CHEN4011
Advanced Modelling and COntrol

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Lecture Note 5
PID Enhancement Techniques: Override, Inferential and Gain Scheduling Control

Outline

- Objectives of Plant Control
- Process Control Roles and Plant Objectives
- Process Constraints – why important?
- PID Control Enhancement Strategies
  1. Override Control
  2. Inferential Control
  3. Scheduling Controller Tuning
  4. Computed Manipulated Variable

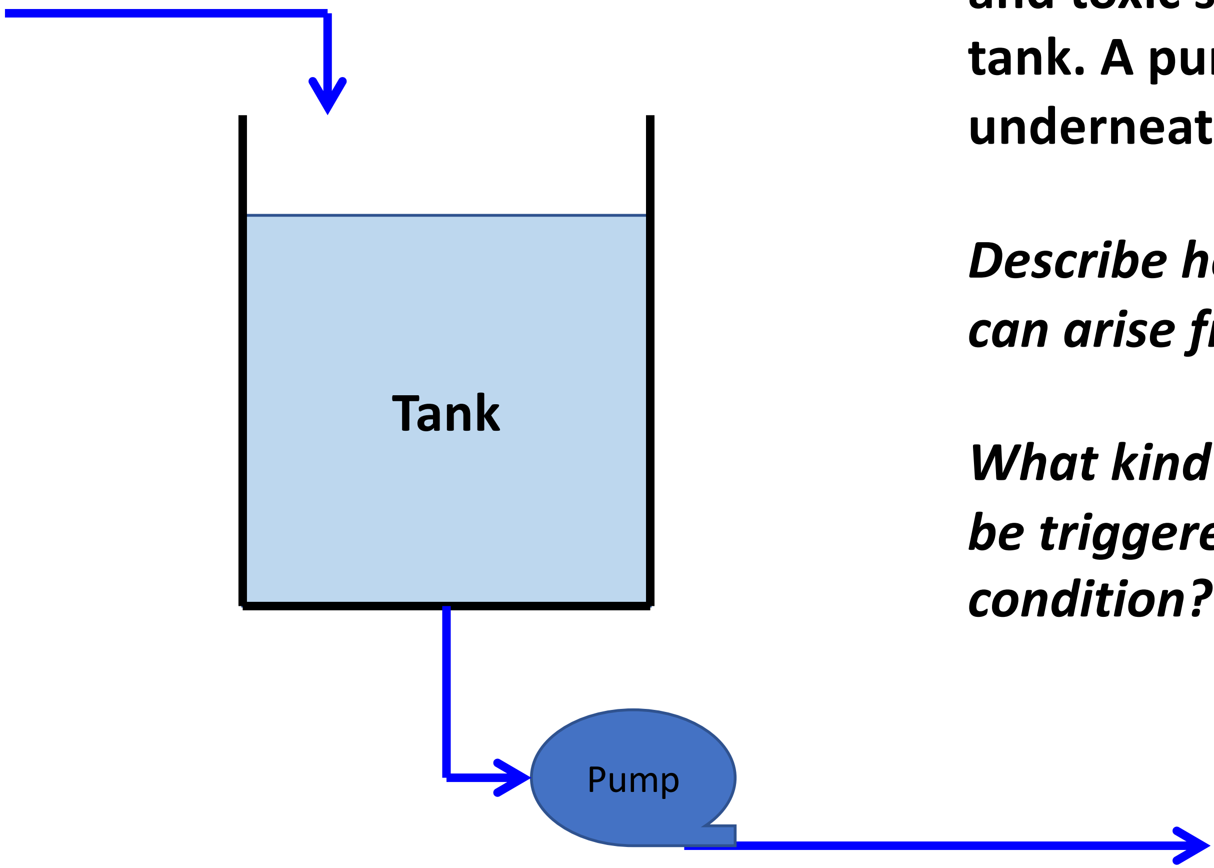
Objectives of Control

- Control system is designed to achieve 5 major plant objectives:
    1) **Safety**
    2) **Equipment Protection**
    3) **Environmental Protection**
    4) **Smooth Operation**
    5) **Profit**
- These objectives are *interrelated*.

Process Safety

- Safety implies free of any accident.
- Accident in process plant can be caused by two factors:
  1) **Unsafe conditions**
  2) **Unsafe acts**
- *Which factors that can be mitigated by proper control system?*
- *How to address these factors?*

Unsafe Conditions



A feed stream containing acidic and toxic solution is fed into a tank. A pump is placed underneath the tank.

Describe how an unsafe condition can arise from the operation.

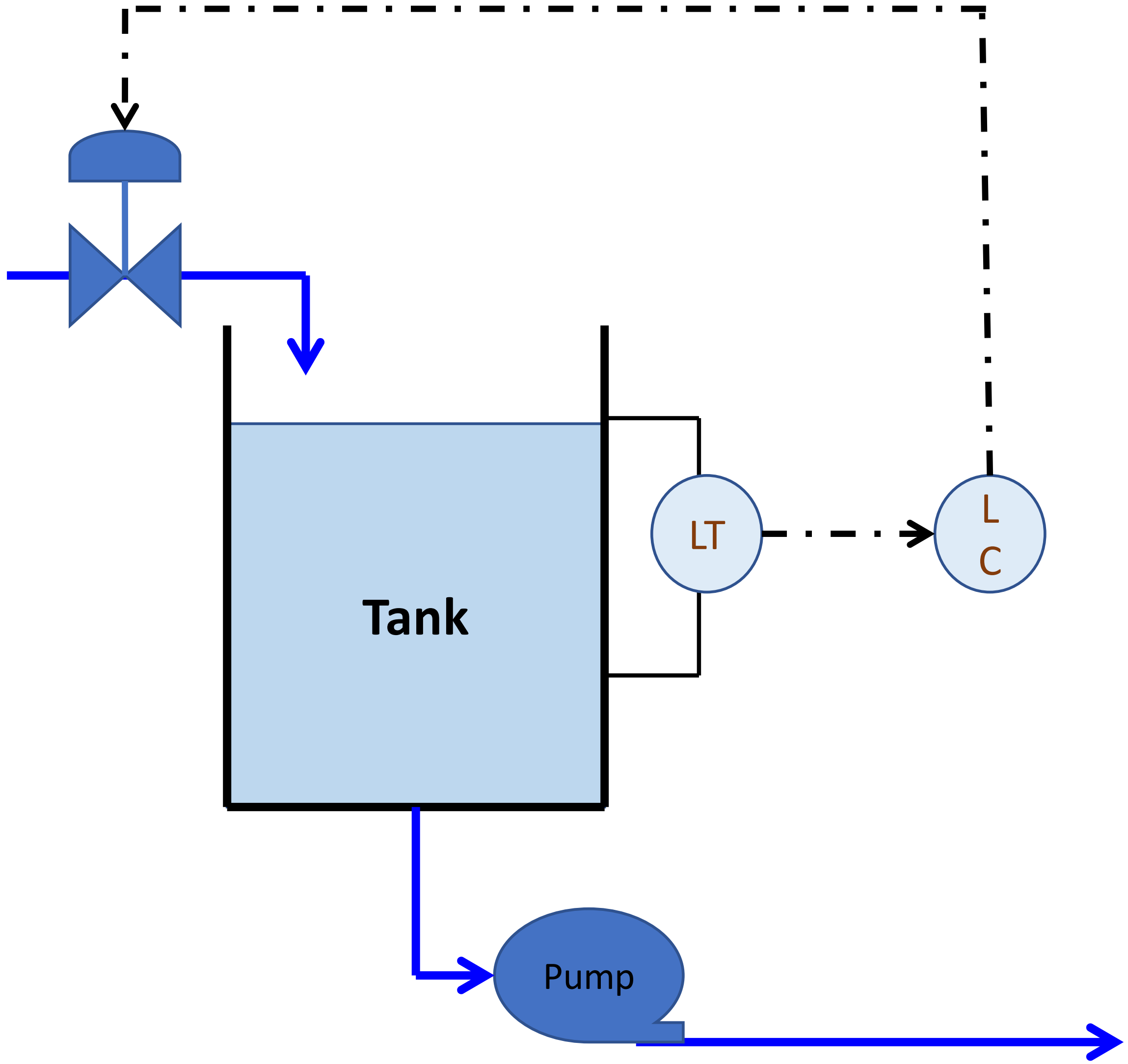
What kind of accidents that can be triggered by the unsafe condition?

Prevention of unsafe conditions

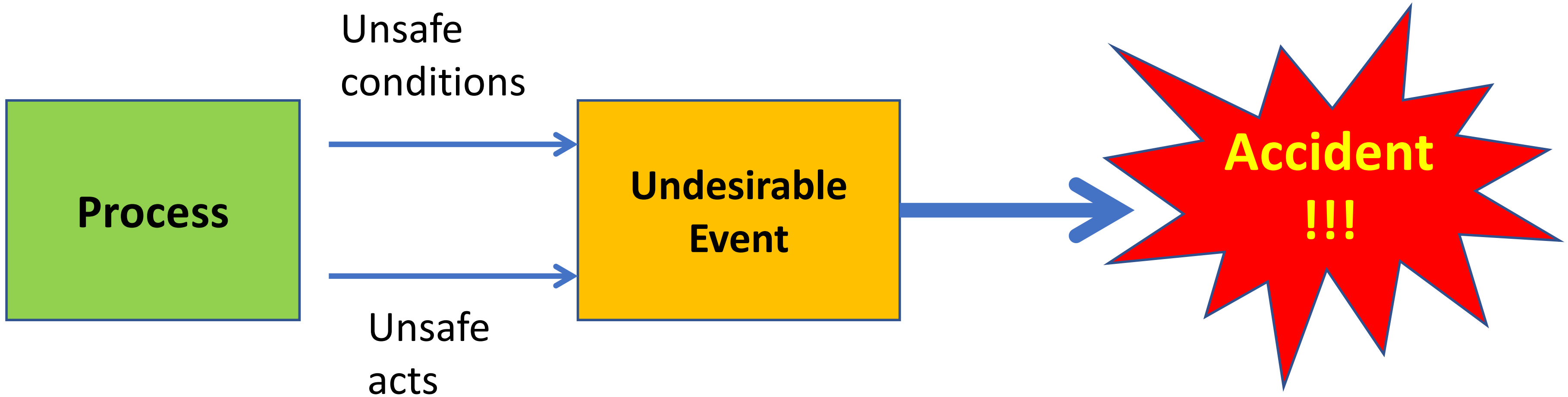
Applying control to the liquid level can ensure that liquid spill over will not occur.

Liquid level control => Prevention of Liquid Spill Over => control objective => Safety

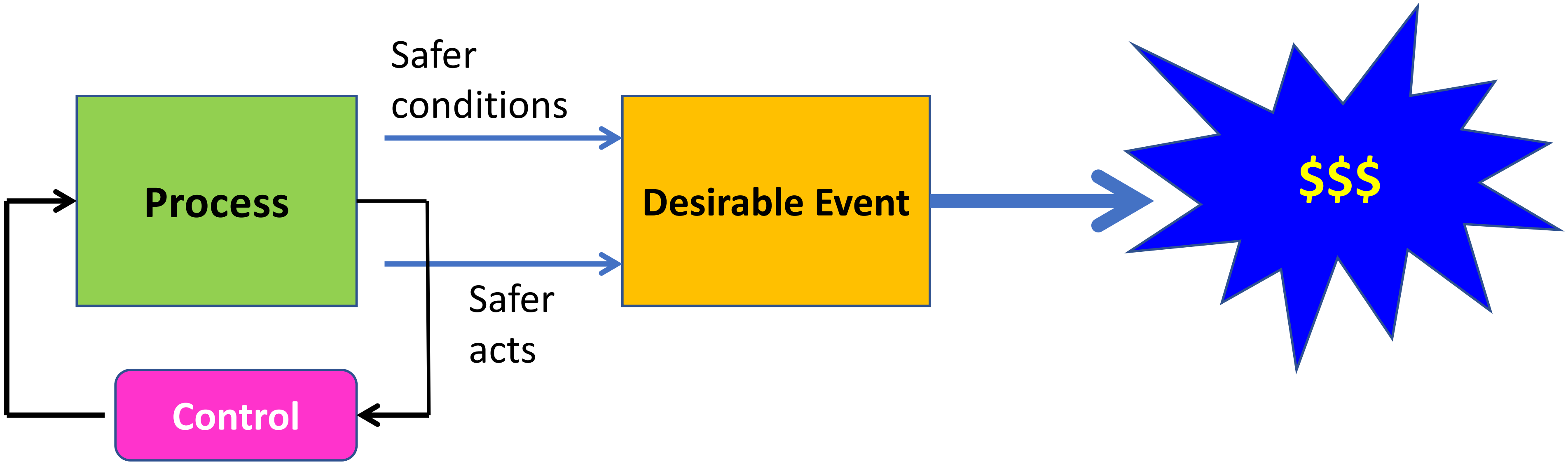
Could you think of another benefit of liquid control?



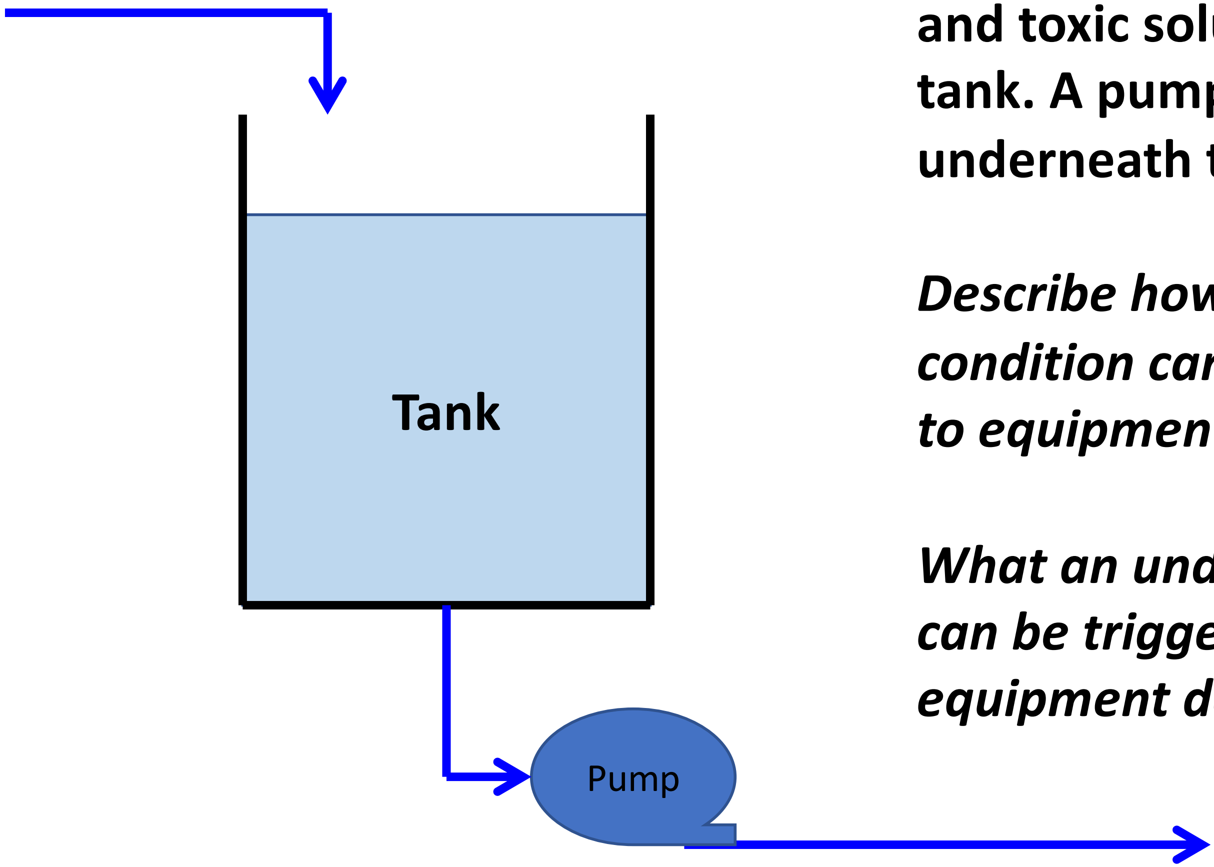
Accident occurs because of unsafe conditions + unsafe acts due to no proper control.



With proper control of a process, safer conditions + safer acts can be achieved, hence leads to safe and profitable operation.



Equipment Protection



A feed stream containing acidic and toxic solution is fed into a tank. A pump is placed underneath the tank.

Describe how an operational condition can arise, which leads to equipment damage.

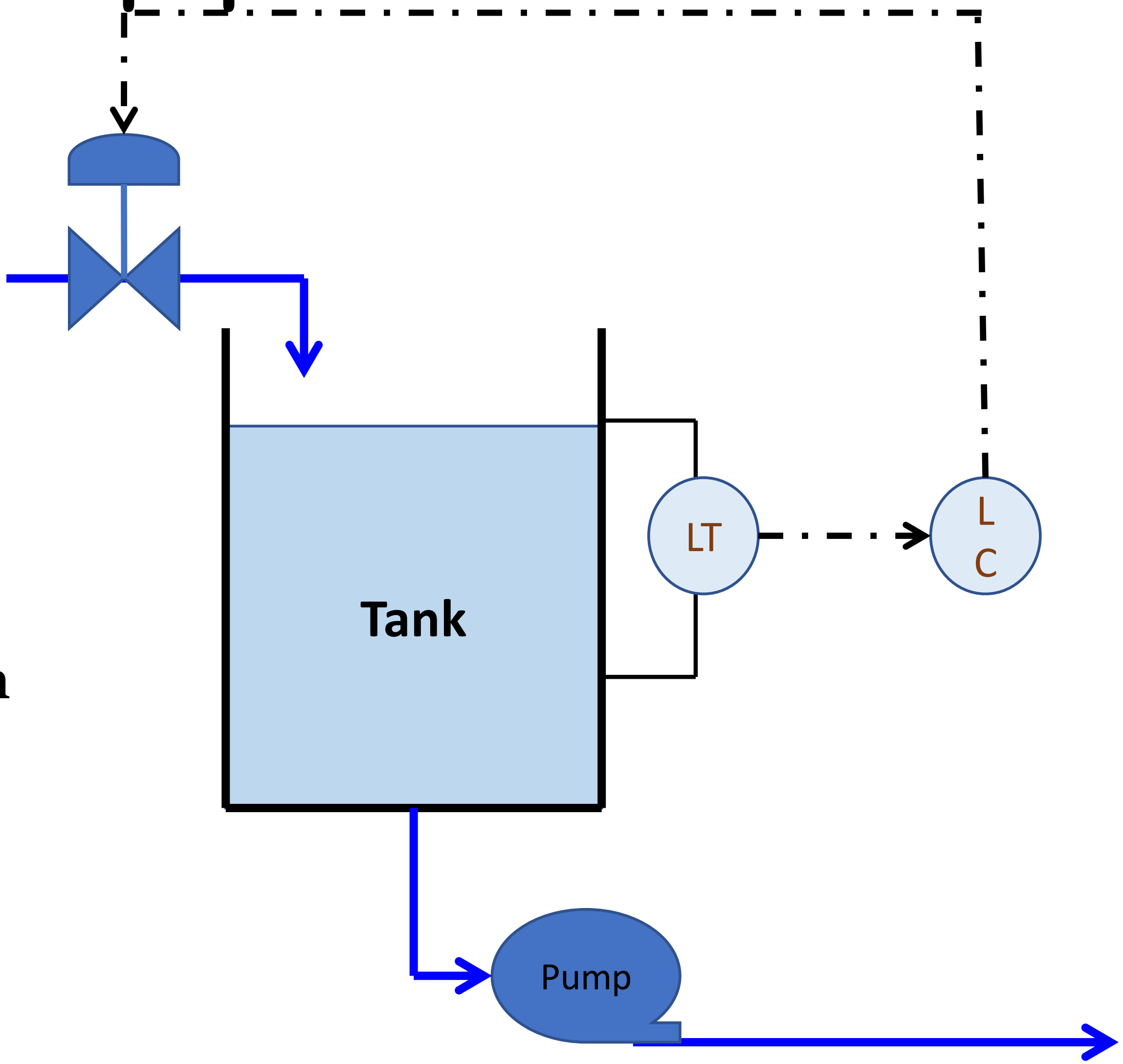
What an undesirable event that can be triggered by the equipment damage?

Protection of Equipment

Applying control to the liquid level can ensure that liquid will not drop below a minimum limit, below which cavitation occurs.

Liquid level control
=> Prevents cavitation
=> control objective
=> Equipment Protection

Could you think of another benefit of liquid level control?



Tank Level Control - Example

- In this example, liquid level control can achieve both objectives
  - i. **Safety**
  - ii. **Equipment protection**
- **Both safety and equipment protection are interrelated.**
- **Failure to protect** the pump can lead to cavitation, which can lead to unsafe conditions, hence to an accident.

Environmental Protection

Flash Tank

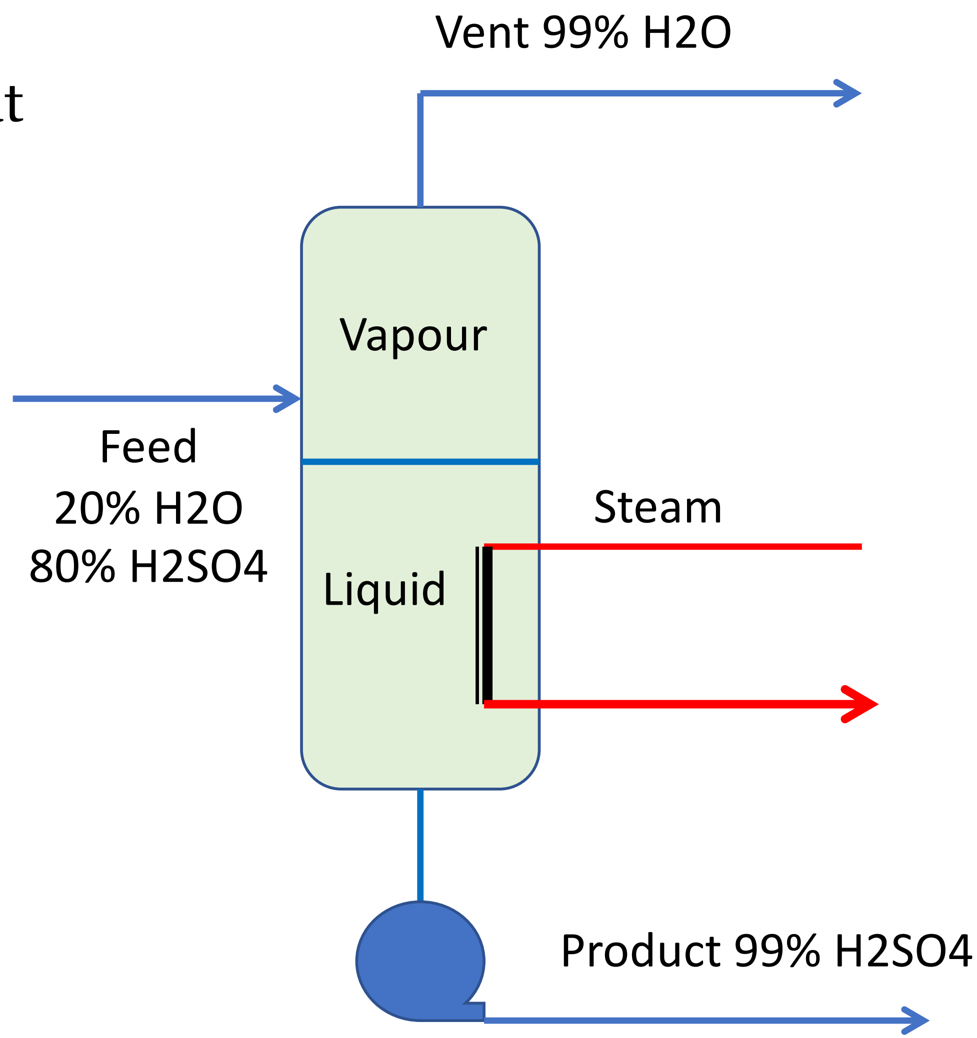
Feed containing 20% water and 80% H_2SO_4. Product must be at least 99% pure H_2SO_4

Vent discharge should not be more than **1% H_2SO_4**, otherwise violates an environmental regulation.

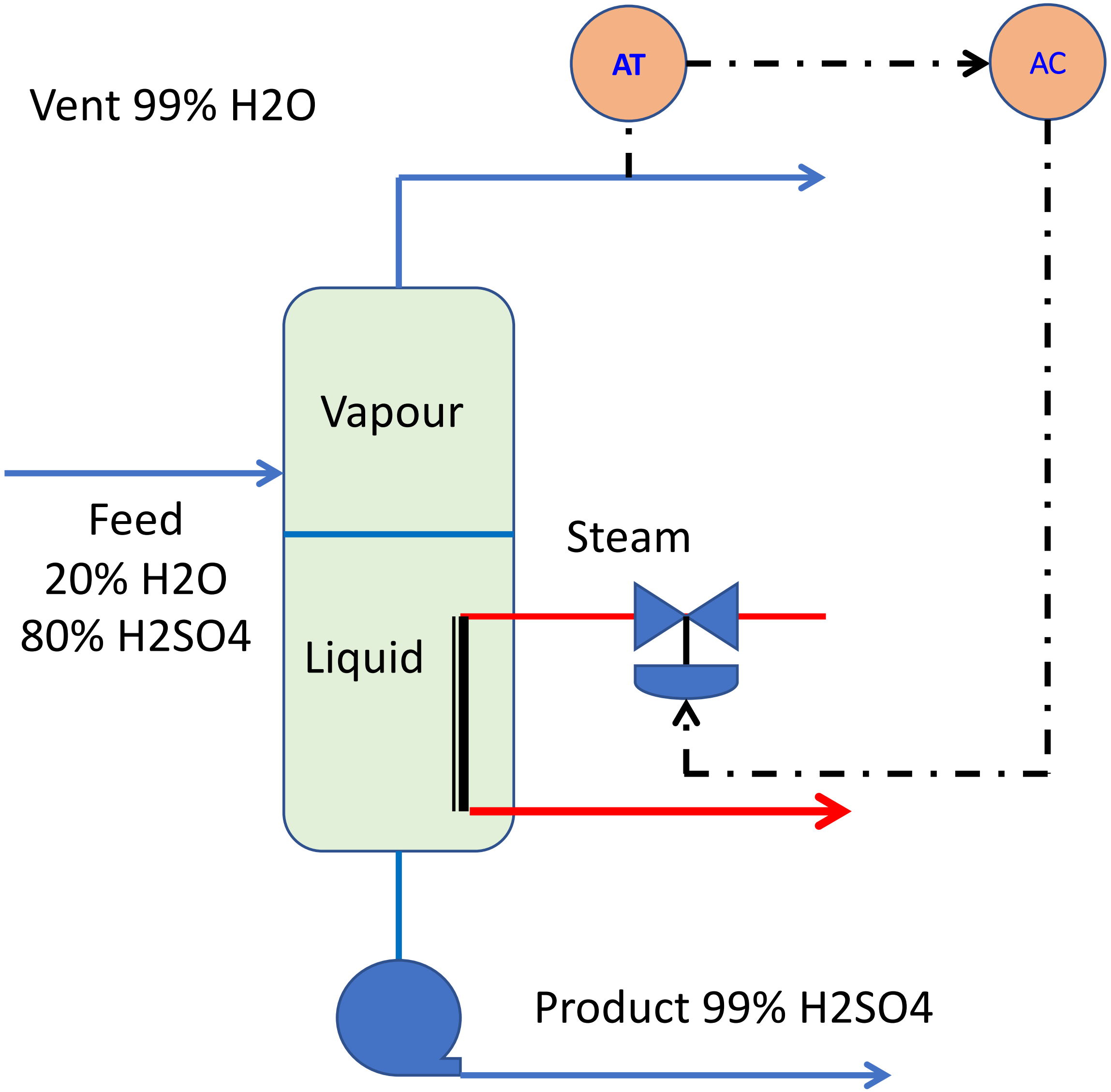
Describe how can the vent discharge exceed 1% limit?

What damages can arise if the limit discharge is exceeded?

What is the implication of this violation on sustainability?



Environmental Protection

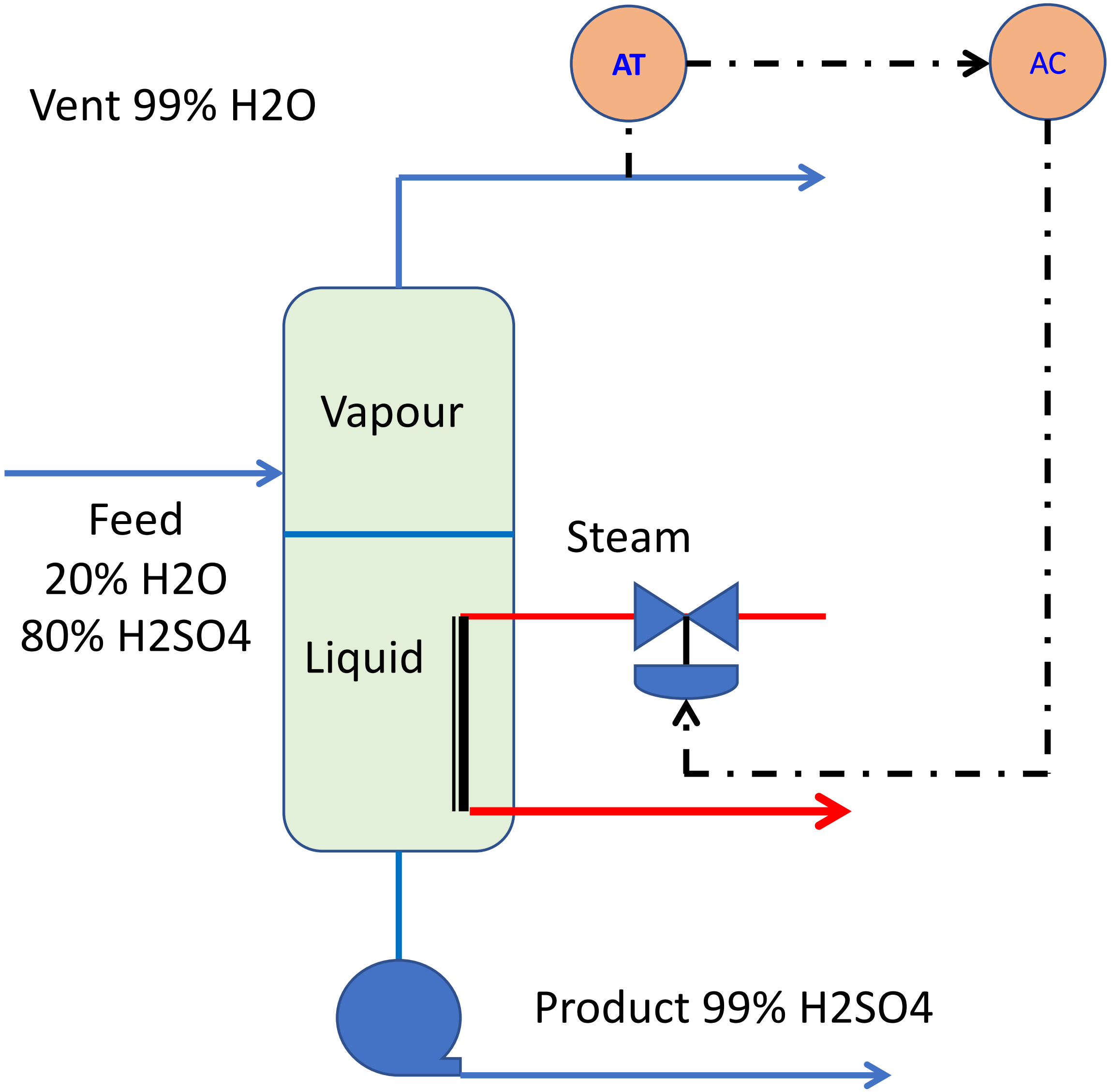


By controlling the H_2SO_4 mass fraction in the vapour using steam flow rate, it can ensure that the limit will not be violated during operation.

The question becomes, is this control strategy sufficient?

Do we need to address safety and equipment Protection issues?

Flash Tank Example

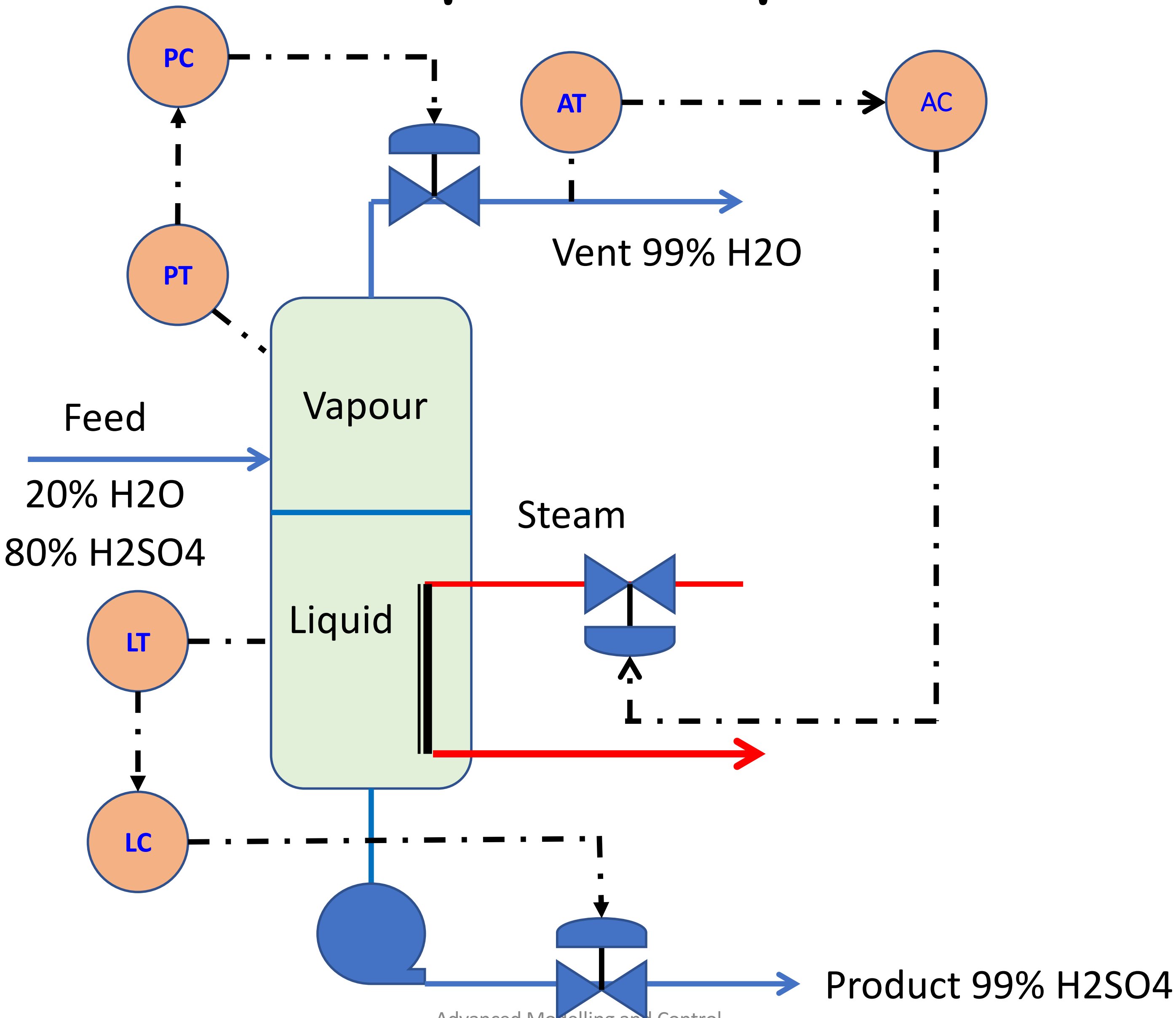


MUST achieve all **basic objectives** of safety and equipment protection for the system.

Which variables are related to safety, and which related to equipment protection?

Must control:
Pressure, Liquid Level

Flash Tank Example – Complete Control

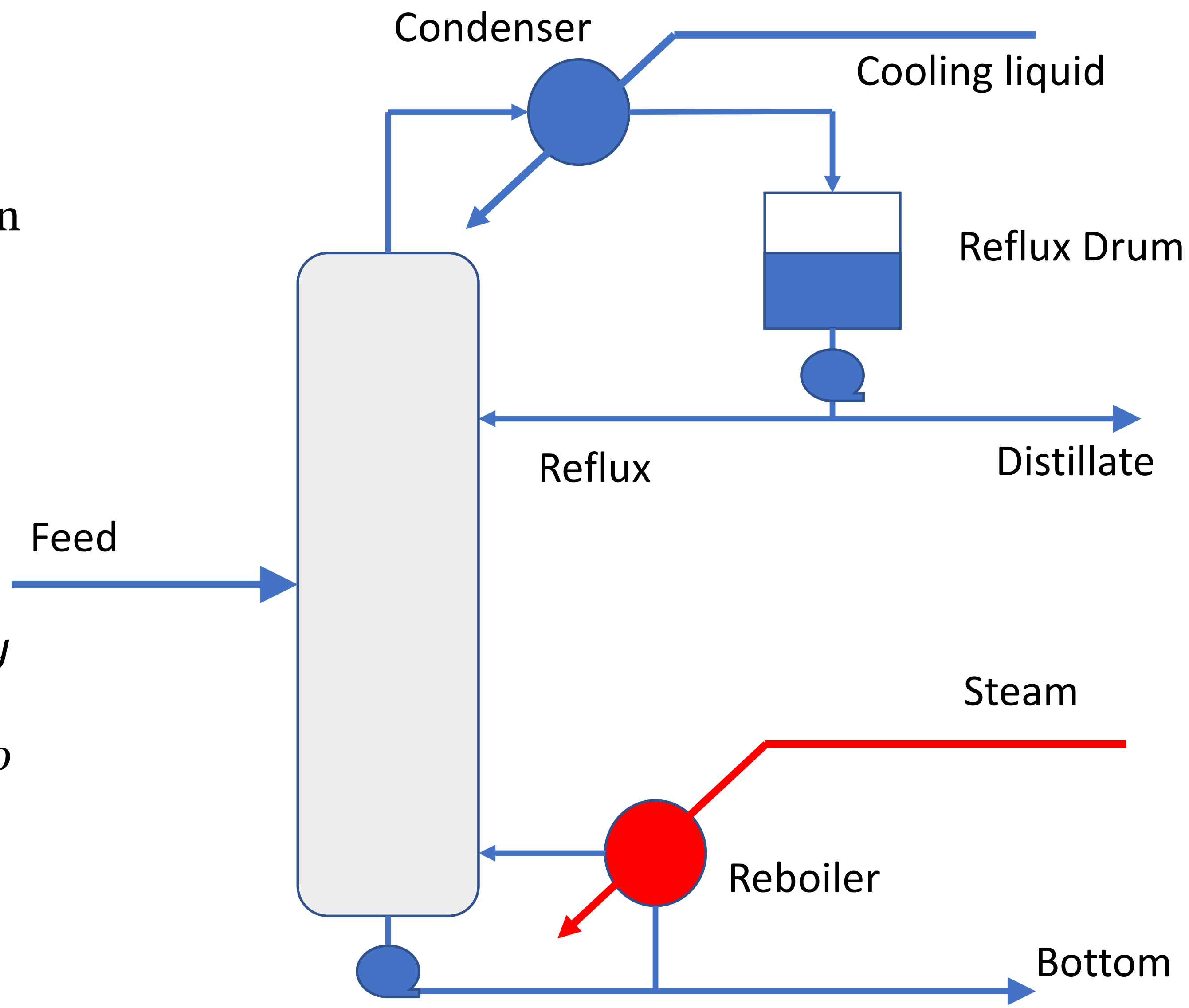


Smooth Operation – Distillation Column

Distillation Column is an important unit in many chemical plants.

The column has several control objectives.

Can you identify which control loop is related to Smooth Operation?



Operating Constraints

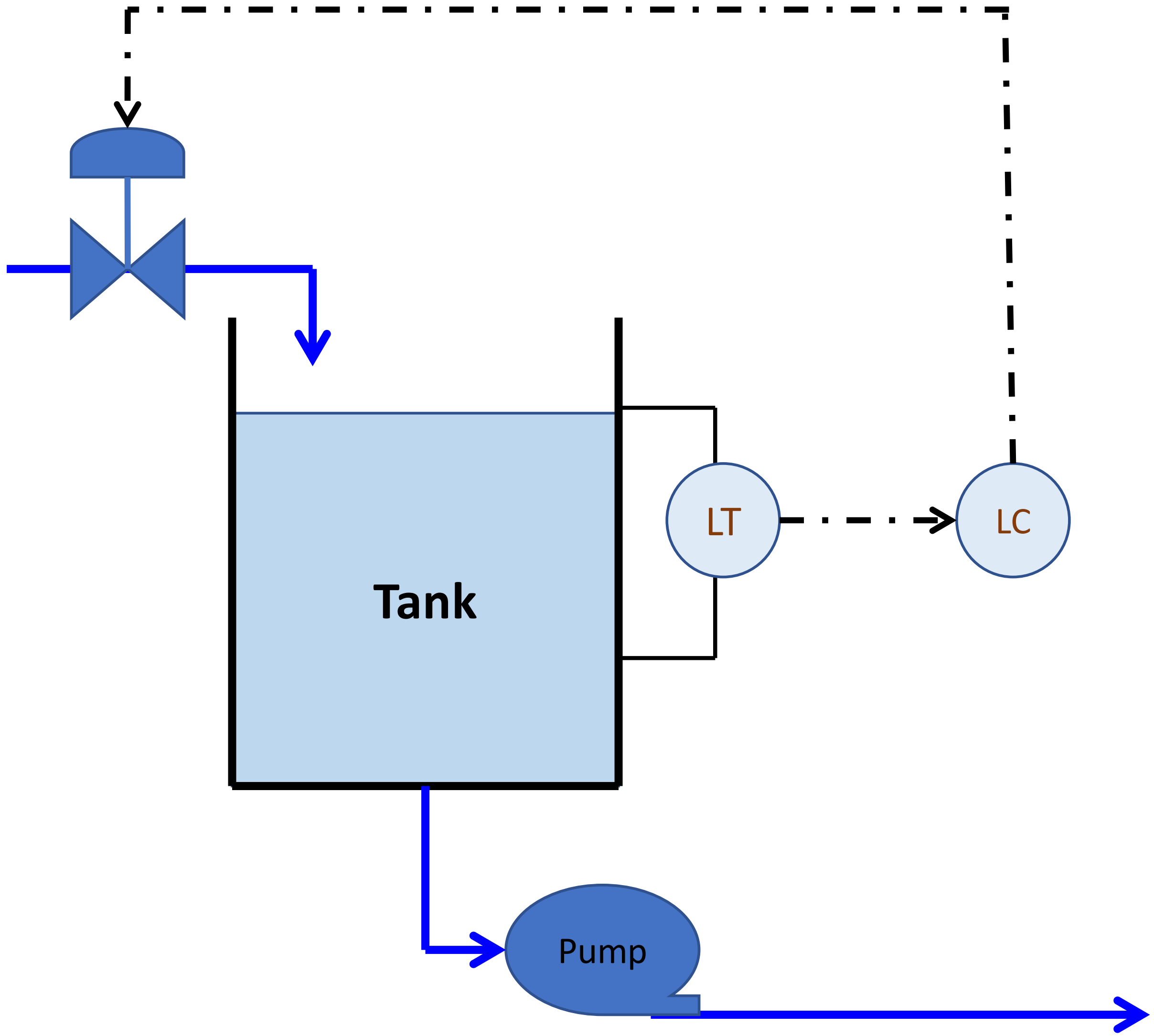
- Constraints are divided into:
  1. Soft constraints
  2. Hard constraints
  - Soft constraints – these can be violated during operation without causing safety problems.
  - Hard constraints – physical limitations on flow rates due to valve sizes. Others, constraints that related directly to Safety – these constraints cannot be violated.

Examples of Constraints

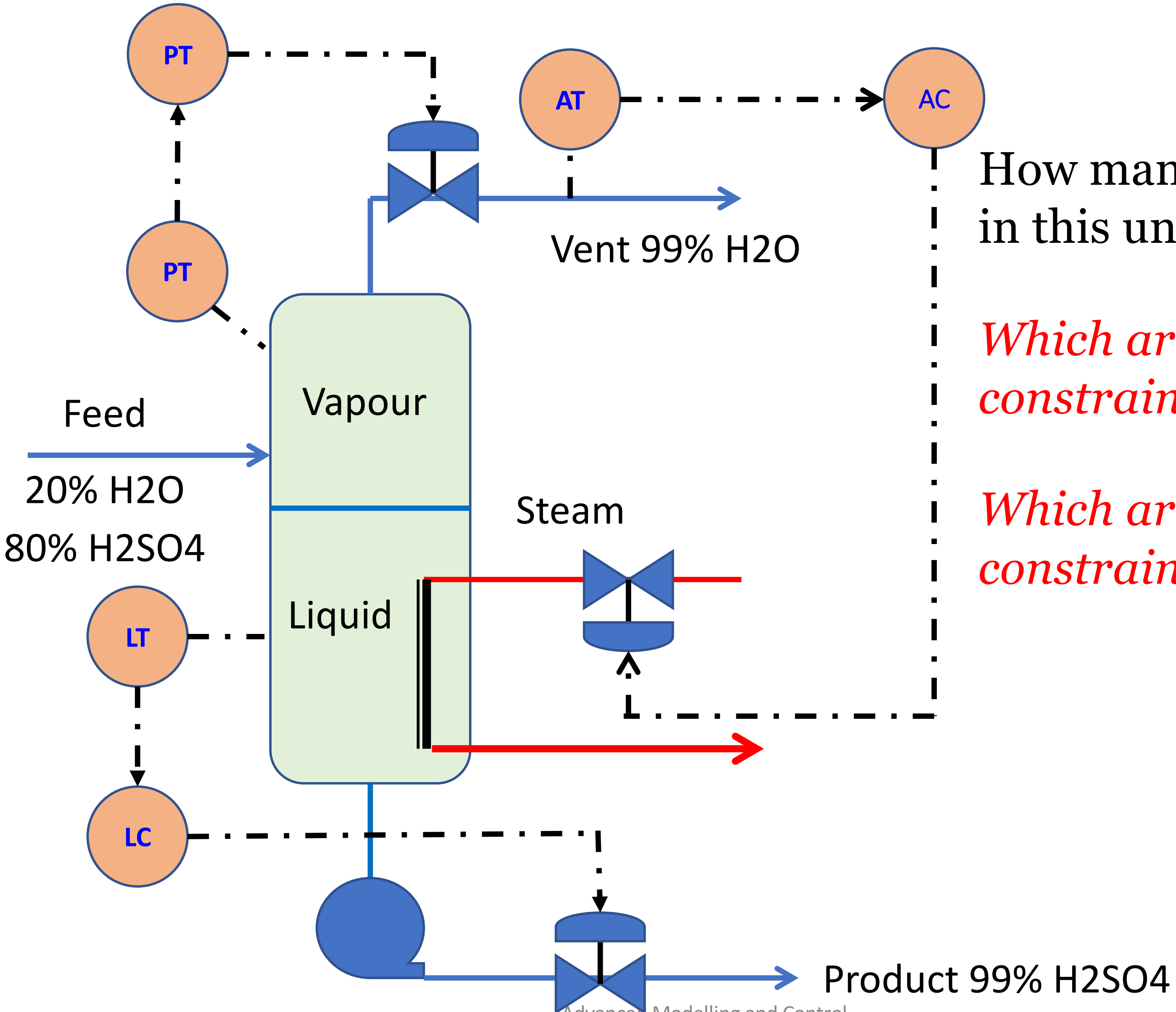
What are the constraints involved?

Which are Hard Constraints?

Which are Soft Constraints?



Examples of Constraints



How many constraints in this unit operation?

Which are hard constraints?

Which are soft constraints?

How to Deal with Process Constraints ?

- Dealing with **Process Constraints** are important to prevent **accidents, unnecessary process disruptions, loss in profit**, etc.
- Conventional **PID controllers are NOT** able to handle constraints.
- **Override Control Strategies** are used to deal with Constraints.

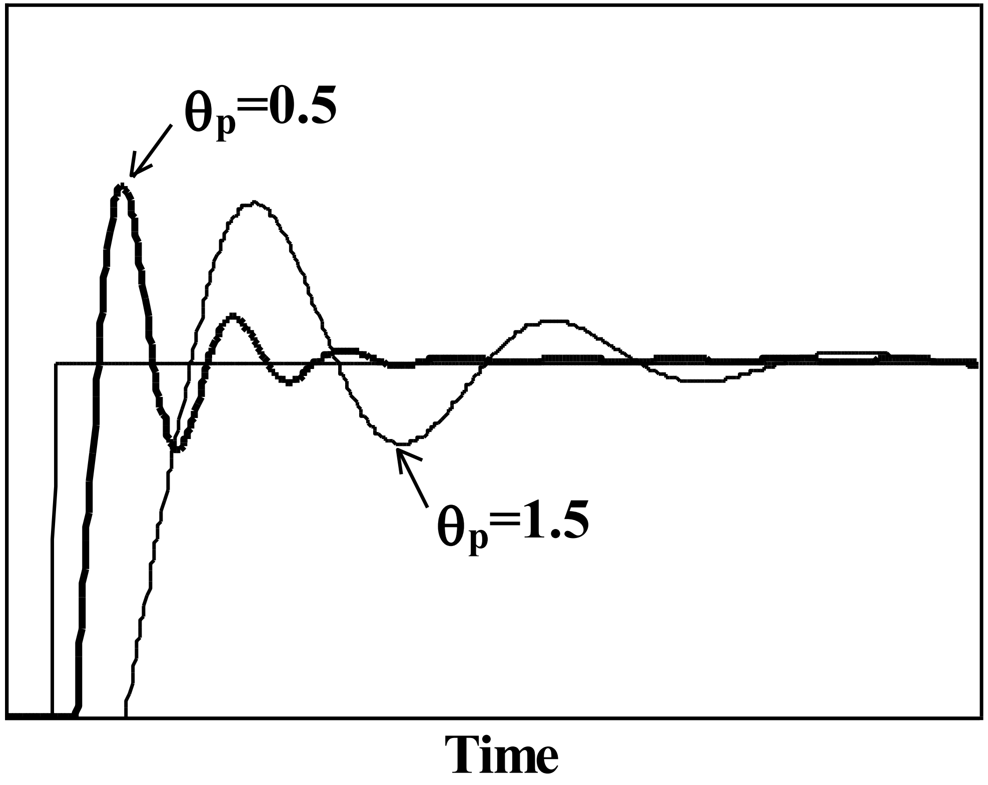
Limitations of Conventional PID Controllers

- The performance of PID controllers can be substantially limited by:
  - Process nonlinearity
  - Measurement deadtime
  - Process constraints
- This chapter will consider approaches for PID controllers to handle each of these problems.

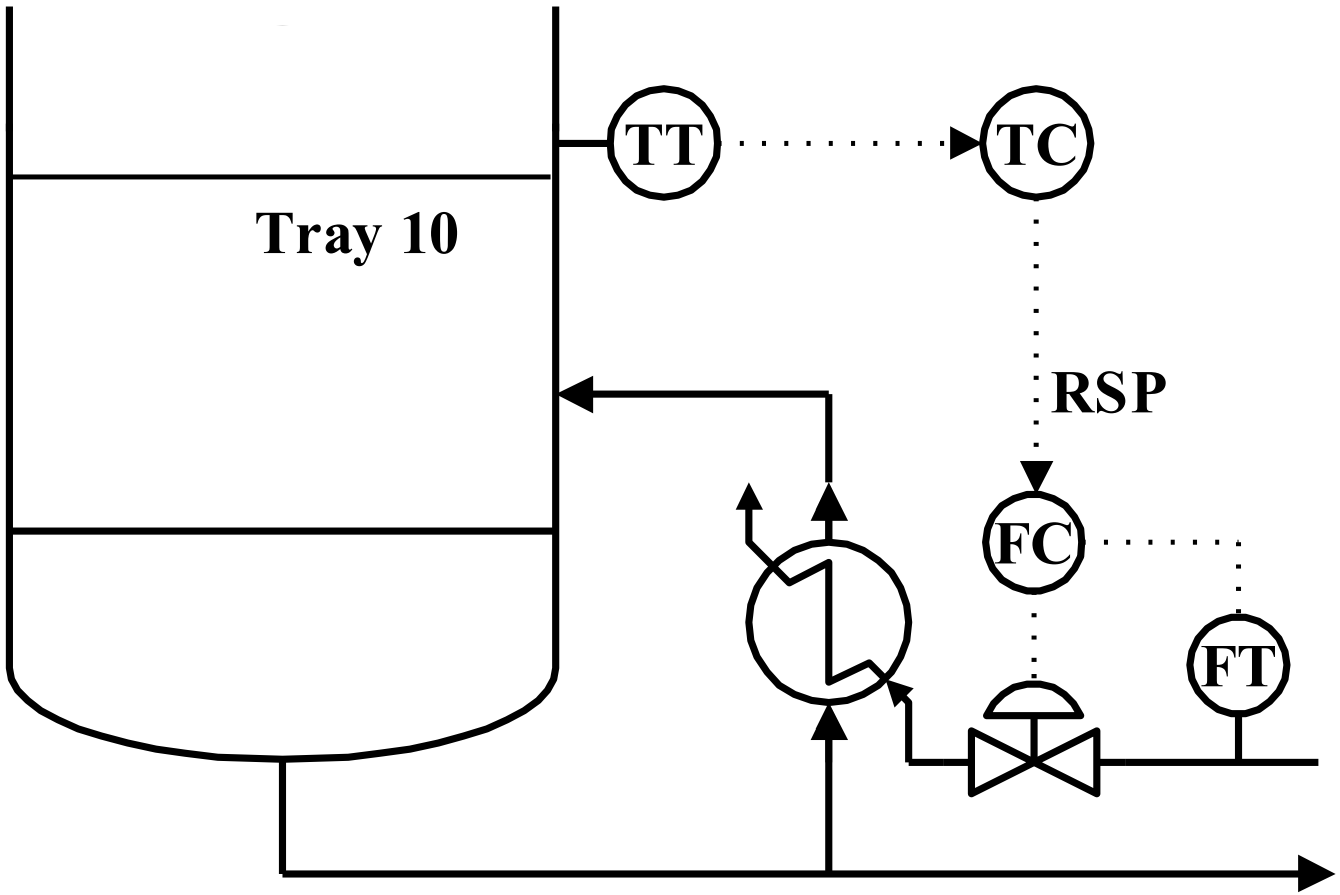
Inferential Control

- Uses easily measure process variables (T, P, F)
  - To infer more **difficult to measure quantities** such as compositions and molecular weight.
- Advantages:
  - Can substantially **reduce analyzer delay**.
  - Can be much **less expensive** in terms of capital and operating costs.
  - Can provide **measurements that are not available** any other way.
- Effective when;
  - Inferential **measurement must correlate strongly** with the controlled variable of interest.

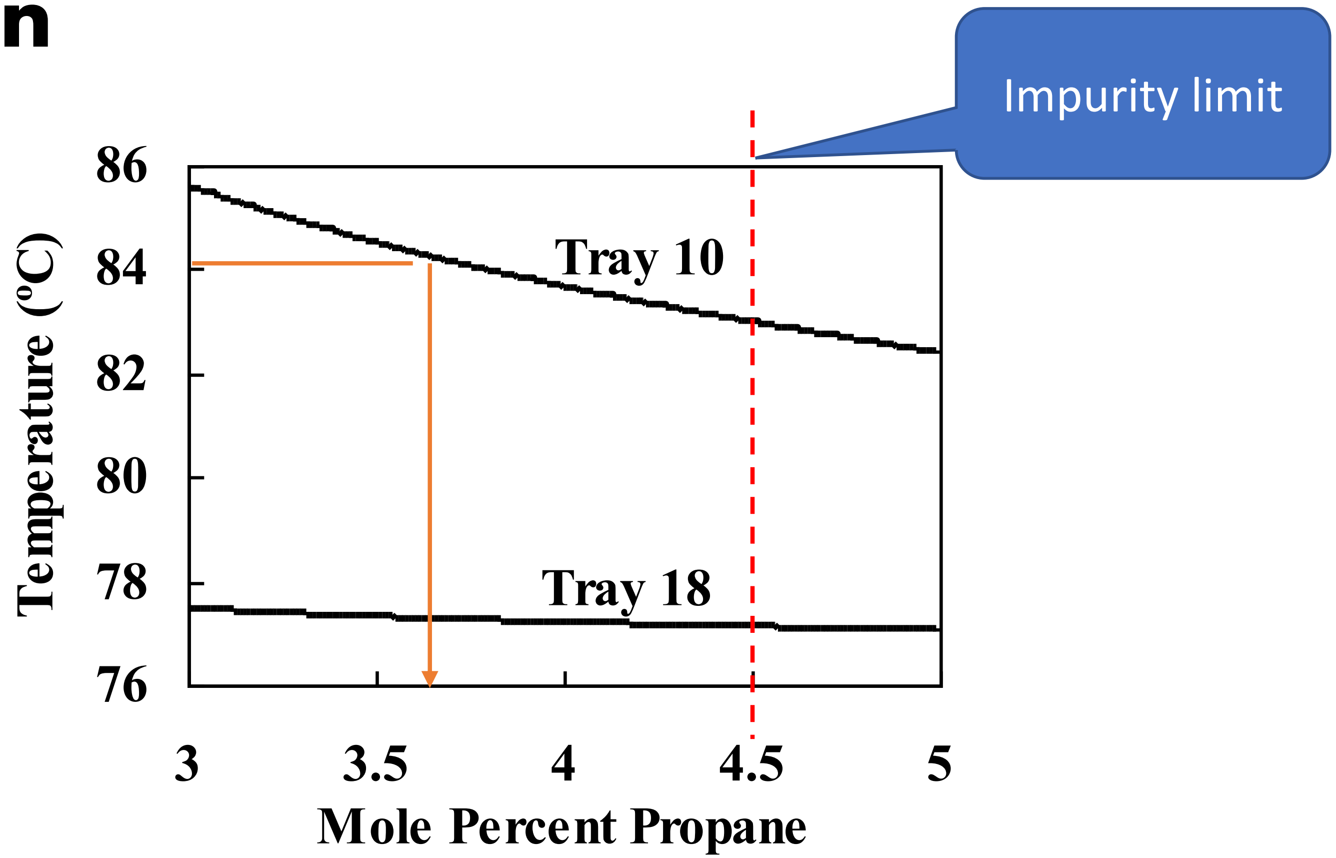
Effect of Deadtime on Control Performance



Inferential Temperature Control for Distillation Columns

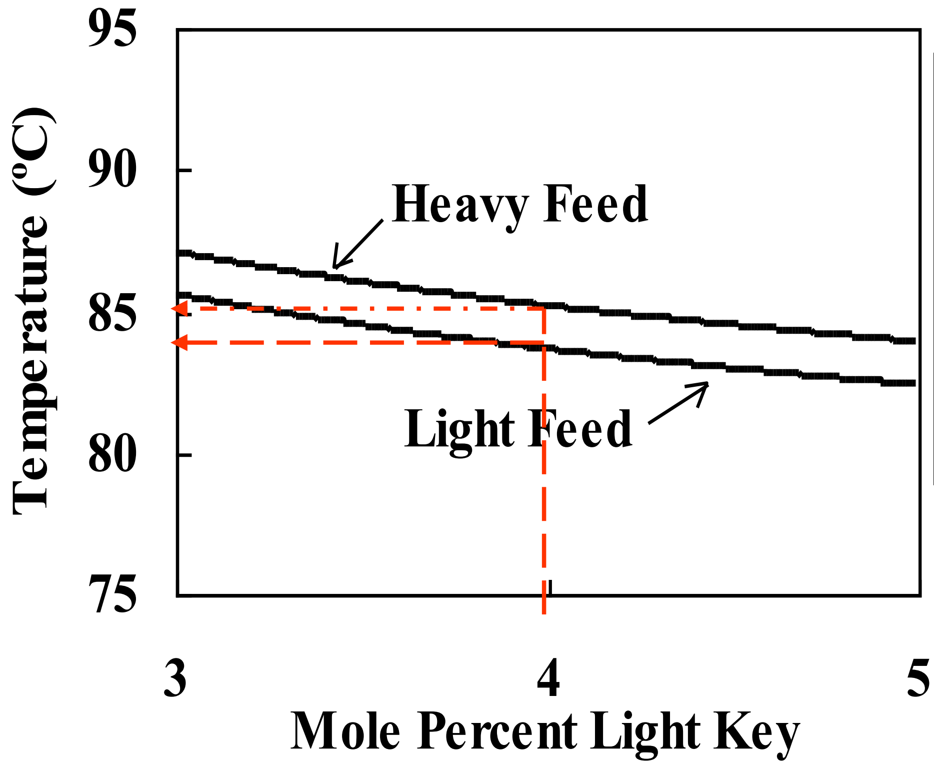


Choosing a Proper Tray Temperature Location



- A tray temperature used for inferential control should show strong sensitivity.
- Tray 10 is more sensitive => change in %mol of propane clearly represented by T
- Tray 18 is not sensitive to change in %mol of propane => change from 3.5% to 4% only leads to very small error signal in temperature
- Larger error signal generated in temperature +> more effective inferential T control of %mol of propane

Composition/Temperature Correlation

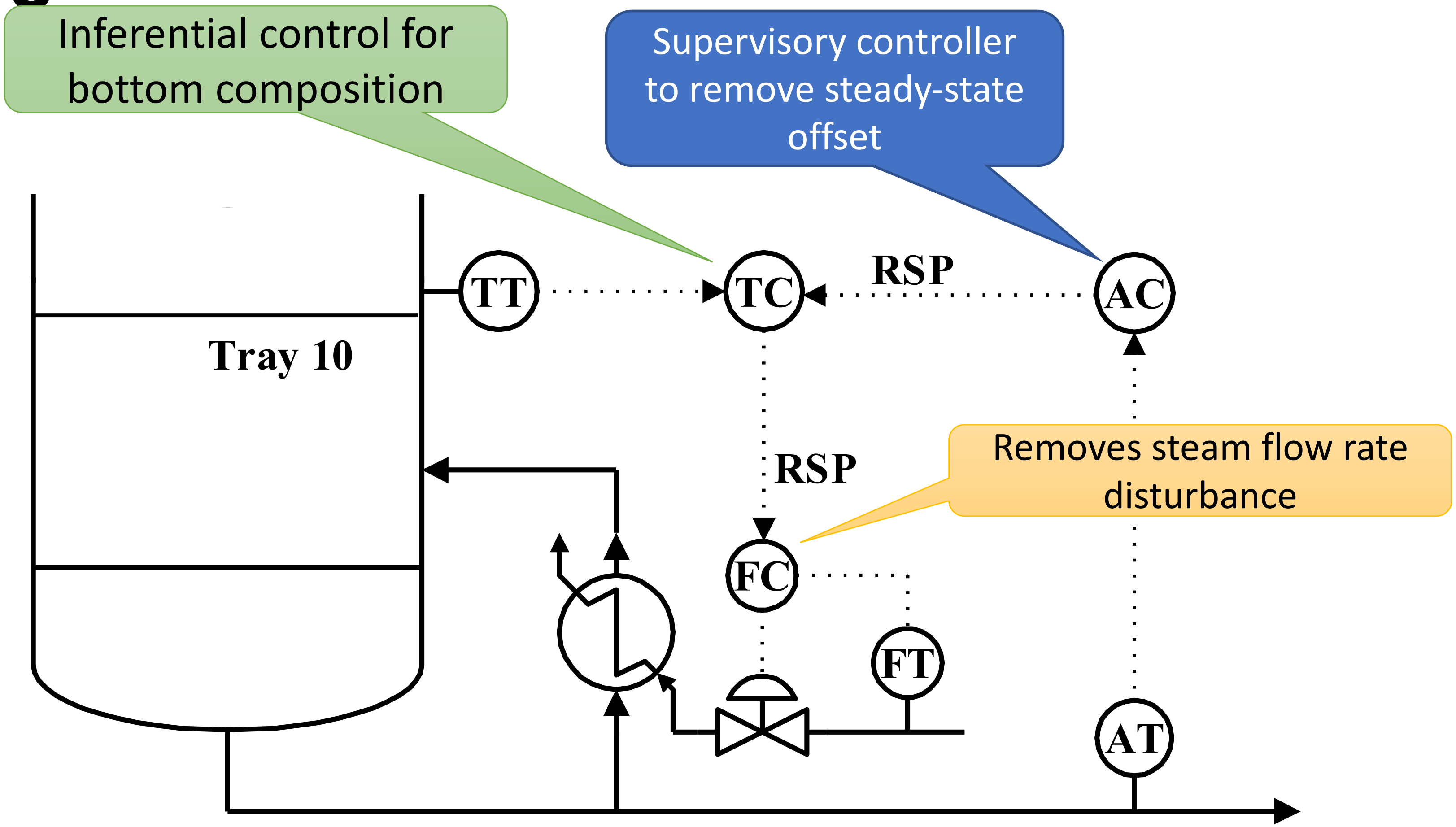


Tray temperature for multicomponent distillation column as a function of the light key in the bottoms product for **different ratios of heavy non-key to light non-key.**

Feed composition affects the composition-temperature correlation.

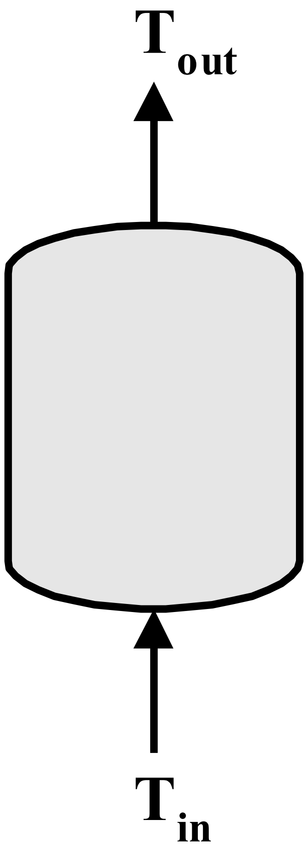
Note: Tray temperature cannot represent the bottom composition well enough when feed composition heavily fluctuates

Feedback Correction for Feed Composition Changes



- In the above scheme, the inferential T controller is now a slave to the composition controller
- Advantages: remove extra disturbances, e.g., feed flow rate and temperature disturbances

Inferential Reactor Conversion Control



Macroscopic Energy Balance:

$$X_A C_{A_{in}}(-\Delta H_{rxn}) = \rho C_p (T_{out} - T_{in})$$

$$X_A = \frac{\rho C_p}{C_{A_o}(-\Delta H_{rxn})}(T_{out} - T_{in})$$

Develop Linear Relationship Based on Plant Data

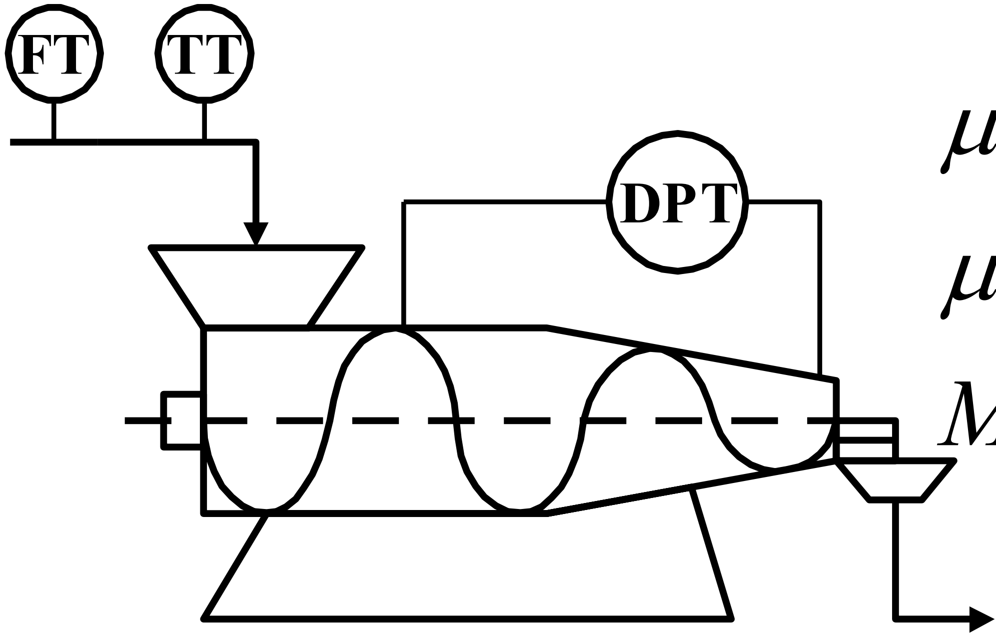
$$X_A = a(T_{out} - T_{in}) + b$$

Temperature difference across the reactor must be **large enough;**

- Hence, **<u>noise</u>** on the temperature measurement has a **<u>minimum effect on X_A</u>**

- Inlet composition and physical properties are constants, or do not change significantly.

Molecular Weight of a Polymer



$$\mu(T) = f_1(\Delta P, F)$$

$$\mu(T_0) = f_2[T, \mu(T)]$$

$$M_{wt} = f_3[\mu(T_0)]$$

- Without inferential, samples requires about **<u>10 hrs</u>** test in the lab.
- Long deadtime will seriously reduce the control performance
- Deadtime imposes an upper limit on the control performance

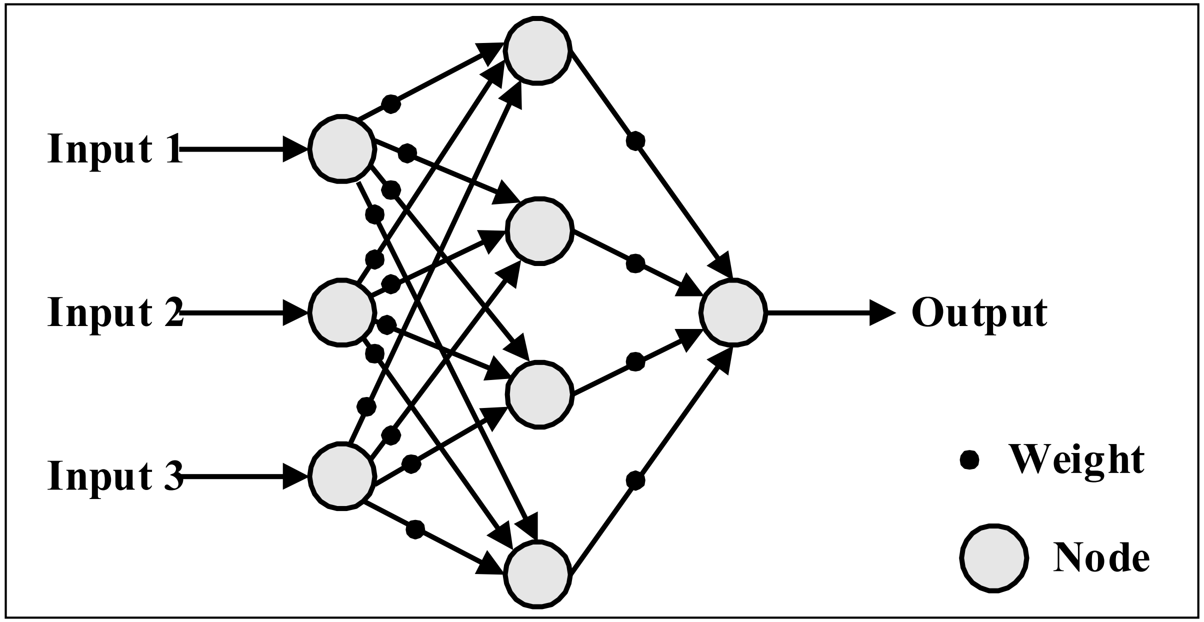
Exercise 1 - Crystallizer

- It is desired to control the size distribution of crystals produced in vacuum continuous crystallizer, but it's very difficult to measure i.e. requires lengthy lab test. Some experiment suggest that crystal size distribution are strongly related to the (1) stirrer speed θ, (2) magma temperature T, (3) degree of supersaturation C-Cs, and (4) mother liquor density ρ. C is concentration of the solute and Cs is the solubility of the solute.
- Answer the following:

❑ Suggest an **inferential control technique** for crystal size distribution

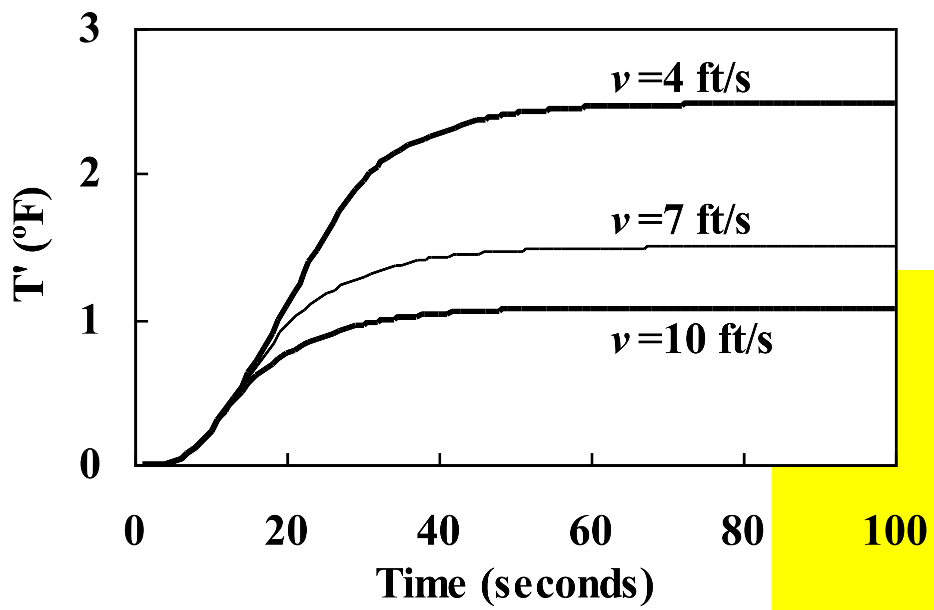
❑ Show the **schematic of the control strategy**. Comment on the effectiveness of the strategy.

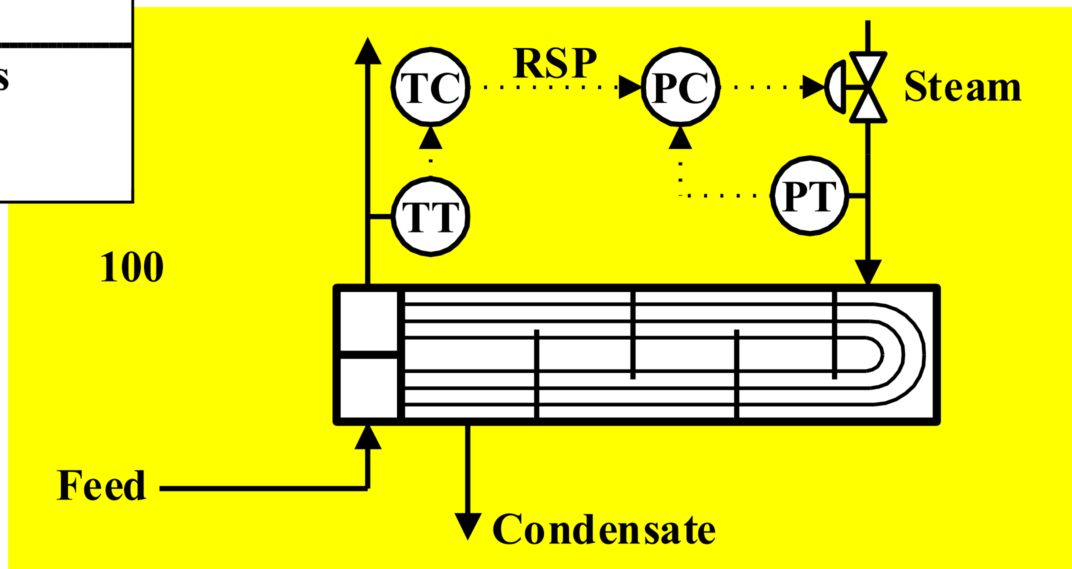
Soft Sensors Based on Neural Networks



- Neural network (NN) provides nonlinear correlation.
- Weights are adjusted until NN agrees with plant data
- NN-based soft sensors are used to infer NO_x levels in the flue gas from power plants.

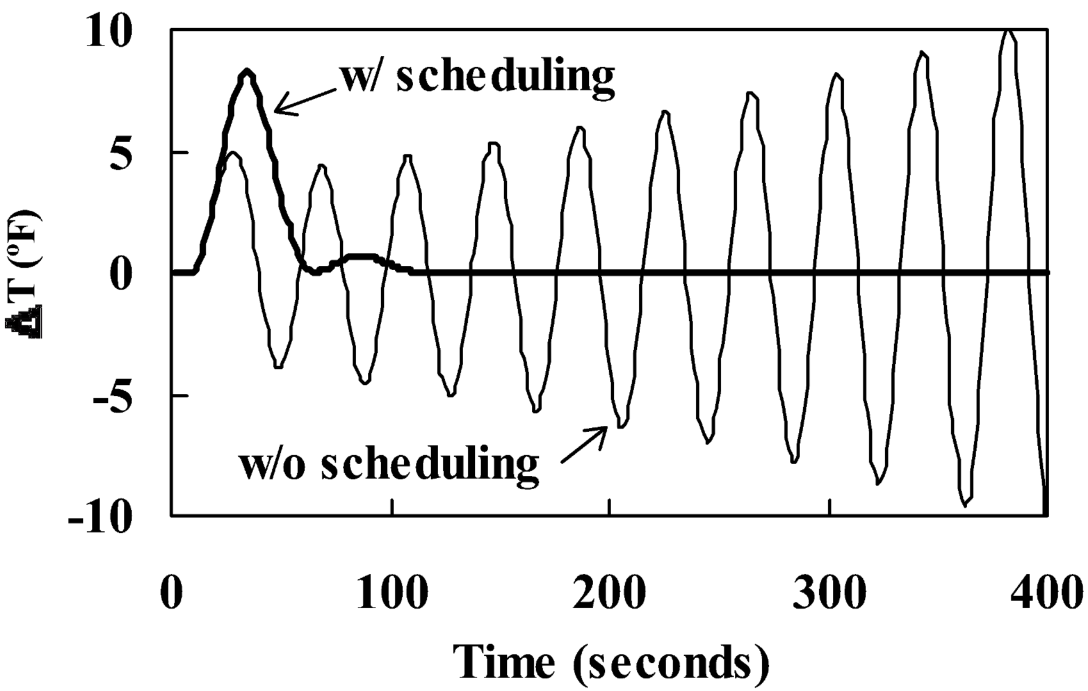
Heat Exchangers are Nonlinear with Respect of Flow Rate Changes





Open-Loop response for a heat exchanger for different feed rates.

Effect of Scheduling Controller Tuning



- Shows the results for a **nonscheduled controller** that was tuned for **v =7 ft/sec** after the feed rate is changed to **v = 4 ft/sec** and the results for a **scheduled controller** for the same upset.

Scheduling Controller Tuning

- Can be **effective**
  - When either a *measured disturbance* or,
  - The *controlled variable correlates* with
    - **Nonlinear process changes**
- Tune the **controller at different levels**;
  - Scheduling parameters and,
  - Combine the results so that the controller tuning parameters,
    - **Vary over the full operating range**.

Exercise 2 – Gain scheduling

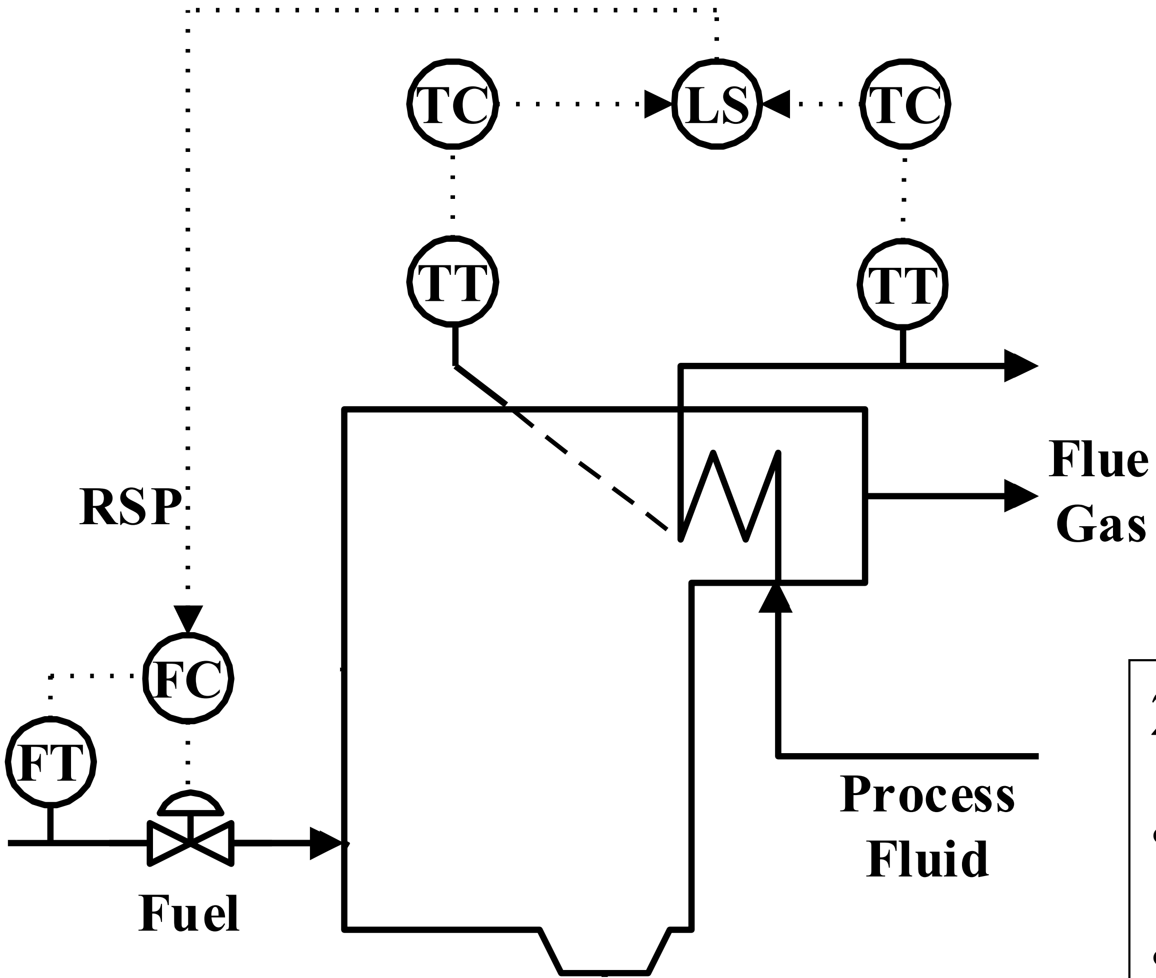
- For the case of heat exchanger previously, show the schematic of control strategy with gain scheduling.

- Can you use other variable as gain scheduling? Give your reasons.

Override/Select Controls

- Process are many times operated at;
  - The safety or equipment limits in order to:
    - **maximize process throughput**
- During upset periods, it is essential that **safety limits** are enforced

Furnace Tube Temperature Constraint Control



Note

$$Q = AU(\Delta T)$$

Increase Fp (process flow), will increase Q

$$\Delta T = T_{tube} - T_p$$

Tube temperature increase, it may violate maximum value, i.e. 500 C

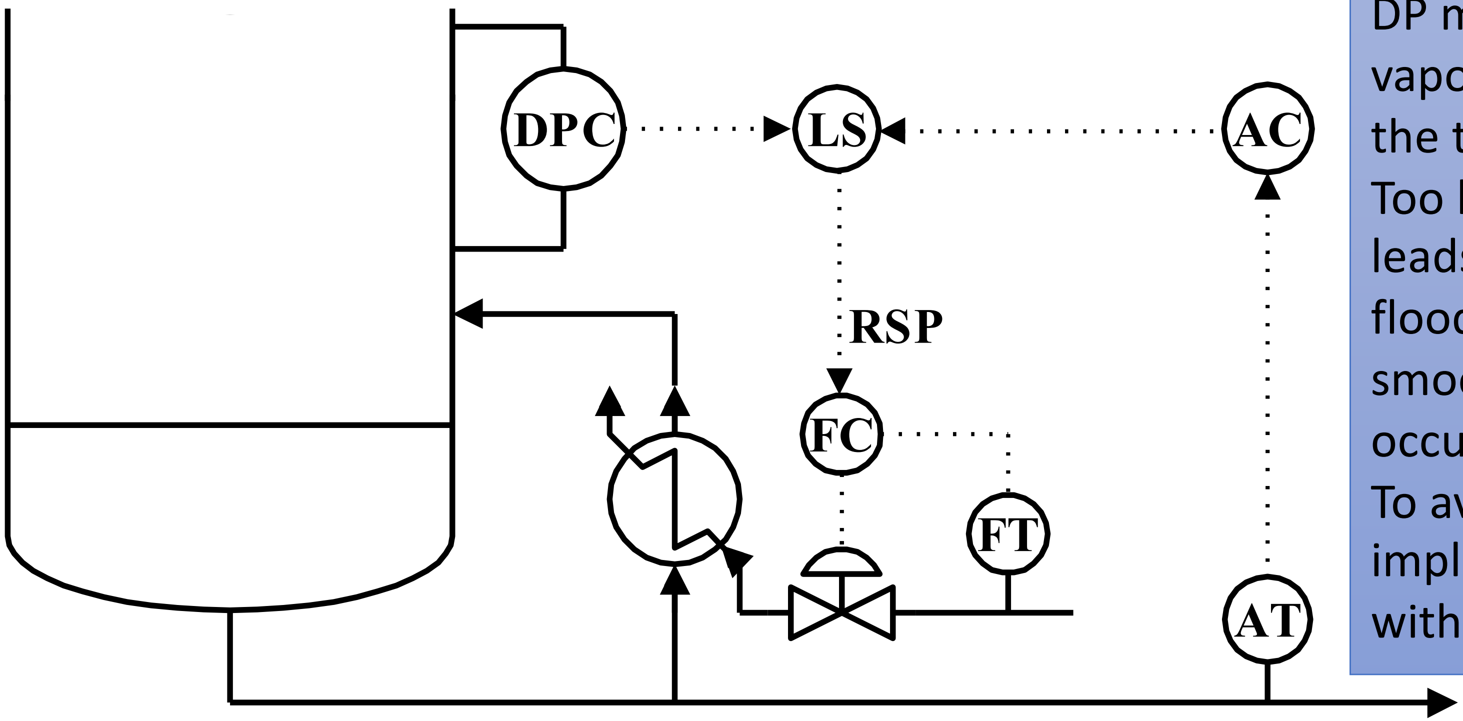
2 T- controls:

- Tube T
- Process Fluid T

Analysis of Tube Temperature Constraint Controller

- Under normal operation,
  - Controller adjusts the furnace firing rate to maintain process stream at the *setpoint* temperature.
  - Process fluid outlet temperature control is selected
- At higher feed rates,
  - Excessive tube temperatures can result in greatly reducing the useful life of the furnace tubes.
    - Tube temperature control selected
- The LS controller reduces,
  - The firing rate to ensure that the furnace tubes are not damaged.

Column Flooding Constraint Control



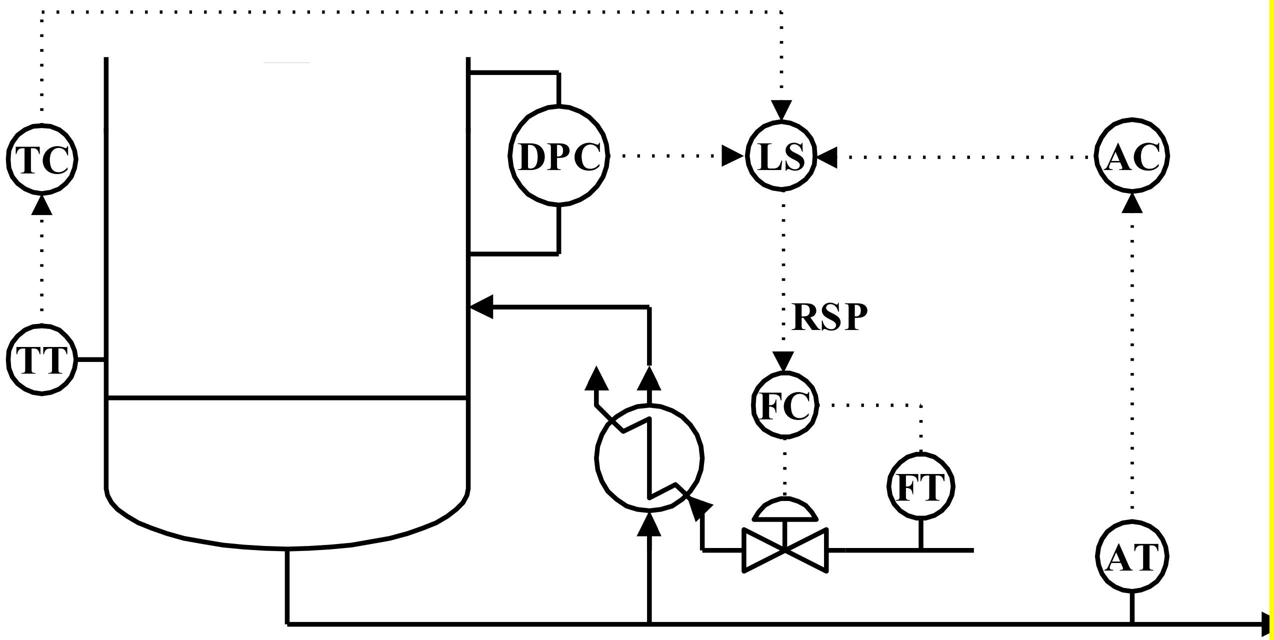
Note:
DP proportional to vapor flow. Higher DP means higher vapor flow across the trays.
Too high vapor flow leads to column flooding – non smooth operation occur.
To avoid flooding, implement DPC with LS controller.

Note:
Under abnormal situation, e.g., sudden increase in Feed Rate, more steam is required. This can dramatically increase the vapor flow leading to flooding. DPC will prevent this from happening.

Analysis of Override/Select Control – Distillation Column

- When <u>pressure drop</u> across the column reaches an <u>upper</u> operational limit,
  - Reboiler duty is switched from controlling;
    - Bottom product composition to
    - Maintaining operation at maximum pressure drop
- When the composition of the <u>impurity</u> in bottom product becomes <u>less than setpoint</u> (over purified),
  - Reboiler duty is switched from controlling at;
    - Maximum pressure drop to
    - Maintaining composition of bottom product

Controlling Multiple Constraints



Note:
AC = control bottom purity
TC = control bottom temperature
DPC = control vapor flow

DPC will be active if excessive vapor flow occurs under sudden increase in Feed Flow.

Note:
TC is used to protect the reboiler from excessively high temperature. Under abnormal situation, e.g., sudden drop in Feed Temperature, a lot of steam is required to maintain the bottom purity. This may lead to violation of maximum tube temperature. TC is used to prevent this from happening.

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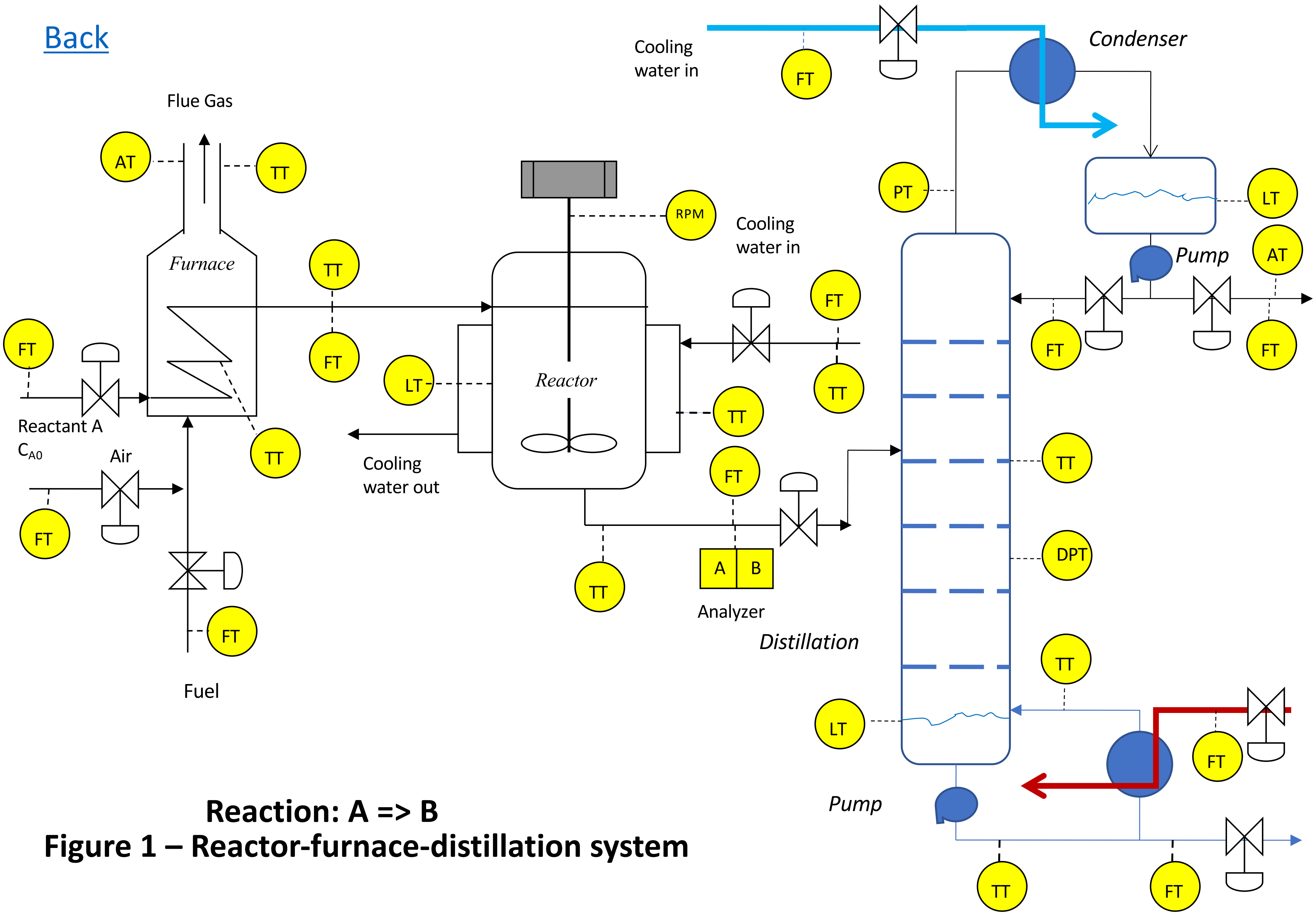


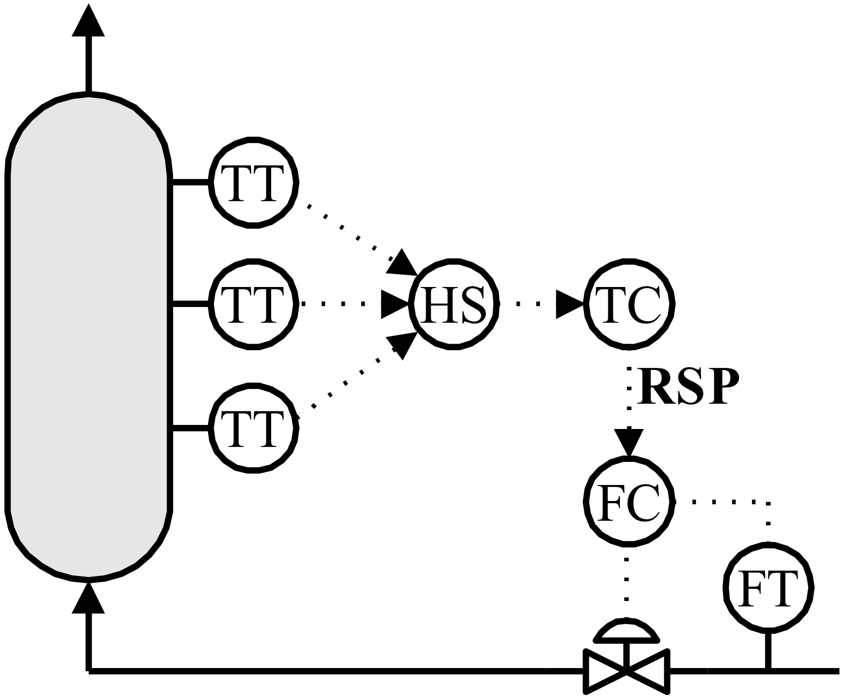
Reaction: A => B

Figure 1 – Reactor-furnace-distillation system

Exercise 3 – LS control

- For RFD system shown in Fig. 1, draw the schematic of LS control strategy for the reactor system, where it is desired to control the component A (Ca) and temperature of the reactor effluent T.
- Which one is usually active and under what conditions?

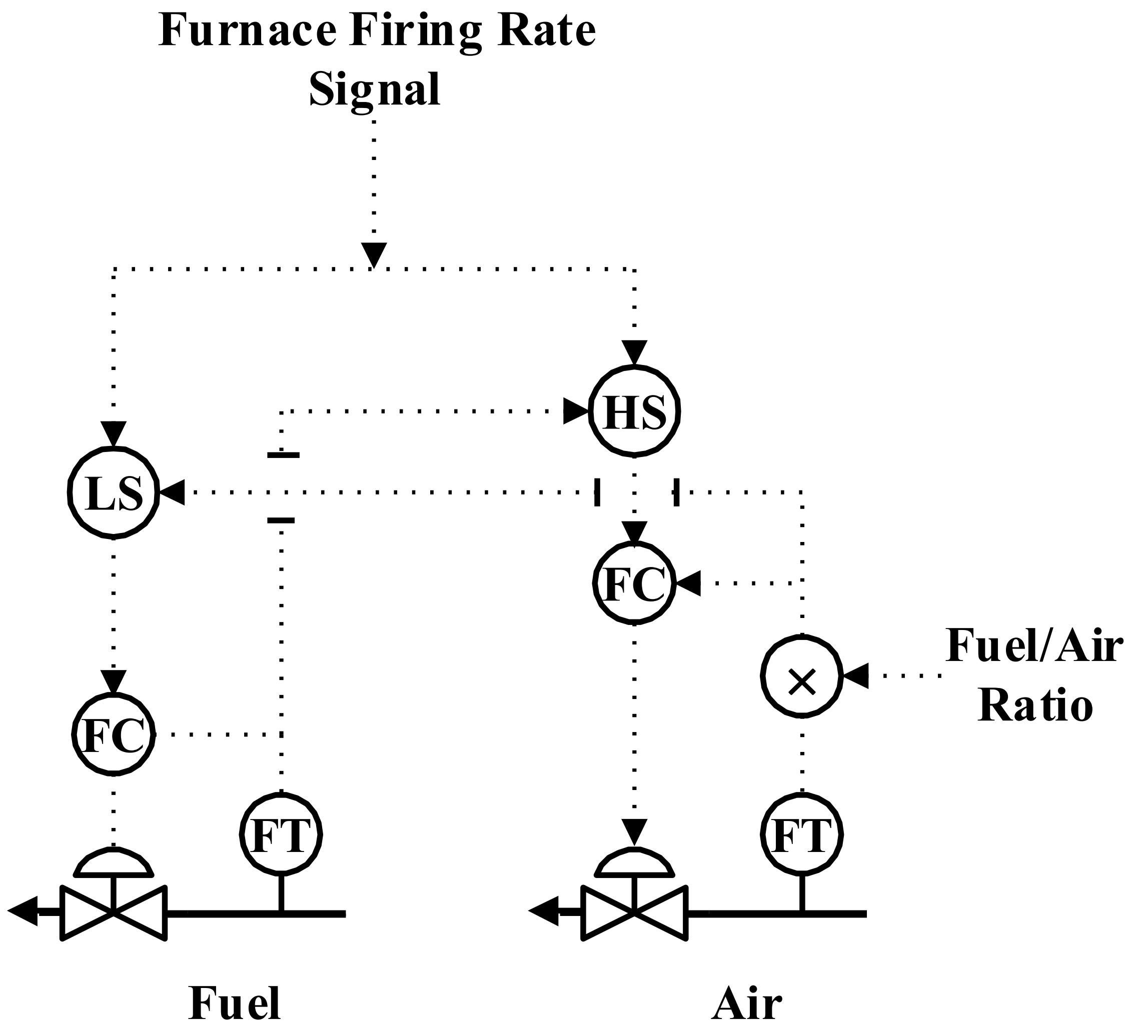
Hot Spot Temperature Control



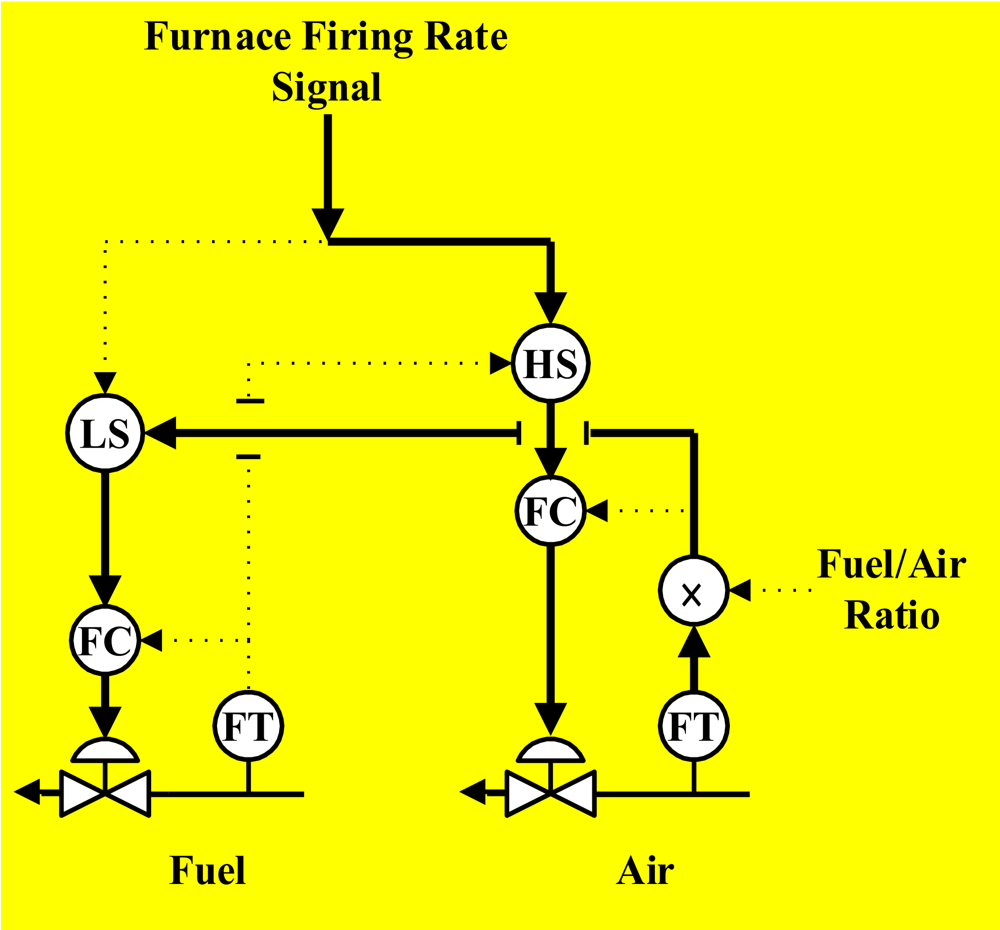
▪ Can be used to control the maximum temperature in a fixed-bed reactor,

- Maximum reactor temperature occurs at different locations in the reactor

Cross-Limiting Firing Controls

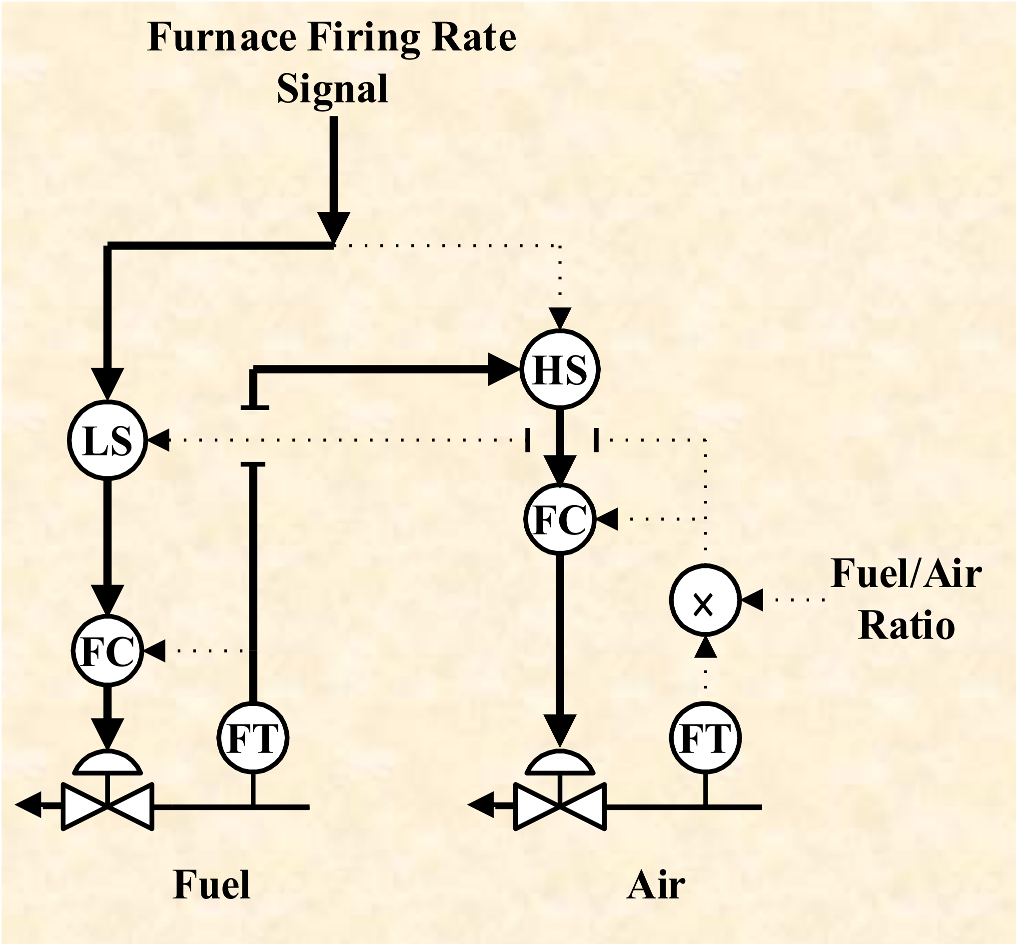


Firing Rate Increase



- HS ensures setpoint for <u>air flow controller</u> increases immediately.
- Then LS sends signal to <u>fuel controller</u> as its setpoint.

Firing Rate Decrease

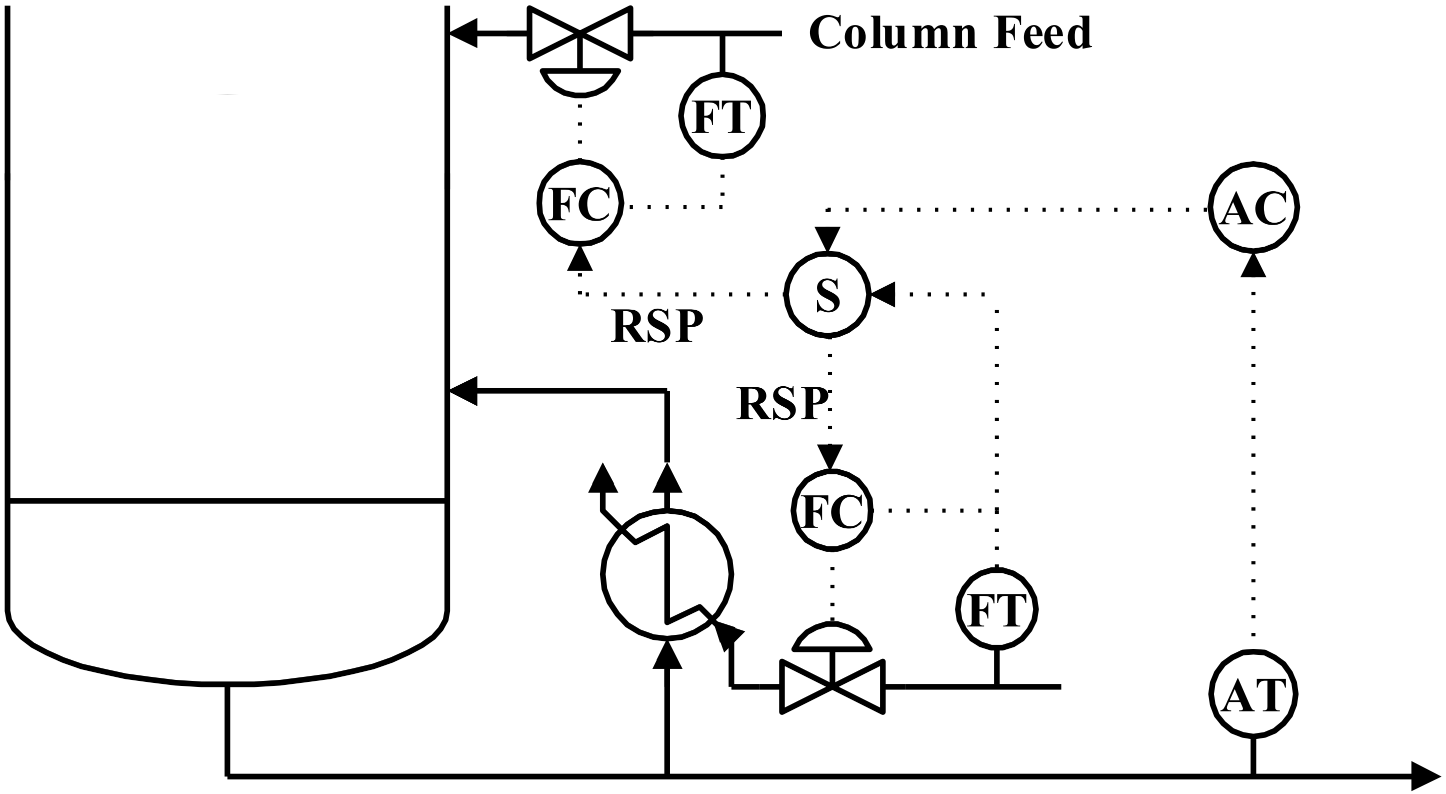


- LS ensures setpoint for <u>fuel controller</u> decreases immediately.
- Then HS sends the signal to <u>air flow controller</u> as its setpoint.

Analysis of Cross-Limiting Firing Controls

- It is critical that **excess oxygen** is maintained during **firing rate increases** or **decreases** or CO will form.
- When the firing rate is increased, the air flow rate will lead the fuel flow rate.
- When the firing rate is decreased, the fuel flow rate will lead the air flow rate.
- Air flow rate controller is based on equivalent fuel flow rate (fuel/air ratio).

Override Control



❖ Select control to maintain bottom product purity when a maximum reboiler constraint is encountered.

Override/Select Control

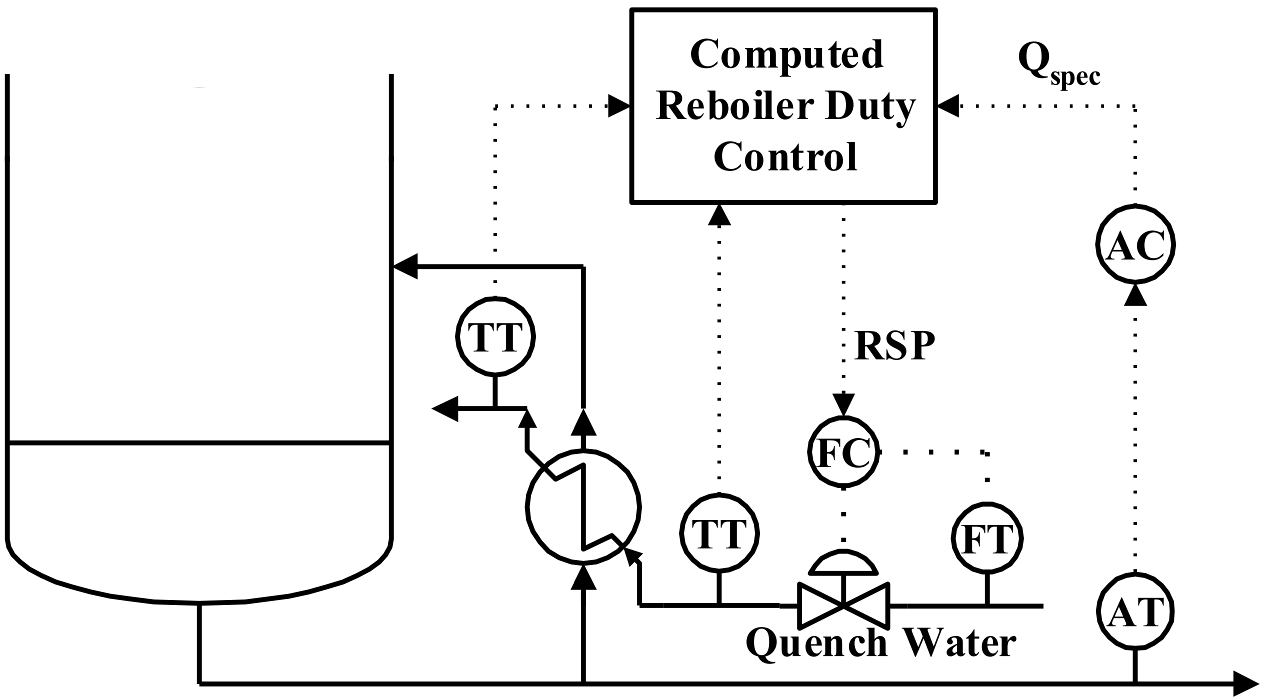
- Override/Select control uses LS and HS action to change which **controller** is applied to the **manipulated variable**.

- Override/Select control uses selected action to switch between **manipulated variables** using the **same control objective.**

Computed Manipulated Variable Control

- Used when the desired manipulated variable is **not directly controllable**.
- Reduces the effect of certain types of disturbances
  - Indirectly adjusting the desired manipulated variable.
  - E.g. distillation column reboiler using waste heat

Computed Reboiler Duty Control



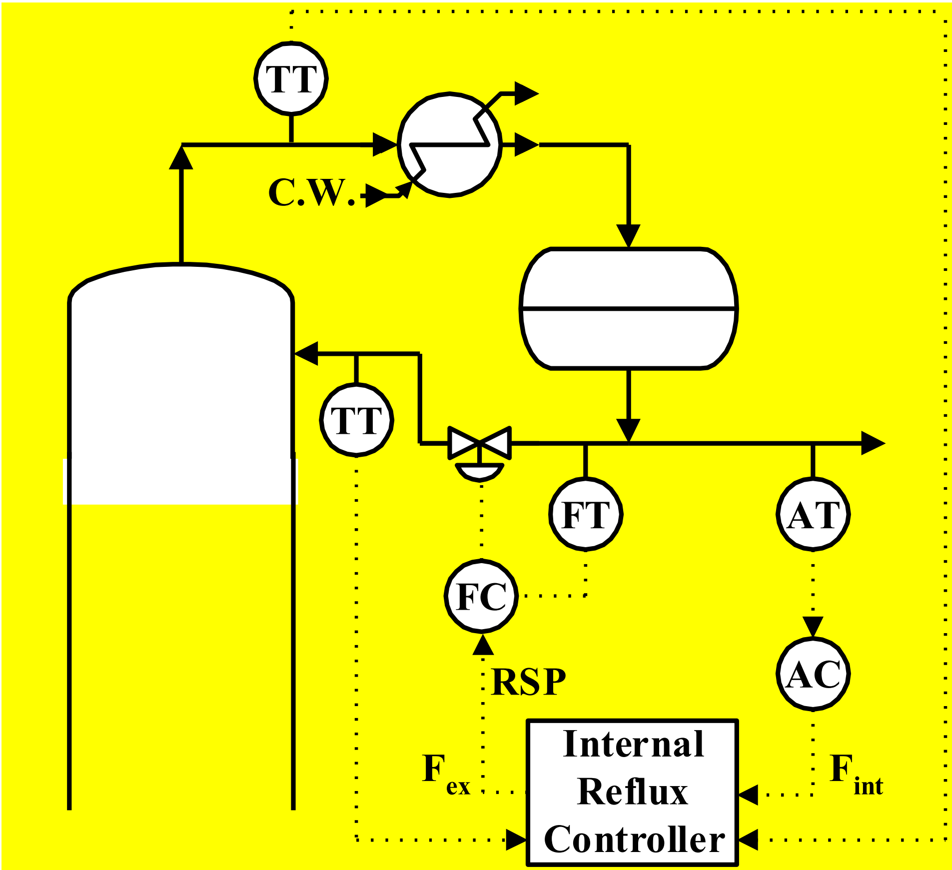
Inlet Temperature of quench water can vary over a wide range (disturbance)

$$F_{sp} = \frac{Q_{spec}}{C_p(T_{in} - T_{out})}$$

Analysis of Computed Reboiler Duty Control

- Inlet T of quench water can vary over a wide range;
  - When T increases, extra boilup results for the column.
  - Composition controller sets the **reboiler duty Q_{spec}**
  - Reboiler duty changes with quench water inlet **Tin and flow rates**
  - Use **steady-state energy balance** on the quench water to calculate desired flow
- The flow can be adjusted accordingly before the disturbances affecting the product compositions.

Internal Reflux Control



$$C_p F_{ex}(T_{oh} - T_r) = \Delta F_{\text{int}} \Delta H_{vap}$$

$$F_{\text{int}} = F_{ex}\left[1 + \frac{C_p(T_{oh} - T_r)}{\Delta H_{vap}}\right]$$

$$F_{ex} = \frac{F_{\text{int}}^{spec}}{1 + \dfrac{C_p(T_{oh} - T_r)}{\Delta H_{vap}}}$$

Analysis of Internal Reflux Control

- Distillation column is sensitive to sudden changes in **ambient conditions**
- Increased heat loss cools the reflux,
  - Causes **added condensation** from vapor in the top column
  - Increases the **internal reflux ratio**, improving the separation
  - Much more desirable to control the **internal reflux** than the external reflux
    - Because internal reflux is **more susceptible** to ambient changes

Exercise 4 – Computed manipulated variable

- For the RFD system (Fig. 1), shows the computed manipulated variable scheme for reactor, where the cooling water temperature and cooling water flow are fluctuating.

- Comment on the effectiveness of this strategy compared to cascade control.

Summary

- Ensuring Safe, Smooth and Profitable Operation requires adequate control system in place.
- Where applicable, inferential control reduces deadtime at a very effective price.
- When process nonlinearity is serious, consider the scheduling controller tuning.
- Use override/select controls to satisfy safety and operational constraints.
  - Control system must be able to deal with multiple constraints to ensure safe, smooth and profitable operation.