SAFETY LAYERS AND LAYER OF PROTECTION ANALYSIS (LOPA)

North Jersey Section AIChE

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WHO AM I?

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ATTRIBUTION

Information presented on these slides was obtained (with permission) from:

- **Consider the Role of Safety Layers in the Bhopal Disaster** – Ronald J. Willey, P.E., CEP Magazine, December 2014

- *…as well as over 30 years of experience in the chemical process industry!*

BHOPAL DISASTER

THE PLANT

- Owned by Union Carbide India, Ltd (UCIL)
  - *Joint venture of UC and a group of Indian government-controlled institutions*
  - *Located about 2 miles north of Bhopal railway station*
- Agricultural Products Division of UCIL operated the plant
  - *Manufactured fungicides, miticides, herbicides and insecticides*
  - *Accounted for just over 8% of UCIL sales*
- Opened (new) in 1970 initially only blending pesticides
- Backward integrated over time, with methyl isocyanate (MIC) production beginning in 1980
- Capacity was 5,250 metric tons (~ 11.6 million lbs) MIC / year
- Bunker constructed, containing three 15,000 gallon storage tanks for MIC

METHYL ISOCYANATE AT A GLANCE

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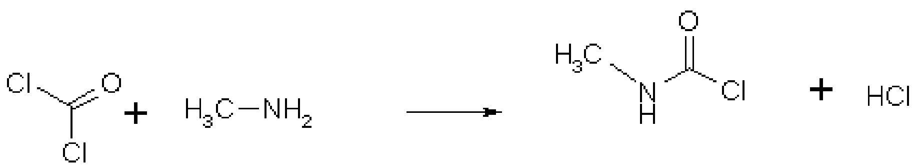
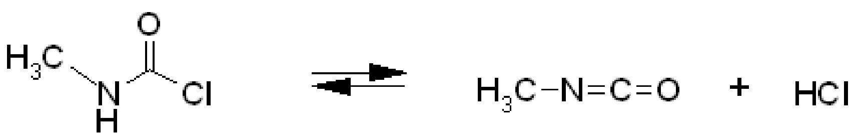
Manufacture [edit]

Methyl isocyanate is usually manufactured by the reaction of monomethylamine and phosgene. For large sc combine these reactants at higher temperature in the gas phase. A mixture of methyl isocyanate and two mo but N-methylcarbamoyl chloride (MCC) forms as the mixture is condensed, leaving one mole of hydrogen chl



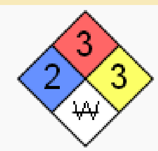
MCC

The methyl isocyanate is obtained by treating the MCC with a tertiary amine, such as N,N-dimethylaniline, or using distillation techniques.[13]

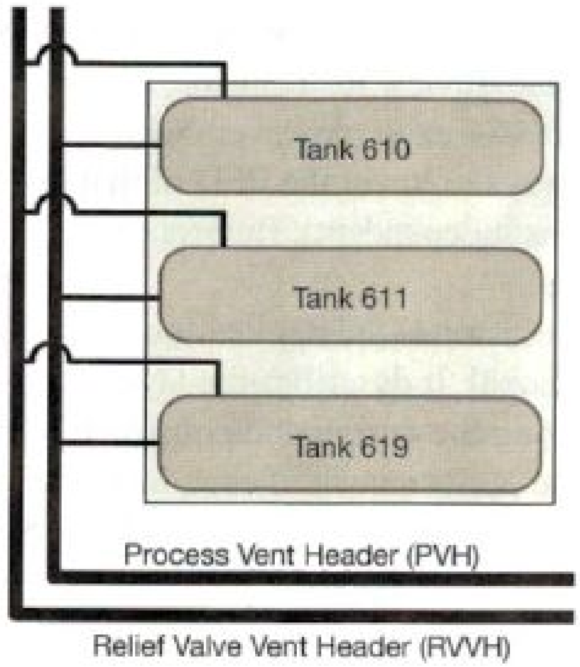


MCC

Methyl isocyanate is also manufactured from N-methylformamide and air. In the latter process, it is immediate process to make methomyl.[14] Other manufacturing methods have been reported.[15][16]

Appearance	Colorless liquid
Odor	Sharp, pungent odor[1]
Density	0.9230 g/cm^3 at 27 °C
Melting point	−45 °C (−49 °F; 228 K)
Boiling point	39.5 °C (103.1 °F; 312.6 K)
Solubility in water	very soluble[2]
Vapor pressure	57.7 kPa
Structure	
Dipole moment	2.8 D
Thermochemistry	
Std enthalpy of formation ($\Delta_f H^\circ_{298}$)	−92.0 kJ·mol^{-1}[2]
Hazards	
NFPA 704	
Flash point	−7 °C (19 °F; 266 K)
Autoignition temperature	534 °C (993 °F; 807 K)
Explosive limits	5.3–26%[2]
Related compounds	
Related compounds	Methyl isothiocyanate

THE STORAGE TANK BUNKER



▲ **Figure 1.** Three 15,000-gal storage tanks were available for MIC storage. Tank 610 was the source of the MIC released into the air. Source: Adapted from Ref. 6.

- Design intent was for Tanks 610 and 611 to each store ½ capacity (7,500 gallons) of MIC

- Tank 619 was reserve capacity for excess and/or O.O.S. MIC

- Tank 610 was the source of the release

THE STORAGE TANK PFD

Process vent header

Relief valve header

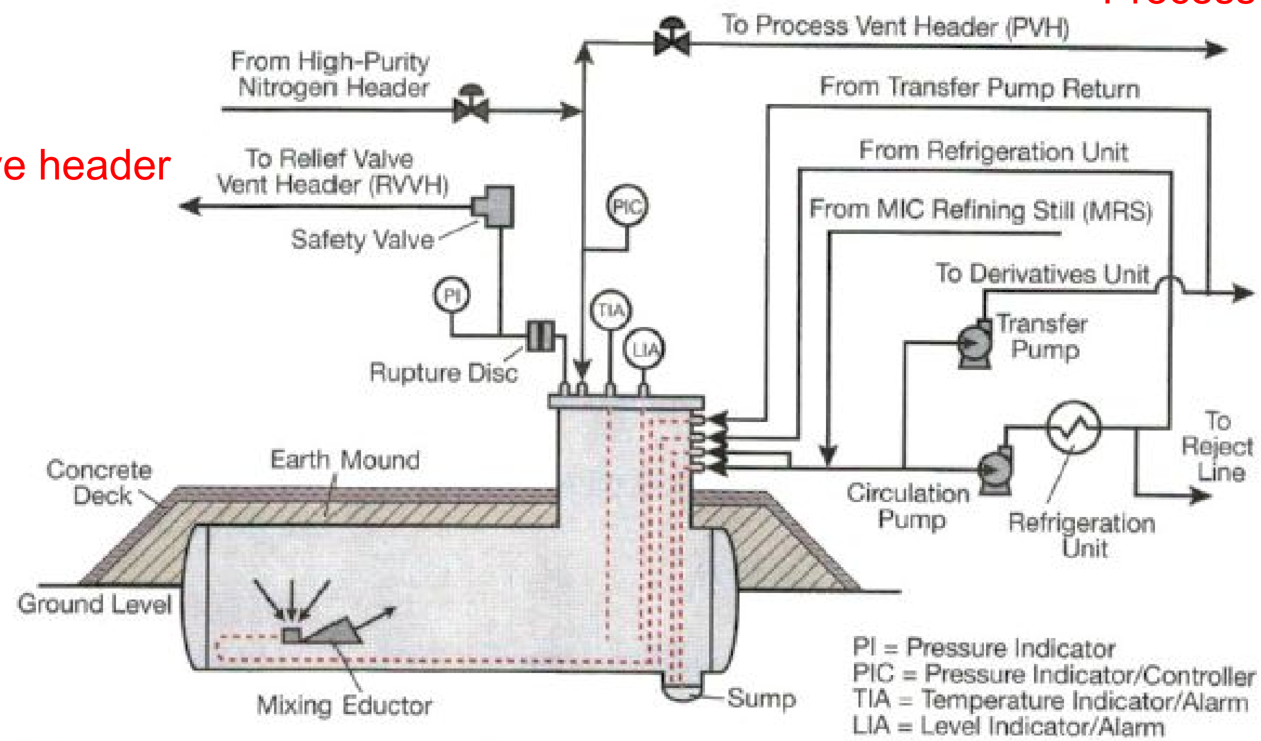
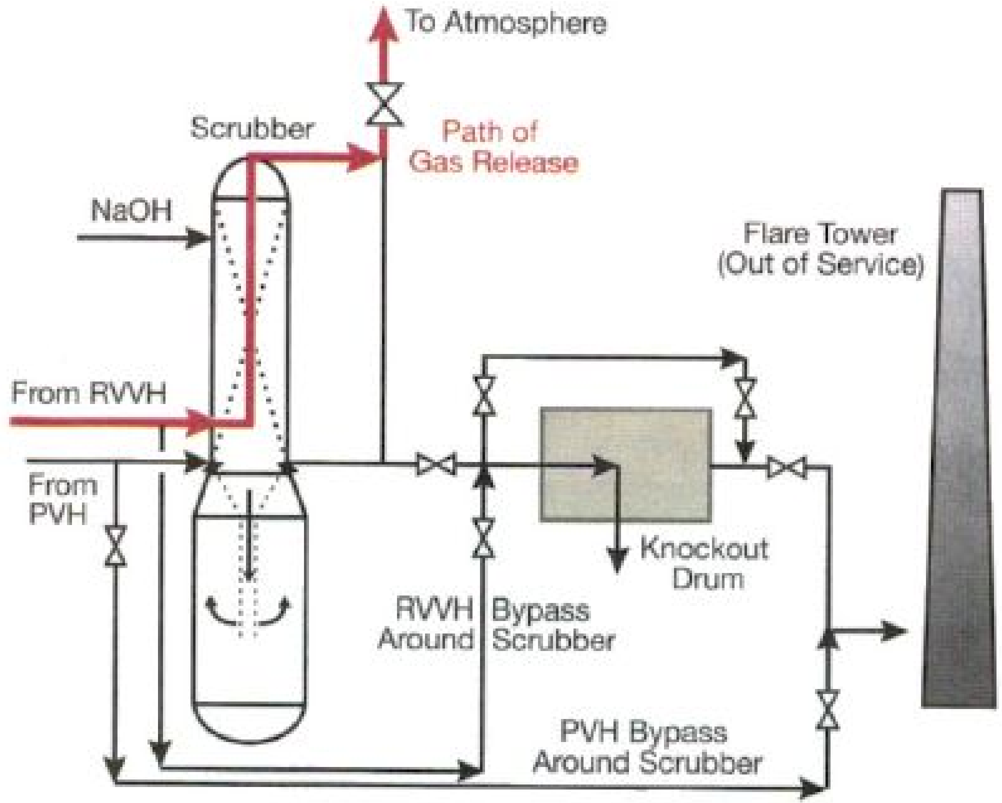


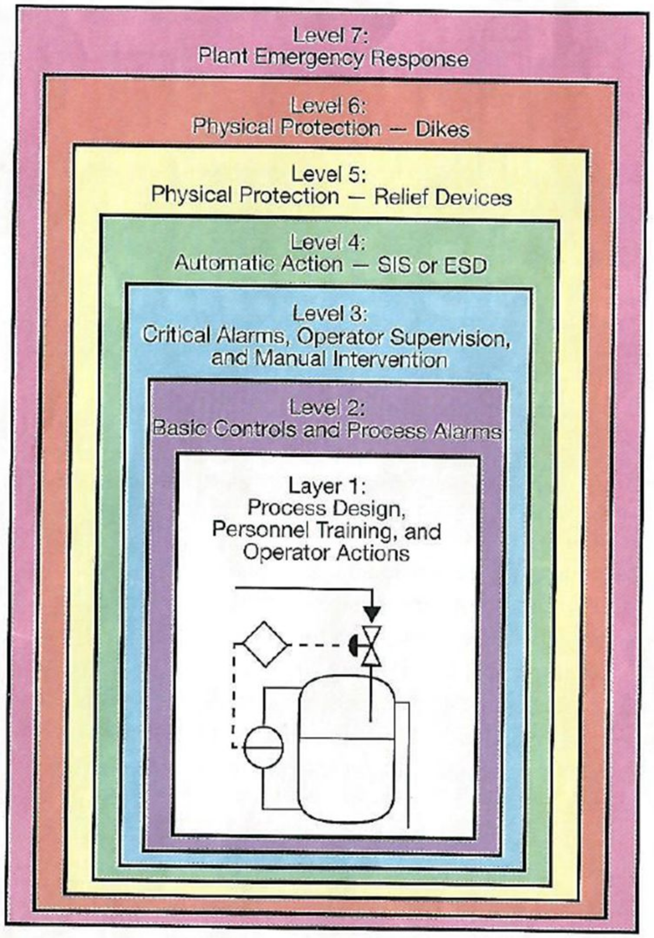
Figure 2. The tanks were equipped with refrigeration units to maintain storage temperatures below 15°C and nitrogen blanketing to prevent ignition of the MIC. Source: Adapted from Ref. 6.

THE VENT GAS SCRUBBER & FLARE TOWER



▲ **Figure 3.** A scrubbing system downstream from the tank was designed to capture toxic emissions and vent them to a flare tower. Source: Adapted from Ref. 7.

7 LAYERS OF PROTECTION TYPICALLY EMPLOYED IN CPI



▲ **Figure 4.** CPI plants are designed with multiple layers of protection.

1ST Layer: Process Design

2nd Layer: Basic Control Systems and Alarms

3rd Layer: Critical Alarms, Manual Intervention

4th Layer: Automated Safety Instrumented System

5th Layer: Relief Devices

6th Layer: Containment of Releases

7th Layer: Plant's Emergency Response

Procedures

"*8th Layer*": *Community Response – when it gets to this level, it's typically catastrophic*

IMPORTANT: Each layer must be independent of the others!

LAYER OF PROTECTION ANALYSIS (LOPA)

- **LOPA**
  - *techniques evolved from the late 1980's to the 1990's to evaluate major layers that can mitigate the injury & damage from an event like a fire, explosion or release*
- **LOPA**
  - *is a holistic approach, identifying major safeguards, categorizing them, determining if they are dependent or independent, and assessing their ability to perform on demand*
- **LOPA**
  - *is a semi-quantitative analysis tool to evaluate whether adequate mitigation exists for a particular process safety incident, (i.e.; Initiating Event, or I.E.)*
- **LOPA**
  - *estimates the effectiveness of existing major layers of protection to prevent/mitigate an I.E., the frequency of which is denoted "IEF"*
- **LOPA**
  - ***is not** a complete event-tree analysis*

LOPA - *continued*

- **In a LOPA analysis, only two outcomes exist:**
  - *The protective measure works when it is needed, or*
  - *The protective measure does not work when it is needed*

- **These two potential outcomes can be characterized by:**
  - *A probability to work on demand (PWD), or*
  - *A probability to fail on demand (PFD)*

- **The sum of these probabilities = 1.0 for each independent protection layer (IPL)**

- **The key equation of the LOPA analysis therefore is:**

$$f_i^c = \mathrm{IEF}_i * \mathrm{PFD}_{i1} * \mathrm{PFD}_{i2} * \ldots. * \mathrm{PFD}_{ij}$$

LOPA - *continued*

$$f_i^c = \mathbf{IEF}_i * \mathbf{PFD}_{i1} * \mathbf{PFD}_{i2} * \ldots. * \mathbf{PFD}_{ij}$$

- f_i^c = the frequency of the consequence occurring for scenario "*i*" per unit time (*time* $^{-1}$)
- f_i^c = a relative number used to compare different layers and scenarios
- IEF_i = the frequency of the initiating event for scenario "*i*" per unit time (*time* $^{-1}$)
- PFD_{ij} = the probability of failure on demand of the independent protection layer "*j*" for scenario "*i*"

LAYER OF PROTECTION ANALYSIS FOR MIC STORAGE TANK 610

- **SCENARIO:**
  - *Major release of MIC vapor into surrounding community*
- **INITIATING EVENT:** *(possibilities)*
  - *Storage tank leak*
  - *Wall of tank fails (e.g.; an explosion)*
  - *Relief system fails*
- **IDENTIFY THE MOST LIKELY EVENT:**
  - *Contamination of storage tank contents (The actual event that initiated the Bhopal disaster was traced to the entry of ~ 500 kg of water into Tank 610)*
- **IDENTIFY THE FREQUENCY OF THE INITIATING EVENT (IEF):**
  - *This may be known, or it may need to be estimated*
    - » *The MIC plant opened in 1980 and the initiating event occurred 4.8 yrs after the plant began operating: IEF = 1 event / 4.8 yrs = 0.21 yr* $^{-1}$

LAYERS OF PROTECTION DESIGNED INTO STORAGE TANK 610

- **LAYER 1: Corporate Design Intent**
  - *Two product storage tanks, (Tanks 610 & 611) each sized for twice the required volume, plus a third tank (Tank 619) for excess and off-spec product*
  - *Tanks were equipped with level control indicators connected to alarms in the Control Room*
  - *Operating training was also a part of this first layer*

- **CALCULATE / ESTIMATE THE PFD FOR THIS LAYER:**
  - *It would be reasonable to estimate the probability for failure on demand for these measures as 1 failure every 10 years, or* $PFD_{11} = 0.1$

LAYERS OF PROTECTION DESIGNED INTO STORAGE TANK 610

- **LAYER 2: Basic Controls**
  - *The tanks were equipped with a temperature control system – an external refrigeration system was used to maintain the tank temperature at less than 15^{o}C*
- **CALCULATE / ESTIMATE THE PFD FOR THIS LAYER:**
  - *It would be reasonable to estimate the probability for failure on demand for this measure as 1 failure every 10 years, or* $PFD_{12} = 0.1$

LAYERS OF PROTECTION DESIGNED INTO STORAGE TANK 610

- **LAYER 3: Critical Alarms and Manual Intervention**
  - *The tanks were equipped with a temperature and level indicators that would sound an alarm and flash warning lights on a Control Room panel.*
  - *The plant's safety manual stated:*
    - ***"If the methyl isocyanate tank becomes contaminated or fails, transfer part or all of the contents to the empty, standby tank"*** *(1)*

- **CALCULATE / ESTIMATE THE PFD FOR THIS LAYER:**
  - *This layer depends on a human response to an abnormal condition, which under the best of circumstances has a* $PFD_{13} = 0.1$ *(2)*

[2] **Center for Chemical Process Safety** "Guidelines for Initiating Events and Independent Protection Layers," AIChE, New York, NY , and John Wiley and Sons, Hoboken, NJ (2014)

[1] **Union Carbide Corp.,** "Methyl Isocyanate Manual (F-41443A-7/76)", Union Carbide, New York, NY (1976)

LAYERS OF PROTECTION DESIGNED INTO STORAGE TANK 610

- **LAYER 4: Safety Instrumented System (SIS) or Emergency Shut-down Device (ESD)**
  - *The MIC plant was not equipped with either an SIS or an ESD*
- **CALCULATE / ESTIMATE THE PFD FOR THIS LAYER:**
  - $PFD_{14} = 1.0$

LAYERS OF PROTECTION DESIGNED INTO STORAGE TANK 610

- **LAYER 5: Relief Devices**
  - *The relief system consisted of a rupture disc, a relief valve, and a flare system, in series.*
    - » ***NOTE:*** *Although the NaOH scrubber was also part of the relief system, it was designed for small releases and therefore does not affect the scenario of a major release of MIC*

- **CALCULATE / ESTIMATE THE PFD FOR THIS LAYER:**
  - *The overall PFD for this combination of devices is* $PFD_{15} = 0.1$

LAYERS OF PROTECTION DESIGNED INTO STORAGE TANK 610

- **LAYER 6: Dike**
  - *The plant did not have a secondary containment dike.*
    - » ***NOTE:*** *Even if a dike were present, it's PFD would = 1.0, MIC is extremely volatile and temperatures in central India can exceed the 39^{o}C boiling point of MIC. Vapors would evolve at deadly concentrations, making a containment dike meaningless.*

- **CALCULATE / ESTIMATE THE PFD FOR THIS LAYER:**
  - $PFD_{16} = 1.0$

LAYERS OF PROTECTION DESIGNED INTO STORAGE TANK 610

- **LAYER 7: Plant Emergency Response**
  - *Some plant personnel were trained in emergency response and attempted to respond.*
- **CALCULATE / ESTIMATE THE PFD FOR THIS LAYER:**
  - *As with Layer 3, this layer depends on a human response to an abnormal condition, which under the best of circumstances has a* $PFD_{13} = 0.1$ [(2)]

[2] **Center for Chemical Process Safety** "Guidelines for Initiating Events and Independent Protection Layers," AIChE, New York, NY , and John Wiley and Sons, Hoboken, NJ (2014)

FREQUENCY OF OCCURRENCE CALCULATION

$$f_i^c = \mathbf{IEF}_i * \mathbf{PFD}_{i1} * \mathbf{PFD}_{i2} * \ldots * \mathbf{PFD}_{ij}$$

- $f_1^c = \mathrm{IEF}_1 * [\ \mathrm{PFD}_{11} * \mathrm{PFD}_{12} * \mathrm{PFD}_{13} * \mathrm{PFD}_{14} * \mathrm{PFD}_{15} * \mathrm{PFD}_{16} * \mathrm{PFD}_{17}\ ]$

- $f_1^c = (0.1\ \mathrm{yr}^{-1}) * [\ 0.1 * 0.1 * 0.1 * 1.0 * 0.1 * 1.0 * 0.1] = 1 \times 10^{-6}\ \mathrm{yr}^{-1}$

In other words – if everything was adequately designed and functioning properly, the frequency of this catastrophic release occurring would be:

1 major release in a million years!

So why, then, did this event occur at all?

Answer: Because all of the layers were compromised, and therefore the PFD for each layer was = 1.0

ANALYSIS - Layer 1: Design, Procedures & Training

- The operating instructions specified**, "*Do not overfill the tank beyond 50% full with MIC".***
  - *Someone within operating supervision made the decision to fill the tank to 85% of capacity*

- **LESSON(S):**
  - *MIC was an intermediate. What you don't have in inventory cannot leak, catch fire or otherwise cause a problem.*
  - *Design the plant to produce and use intermediates on demand.*

ANALYSIS - Layer 2: Cooling System

- The refrigeration system installed to remove the exothermic heat of reaction within the storage tank was disabled by plant management
  - *This was portrayed as a cost-saving measure as plant management was under pressure to cut costs to avoid plant closure*

- **LESSON(S):**
  - *Management continually looks for ways to reduce costs. Engineers need to communicate that cost reductions should not be undertaken for critical safety systems.*
  - *Evaluate the removal of any safety systems through an MOC analysis to understand the implications.*

ANALYSIS - Layer 3: Instrumentation & Manual Intervention

- The plant had high-temperature and high-level indicators and alarms to alert personnel
  - *Operators were aware of the rising pressure and temperature in Tank 610; however, there is no record of a manual intervention to transfer material to Tank 619*

- **LESSON(S):**
  - *This layer relies on human factors and requires people to take corrective action in an emergency*
  - *Training exercises that simulate the proper corrective action(s) should be developed within the plant and practiced by operators.*

ANALYSIS - Layer 4: Automation

- No Safety Instrumented System (SIS) or Emergency Shut-down Device (ESD) was evident in the design of the Bhopal plant
  - *For example, there was no automated device that might quench a runaway reaction with the storage tank*

- **LESSON(S):**
  - *Under the right conditions SIS and ESD can have a PFD = 0.01*
  - *It is important that the SIS and/or ESD be completely independent and work without any human intervention.*

ANALYSIS - Layer 5: Relief System

- The rupture disc followed by the relief valve worked on demand and the RVVH had sufficient capacity, preventing what could have been a even more catastrophic explosion
  - *However, the relief system failed because the flare system was out of service awaiting replacement of a 4-foot section of corroded pipeline. The material in the RVVH had nowhere to go but into the air.*

- **LESSON(S):**
  - *Are any of your safety systems out of service awaiting repair?*
  - *If so, is there a sense of urgency to make the repair so that the safety systems are available to do their job on demand?*

ANALYSIS - Layer 6: Diking

- The existence of a dike is irrelevant, since this was a toxic gas release
  - *Diking around the storage tanks would not have affected the outcome of this disaster.*

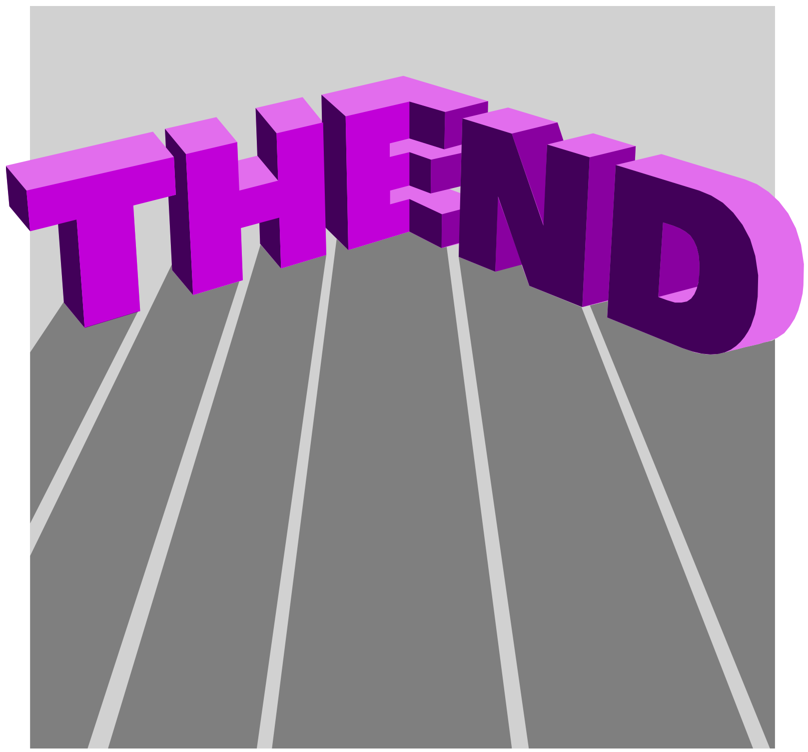
- **LESSON(S):**
  - *Do your liquid storage tanks have diking and has it been inspected recently?*
  - *If not equipped with a dike or catch basin would you be concerned if a major release were to occur?*

ANALYSIS - Layer 7: Emergency Response

- A few operators tried spraying water on the gas plume leaving the scrubber
  - *The hoses were insufficiently pressurized and the 100-foot-high stream could not reach the plume, which was exiting at 120 feet.*

- **LESSON(S):**
  - *Emergency response must be practiced . Mock scenarios need to be run through so things like low water pressure will be discovered beforehand*
  - *Should every employee at your facility have the authority to shut down the plant if a potentially unsafe event appears to be happening?*

IN CONCLUSION…



“There is no expedient to which a man will not resort to avoid the real labor of thinking.“

Sir Joshua Reynolds

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