Choose the right time
  - Not at a shift changeover
  - Not during a feed switch
  - Not at dawn or dusk
  - Not on Monday morning!
  - Not on Friday afternoon!
- Set up sampling/lab analysis if required
- Talk about test with operations and get approval for test
- Ensure instrumentation is OK
- Ensure process is steady

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Why right time? to not cause hassle for operators

Why not at dawn or dusk? temperature changes due to ambient change

Why set up sampling? to get all the data we need

Why approval? not to get operators annoyed/follow correct procedures, be safe, make large moves rather than small moves, too small moves might not be visible!

Why instrumentation OK? to ensure tests are not a waste of time!

Plant Tests, Guidelines (2)

- Open required loop, make step change of say 2-5% valve movement
- Record trend of OP and PV
- Reach new steady state some people use $\theta+5\tau$
- Carry out test again in opposite direction, double amount if possible
- Ensure Manipulated variable really changes
- Document results
- Do tests under all modes of operations
- Step away from any constraints on the unit for safety

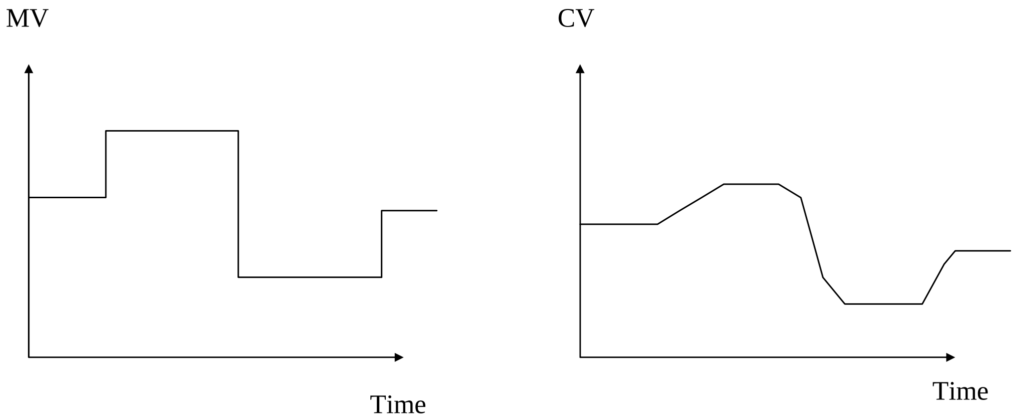
Why other direction? to check linearity

Why twice amount? bigger step gives better estimate of steady-state gain

Why all modes? different dynamics!

Why away from constraints? Not to give operators/the plant a hard time!

Plant Tests



Conclusion

- Understanding dynamics is the key to controlling any process
- Simple dynamics can be represented by gain, deadtime and lag
- These may be determined by carrying out plant step tests

Process Dynamics

Exercises

Exercise in Process Dynamics

- Using both of the methods in the lecture (63.2% and 80/20 method) calculate the process dynamics for the responses in fig 1. The response is that of a heater coil outlet temperature to a step change in fuel gas flow of 50 m3/h
- Fig 2a and 2b show the results of tests carried out on the same heater. The fuel gas flow change was 40m3/h. Calculate dynamics using the 80/20 method, comment on results
- Comment on fig 3a,b,c,d process responses
- Carry out PID tutorial exercise on dynamics

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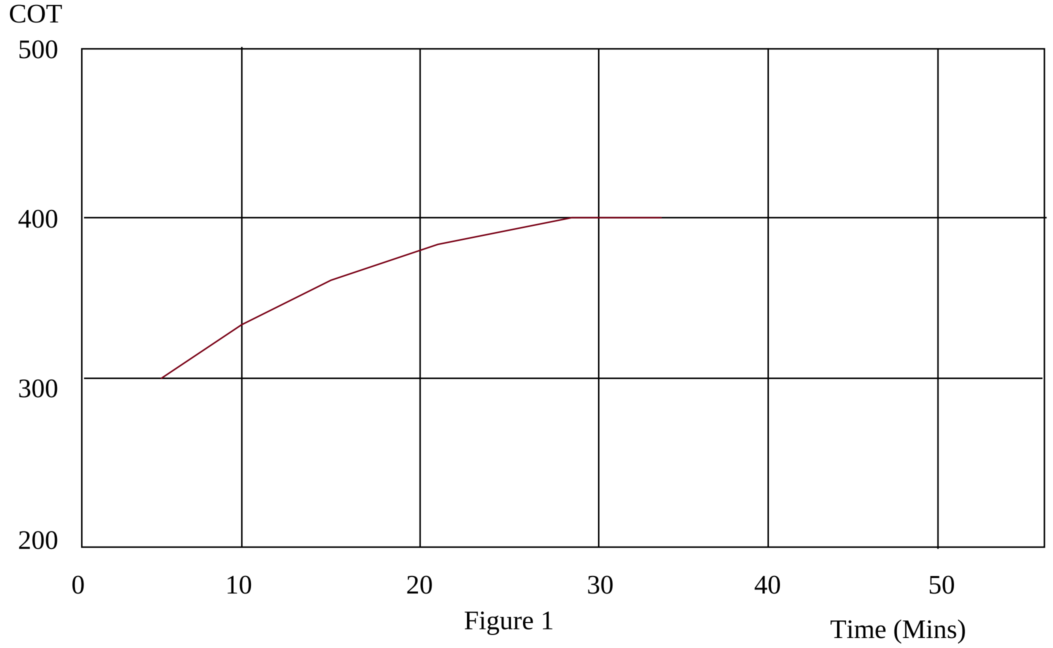

Figure 1

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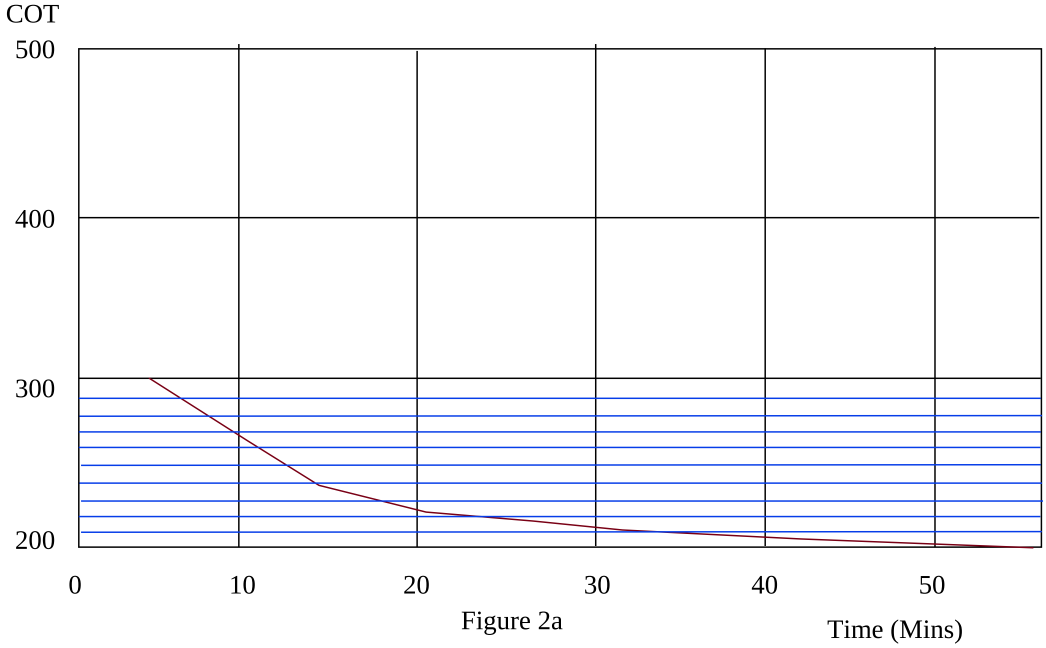

Figure 2a

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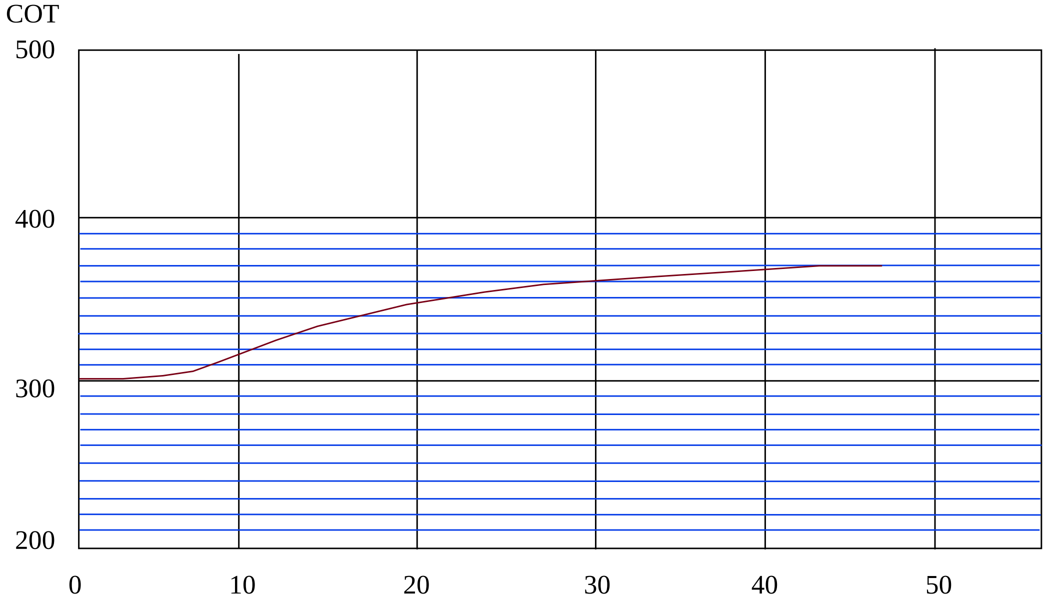

Figure 2b

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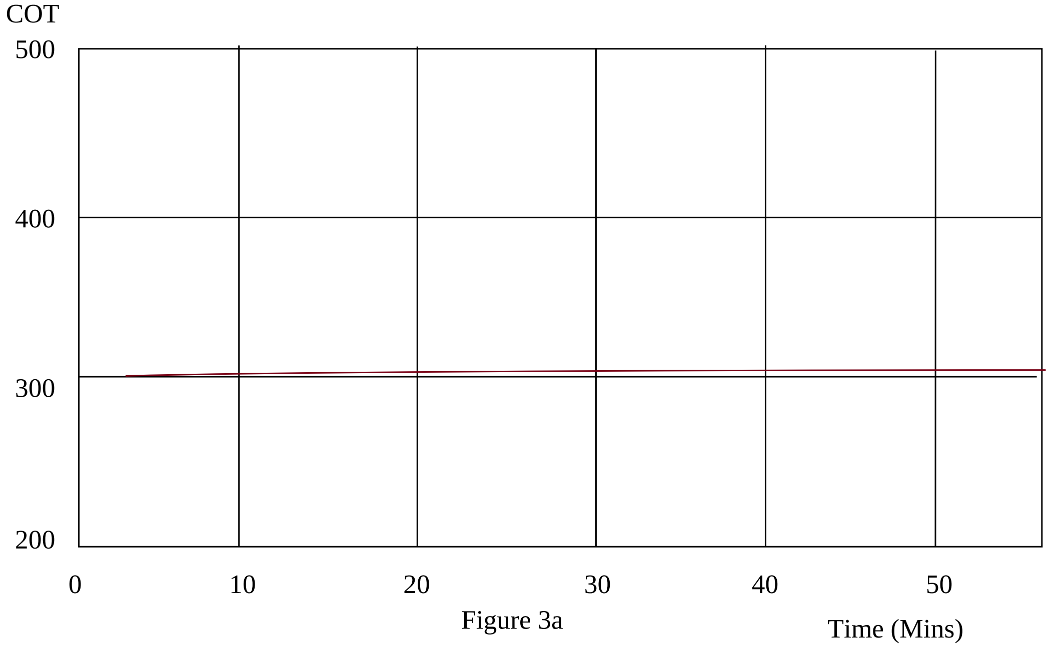

Figure 3a

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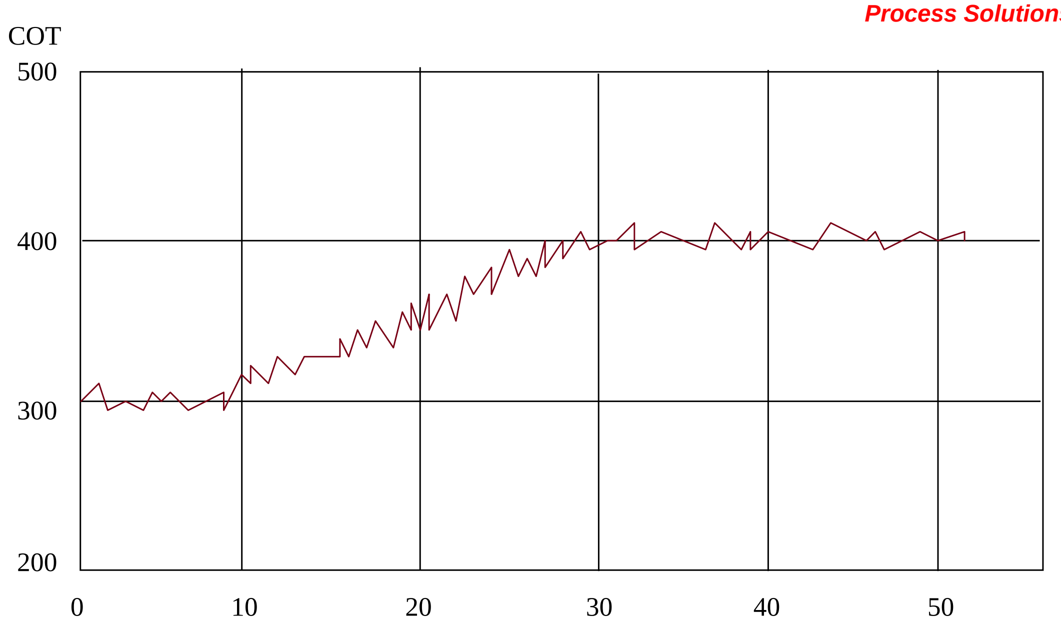

Figure 3b

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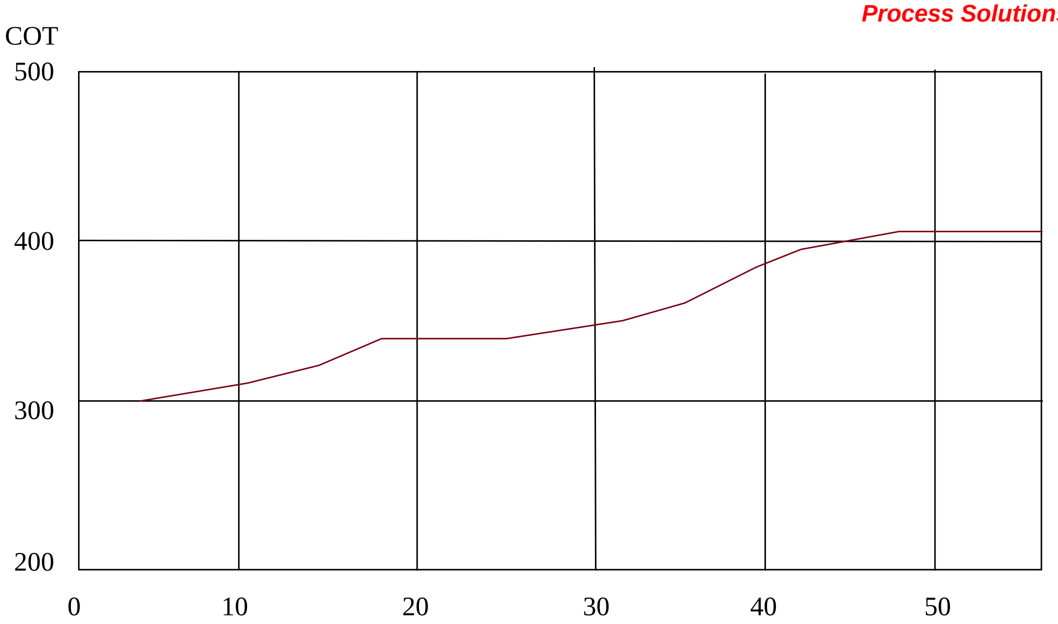

Figure 3c

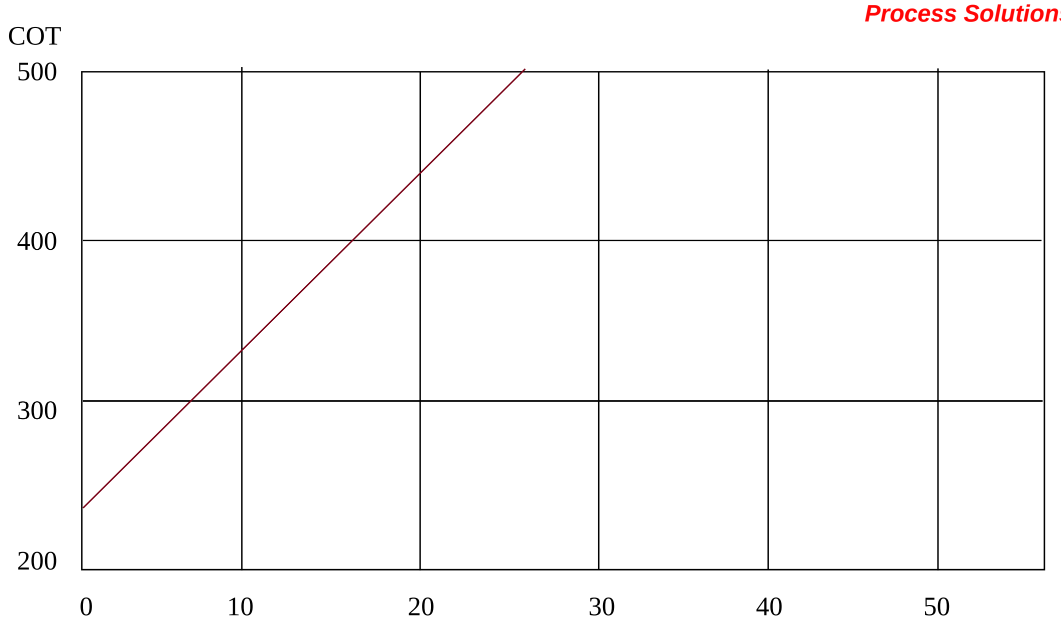

Figure 3d

Time (Mins)

Interactive Exercises

- Tutorial Software
  - Tutorial Menu
    - PID Algorithm
  - Lesson Menu
    - Introduction
    - Open Loop
    - Closed Loop
    - On-Off Control
    - Definitions

Use the arrow keys to navigate to the next / previous screen.

Use the <backspace> key to change tuning constants, etc.

Do not use the numeric keypad.