

FIRE FUNDAMENTALS

Fire is the combination of oxygen and fuel in proper proportions and at the proper temperature to sustain combustion.

To produce combustion, four conditions must coexist:

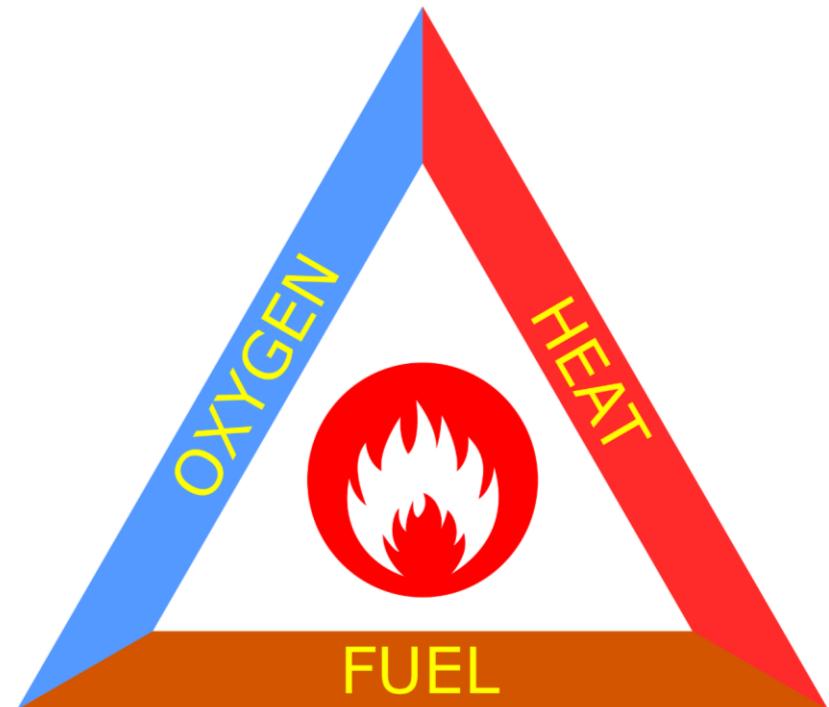
- (1) Presence of fuel
- (2) Presence of oxygen
- (3) Heat
- (4) Mixing

Presence of Fuel – A combustible material must be present (e.g., wood, gasoline, paper, etc.).

Presence of Oxygen – Oxygen or an oxidizing agent is required to sustain combustion.

Heat (Ignition Source) – A sufficient heat source is needed to ignite the fuel.

Mixing – The fuel and oxygen must mix properly for combustion to occur.



Flammability Characteristics

1. Flammability Limits:

Flammability limits refer to the concentration range of a **flammable gas or vapor in air** that can ignite when exposed to an ignition source.

These limits are given as:

• **Lower Flammability Limit (LFL)** – The minimum concentration of fuel in air needed to sustain combustion.

• **Upper Flammability Limit (UFL)** – The maximum concentration of fuel in air beyond which combustion cannot occur.

Flammability limits depend on factors such as temperature, pressure, and fuel type.

The general empirical relation for estimating LFL is:

$$LFL = \frac{1}{A + B(T - T_0)}$$

Where

A,B = Fuel-specific constants

T = Temperature (K)

T_0 = Reference temperature (K)

Compound	Limits of Flammability	
	Lower (% v/v)	Upper (% v/v)
Acetone	2.6	13.0
Acetylene	2.5	100.0
Ammonia	15.0	28.0
Amylene	1.8	8.7
Benzene	1.4	8.0
n-Butane	1.8	8.4
i-Butane	1.8	8.4
1-Butene	2.0	10.0
2-Butene	1.7	9.7
Carbon disulfide	1.3	50.0
Carbon monoxide	12.5	74.0
Cyclohexane	1.3	7.8
Decane	0.8	5.4
Ethane	3.0	12.4
Ethyl alcohol	3.3	19.0
Ethylene	2.7	36.0
Ethylene dichloride	6.2	15.9
Ethylene oxide	3.0	100.0
Heptane	1.2	6.7
Hexane	1.4	7.4
Hydrogen	4.0	75.0
Kerosene	0.7	5.0
Methane	5.0	15.0
Methanol	6.4	37.0
Methyl ethyl ketone	1.7	11.4
Naphthalene	0.9	7.8
n-Pentane	1.8	7.8
Petroleum ether	1.1	5.9
Propane	2.1	9.5
Propylene	2.4	11.0
Isopropyl alcohol	2.0	12.0
n-Propyl alcohol	2.1	13.7
Styrene	1.1	6.1
Toluene	1.3	7.0
Turpentine	0.8	
o-Xylene	1.0	6.0
Vinyl Chloride	4.0	22.0
2,2-Dimethylpropane	1.3	7.5
2,3-Dimethylpentane	1.1	6.8

^a From Manual of Industrial Hazard Assessment Techniques.⁴

Flammability Characteristics

2. Flash Point :

The *flash point* of a flammable liquid is defined as the temperature at which the vapor pressure of the liquid is the same as the vapor pressure corresponding to the lower flammability limit concentration.

The two major methods of measuring the flash point are:

1. The Cleveland open cup method : Gives a slightly higher flash point
2. The Penskey-Martens closed cup tester : Gives a lower flash point.

Equation (Approximate for hydrocarbons):

$$T_f = \frac{LFL \cdot P_v}{P_{atm}}$$

Where

T_f = Flash point (K)

LFL = Lower flammability limit (mass %)

P_v = Vapor pressure of the liquid at a given temperature (Pa)

P_{atm} = Atmospheric pressure (Pa)

Compound	Flash Point (°C)	
	Closed Cup	Open Cup
Acetone	-18	-9
Benzene	-11	
<i>n</i> -Butane	-60	
Carbon disulfide	-30	
Cyclohexane	-20	
Ethane	-135	
Ethylene	-121	
Ethylene dichloride	13	18
Ethylene oxide		-20
Propane	-104	
Propylene	-108	
Styrene	32	38
Toluene	4	7
Vinyl chloride		-78

^a From Lees.³

Flammability Characteristics

3. **Burning velocity** is the velocity of the flame relative to the motion of the unburned gas or gas mixture.

This measurable quantity is an excellent index to the energetic state of the reaction.

- ❖ The burning velocity is a function of gas mixture composition, pressure, and temperature.
- ❖ The maximum velocity is observed at the stoichiometric concentration of the mixture.
- ❖ The effect of pressure on the burning velocity is different for different pressure ranges.

The effect of temperature is expressed as

$$S_b = A + BT^n$$

where S_b = burning velocity

T = absolute temperature

A, B = constants

n = index (e.g., $n = 2$ for paraffinic hydrocarbons)

Compound	Maximum Fundamental Burning Velocity S_b^b	
	cm/s	ft/s
<u>In Air</u>		
Methane	36.4 ^c	1.2
<i>n</i> -Butane	45.0 ^c	1.5
<i>n</i> -Hexane	38.5	1.3
Cyclohexane	20	
Ethane	40.1	
Ethylene	68.8 ^c	2.3
Town gas ^d		3.7
Acetylene	173	5.8
Propane	45.0 ^c	1.5
Hydrogen	320	11
Benzene	40.7 ^c	
<u>In Oxygen</u>		
Methane	393 ^e	
Propane	390	
Ethylene	550	
Acetylene	1140	
Hydrogen	1175	

^a From Lees.³

^b The values given in the first column are those of Flock (1955) and in the second column those of the HSE (1965 HSW). The values quoted from Flock are for initial pressure (atmospheric) and initial temperature (room temperature) and in most cases dry gas and generally are selected from several values listed.

^c Some higher values are also listed by Flock.

^d For town gas containing 63% H₂.

^e For stoichiometric mixture.

Flammability Characteristics

A flammable gas-air mixture can be ignited by a local source of ignition (flame, spark, hot gas, shock wave, adiabatic heating, etc.), provided the local source possesses the *minimum ignition energy*-that is, the ignition energy required to raise the temperature of the gas-air mixture above the threshold temperature and to initiate a reaction.

- When the temperature of a flammable mixture is raised to or above the autoignition temperature, ignition is not instantaneous.
- Most notably in liquids, there is a finite delay before ignition takes place, that is, a lapse between the time a flammable mixture reaches its flame temperature and the first appearance of a flame.

SEMENOV gave correlation between the time delay and ignition temperature

$$\ln t = k_1(E/T) + k_2$$

where E = apparent activation energy
T = absolute temperature
 k_1, k_2 = constants
t = time delay before ignition

PLANT FIRES

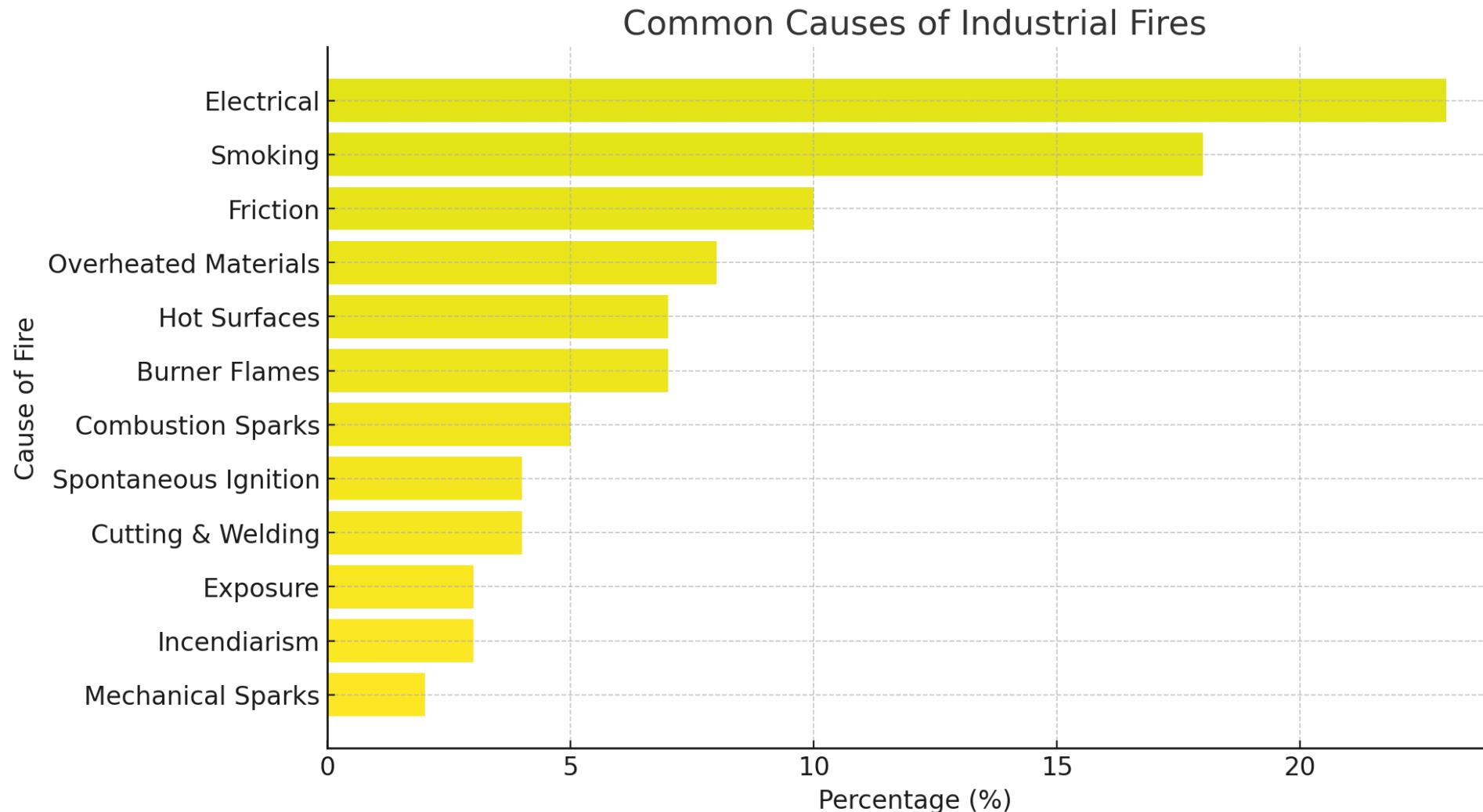
Classes of Fires : The National Fire Protection Association recognizes four general classification of fires.



Fire Class		Fire Type	Materials involved
A		General	Wood, paper, cloth, trash etc...
B		Flammable Liquids	Flammable solvents, liquids, Oils, Greases, Paints etc...
C		1. Electrical 2. Flammable Gases	Energized electrical equipment and All flammable gases
D		Metals	Water reactive Chemicals, Combustible metals etc...

PLANT FIRES

Ignition Sources: Industrial plants contain a great number of possible ignition sources. A study made by the Factory Mutual Engineering corporation of almost 25,000 industrial fires reported over a decade indicates the following



PLANT FIRES

Fire accidents in **process plants** are primarily caused by **equipment failure** and **lack of knowledge about chemical processes**

1. Equipment Failure (Most Common Cause)

Cause:

- Poor equipment maintenance.
- Improper equipment layout and design.
- Leaks and spills due to seal, flange, or pump failures.

Prevention:

- Implement a **detailed maintenance schedule**.
- Use **double mechanical seals** to reduce pump leaks.
- **Insulating pads** in pipe flanges to minimize fire risk.
- Use **stronger flanges** to lower temperature gradients.

2. Lack of Knowledge About Chemical Properties

Cause:

- Employees unaware of **chemical reactivity, ignition risks, and handling procedures**.
- Improper handling of **flammable chemicals** leading to accidental ignition.

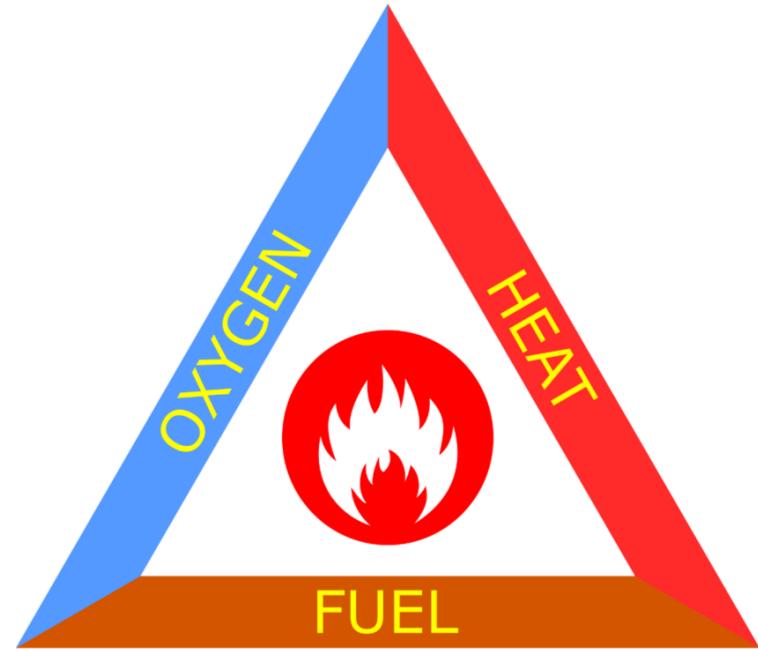
Prevention:

- **Employee training** on chemical hazards and fire safety.
- **Proper chemical process education** to avoid mishandling.
- Use of **MSDS (Material Safety Data Sheets)** for guidance

Fire Extinguishing Systems & Methods

The best way to fight a fire is to remove **any one** of the three essential conditions required for combustion:

Fire Element	Method of Removal	Example
Fuel (Combustible Material)	Stop fuel supply, remove flammable materials	Fix leaks in a process plant, shut off gas valves
Heat (Ignition Source)	Cool the fire to below ignition temperature	Douse fire with water, use cooling agents
Oxygen (Oxidizing Agent)	Cut off oxygen supply	Apply foam, use CO ₂ or inert gases



Fire Extinguishing Systems & Methods

Types of Fire Extinguishing Systems

Various fire extinguishing systems are used based on **fire class and risk factors**:

1. Water-Based Systems

Used for Class A fires (wood, paper, cloth, etc.).

- **Automatic Sprinklers** – Activate when heat is detected.

- **Fire Hoses** – Provide a directed water stream to control flames.



2. Foam Systems

Used for Class B fires (flammable liquids like oil and gasoline).

Types of Foam Systems:

- **Chemical Foams** – Created by a chemical reaction between CO₂ gas and a foaming agent, forming a stable froth.

- **Mechanical Foams** – Generated by mechanically mixing air and water with a foam-forming agent.

- **High Expansion Foam** – Tiny foam bubbles blown by a fan over a detergent-based solution.

- **Best for** confined spaces or areas where **water damage is a concern**.
- **Example:** Storage tanks with flammable liquids

Fire Extinguishing Systems & Methods

3. Carbon Dioxide (CO₂) Systems

Used for Class B and Class C fires (liquids, gases, electrical fires).

- CO₂ replaces oxygen and **suffocates the fire**.
 - Does not leave residue or cause water damage.
- CO₂ expands and displaces oxygen **below the combustion threshold**.



4. Dry Chemical Systems

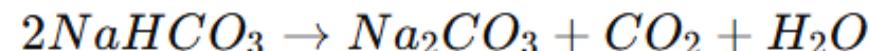
Used for Class B and Class C fires.

- Example: Sodium bicarbonate (NaHCO₃)

Benefits:

- Non-toxic
- Non-conductive (**safe for electrical fires**)
- Does not freeze

Reaction for Sodium Bicarbonate Suppression:



- CO₂ gas helps smother flames.

- Water vapor cools the fire.

Fire Extinguishing Systems & Methods

5. Water Spray Systems

Used for:

- Exposure protection of buildings and tanks.
- Class B flammable liquid fires.

How It Works:

- Delivers **fine mist** instead of direct streams.
- Helps **prevent ignition of surrounding structures**.



6. Steam Jet Systems

Used for enclosed spaces or **closed containers**.

- Steam **displaces oxygen** and **smothers flames**.
- Effective in **confined areas** where other methods might not work.



A flammable vapor flows through a 2-inch-diameter insulated pipe at a flow rate of 4.5 acfm. A lagging fire started and heated a 4-foot length of the pipe to 150 °F, which is above the ignition temperature of the vapor. The ignition delay time of the vapor is expressed by

$$\ln(t) = (250/T) + 0.5$$

where t = ignition time delay (s)

T = absolute temperature (R)

Will ignition take place?

EXPLOSION FUNDAMENTALS

AN EXPLOSION: defined by Strehlow and Baket as an event in which energy is released over a **sufficiently small period of time** and **in a sufficiently small volume** to generate a **pressure wave of finite amplitude** traveling away from the source.

	Fire	Explosion
	A fire is a slow, continuous combustion process where heat and flames are produced.	An explosion is a sudden and violent release of energy , often resulting in a shockwave.
Speed of Reaction	Slow burning reaction. The combustion spreads at a steady rate	Extremely fast reaction, often occurring in milliseconds .
Pressure Increase	Pressure increase is gradual and localized.	Pressure increases suddenly , causing structural damage.
Cause of Ignition	Ignited by an open flame, heat, sparks, or electrical faults	Often triggered by a shock, spark, or rapid chemical reaction
Confinement Requirement	Can occur in open air or inside confined spaces	Requires confinement or rapid expansion of gases to create a blast effect .
Damage and Impact	Causes localized damage. Spreads gradually, affecting materials and structures.	Causes instant and widespread destruction due to the shockwave and blast .
Fire and Explosion Triangle	Fuel + Oxygen + Heat = Fire	Fuel + Oxygen + Ignition + Confinement + Dispersion= Explosion

Fire vs Explosion



Types of Accidental Explosions

1. Condensed Phase Explosions (Liquids and Solids)

- Occurs with or without confinement.
- Results from a **rapid chemical reaction** releasing energy.
- Example: **Detonation of unstable liquid chemicals.**



2. Combustion Explosions in Enclosures (Gases and Dusts)

- Flammable **gases** or **dust particles** ignite inside a **closed space**.
- High pressure builds up, leading to an **explosion**.
- Example: **Coal dust explosions in mines.**



Types of Accidental Explosions

3. Explosions in Pressure Vessels

- A vessel containing high-pressure gas or liquid ruptures due to failure of structural integrity.
- Example: Boiler explosions, gas cylinder ruptures.

4. Boiling Liquid Expanding Vapor Explosions (BLEVEs)

- Occurs when a **pressurized liquid** (e.g., LPG, ammonia) rapidly vaporizes due to **container failure**.
- Leads to **shock waves**, intense fires, and **flying debris**.
- Example: **LPG storage tank rupture**.

Types of Accidental Explosions

5. Unconfined Vapor Cloud Explosions (UVCEs)

- A large **cloud of flammable vapor** disperses in open air and **finds an ignition source**.
- The vapor ignites, causing an **explosive fireball**.
- Example: **Gas leaks from refineries forming explosive clouds**



Explosion fundamental principles

- Explosion pressure (P_{ex}) is the **pressure exceeding the initial pressure** at which an **explosive mixture ignites**.
- It represents the **maximum pressure** generated by the combustion of a flammable gas or dust in a **confined space**.
- The rate of change of pressure **over time** ($\frac{dP}{dt}$) indicates the **speed of flame propagation** and the **violence of the explosion**.
- The **maximum rate of pressure rise** is influenced by the **vessel volume**.
- The relationship is given by the **Cubic Law**:

$$\left(\frac{dP}{dt} \right)_{max} = K_G V^{-n}$$

Where:

- $\left(\frac{dP}{dt} \right)_{max}$ = Maximum rate of pressure rise (bar/s).
- K_G = Gas-specific explosion constant.
- V = Volume of the vessel (m^3).
- n = Empirical constant (typically 0.33 for gases).

Explosion fundamental principles

The **Cubic Law** is a useful tool, but it must be applied cautiously in explosion analysis.

If key variables like **vessel shape, turbulence, ignition, and gas concentration** change, the law may **not accurately predict explosion behavior**

Cubic Law for Dust Explosions:

$$\left(\frac{dP}{dt} \right)_{max} = K_{St} V^{-n}$$

Where:

- $\left(\frac{dP}{dt} \right)_{max}$ = Maximum rate of pressure rise (bar/s).
- K_{St} = **Dust explosion constant** (varies by dust type, similar to K_G for gases).
- V = Vessel volume (m^3).
- n = **Empirical exponent** (typically 0.33 for dust explosions, similar to gas explosions).

K_G values of some flammable gases obtained by using spark gap ignition with ignition energy of 10 J.

Flammable Gas	K_G (bar·m/s)
Methane	55
Propane	75
Hydrogen	550

^a From Bartknecht.¹

K_{St} Values of Technical Fine Dusts: High Ignition Energy

Type of Dust	P_{max} (bar)	K_{St} (bar·m/s)
PVC	6.7 - 8.5	27 - 98
Milk powder	8.1 - 9.7	58 - 130
Polyethylene	7.4 - 8.8	54 - 131
Sugar	8.2 - 9.4	59 - 131
Resin dust	7.8 - 8.9	108 - 174
Brown coal	8.1 - 10.0	93 - 176
Wood dusts	7.7 - 10.5	83 - 211
Cellulose	8.0 - 9.8	56 - 229
Pigments	6.5 - 10.7	28 - 344
Aluminum	5.4 - 12.9	16 - 750

^a From Bartknecht.¹

Explosion Waves and Overpressure Effects in Air

An explosion in air is characterized by a pressure wave (blast wave) caused by the rapid release of energy. This wave leads to sudden pressure variations, which can cause structural damage and injuries

Characteristics of an Explosion Wave

- **Overpressure (Positive Pressure):** When the blast wave **compresses air**, creating a **high-pressure front**.
- **Under pressure (Negative Pressure):** A **weaker** region follows the overpressure phase, creating a **vacuum effect**.
 - This **under pressure** is usually **below 4 psi**.

Effects of a Blast Wave

• Changes in Air Properties:

- **Density** increases at the blast front.
- **Temperature** rises due to compression.
- **Particle velocity** increases as air molecules move rapidly.

• Structural Damage:

- Buildings and equipment experience **dynamic stresses** from overpressure.

• Human Injury:

- High-intensity shock waves can cause **lung damage, ruptured eardrums, and internal injuries**.

Explosion Waves and Overpressure Effects in Air

The Modified Friedlander Equation:

The **overpressure curve** from an explosion follows the **Modified Friedlander equation**:

$$P_o(t) = P_{so} \left(1 - \frac{t}{t_s} \right) e^{-\frac{t}{t_s}}$$

Where:

- $P_o(t)$ = Overpressure at time t .
- P_{so} = Peak overpressure.
- t_s = Shock wave arrival time.
- t = Time elapsed after shock arrival.

Key Insights from this Equation:

- The pressure rises quickly to a peak and then decays exponentially.
- The overpressure is strongest at the explosion center.
- Over time, both overpressure and underpressure diminish.

Confined Combustion Explosions

- Occur when **flammable vapor** leaks into a **closed enclosure**, mixing with air.
- An **ignition source** present in the area causes the **mixture to ignite**.

Common locations:

- **Storage tanks** with flammable vapor above liquid fuel.
- **Ships** where fuel vapor is trapped in compartments.
- **Chemical plants** handling volatile solvents.

Explosion Risk Factors:

- **Fuel-air mixture in the flammability range.**
- **Presence of ignition sources (sparks, static electricity, hot surfaces).**
- **Lack of ventilation, allowing vapor accumulation.**

Confined Dust Explosions

- Occur in industries where **fine dust particles** accumulate in **closed spaces**.
- Common in **coal mines, grain elevators, flour silos, boilers, and chemical plants**.

How it happens:

- A **primary explosion** occurs (e.g., ignition of methane in a mine).
- The **shockwave disturbs layered dust**, creating a **suspended dust cloud**.
- The **suspended dust ignites**, leading to a **secondary explosion** (often more destructive).

Examples of Confined Dust Explosions:

- **Coal Mines:** Methane ignition triggers **secondary coal dust explosion**.
- **Grain Elevators:** Fine grain dust in **poorly ventilated silos** ignites from a spark.
- **Chemical & Pharmaceutical Plants:** Powdered chemicals ignite inside enclosed processing equipment.

Prevention & Mitigation Strategies

Vapor & Gas Explosions:

- **Leak detection systems** for flammable gases.
- **Ventilation systems** to prevent gas buildup.
- **Explosion-proof electrical equipment.**

Dust Explosions:

- **Proper dust collection & filtration systems.**
- **Inert gas suppression** to prevent ignition.
- **Explosion venting panels** to release pressure safely.

General Protection:

- **Monitor pressure and temperature levels** in enclosures.
- **Use flame arrestors** to prevent flame propagation.
- **Regular inspections** of confined spaces.

TOXIC Emissions

Toxic emissions hazard refers to the **risk posed by the release of harmful chemicals into the environment**, which can lead to **acute or chronic health effects**, environmental contamination, and potential fatalities

Type	Purpose
Clinical toxicology	To determine the effects of chemical poisoning and the treatment of poisoned people
Descriptive toxicology	To test the toxicity of chemicals
Environmental toxicology	To determine the environmental fate of chemicals and their ecological and health effects
Forensic toxicology	To answer medicolegal questions about health effects
Industrial toxicology	To determine health effects of occupational exposures
Mechanistic toxicology	To describe the biochemical mechanisms that cause health effects
Regulatory toxicology	To assess the risk involved in marketing chemicals and products, and establish their subsequent regulation by government agencies

TOXIC Emissions

Toxic emissions hazard refers to the **risk posed by the release of harmful chemicals into the environment**, which can lead to **acute or chronic health effects**, environmental contamination, and potential fatalities

Threshold Limit Values (TLVs) for Toxic Exposure in the Workplace

- TLVs are exposure guidelines that define the acceptable concentration of hazardous substances in workplace environments.**
- These values help protect workers from long-term and short-term health effects due to toxic chemical exposure.**
- Three Categories of TLVs**

TOXIC Emissions

① TLV-TWA (Time-Weighted Average)

Definition:

- The **average concentration** of a substance **over an 8-hour workday and a 40-hour workweek.**
- Assumes **continuous exposure** is safe **without long-term health effects.**

Purpose:

- Protects workers from **chronic exposure** (long-term effects).
- Designed for **repeated exposure over years.**

Lethal Concentration 50 (LC₅₀) is a toxicological term referring to the concentration of a chemical in air (or another medium such as water) that is expected to cause death in 50% of a specified test population of animals after a particular exposure duration.

TOXIC Emissions

2 TLV-STEL (Short-Term Exposure Limit)

Definition:

- The **maximum concentration** a worker can be exposed to for a **short duration (15 minutes)** without:
 - Irritation
 - Chronic or irreversible tissue damage
 - Increased risk of accidental injury

Purpose:

- Prevents acute (short-term) toxic effects.
- Not an independent limit → Works alongside TLV-TWA.

TOXIC Emissions

3 TLV-C (Ceiling Limit)

Definition:

- The **absolute maximum concentration** that **must never be exceeded** at any time.
- Designed for **highly toxic substances** that cause **immediate harm** even in **short exposures**.

Purpose:

- Prevents **instantaneous toxic effects**.
- Sets a **hard safety boundary**.

Problems

A round vessel filled with hydrogen is ignited. The volume of the vessel is 0.5 m^3 . Calculate the maximum pressure rise. Also calculate the maximum pressure rise for the same vessel filled with methane. KG for hydrogen and methane is 550 and 55, respectively.

Chemical Hazard

Chemical hazards are among the most critical concerns in **process plant safety**.

These involve the **presence, handling, storage, and reaction** of chemicals that can cause harm to people, property, and the environment if not properly managed.

Categories of Chemical Hazards in Process Plants

Flammable and Combustible Substances

- **Examples:** Gasoline, ethanol, hydrogen, methane
- **Hazard:** Can ignite easily, leading to **fires or explosions**
- **Control:** Flame arrestors, proper ventilation, bonding/grounding of equipment

Chemical Hazard: Categories of Chemical Hazards in Process Plants

Toxic Substances

Examples: Chlorine, ammonia, hydrogen sulfide (H₂S), benzene

Hazard Profile: Chlorine

- **Physical state:** Greenish-yellow gas at room temperature
- **Odor:** Pungent, irritating
- **Toxicity:**
 - Irritant to eyes, nose, throat, and lungs
 - Causes **chemical burns** and **pulmonary edema**
- **TLV-TWA:** 0.5 ppm
- **TLV-STEL:** 1 ppm

Sources in Process Plants:

- Water treatment facilities
- Chlor-alkali production
- PVC and paper manufacturing

Mitigation Measures:

- **Gas leak detection systems**
- **Scrubbers** using caustic solutions to neutralize chlorine leaks
- **Enclosed handling systems**
- **Emergency shutdown systems and alarms**
- **Chlorine Emergency Kits** (Kit A, B, C – based on container size)

Chemical Hazard: Categories of Chemical Hazards in Process Plants

Hazard Profile: Hydrogen Sulfide (H₂S)

- **Physical state:** Colorless gas with "rotten egg" smell

- **Toxicity:**

- Highly toxic even at **low concentrations**

- **Paralyzes olfactory nerves**, making leaks hard to detect by smell

- Causes **respiratory paralysis** and **death**

- **TLV-TWA:** 1 ppm

- **TLV-STEL:** 5 ppm

- **IDLH** (Immediately Dangerous to Life or Health): 100 ppm

Sources in Process Plants:

- Petroleum refining

- Natural gas processing

- Wastewater treatment

Mitigation Measures:

- **Continuous H₂S monitors** with visual and audio alarms

- **Confined space entry permits and monitoring**

- **Supplied-air respirators** or SCBA for high-risk areas

- **Emergency drills and gas exposure response plans**

- **Flare systems** or neutralization processes

- **Fixed and portable gas detectors**

Chemical Hazard: Categories of Chemical Hazards in Process Plants

Hazard Profile: Benzene (C_6H_6)

- **Physical state:** Volatile, colorless liquid with sweet odor
- **Toxicity:** **Carcinogenic** (causes leukemia)
- **Neurotoxic and hematotoxic** (damages bone marrow and blood)
- **TLV-TWA:** 0.5 ppm
- **TLV-STEL:** 2.5 ppm

Sources in Process Plants:

- Petrochemical refineries
- Solvent production
- Manufacturing of plastics, resins, synthetic fibers

Mitigation Measures:

- **Closed-loop systems** for transfer and handling
- **Vapor recovery units** to control emissions
- **Substitution with less hazardous solvents** when possible
- **Routine air monitoring for benzene concentrations**
- **Medical surveillance** for long-term exposure
- **Proper PPE**, including chemical-resistant gloves and masks

Chemical Hazard: Reactive Chemicals

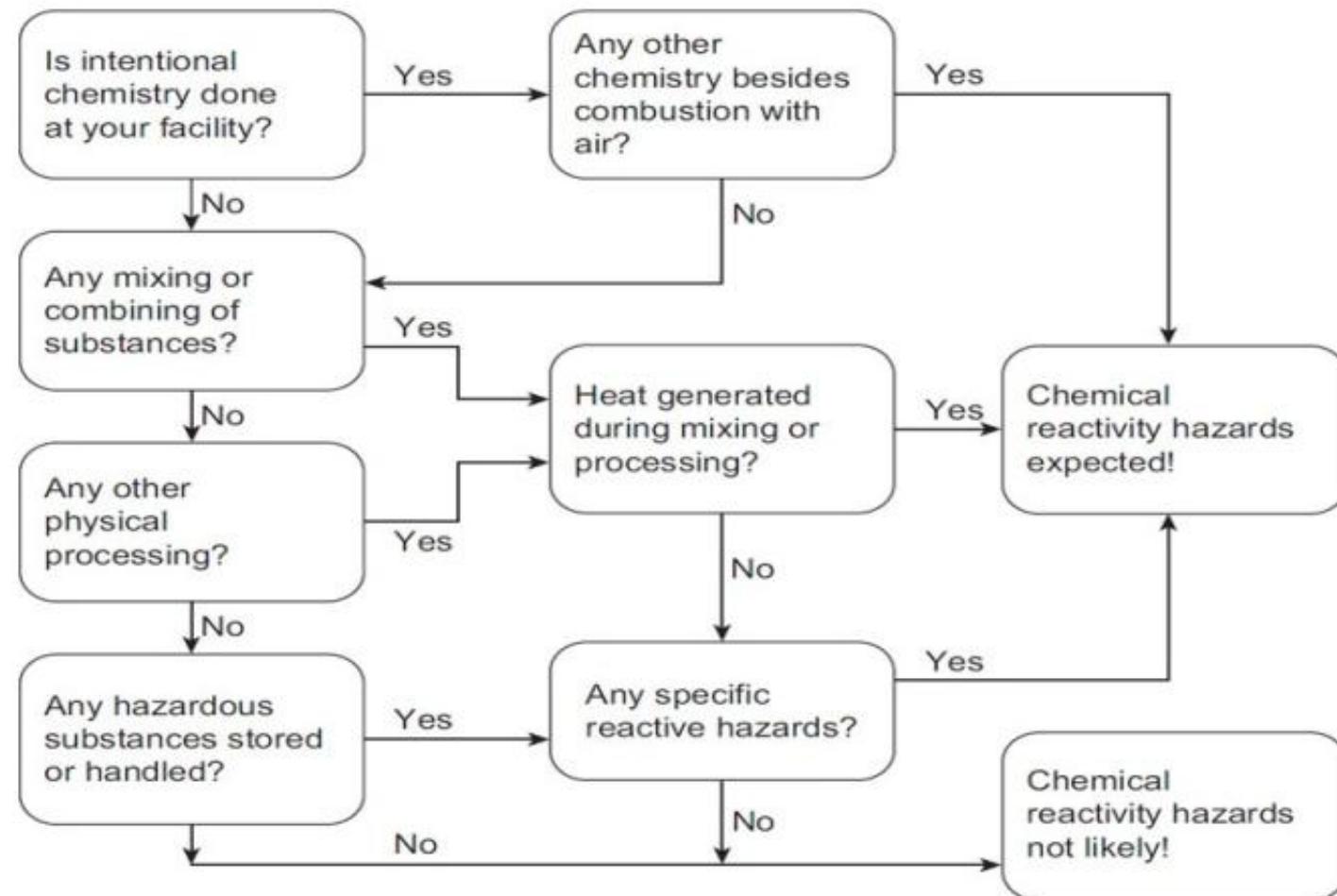
A chemical reactivity hazard is “a situation with the potential for an uncontrolled chemical reaction that can result directly or indirectly in serious harm to people, property or the environment.

Chemical reactivity hazards are likely to be found with the following operations:

1. Intentional chemical operations, where chemicals react by design, including chemical plants.
2. Mixing and physical processing, which may include the following operations: combine, formulate, crush, blend, screen, dry, distill, absorb, heat, dilute, and so on.
3. Storage, handling, and repackaging, which does not include mixing, but may include warehousing, tank storage, dividing, and other processes.

Chemical Hazard: Reactive Chemicals

Screening flowchart for reactive chemical hazards: This figure contains seven questions to determine if reactive chemical hazards are present.



Chemical Hazard: Reactive Chemicals

1. *Is intentional chemistry performed at your facility?* In most cases this is easy to determine. The bottom line is: Are the products that come out of your facility in a different molecular configuration from the raw materials? A precise answer to this question is required prior to moving forward in the flowchart.
2. *Is there any mixing or combining of different substances?* If substances are mixed or combined, or even dissolved in a liquid or water, then it is possible that a reaction, either intended or unintended, may occur.
3. *Does any other physical processing of substances occur in your facility?* This could include size reduction, heating/drying, absorption, distillation, screening, storage, warehousing, repackaging, and shipping and receiving.
4. *Are there any hazardous substances stored or handled at your facility?* The Safety Data Sheet (SDS) is a good source of information here.
5. *Is combustion with air the only chemistry intended at your facility?* This includes combustion of common fuels such as natural gas, propane, and fuel oil. Combustion is a special reactive hazard that is handled by separate codes and standards and is not addressed here.
6. *Is any heat generated during the mixing, phase separation, or physical processing of substances?* Heat generation when chemicals are mixed is a prime indication that a reaction is taking place. Note that many chemicals do not release much heat during the reaction; thus, even if limited heat is released, a chemical reaction may still be occurring. Some physical heat effects, such as absorption or mechanical mixing, can also cause heat generation. This heat release, even though not caused by chemical reaction, may increase the temperature and cause a chemical reaction to occur.
7. *Are there any specific reaction hazards that occur?*

Chemical Hazard: Reactive Chemicals

7. Are there any specific reaction hazards that occur?

Pyrophoric and spontaneously combustible: Readily react with the oxygen in the atmosphere, igniting and burning even without an ignition source. Ignition may be immediate or delayed.

Identification: SDS or labeling identifies this as "spontaneously combustible or pyrophoric."

NFPA Flammability rating of 4.

DOT/UN Hazard Class 4.2 (spontaneously combustible solids).

Examples: Aluminum alkyl, Grignard reagent, finely divided metals, iron sulfide, triethyl aluminum.

Peroxide-forming: React with oxygen in the atmosphere to form unstable peroxides.

Identification: Not easily identified as a peroxide former from SDS or other resources.

Examples: 1,3-Butadiene, 1,1-dichloro-ethylene, isopropyl and other ethers, alkali metals.

Chemical Hazard: Reactive Chemicals

7. Are there any specific reaction hazards that occur?

Water-reactive chemicals: Chemically react with water, particularly at normal ambient conditions.

Identification: Usually identified as water-reactive on SDS.

May be identified as DOT/UN Hazard Class 4.3 (dangerous when wet).

May be labeled as "dangerous when wet."

NFPA Special Rating with symbol.

Examples: Sodium, titanium tetrachloride, boron trifluoride, acetic anhydride.

Oxidizers: Readily yield oxygen or other oxidizing gas, or readily react to promote or initiate combustion of combustible materials.

Identification: Identified as an oxidizer on the SDS.

DOT/UN Hazard Class 5.1 (oxidizing agent) or other rating groups.

NFPA Special Rating with symbol OX.

Examples: Chlorine, hydrogen peroxide, nitric acid, ammonium nitrate, ozone, hypochlorites, benzyl peroxide.

Chemical Hazard: Reactive Chemicals

7. Are there any specific reaction hazards that occur?

Self-Reactive: Self-react, often with accelerating or explosive rapidity.

Identification: Generally identified on SDS or labeling as "self-reactive."

NFPA stability or reactivity rating of 1 or higher.

Polymerizing: Monomers combining together to form very large, chain-like or cross-linked polymer molecules.

Examples: Acrolein, ethylene and propylene oxide, styrene, vinyl acetate.

Shock-sensitive: React on impact.

Example: Picric acid.

Thermally decomposing: Large molecules breaking into smaller, more stable molecules.

Rearranging: Atoms in the molecule rearranging into a different molecular structure, such as a different isomer

Incompatible materials: Incompatible materials contacting each other.

Examples: Ammonia-methacrylic acid; caustic soda- epichlorohydrin; acids-bases.

Chemical Hazard: Reactive Chemicals

The easiest way to show graphically the various interactions between chemicals is a **chemical compatibility matrix**

Chemical	Acetic anhydride	Hydrochloric acid solution	Methanol	Sodium hydroxide, solid	Water
Acetic anhydride					
Hydrochloric acid solution	N				
Methanol	C	C			
Sodium hydroxide, solid	N	N	N		
Water	N	C	Y	C	

Key: N: Not compatible

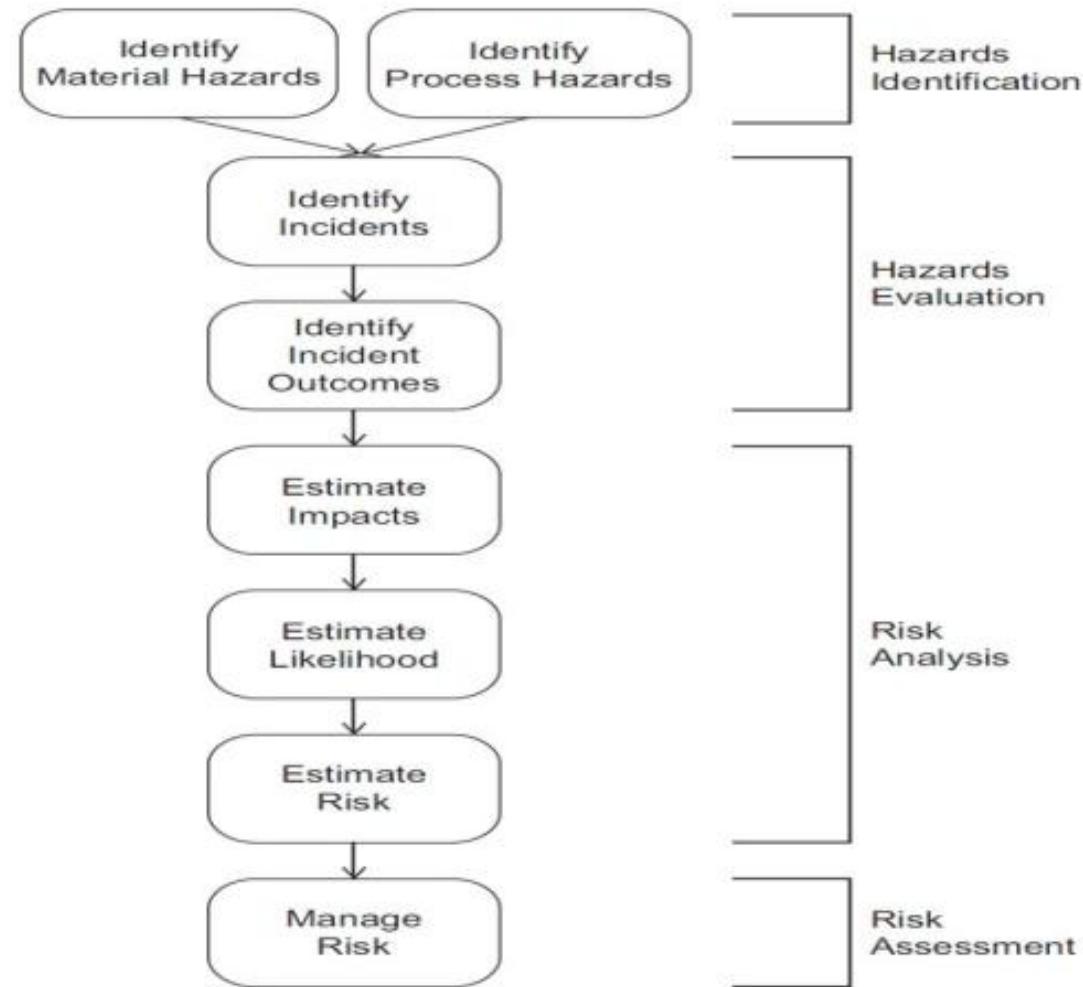
C: Caution

Y: Compatible

- The chemical compatibility matrix considers only binary interactions between two chemicals.
- Binary interactions would be expected during routine operations, while combinations of several chemicals may occur during emergency situations.

Hazards Identification and Evaluation

Major steps in the hazards identification/evaluation and risk analysis/assessment procedures



Hazards Identification and Evaluation

Non-scenario-based methods: Depend on the experience of the review team.

Scenario-based methods employ predictive and analytical techniques to **define specific incident scenarios**.

These methods try to anticipate all relevant “what-if” events.

HAZOP, Fault Tree Analysis, Event Tree Analysis, and Bowtie Analysis

1. Checklist Analysis:

- A **systematic listing** of items, equipment, or procedural steps to be verified and validated.
- Typically covers known best practices, regulatory requirements, and lessons learned.
- Effectiveness depends heavily on how well the checklist is crafted and how thoroughly it is applied.

Hazards Identification and Evaluation

Item	Completed	Does Not Apply	Further Work Required
Layout of process and facilities:			
1. Proper drainage for rainwater and process fluids?			
2. Adequate spacing for access?			
3. Adequate fire protection, i.e. fire walls, dikes, etc.?			
4. Overhead hazards considered?			
5. Proper emergency access and exits?			
6. Adequate headroom in all areas?			
7. Adequate storage space for raw materials and products?			
8. Adequate access for maintenance?			
9. Adequate clearance for overhead power lines?			
10. Adequate lighting for night operation?			
Process			
1. Safety Data Sheets available for all chemicals?			
2. PFDs and P&IDs all up-to-date?			
3. Inherent safety review of process?			
4. Codes and standards reviewed for attainment?			
5. Adequate ventilation for vapors and dusts?			
6. Proper storage for unstable chemicals?			
7. Explosion protection for process equipment?			
8. Process chemistry completely understood?			
9. Reactivity review of all chemistry and chemicals?			
10. Review of hazards due to equipment failures?			
11. Containment / mitigation of all relief discharges?			
12. Containment / mitigation of all process fluid leaks?			
13. Waste disposal for chemical and other wastes?			
14. Review of hazards due to piping or equipment blockages?			
15. Review of consequences of utility failures?			
16. Review of any design revisions?			
17. All electrical equipment meets code requirements?			
18. Safety showers / eye wash stations provided?			
19. All process lines and equipment labelled?			
20. Fireproofing for all structural steel?			
Buildings			
1. All occupied buildings hardened for explosions?			
2. Adequate ventilation in control rooms?			
3. Emergency egress adequate for all occupied areas?			
Piping			
1. All piping designed to code requirements?			
2. Provisions for thermal expansion of liquids?			
3. Hot process lines insulated for burn protection?			
4. All overflow lines discharging to safe areas?			
5. All pipes labelled properly?			
6. Adequate support provided for all pipelines?			
Equipment			
1. Design codes met for all equipment?			
2. Pressure / vacuum rating meets process requirements?			
3. Design basis for all equipment available and up-to-date?			
4. Materials are compatible with chemicals?			
5. Corrosion allowance considered?			
6. Construction materials compatible?			
7. Guards on all rotating equipment and belts?			
8. Isolation provided for equipment maintenance?			
9. Maintenance schedule reviewed and up-to-date?			
10. All equipment labelled properly?			
11. Lockout capability provided?			
12. Management of Change (MOC) review for all equipment replacements?			
Instrument and Electrical			
1. All controls designed for proper fail safe function?			
2. Special interlocks provided?			
3. Emergency standby power provided?			
4. Emergency instrument air provided?			
5. All instruments, electrical systems and process equipment grounded properly?			
Safety Equipment			
1. Fire protection equipment adequate?			
2. Respirators and SCBAs available and maintained?			
3. Fire extinguishing materials compatible with process materials and chemicals?			
4. Personal protective equipment available and maintained?			
5. Gas sampling equipment available?			
6. Flammable vapor detectors installed and in proper locations in process?			
7. Alarm functions properly designed to provide operators with necessary information?			
8. Adequate fire water supply and source?			

- The first column is used to indicate those areas that have been **thoroughly investigated**.
- The second column is used for those items that **do not apply** to the particular plant.
- The last column is used to mark those areas requiring further investigation. (**Further work Required**)

Hazards Identification and Evaluation

2. Safety Review:

A **committee-based** process where plant conditions and operating procedures are reviewed to identify potential hazards.

Draws on team members' experience and knowledge of historical incidents.

Often used for **plant walkdowns** or when a broader perspective on day-to-day operations is needed.

Hazard and Operability Studies (HAZOP)

The objective of a HAZOP is to systematically identify and evaluate scenario-based hazards in a chemical plant and to identify operability problems that could impact plant productivity.

The **HAZOP method** is versatile and can be applied at multiple stages throughout the **process lifecycle**, including:

1. Pilot Plant Phase

1. During early trials or pilot plant operation, HAZOP helps identify and correct design weaknesses before full-scale implementation.

2. Detailed Engineering

1. In the detailed design stage, a HAZOP study verifies that equipment, instrumentation, and control schemes address potential deviations.

3. Routine Operation

1. Periodic HAZOPs can detect new or evolving hazards due to wear, changing operating conditions, and other routine process variations.

4. Process Modification or Plant Expansion

1. Any time the plant undergoes modifications or expansions, HAZOP reassesses the new configuration for hazards and operability issues.

5. Incident Investigation

1. After an incident or near-miss, a HAZOP-type review helps uncover underlying causes and guides corrective actions to prevent recurrence.

Hazard and Operability Studies (HAZOP)

Before beginning a **HAZOP study**, it is essential to gather **comprehensive and up-to-date information** about the process. This ensures the analysis is accurate and that potential hazards or operability issues are not overlooked.

1. Process Flow Diagrams (PFDs)

1. Provide an overview of major equipment and process flows.
2. Help identify high-level process steps and their interconnections.

2. Piping and Instrumentation Diagrams (P&IDs)

1. Show detailed equipment, piping, valves, and instrumentation (e.g., sensors, controllers).
2. Offer critical insights into how each segment of the process is controlled and monitored.

3. Equipment Specifications

1. Document the design and operating limits (e.g., pressure ratings, temperature limits, capacities).
2. Ensure the HAZOP team can assess whether equipment is used within safe and intended parameters.

4. Materials of Construction

1. Helps evaluate compatibility between equipment and process media (e.g., corrosion, erosion).
2. Aids in assessing potential failure modes or long-term integrity issues.

5. Chemical and Process Material Lists (Including SDSs)

1. Identify physical, chemical, and toxic properties of substances in use.
2. Pinpoint possible reaction hazards, fire or explosion risks, and health hazards.

6. Mass and Energy Balances

1. Show flow rates, compositions, and energy flows across the process.
2. Facilitate understanding of where deviations in material or heat could pose hazards.

Key terms commonly used in a HAZOP study

Node

A **node** is a specific location or section in the process where you systematically examine process parameters for potential deviations.

- **Examples of Nodes:**

- A pipeline transferring material between two units
- A specific tank or vessel
- A pump or reactor within the process

Design Intent

The **design intent** describes how the system (or node) is intended to operate under normal conditions. It serves as the reference point against which deviations are identified.

- In **HAZOP tables**, the design intent can be embedded directly or described in a dedicated “Intent” section.

Key terms commonly used in a HAZOP study

Parameter

A **parameter** is any physical or chemical characteristic that describes the process at a given node.

- **Specific Parameters:** Flow, temperature, pressure, level, composition, etc.

- **General Parameters:** Addition, reaction, maintenance, relief, etc.

By analyzing each parameter using guidewords, the HAZOP team identifies possible deviations.

Deviations

A **deviation** is any departure from the normal design intent discovered by applying the guidewords to each parameter at each node.

- **Example:**

- Design Intent: Maintain a temperature of 100°C in a reactor
- Deviation: “Higher Temperature” (i.e., temperature > 100°C)

Key terms commonly used in a HAZOP study

Guidewords:

Guidewords are short, standard terms or phrases (e.g., “No,” “More,” “Less,” “Reverse”) used to systematically explore how a parameter could deviate from its design intent.

•Application Example:

- “More” + “Temperature” ⇒ “Higher Temperature”

Causes

Causes are the underlying reasons why a deviation might occur.

•Examples:

- Equipment failure (e.g., pump malfunction)
- Human error (e.g., incorrect valve operation)
- External events (e.g., power outage, extreme weather)

Consequences

Consequences are the potential impacts or outcomes if the deviation occurs.

•Examples:

- Damage to equipment, loss of containment, product quality issues
- Health, safety, and environmental impacts

Key terms commonly used in a HAZOP study

Safeguards

Safeguards are the existing protective measures, systems, or controls that reduce the likelihood or severity of a deviation's consequences.

- **Examples:**

- Alarms and interlocks
- Pressure relief devices
- Operator training and standard operating procedures

Recommendations

Recommendations are suggested actions to **prevent or mitigate** deviations (or to gather more data if needed).

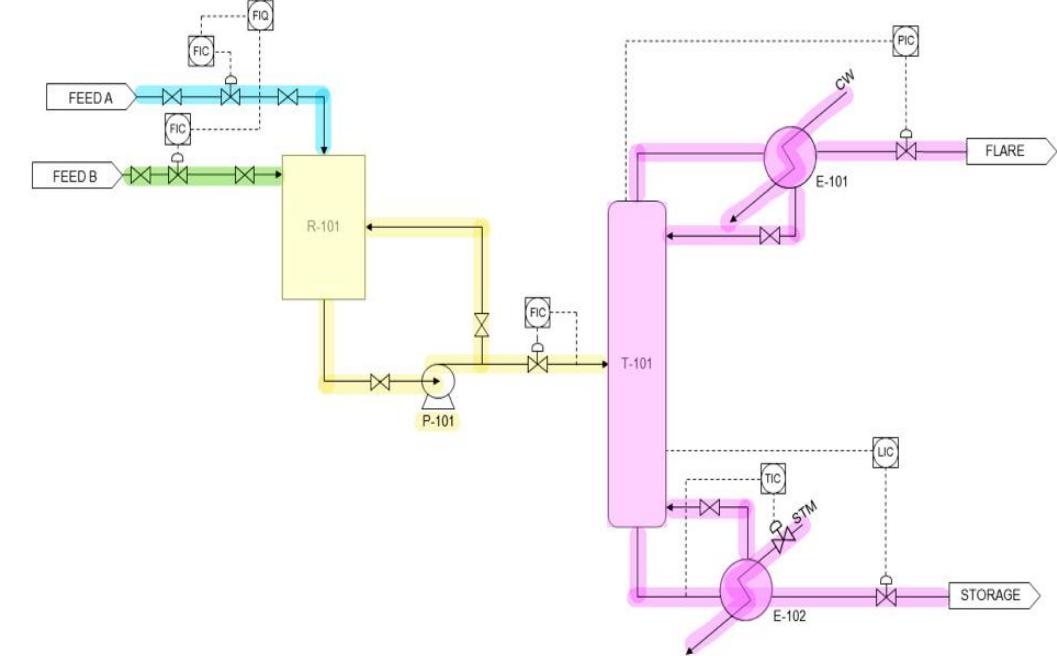
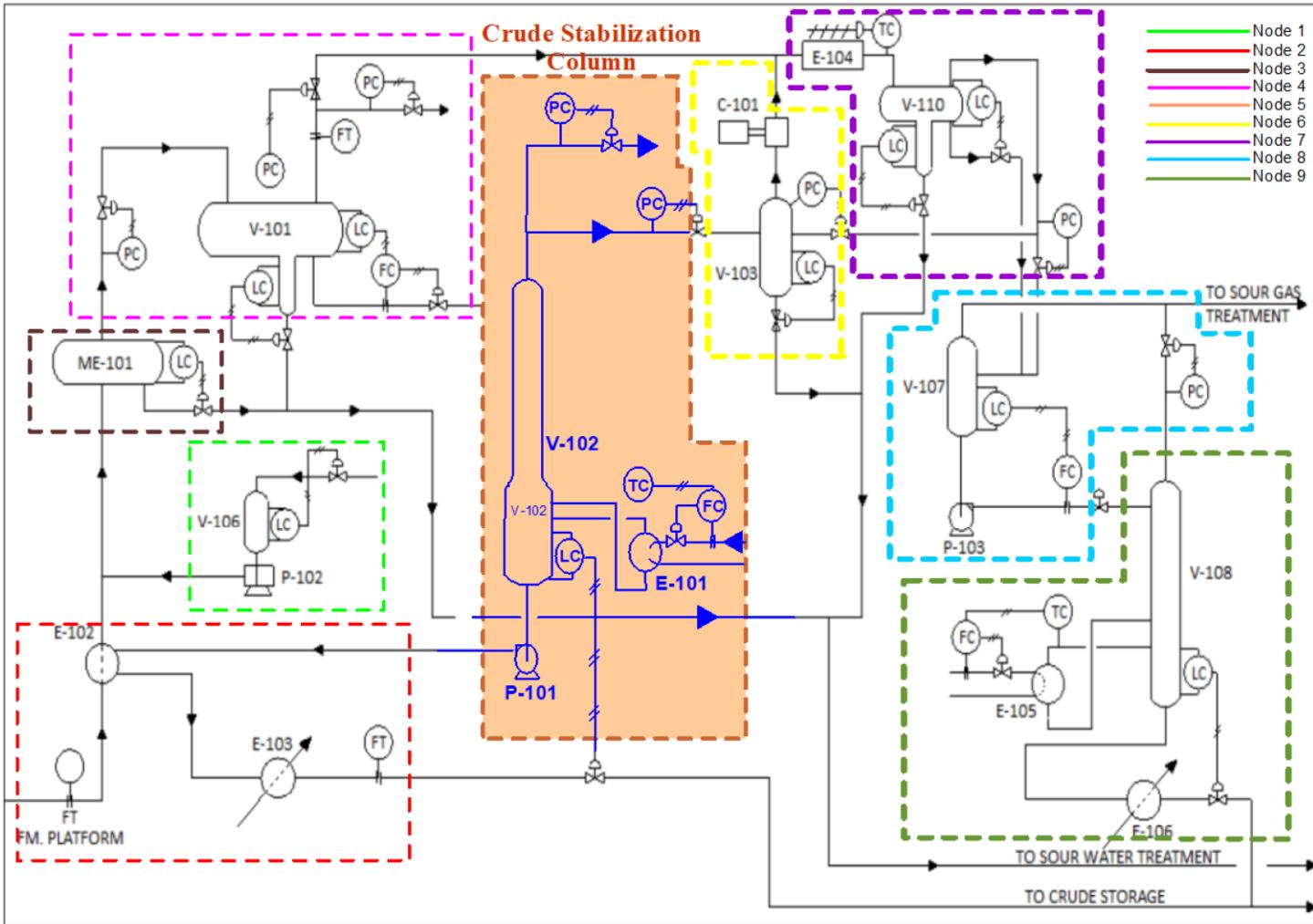
- **Possible Recommendations:**

- Installation of additional instrumentation
- Modification of operating procedures
- Further risk analysis or testing

Steps in HAZOP study

1. **Begin with a detailed flow sheet.** Divide the flow sheet into a number of process units. Thus, the reactor area might be one unit, and the storage tank area another. Select a unit for study.
2. **Choose a study node**, such as vessel, line, or operating instruction.
3. **Describe the design intent of the study node.**
For example, vessel is designed to store the benzene feedstock and provides it on demand to the reactor.
4. **Pick a process parameter:** flow, level, temperature, pressure, concentration, pH, viscosity, state (solid, liquid, or gas), agitation, volume, reaction, sample, component, start, stop, stability, power, or inert.
5. **Apply a guide word** to the process parameter to suggest possible deviations.

Steps in HAZOP study



Hazards Identification and Evaluation

Guide words	Meaning	Comments
no, not, none	The complete negation of the intention	No part of the design intention is achieved, but nothing else happens.
more, higher, greater	Quantitative increase	Applies to quantities such as flow rate and temperature and to activities such as heating and reaction.
less, lower	Quantitative decrease	Applies to quantities such as flow rate and temperature and to activities such as heating and reaction.
as well as	Qualitative increase	All the design and operating intentions are achieved along with some additional activity, such as contamination of process streams.
part of reverse	Qualitative decrease The logical opposite	Only some of the design intentions are achieved; some are not. Most applicable to activities such as flow or chemical reaction. Also applicable to substances—for example, poison instead of antidote.
other than	Complete substitution	No part of the original intention is achieved; the original intention is replaced by something else.
sooner than	Too early or in the wrong order	Applies to process steps or actions.
later than	Too late or in the wrong order	Applies to process steps or actions.
where else	In additional locations	Applies to process locations, or locations in operating procedures.

Steps in HAZOP study

6. If the deviation is applicable, determine possible causes and note any protective systems.
7. Evaluate the consequences of the deviation (if any).
8. Recommend action (what? by whom? by when?).
9. Record all information.
10. Repeat steps 5 through 9 until all applicable guide words have been applied to the chosen process parameter.
11. Repeat steps 4 through 10 until all applicable process parameters have been considered for the given study node.
12. Repeat steps 2 through 11 until all study nodes have been considered for the given section and proceed to the next section on the flow sheet.

Hazards Identification and Evaluation

Valid Guide Word and Process Parameter Combinations for Process Lines

Process parameters	No, not, none	More, higher, greater	Less, lower	As well as	Part of	Rever se	Other than	Sooner, faster	Later, slower	Where else
Flow	x	x	x	x	x	x	x	x	x	
Temperature		x	x					x	x	
Pressure		x	x	x				x	x	
Concentration	x	x	x	x	x		x	x	x	
pH		x	x					x	x	
Viscosity		x	x					x	x	
State				x				x	x	

Note: x's represent valid combinations.

Hazards Identification and Evaluation

Valid Guide Word and Process Parameter Combinations for Process Vessels

Process Parameters	No, Not, None	More, Higher, Greater	Less, Lower	As Well As	Part of	Reverse	Other Than	Sooner, Faster	Later, Slower	Where Else
Level	X		X	X	X		X	X	X	X
Temperature			X					X		X
Pressure		X		X				X		X
Concentration	X	X	X	X	X		X	X	X	
pH		X	X					X		X
Viscosity		X	X					X		X
Agitation	X	X	X		X	X		X		X
Volume	X	X	X	X	X			X	X	X
Reaction	X	X	X				X	X	X	
State				X			X	X		X
Sample	X			X	X		X	X		X

Note: x's represent valid combinations.

Hazards Identification and Evaluation

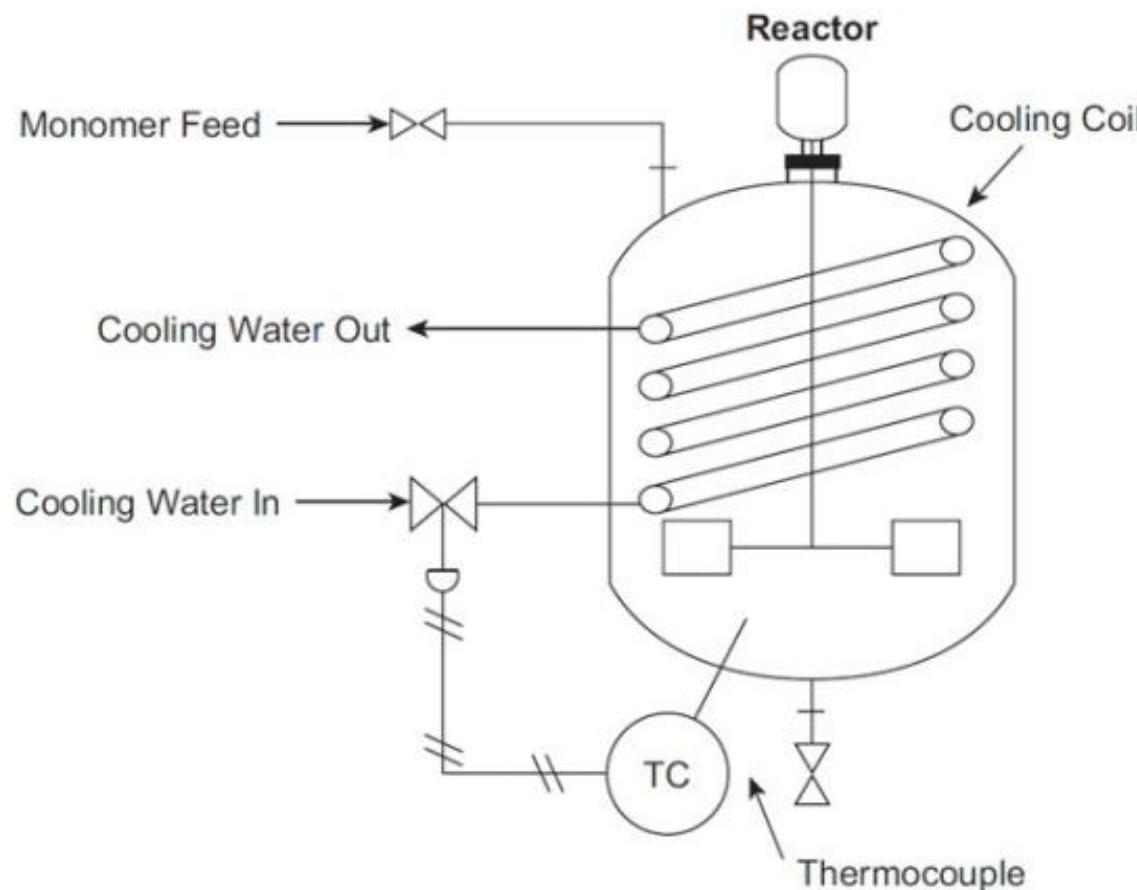
HAZOP Deviations for Different Guidewords and Parameters

Guidewords							
Parameters	More	Less	None	Reverse	Part of	As well as	Other than
Flow	High Flow	Low Flow	No flow	Backflow			Loss of containment
Pressure	High pressure	Low pressure	Vacuum		Partial pressure		
Temperature	High temperature	Low temperature				Cryogenic	
Level	High level	Low level	No level				Loss of containment
Reaction	High reaction rate	Low reaction rate	No reaction	Reverse reaction	Incomplete reaction	Side reaction	Wrong reaction

Steps in HAZOP study

Consider the reactor system shown below.

Perform a partial HAZOP study on this unit to improve the safety of the process.



Safety Strategies, Procedures, and Designs

Process Safety Hierarchy

- (1) Human factors,
- (2) Managing safety using the CCPS 20 elements of risk-based process safety (RBPS)
- (3) Incident investigations

Safety Strategies, Procedures, and Designs

Human Factors

Operators sometimes make mistakes, and the consequences of those errors may be serious.

A few issues related to human factors include the following:

- Ergonomics: Can the operator reach what needs to be reached to work safely?
- Operability: Is the workflow designed to minimize taking shortcuts?
- Procedures: Are the procedures clear and easy to follow, and do they clearly explain the consequences of deviations?
- Maintenance: Is there access and capability to maintain equipment?
- Simplify: Are the equipment designs, computer operating screens, operating procedures, safety instructions, safety requirements, and so forth, designed to facilitate comprehension and understanding to minimize hazards and risks?

Operators make fewer errors when they are appropriately trained, not under stress, not fatigued, and not overloaded with work; when they have enough time for the task; and when they receive active feedback

Safety Strategies, Procedures, and Designs

Managing Safety

The 20 elements provide guidance on how to

- (1) Design a process safety management system,
- (2) Correct a deficient system
- (3) Improve process safety management practices.

Safety Strategies, Procedures, and Designs

Incident Investigations

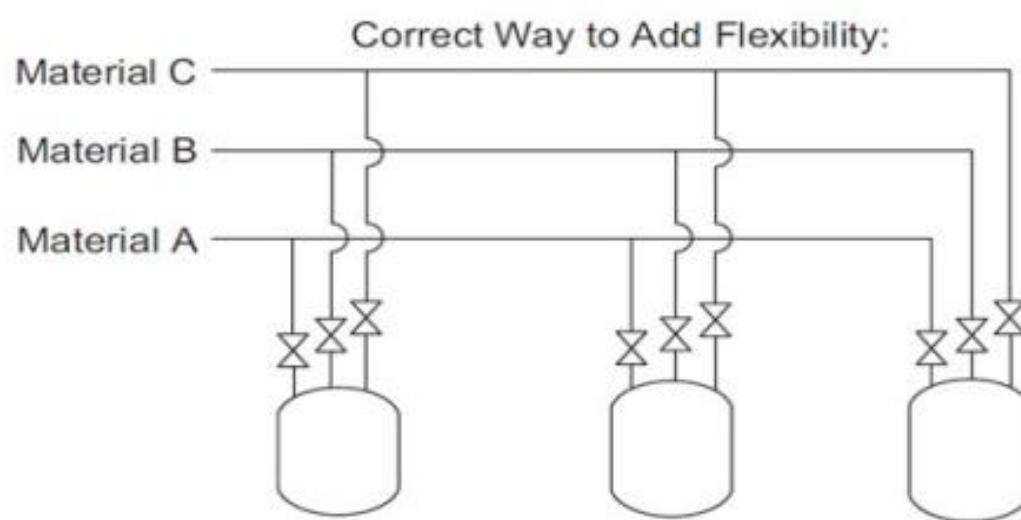
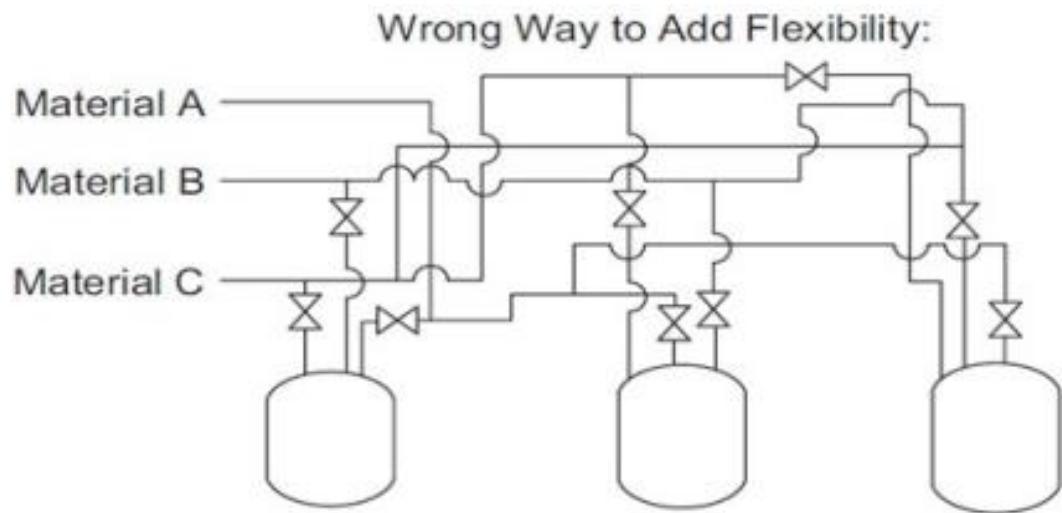
It must include

- (1) a formal process for investigating incidents, including staffing, performing, documenting, and tracking investigations.
- (2) a method to identify incidents that are recurring

Designs for Process Safety

Inherently Safer Designs

A simple design feature includes the mechanical configurations of vessels, pumps, and pipelines.

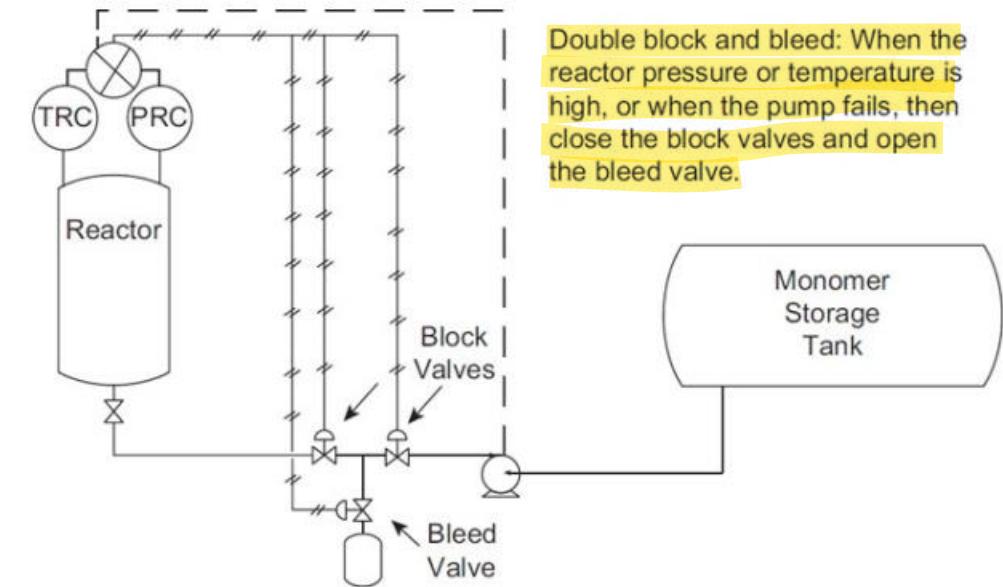


Designs for Process Safety

Controls: Double Block and Bleed

Normal Operation:

- Monomer is pumped from the **monomer storage tank** (low pressure) to the **reactor** (high pressure).
- The monomer flow is controlled and continuously monitored for **temperature (TRC)** and **pressure (PRC)**



Abnormal/Fault Conditions:

If the **monomer pump fails**, the **reactor (high pressure)** could push contents **back into the storage tank**, carrying **catalysts** that could:

- Cause an **uncontrolled polymerization reaction** inside the storage tank,
- Lead to **runaway reactions** or even **explosions**, as the tank is not designed for that.

Designs for Process Safety

Controls: Double Block and Bleed

Block Valves Close

→ Prevent flow from reactor to tank and from tank to reactor.

Bleed Valve Opens

→ Releases any residual pressure or leaks between the block valves to a safe vent or containment.

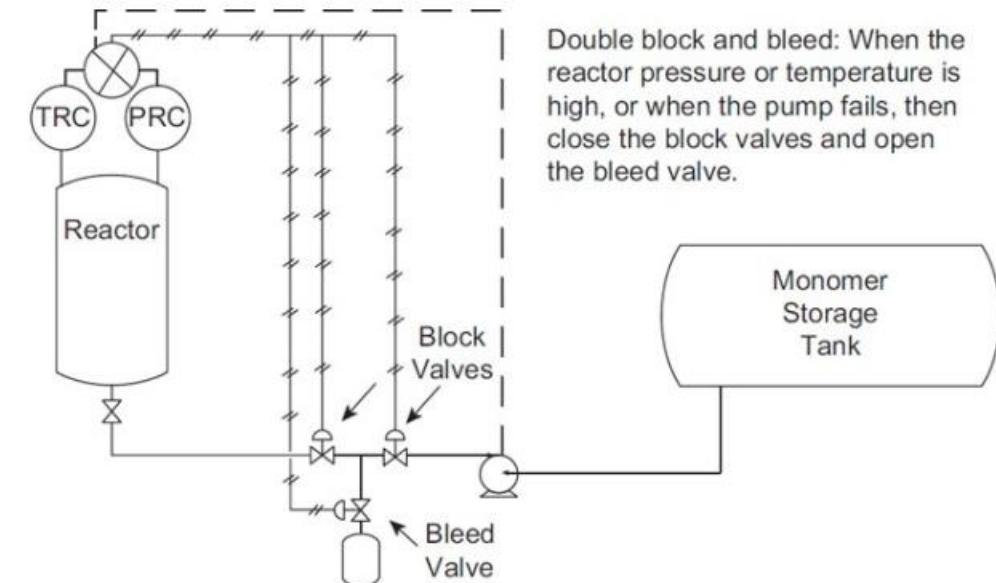
No possible backflow

→ Even if one valve leaks, the second valve and bleed mechanism ensure containment.

Check valves allow flow in only one direction, but:

- They can leak under pressure,

- Not reliable for critical safety applications,



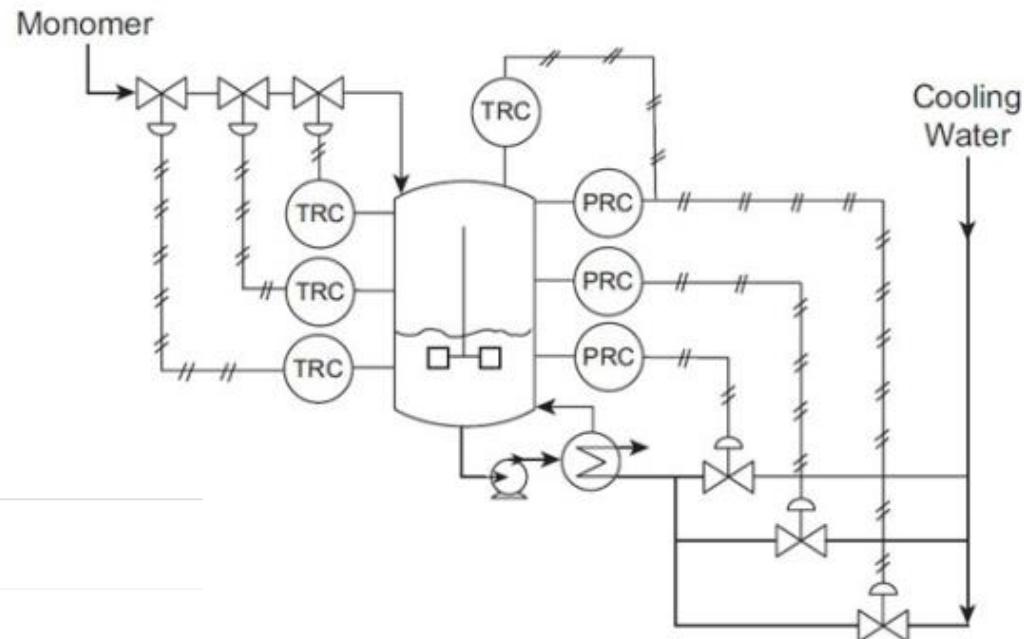
Designs for Process Safety

Controls: Safeguards and Redundancy

This is a **safety-critical reactor system** where:

- Monomer is fed into a reactor.
- Reaction is **highly exothermic**.
- Cooling is essential to maintain temperature within safe limits.
- Several layers of **redundant sensors and controls** are employed.

Component	Symbol	Description
TRC	Temperature Recorder/Controller	Measures and controls reactor temperature
PRC	Pressure Recorder/Controller	Measures and controls reactor pressure
Pump	✓ (bottom center)	Circulates reactor contents through heat exchanger
Heat Exchanger	□	Removes heat using cooling water
Monomer Feed System	Multiple valves + TRCs	Introduces monomer through double block and bleed valves
Cooling Water Lines	Right side of image	Supplies cooling to the heat exchanger



Designs for Process Safety

Controls: Safeguards and Redundancy

Safety Logic and Control Actions

Failure Condition

🔥 Temperature too high (TRC)

Automatic Actions Triggered

- Open cooling valves to increase heat removal
- Close monomer valves to stop feed
- Activate double block & bleed

📈 Pressure too high (PRC)

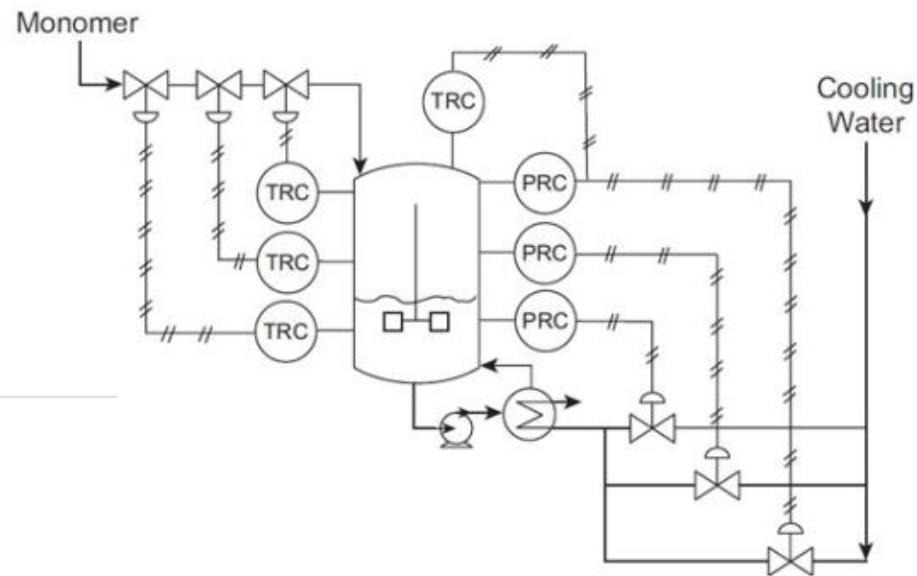
- Same as above

✗ Agitator or pump failure

- Same: open cooling, close monomer, activate DBB

✗ Heat balance off

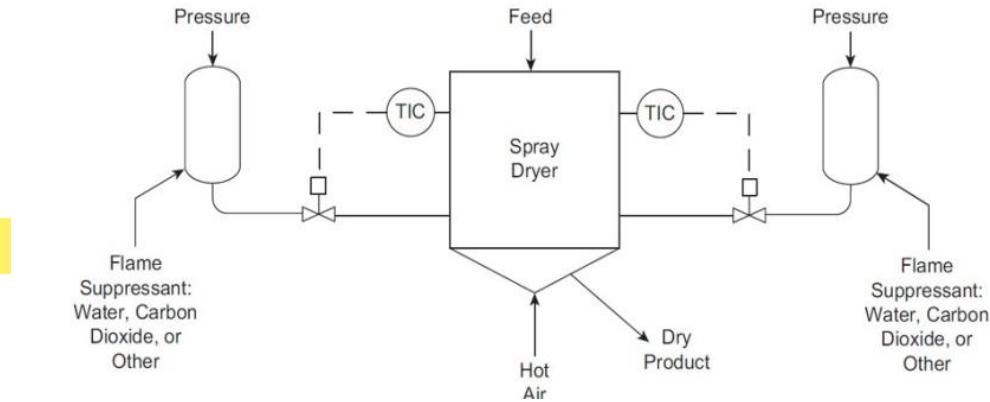
- Indicates exothermic reaction not matched by cooling → same



Designs for Process Safety

An explosion suppression system:

- Detects the flame or pressure rise at the incipient phase of an explosion.
- Instantly releases a flame suppressant (like water, CO₂, or powder) into the system.
- Prevents full-scale explosion, equipment damage, and fire spread.



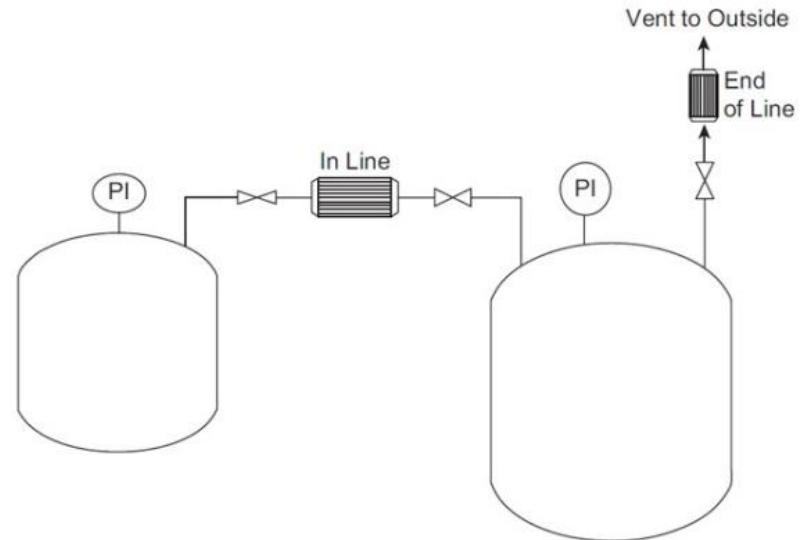
Working Principle in Spray Dryer Setup

Location	Function
🔥 Spray Dryer	A high-risk zone for dust explosions due to fine particulates + hot air
⚠ Detection System	Connected to TICs to monitor sudden temperature rises
⚡ Pressurized Tanks	Contain flame suppressant at both ends to flood system immediately
🔒 Valves	Automatically triggered by flame or pressure spike detection
🚫 Flame Arrest	Prevents propagation to connected equipment or pipes

Designs for Process Safety

A. In-Line Flame Arrestor (Between Two Tanks)

- **Location:** Between two vessels.
- **Function:** Prevents fire/explosion from one tank from traveling through the pipe to the **second tank**.
- **Typical Use:** Process connections or liquid transfer lines.
- **Design:** Bi-directional (stops flame in either direction), must be rated for pressure and flow.



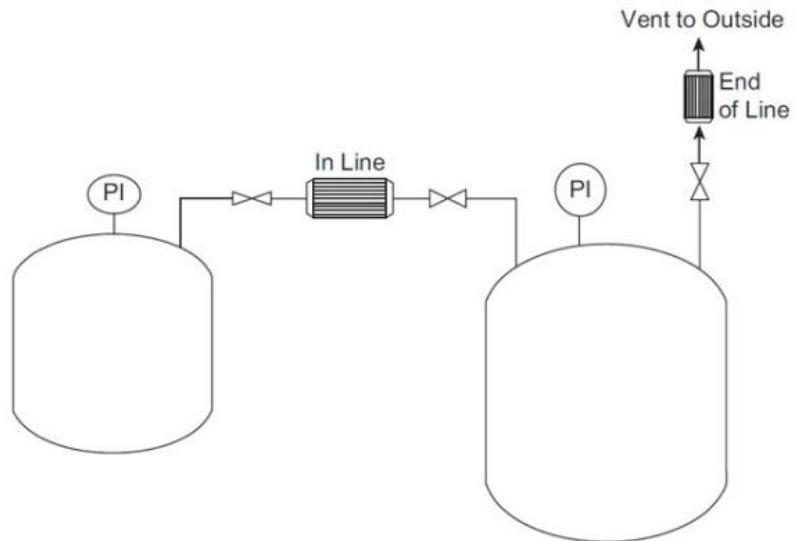
B. End-of-Line Flame Arrestor (Vent to Atmosphere)

- **Location:** At the **end of a vent line** (open to outside atmosphere).
- **Function:** Prevents **external fire** (e.g., wildfire or open flame near vent) from propagating **into the vessel**.
- **Typical Use:** Storage tanks venting flammable vapors.
- **Design:** Typically unidirectional, designed for low back pressure.

Designs for Process Safety

How the System Works

PI (Pressure Indicator)	Monitors pressure in both vessels
Check Valves (◀ ▶)	Prevent backflow, ensure controlled direction of fluid
In-Line Flame Arrestor	Prevents fire spread from one tank to another
End-of-Line Flame Arrestor	Prevents external flames from igniting vapors in the tank via vent
Vent to Outside	Safely directs pressure/vapors to open atmosphere



Why This Is Important

Flammable materials stored in tanks pose a **significant fire/explosion risk**.

Fire originating from **one source or outside the plant** can travel through lines and cause **chain explosions**.

Flame arrestors **protect assets and personnel**, and ensure compliance with **fire safety codes** (e.g., NFPA, OSHA).