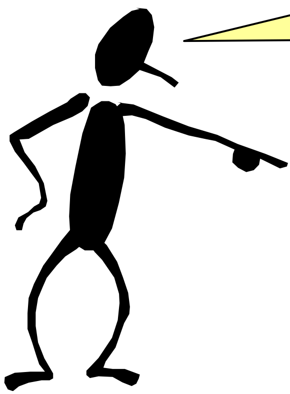
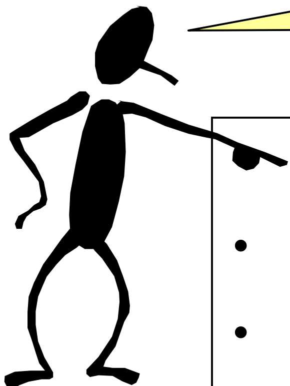
CHAPTER 24: CONTROL DESIGN



When I complete this chapter, I want to be able to do the following.

- Define the control problem
- Evaluate if desired performance is possible; if not, modify process
- Select instrumentation
- Design loop pairing for control
- Provide sensors for process monitoring

CHAPTER 24: CONTROL DESIGN



Outline of the lesson.

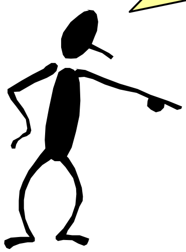
THE CONTROL DESIGN PROCEDURE

- **Define the control problem (challenge)**
- **Evaluate/achieve operability**

  - Degrees of freedom
  - Controllability
  - Operating Window

- **Process dynamics for good performance**
- **Loop pairing**
- **Control for safety**
- **Monitoring and diagnosis**

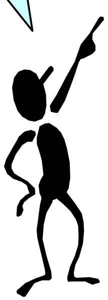
CHAPTER 24: CONTROL DESIGN

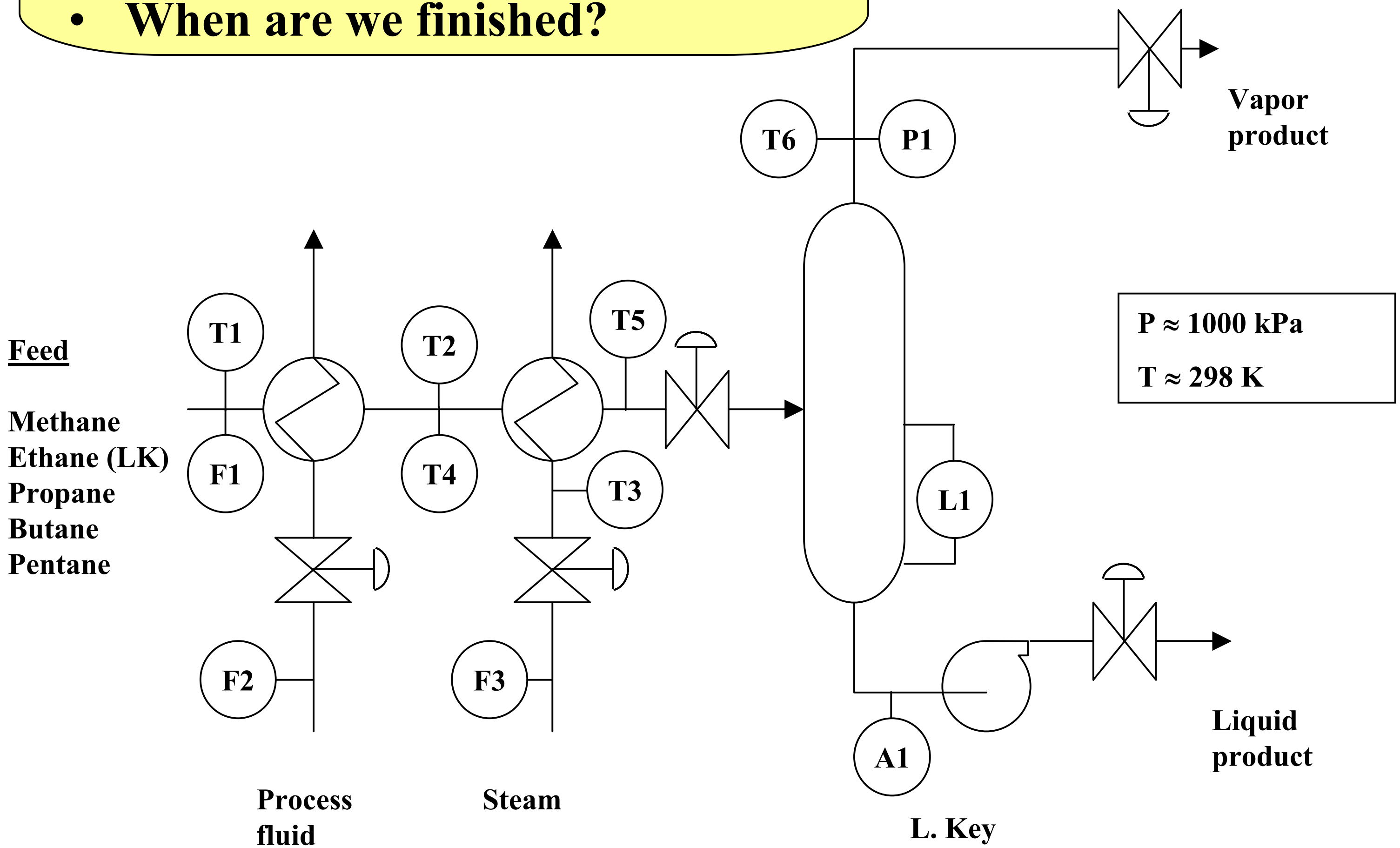


Let's design controls for this process

- How do we start?
- What are the common steps?
- When are we finished?

Let's review the process

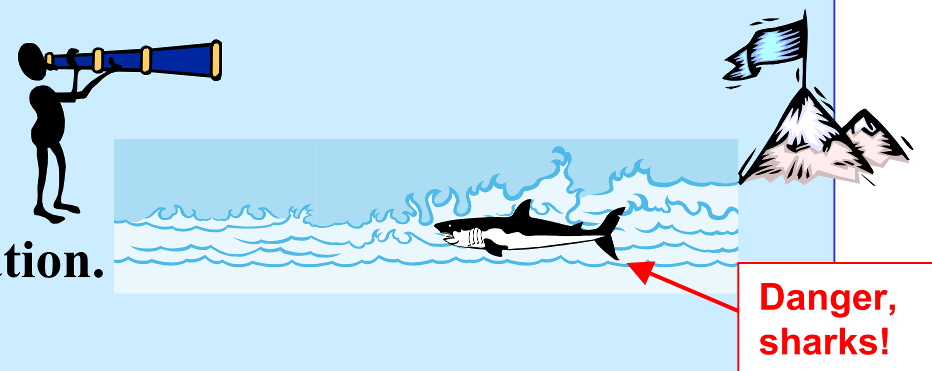




CHAPTER 24: CONTROL DESIGN

Design is a goal-oriented task. We must determine the goals before we start to design.

This is consistent with the problem solving methods used widely in engineering education.



- **Woods, Donald, *Problem Based Learning: How to Gain the Most from PBL*, Griffin Printing, Hamilton, Ontario, 1994.**
- **Fogler, H. Scott and Steve LeBlanc, *Strategies for Creative Problem Solving*, Prentice Hall PTR, Upper Saddle River, 1995.**

We will use the Control Design Form to summarize the problem definition.

CHAPTER 24: CONTROL DESIGN

Control Design Form

Objectives

Measurements

Manipulated variables

Constraints

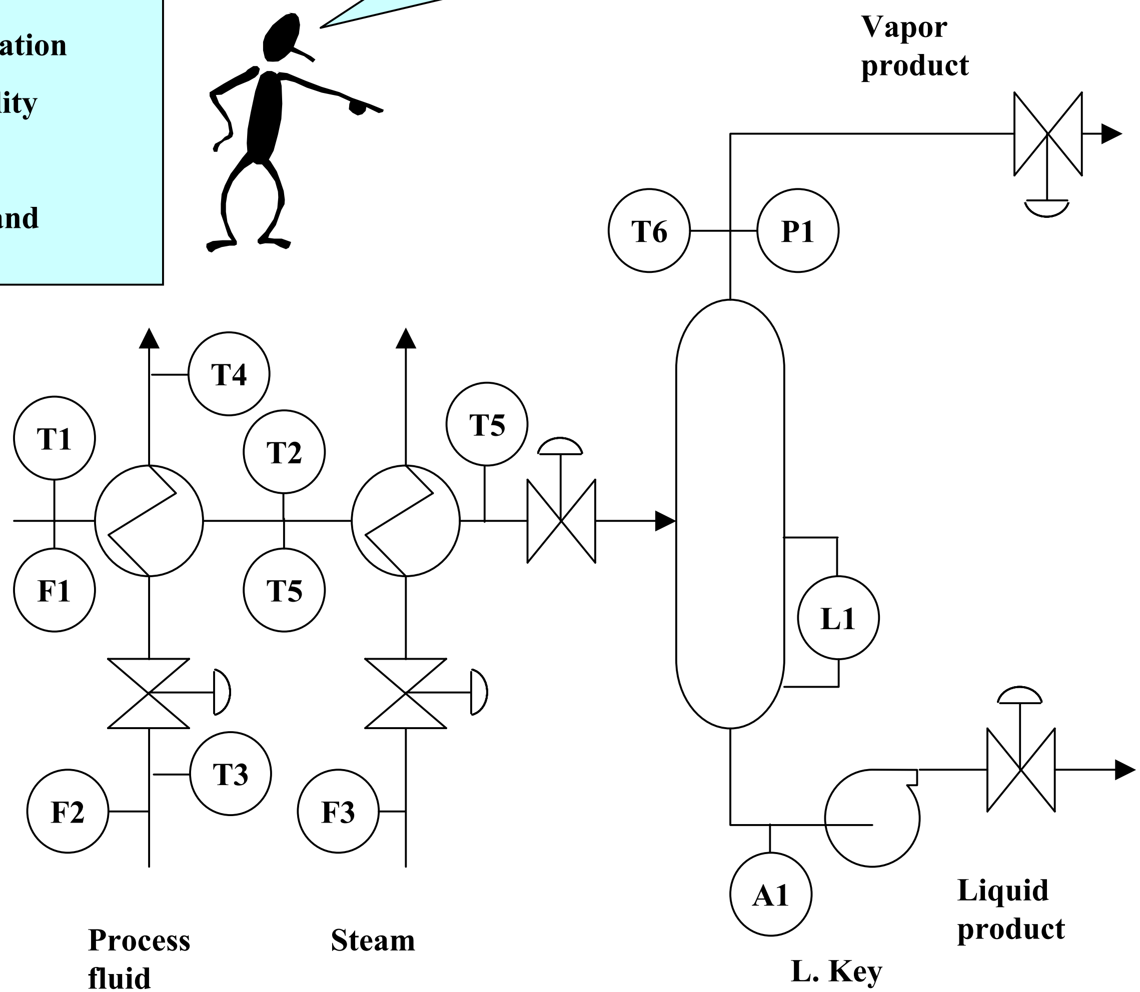
Disturbances

Dynamic responses

Additional considerations

1. Safety
2. Environmental protection
3. Equipment protection
4. Smooth operation
5. Product quality
6. Profit
7. Monitoring and diagnosis

WORKSHOP: Define at least one for each category. But, do not design the controls (yet)!



CHAPTER 24: CONTROL DESIGN

1. Safety

   Maintain vessel pressure below 1200 kPa

2. Environmental protection

   Prevent release of hydrocarbons to the atmosphere

3. Equipment protection

   Ensure that liquid flows through the pump

4. Smooth operation

   When possible, make slow adjustments to liquid product product flow rate

5. Product quality

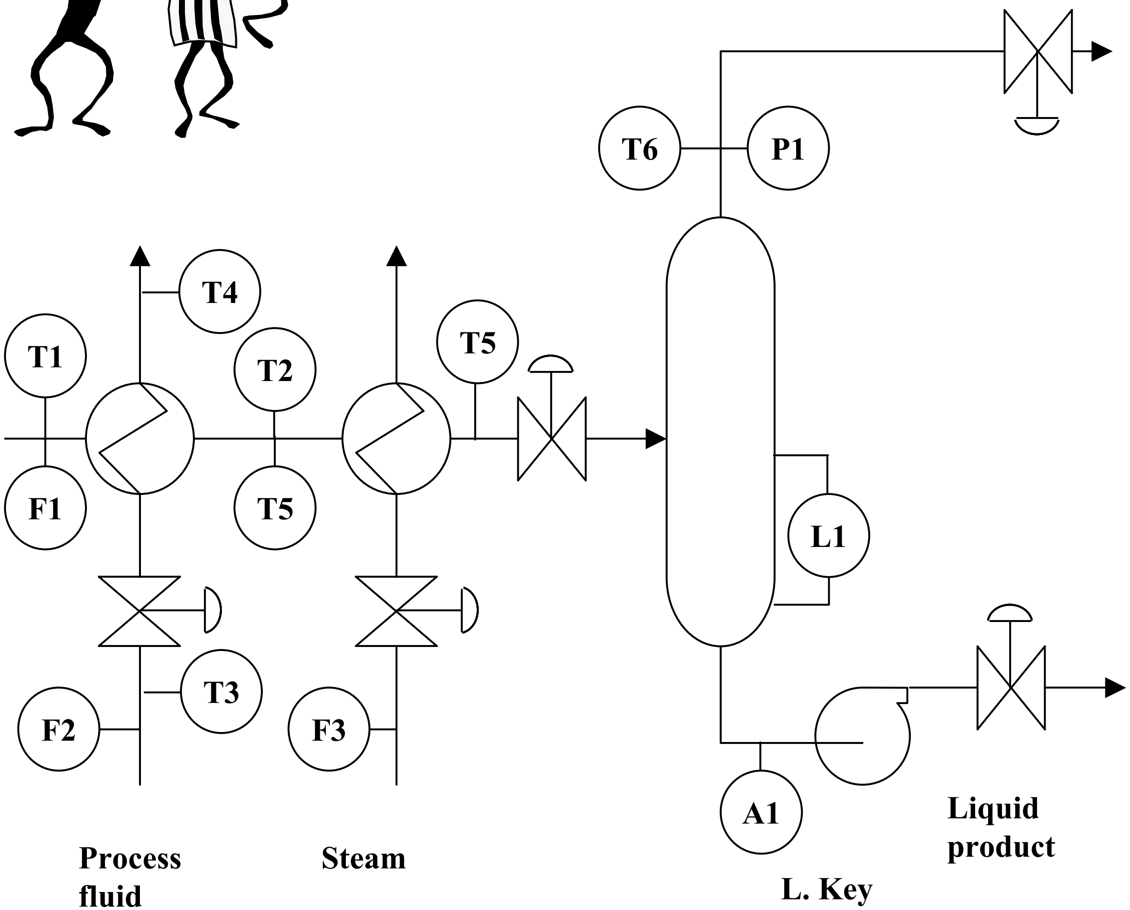
   Maintain the liquid product at 10 ± 1 mole% L. Key.

6. Profit

   Maximize the use of the expensive steam for heating

7. Monitoring and diagnosis

   Provide alarms for immediate attention by operating personnel



CHAPTER 24: CONTROL DESIGN

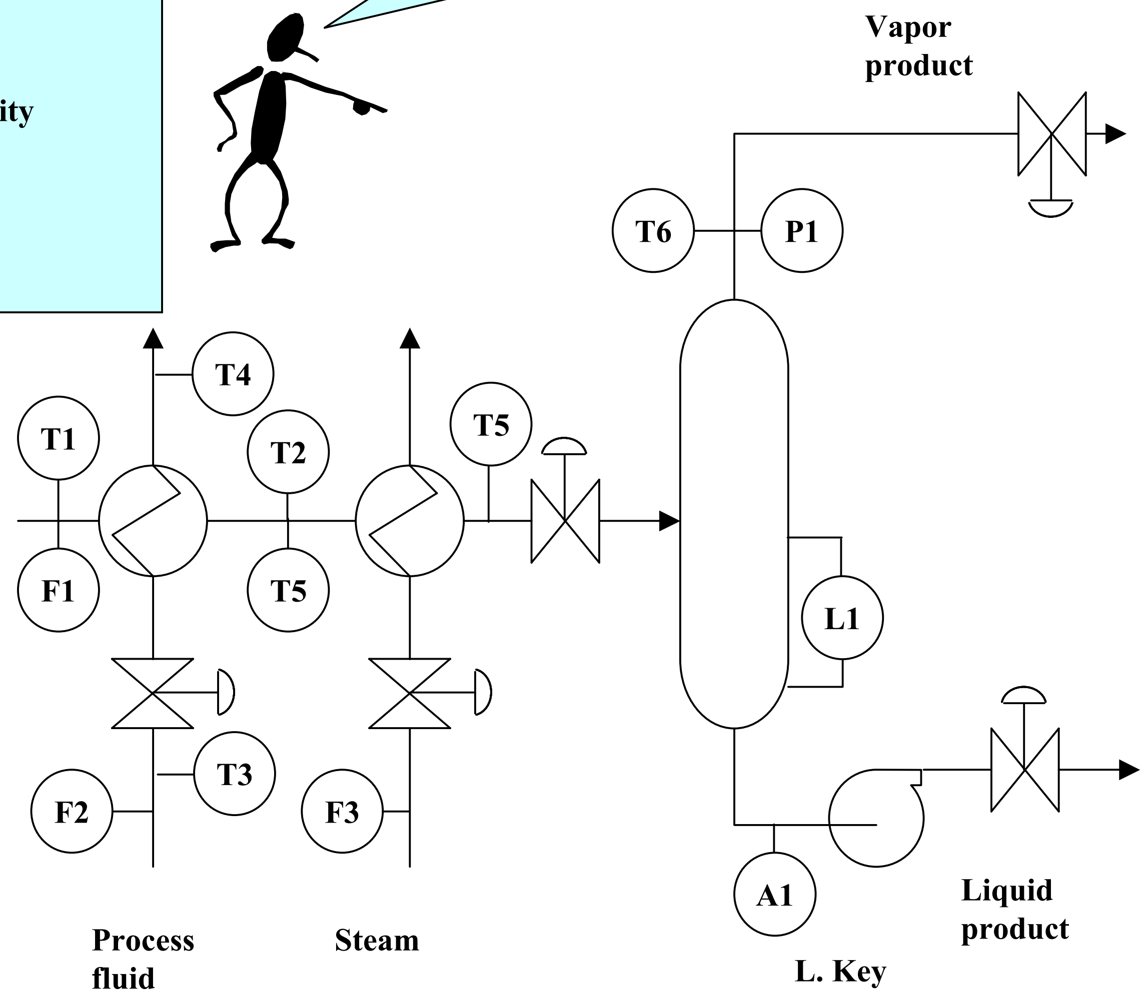
<u>Control Design Form</u>

- **Objectives**
- **Measurements**
- **Manipulated variables**
- **Constraints**
- **Disturbances**
- **Dynamic responses**
- **Additional considerations**

<u>Sensors to achieve objectives</u>

- **Feasibility**
- **Accuracy**
- **Reproducibility**
- **Dynamics**
- **Reliability**
- **Cost**

<u>WORKSHOP</u>: Propose sensors for one F, T, P, L measurement.

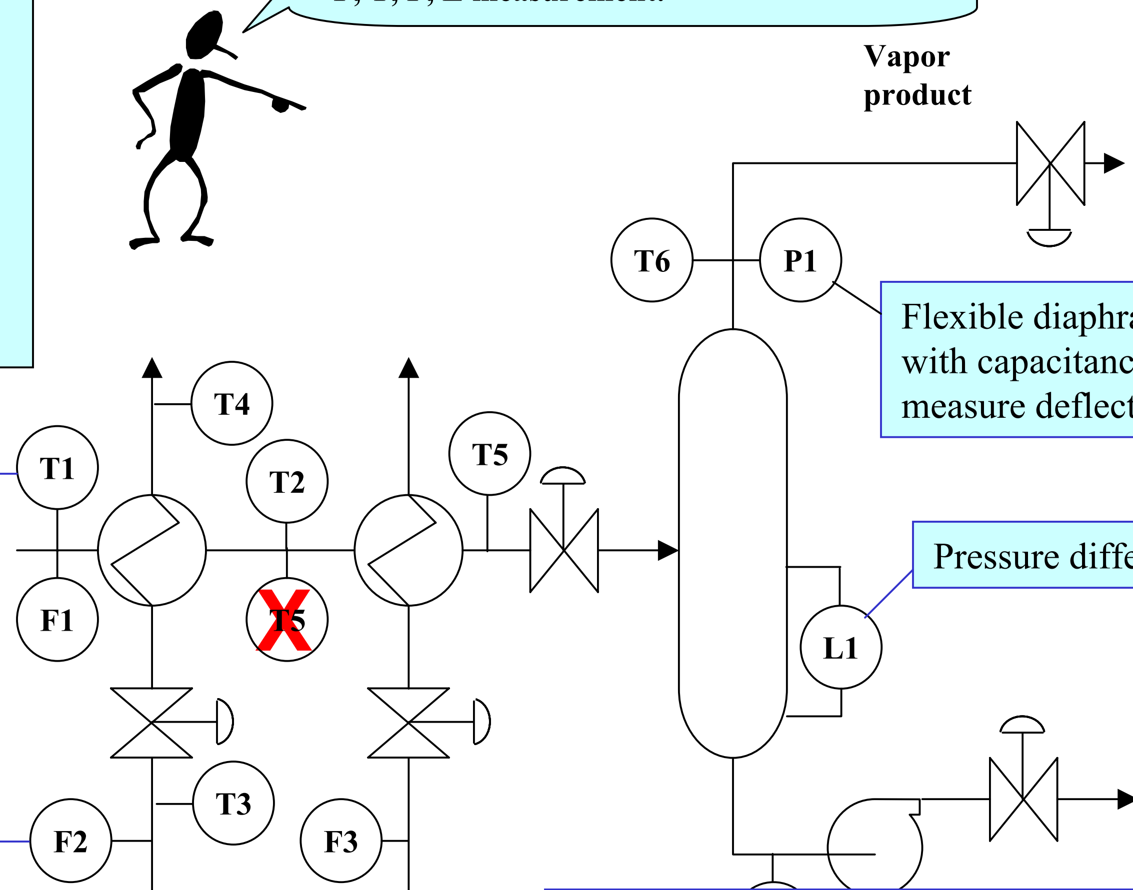


CHAPTER 24: CONTROL DESIGN

Sensors

- **Feasibility**
- **Accuracy**
- **Reproducibility**
- **Dynamics**
- **Reliability**
- **Cost**

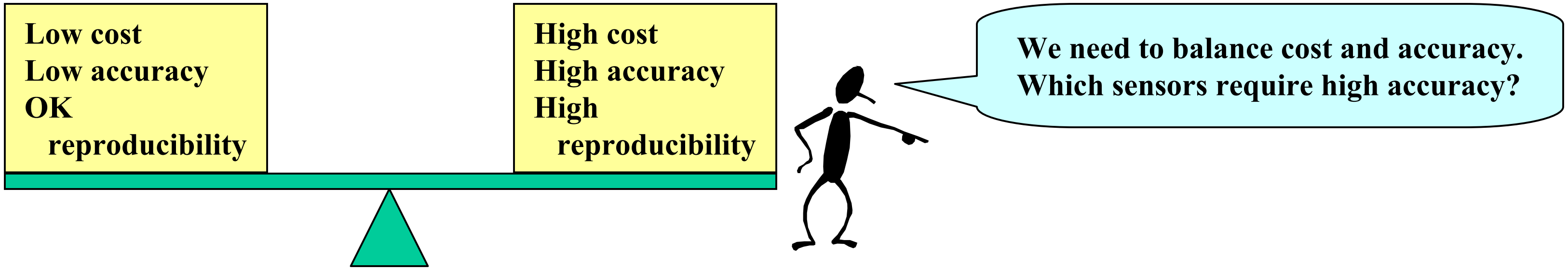
WORKSHOP: Propose sensors for one F, T, P, L measurement.

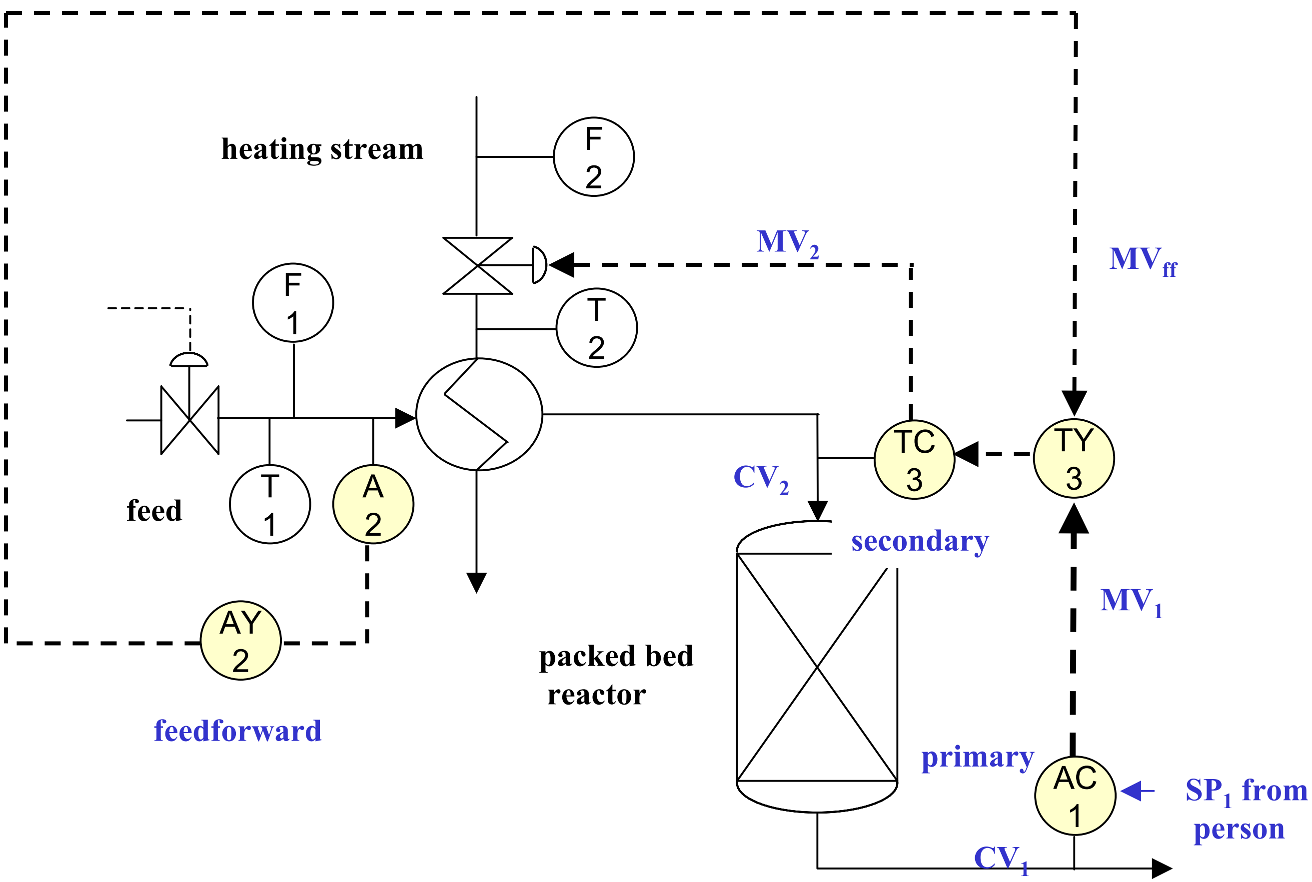


Typically, the sensor range covers the expected values of the variable (including disturbances), but not more.

An orifice meter would typically read the design value at ~ 70% of its maximum range.

CHAPTER 24: CONTROL DESIGN





CHAPTER 24: CONTROL DESIGN

Control Design Form

Objectives

Measurements

Manipulated variables

Constraints

Disturbances

Dynamic responses

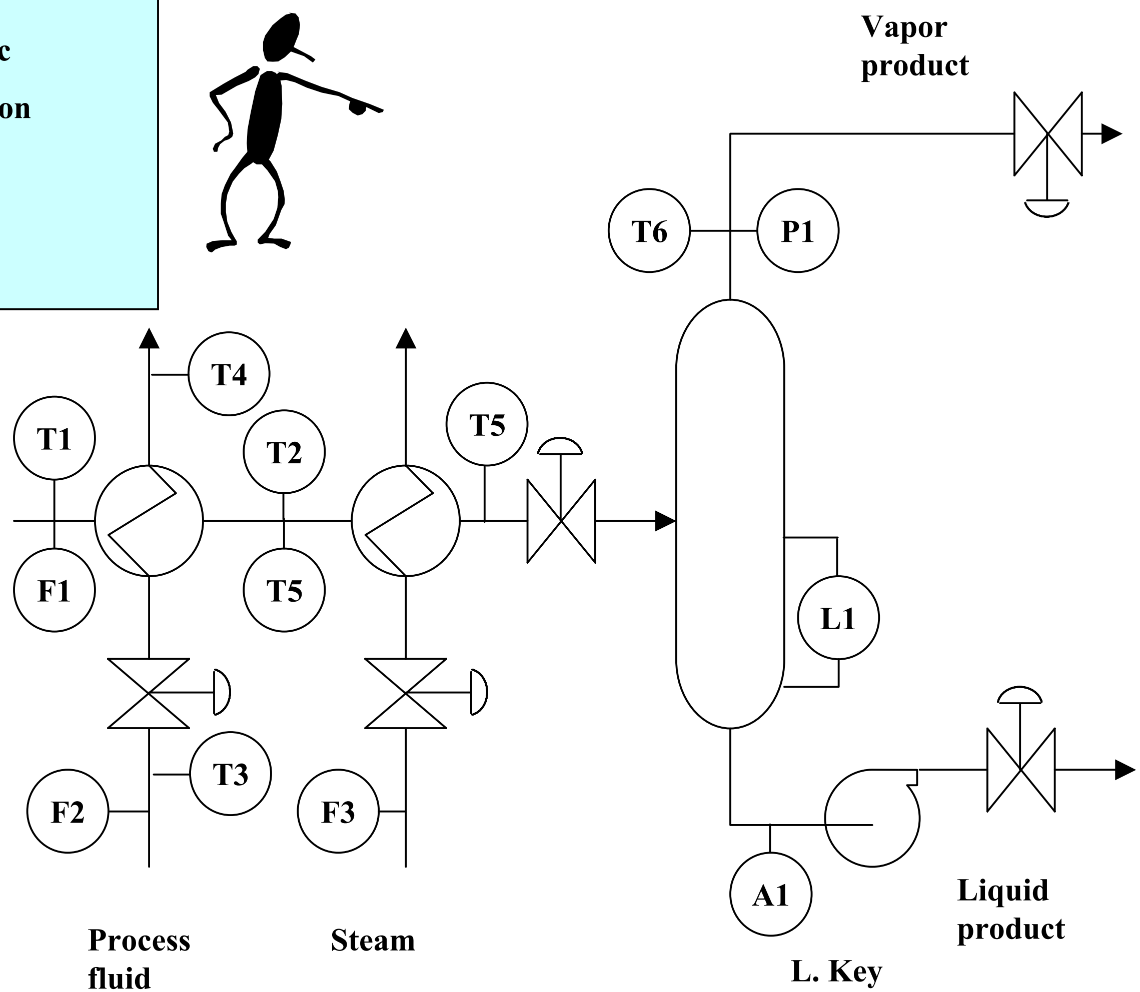
Additional considerations

FINAL ELEMENTS

- **Capacity**
- **Precision**
- **Range**
- **Characteristic**
- **Failure position**
- **Dynamics**
- **Reliability**
- **Cost**

WORKSHOP:

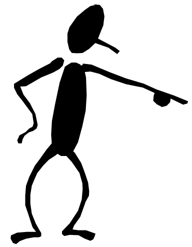
- **Define failure position (as best possible, without the remainder of plant design).**
- **Select the body for a valve**



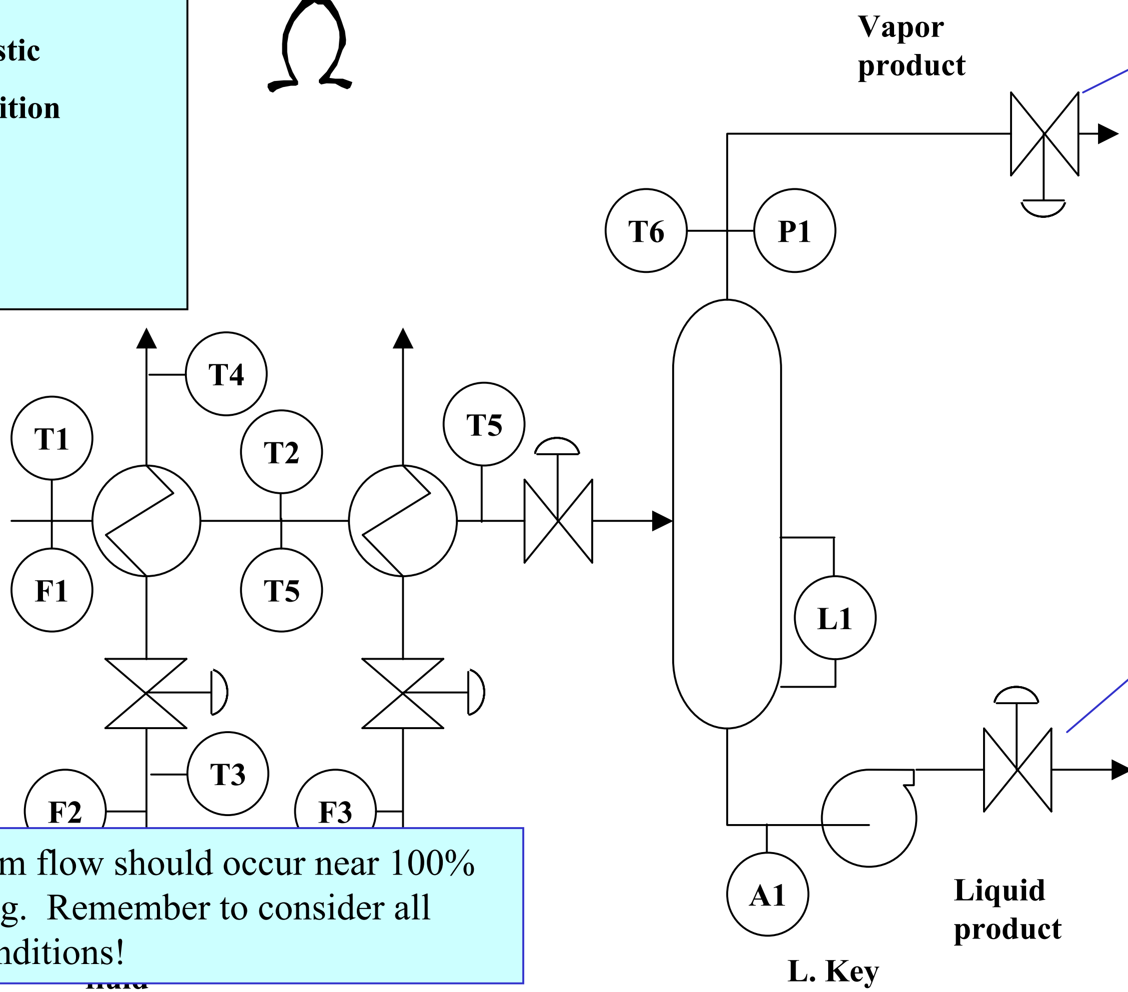
CHAPTER 24: CONTROL DESIGN

FINAL ELEMENTS

- Capacity
- Precision
- Range
- Characteristic
- Failure position
- Dynamics
- Reliability
- Cost



WORKSHOP:
- Define failure position (as best possible, without the remainder of plant design).
- Select the body for a valve



Fail opened to relieve pressure in vessel. (we assume that the downstream unit can accept the material and not release.)

Globe valve for clean fluid with moderate pressure loss acceptable.

The maximum flow should occur near 100% valve opening. Remember to consider all operating conditions!

CHAPTER 24: CONTROL DESIGN

<u>WORKSHOP</u>: Determine some constraints

<u>Control Design Form</u>

Objectives

Measurements

Manipulated variables

Constraints

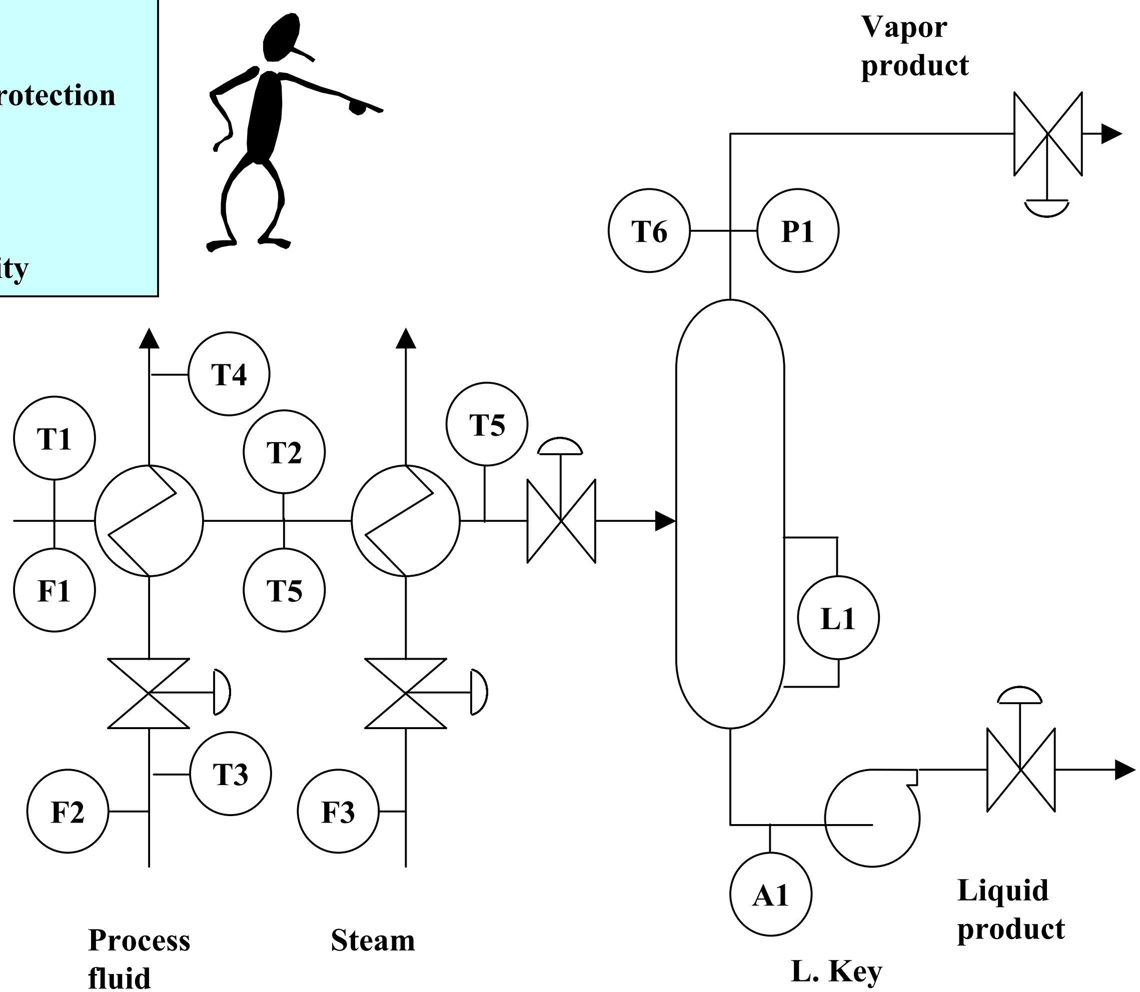
Disturbances

Dynamic responses

Additional considerations

<u>CONSTRAINTS</u>

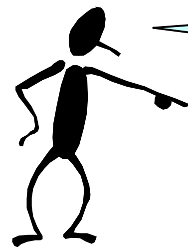
- **Safety**
- **Equipment protection**
  - **- Short term**
  - **- Long term**
- **Product quality**



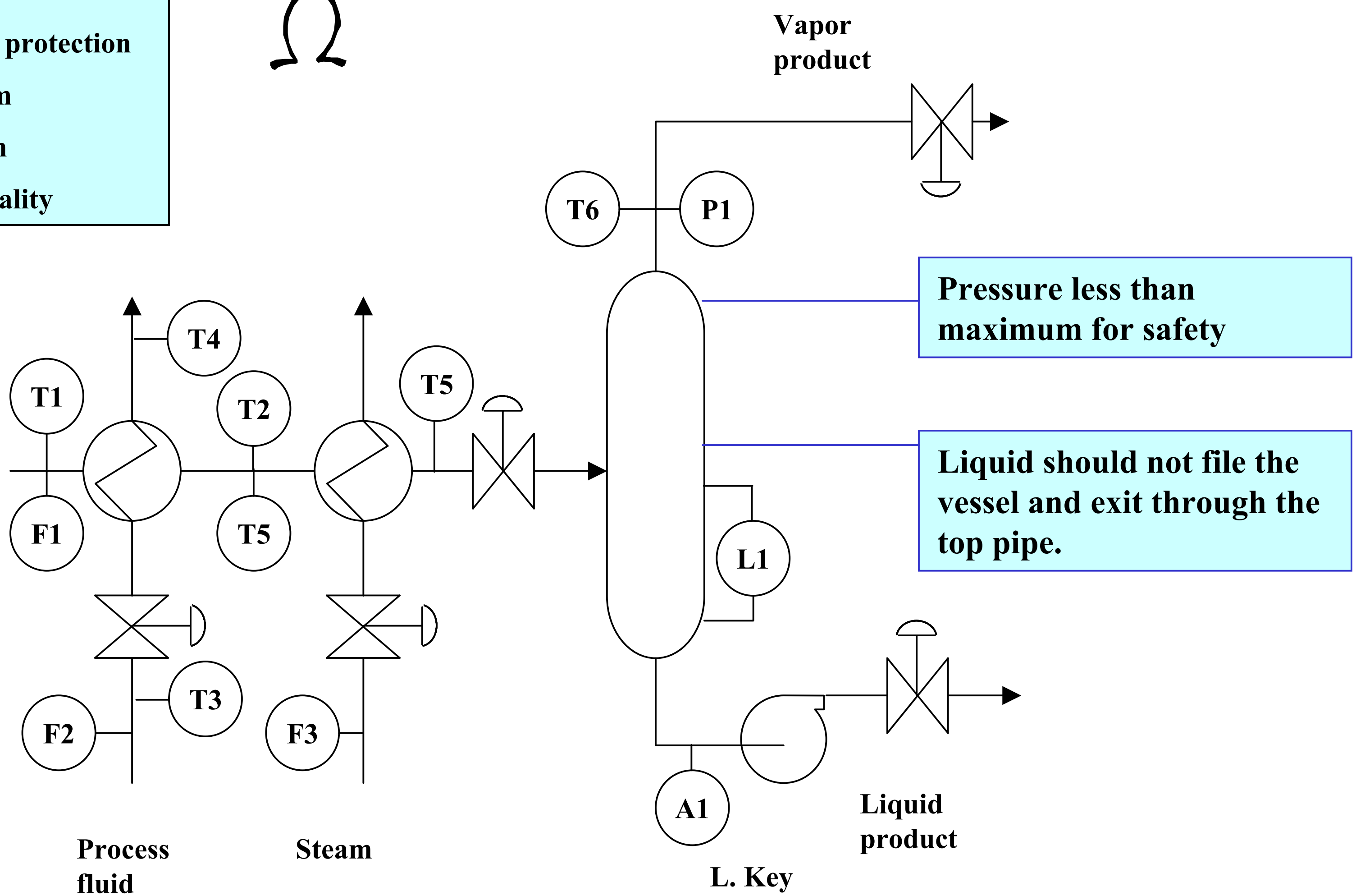
CHAPTER 24: CONTROL DESIGN

CONSTRAINTS

- Safety
- Operating range of equipment
- Equipment protection
  - Short term
  - Long term
- Product quality



WORKSHOP: Determine some constraints



CHAPTER 24: CONTROL DESIGN

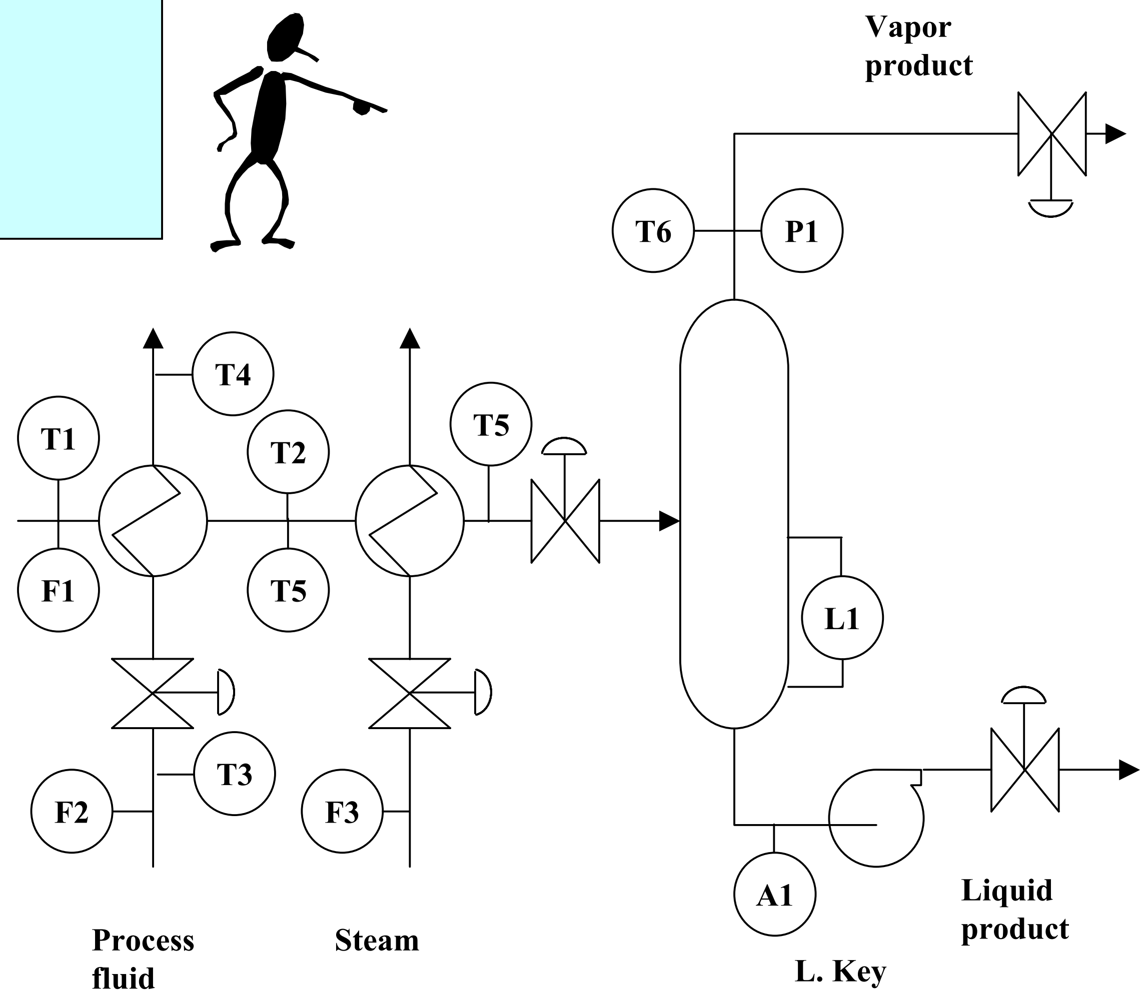
WORKSHOP: Determine some likely disturbances

Control Design Form

- Objectives
- Measurements
- Manipulated variables
- Constraints
- Disturbances
- Dynamic responses
- Additional considerations

DISTURBANCES

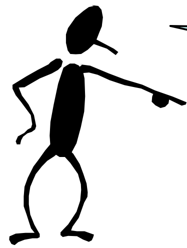
- Variables
- Magnitude
- Sign
- Frequency



CHAPTER 24: CONTROL DESIGN

DISTURBANCES

- Variables
- Magnitude
- Sign
- Frequency

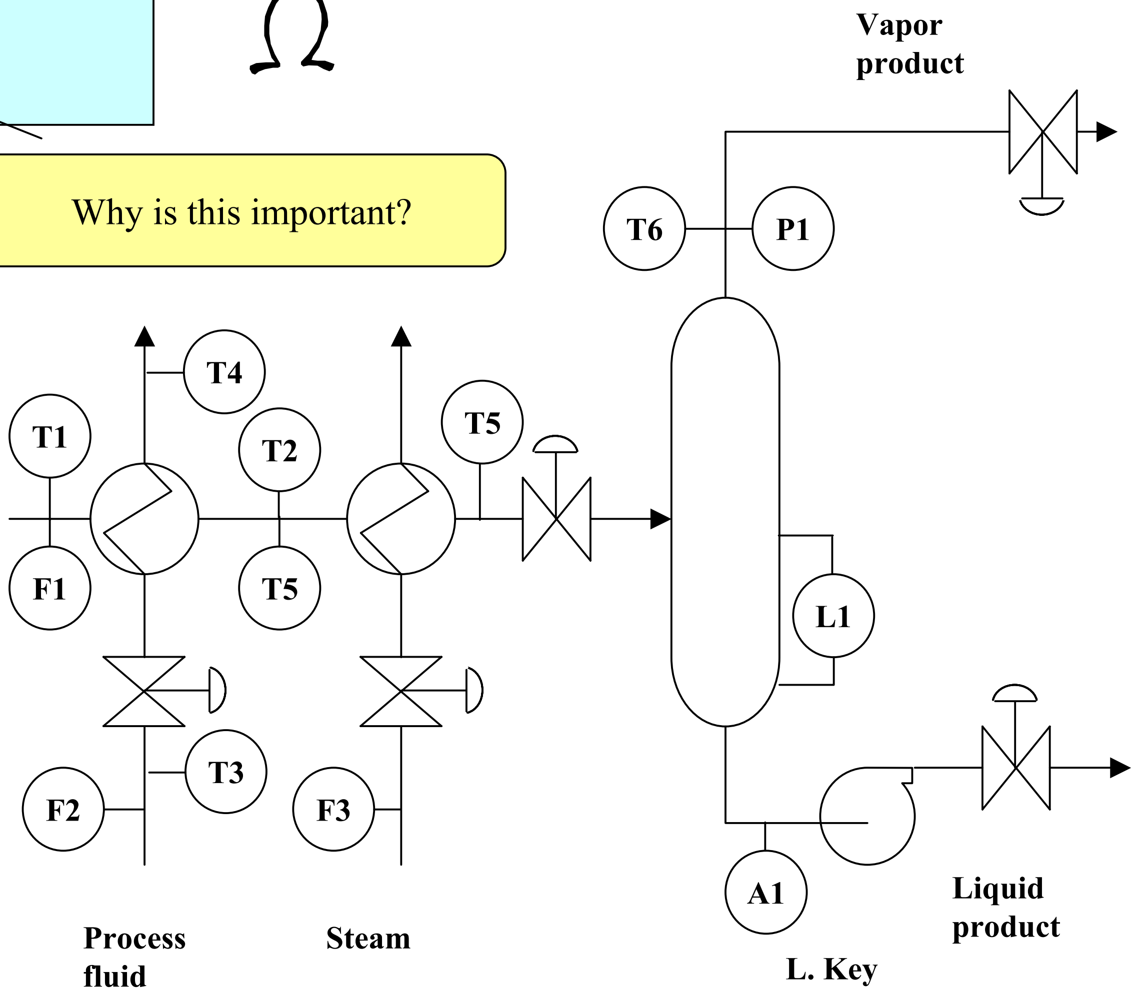


WORKSHOP: Determine some likely disturbances

Why is this important?

FEED COMPOSITION

- Due to upstream processing
- Components change in a correlated manner
- Magnitude is estimated



CHAPTER 24: CONTROL DESIGN

WORKSHOP: How would you use models in control design?

Control Design Form

Objectives

Measurements

Manipulated variables

Constraints

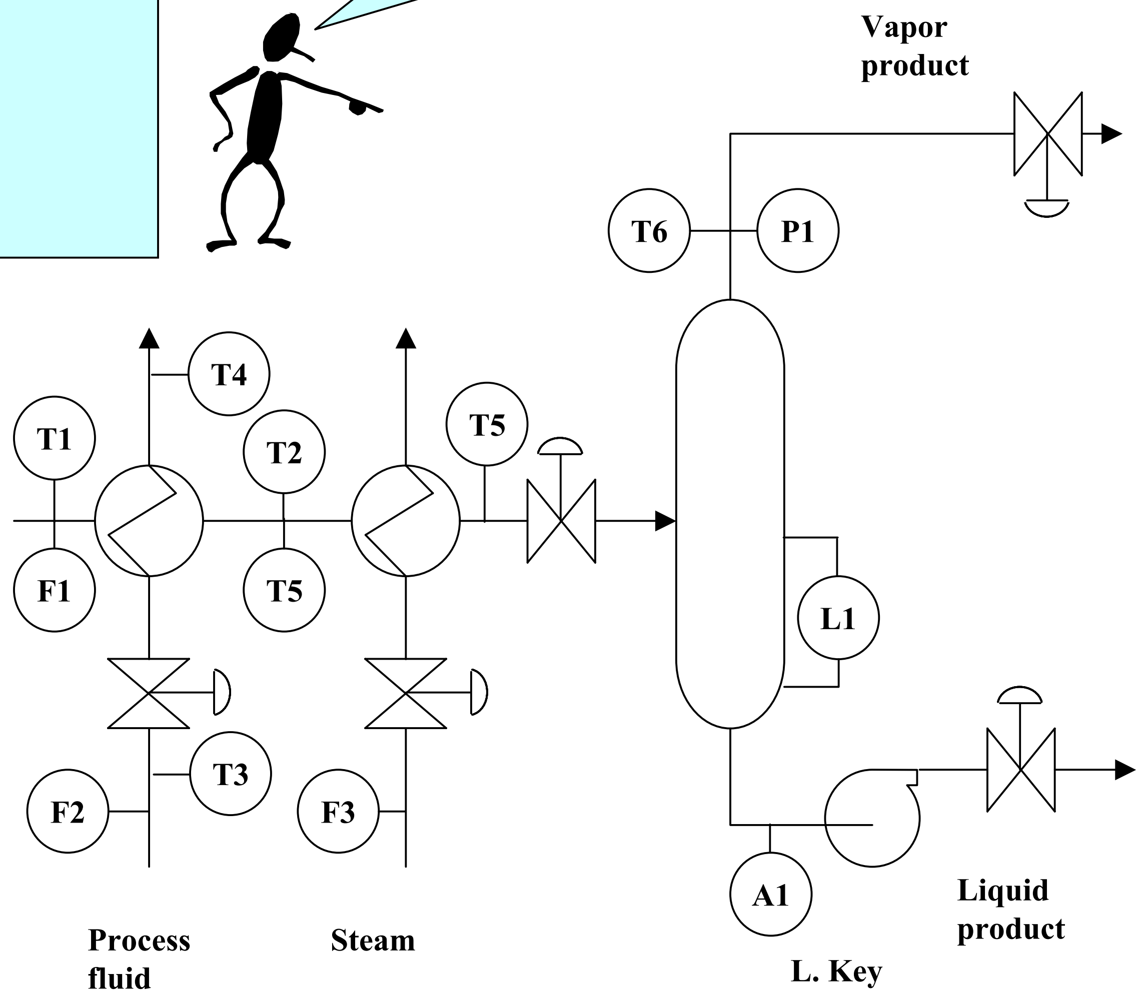
Disturbances

Dynamic responses

Additional considerations

DYNAMIC MODELS

- Fundamental modelling
- Empirical identification



CHAPTER 24: CONTROL DESIGN

THE CONTROL DESIGN PROCEDURE

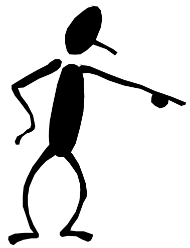
- Define the control problem (challenge) ✓
- Evaluate/achieve operability

  - Degrees of freedom
  - Controllability
  - Operating Window
- Process dynamics for good performance
- Loop pairing
- Control for safety
- Monitoring and diagnosis

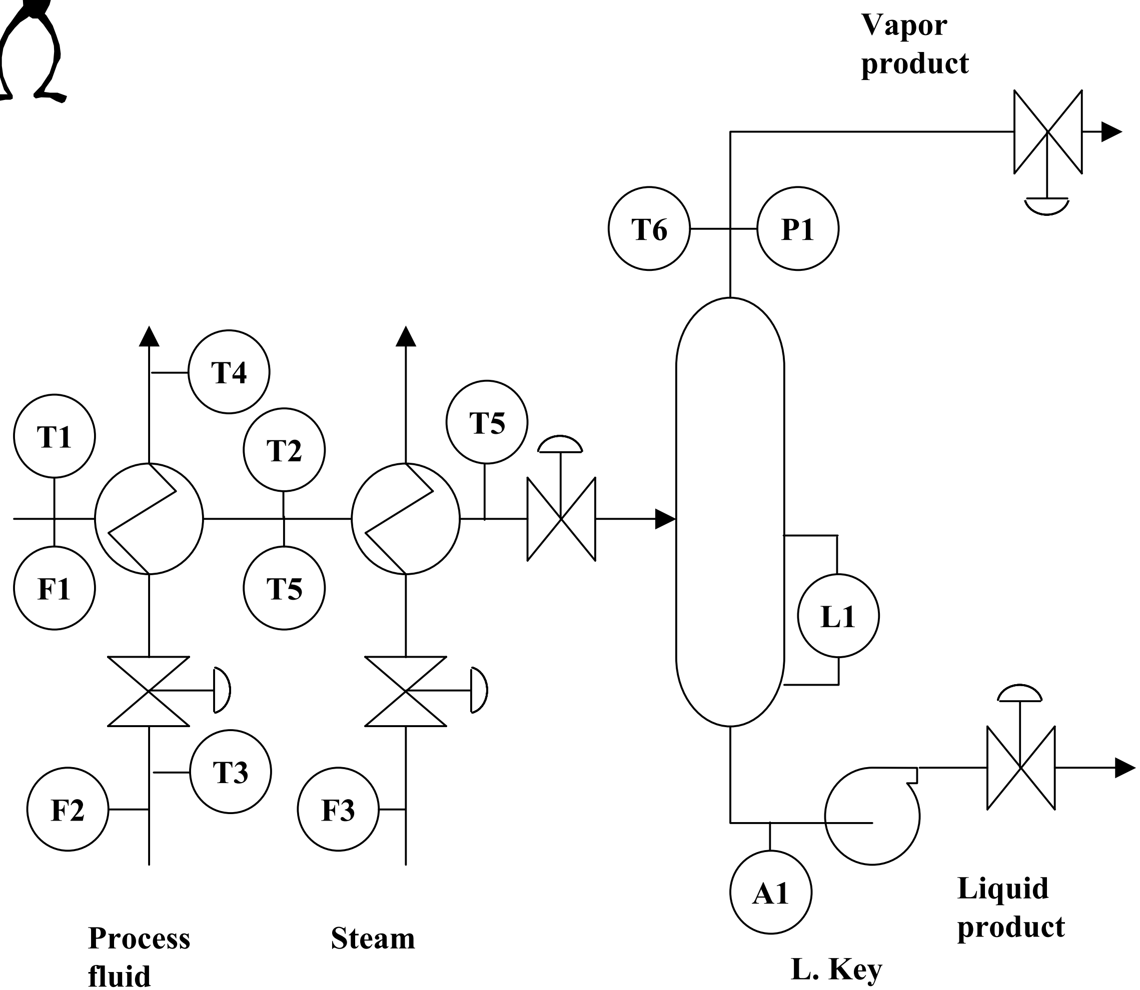
CHAPTER 24: CONTROL DESIGN

DYNAMIC MODELS

- **Fundamental modelling**
- **Empirical identification**



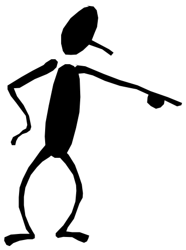
WORKSHOP: How would you use models in control design?



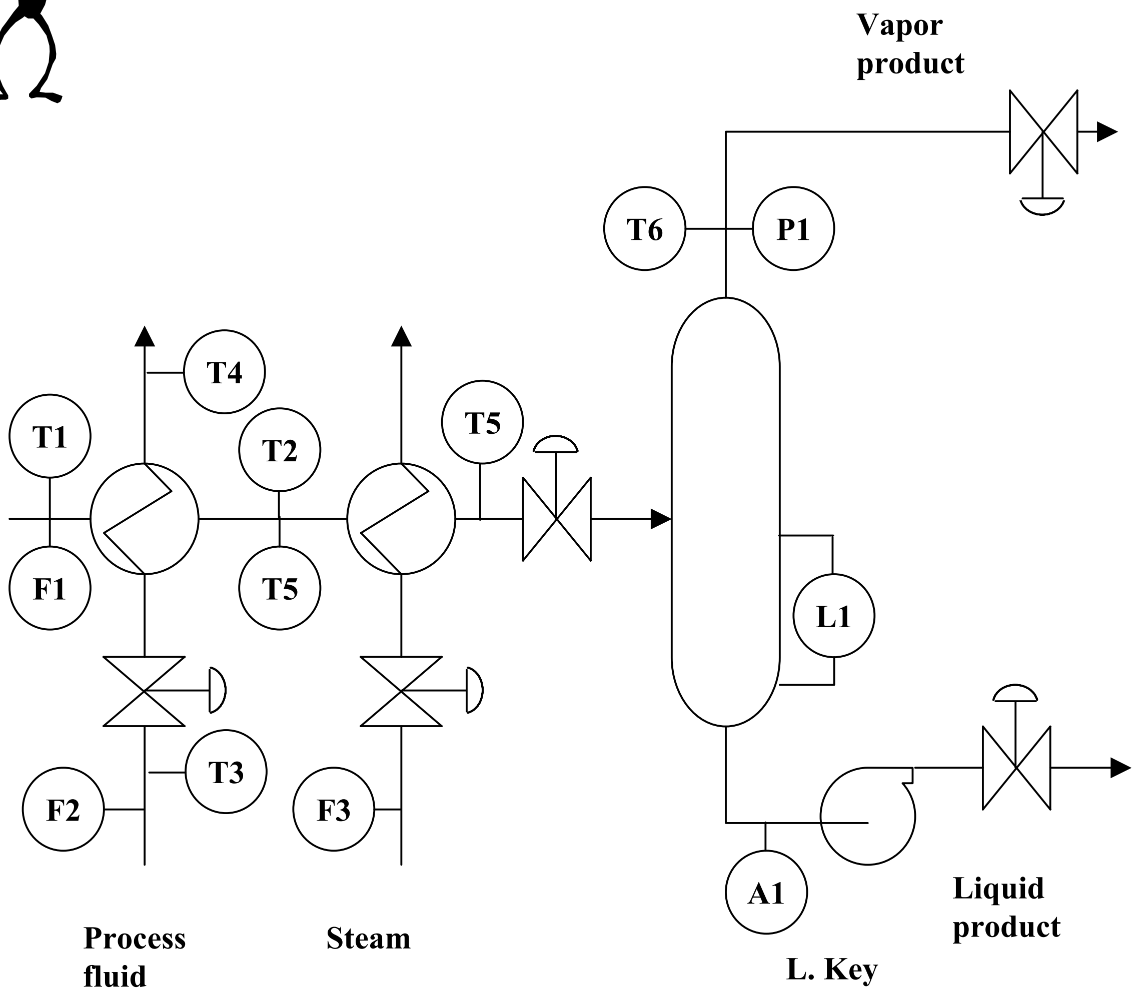
CHAPTER 24: CONTROL DESIGN

DYNAMIC MODELS

- Fundamental modelling
- Empirical identification



WORKSHOP: How would you use models in control design?



- Determining controllability
- Estimating operating windows
- Pairing loops
- Tuning controllers

Models required, do not design entirely on qualitative model.

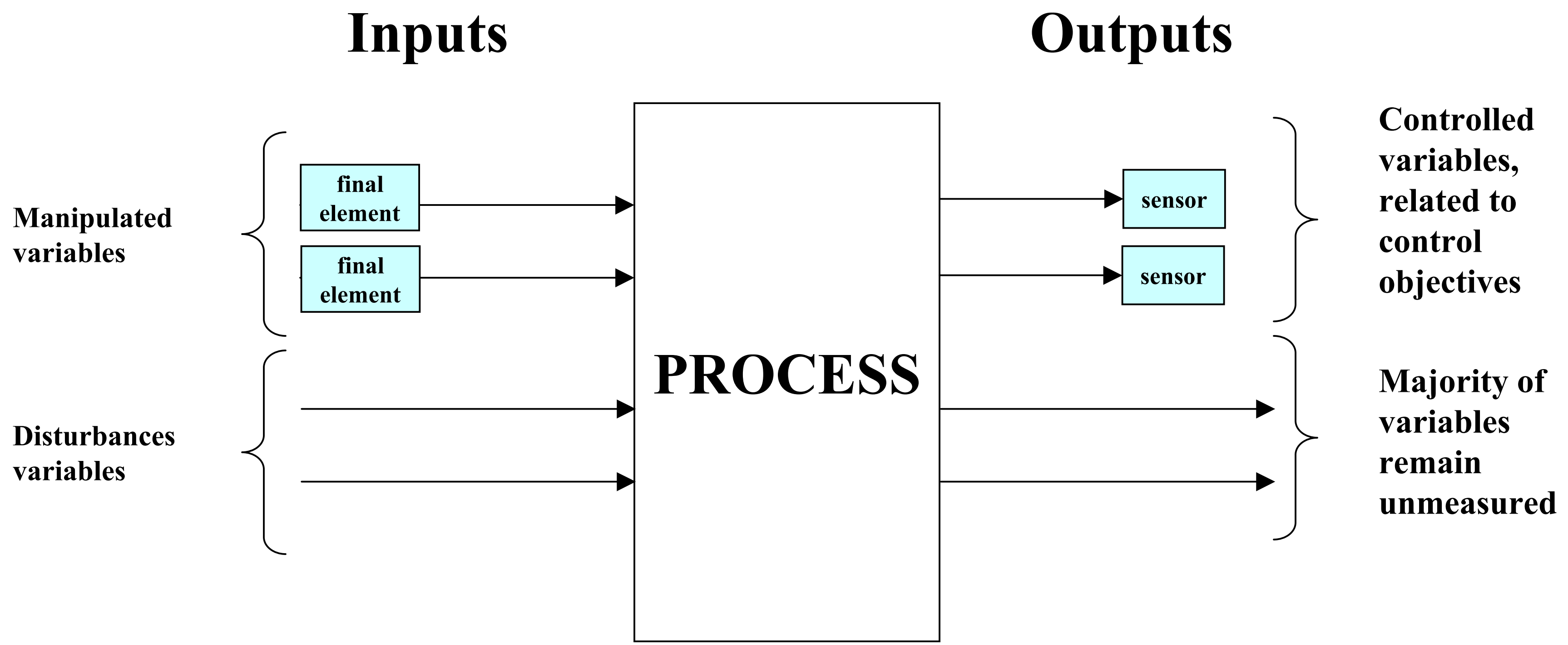
CHAPTER 24: CONTROL DESIGN

PROCESS OPERABILITY

- Degrees of freedom
- Controllability
- Operating Window

Is control possible given the manipulated and control variables?

If not, the process (or objectives) must be changed

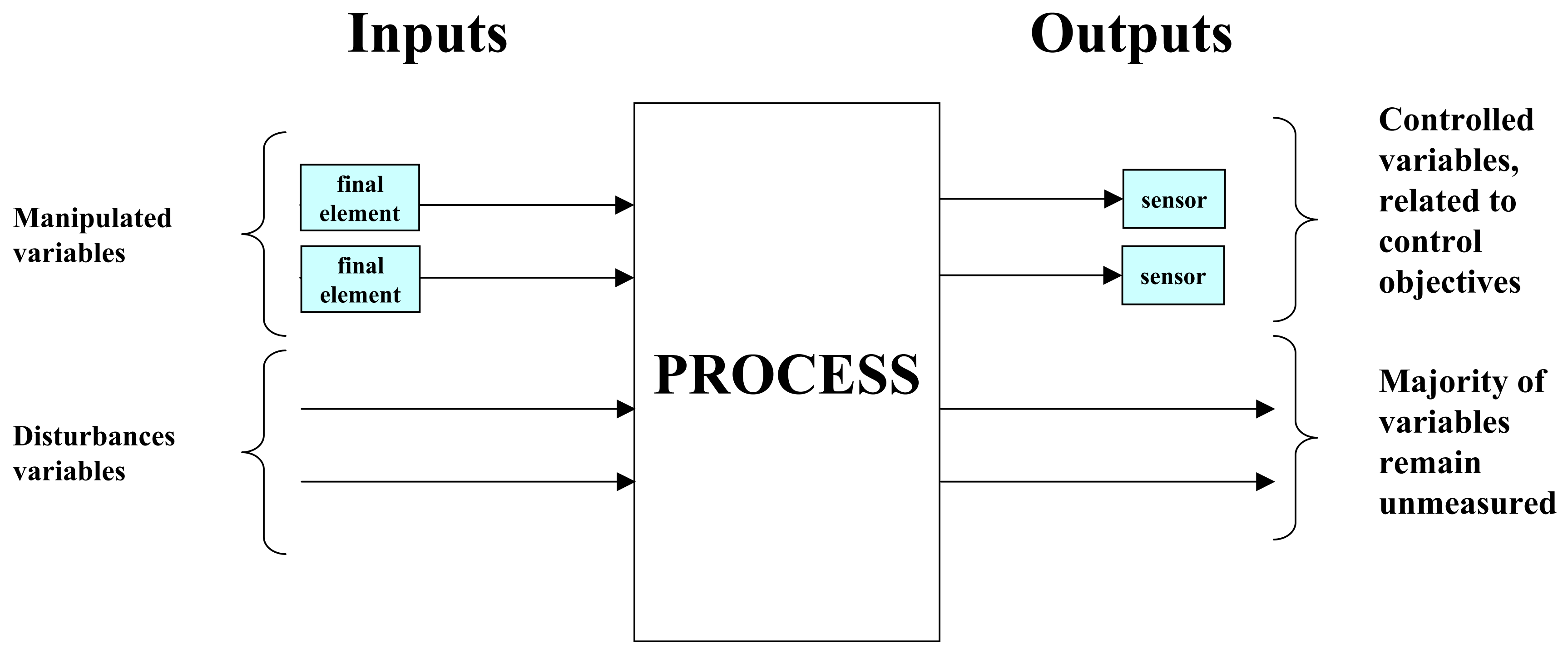


CHAPTER 24: CONTROL DESIGN

DEGRESS OF FREEDOM

QUICK REVIEW: The system is has sufficient degrees of freedom if

# of manipulated variables $\geq$ # of controlled variables



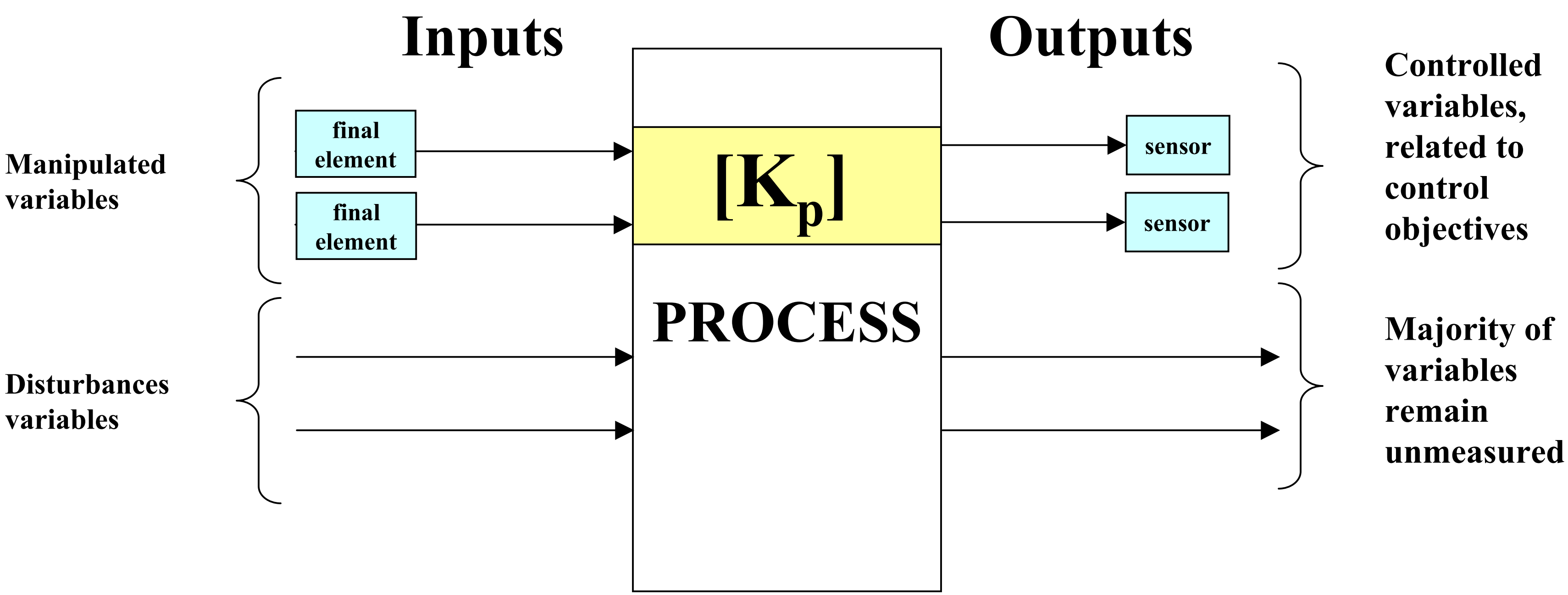
CHAPTER 24: CONTROL DESIGN

CONTROLLABILITY

QUICK REVIEW: Controllability ensures that the selected controlled variables can be changed to desired values

The system is controllable if

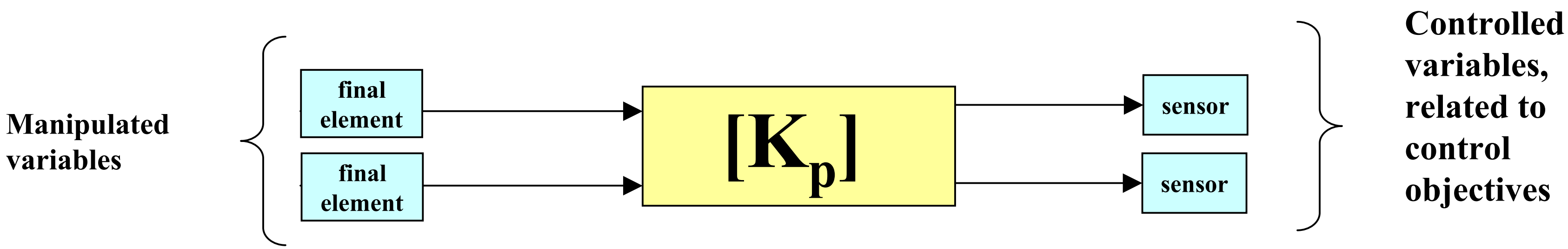
$$\text{Det}\ [K_p] \neq 0$$



CHAPTER 24: CONTROL DESIGN

CONTROLLABILITY

QUICK REVIEW: Controllability ensures that the selected controlled variables can be changed to desired values



Why might we come to an <u>incorrect result</u> from qualitative analysis?

Some seemingly independent variables are “linked” through

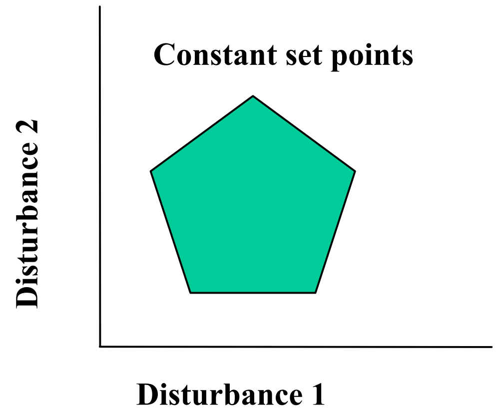
- **material balance**
- **energy balance**
- **equilibrium**
- **reaction stoichiometry**

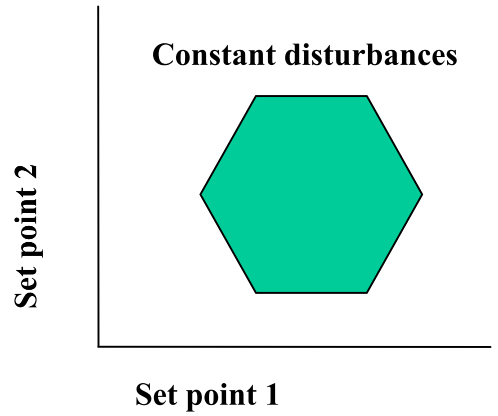
CHAPTER 24: CONTROL DESIGN

OPERATING WINDOW

QUICK REVIEW: This is the "reachable" region of steady-state values as disturbances occur and set points are changed.

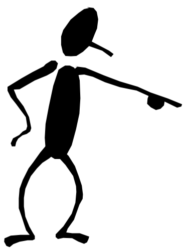
- **Covers a wide range - linear models not usually adequate**
- **Sometimes called the feasible region**
- **Usually plotted in one of the forms sketched below**



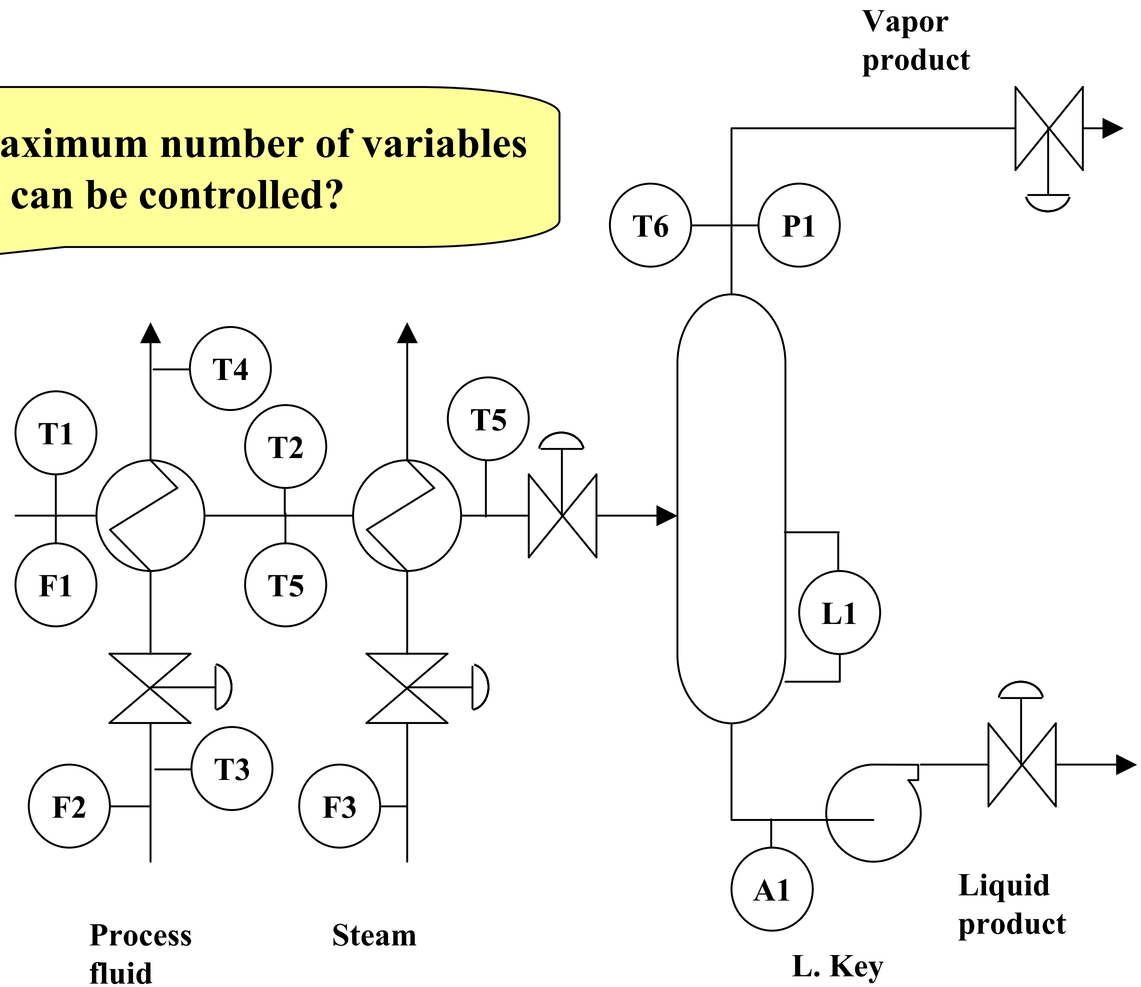


CHAPTER 24: CONTROL DESIGN

DEGRESS OF FREEDOM

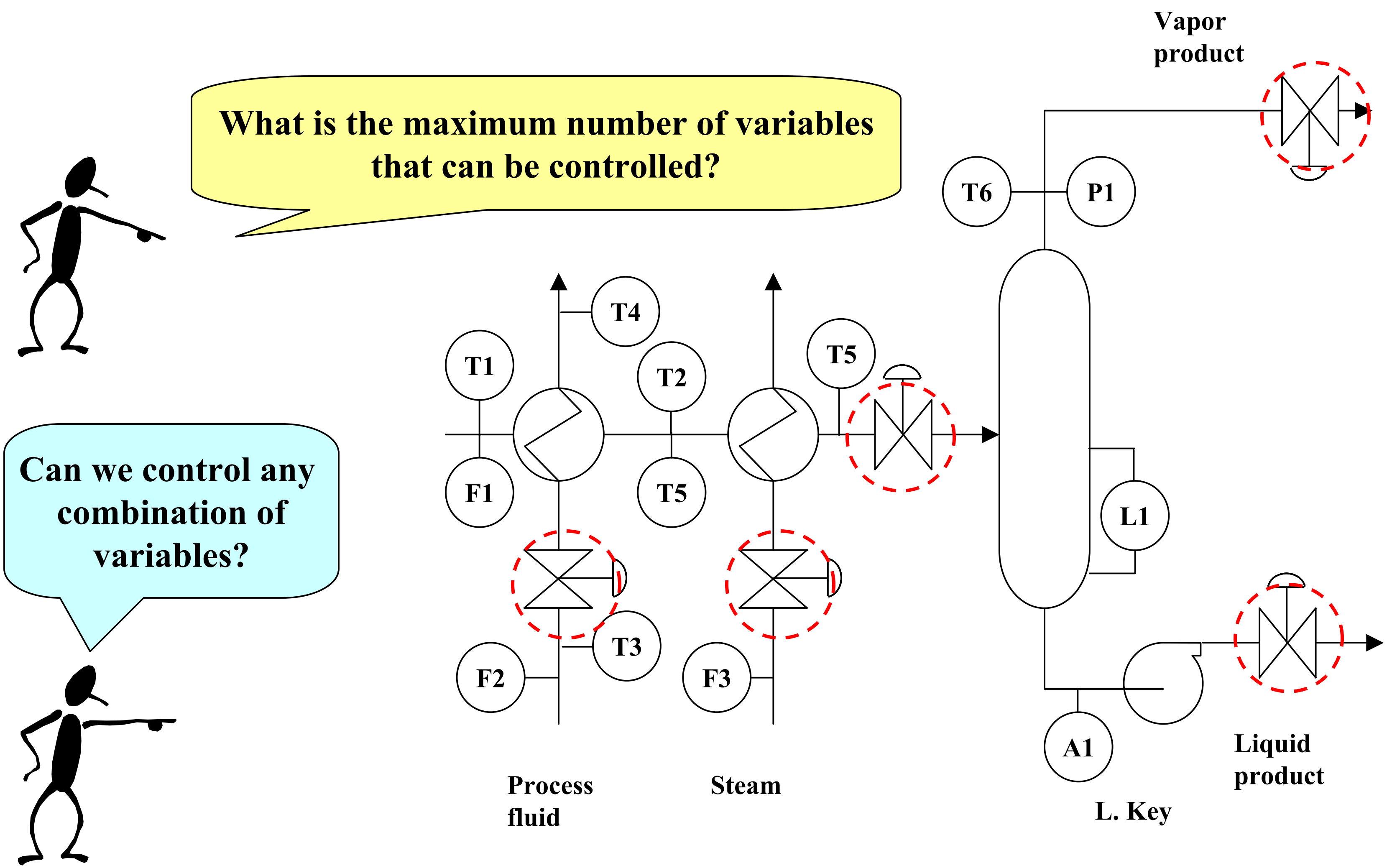


What is the maximum number of variables that can be controlled?



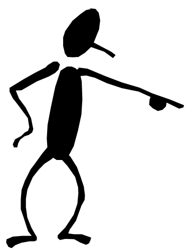
CHAPTER 24: CONTROL DESIGN

DEGRESS OF FREEDOM

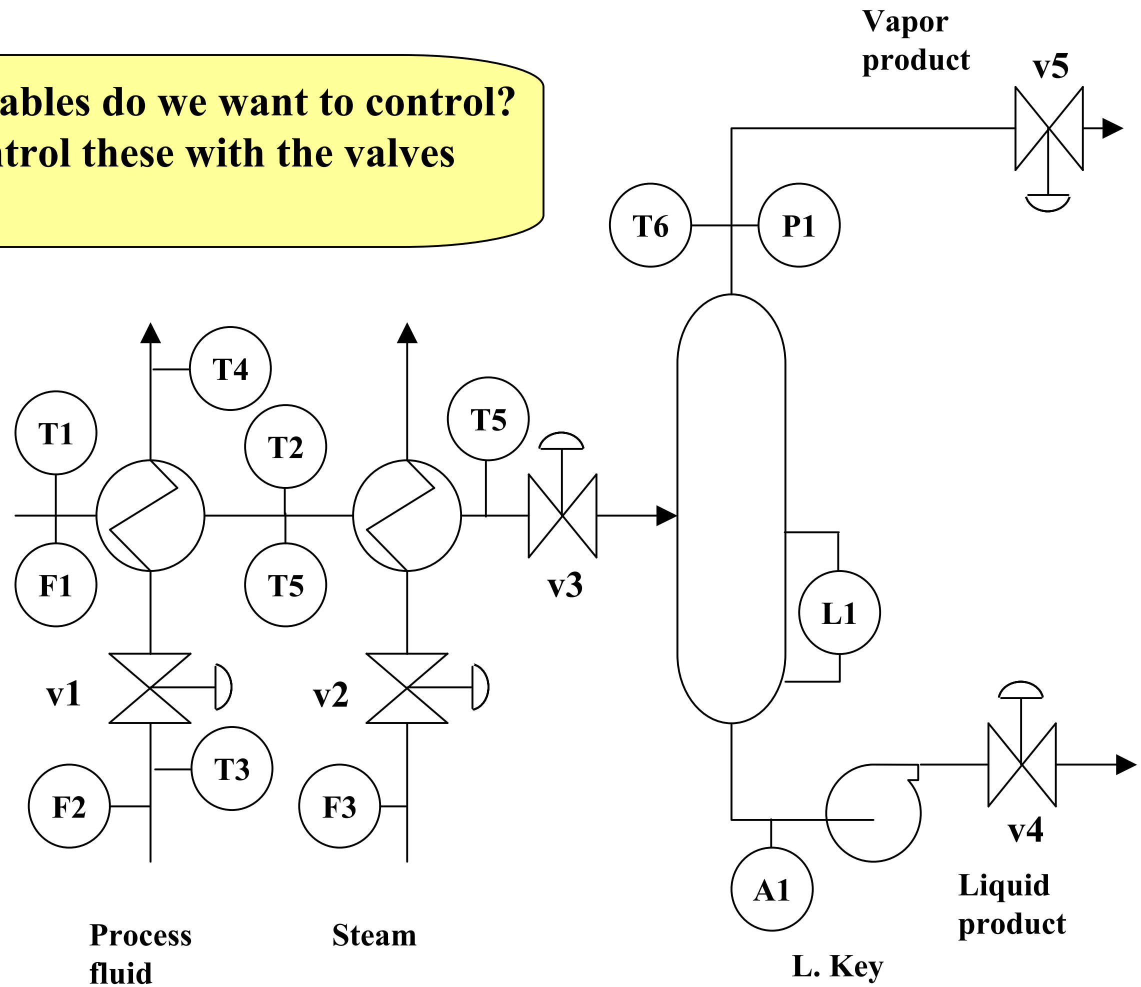


CHAPTER 24: CONTROL DESIGN

CONTROLLABILITY



- **Which variables do we want to control?**
- **Can we control these with the valves shown?**

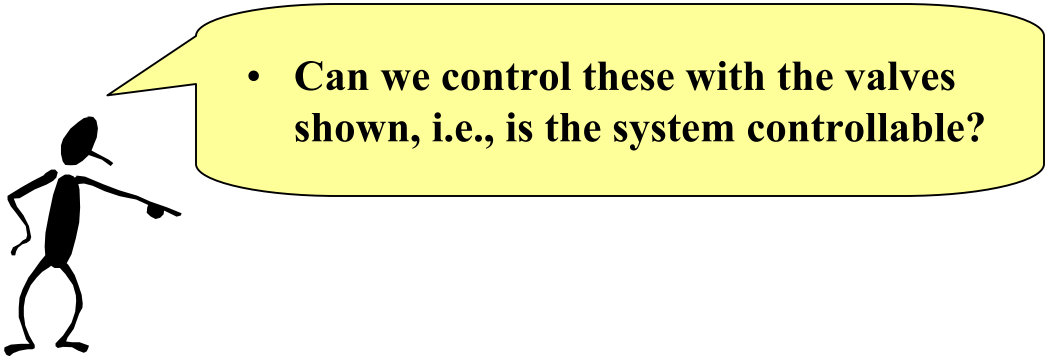


Let's select:

F1	**production rate**
T6	**feed vaporization**
A1	**product quality**
P	**safety**
L	**liquid to pump**

CHAPTER 24: CONTROL DESIGN

CONTROLLABILITY



Let's select:

F1 production rate

T6 feed vaporization

A1 product quality

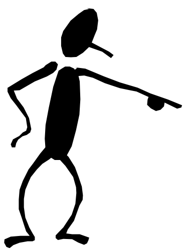
P safety

L liquid to pump

$$\begin{bmatrix} F1 \\ T6 \\ A1 \\ P1 \\ dL/dt \end{bmatrix} = \begin{bmatrix} 0 & 0 & 2.0 & 0 & 0 \\ .0708 & .85 & -.44 & 0 & -.19 \\ -.00917 & -.11 & -.44 & 0 & .043 \\ .567 & 6.80 & 1.39 & 0 & -5.36 \\ -.0113 & -.136 & .31 & -.179 & -.0265 \end{bmatrix} \begin{bmatrix} v1 \\ v2 \\ v3 \\ v4 \\ v5 \end{bmatrix}$$

CHAPTER 24: CONTROL DESIGN

CONTROLLABILITY



- **Can we control these with the valves shown, i.e., is the system controllable?**

The effects of v1 and v2 are identical, within a constant. Therefore, the five CVs cannot be independently affected by the five valves.

Let's select:

F1	**production rate**
T6	**feed vaporization**
A1	**product quality**
P	**safety**
L	**liquid to pump**

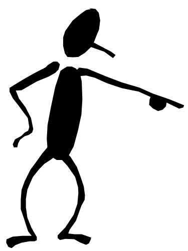
$$\begin{bmatrix} F1 \\ T6 \\ A1 \\ P1 \\ dL/dt \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 0 & 2.0 & 0 & 0 \\ .0708 & .85 & -.44 & 0 & -.19 \\ -.00917 & -.11 & -.44 & 0 & .043 \\ .567 & 6.80 & 1.39 & 0 & -5.36 \\ -.0113 & -.136 & .31 & -.179 & -.0265 \end{bmatrix}}_{\text{Det }[K_P] = 10^{-7}} \begin{bmatrix} v1 \\ v2 \\ v3 \\ v4 \\ v5 \end{bmatrix}$$

Det $[K_P] = 10^{-7}$

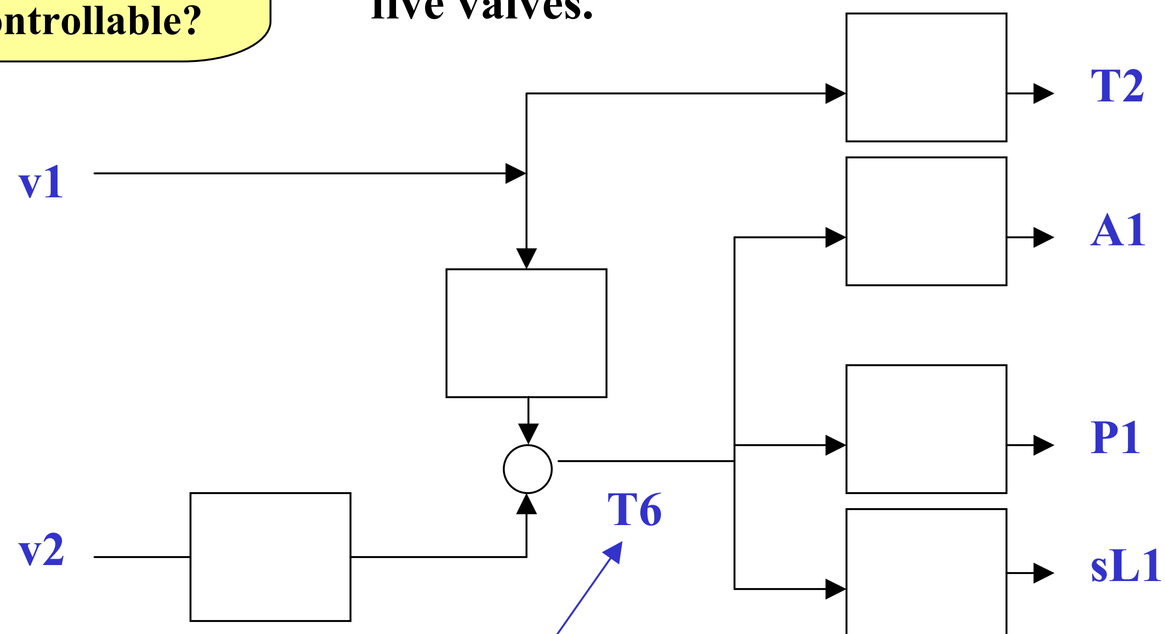
CHAPTER 24: CONTROL DESIGN

CONTROLLABILITY

- **Can we control these with the valves shown, i.e., is the system controllable?**



The effects of v1 and v2 are identical, within a constant. Therefore, the five CVs cannot be independently affected by the five valves.



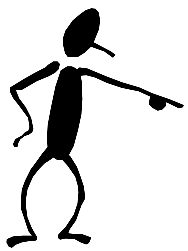
Let's select:

F1	**production rate**
T6	**feed vaporization**
A1	**product quality**
P	**safety**
L	**liquid to pump**

Both v1 and v2 affect CVs of interest through T6. This is a contraction that reduces the controllability.

CHAPTER 24: CONTROL DESIGN

CONTROLLABILITY



- Can we control these with the valves shown, i.e., is the system controllable?

The effects of v1 and v2 are identical, within a constant. Here, we remove v1 (arbitrarily).

Yes, controllable!

Let's select:

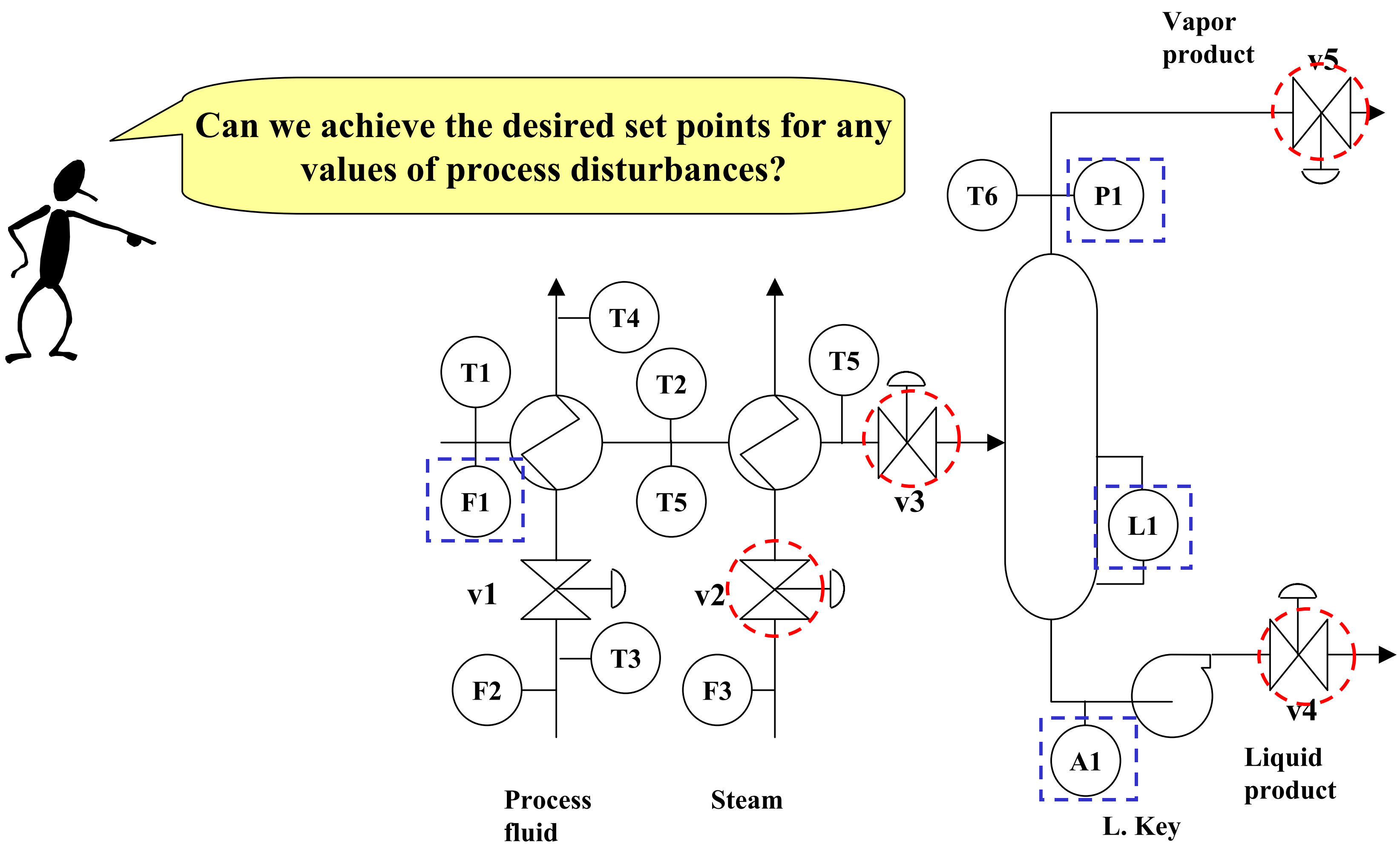
F1	**production rate**
~~**T6**~~	~~**feed vaporization**~~
A1	**product quality**
P	**safety**
L	**liquid to pump**

$$\underbrace{\begin{bmatrix} F1 \\ A1 \\ P1 \\ dL/dt \end{bmatrix} = \begin{bmatrix} 0 & 2.0 & 0 & 0 \\ -.11 & -.44 & 0 & .043 \\ 6.80 & 1.39 & 0 & -5.36 \\ -.136 & .31 & -.179 & -.0265 \end{bmatrix} \begin{bmatrix} v2 \\ v3 \\ v4 \\ v5 \end{bmatrix}}_{}$$

$$\mathrm{Det}\,[K_P] = 10^{-1} \neq 0$$

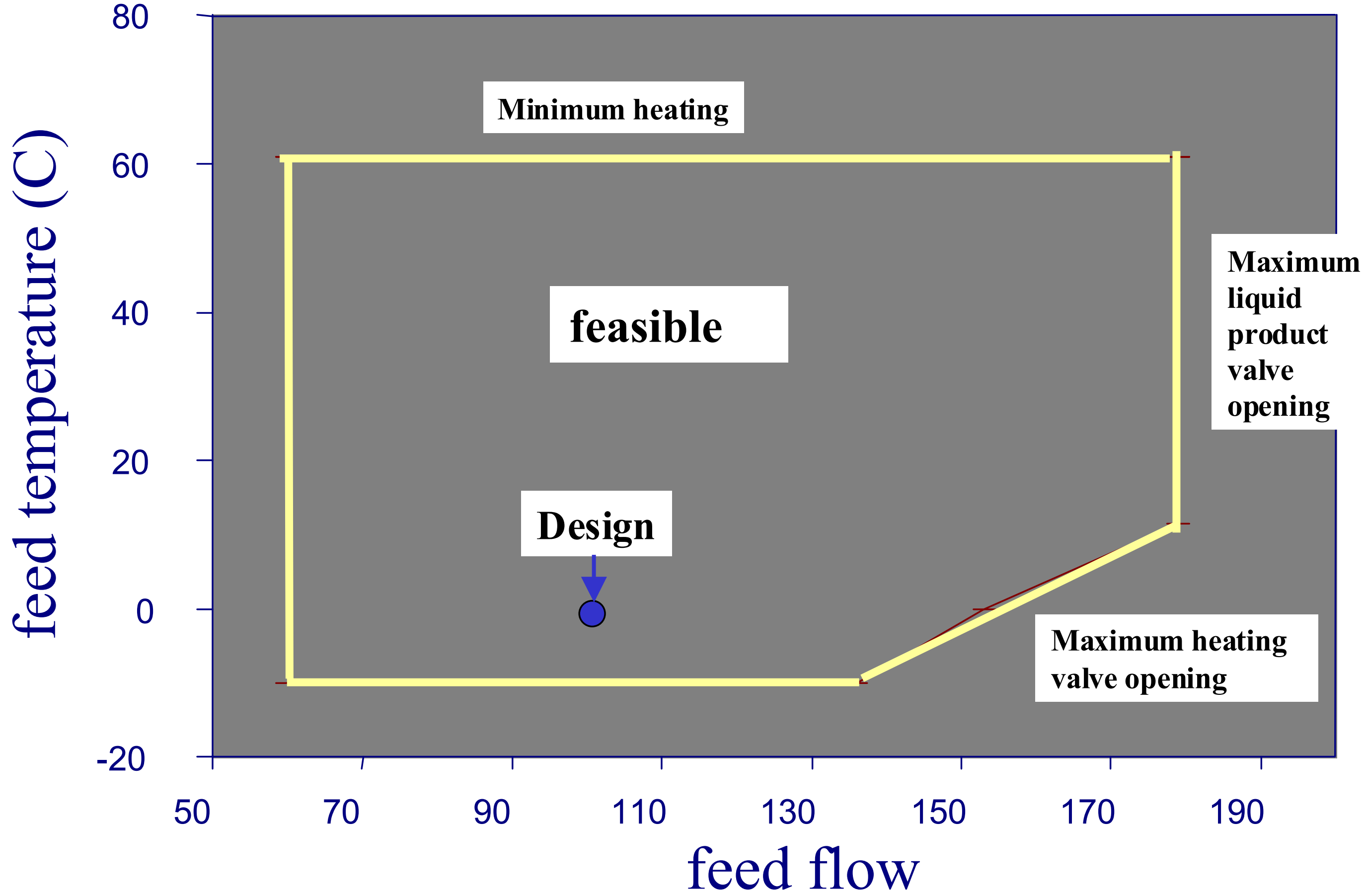
CHAPTER 24: CONTROL DESIGN

OPERATING WINDOW



OPERATING WINDOW

To achieve this large window, both v1 and v2 must be adjusted.
We will take this into consideration when we complete the design.



CHAPTER 24: CONTROL DESIGN

THE CONTROL DESIGN PROCEDURE

- Define the control problem (challenge)
- Evaluate/achieve operability

  - Degrees of freedom
  - Controllability
  - Operating Window
- Process dynamics for good performance
- Loop pairing
- Control for safety
- Monitoring and diagnosis

CHAPTER 24: CONTROL DESIGN

DYNAMICS FOR GOOD PERFORMANCE

- **The importance of disturbance dynamics**

  - Large time constants decrease the effect of the disturbance on the controller variable

  - Dead time has no effect

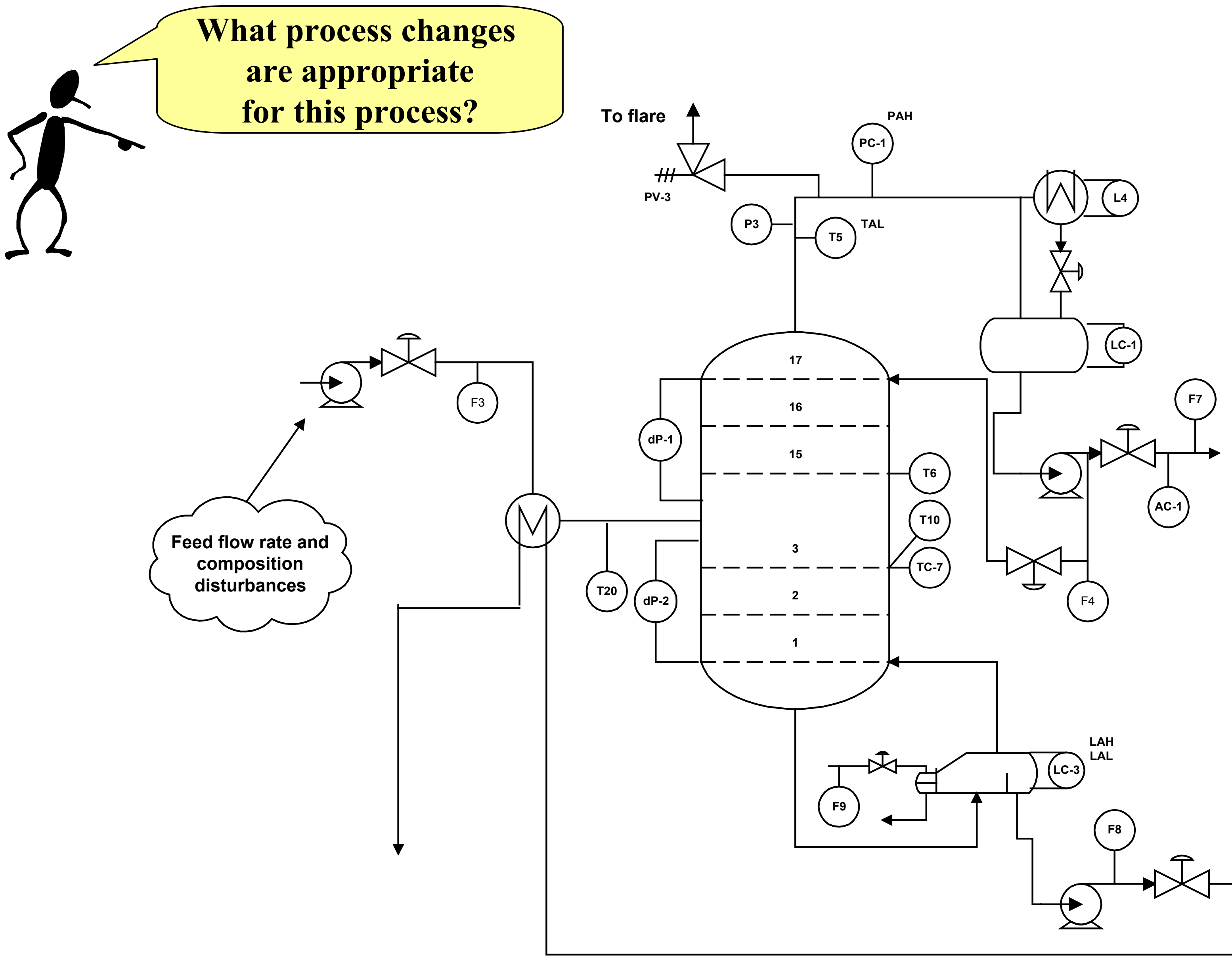
- **The importance of feedback dynamics**

  - Large dead times and time constants are bad!!

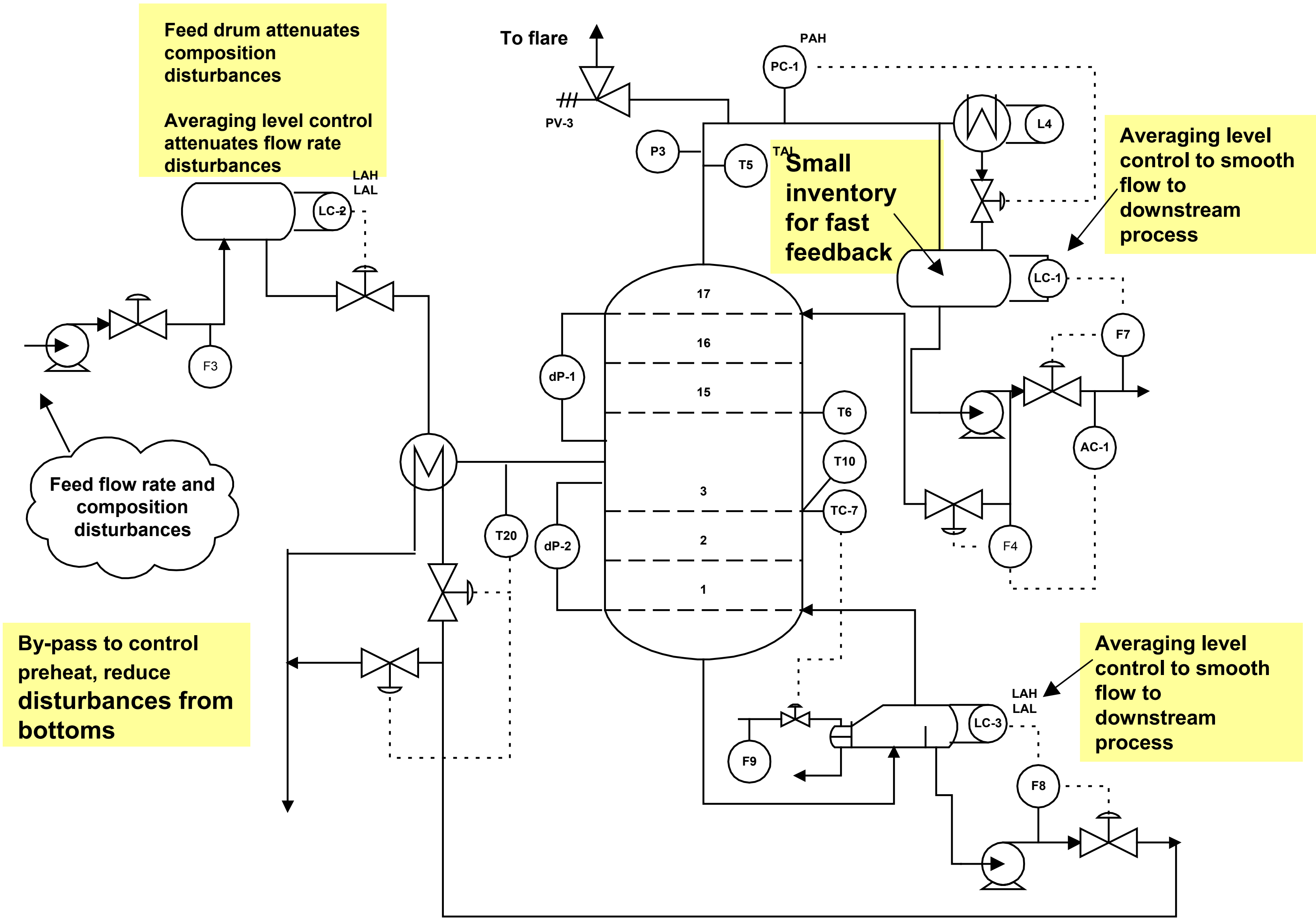
- **The importance of the disturbance frequency**

  - Low frequencies are easy to control. Critical frequency cannot be controlled.

CHAPTER 24: CONTROL DESIGN



CHAPTER 24: CONTROL DESIGN



CHAPTER 24: CONTROL DESIGN

THE CONTROL DESIGN PROCEDURE

- Define the control problem (challenge) ✓
- Evaluate/achieve operability ✓

  - Degrees of freedom
  - Controllability
  - Operating Window
- Process dynamics for good performance ✓
- Loop pairing
- Control for safety
- Monitoring and diagnosis

CHAPTER 24: CONTROL DESIGN

LOOP PAIRING QUALITATIVE GUIDELINES

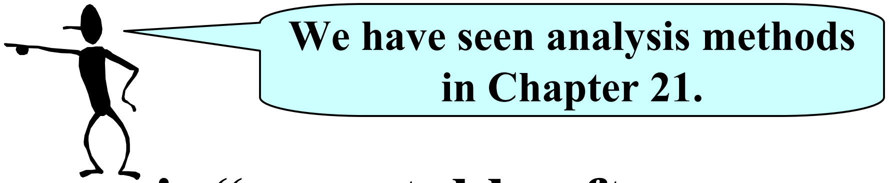
- CV_i - MV_j pairing that has strong effect (large K_p)
- CV_i - MV_j pairing that has fast dynamics
- CV_i - MV_j pairing that has large range (MV min to max)
- CV_i - MV_j pairing with causal relationship that is independent of other loops
- Adjust MV_j that has lowest cost; keep high cost MV near zero

Often, these guidelines cannot all be satisfied. In some cases, they must be violated to achieve good performance. See the next slide for quantitative metrics for control design.

CHAPTER 24: CONTROL DESIGN

REQUIRED: **DOF, Controllability, Operating Window**

HIGHLY DESIRED



- **Integrity** - **Performance is "acceptable after one or more controllers become inactive (RGA)**

- **Control performance**

  - CVs achieve zero offset and low deviations from SP
  - MVs have acceptable dynamic variability

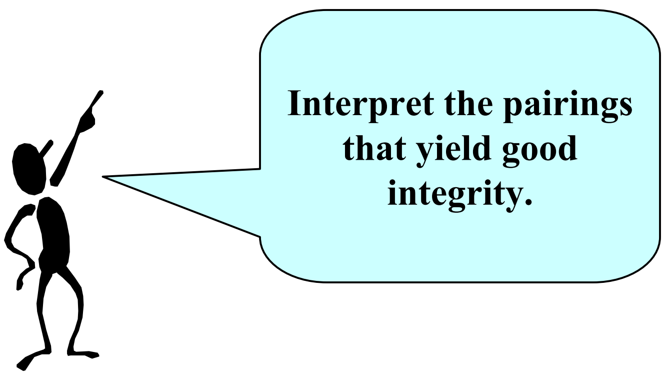
- **Robustness** - **Performance (not just stability) is achieved for a range of plant dynamics**

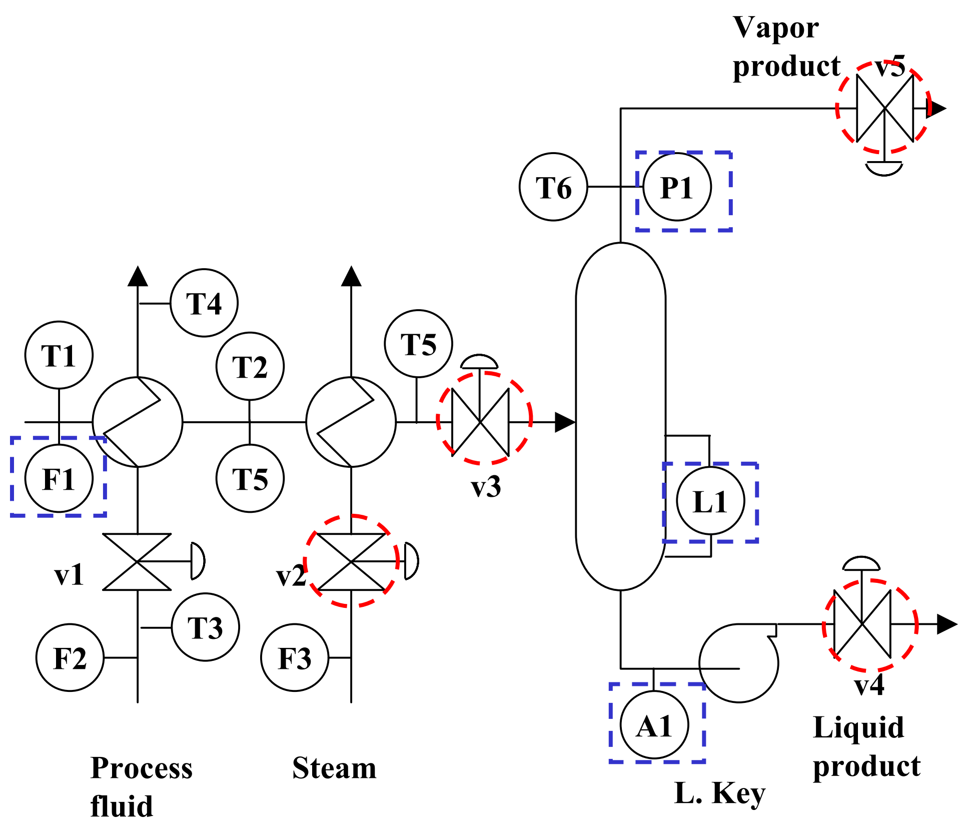
- **Range** - **Strong effect to compensate large disturbances**

CHAPTER 24: CONTROL DESIGN

Let's evaluate the Relative Gain Array, which can be used to evaluate integrity.

	$v2$	$v3$	$v4$	$v5$
$F1$	0	1	0	0
$A1$	1.83	0	0	$-.83$
$P1$	$-.83$	0	0	1.83
$dL1/dt$	0	0	1	0





CHAPTER 24: CONTROL DESIGN

THE CONTROL DESIGN PROCEDURE

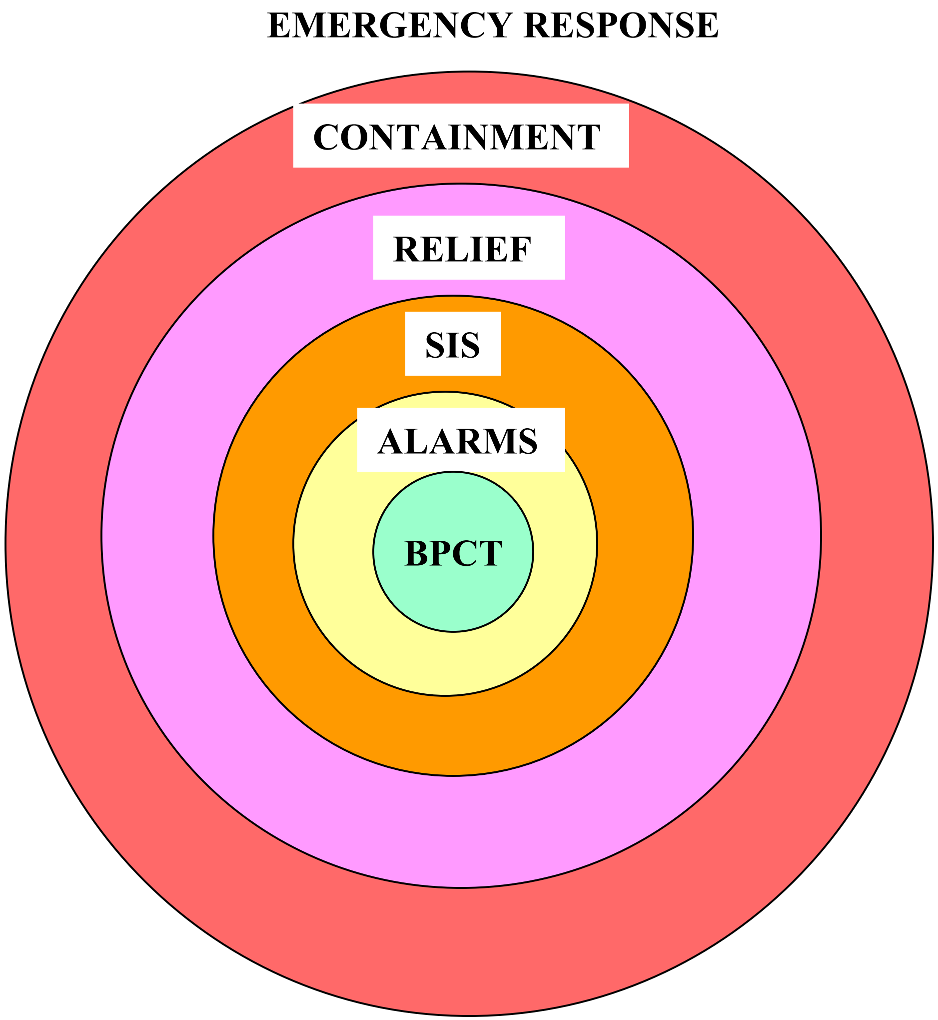
- Define the control problem (challenge)
- Evaluate/achieve operability

  - Degrees of freedom
  - Controllability
  - Operating Window

- Process dynamics for good performance
- Loop pairing
- Control for safety
- Monitoring and diagnosis

CHAPTER 24: CONTROL DESIGN

CONTROL FOR SAFETY



Strength in Reserve

- **BPCT - Basic process control**
- **Alarms - draw attention**
- **SIS - Safety interlock system to stop/start equipment**
- **Relief - Prevent excessive pressure**
- **Containment - Prevent materials from reaching community or environment**

See extra lecture on "Control for Safety"

CHAPTER 24: CONTROL DESIGN

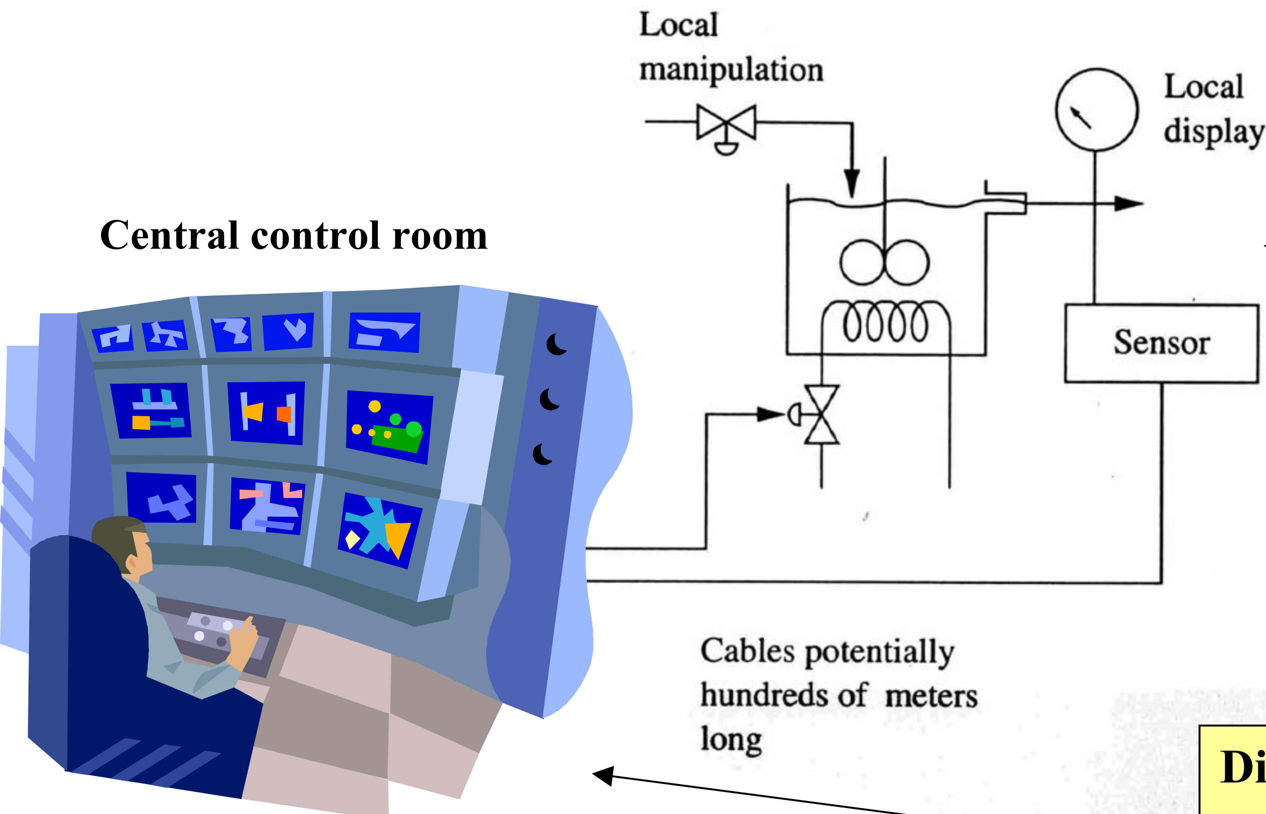
THE CONTROL DESIGN PROCEDURE

- Define the control problem (challenge) ✓
- Evaluate/achieve operability ✓

  - Degrees of freedom
  - Controllability
  - Operating Window
- Process dynamics for good performance ✓
- Loop pairing ✓
- Control for safety ✓
- Monitoring and diagnosis

CHAPTER 24: CONTROL DESIGN

People monitor and diagnose the plant and control system. They are responsible for intervening quickly when needed and for planning non-critical maintenance corrections.



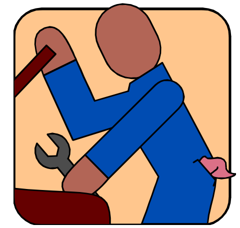
Sensors, local indicators, and valves in the process

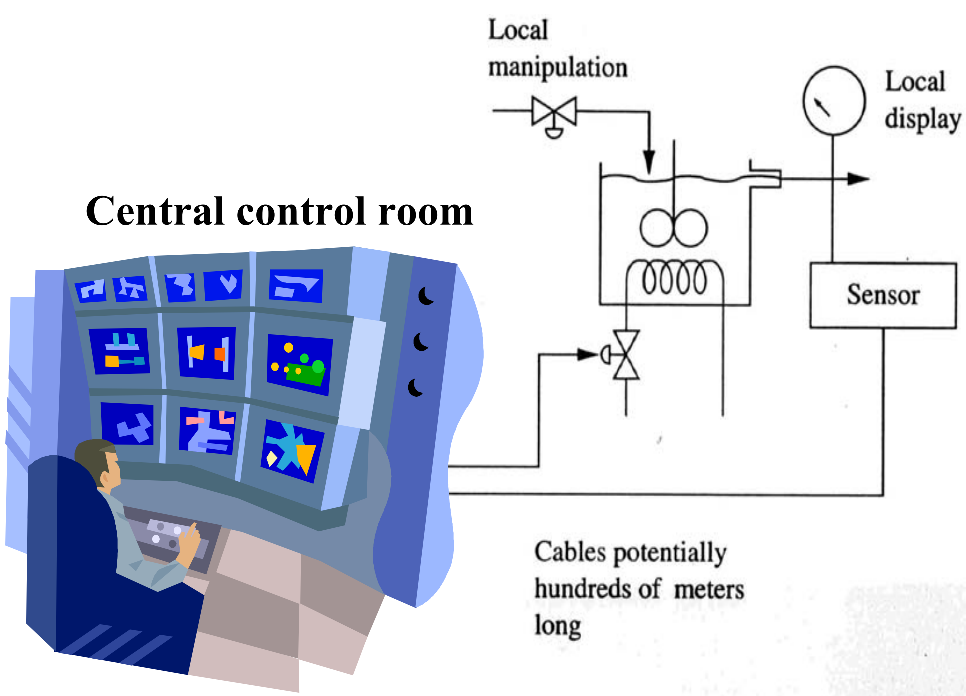
Displays of variables, calculations, and commands to valves are in the centralized control center.

CHAPTER 24: CONTROL DESIGN

LOCAL INSTRUMENTATION

Local manipulated variables are needed for start-up, shutdown, and actions taken infrequently.





Local displays are needed by plant operators when working at the process equipment, e.g., starting a pump or opening a manual by-pass.

They are also used for longer-term monitoring of slow changes, when shift or daily measurements are OK.

CHAPTER 24: CONTROL DESIGN

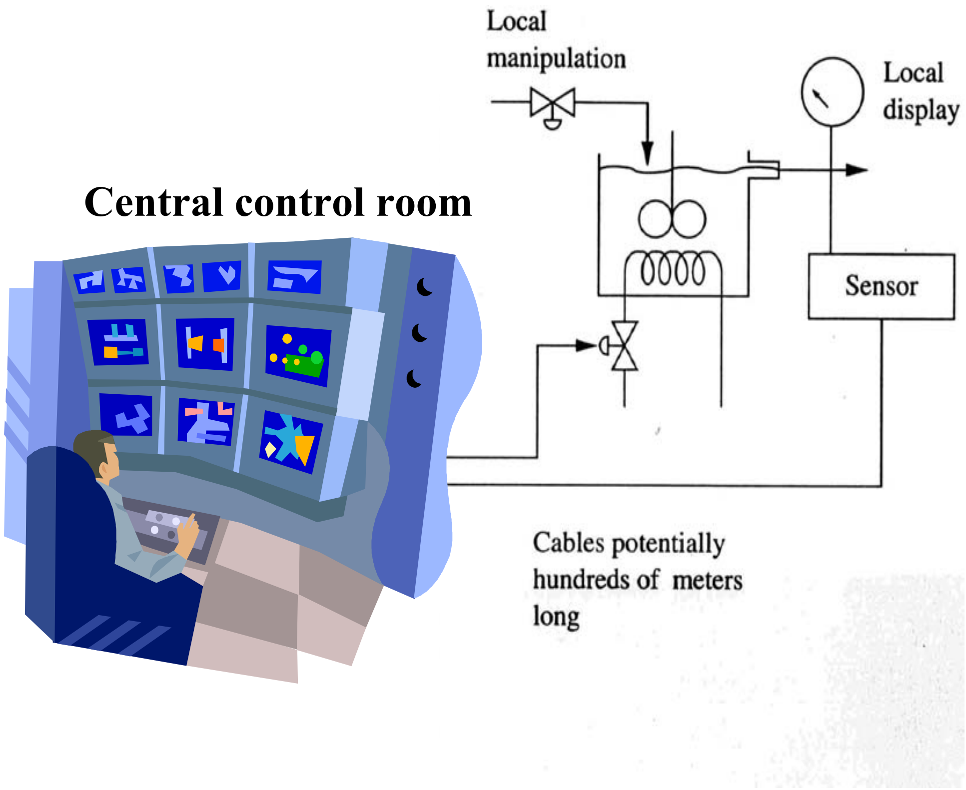
SHORT-TERM DATA ANALYSIS

The centralized control room provides information on the integrated plant.

- Trouble shooting
- product quality
- production control

Information must be presented in a easily understood manner, graphically in context with process schematics.

Mainly used by plant operators.



CHAPTER 24: CONTROL DESIGN

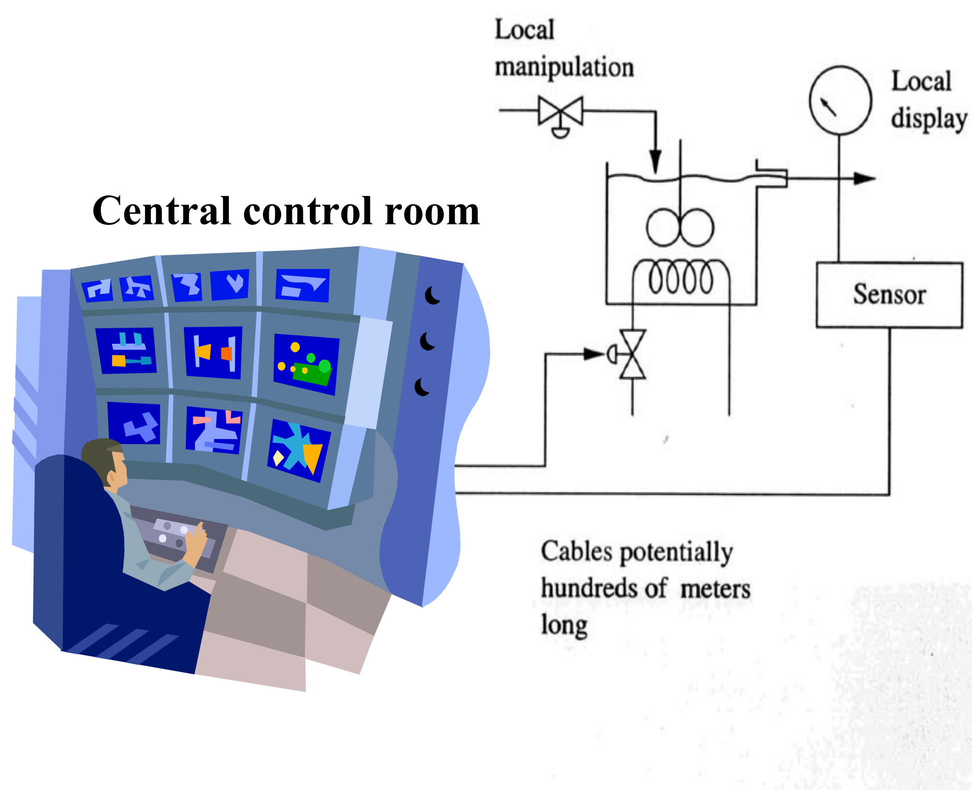
LONGER-TERM DATA ANALYSIS

The centralized control room provides information on the integrated plant.

- Process performance (energy/kg of product)
- Equipment performance (compressor efficiency, heat exchanger fouling, etc.)

Information must be in a format that can be used by other programs.

Mainly used by engineers.



CHAPTER 24: CONTROL DESIGN

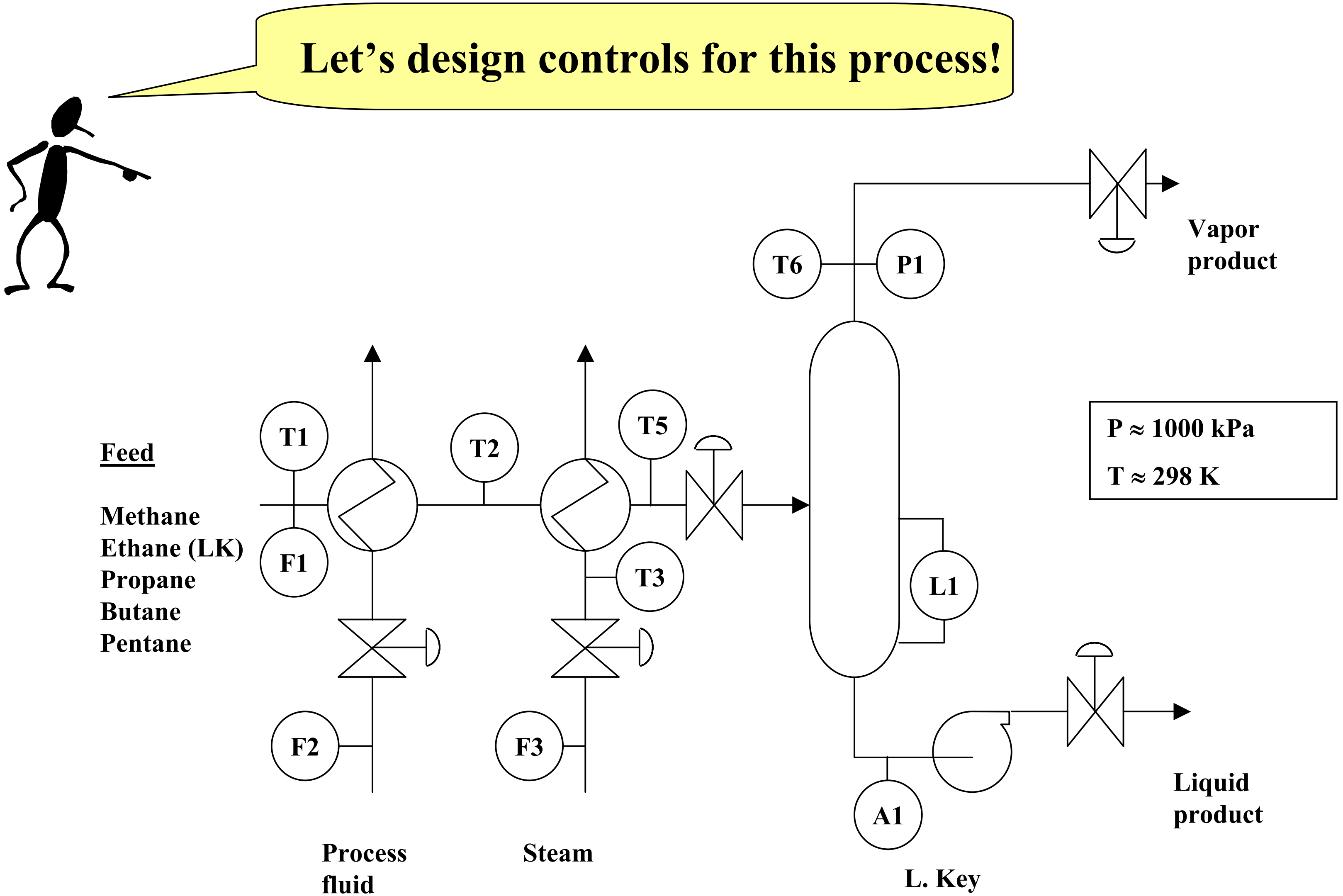
THE CONTROL DESIGN PROCEDURE

- **Define the control problem (challenge)** ✓
- **Evaluate/achieve operability** ✓

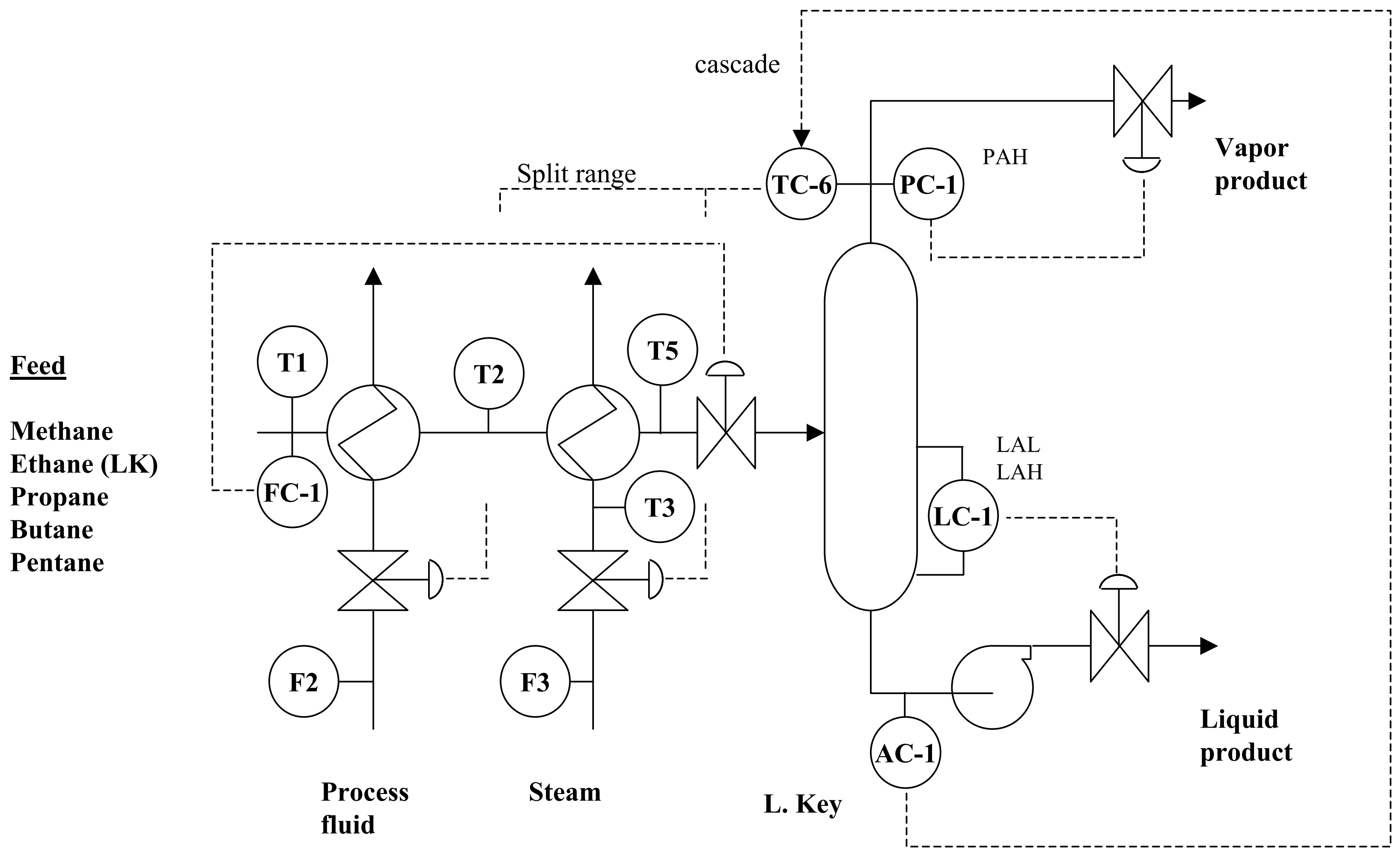
  - Degrees of freedom
  - Controllability
  - Operating Window

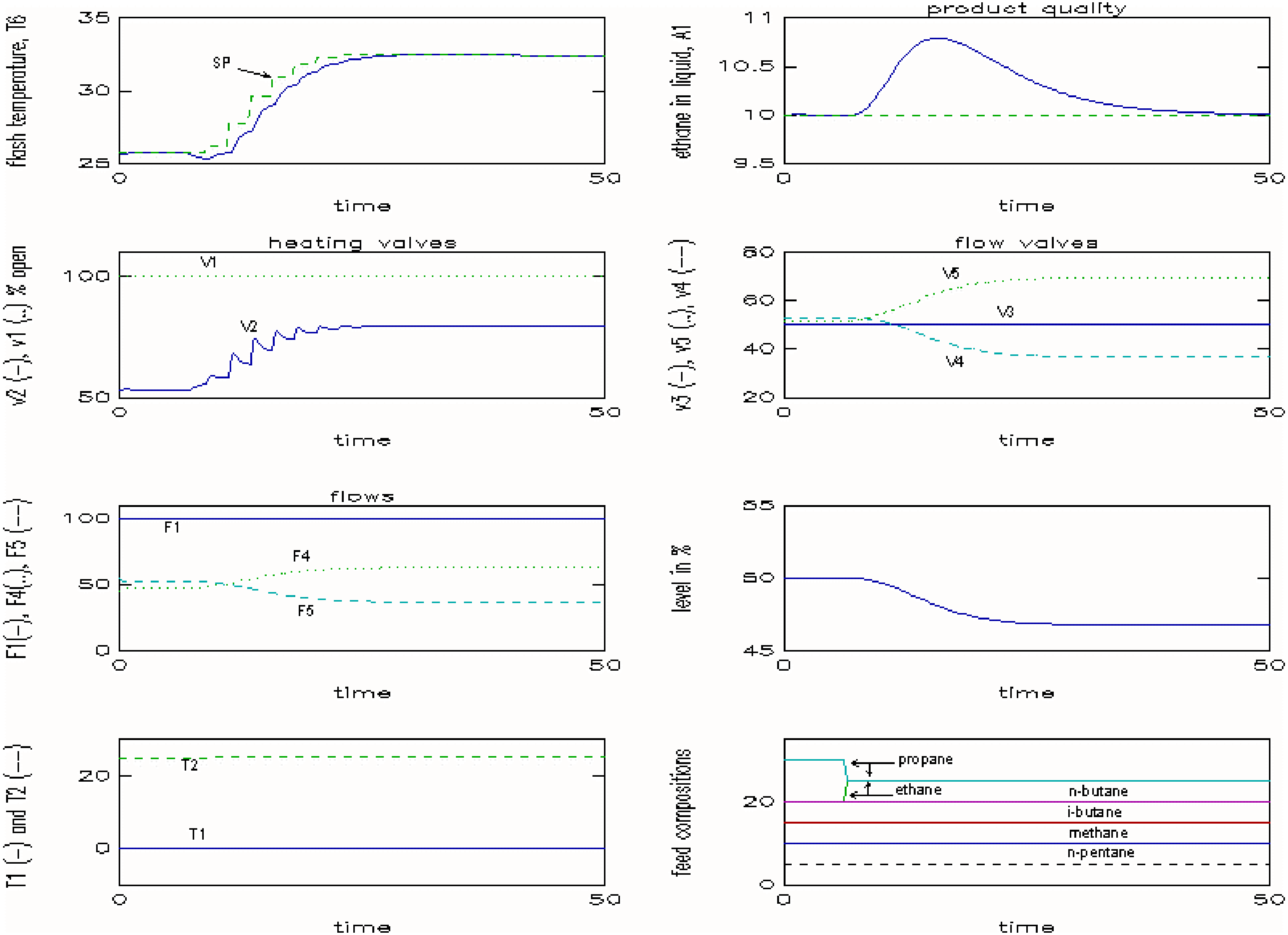
- **Process dynamics for good performance** ✓
- **Loop pairing** ✓
- **Control for safety** ✓
- **Monitoring and diagnosis** ✓

CHAPTER 24: CONTROL DESIGN



CHAPTER 24: CONTROL DESIGN

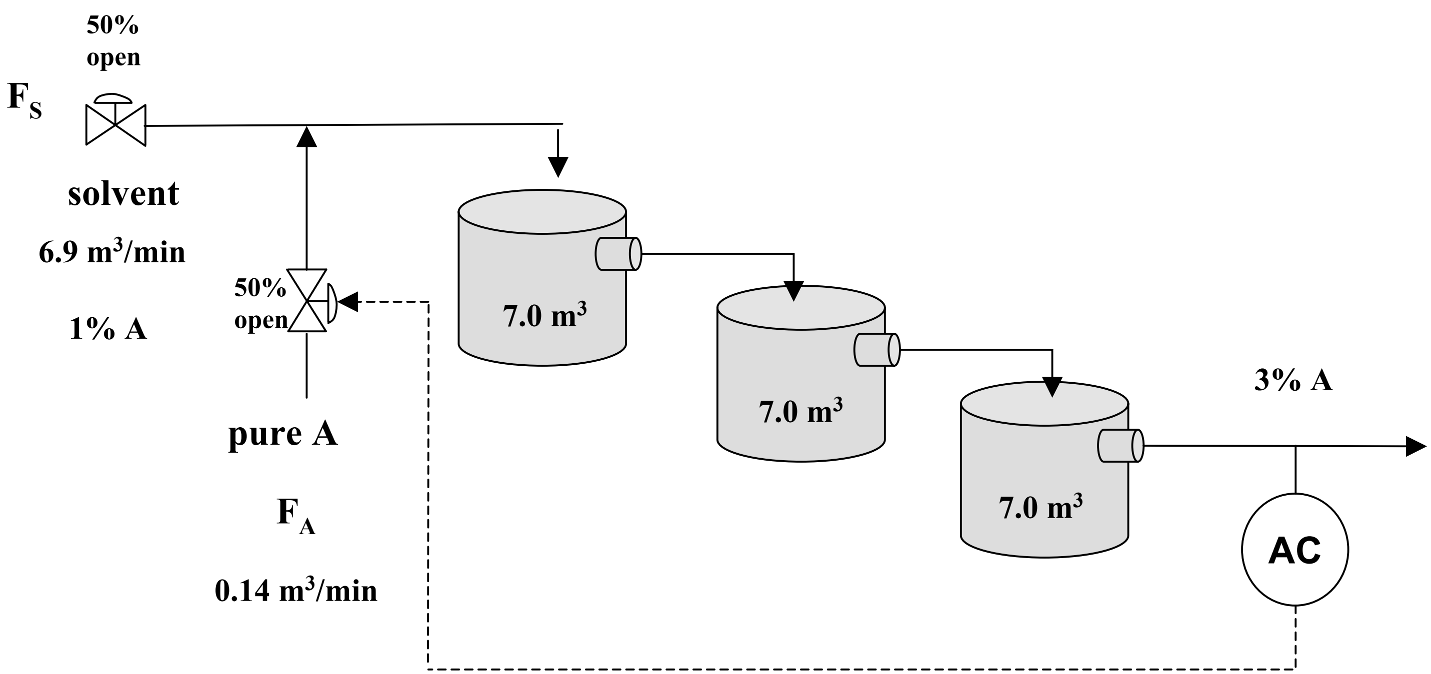




Response of design to a step change in feed composition

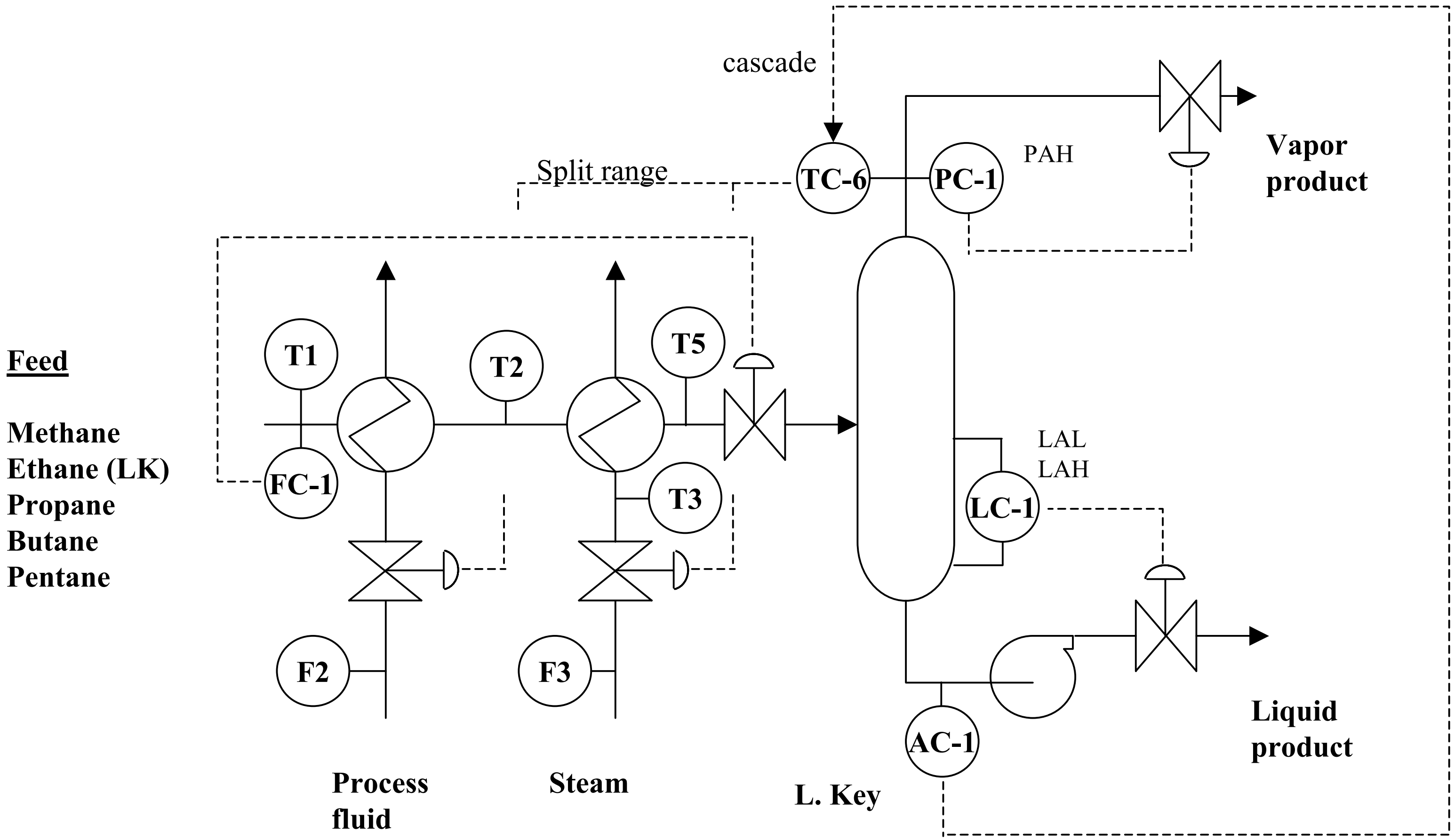
CHAPTER 24: CONTROL DESIGN WORKSHOP 1

Determine the operating window for the three-tank mixer. Plot the set point of effluent concentration and the feed flow. Base case data is summarized in the figure and further information is available in Example 7.2.



CHAPTER 24: CONTROL DESIGN WORKSHOP 2

Discuss how the concepts of partial control were used in design controls for the flash process. (Note, safety elements not shown on diagram.) See Chapter 24 for partial control.

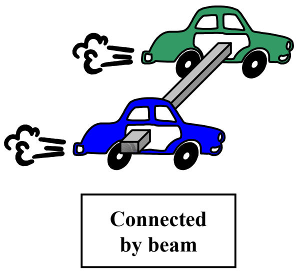


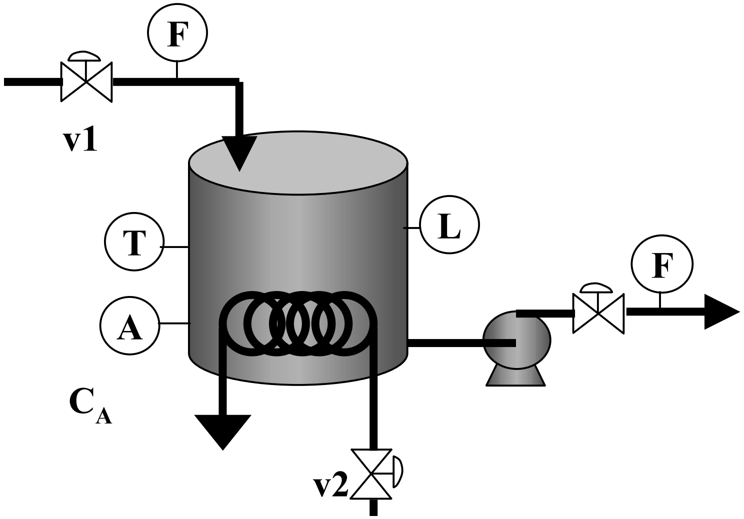
CHAPTER 24: CONTROL DESIGN WORKSHOP 3

Give a process example for a situation in which each of the factors below affect the controllability of a process. See lecture slides for Chapter 20 as a refresher.

Some seemingly independent variables are "linked" through

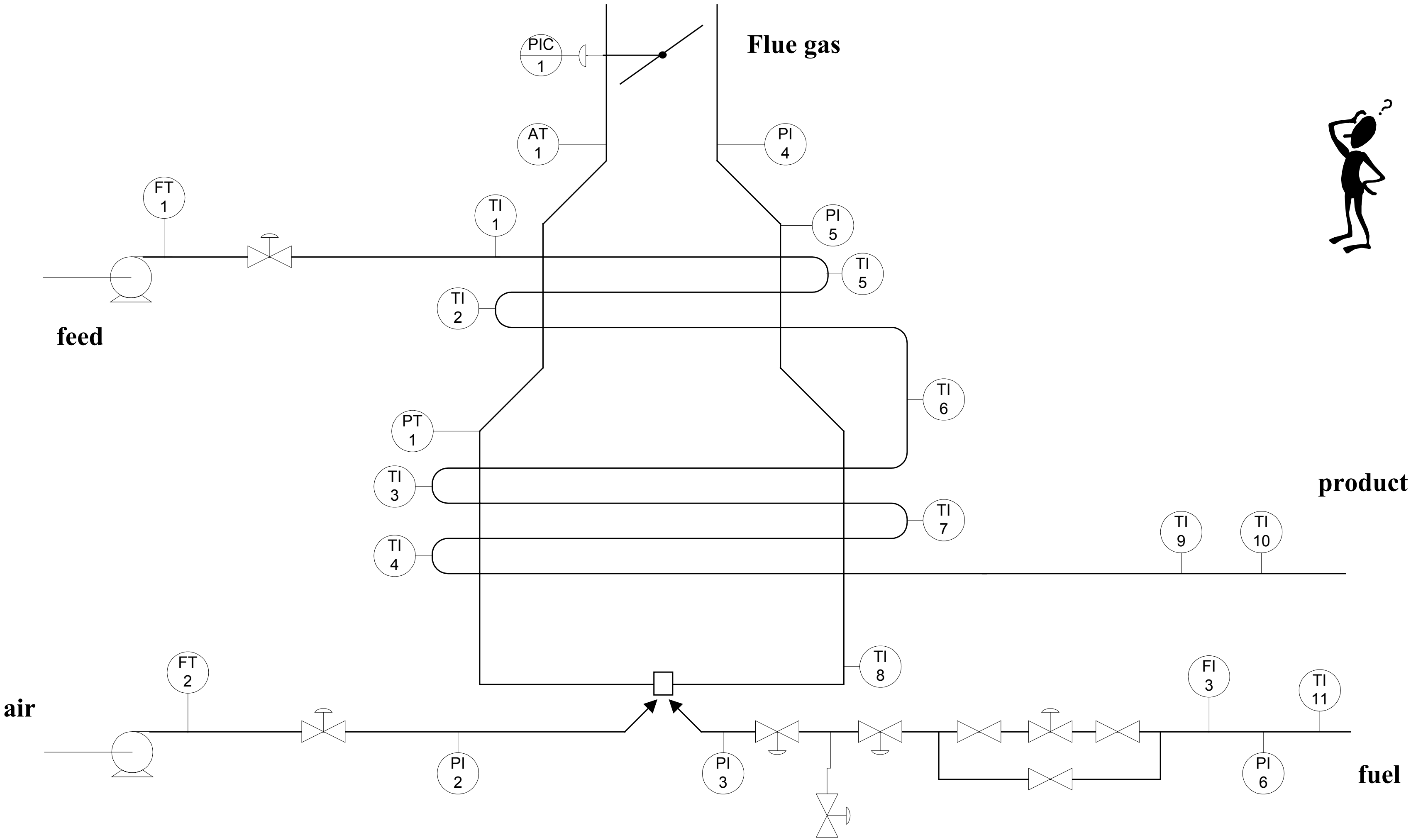
- **material balance**
- **energy balance**
- **equilibrium**
- **reaction stoichiometry**



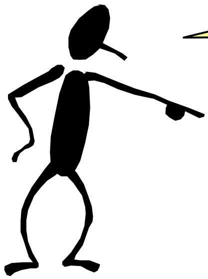


CHAPTER 24: CONTROL DESIGN WORKSHOP 4

Develop a control design form for the fired heater in the figure.

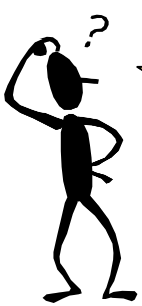


CHAPTER 24: CONTROL DESIGN WORKSHOP 4



When I complete this chapter, I want to be able to do the following.

- **Define the control problem**
- **Evaluate if desired performance is possible; if not, modify process**
- **Select instrumentation**
- **Design loop pairing for control**
- **Provide sensors for process monitoring**



Lot's of improvement, but we need some more study!

- **Read the textbook**
- **Review the notes, especially learning goals and workshop**
- **Try out the self-study suggestions**
- **Naturally, we'll have an assignment!**

CHAPTER 24: LEARNING RESOURCES

- **<u>SITE PC-EDUCATION WEB</u>**

  - Textbook, Chapter 24

  - Interactive Learning Module (Chapter 2)

  - Tutorials (Chapter 24)

- **Other views of control design**

  - Luyben, W., Tyreus, B. and Luyben, M., *Plantwide Process Control*, McGraw-Hill, New York, 1999

CHAPTER 24:
SUGGESTIONS FOR SELF-STUDY

1. **Compare the control design procedure presented here with the design procedure that you learned in your process design course.**

2. **Discuss how you could evaluate the steady-state controllability of a process using a flowsheeting program (such as ASPEN, HYSYS, or PROII).**

3. **Review the bonus lecture slides for Control for Safety. Apply the safety principles to the fired heater example in Workshop 4.**

CHAPTER 24:
SUGGESTIONS FOR SELF-STUDY

4. Search the WWW for information on the control design for a process of interest to you.

- Separation (distillation, membrane, settling)

- Chemical Reactor

- Biological reactor (waste water treating or pasteurization)

- Rotating equipment (pump or compressor)

- Heat exchanger

- Flow and pressure system

- Combustion system