Engineering Risk Management
Lecture 3

Process safety

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Chemical industry: perception?

Chemical industry: perception!

Why? - Safety and Security Concerns

- **Prudence due to industrial activities** should be present in every industry, and certainly also in the hazardous materials using industries
- **Characteristics of chemicals using industries**: use of hazardous materials, existence of chemical industrial parks, license to operate/acceptability linked with reputation, high uncertainties linked with debatable opinions
- **The Netherlands & Belgium:** densely populated areas combined with highly concentrated chemical industrial activities
- The Rotterdam & Antwerp Port Areas are part of the **"ARRRA"** and are extremely important for the Dutch (/Belgian/German/European) economies

The “Delta Region” in Europe

Belgian Seveso Industry (1)

~400 "Seveso" Companies

~200 Upper tier
~200 Lower tier

Concentrations:

Antwerp

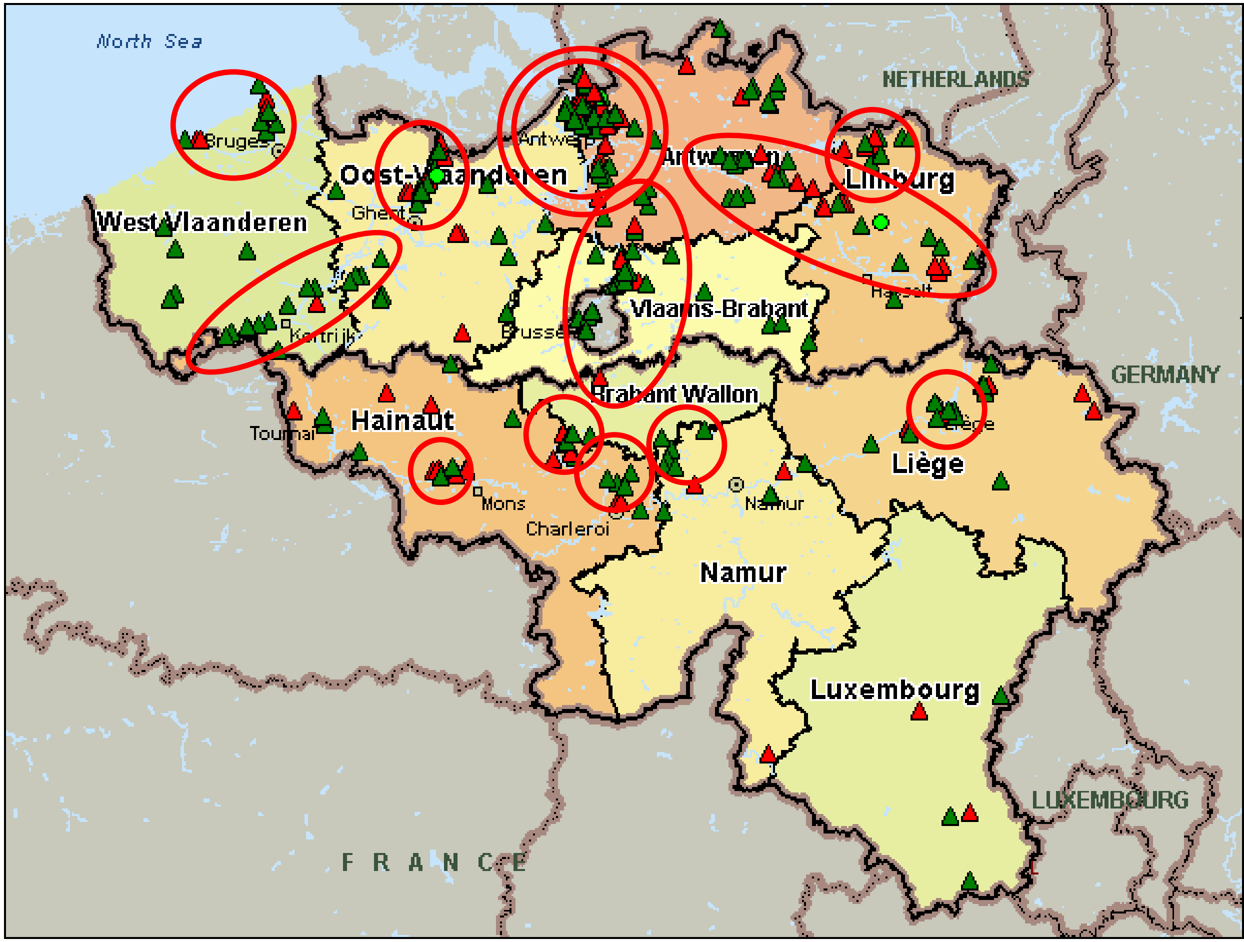
Ghent-Coast

Kortrijk

Mechelen-Brussel

Albert Channel - Lommel

Mons – Feluy - Charleroi - Liège



Belgian Seveso Industry (2)

Antwerp

Largest European chemical and petrochemical complex

“second to Houston”

The Antwerp Harbour

PROCESS RISKS ?

Process installations

- Unique composition of unit operations:
  - Pressure vessels
  - Storage tanks
  - pipelines
  - Pumps, compressors
  - Heat exchangers
  - Chemical reactors
  - Distillation towers ….

- Typical dangers
  - Chemical substances (at certain pressures and temperatures)
  - Chemical reactions

Definition Process safety

- CCPS – Center for Chemical Process Safety

Is a **discipline** aimed at the **prevention and mitigation of fires, explosions and accidental releases** of **chemicals in process installations**. It is not about the well-known personal safety issues (occupational safety).

Process safety is a blend of engineering and management characteristics focusing on the prevention of catastrophic accidents such as explosions, fires and toxic releases, due to the use of chemicals and petroleum derivates.

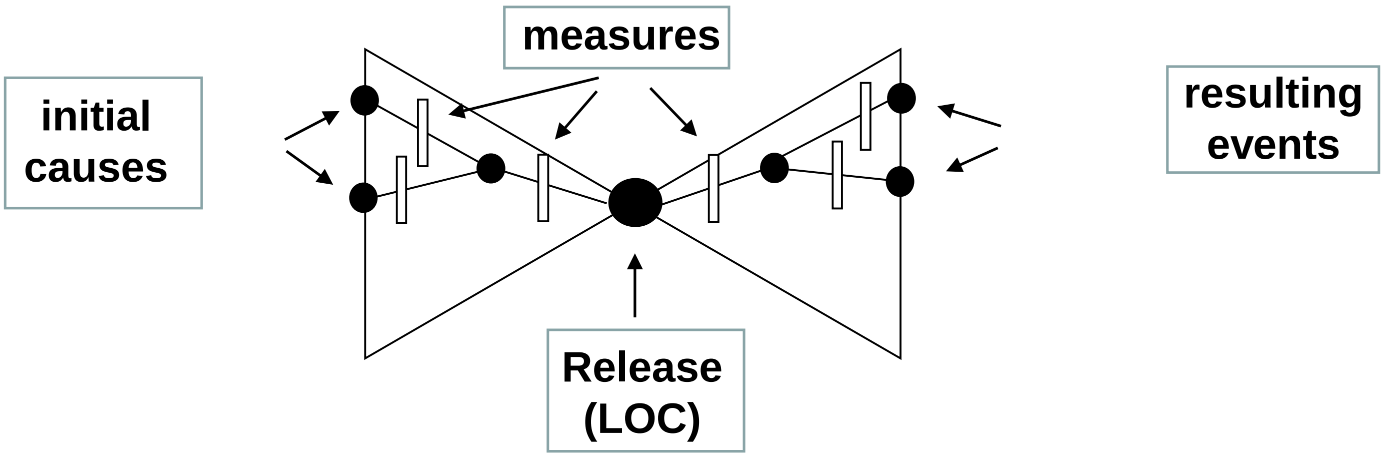
Process safety incident

- A sudden or unexpected event, in which chemicals or petroleum derivates are involved or within a (petro)chemical installation, that resulted, or **had the potential to result** in a release of a hazardous material.
  Such incidents may cause toxic effects, fires or explosions and may lead to serious injuries, fatalities, environmental damage, damages to the installation and product loss.

- Process safety incidents may happen as a result of the operation of the installation under normal, abnormal or transient conditions or due to activities taking place within the installation (maintenance, construction, pipework, ...)

Process safety

- Twofold objective
  - Prevention of unwanted releases of substances and/or energy (Loss Of Containment or ‘LOC’) from process installations
  - Limitation of the consequences
- Visual representation in the bow-tie model:



What is specific about process safety?

Process safety – some characteristics

- HILP (large uncertainties)
- Process safety is difficult to measure
- Process safety is difficult to observe
- Process safety delivers the ‘license to operate’!

HILP

- Own employees, surrounding communities, financial/economic, reputation, license to operate (industry)
- Chemical disasters are rare
- Danger of complacency (habituation and denial of risks ("We work so long without any accident now")
- Probabilities are difficult to quantitatively estimate
- Cost-benefit analysis is difficult
- Large prevention investments for technical safety measures that (hopefully) will never have to work

Difficult to measure

- Occupational accidents (type I) are no measure of process safety (type II)

- Measurement of process safety via "indicators" (process safety indicators providing a proxy of reality) is difficult

- Importance of safety culture
  - Focus on minor shortcomings, besides evident matters
  - Strong respons on weak signals
  - Typical for so-called "High Reliability Organisations"

Difficult to observe

- Problems with installations only in a limited way visually observable

- Behaviour of engineers, technicians, management … in design, maintenance, exploitation, …of installations of crucial importance, but very hard to observe → importance of safety culture

Process safety delivers the ‘license to operate’!

Some iconic accidents that influenced the ‘license to operate’ in the past:

- Seveso (1976)
- Bhopal (1984)
- Chernobyl (1986)
- Macondo well (Deepwater Horizon) (2010)
- Fukushima (2011)

MOVIE

- Movie Bhopal disaster!

PROCESS SAFETY LEGISLATION/ MGT/ INSPECTION in Europe?

Seveso (III) legislation

"Lower tier" (Low tier) companies and "Upper tier" (Top tier) companies: obligations:

- **Lower Tier:** prevention policy, prevention policy document, safety management system, inspection at least every 3 years

- **Upper tier:** prevention policy, prevention policy document, safety management system
  + safety report, scenarios of major accidents, internal emergency plan, QRA calculations (IR, SR), actualized list of substances, environmental risk assessment, inspection at least every year

Performance monitoring, internal audit, accident & incident investigations, knowledge management

Design and construction
Inspection and maintenance
Risk analyses reviews

Process installations + infrastructure

Staffing level mgt
Instructions
Training & educat.
Alarm management
PPE

Operational personnel

Working permit system
Organisation of turnover & shutdowns

Carry out operations and work (a.o. contracting)

Identification of emergency scenarios
Inspection and maintenance
Instruction + training

Emergency plan

Background of process safety: <u>Observable</u> causes of LOCs

- Deviations (due to defects in equipment or due to errors of operators)
- Degradation of 'containments'

} Risk analysis (of installation)

- Carrying out tasks

} Risk analysis (of tasks)

- Design errors
- Construction errors
- Maintenance errors
- Errors at commissioning and decommiss.

} Mgt systems for design, maintenence and inspection, exploitation

Consequences of LOC: highly uncertain

- LOC
  - Where in the installation? Size of leak?
  - Duration of leak?
  - Difficult to determine probability
- Loss of Containment of inflammable substances
  - Formation of explosive atmosphere? (conditions of ventilation?)
  - Ignition source(s)?
  - Overpressure outcome or flash fire?
  - Effects of overpressure on buildings?
  - Presence of people?
  - Protection?
  - Domino-effects?

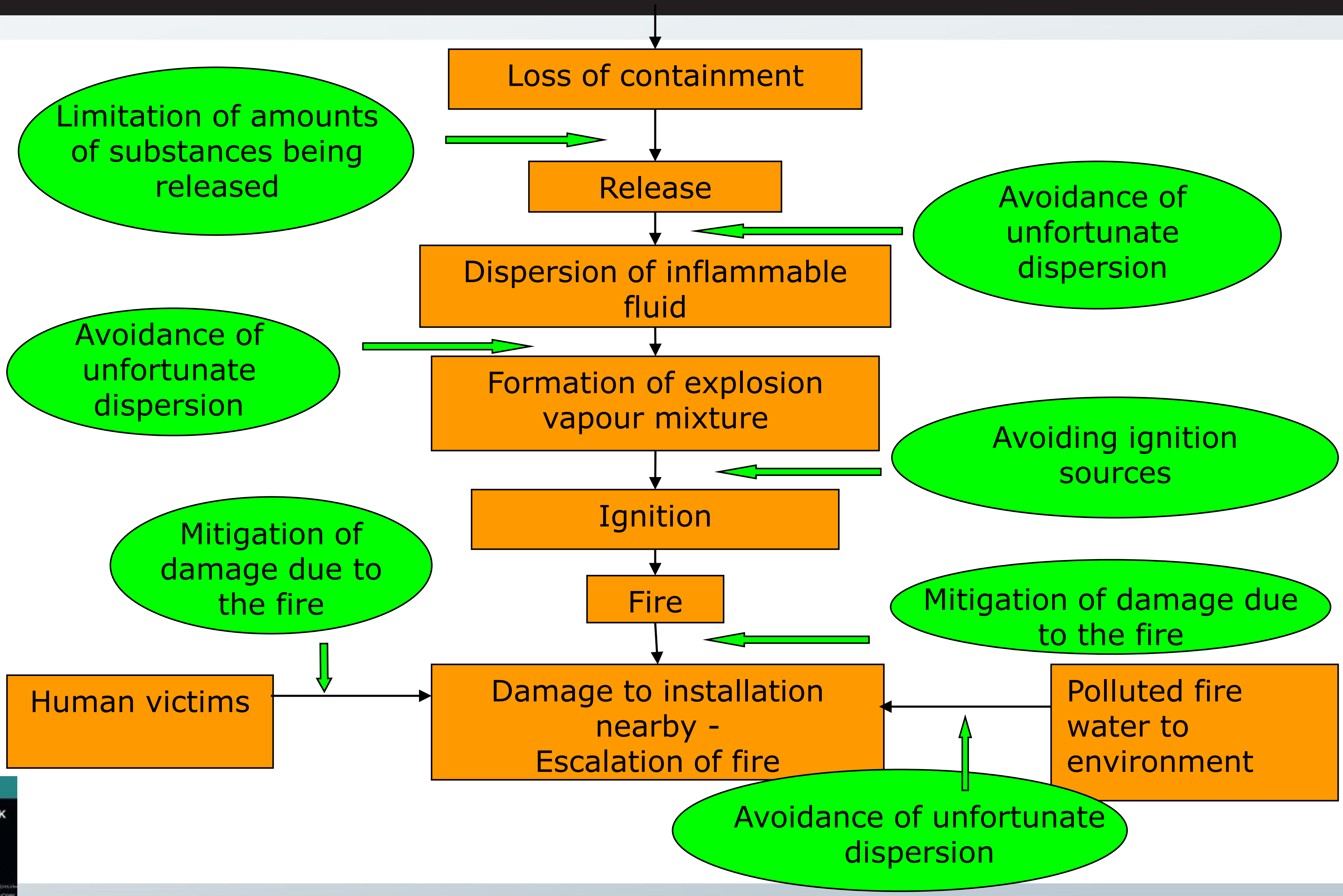
Consequences of LOC: highly uncertain

- Release of toxic substance
  - Formation of cloud?
  - Concentration within cloud?
  - Dispersion of the cloud?
  - Presence of people?
  - Possibilities of evacuation?
  - Uncertainties regarding dose-response

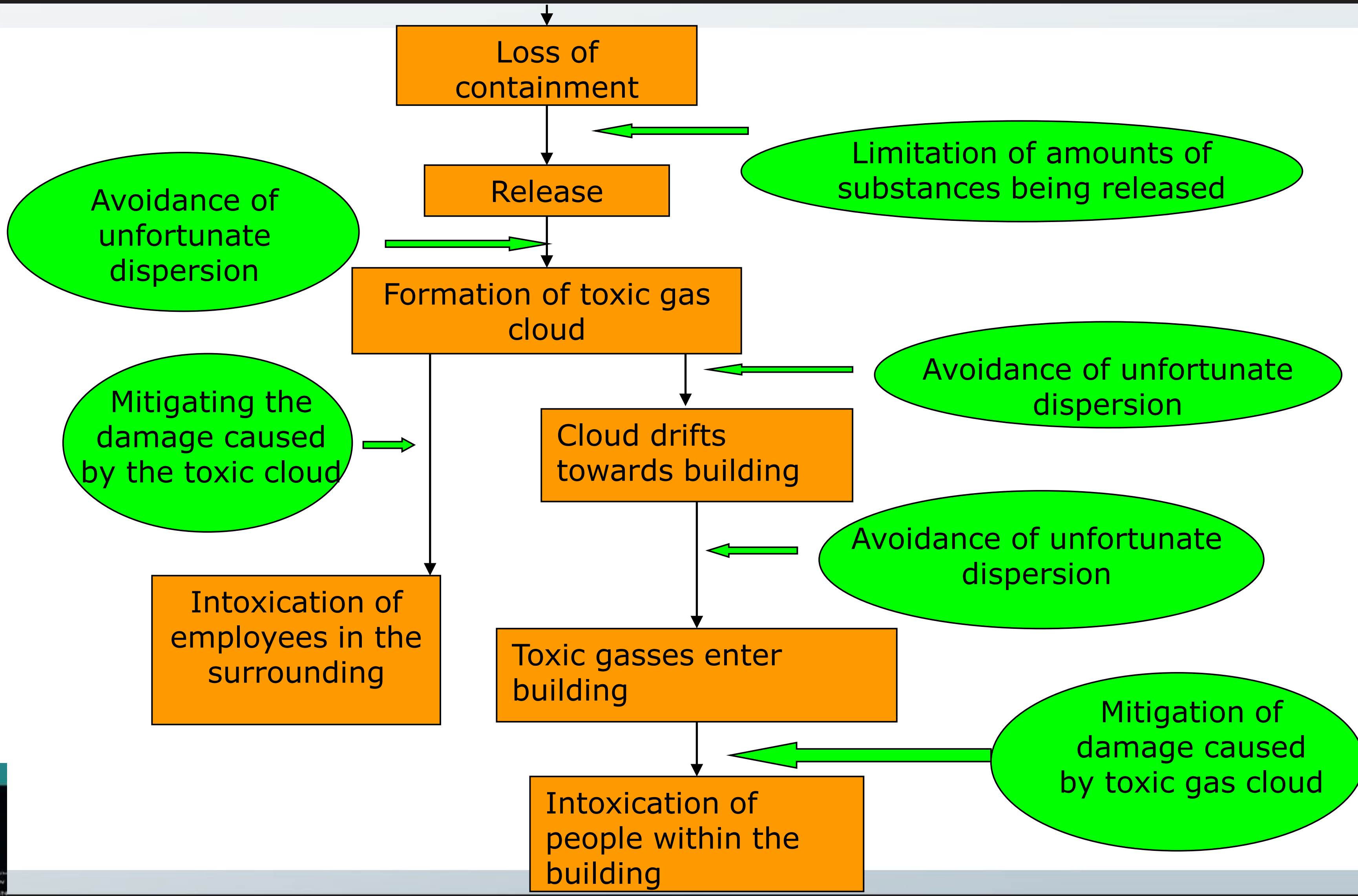
Control of process risks

- Basic principle: multiple “barriers”
  - Literature: “protection layers”, “swiss cheese”
  - No ‘trade off’ prevention – mitigation
- Types of “barriers” or “safety functions”
  - 8 strategies to intervene in the chain of events
- Separate study of every safety function
  - Separate evaluation criteria
    - Preventive: rather risk-based
    - Mitigation: rather hazard-based
  - Every study requires specific expertise
  - Corresponds to existing industrial practice

Control of process risk scenarios (due to inflammable liquids)



Control of process risk scenarios (due to toxic substances)



Safety functions

Prevention

- Control of process deviations
- Control of degradation of containment

Mitigation

- Limitation of releases
- Control of the dispersion of released substances
- Avoidance of ignition sources
- Mitigation of damage due to the fire
- Mitigation of damage due to explosion
- Avoidance of damage due to toxic gas clouds

Process deviations

- Process deviations are deviations from the ‘normal’ process operation
- Normal operation is characterized by
  - The control system
    - Directs the process: automatic (DCS) or manually (operators)
    - Defines an ‘operational window’: ‘normal’ values of process parameters
  - The ‘containments’:
    - Keep substances and energy enclosed (pipework, pressure vessels, storage tanks, pumps, etc.)
    - Are able to withstand ‘normal’ process conditions (pressure, temperature, corrosive substances, …)
    - Are able to withstand ‘normal’ external influences (wind, ice, …)

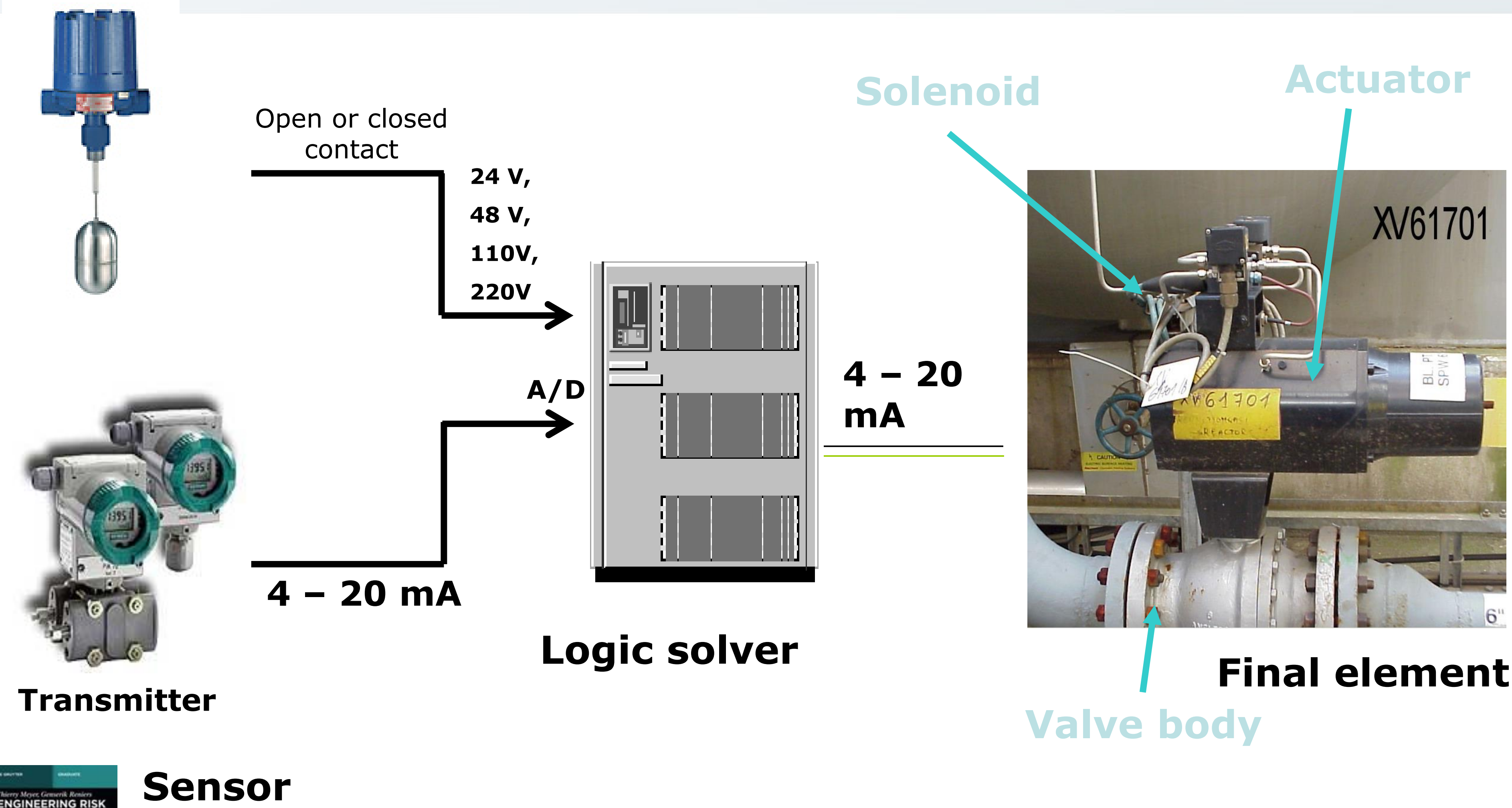
Risks of process deviations

- Undesired loss of containment of substances and/or energy:
  - By surpassing design boundaries of the containments
    - Too high or too low pressure, temperature, …
  - By breaking through in outgoing streams/flows
    - Eg. Flowing out of atmospheric tank in case of overfilling (Buncefield)
    - Eg. Flowing out of dangerous gasses from scrubber (Bhopal)
    - Eg. Flowing out in case of draining
  - By undesired opening of installation
    - Uncoupling of (filled) flexibles
    - Opening of installation part for adding products

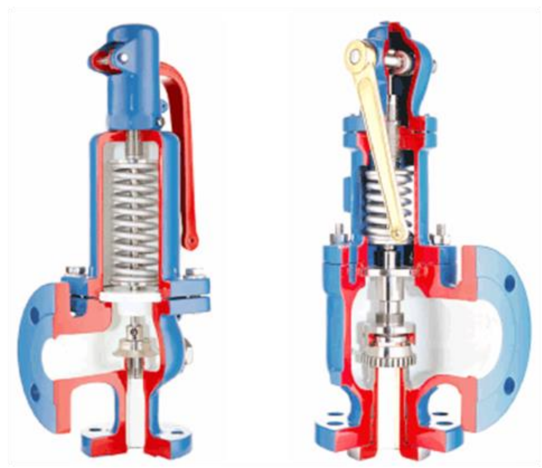
Measures to control process disturbances

- Containments that are able to withstand abnormal forces/load
  - For disturbances/deviations that lead to surpassing the design enveloppe / design boundaries
  - ‘Inherent safety’ (if control of degradation)
  - Economics plays a role
- Preventive active (safety)measures:
  - Instrumental safety (SIF: safety instrumented functions)
    - Automatic actions or locks
  - Mechanical pressure relief
    - Safety valves, rupture discs, explosion hatches
  - Corrective human behavior/handling
    - Human actions based on alarm(s)

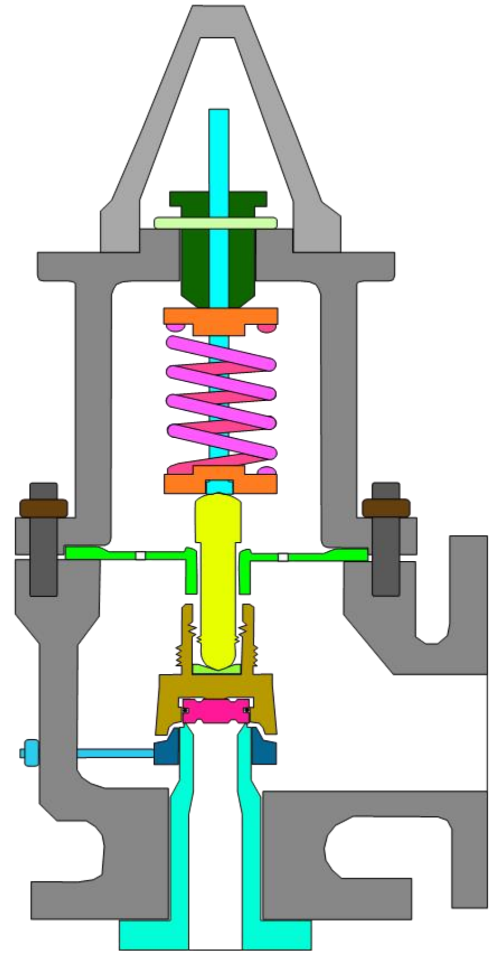
Instrumental safety (SIFs)



Safety valves (with springs)

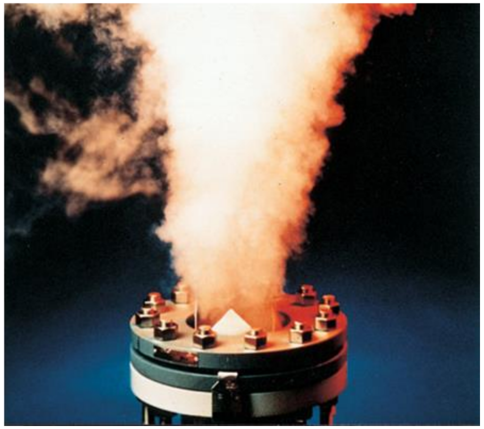


Safety valves (with springs)



Rupture discs

Rupture discs



Approach to control process deviations

- Identify the need for measures
  1. Type-deviations and type-measures for type-installation parts
     - Checklists
       - E.g. Design solutions for equipement failures (CCPS)
       - E.g. Process safety in batch reactor systems (IChemE)
     - Risk assessment methods such as Planop (www.planop.be)
  2. Identify 'rest' risks of deviations
     - Use a structured/systematic risk assessment method (e.g. HAZOP)
  3. Use risk evaluation techniques
- Specify measures in detail + implement

Type-measures for type-installation parts

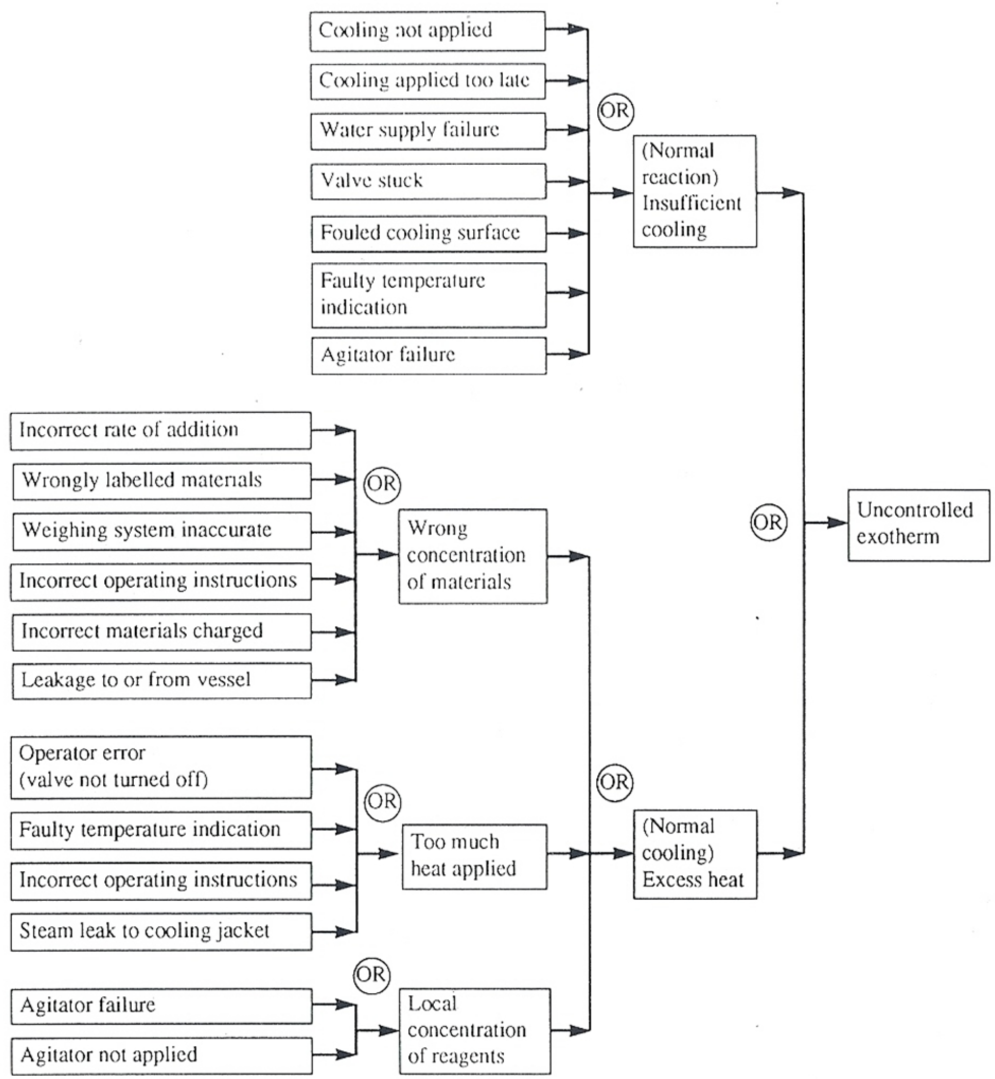
- “Design solutions for equipment failures” (CCPS)
  - Contains tables with typical deviations and typical measures for the following types of installation parts:
    - Vessels
    - Reactors
    - Mass transfer equipment
    - Heat transfer equipment
    - Dryers
    - Fluid transfer equipment
    - Solid-fluid separators
    - Solids handling and processing equipment
    - Fired equipment
    - Piping and piping components

Example (excerpt) of table from “Design solutions for equipment failures” (CCPS)

TABLE 4. FAILURE SCENARIOS FOR REACTORS

No.	Operational Deviations	Failure Scenarios	Potential Design Solutions: Inherently Safer/Passive	Potential Design Solutions: Active	Potential Design Solutions: Procedural
1	Overpressure (Batch, Semi-batch, and Plug Flow Reactors)	Overcharge of catalyst resulting in runaway reaction	• Use dedicated catalyst charge tank sized to hold only the amount of catalyst needed • Vessel design accommodating maximum expected pressure • Use different type of reactor	• Emergency relief device • Pressure or temperature sensors actuating bottom discharge valve to drop batch into a dump tank with diluent, poison or short-stopping agent, or to an emergency containment area • Automatic addition of diluent, poison, or short-stopping agent directly to reactor • Limit quantity of catalyst added by flow totalizer	• Procedural controls on the amount or concentration of catalyst to be added • Manual activation of bottom discharge valve to drop batch into dump tank with diluent, poison, or short-stopping agent, or to an emergency containment area • Manual addition of diluent, poison, or short-stopping agent directly to reactor • Intermediate location for pre-weighed catalyst charges
2	Overpressure (Batch and Semi-batch Reactors)	Addition of a reactant too rapidly resulting in runaway reaction	• Limit delivery capacity of feed system to within safe feed rate limitations (e.g., screw feeder for solids or flow orifice for liquids) • Vessel design accommodating maximum expected pressure • Select feed system pressure characteristic so that feed cannot continue at reactor overpressure • Use different type of reactor	• Temperature or pressure sensor interlocked to a shutoff valve in the feed line • Emergency relief device • Pressure or temperature sensors actuating bottom discharge valve to drop batch into a dump tank with diluent, poison or short-stopping agent, or to an emergency containment area • Automatic addition of diluent, poison, or short-stopping agent directly to reactor • High flow shutdown alarm and interlock	• Manual addition of diluent, poison, or short-stopping agent directly to reactor • Manual shutdown on high flow alarm • Manual activation of bottom discharge valve to drop batch into dump tank with diluent, poison, or short-stopping agent, or to an emergency containment area • Procedural controls on concentration of reactants

General Failure Tree for overpressure in reactor from “Chemical reaction hazards” (IChemE)



Use of evaluation techniques

- How many protection layers are necesssary?
  - For instance scenarios of overpressure
    - A safety valve?
    - A SIF + a safety valve…?

- Evaluation techniques (for process deviations)
  - Risk matrix
  - LOPA: Layer of Protection Analysis

- Prevention of loss of containment by degradation

Degradation of containment

- ‘Slow’, irreversible damage of containment
- Slow:
  - To be followed-up by inspections, monitoring, …
  - Very sudden degradation => to be considered as process disturbance
- Damage:
  - Decreasing wall thickness (local or general)
  - tears, hydrogen embrittlement, prolapse
- Irreversible:
  - Risk of loss of containment (leak, rupture, …) increases with time
  - Until reparation or replacement

Degradation phenomenon

- Decrease of wall thickness
  - Internal corrosion
    - By substances present, sediments
    - Differential aëration (at the level of the liquid level)
  - Erosion
    - Cavitation
    - High liquid velocities (curves, narrowings)
    - Presence of particles
  - Erosion-corrosion
    - The protective corrosion layer disappears due to erosion
  - External corrosion
    - underground corrosion
    - Exposure to atmospheric conditions
    - Corrosion under isolation (rain water and condens in contact with steel)

Degradation phenomenon

- Formation of tear
  - Stress corrosion cracking
- Degradation by hydrogen
  - Hydrogen embrittlement
  - Hydrogen blistering
- Creep
  - By (very) high temperature
- Fatigue
  - By cyclic load/forces
- Prolapses
  - By an unstable underground
- Deformations

Degradation – some examples

Microscopic detail of stress corrosion cracking

Pitting corrosion

Resulting risks due to degradation

- Containment can no longer carry out its function, which is
  - To offer resistance against forces
  - To shield from the surrounding
- During the ‘normal’ working or in case of deviations
- May result in:
  - Explosive failure
  - rupture
  - Leak

Measures against degradation

- Choice of process conditions
- Choice of materials
- Layers of protection (internal or external)
- Inspection
  - Detection of damage
  - Evaluation of damage
  - Corrigerende actie nemen
    - Repair (temporary, permanently, …)
    - Adapted/changed working conditions
    - decommissioning
  - Determine new inspection period

Detection of damage

- Visually
- Detection- and measuring equipment
  - Technique is tuned into the to be expected damage
  - Mesaure where damage can be expected
- Qualification/knowledge of inspectors very important

Evaluation of determined damage

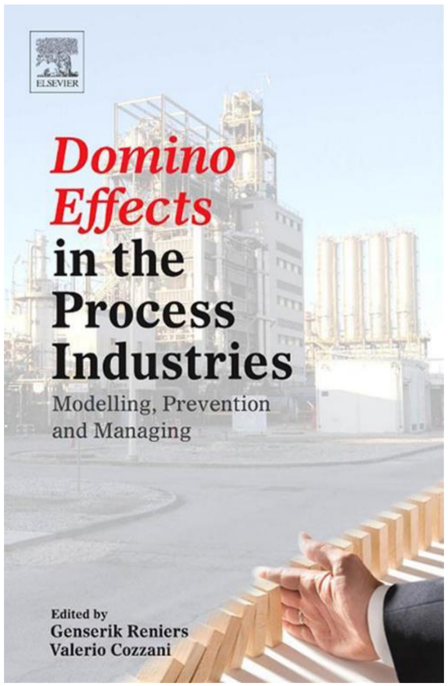
- Need for unambiguous and clear criteria
  - E.g. measurement of thickness: minimal thickness
- Well-described conclusions in the report!
- Sometimes calculations are necessary for ‘fitness for service analysis’

Approach to deal with degradation of containment

- Identification of all containments
  - All pipework
  - All process vessels
  - All atmospheric storage tanks
- Per containment: identification of to be expected degradation phenomena
  - Internal: based on operational conditions
  - External: isolation? Loss of containment in surrounding and/or environment?
- Draft inspection program
  - Techniques in function of to be expected damage
  - First inspection-interval should be relatively short
- Carry out inspections, evaluate results
  - If necessary: take actions

Overview of prevention and protection measures (also for dealing with domino effects)

See Book "Domino Effects in the Process Industries" (Reniers and Cozzani) - Elsevier

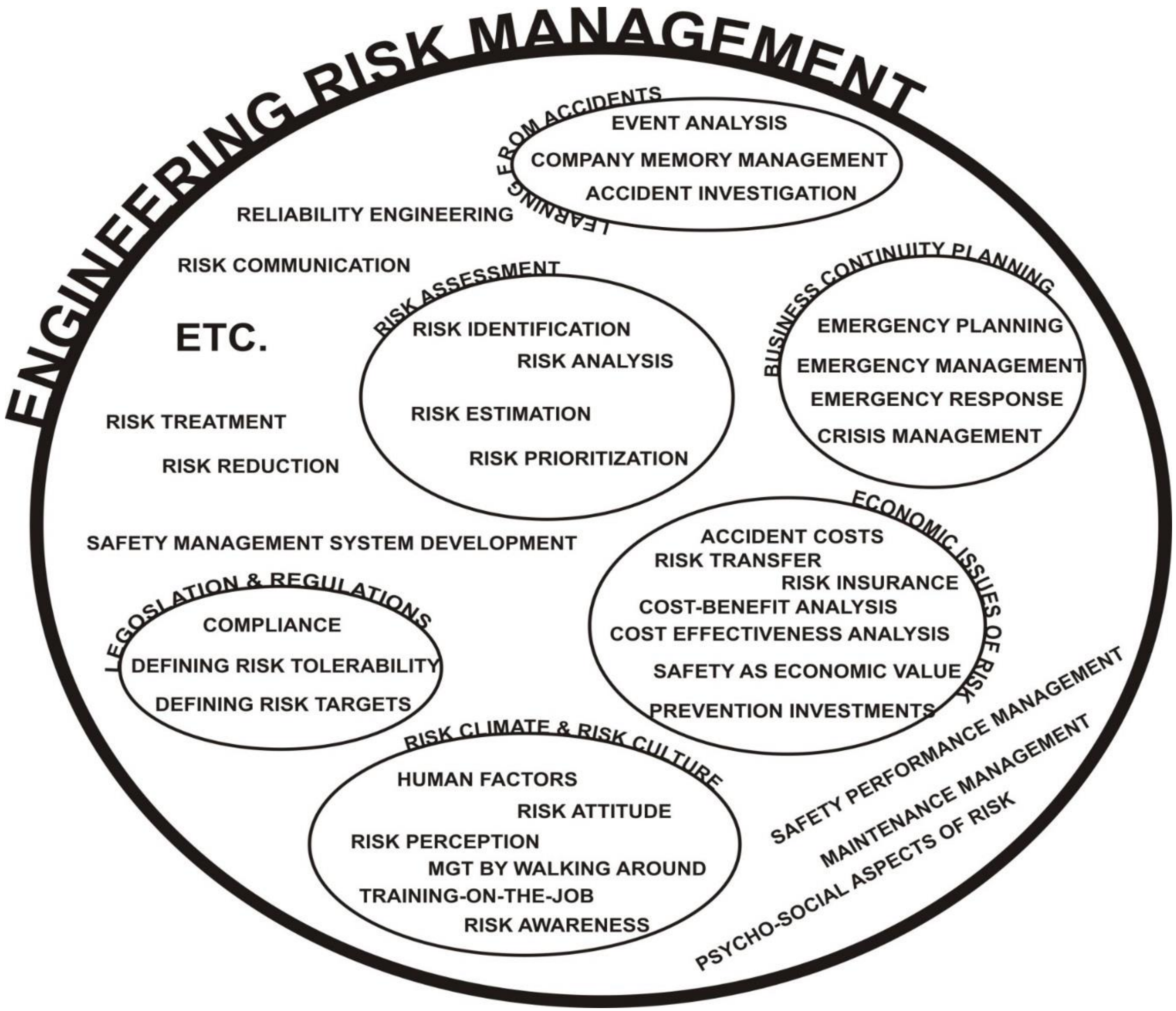


Damage preventing	Design or controle	Measure
Damage-preventing	Design Equipment lay out	· Choice of the right materials. · Pressure resistance of the equipment. · Mechanical overpressure protection, rupture disks, pressure relief valves, blow down tanks. · Corrosion resistance. · Supporting equipment for recipients and pipes. · Vent sizing. · Inherent safety design (can tolerate some equipment failures). · Emergency stop buttons. · Flame arrestors.
Damage-preventing	Design Preventing Fire	· Thermal protections. · Differential Protections. · Use of non flammable materials. · Non flammable gaskets and valves. (containment) · Avoiding unstable products. · Preventing oil getting into substances as rockwool. · Gas detectors. · Smoke detectors. · The permanent leakage detection system is incorporated in the inspection programme. · Radiation shields. · Pressure shields and explosion films.
Damage-preventing	Design Proces controle	· Safety integrity levels, redundancy. · Preventive maintenance logging and investigations. · Automatic monitoring, continu monitoring. · Safety studies installation and product: HAZOP, What if, Swift, ... · Incidents/dangerous situations/near misses, logging and investigations. · Steering of installations by remote controll. · Installation of independant interlocks. · Instrumental protections. · Alarm on abnormal level changes in a (storage)tank. Stop producttransfer if amounds are larger than considered normal.
Damage-limiting or preventing	Design Explosion related	· Explosion hatches. · Emergency cooling systems.
Damage-preventing	Design ATEX related	· Avoiding flammable liquids. · Covering with foam blankets (aut/man). · Forced ventilation. · Avoiding ignition sources, grounding. · Nitrogen blanketing. · Intrinsic safe.
Damage-limiting	Design Containing	· The bund walls keep the product/fire away from other tanks. · Sloped fire trench keep the fire under controle and away from other tanks/equipment. · Prevent spread of flammable products via sewers. · Release volumecontaining. Keep gas releases inside for safe scrubbering. · Dubbel wall tanks and pipes to prevent leakage. · Safety couplings (unique for one product).
Damage-limiting	Design Compartimentation	· Emergency stops. Immediate stop and go to a safe position. · The break-away coupling prevents spills in case of a separation of the temporary connection. · Detection of a loss of containment in combination with an automatic compartimentation. Devide in smaller volume sections that when a loss of containment take place only the small volume is lost. · Checkvalves. Stop product going back with a unwanted effect as a consequence. · Fire activated valves. Spring-loaded valve closes if a fire melt a substance that keep the valve open.
Damage-limiting	Design Limit fire damage	· Automatic sprinklers with or without foam addition. · Fire resistant materials. · Fire retardant materials. · Fire proof due structure sprinklers. · Automatic or semiautomatic deluges with sprinklerheads as detection or other detection system. · Fire protection for electrical installations.
Damage-limiting and or preventing	Design Evacuation Safety shelter	· Area protection against pressure waves. · Area protection against toc gases (air tight), manually or (semi)automatic systems. · Area protection against radiation IR, ... · Decreasing staffing possibility's in the still active zones. · Alarm on the airquality intake.

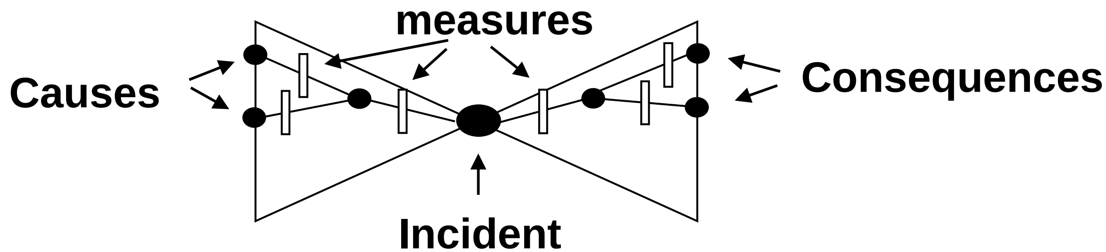
New trends in process safety?

Safety in organisations (a.o. process safety)

- Law & crimin.
- Economics
- Engineering
- Mathematics
- Psychology
- Sociology
- S&S Sciences
- Emergency Sc.
- Comm. Sc.
- Business & Mgt.
- Philosophy



Process safety in organisations - Using the Bow-tie



- **PRO-ACTIVE PHASE:** collaboration (scale + O³), dynamic risk assessments, big data, economic analyses, security TAs, harsh environments, performance mgt, trans-disciplinary solutions, systemic solutions / barriers, educate people pro-active communication (safety apps), ‘culture’ (single + cross-c), how safe is safe enough / ethics, mental models

- **INCIDENT PHASE:** use real-time data to make assessments, big data, communication, collaboration, simulation exercises: more ‘real’ and more involvement from public; serious games

- **RE-ACTIVE PHASE:** collaboration (scale + O³), communication, psychological aspects

Different possibilities for advancing process safety

- <u>Old wine in old barrels:</u> keep using successful safety models/theories/practices/algorithms/software/… → companies

- <u>Old wine in new barrels:</u> use of new algorithms/software with the same old data/info to further improve/optimize solutions (faster etc.)

  → consultants (and universities)

- <u>New wine in old barrels:</u> use of new data/info (e.g. big data) using the old algorithms/software to further improve/optimize (more accurate etc.) → consultants (and universities)

- <u>New wine in new barrels:</u> new info/data and new algorithms/software (e.g. domino effects in QRA, dynamic risk assessments, big data linked to real-time risk software, innovative communication tools, etc.) → universities

Process safety in society: a complex problem

- When is ‘safe’, ‘safe enough’?

  → Problem surrounding the **acceptability** of risks
  (solution = ‘AND’ story; collaboration and research)

- How much should one invest in safety?

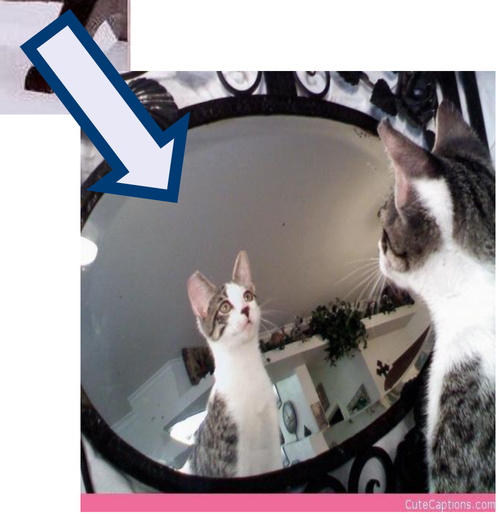
  → Problem surrounding **costs and benefits disproportionality** of risks
  (solution = fundamental and applied research)

- Does the perceived risk correspond to the real risk?

  → Problem surrounding the **perception** of risks
  (solution = education)

Process safety: an 'AND' story

- Specialistic **AND Generalistic**
- Technology **AND HOFS**
- Reactive **AND Proactive**
- Short-term **AND Long-term**
- Top-down **AND Bottom-up**
- Normal acc. **AND Disaster**
- Operational **AND Strategic**
- Blue-collar **AND White-collar**
- Simple **AND Complicated**
- Individu **AND Group**
- Confidential **AND Transparant**
- Static **AND Dynamic**
- Realist/Pragmatic **AND Dreamer/Idealistic**
- Analytic **AND Systemic**
- Current practice **AND Innovation**
- Linear **AND Cyclic**
- Practical **AND Theoretical/Fundamental/Conceptual**
- Mono-disc. **AND Multi-disc. AND inter-disc. AND trans-disc.**



Things to remember in relation to risks in the chemical industry

- There exist different types of risk (**occupational safety versus process safety**) → treat them differently with respect to safety investments

- Safety (also process safety) is an important domain of excellence → (occ & process) safety is 'not losing money' (is identical to 'winning money'!)

- **Process safety: still much improvement to make, technological as well as HOFS-related!**

Safety versus security?

“Security risk” examples

Large

Likelihood

Most security issues: burglary, swindle, attempted murder, manslaughter, etc.	War, Civil war ..
Murder	Terrorist attacks

Small

Consequences