CEB2083 PROCESS INSTRUMENTATION & CONTROL
MAY 2020 SEMESTER

Chapter 12:
Process Instrumentation

BY

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Chapter Outcome:

End of the chapter, you should be able to:

1. Describe basic components of P & ID
2. Describe basic control instruments
   - Sensors and transmitters
   - Controller
   - Final control elements

Piping & Instrumentation Diagram (P&ID)

- A **piping and instrumentation diagram/drawing (P&ID)** is a diagram in the process industry which shows the piping of the process flow together with the installed equipment and instrumentation.

- P & ID shows the interconnection of process equipment and the instrumentation used to control the process.

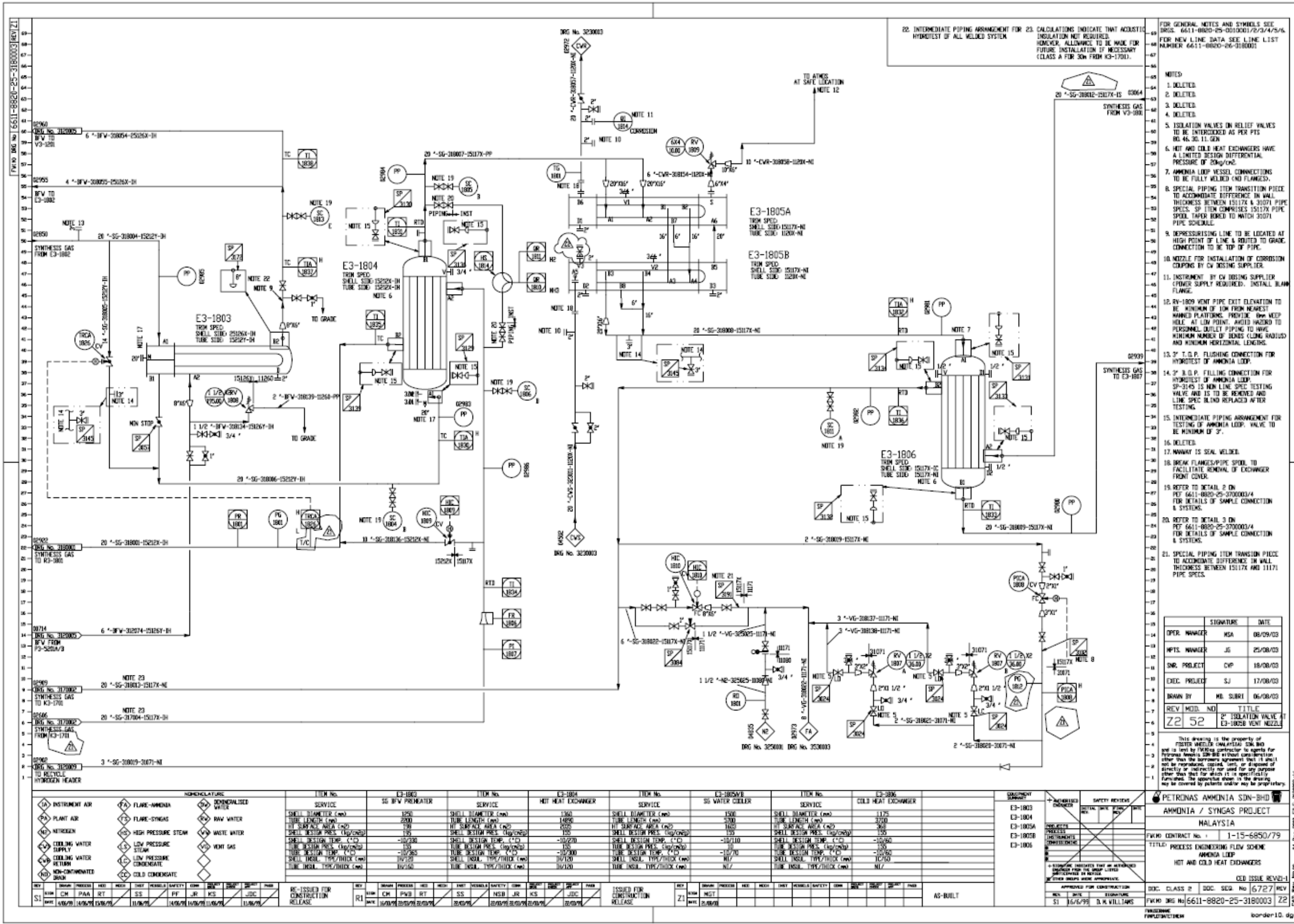
Piping & Instrumentation Diagram (P&ID)

- Each instrument may be represented on diagram by a symbol which follows specific standard representation

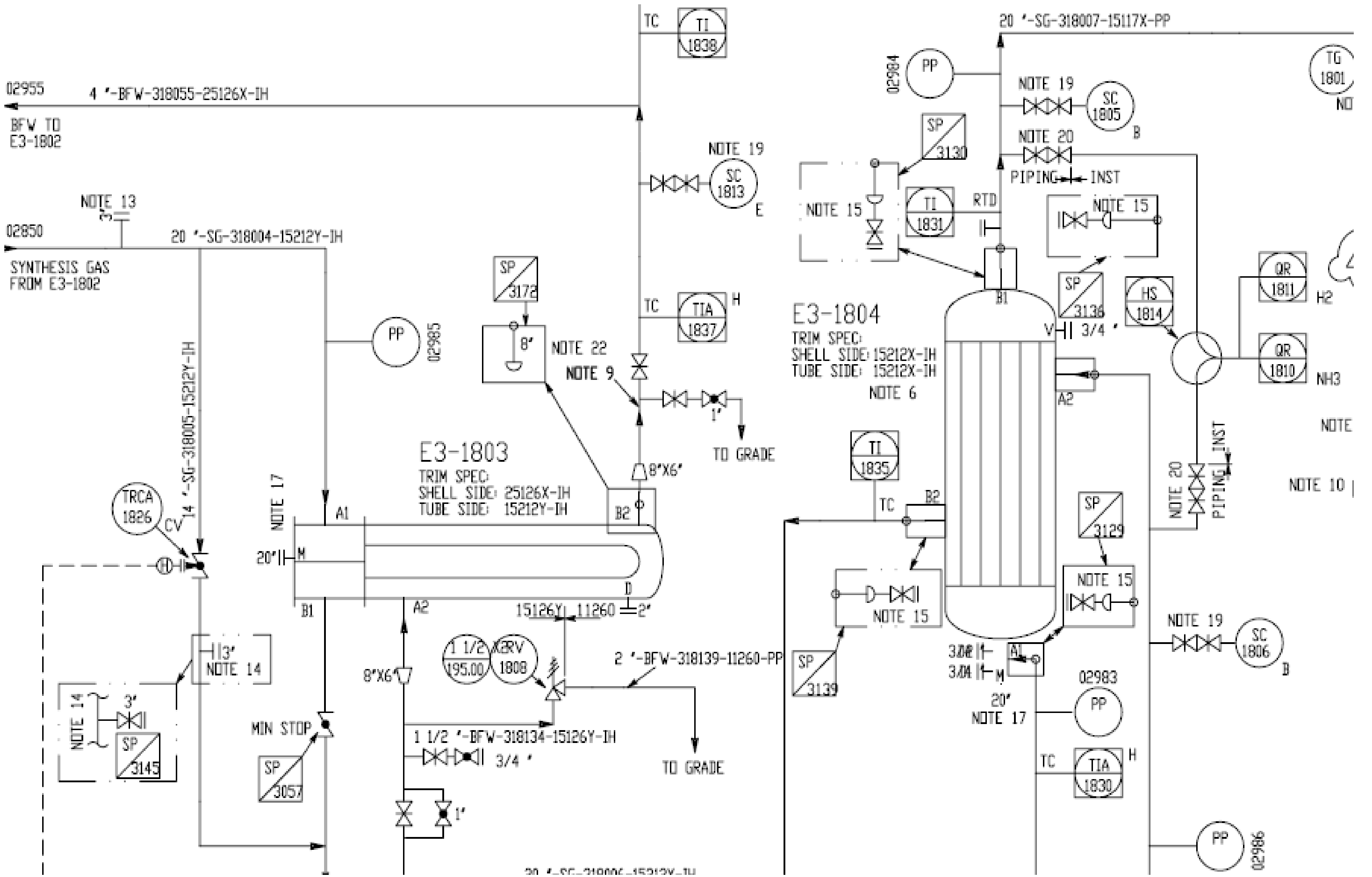
  1. PETRONAS Technical Standard (PTS)
  2. Standard ISA-5.1 (ISA stands for International Society of Automation)

- The symbol may be accompanied by a tag number

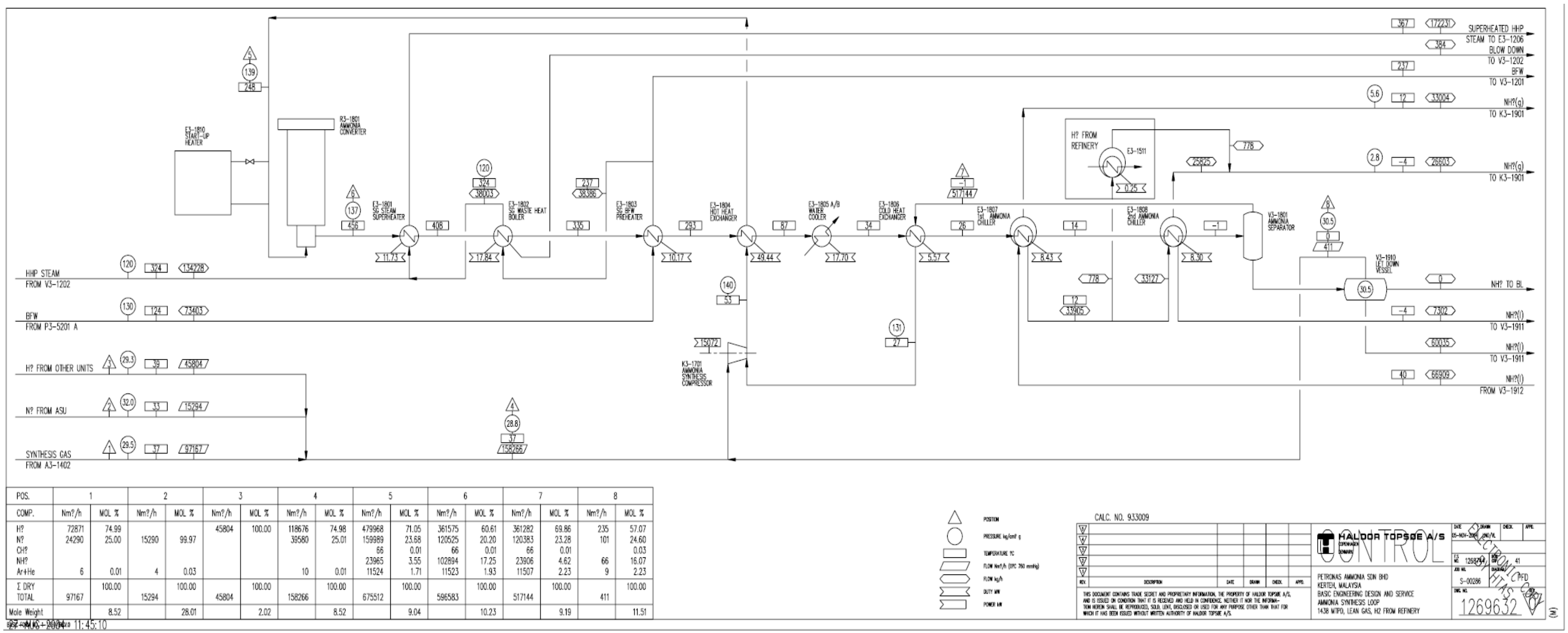
EXAMPLE – P&ID


E3-1803
E3-1804
E3-1805A
E3-1805B
E3-1806
PETRONAS AMMONIA SDN-BHD
AMMONIA / SYNGAS PROJECT
MALAYSIA
6611-8820-25-3180003

EXAMPLE – P&ID zoom-in

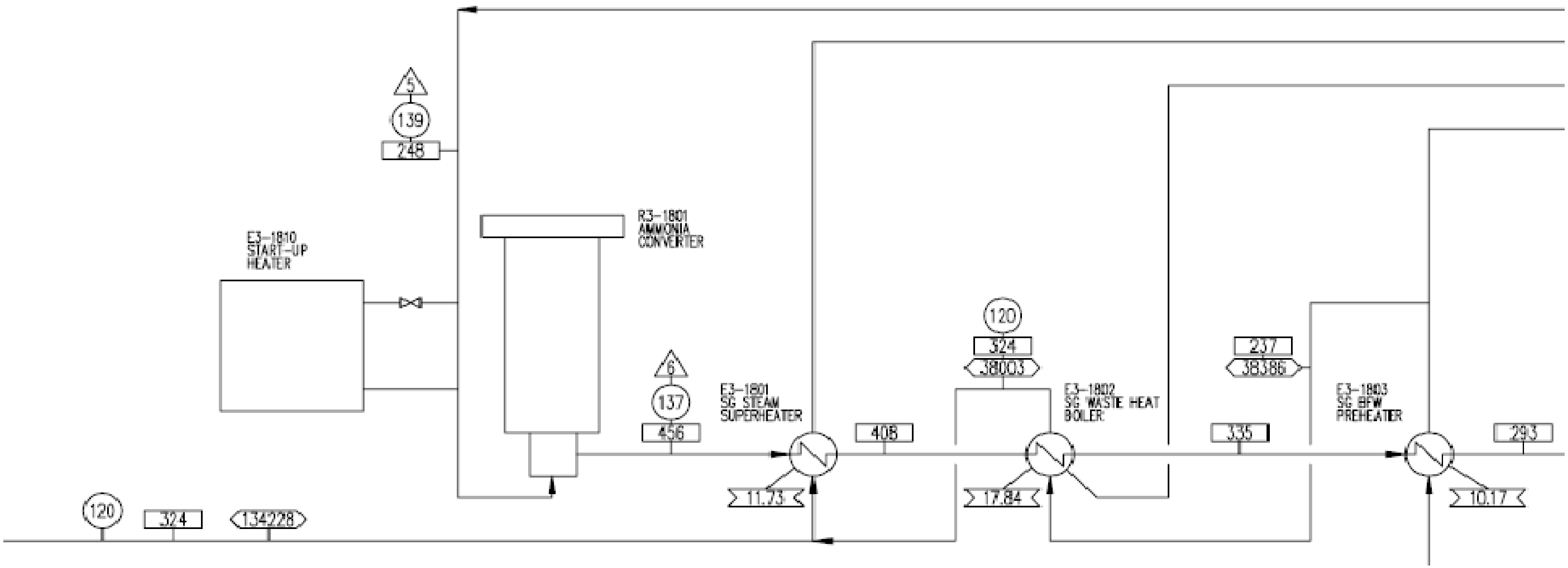


Example of PFD



POS.	1		2		3		4		5		6		7		8	
COMP.	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %
H?	72871	74.99			45804	100.00	118676	74.98	479968	71.05	361575	60.61	361282	69.86	235	57.07
N?	24290	25.00	15290	99.97			39580	25.01	159989	23.68	120525	20.20	120383	23.28	101	24.60
CH?									66	0.01	66	0.01	66	0.01		0.03
NH?									23965	3.55	102894	17.25	23906	4.62	66	16.07
Ar+He	6	0.01	4	0.03			10	0.01	11524	1.71	11523	1.93	11507	2.23	9	2.23
Σ DRY		100.00		100.00		100.00		100.00		100.00		100.00		100.00		100.00
TOTAL	97167		15294		45804		158266		675512		596583		517144		411	
Mole Weight		8.52		28.01		2.02		8.52		9.04		10.23		9.19		11.51

Example of PFD-Zoom in



POS.	1		2		3		4		5		6		7		8	
COMP.	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %	Nm?/h	MOL %
H?	72871	74.99			45804	100.00	118676	74.98	479968	71.05	361575	60.61	361282	69.86	235	57.07
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Mole Weight		8.52		28.01		2.02		8.52		9.04		10.23		9.19		11.51

List of P & ID Items

- Instrumentation and designations
- Mechanical equipment with names and numbers
- All valves and their identifications
- Process piping, sizes and identification
- Miscellanea - vents, drains, special fittings, sampling lines, reducers, increasers and swagers
- Permanent start-up and flush lines
- Flow directions
- Interconnections references
- Control inputs and outputs, interlocks
- Interfaces for class changes
- Computer control system input
- Identification of components and subsystems delivered by others

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P & ID Components

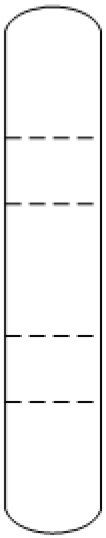
Equipment symbols

Instrument Line Symbols

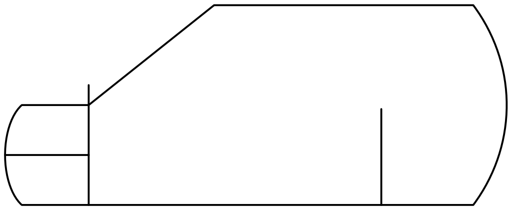
Basic Instrument or Function Symbols

Tag Numbers

Equipment symbols

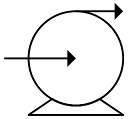


Tray column

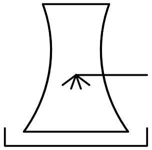


Kettle Reboiler

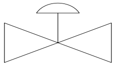
Heat exchanger



Centrifugal pump

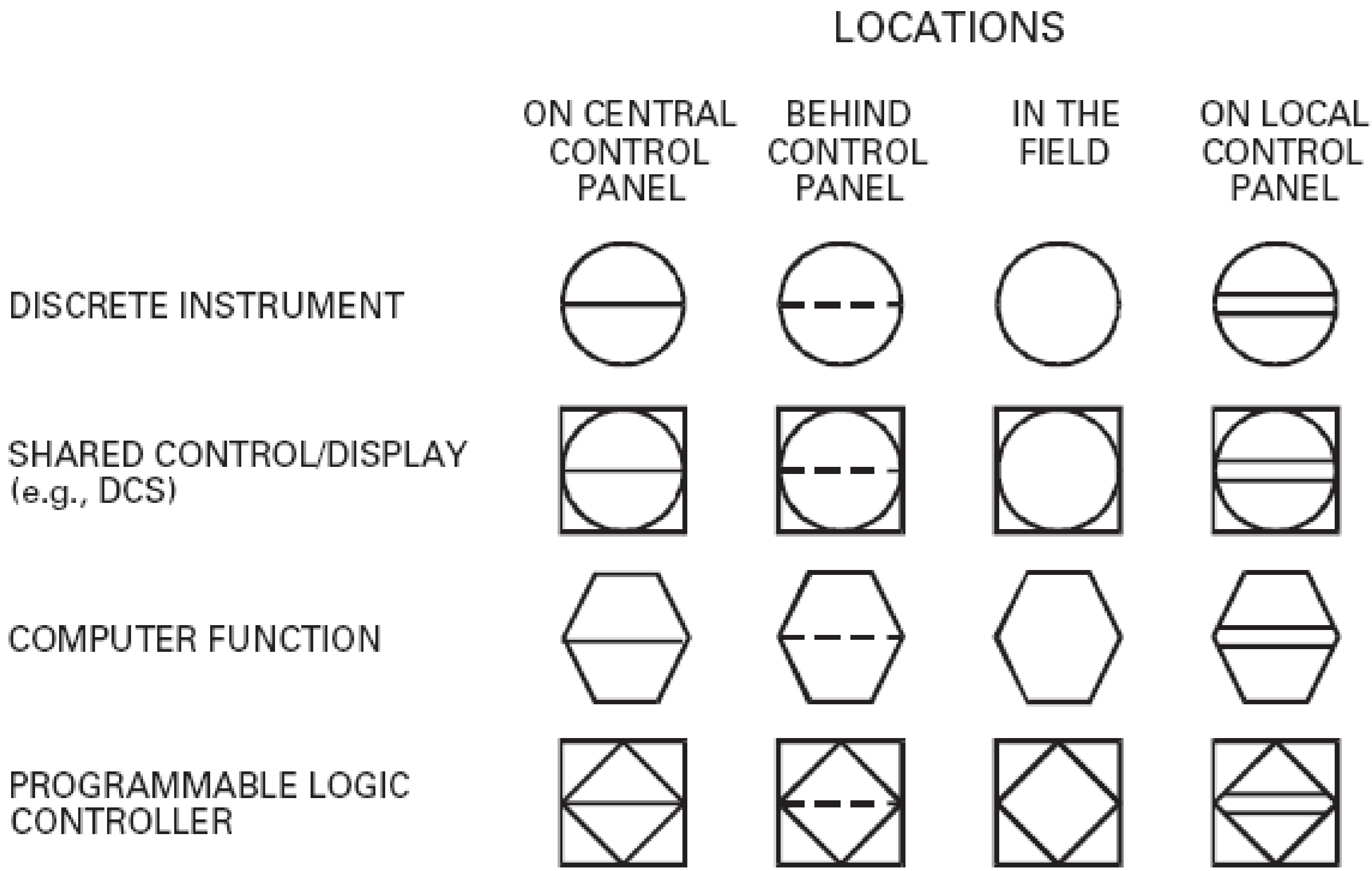


Cooling Tower

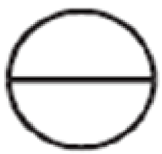
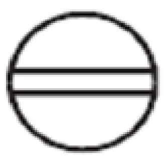


Control valve

Basic Instrument or Function Symbols



Equipment Symbols

	The device is field mounted (located in the process area of the plant)
	The device is located in the primary location normally accessible to the operator (the central control room).
	The device is located in an auxiliary location, normally accessible to the operator (a local panel or on the starter cassette in the motor control centre).
	The device is normally inaccessible to the operator (behind the panel).

Instrument Line Symbols

(1) INSTRUMENT SUPPLY *
OR CONNECTION TO PROCESS

(2) UNDEFINED SIGNAL

(3) PNEUMATIC SIGNAL **

(4) ELECTRIC SIGNAL

(5) HYDRAULIC SIGNAL

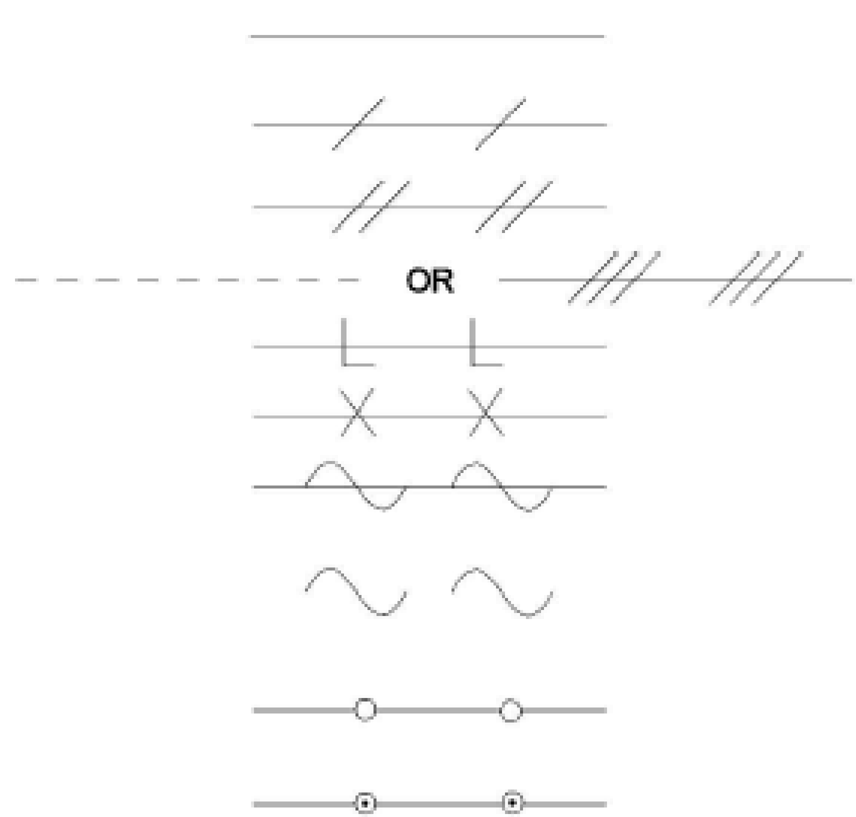
(6) CAPILLARY TUBE

(7) ELECTROMAGNETIC OR SONIC SIGNAL ***
(GUIDED)

(8) ELECTROMAGNETIC OR SONIC SIGNAL ***
(NOT GUIDED)

(9) INTERNAL SYSTEM LINK
(SOFTWARE OR DATA LINK)

(10) MECHANICAL LINK



Tag Number

TIC 103

↓

T 103 - Loop identification

103 - Loop number

TIC - Functional Identification

T - First letter

IC - Succeeding Letters

Identification Letters

TABLE A.1 Identification Letters

	First Letter	Succeeding Letters
A	Analyzer	Alarm
C	Concentration	Control
D	Density	
E	Voltage	
F	Flow	
H		High
I		Indicating
L	Level	Low
P	Pressure	
Q		Totalize
S	Speed, slide gate	Switch
T	Temperature	Transmitter
V		Valve
X	Discrete (on–off)	Motor
Y		Compute, convert
Z	Position	

TABLE 2
TYPICAL LETTER COMBINATIONS

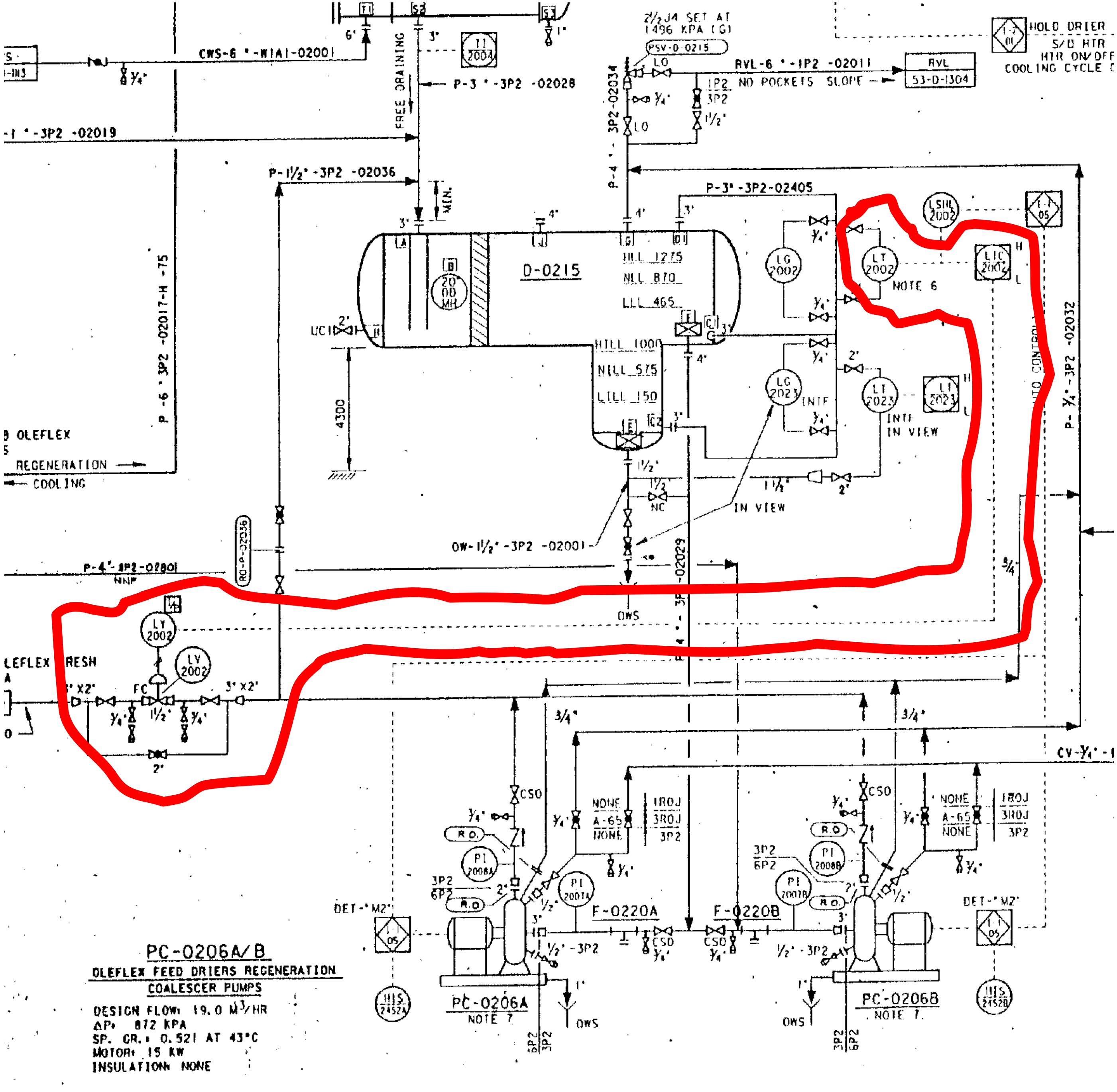
First-Letters	Initiating or Measured Variable	Controllers: Recording	Controllers: Indicating	Controllers: Blind	Controllers: Self-Actuated Control Valves	Readout Devices: Recording	Readout Devices: Indicating	Switches and Alarm Devices*: High**	Switches and Alarm Devices*: Low	Switches and Alarm Devices*: Comb	Transmitters: Recording	Transmitters: Indicating	Transmitters: Blind	Solenoids, Relays, Computing Devices	Primary Element	Test Point	Well or Probe	Viewing Device, Glass	Safety Device	Final Element
A	Analysis	ARC	AIC	AC		AR	AI	ASH	ASL	ASHL	ART	AIT	AT	AY	AE	AP	AW			AV
B	Burner/ Combustion	BRC	BIC	BC		BR	BI	BSH	BSL	BSHL	BRT	BIT	BT	BY	BE		BW	BG		BZ
C	User's Choice																			
D	User's Choice																			
E	Voltage	ERC	EIC	EC		ER	EI	ESH	ESL	ESHL	ERT	EIT	ET	EY	EE					EZ
F	Flow Rate	FRC	FIC	FC	FCV, FICV	FR	FI	FSH	FSL	FSHL	FRT	FIT	FT	FY	FE	FP		FG		FV
FQ	Flow Quantity	FQRC	FQIC			FQR	FQI	FQSH	FQSL			FQIT	FQT	FQY	FQE					FQV
FF	Flow Ratio	FFRC	FFIC	FFC		FFR	FFI	FFSH	FFSL						FE					FFV
G	User's Choice																			
H	Hand		HIC	HC						HS										HV
I	Current	IRC	IIC			IR	II	ISH	ISL	ISHL	IRT	IIT	IT	IY	IE					IZ
J	Power	JRC	JIC			JR	JI	JSH	JSL	JSHL	JRT	JIT	JT	JY	JE					JV
K	Time	KRC	KIC	KC	KCV	KR	KI	KSH	KSL	KSHL	KRT	KIT	KT	KY	KE					KV
L	Level	LRC	LIC	LC	LCV	LR	LI	LSH	LSL	LSHL	LRT	LIT	LT	LY	LE		LW	LG		LV
M	User's Choice																			
N	User's Choice																			
O	User's Choice																			
P	Pressure, Vacuum	PRC	PIC	PC	PCV	PR	PI	PSH	PSL	PSHL	PRT	PIT	PT	PY	PE	PP			PSV, PSE	PV
PD	Pressure, Differential	PDRC	PDIC	PDC	PDCV	PDR	PDI	PDSH	PDSL		PDRT	PDIT	PDT	PDY	PE	PP				PDV
Q	Quantity	QRC	QIC			QR	QI	QSH	QSL	QSHL	QRT	QIT	QT	QY	QE					QZ
R	Radiation	RRC	RIC	RC		RR	RI	RSH	RSL	RSHL	RRT	RIT	RT	RY	RE		RW			RZ
S	Speed Frequency	SRC	SIC	SC	SCV	SR	SI	SSH	SSL	SSHL	SRT	SIT	ST	SY	SE					SV
T	Temperature	TRC	TIC	TC	TCV	TR	TI	TSH	TSL	TSHL	TRT	TIT	TT	TY	TE	TP	TW		TSE	TV
TD	Temperature, Differential	TDRC	TDIC	TDC	TDCV	TDR	TDI	TDSH	TDSL		TDRT	TDIT	TDT	TDY	TE	TP	TW			TDV
U	Multivariable					UR	UI							UY						UV
V	Vibration Machinery Analysis					VR	VI	VSH	VSL	VSHL	VRT	VIT	VT	VY	VE					VZ
W	Weight Force	WRC	WIC	WC	WCV	WR	WI	WSH	WSL	WSHL	WRT	WIT	WT	WY	WE					WZ
WD	Weight Force, Differential	WDRC	WDIC	WDC	WDCV	WDR	WDI	WDSH	WDSL		WDRT	WDIT	WDT	WDY	WE					WDZ
X	Unclassified																			
Y	Event State Presence		YIC	YC		YR	YI	YSH	YSL				YT	YY	YE					YZ
Z	Position Dimension	ZRC	ZIC	ZC	ZCV	ZR	ZI	ZSH	ZSL	ZSHL	ZRT	ZIT	ZT	ZY	ZE					ZV
ZD	Gauging Deviation	ZDRC	ZDIC	ZDC	ZDCV	ZDR	ZDI	ZDSH	ZDSL		ZDRT	ZDIT	ZDT	ZDY	ZDE					ZDV

Note: This table is not all-inclusive.
*A, alarm, the annunciating device, may be used in the same fashion as S, switch, the actuating device.

**The letters H and L may be omitted in the undefined case.

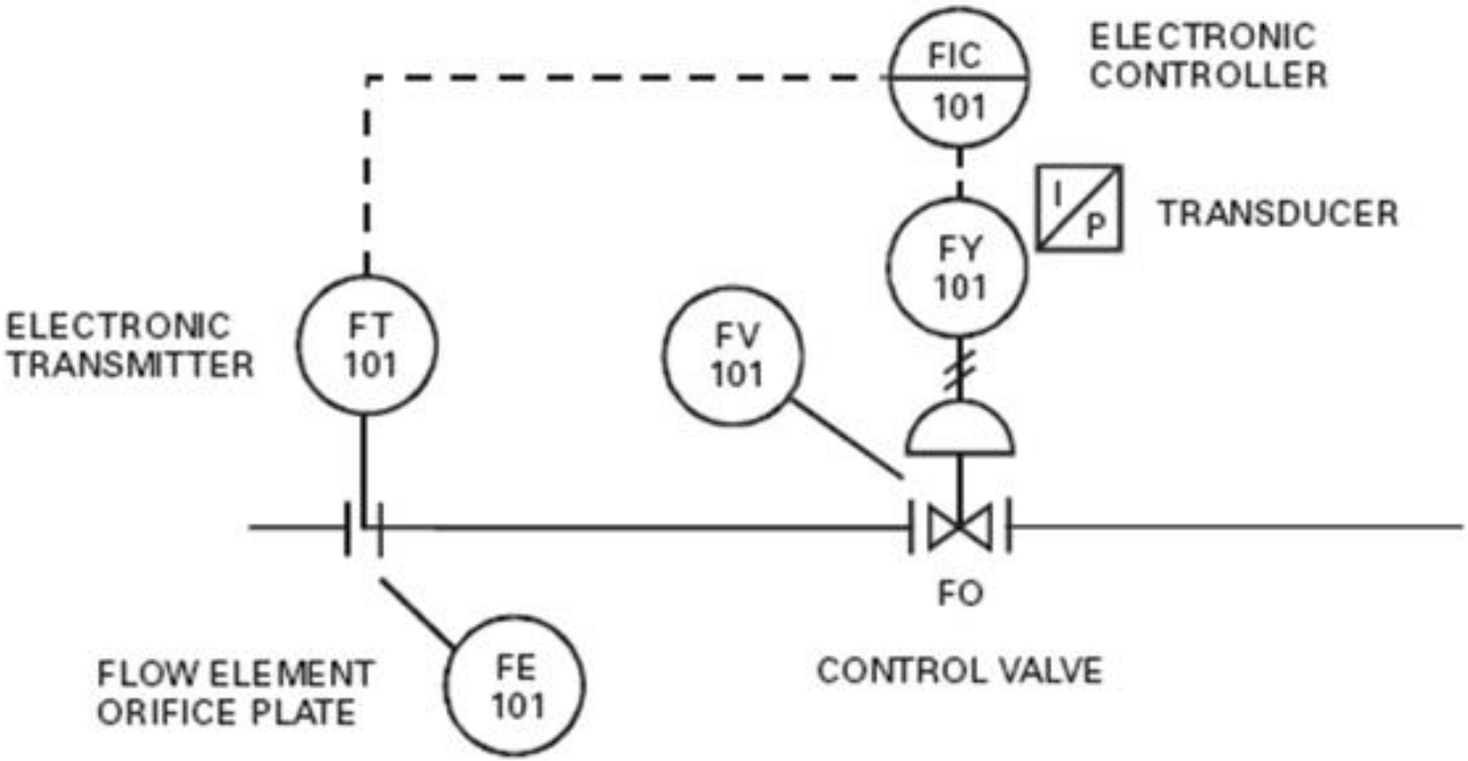
Other Possible Combinations:

FO	(Restriction Orifice)	PFR	(Ratio)
FRK, HIK	(Control Stations)	KQI	(Running Time Indicator)
FX	(Accessories)	QQI	(Indicating Counter)
TJR	(Scanning Recorder)	WKIC	(Rate-of-Weight-Loss Controller)
LLH	(Pilot Light)	HMS	(Hand Momentary Switch)



CWS-6 "-WIA1-02001
FREE DRAINING
P-3 " -3P2 -02028
-1 "-3P2 -02019
P-1½" -3P2 -02036
MIN.
2½J4 SET AT
1496 KPA (G)
PSV-D-0215
LO
RVL-6 "-1P2 -02011
RVL
53-D-1304
1P2 NO POCKETS SLOPE
3P2
3P2-02034
P-4 "
HOLD DRIER
S/D HTR
HTR ON/OFF
COOLING CYCLE
P-3" -3P2-02405
LSHL
2002
LG
2002
LT
2002
LIC
2002
NOTE 6
D-0215
HLL 1275
NLL 870
LLL 465
HILL 1000
NILL 575
LILL 150
20
OD
MH
UC
4300
LG
2023
LT
2023
INTF
IN VIEW
P-6 " 3P2 -02017-H -75
OLEFLEX
REGENERATION
COOLING
RO-P-02036
P-4"-3P2-02801
OW-1½" -3P2 -02001
OWS
3P2-02029
TO CONTROL
P-¾"-3P2 -02032
LY
2002
LV
2002
FC
OLEFLEX FRESH
3" X2"
CSO
NONE
A-65
1ROJ
3ROJ
R.O.
PI
2008A
PI
2007A
PI
2008B
PI
2007B
F-0220A
F-0220B
DET-"M2"
HIS
2452A
HIS
2452B
PC-0206A
NOTE 7
PC-0206B
NOTE 7.
CV-¾"
PC-0206A/B
OLEFLEX FEED DRIERS REGENERATION
COALESCER PUMPS
DESIGN FLOW: 19.0 M³/HR
ΔP: 872 KPA
SP. GR.: 0.521 AT 43°C
MOTOR: 15 KW
INSULATION: NONE

Control-Loops



Control Instrumentation

Control Instrumentation includes

1. Sensor
2. Transmitter
3. Controller
4. Transducer (Signal converter)
5. Final Control Element

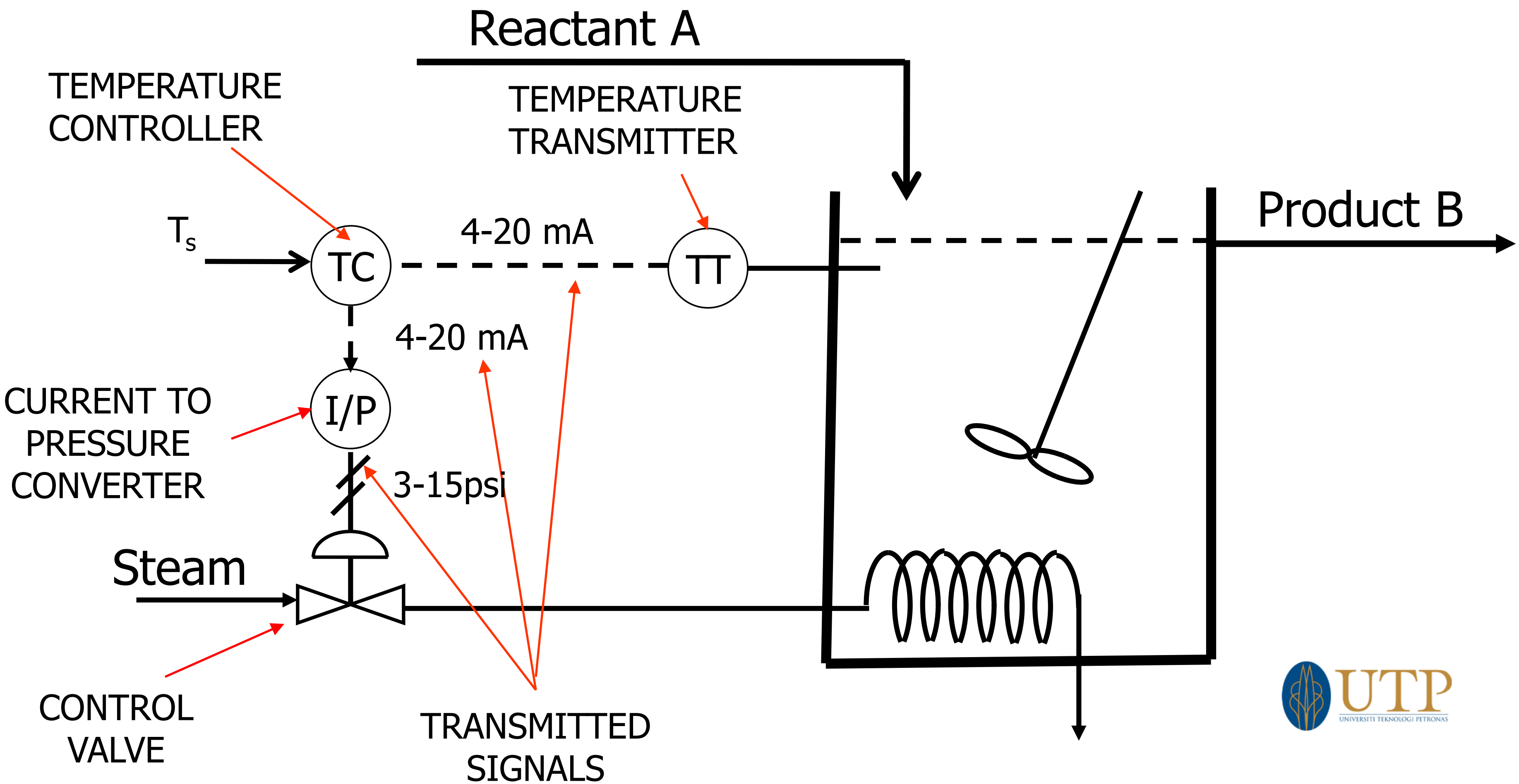
Sensors

Sensors are the first element in the control loop to measure the process variable, they are also called *primary elements.*

Process Variable	**Sensor**
Pressure	Diaphragms, strain gauges, capacitance cells
Temperature	
Flow Rate	

Signal Transmission

Signal Transmission in Feedback Control System



Standard Transmission range

- The advantage of having a standard range or using digital signals is that all equipment may be purchased ready calibrated.

- For analogue systems the minimum signal (Temperature, speed, force, pressure and so on) is represented by 4 mA or 0.2 bar and the maximum signal is represented by 20 mA or 1.0 bar.

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Transmitter

A *transmitter is a device that converts a reading from a sensor* or a transducer into a standard signal and transmits that signal to a monitor or controller.

Transmitter types include:

- Pressure transmitters
- Flow transmitters
- Temperature transmitters
- Level transmitters
- Analytic (O_2, CO, and pH) transmitters

Transmitters

Transmitters are specified by their zero, range, span and gain:

Zero : The minimum input of the transmitter

Range : The range of the input of a transmitter as identified by its minimum and maximum value.

Example. The range of a temperature transmitter is 10°C to 100°C

Span : The maximum input(output) minus minimum input (output)

Gain : Output span divided by input span

$$Gain = \frac{Output\ Span}{Input\ Span}$$

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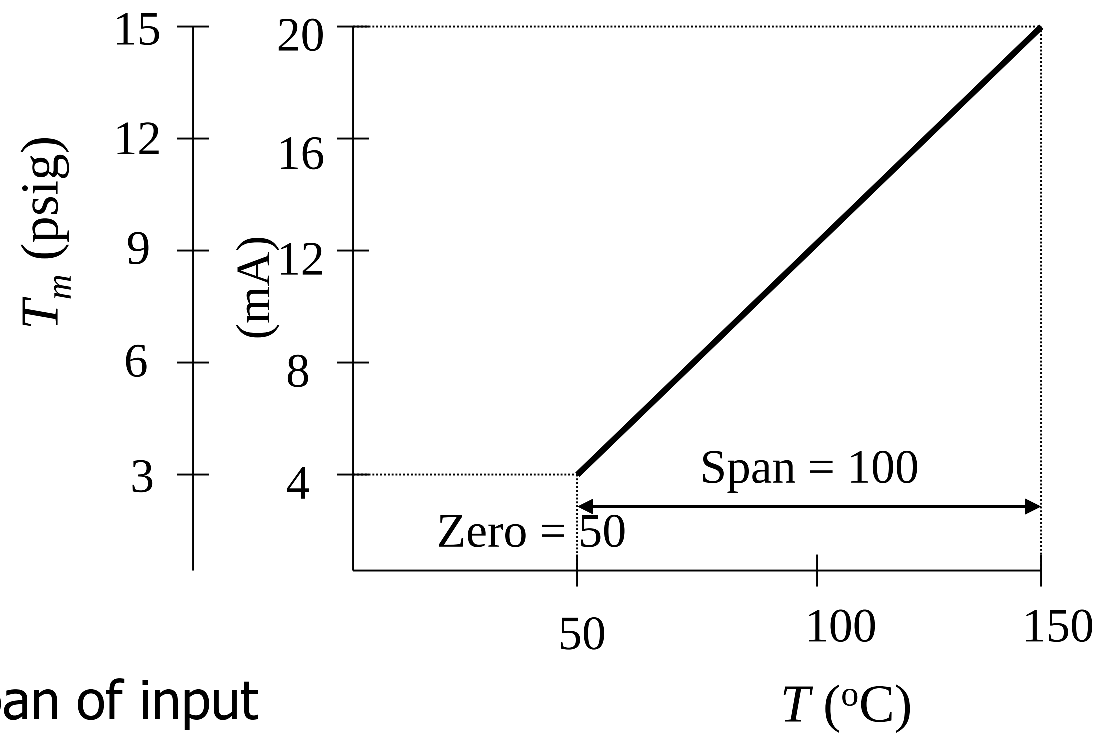
Transmitted Standard Signals

Electronic
4 - 20 mA
1- 5 V

Pneumatic
3 - 15 psig



Gain = K_m = span of output/ span of input

$$K_m = \frac{20 - 4 \text{ mA}}{150 - 50\ ^{\circ}\text{C}} = 0.16 \text{ mA}/^{\circ}\text{C}$$

$$T_m(\text{mA}) = K_m(T - 50^{\circ}\text{C}) + 4\text{mA}$$

PID Controller

The controllers will have knobs/buttons to adjust

- Set point
- Control Mode (Automatic/manual)
- Proportional gain (Proportional band)
- Derivative time (Rate time)
- Integral time (Reset rate)

It will display

- current values of CV, MV and set point
- trend of the CV and MV

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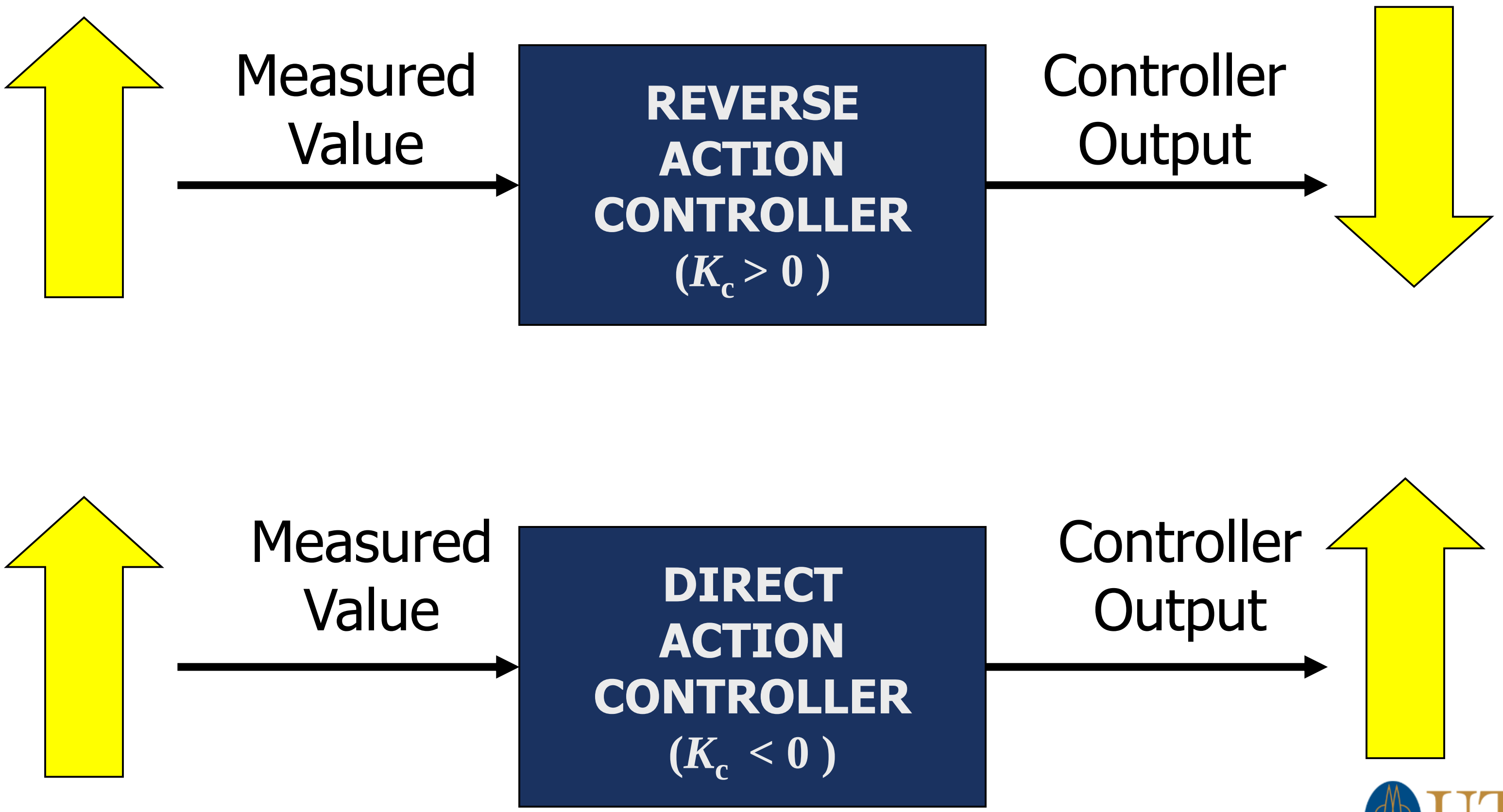
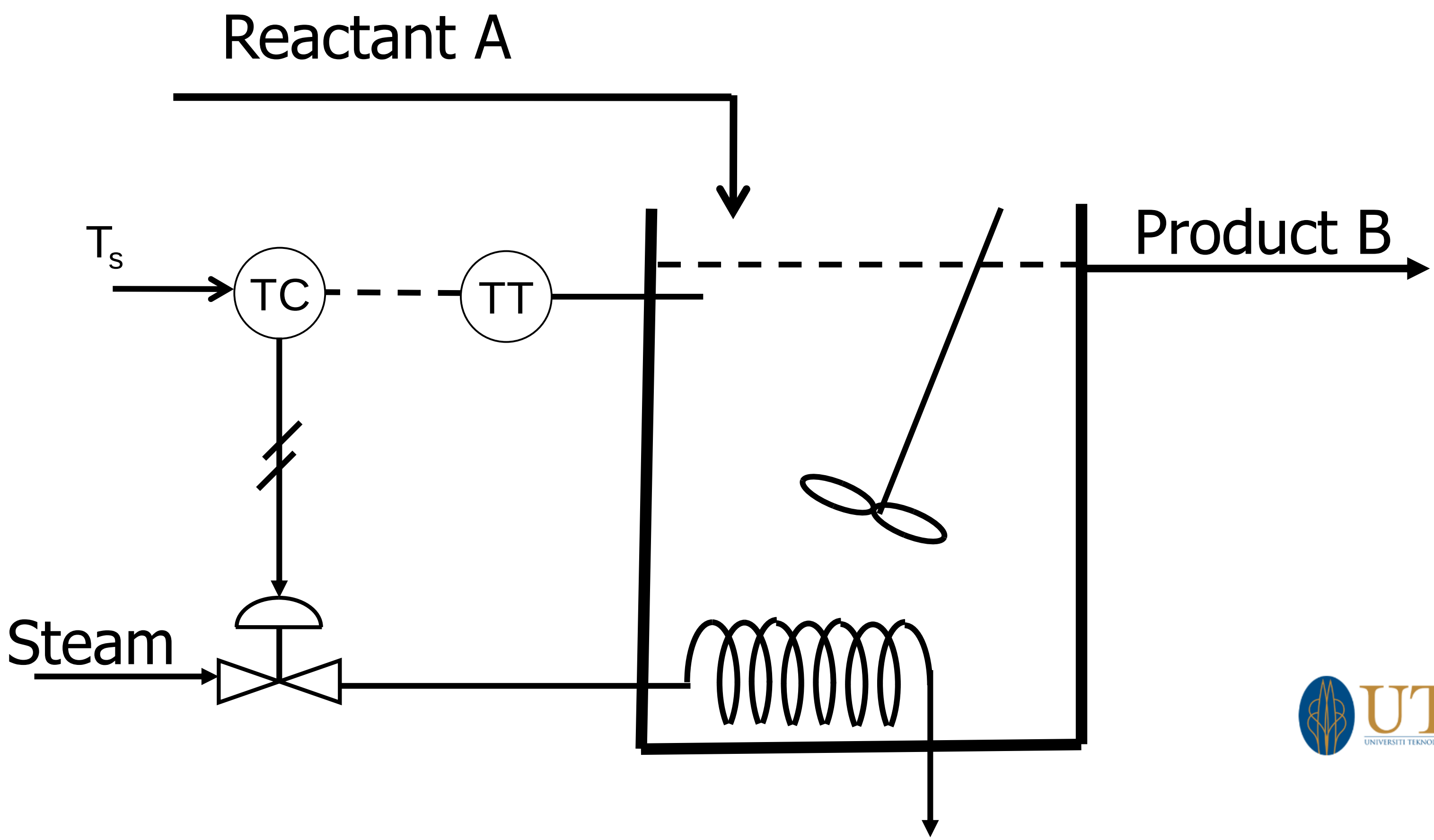
Controller action

Reverse or Direct Action:



Controller Action: Example

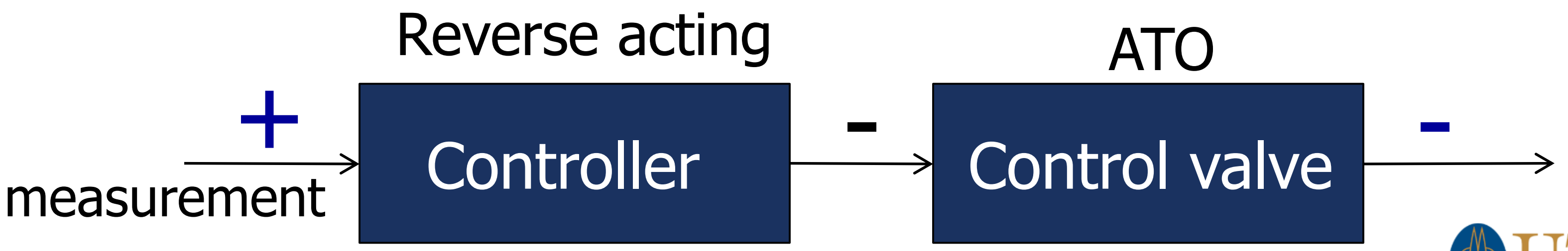
For the temperature control system shown below. Determine, the controller action if the valve is air-to-open (ATO).



Controller Action: Example

Solution

- **Overall action:** When the temperature inside the tank increases the steam flow rate should be decreased.
- **Control Valve:** It is given that the control valve is direct acting. This means, to get a decreased steam flow rate the control output should also decrease.
- **Controller action:** The controller action should be reverse since increase in measured output requires decrease in controller output.



Final Control Elements

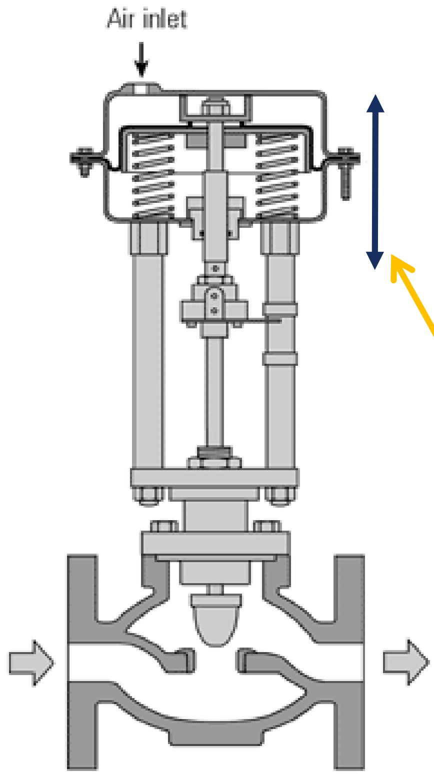
- Final control elements: Part of the control system that receives decision from the controller and adjusts the manipulated variable.
- Examples of final control elements
  - Control valves
  - Variable speed motors
  - Variable resistance heater
- Control valve is the most common final control element in process industries.

Types of Control Valves

Control Valves

- Sliding stem valves
  - Globe valves
  - Gate valves
- Rotating shaft valves
  - Butter fly valves
  - Ball valves

Types of Control Valves

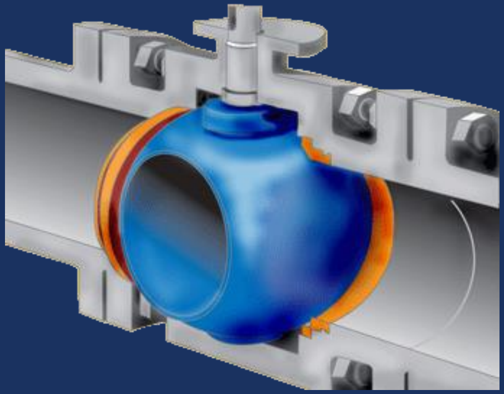


Direction of
shaft movement

Sliding shaft valve

Rotating shaft valve

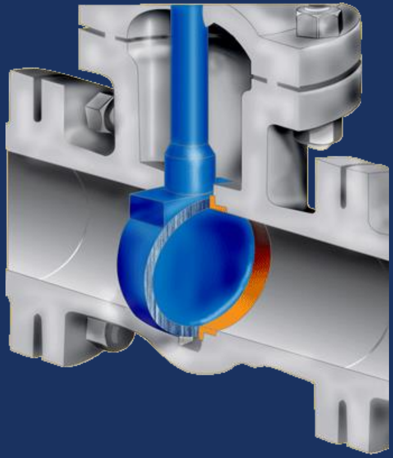
Rotating Shaft Valves

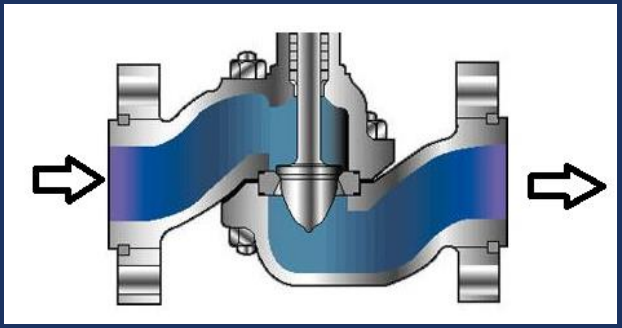


Ball Valve

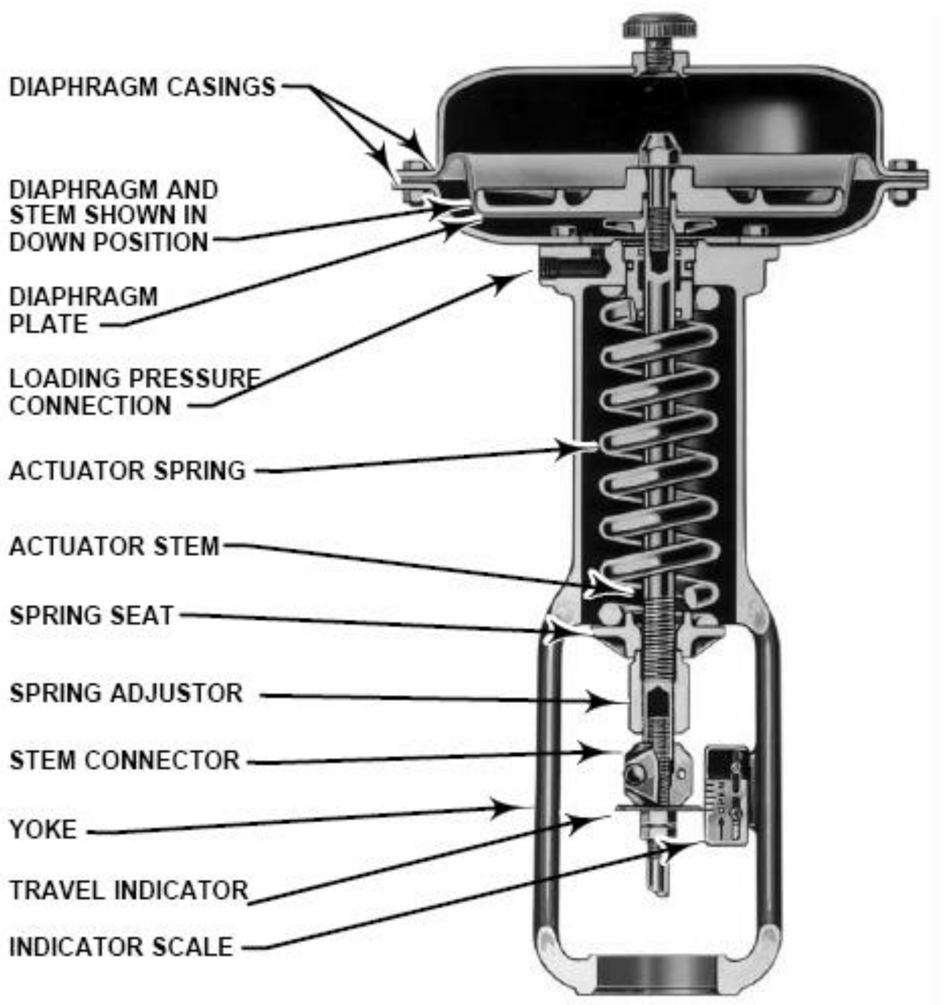
Butterfly valve

Sliding Shaft Valves





Control Valve - Schematic



Types of Control Valves: Comparison

- Rotary valves (butterfly valves) are generally cheaper than linear valves in sizes above 2 in (50 mm) and globe valves are the most effective for control purpose in sizes < 4 in.
- Bodies require minimum space for installation (small face to face dimension).
- They provide high capacity with low pressure loss through the valves.
- The most economical for larger pipe-size applications.

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Essential Features of a Control Valve

The following are the most essential features of a valve related to control

- Valve action/ fail safe position
- Valve size
- Valve characteristics
- Rangeability
- Cavitation

Essential Features: Valve Action

- Valve fail safe position is the position of the valve in the emergency situation of no compressed air to the valve.
- Fail Closed (Air to open) valve is a valve that is completely closed when the compressed air to the valve fails.
- Fail open (Air to close) valve is a valve that is completely open when the compressed air to the valve fails.

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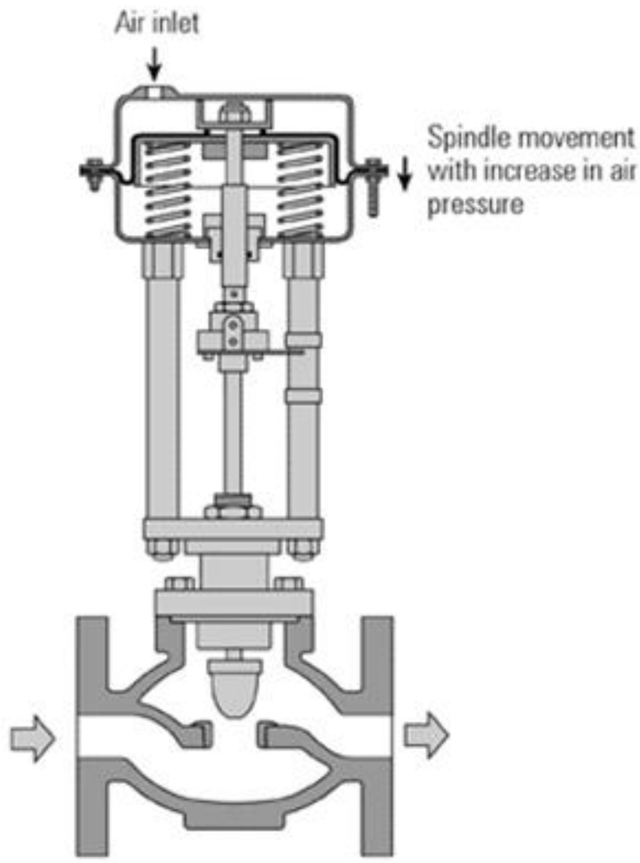
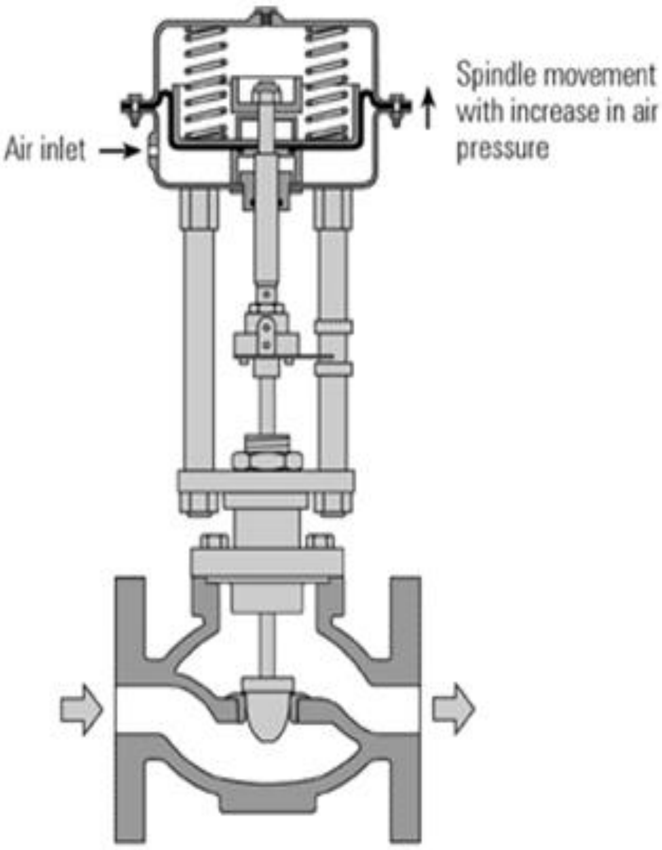
Essential Features: Valve Action





Fail Open (Air to close), reverse acting valve

Fail Closed (Air to open), direct acting valve

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Essential Features: Valve Action

- Fail closed valves are direct acting since increase in air pressure causes the valve to open more.
- Fail open valves are reverse acting since increase in air pressure causes the valve to close.
- The main consideration in selecting the valve fail position (action of valve) is safety.
- When the safest position of the valve is open, we order Fail Open (FO)/ Air to Close valve (ATC).
- When the safest position of the valve is closed, we order Fail closed (FC)/ Air to Open (ATO) valve.

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Essential Features: Valve Action

Examples:

Specify the appropriate fail safe position of the valve in the following services:

- A flammable solvent is heated by steam in a heat exchanger. The valve manipulates the flow of steam.

- A stirred tank heater contains a liquid polymer that is heated by steam. When the temperature is low in the tank the polymer solidifies and damages the tank, the stirrer and pump and other components.

Essential Features: Valve Action

- The inherent characteristic is the relationship between the valve flow capacity and the valve travel when the differential pressure drop across the valve is held constant.

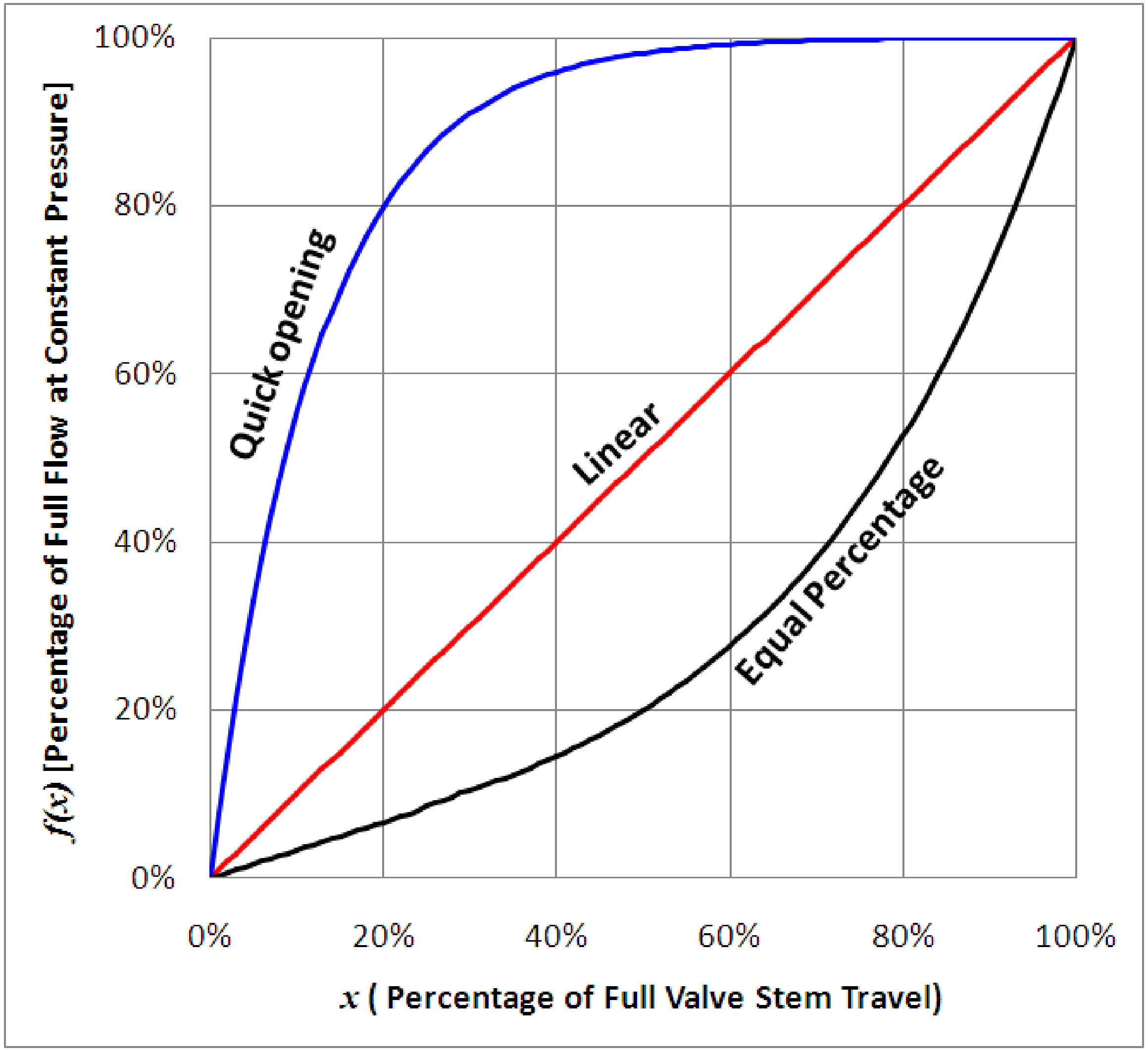
- Since valve flow is a function of both the valve travel and the pressure drop across the valve, it is traditional to conduct inherent valve characteristic tests at a constant pressure drop.

Essential Features: Valve characteristics

Typical inherent valve characteristics

- ☞ linear
- ☞ equal percentage
- ☞ quick opening

Essential Features: Valve characteristics



Approximating Equations

Linear

$$f(x) = x$$

Equal percentage

$$f(x) = \alpha^{x-1}$$

Quick opening

$$f(x) = 1 - \alpha^{-2.5x}$$

$$\alpha = 20 \text{ to } 50$$

Essential Features: Valve characteristics

Under the specific conditions of constant pressure drop, the valve flow becomes only a function of the valve travel and the inherent design of the valve trim.

QUICK OPENING

LINEAR

EQUAL PERCENTAGE

Essential Features: Valve characteristics

Linear Flow Characteristic

- A valve with an ideal linear inherent flow characteristic produces flow rate directly proportional to the amount of valve plug travel, throughout the travel range.
- Select a valve with linear characteristic when variation in the systems pressure drop is fairly constant

Essential Features: Valve characteristics

Equal-Percentage Flow Characteristic

For equal increments of valve plug travel, the change in flow rate is expressed as a constant percent of the flow rate at the time of the change.

Example :- The following percent flow rates are given below for an equal percentage valve. Determine the flow rate when the valve moves to 30%.

x [%]	f
10	6.75
20	9.10
30	f_3

$$p = \frac{(9.1 - 6.75)}{6.75} 100\% = 34.81\%$$

$$f_3 = 1.3481 \times 9.1 = 12.27$$

Use a valve with equal percentage characteristics for systems that have significant variation in the systems pressure drop.

Essential Features: Valve characteristics

Quick-Opening Flow Characteristic

- A valve with a quick opening flow characteristic provides a maximum change in flow rate at low travels.
- The curve is basically linear through the first 40 percent of valve plug travel.
- Use control valves with quick-opening flow characteristics for applications where valve dynamics is not essential, they are cheaper.

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Essential Features: Rangeability

- Rangeability (turn-down ratio) is the ratio of the maximum controllable flow to the minimum controllable flow.
- It is the measure of the width of the operating flows the valve can control.
- Commonly used relation

$$Rangeability = \frac{Flow\ at\ 95\%\ valve\ stem\ position}{Flow\ at\ 5\%\ valve\ stem\ position}$$

- Valves with high rangeability allow wide range of flow adjustment

Essential Features: Rangeability

Example: For constant pressure drop across the valve estimate the rangeability of linear, equal percentage and quick opening valve use α =25, 50 and 100 for equal percentage and quick opening valve.

Linear

$$Rangeability = \frac{0.95}{0.05} = 19$$

Quick opening

$$Rangeability = \frac{1 - 25^{-2.5 \times 0.95}}{1 - 25^{-2.5 \times 0.05}} = 3.0$$

Equal percentage

$$Rangeability = \frac{25^{(0.95-1)}}{25^{(0.05-1)}} = 18$$

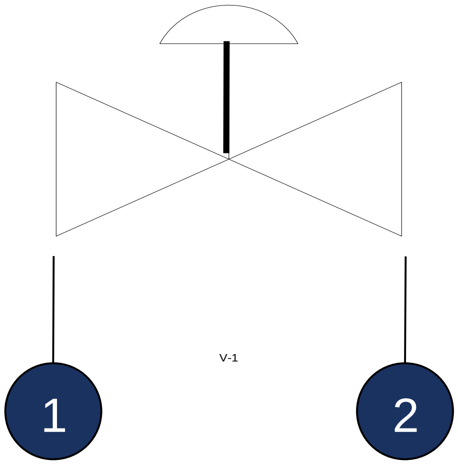
α	25	50	100
Quick opening	3	2.6	2.3
Equal percentage	18	33.8	63

Essential Features: Valve Sizing

- Valve sizing is a compromise between two important factors: pumping cost and control performance.
  - small valves cause high pressure drop resulting in high pumping cost but are good for control performance.
  - Larger valves cause less pressure drop resulting in less pumping cost, however, control performance is poor.
- Note that if the pump is already selected, smaller valves means they can not deliver the required flow rate.

Essential Features: Valve Sizing

The valve sizing equation for liquids



The Bernoulli equation between point 1 and 2

$$\frac{P_1}{\rho g} + \cancel{\frac{v_1^2}{2g}} + \cancel{h_1} = \frac{P_2}{\rho g} + \cancel{\frac{v_2^2}{2g}} + \cancel{h_2} + f\,\frac{v_2^2}{2g}$$

Essential Features: Valve Sizing

Simplifying and rearranging

$$\frac{P_1 - P_2}{\rho g} = f \frac{v^2}{2g}$$

Using continuity equation $Q = v\,A$ and $\rho = \rho_w\, sg$ and rearranging

$$\frac{\Delta P}{sg} = \frac{\rho_w f}{2A^2} Q^2$$

Q = flow rate (gpm)

sg = specific gravity

DP =pressure drop (psi)

Essential Features: Valve Sizing

Collecting constant terms for a given valve of a given geometry as C_V and rearranging we get the Valve Sizing Equation.

$$Q = C_v \sqrt{\frac{\Delta P}{sg}} \qquad C_v = Q\sqrt{\frac{sg}{\Delta P}}$$

C_v is the number of US gallons per minute of water at 60°F with a pressure drop of 1 psi across the valve

Essential Features: Valve Sizing

Steps for Selecting Control Valve

- STEP 1 : Determine the design flow rate and pressure drop across the valve
- STEP 2: Calculate C_V

For liquid service:

$$Cv = Q\sqrt{\frac{sg}{\Delta P}}$$

Q - flow rate (gpm)
sg - specific gravity
DP - pressure drop (psi)

For gas and steam services:

formula varies from manufacturer to manufacturer. Consult control valve manufacturer.

- STEP 3: Select the appropriate valve size from manufacturers catalogue using C_v in consultation with the manufacturer.

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Control Valve sizing

FLOW COEFFICIENTS

For additional body information see *Bulletin 51.1:EB(10)*

Linear

Linear Characteristic

Coefficients	Body Size, In.	Port Diameter, In.	Total Travel, In.	Valve Opening—Percent of Total Travel: 10	20	30	40	50	60	70	80	90	100	K_m* and C_1
C_v (Liquid)	1	1	3/4	2.01	3.52	4.81	5.96	7.46	8.93	10.1	11.0	11.8	12.4	.90
	1-1/2	1-1/2	3/4	4.20	7.93	11.7	15.6	19.7	23.7	27.1	30.7	32.8	33.6	.87
	2	2	1-1/8	5.96	11.7	17.6	23.6	29.5	35.7	42.0	48.6	51.0	51.4	.96
	3	3	1-1/2	16.7	32.2	47.2	63.4	78.0	91.2	102	112	117	120	.85
	4	4	2	20.5	38.2	55.3	60.3	96.5	124	151	173	191	201	.84
	1-1/2•	1	3/4	1.90	3.32	4.80	5.93	7.58	9.00	10.6	12.6	14.7	16.2	.90
	2•	1	3/4	1.81	3.28	4.76	6.24	7.75	9.30	10.8	12.3	13.8	15.1	.90
		1-1/2	3/4	4.39	7.93	11.7	15.5	19.3	22.9	27.0	30.2	33.0	35.1	.81
	3•	1-1/2	3/4	4.24	7.97	11.7	15.4	19.3	23.2	27.2	31.3	35.1	38.5	.80
		2	1-1/8	5.63	11.4	17.7	24.0	30.8	37.6	47.5	57.7	65.1	68.7	.81
	4•	2	1-1/8	5.45	11.3	17.7	24.6	31.9	39.9	52.0	59.7	69.7	76.8	.81
		3	1-1/2	14.8	30.1	44.9	59.8	75.3	91.9	109	125	133	136	.87
C_g (Gas)	1	1	3/4	66.6	113	159	197	247	294	334	376	430	469	37.8
	1-1/2	1-1/2	3/4	131	251	371	507	633	762	888	1010	1120	1190	35.4
	2	2	1-1/8	173	365	553	753	960	1180	1440	1660	1840	1920	37.4
	3	3	1-1/2	512	999	1520	2040	2510	3000	3440	3850	4150	4380	36.4
	4	4	2	610	1210	1830	2490	3150	3870	4970	6290	7090	7480	37.2
	1-1/2•	1	3/4	51.6	99.7	147	195	242	289	335	395	492	573	35.4
	2•	1	3/4	55.9	99.8	146	195	242	291	343	388	473	570	37.7
		1-1/2	3/4	129	249	367	497	614	739	864	980	1110	1240	35.3
	3•	1-1/2	3/4	122	247	362	489	614	742	864	986	1130	1280	33.2
		2	1-1/8	172	327	520	763	951	1180	1450	1790	2180	2420	35.2
	4•	2	1-1/8	184	357	557	761	974	1220	1520	1840	2200	2590	33.7
		3	1-1/2	482	963	1470	1960	2440	2920	3460	4060	4710	5150	37.9
C_s (Steam)	1	1	3/4	3.33	5.65	7.95	9.85	12.4	14.7	17.2	18.8	21.5	23.5	37.8
	1-1/2	1-1/2	3/4	6.55	12.6	18.6	25.4	31.7	38.1	44.4	50.5	56.0	59.5	35.4
	2	2	1-1/8	8.65	18.3	27.7	37.7	48.0	59.0	72.0	83.0	92.0	96.0	37.4
	3	3	1-1/2	25.6	50.0	76.0	102	126	150	172	193	208	219	36.4
	4	4	2	30.5	60.5	91.5	125	158	194	249	315	355	374	37.2
	1-1/2•	1	3/4	2.58	4.99	7.35	9.75	12.1	14.5	16.8	19.8	24.6	28.7	35.4
	2•	1	3/4	2.80	4.99	7.30	9.75	12.1	14.6	17.2	19.4	23.7	28.5	37.7
		1-1/2	3/4	6.45	12.5	18.4	24.9	30.7	37.0	43.2	49.0	55.5	62.0	35.3
	3•	1-1/2	3/4	6.10	12.4	18.1	24.5	30.7	37.1	43.2	49.3	56.5	64.0	33.2
		2	1-1/8	8.60	16.4	26.0	38.2	47.6	59.0	72.5	89.5	109	121	35.2
	4•	2	1-1/8	9.20	17.9	27.9	38.1	48.7	61.0	76.0	92.0	110	130	33.7
		3	1-1/2	24.1	48.2	73.5	98.0	122	146	173	203	236	258	37.9

*This column lists the K_m values for the C_v coefficients and the C_1 values for the C_g and C_s coefficients at 100% travel.

• Restricted Trim