ExxonMobil

October 11, 2023

Process Safety and the Energy Transition

Rebecca Peterson
Senior Principal Engineer, Process Safety Engineering
ExxonMobil Technology and Engineering Company

The Challenge of the Energy Transition is Immense

According to the International Energy Agency:

- Net zero to 2050 hinges on an **unprecedented** clean technology push to 2030
- Net zero to 2050 requires **large leaps** in clean energy innovation

Source: International Energy Agency Special Report "Net Zero by 2050"

ExxonMobil

What are some of the technologies involved?

Wind and Solar

Carbon Capture and Storage

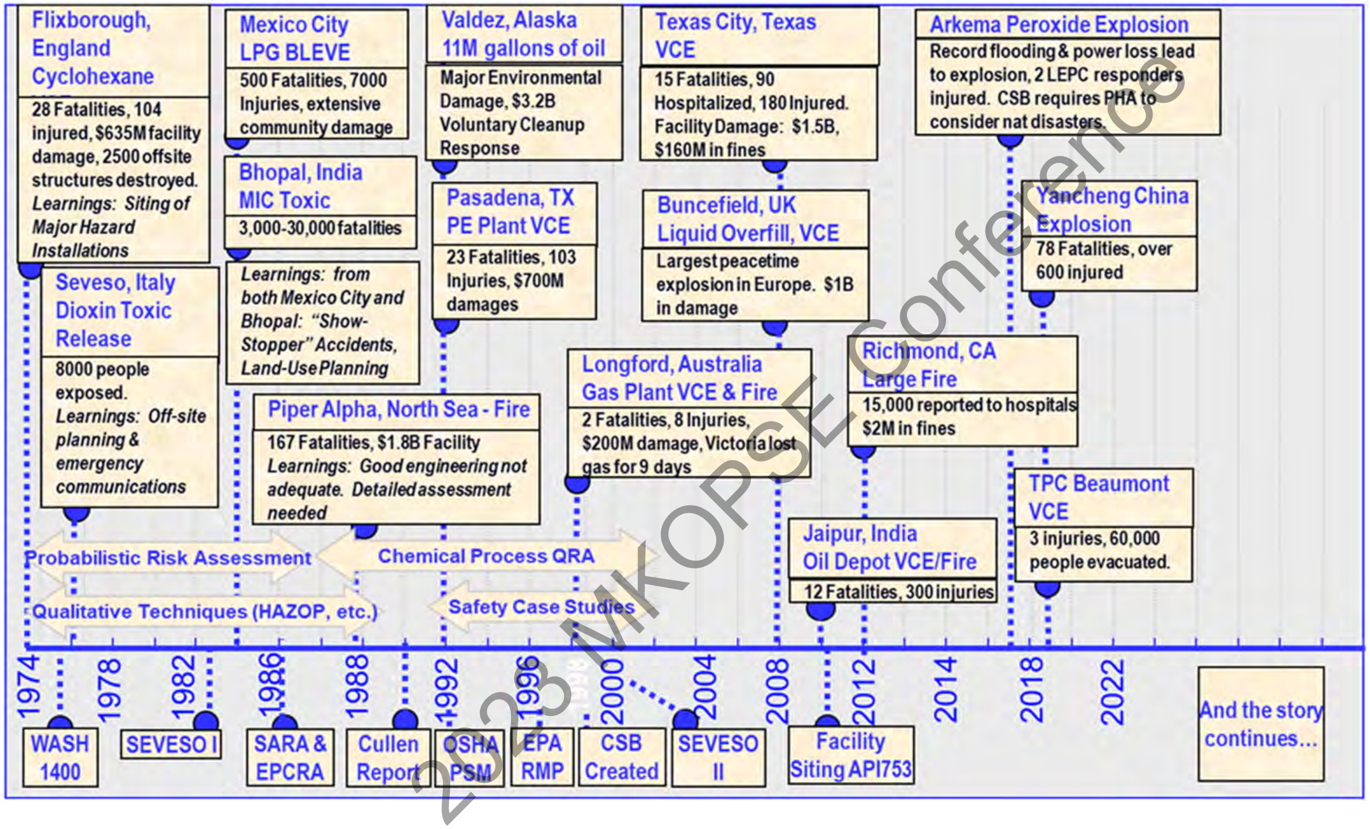
Low Emissions Fuels

Nuclear

And what are the hazards associated with them?

ExxonMobil

We Can Draw On Our Knowledge of the Past . . .



Flixborough, England Cyclohexane
28 Fatalities, 104 injured, $635M facility damage, 2500 offsite structures destroyed.
Learnings: Siting of Major Hazard Installations

Seveso, Italy Dioxin Toxic Release
8000 people exposed.
Learnings: Off-site planning & emergency communications

Mexico City LPG BLEVE
500 Fatalities, 7000 Injuries, extensive community damage

Bhopal, India MIC Toxic
3,000-30,000 fatalities

Learnings: from both Mexico City and Bhopal: "Show-Stopper" Accidents, Land-Use Planning

Piper Alpha, North Sea - Fire
167 Fatalities, $1.8B Facility
Learnings: Good engineering not adequate. Detailed assessment needed

Valdez, Alaska 11M gallons of oil
Major Environmental Damage, $3.2B Voluntary Cleanup Response

Pasadena, TX PE Plant VCE
23 Fatalities, 103 Injuries, $700M damages

Longford, Australia Gas Plant VCE & Fire
2 Fatalities, 8 Injuries, $200M damage, Victoria lost gas for 9 days

Texas City, Texas VCE
15 Fatalities, 90 Hospitalized, 180 Injured. Facility Damage: $1.5B, $160M in fines

Buncefield, UK Liquid Overfill, VCE
Largest peacetime explosion in Europe. $1B in damage

Jaipur, India Oil Depot VCE/Fire
12 Fatalities, 300 injuries

Richmond, CA Large Fire
15,000 reported to hospitals $2M in fines

Arkema Peroxide Explosion
Record flooding & power loss lead to explosion, 2 LEPC responders injured. CSB requires PHA to consider nat disasters.

Yancheng China Explosion
78 Fatalities, over 600 injured

TPC Beaumont VCE
3 injuries, 60,000 people evacuated.

Probabilistic Risk Assessment

Chemical Process QRA

Qualitative Techniques (HAZOP, etc.)

Safety Case Studies

WASH 1400

SEVESO I

SARA & EPCRA

Cullen Report

OSHA PSM

EPA RMP

CSB Created

SEVESO II

Facility Siting API753

And the story continues...

To Inform the Future of Process Safety

We Know What To Do

Risk-Based Process Safety Management

Commit

Process Safety Culture

Comply with Standards

Process Safety Competency

Workforce Involvement

Stakeholder Outreach

Understand

Process Knowledge Management

Hazard Identification and Risk Analysis

Manage

Operating Procedures

Safe Work Practices

Asset Integrity and Reliability

Training and Performance Management

Contractor Management

Management of Change

Operational Readiness

Conduct of Operations

Emergency Management

Learn

Incident Investigation

Measurement and Metrics

Auditing

Management Review and Continuous Improvement

Reference: CCPS Risk-Based Process Safety 20 Elements (Four Pillars)

What We Must Do

- Consider the energy transition may bring new process safety challenges and hazards.
- Leverage current expertise to manage potential new hazards.
- As process safety professionals we must take a leading position to ensure the proper management of all hazards in the energy business – old and new.
- As new hazards emerge, we must lead the way to ensure our own organizations, regulators, standards bodies, policy makers and members of the communities in which we operate understand and effectively manage those hazards.

Thank you

ExxonMobil

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with IChemE

October 11-13, 2023

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

26th Process Safety International Symposium

Speaker profile

- Hema Divya Katna
    - Hema Divya is currently pursuing her Masters in Process Safety at University of Aberdeen, Scotland, UK. She worked as a Process Safety Management Consultant at Kaypear from 2018. At Kaypear, she provides PSM consultancy services to Oil & Gas and Petrochemical industries. She has worked with both domestic and international clients providing specialized relief system validation that includes risk mitigation services and has strong knowledge of API 520, API 521, and ASME Section VIII Div.1. She is a scribe and assists the PHA facilitator in noding of P&IDs, consolidation of risk register, prioritization of action items, and generation of technical reports. She is an Associate Member with Chartered Engineering Certificate from Institute of Engineers India(IEI). Hema Divya graduated with a Bachelors in Technology in Chemical Engineering from SVCE, Chennai [Anna University] in 2018 and a PG Diploma in Petrochemical Process Safety and Engineering from Bharat Sevak Samaj in 2020.

Threshold Quantity for Process Safety Metrics for Special / Coded Chemicals

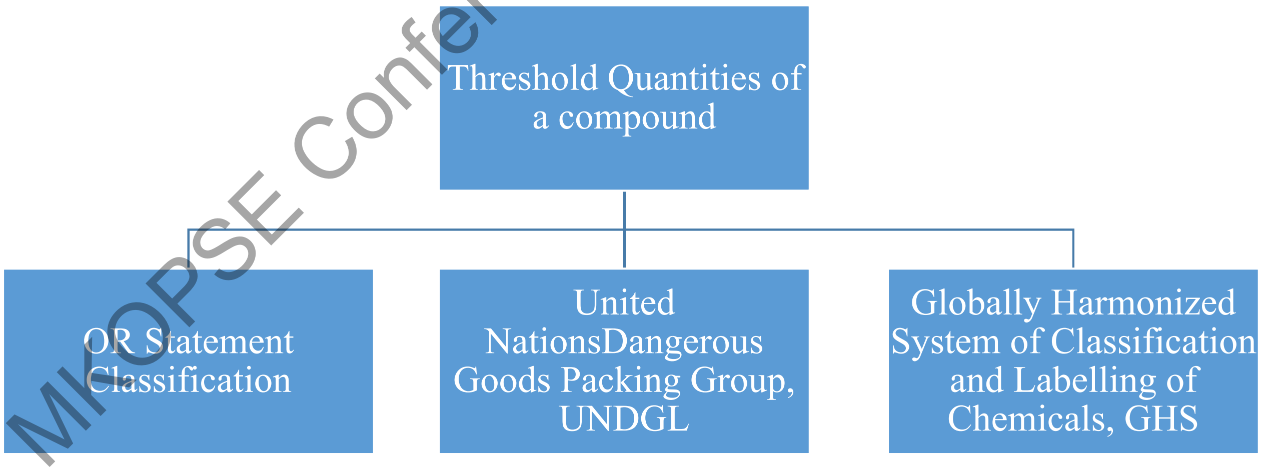
- Essential element in improving the process safety program is to identify existing process safety performance to improve future performance
- To improve the performance, a company has to implement leading and lagging process safety metrics
- Lagging indicators measures what has already happened, such as accidents and injuries
- Lagging process metrics can be developed using the following guideline document CCPS Process Safety Metrics and API-754
- Major step involved in implementation is grouping the compounds based on its physical and chemical properties to define its threshold quantities

Problems Faced In Using Guideline

- Guidance provided is not exhaustive
- Especially leaves interpretation of determining threshold quantities for chemical compounds with ambiguity due to the material complexities in a multi-product plant
- Standards are US-centric and more guidance is needed for companies who want to implement it in a global scale
- Difficulty faced by these companies are grouping the materials and assigning the correct threshold quantities
- As these companies use coded chemicals and introduce at least 50 new compounds in 2-3 months of time frame

Understanding the Classification

- Use UNDG Classification - primary method
- Globally Harmonized System of Classification and Labelling of Chemicals - GHS Standard - primary method
- Simple characteristics such as toxicity, flammability or corrosivity of the compound - OR statement classification - secondary method



Threshold Quantities of a compound

OR Statement Classification

United NationsDangerous Goods Packing Group, UNDGL

Globally Harmonized System of Classification and Labelling of Chemicals, GHS

Precedence of Hazard Characteristics

- UNDG classification and secondary method of classification
- One compound can be classified in more than one class by the supplier based on transportation rules
- OR statement classification a compound can have two characteristics at the same time
- Example - styrene is reactive, toxic, and flammable
- Precedence table based on the Department Of Transportation (DOT) regulations - used to determine which property or class/packing group of the compound to be used to determine the threshold quantities

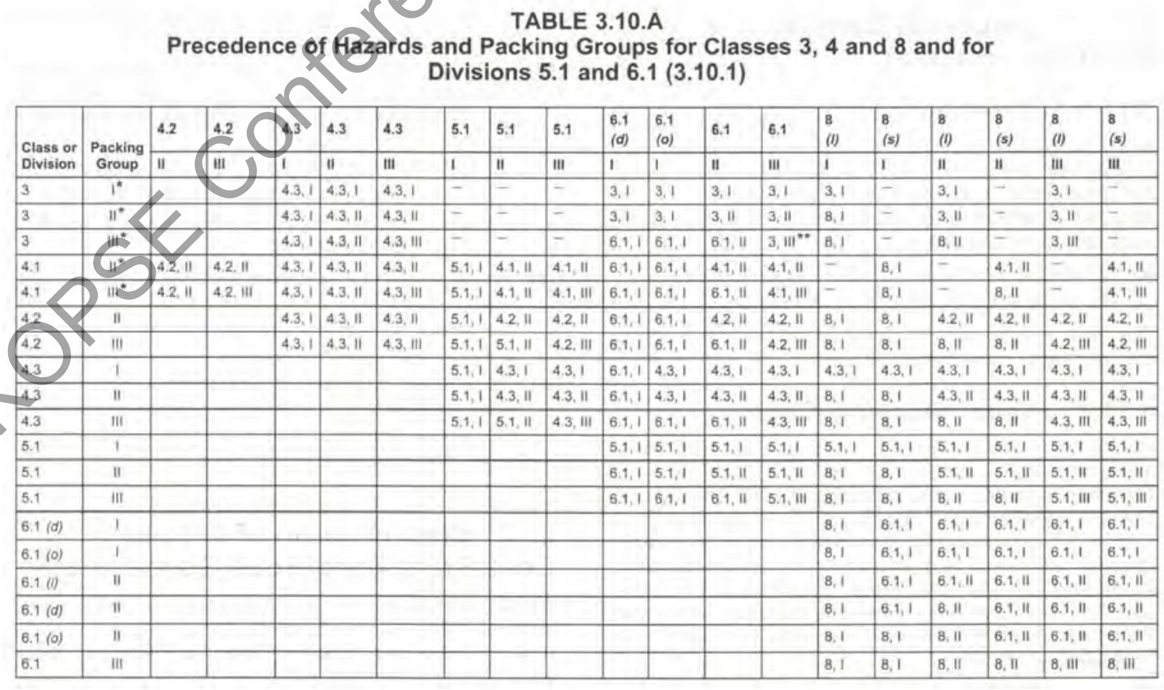


TABLE 3.10.A
Precedence of Hazards and Packing Groups for Classes 3, 4 and 8 and for Divisions 5.1 and 6.1 (3.10.1)

Class or Division	Packing Group	4.2	4.2	4.3	4.3	4.3	5.1	5.1	5.1	6.1 *(d)*	6.1 *(o)*	6.1	6.1	8 *(l)*	8 *(s)*	8 *(l)*	8 *(s)*	8 *(l)*	8 *(s)*
		II	III	I	II	III	I	II	III	I	I	II	III	I	I	II	II	III	III
3	I*			4.3, I	4.3, I	4.3, I	—	—	—	3, I	3, I	3, I	3, I	3, I	—	3, I	—	3, I	—
3	II*			4.3, I	4.3, II	4.3, II	—	—	—	3, I	3, I	3, II	3, II	8, I	—	3, II	—	3, II	—
3	III*			4.3, I	4.3, II	4.3, III	—	—	—	6.1, I	6.1, I	6.1, II	3, III**	8, I	—	8, II	—	3, III	—
4.1	II*	4.2, II	4.2, II	4.3, I	4.3, II	4.3, II	5.1, I	4.1, II	4.1, II	6.1, I	6.1, I	4.1, II	4.1, II	—	8, I	—	4.1, II	—	4.1, II
4.1	III*	4.2, II	4.2, III	4.3, I	4.3, II	4.3, III	5.1, I	4.1, II	4.1, III	6.1, I	6.1, I	6.1, II	4.1, III	—	8, I	—	8, II	—	4.1, III
4.2	II			4.3, I	4.3, II	4.3, II	5.1, I	4.2, II	4.2, II	6.1, I	6.1, I	4.2, II	4.2, II	8, I	8, I	4.2, II	4.2, II	4.2, II	4.2, II
4.2	III			4.3, I	4.3, II	4.3, III	5.1, I	5.1, II	4.2, III	6.1, I	6.1, I	6.1, II	4.2, III	8, I	8, I	8, II	8, II	4.2, III	4.2, III
4.3	I						5.1, I	4.3, I	4.3, I	6.1, I	4.3, I	4.3, I	4.3, I	4.3, I	4.3, I	4.3, I	4.3, I	4.3, I	4.3, I
4.3	II						5.1, I	4.3, II	4.3, II	6.1, I	4.3, I	4.3, II	4.3, II	8, I	8, I	4.3, II	4.3, II	4.3, II	4.3, II
4.3	III						5.1, I	5.1, II	4.3, III	6.1, I	6.1, I	6.1, II	4.3, III	8, I	8, I	8, II	8, II	4.3, III	4.3, III
5.1	I									5.1, I	5.1, I	5.1, I	5.1, I	5.1, I	5.1, I	5.1, I	5.1, I	5.1, I	5.1, I
5.1	II									6.1, I	5.1, I	5.1, II	5.1, II	8, I	8, I	5.1, II	5.1, II	5.1, II	5.1, II
5.1	III									6.1, I	6.1, I	6.1, II	5.1, III	8, I	8, I	8, II	8, II	5.1, III	5.1, III
6.1 *(d)*	I													8, I	6.1, I	6.1, I	6.1, I	6.1, I	6.1, I
6.1 *(o)*	I													8, I	6.1, I	6.1, I	6.1, I	6.1, I	6.1, I
6.1 *(l)*	II													8, I	6.1, I	6.1, II	6.1, II	6.1, II	6.1, II
6.1 *(d)*	II													8, I	6.1, I	8, II	6.1, II	6.1, II	6.1, II
6.1 *(o)*	II													8, I	8, I	8, II	6.1, II	6.1, II	6.1, II
6.1	III													8, I	8, I	8, II	8, II	8, III	8, III

Based on Toxicity – Gases

- Threshold Quantities for Toxic Vapors

Zones	Inhalation Toxicity	Threshold Quantities for Tier-1 (Outdoor)	Threshold Quantities for Tier-1 (Indoor)	Threshold Quantities for Tier-2 (Outdoor)	Threshold Quantities for Tier-2 (Indoor)
Hazard Zone A	LC_{50} less than or equal to 200 ppm	5 kg (11 lb)	0.5 kg (1.1 lb)	0.5 kg (1.1 lb)	0.25 kg (0.55 lb)
Hazard Zone B	LC_{50} greater than 200 ppm and less than or equal to 1000 ppm	25 kg (55 lb)	2.5 kg (5.5 lb)	2.5 kg (5.5 lb)	1.25 kg (2.75 lb)
Hazard Zone C	LC_{50} greater than 1000 ppm and less than or equal to 3000 ppm	100 kg (220 lb)	10 kg (22 lb)	10 kg (22 lb)	5 kg (11 lb)
Hazard Zone D	LC_{50} greater than 3000 ppm or less than or equal to 5000 ppm	200 kg (440 lb)	20 kg (44 lb)	20 kg (44 lb)	10 kg (22 lb)

Based on Toxicity – Liquids

- V is the saturated vapor concentration in air of the material in mL/m^3 at 20 °C and standard atmospheric pressure.
- Volatility V_i is given by
- $V_i = P_i \times \frac{10^6}{101.3}\, mL/m^3$
- Where, P_i is vapor pressure in kPa at 20 °C and standard atmospheric pressure.

Zones	Vapor concentration and toxicity	Threshold Quantities for Tier-1 (Outdoor)	Threshold Quantities for Tier-1 (Indoor)	Threshold Quantities for Tier-2 (Outdoor)	Threshold Quantities for Tier-2 (Indoor)
Hazard Zone A	V ≥ 500 LC_{50} and LC_{50} ≤ 200 mL/m^3	5 kg (11 lb)	0.5 kg (1.1 lb)	0.5 kg (1.1 lb)	0.25 kg (0.55 lb)
Hazard Zone B	V ≥ 10 LC_{50}; LC_{50} ≤ 1000 mL/m^3; and the criteria for Packing Group I, Hazard Zone A are not met.	25 kg (55 lb)	2.5 kg (5.5 lb)	2.5 kg (5.5 lb)	1.25 kg (2.75 lb)
Packing Group II	V ≥ LC_{50}; LC_{50} ≤ 3000 mL/m^3; and the criteria for Packing Group I, are not met.	1000 kg (2200 lb)	100 kg (220 lb)	100 kg (220 lb)	50 kg (110 lb)
Packing Group III	V ≥ 0.2LC_{50}; LC_{50} ≤ 5000 mL/m^3; and the criteria for Packing Group I and II, are not met.	2000 kg (4400 lb)	200 kg (440 lb)	200 kg (440 lb)	100 kg (220 lb)

Based on Oral, Dermal and Inhalation of mists and dusts

- Threshold Quantities for Oral, Dermal and Inhalation mists and dusts

Oral Toxicity LD50 (mg/kg)	Dermal Toxicity LD50 (mg/kg)	Inhalation mists and dusts LC50 (mg/L)	Threshold Quantities for Tier-1 (Outdoor)	Threshold Quantities for Tier-1 (Indoor)	Threshold Quantities for Tier-2 (Outdoor)	Threshold Quantities for Tier-2 (Indoor)
Less than equal to 5	Less than equal to 50	Less than equal 0.2	500 kg (1100 lb)	50 kg (110 lb)	50 kg (110 lb)	25 kg (55 lb)
Greater than 5 and less than equal to 50	Greater than 50 and less than equal to 200	Greater than 0.2 and less than equal to 2	1000 kg (2200 lb)	100 kg (220 lb)	100 kg (220 lb)	50 kg (110 lb)
Greater than 50 and less than equal to 300	Greater than 200 and less than equal to 1000	Greater than 2 and less than equal to 4	2000 kg (4400 lb)	200 kg (440 lb)	200 kg (440 lb)	100 kg (220 lb)

Based on Flammability

- Threshold Quantities for flammability

Description	Threshold Quantities for Tier-1 (Outdoor)	Threshold Quantities for Tier-1 (Indoor)	Threshold Quantities for Tier-2 (Outdoor)	Threshold Quantities for Tier-2 (Indoor)
Flammable gases	500 kg (1100 lb)	50 kg (110 lb)	50 kg (110 lb)	25 kg (55 lb)
Liquids with normal boiling point less than 35 °C (95 °F) and flash point less than 23 °C (73 °F)				
Liquids with normal boiling point greater than 35 °C (95 °F) and flash point less than 23 °C (73 °F)	1000 kg (2200 lb)	100 kg (220 lb)	100 kg (220 lb)	50 kg (110 lb)
Liquids with flash point greater than equal to 23 °C (73 °F) and less than and equal to 60 °C (140 °F)	2000 kg (4400 lb)	200 kg (440 lb)	200 kg (440 lb)	100 kg (220 lb)
Liquids with flash point greater than 60 °C (140 °F) released at a temperature at or above flash point				
Liquids with flash point greater than 60 °C (140 °F) and less than equal to 93 °C (200 °F) released at a temperature below flash point	N/A	N/A	1000 kg (2200 lb)	500 kg (1100 lb)

Based on Crude Oil

- Threshold Quantities for Crude Oil

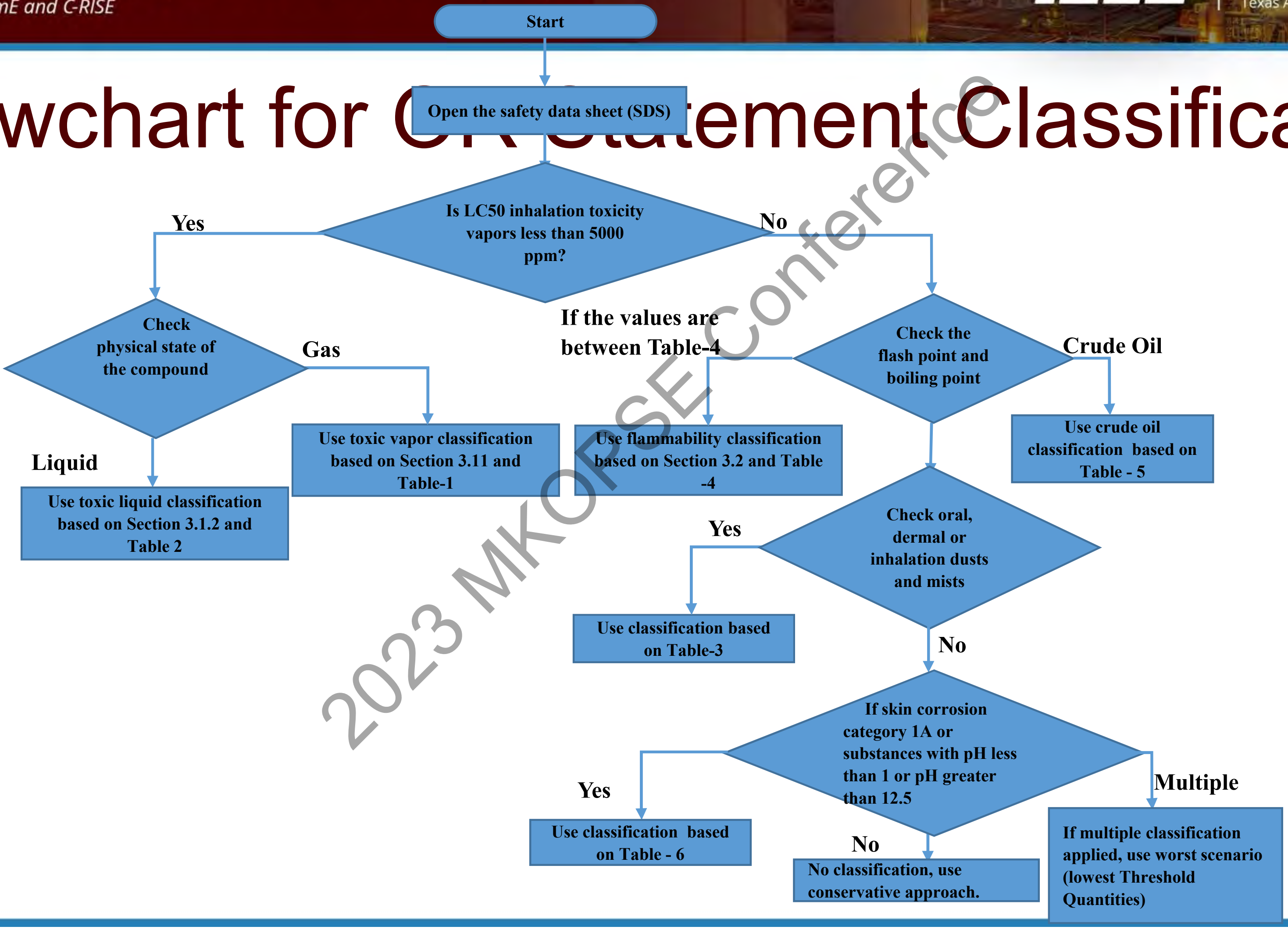
Description	Threshold Quantities for Tier-1 (Outdoor)	Threshold Quantities for Tier-1 (Indoor)	Threshold Quantities for Tier-2 (Outdoor)	Threshold Quantities for Tier-2 (Indoor)
Crude oil less than equal to 15 API Gravity (unless actual flash point available)	1000 kg (2200 lb)	100 kg (220 lb)	100 kg (220 lb)	50 kg (110 lb)
Crude oil greater than 15 API Gravity (unless actual flash point available)	2000 kg (4400 lb)	200 kg (440 lb)	200 kg (440 lb)	100 kg (220 lb)

Based on Corrosivity

- Threshold Quantities for Corrosivity

Description	Threshold Quantities for Tier-1 (Outdoor)	Threshold Quantities for Tier-1 (Indoor)	Threshold Quantities for Tier-2 (Outdoor)	Threshold Quantities for Tier-2 (Indoor)
Strong acids/bases, (substances with GHS Skin Corrosion Category 1A (exposure less than equal to 3 minutes during an observation period less than equal than 1 hour) or substances with pH less than 1 or pH greater than 12.5	N/A	N/A	1000 kg (2200 lb)	500 kg (1100 lb)

Flowchart for CR Statement Classification



Example for OR Statement Usage

Styrene

Source of MSDS: fishersci [9]

Step -1: Check the toxic LC50 Inhalation

LC50 = 11.7 mg/L

LC50 = 2746.66 ppm

We should use toxic liquid as the physical state is liquid

Pi = 7 mbar = 0.7 kPa

$$V_i = 0.7 \times \frac{10^6}{101.3} = 6910.17\, mL/m^3$$

Vi > LC50, LC50 < 3000

So,

Tier I (Outdoor) = 1000 kg (2200 lb)

Tier I (Indoor) = 100 kg (220 lb)

Tier II (Outdoor) = 100 kg (220 lb)

Tier II (Indoor) = 50 kg (110 lb)

Methanol

Source: Pioneer Forensics [10]

Step -1: Check the toxic LC50 Inhalation

LC50 = 81778.67 ppm for 4 hrs

LC50 > 5000 ppm

Step-2: Check the boiling point and flash point

Boiling point = 64.7 °C

Flash point = 12 °C

Using flammability classification

Tier I (Outdoor) = 1000 kg (2200 lb)

Tier I (Indoor) = 100 kg (220 lb)

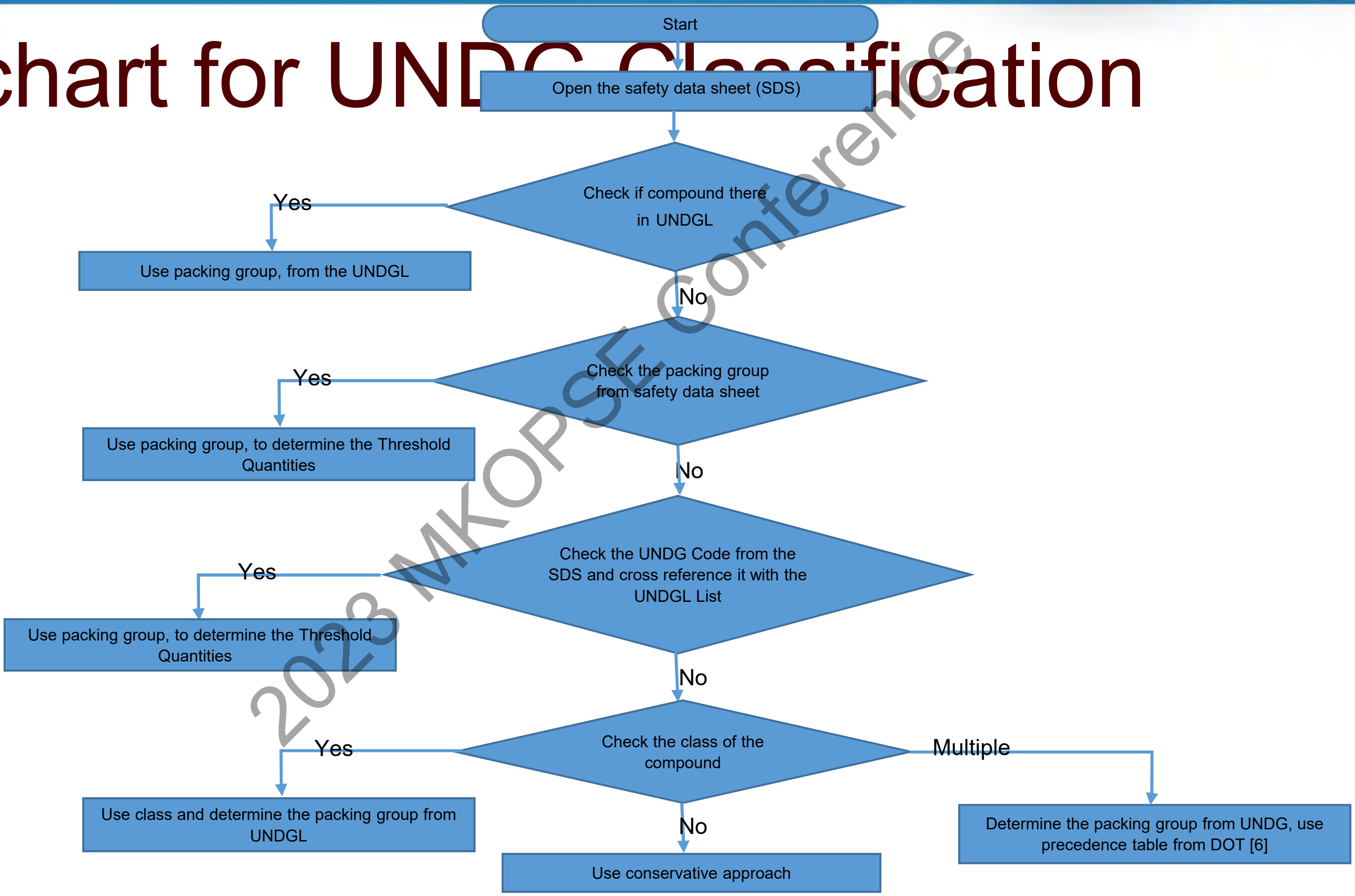
Tier II (Outdoor) = 100 kg (220 lb)

Tier II (Indoor) = 50 kg (110 lb)

Sodium Hydroxide

Source of MSDS: DCM Shriram [11]
Step -1: Check the toxic LC50 Inhalation
LC50 = Not available
Step-2: Check the boiling point and flash point
Boiling point = Not available
Flash point = Not available
Step-3: Check the oral, dermal and inhalation dusts and mists
Oral, dermal and inhalation dusts and mists = Not available
Step-4: Check pH and skin corrosivity category
pH = 13 to 14
Using corrosivity classification
Tier I (Outdoor) = NA
Tier I (Indoor) = NA
Tier II (Outdoor) = 1000 kg (2200 lb)
Tier II (Indoor) = 500 kg (1100 lb)

Flowchart for UNDG Classification



Start

Open the safety data sheet (SDS)

Check if compound there in UNDGL

Yes

Use packing group, from the UNDGL

No

Check the packing group from safety data sheet

Yes

Use packing group, to determine the Threshold Quantities

No

Check the UNDG Code from the SDS and cross reference it with the UNDGL List

Yes

Use packing group, to determine the Threshold Quantities

No

Check the class of the compound

Yes

Use class and determine the packing group from UNDGL

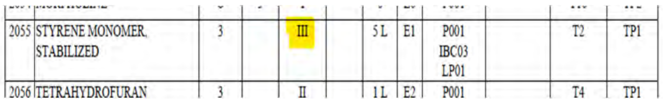
No

Use conservative approach

Multiple

Determine the packing group from UNDG, use precedence table from DOT [6]

Example for UNDG Classification



2055	STYRENE MONOMER, STABILIZED	3		III		5 L	E1	P001 IBC03 LP01		T2	TP1
2056	TETRAHYDROFURAN	3		II		1 L	E2	P001		T4	TP1

It is classified in Class 3, Packing Group III

So

Tie

Tie

Tie

UN-N

Prope

Hazar

Packi

Ste

So

Cla

So

Tie

Tie

Tie

Tie

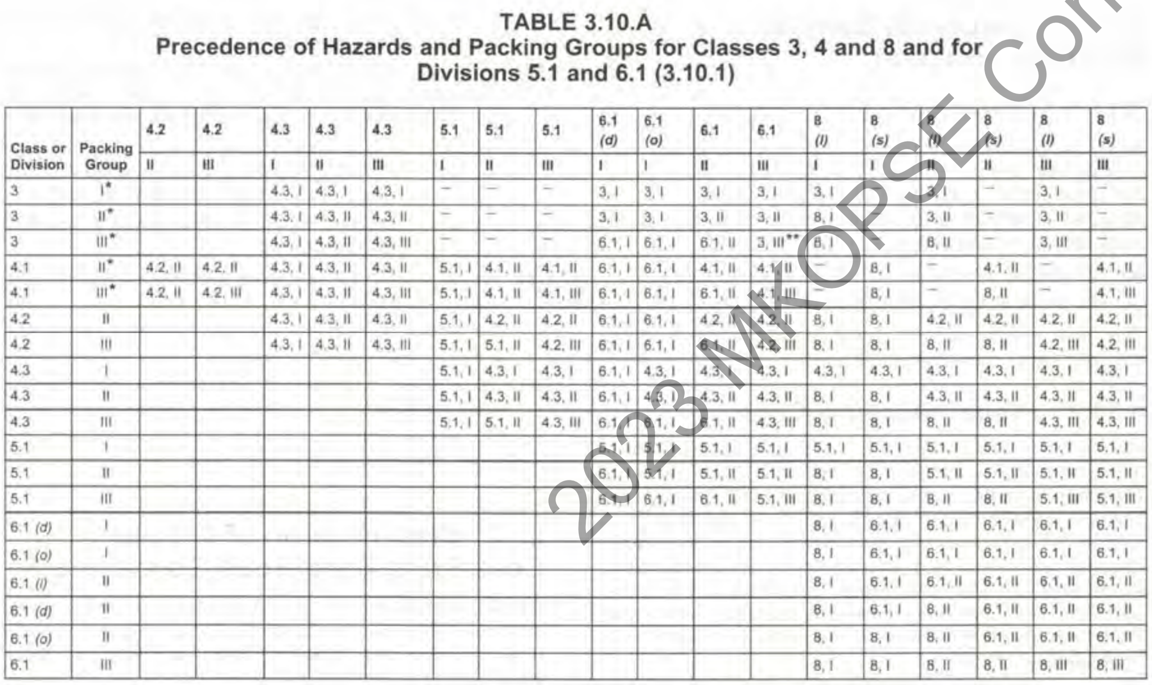


TABLE 3.10.A
Precedence of Hazards and Packing Groups for Classes 3, 4 and 8 and for Divisions 5.1 and 6.1 (3.10.1)

Class or Division	Packing Group	4.2	4.2	4.3	4.3	4.3	5.1	5.1	5.1	6.1 (d)	6.1 (o)	6.1	6.1	8 (l)	8 (s)	8 (l)	8 (s)	8 (l)	8 (s)
		II	III	I	II	III	I	II	III	I	I	II	III	I	I	II	II	III	III
3	I*			4.3, I	4.3, I	4.3, I	—	—	—	3, I	3, I	3, I	3, I	3, I	—	3, I	—	3, I	—
3	II*			4.3, I	4.3, II	4.3, II	—	—	—	3, I	3, I	3, II	3, II	8, I	—	3, II	—	3, II	—
3	III*			4.3, I	4.3, II	4.3, III	—	—	—	6.1, I	6.1, I	6.1, II	3, III**	8, I	—	8, II	—	3, III	—
4.1	II*	4.2, II	4.2, II	4.3, I	4.3, II	4.3, II	5.1, I	4.1, II	4.1, II	6.1, I	6.1, I	4.1, II	4.1, II	—	8, I	—	4.1, II	—	4.1, II
4.1	III*	4.2, II	4.2, III	4.3, I	4.3, II	4.3, III	5.1, I	4.1, II	4.1, III	6.1, I	6.1, I	6.1, II	4.1, III	—	8, I	—	8, II	—	4.1, III
4.2	II			4.3, I	4.3, II	4.3, II	5.1, I	4.2, II	4.2, II	6.1, I	6.1, I	4.2, II	4.2, II	8, I	8, I	4.2, II	4.2, II	4.2, II	4.2, II
4.2	III			4.3, I	4.3, II	4.3, III	5.1, I	5.1, II	4.2, III	6.1, I	6.1, I	6.1, II	4.2, III	8, I	8, I	8, II	8, II	4.2, III	4.2, III
4.3	I						5.1, I	4.3, I	4.3, I	6.1, I	4.3, I	4.3, I	4.3, I	4.3, I	4.3, I	4.3, I	4.3, I	4.3, I	4.3, I
4.3	II						5.1, I	4.3, II	4.3, II	6.1, I	4.3, I	4.3, II	4.3, II	8, I	8, I	4.3, II	4.3, II	4.3, II	4.3, II
4.3	III						5.1, I	5.1, II	4.3, III	6.1, I	6.1, I	6.1, II	4.3, III	8, I	8, I	8, II	8, II	4.3, III	4.3, III
5.1	I									5.1, I	5.1, I	5.1, I	5.1, I	5.1, I	5.1, I	5.1, I	5.1, I	5.1, I	5.1, I
5.1	II									6.1, I	5.1, I	5.1, II	5.1, II	8, I	8, I	5.1, II	5.1, II	5.1, II	5.1, II
5.1	III									6.1, I	6.1, I	6.1, II	5.1, III	8, I	8, I	8, II	8, II	5.1, III	5.1, III
6.1 (d)	I													8, I	6.1, I	6.1, I	6.1, I	6.1, I	6.1, I
6.1 (o)	I													8, I	6.1, I	6.1, I	6.1, I	6.1, I	6.1, I
6.1 (i)	II													8, I	6.1, I	6.1, II	6.1, II	6.1, II	6.1, II
6.1 (d)	II													8, I	6.1, I	8, II	6.1, II	6.1, II	6.1, II
6.1 (o)	II													8, I	8, I	8, II	6.1, II	6.1, II	6.1, II
6.1	III													8, I	8, I	8, II	8, II	8, III	8, III

Tier II (Indoor) = 50 kg (110 lb)

Methanol

Source: Pioneer Forensics [10]

Step -1: Check if the compound there in UNDGL

Let us assume, the packing group is not there in the SDS as well

Step-3: Check the class the compound

Source of MSDS: Sigma Aldrich [12]

Class of methanol 3, packing group II and 6.1 packing group II

Based on Precedence Table [6], Class 3 Packing Group II is preferred

So,

Tier I (Outdoor) = 1000 kg (2200 lb)

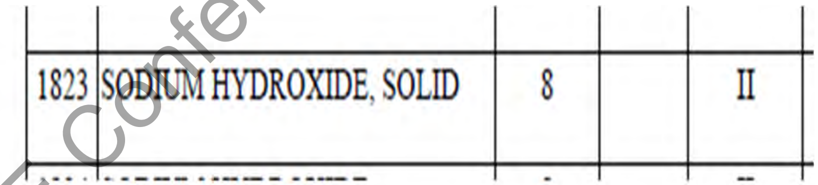
Tier I (Indoor) = 100 kg (220 lb)

Tier II (Outdoor) = 100 kg (220 lb)

Tier II (Indoor) = 50 kg (110 lb)

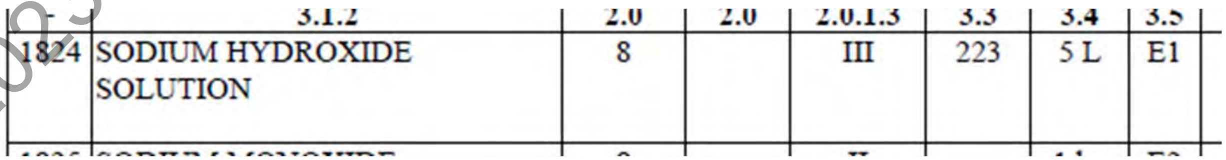
Example for UNDG Classification

Sodium Hydroxide



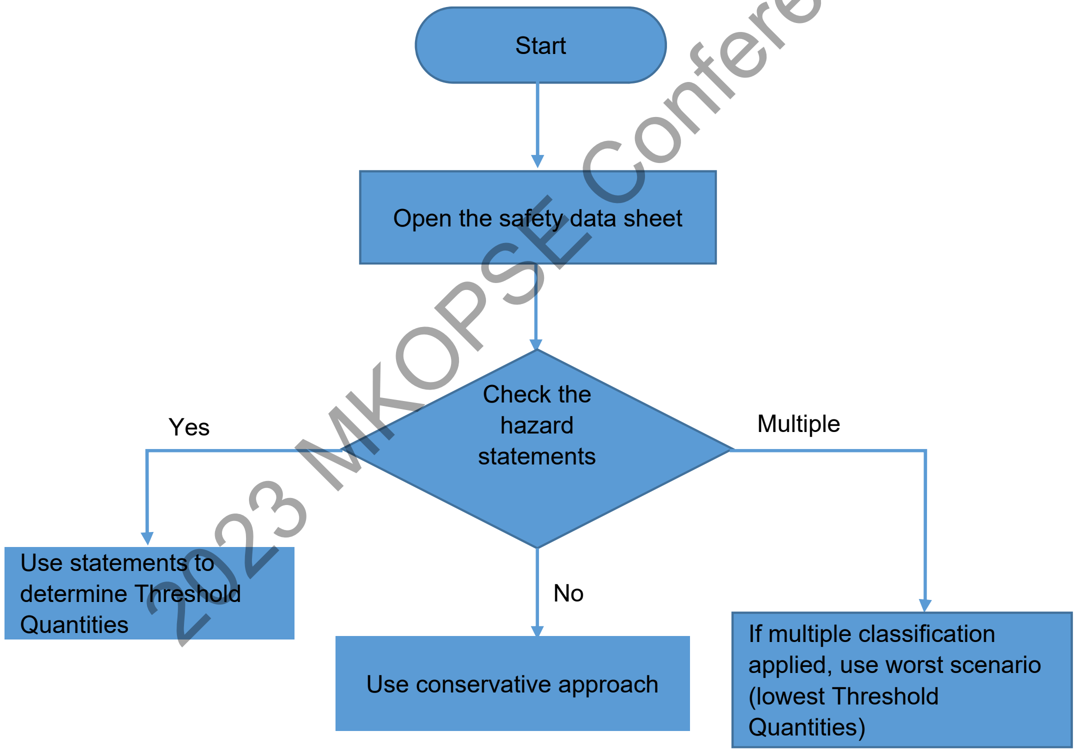
1823	SODIUM HYDROXIDE, SOLID	8		II

Step -1: Check if the compound there in UNDGL
In this case, refer to the physical properties if solid or vapor and then decide the packing group. Here let us assume its solid
It is classified has packing group II
So,
Tier I (Outdoor) = 1000 kg (2200 lb)
Tier I (Indoor) = 100 kg (220 lb)
Tier II (Outdoor) = 100 kg (220 lb)
Tier II (Indoor) = 50 kg (110 lb)



-	3.1.2	2.0	2.0	2.0.1.3	3.3	3.4	3.5
1824	SODIUM HYDROXIDE SOLUTION	8		III	223	5 L	E1

Flowchart for GHS Classification



Start

Open the safety data sheet

Check the hazard statements

Yes

Use statements to determine Threshold Quantities

No

Use conservative approach

Multiple

If multiple classification applied, use worst scenario (lowest Threshold Quantities)

Example for GHS

Styrene

Source of MSDS: eChem Portal [13]

The hazard statements are

H226 – Flammable Liquid Category 3

H315 – Skin Irritation Category 2

H319 - Eye Irritation Category 2

H332 - Acute Toxicity Category 4

Based on the hazard statements H332 - Acute Toxicity Category 4, is having the lowest threshold quantities

So,

Tier I (Outdoor) = 200 kg (440 lb)

Tier I (Indoor) = 20 kg (44 lb)

Tier II (Outdoor) = 20 kg (44 lb)

Tier II (Indoor) = 10 kg (22 lb)

Methanol

Source of MSDS: eChem Portal [14]

The hazard statements are

H225 – Flammable Liquid Category 2

H301 – Acute Toxicity Category 3

H311 - Acute Toxicity Category 3

H331 - Acute Toxicity Category 3

Based on the hazard statements H331 - Acute Toxicity Category 3, is having the lowest threshold quantities

So,

Tier I (Outdoor) = 100 kg (220 lb)

Tier I (Indoor) = 10 kg (22 lb)

Tier II (Outdoor) = 10 kg (22 lb)

Tier II (Indoor) = 5 kg (11 lb)

Sodium Hydroxide

Source of MSDS: eChem Portal [15]

The hazard statements are

H314 – Skin Corrosion Category 1A

H319 – Eye Irritation Category 2

H315 – Skin Irritation Category 2

Based on the hazard statements H314 - Skin Corrosion Category 1A, is having the lowest threshold quantities

So,

Tier I (Outdoor) = NA

Tier I (Indoor) = NA

Tier II (Outdoor) = 1000 kg (2200 lb)

Tier II (Indoor) = 500 kg (1100 lb)

Conclusion

Compounds	OR Statement	United Nations Dangerous Goods Packing Group, UNDGL	GHS Method
Styrene	Tier I (Outdoor) = 1000 kg (2200 lb)	Tier I (Outdoor) = 2000 kg (4400 lb)	Tier I (Outdoor) = 200 kg (440 lb)
	Tier I (Indoor) = 100 kg (220 lb)	Tier I (Indoor) = 200 kg (440 lb)	Tier I (Indoor) = 20 kg (44 lb)
	Tier II (Outdoor) = 100 kg (220 lb)	Tier II (Outdoor) = 200 kg (440 lb)	Tier II (Outdoor) = 20 kg (44 lb)
	Tier II (Indoor) = 50 kg (110 lb)	Tier II (Indoor) = 100 kg (220 lb)	Tier II (Indoor) = 10 kg (22 lb)
		Assumption 1 – Based on the MSDS	
		Tier I (Outdoor) = 2000 kg (4400 lb)	
		Tier I (Indoor) = 200 kg (440 lb)	
		Tier II (Outdoor) = 200 kg (440 lb)	
		Tier II (Indoor) = 100 kg (220 lb)	
Methanol	Tier I (Outdoor) = 1000 kg (2200 lb)	Tier I (Outdoor) = 1000 kg (2200 lb)	Tier I (Outdoor) = 100 kg (220 lb)
	Tier I (Indoor) = 100 kg (220 lb)	Tier I (Indoor) = 100 kg (220 lb)	Tier I (Indoor) = 10 kg (22 lb)
	Tier II (Outdoor) = 100 kg (220 lb)	Tier II (Outdoor) = 100 kg (220 lb)	Tier II (Outdoor) = 10 kg (22 lb)
	Tier II (Indoor) = 50 kg (110 lb)	Tier II (Indoor) = 50 kg (110 lb)	Tier II (Indoor) = 5 kg (11 lb)
		Assumption 1 – Based on the MSDS	
		Tier I (Outdoor) = 1000 kg (2200 lb)	
		Tier I (Indoor) = 100 kg (220 lb)	
		Tier II (Outdoor) = 100 kg (220 lb)	
		Tier II (Indoor) = 50 kg (110 lb)	
		Assumption 2 - Based on the class	
		Tier I (Outdoor) = 1000 kg (2200 lb)	
		Tier I (Indoor) = 100 kg (220 lb)	
		Tier II (Outdoor) = 100 kg (220 lb)	
		Tier II (Indoor) = 50 kg (110 lb)	
Sodium Hydroxide	Tier I (Outdoor) = NA	Tier I (Outdoor) = 1000 kg (2200 lb)	Tier I (Outdoor) = NA
	Tier I (Indoor) = NA	Tier I (Indoor) = 100 kg (220 lb)	Tier I (Indoor) = NA
	Tier II (Outdoor) = 1000 kg (2200 lb)	Tier II (Outdoor) = 100 kg (220 lb)	Tier II (Outdoor) = 1000 kg (2200 lb)
	Tier II (Indoor) = 500 kg (1100 lb)	Tier II (Indoor) = 50 kg (110 lb)	Tier II (Indoor) = 500 kg (1100 lb)

Conclusion

- Based on the three approaches, a company has to use a consistent approach for all the compounds.
- Choosing the Safety Data Sheet (SDS) is the key factor, company should use an appropriate safety data sheet during the process of classification.
- Company has to decide a conversative approach for the classification.
- Above table shows that different Threshold Quantities can be obtained when using the various approaches.
- The GHS classification is most conservative due to the lower threshold values.
- Companies dealing with many coded/special chemicals with global operations must determine the best classification method and consistent so that they can obtain proper process safety metrics across various sites.

Thank You

Hema Divya – khdivya@gmail.com
Rahul Raman – rahul@kaypear.com

NATIONAL ACADEMIES *Sciences Engineering Medicine*

The work of the Gulf Research Program in offshore safety

MKO Process Safety & Risk Conference

11 October 2023

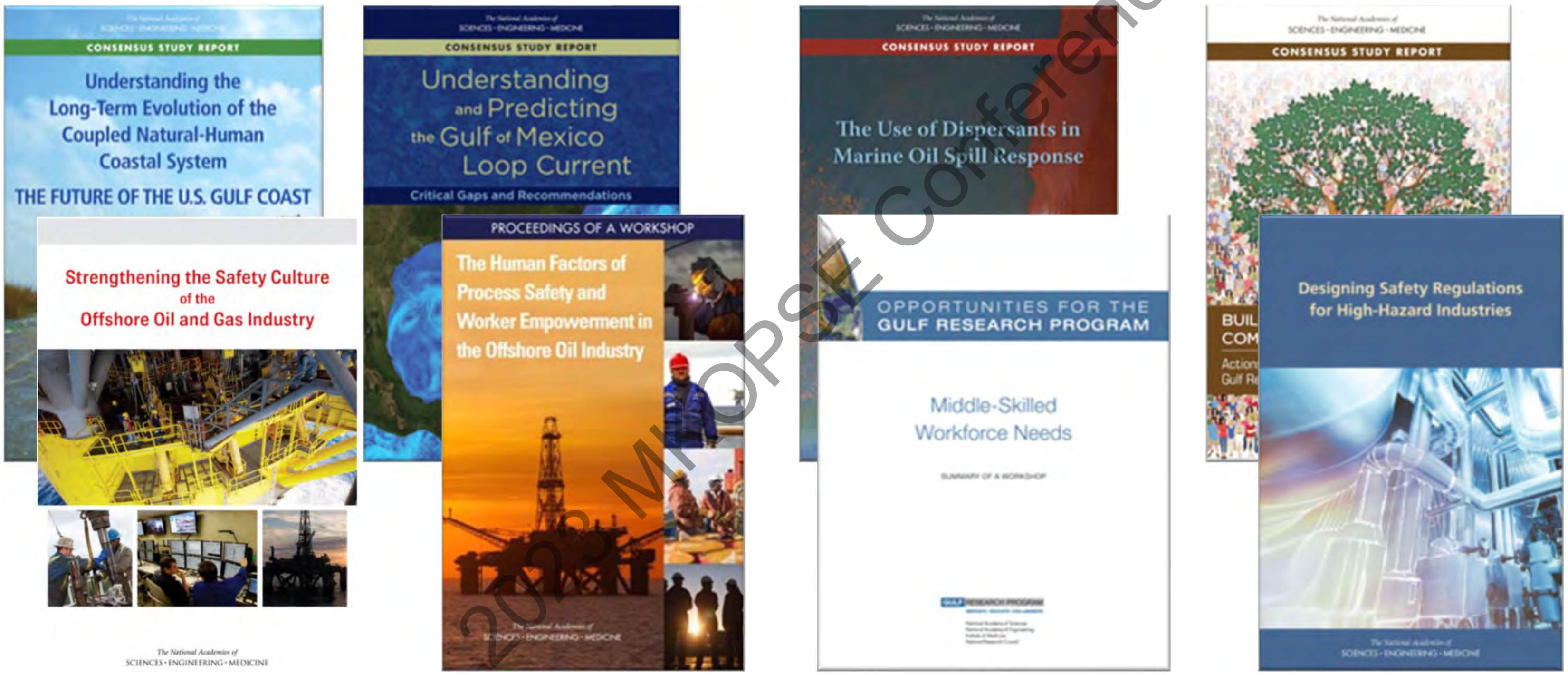
Hallie Graham

Jim Pettigrew, CAPT, USN (Ret),
Board Director

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE

- Advisors to the Nation on sciences, engineering, and medicine.
- NAS created in 1863 under Lincoln Administration.
- Non-profit, non-governmental organization
- The National Academies is the umbrella term for NAS, NAE, and NAM.
- Strengths of our work:
  - Independence
  - Scientific objectivity
  - Balance

CONSENSUS STUDIES & WORKSHOPS



CONSENSUS STUDY REPORT

Understanding the Long-Term Evolution of the Coupled Natural-Human Coastal System

THE FUTURE OF THE U.S. GULF COAST

Strengthening the Safety Culture of the Offshore Oil and Gas Industry

The National Academies of SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

Understanding and Predicting the Gulf of Mexico Loop Current

Critical Gaps and Recommendations

PROCEEDINGS OF A WORKSHOP

The Human Factors of Process Safety and Worker Empowerment in the Offshore Oil Industry

The National Academies of SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

The Use of Dispersants in Marine Oil Spill Response

OPPORTUNITIES FOR THE GULF RESEARCH PROGRAM

Middle-Skilled Workforce Needs

SUMMARY OF A WORKSHOP

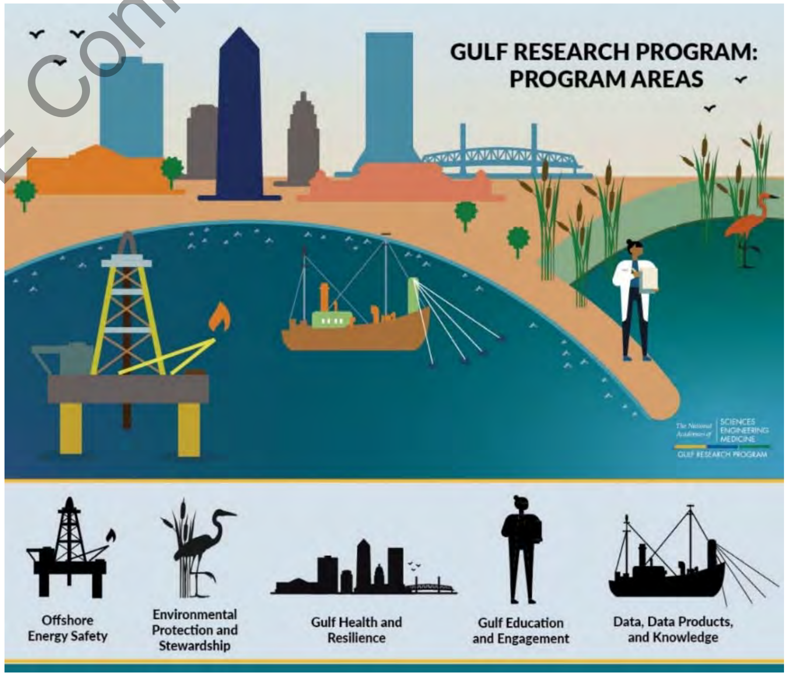
CONSENSUS STUDY REPORT

Designing Safety Regulations for High-Hazard Industries

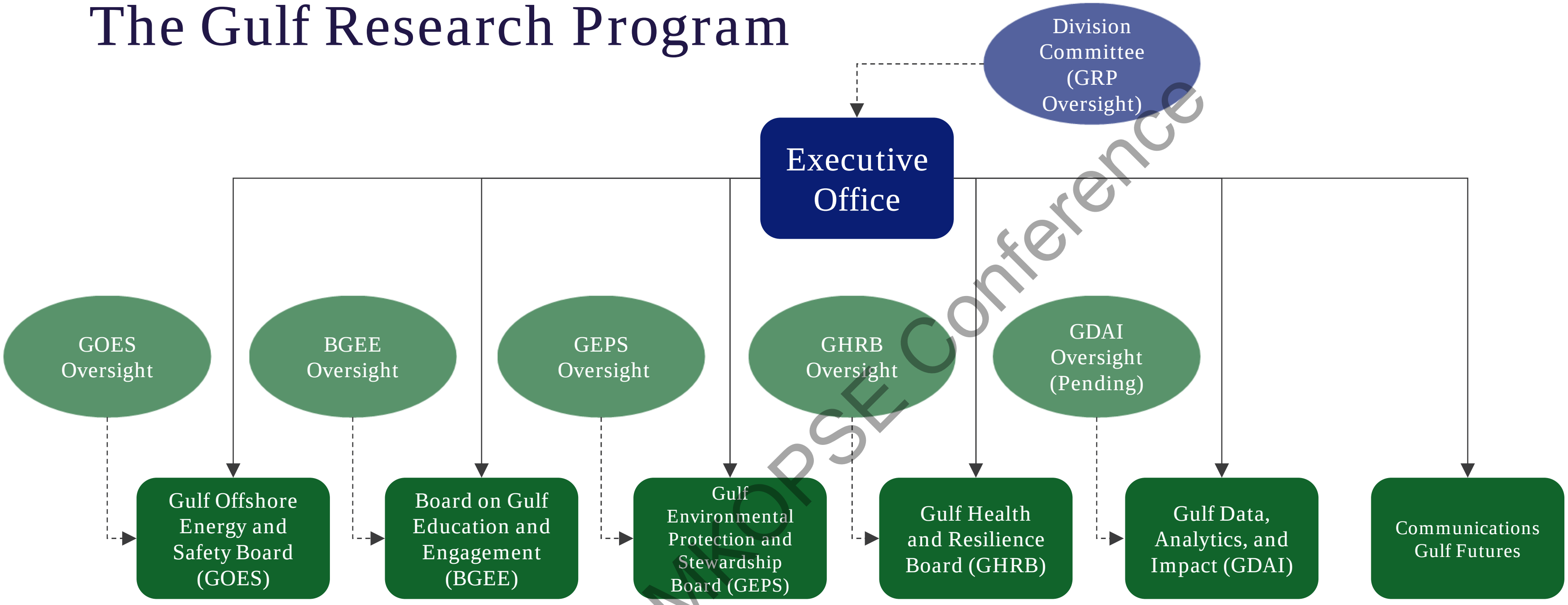
The National Academies of SCIENCES · ENGINEERING · MEDICINE

THE GULF RESEARCH PROGRAM (GRP)

- A 30-year program (2013 - 2043) managed by the National Academies.
- Funds research grants, fellowships, studies, and other activities.
- Operate in five areas:
  - Offshore energy safety
  - Environmental protection and stewardship
  - Human health and resilience
  - Education and engagement
  - Data, analysis, and information



The Gulf Research Program



Division Committee (GRP Oversight)

Executive Office

GOES Oversight

BGEE Oversight

GEPS Oversight

GHRB Oversight

GDAI Oversight (Pending)

Gulf Offshore Energy and Safety Board (GOES)

Board on Gulf Education and Engagement (BGEE)

Gulf Environmental Protection and Stewardship Board (GEPS)

Gulf Health and Resilience Board (GHRB)

Gulf Data, Analytics, and Impact (GDAI)

Communications Gulf Futures

NATIONAL ACADEMIES Sciences Engineering Medicine

GULF RESEARCH PROGRAM

Offshore Energy Safety Board

Contribute to the reduction of systemic risk across offshore energy activities

…issues concerning the safety of offshore oil drilling and hydrocarbon {*Energy*} production and transportation in the Gulf of Mexico and on the United States' outer continental shelf.

NATIONAL ACADEMIES Sciences Engineering Medicine

GULF RESEARCH PROGRAM

GOES BOARD

- San Burnett, *BHP* (Chair)
- Najm Meshkati, *USC*
- Monica Phillipart, *EHFS*
- Roland Moreau, *ExxonMobil*
- Terrance Sookdeo, *Baker Hughes*
- Dustin Torkay, *Seadrill*
- Sylvie Tran, *Suncor Energy*
- Latonia Batiste, *WSP USA*
- Michael Will, *MRW Ops*
- Ding Zhu, *TAMU*
- Mike Drieu, *Occidental Offshore, US*

NATIONAL ACADEMIES Sciences Engineering Medicine

GULF RESEARCH PROGRAM

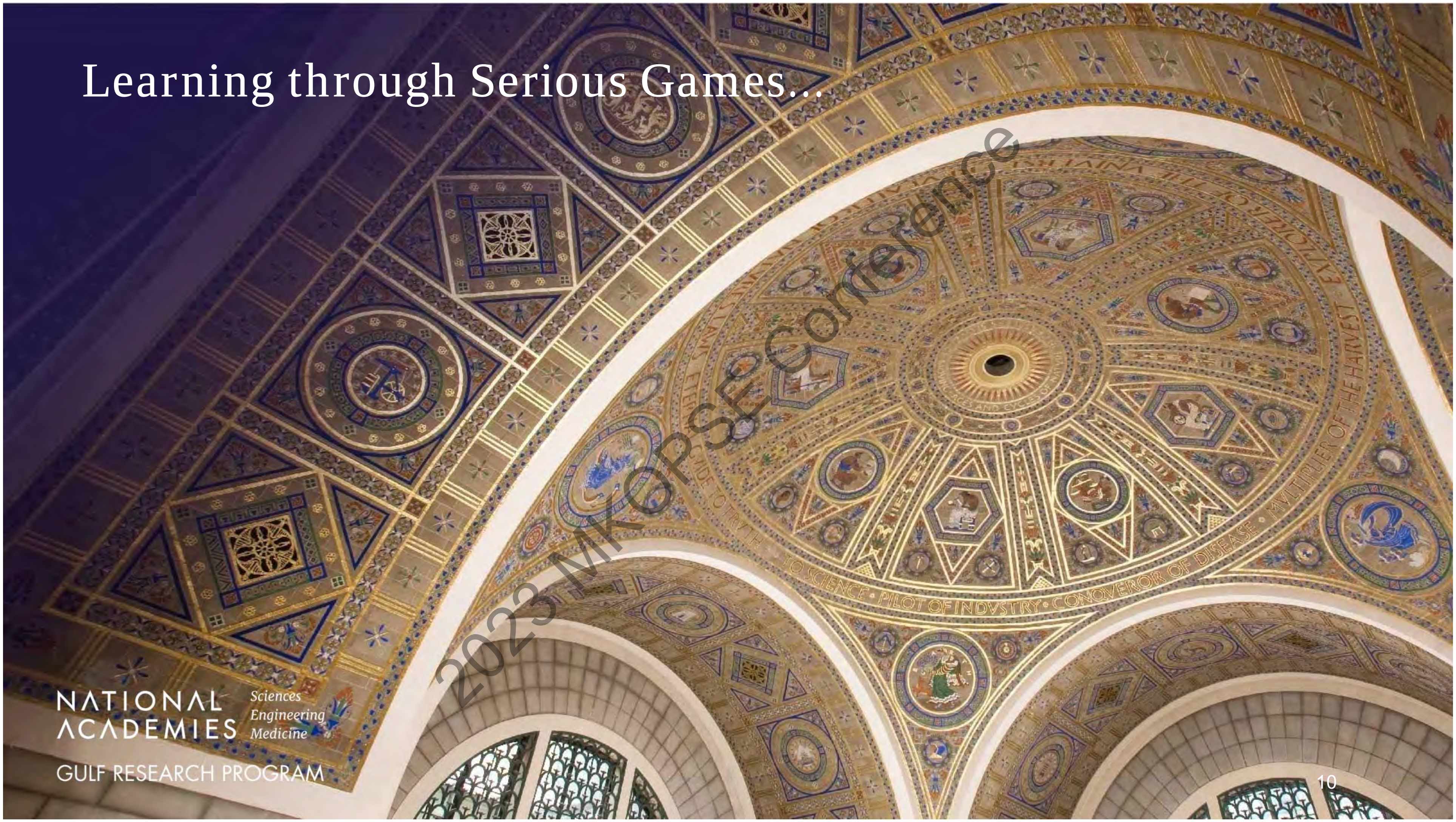
The overarching goal for the GRP’s Offshore Energy Safety (GOES) program area is to contribute to the management of systemic risk and improve operational safety for offshore energy activities. Additionally, lead GRP efforts related to the Energy Transition

Learning…

NATIONAL ACADEMIES *Sciences Engineering Medicine*

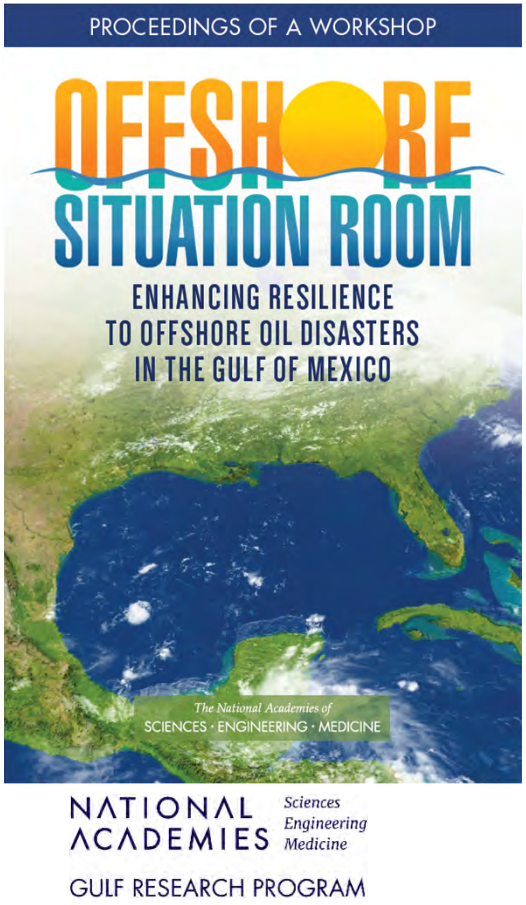
GULF RESEARCH PROGRAM

Learning through Serious Games…



NATIONAL ACADEMIES *Sciences Engineering Medicine*
GULF RESEARCH PROGRAM

Oil Spill response and restoration…


PROCEEDINGS OF A WORKSHOP

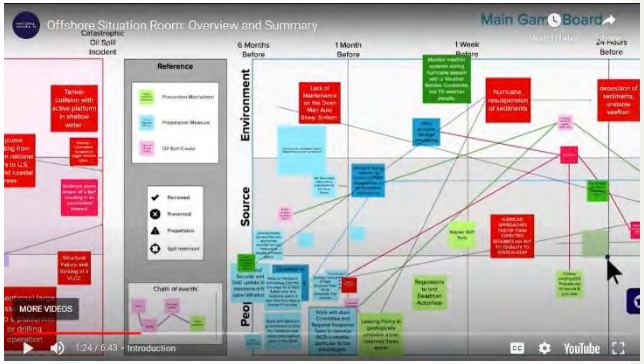
OFFSHORE SITUATION ROOM

ENHANCING RESILIENCE
TO OFFSHORE OIL DISASTERS
IN THE GULF OF MEXICO

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

NATIONAL ACADEMIES *Sciences Engineering Medicine*

GULF RESEARCH PROGRAM



Navigating the Energy Transition in the Gulf of Mexico, a Workshop

- How do we achieve 2050 goals?
- Bring together diverse stakeholders
- Look for GRP opportunities

NATIONAL ACADEMIES Sciences Engineering Medicine

GULF RESEARCH PROGRAM

Fellowships

NATIONAL ACADEMIES Sciences Engineering Medicine

GULF RESEARCH PROGRAM

Early-Career Research Fellows:

- Receive two years of funding to pursue innovative research paths
- Connect with a network of researchers across disciplines
- Build research skills and confidence with the support of a mentor

Science Policy Fellows:

- Gain a year of hands-on experience alongside decision-makers in the Gulf of Mexico region
- Connect with a network of colleagues at their host office
- Build skills with professional development opportunities and the guidance of a mentor

Legacy Infrastructure, Decommissioning…

- Legacy Infrastructure
  - End of service life of platforms and structures
  - Abandoned pipelines
  - Transition to enabling new energy sources

Legacy oil and gas infrastructure in the Gulf of Mexico: environmental, conservation, and research perspectives

NATIONAL ACADEMIES Sciences Engineering Medicine

GULF RESEARCH PROGRAM

- Decommissioning
  - Meeting of Experts, 14-15 September, Houston, TX

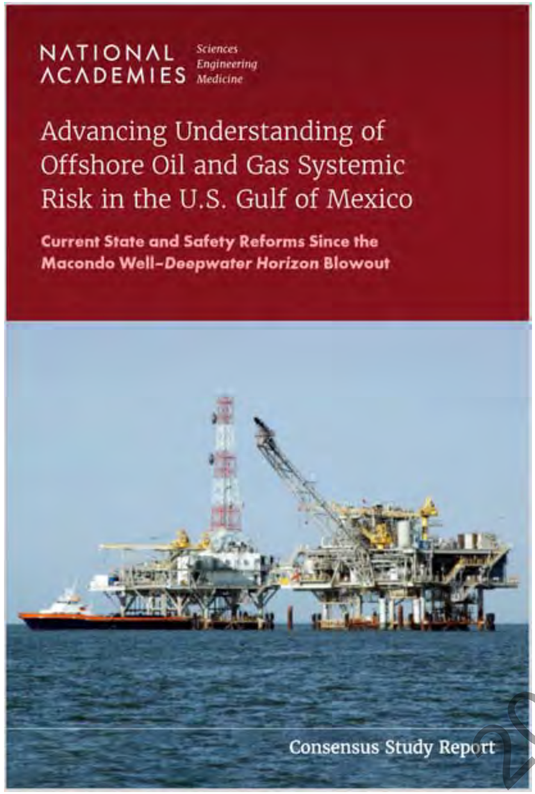
NATIONAL ACADEMIES *Sciences Engineering Medicine*

GULF RESEARCH PROGRAM

Safer Offshore Energy Systems (SOES) Grants

- Previous SOES Grants (~$20M)
  - Advancing Safety Culture in the Offshore Oil and Gas Industry
  - Preventing the Next Spill: Understanding Systemic Risk in the Offshore Oil and Gas Environment
  - Scenario Planning to Advance Safety Culture and Minimize Risk in Offshore Oil and Gas Operations
  - Exploring Approaches for Effective Education and Training of Workers in the Offshore Oil and Gas Industry and Health Professions
- Current SOES Grants (~$5M)
  - Evolution of Offshore Energy Safety Management Systems
- Future SOES efforts
  - Reduction of risk during offshore oil and gas decommissioning activities
  - Increasing awareness of leading indicators and barrier health through artificial intelligence and machine learning

Consensus Study


NATIONAL ACADEMIES Sciences Engineering Medicine

Advancing Understanding of Offshore Oil and Gas Systemic Risk in the U.S. Gulf of Mexico

Current State and Safety Reforms Since the Macondo Well–*Deepwater Horizon* Blowout

Consensus Study Report

- Define the current profile of systemic risks of offshore oil and gas operations in the Gulf of Mexico.

- Assess the impact of technological, regulatory, environmental, organizational, and process changes.

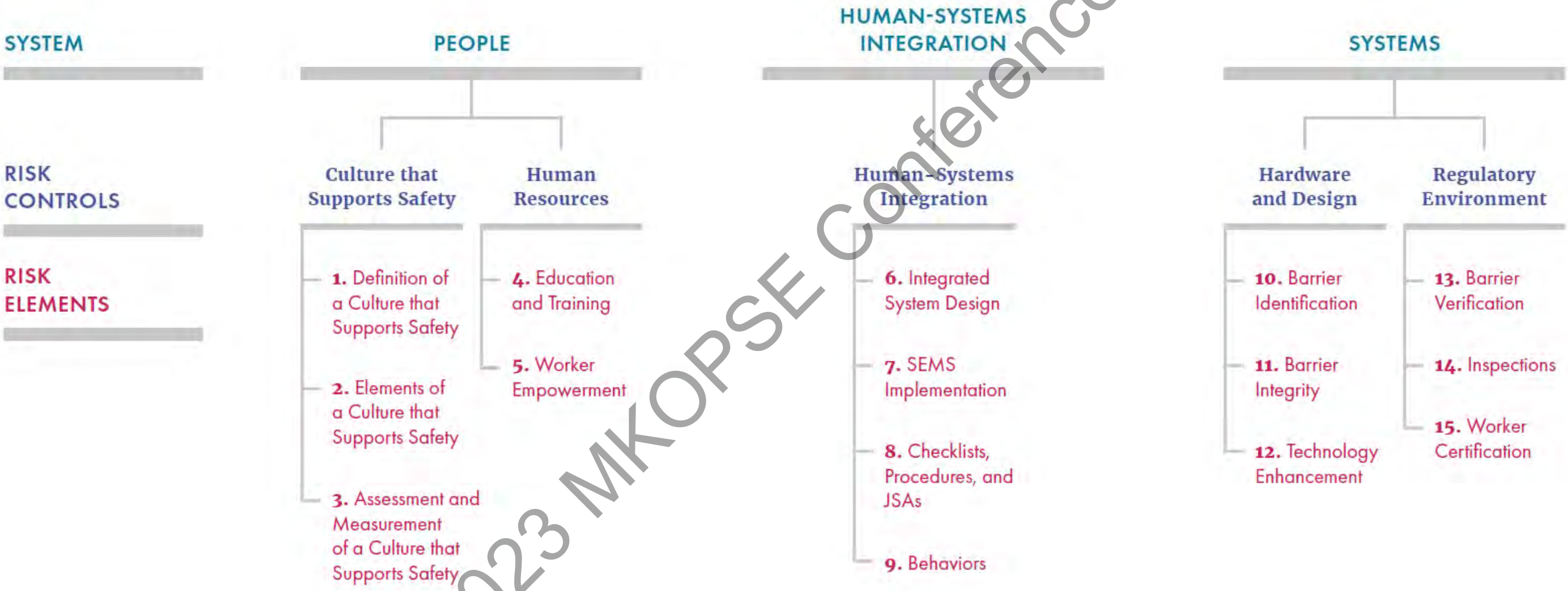
- Consider the impact of the regulatory structure.

- Assess the impact and potential of GRP.

NATIONAL ACADEMIES Sciences Engineering Medicine

GULF RESEARCH PROGRAM

RISK PROFILE FOR OFFSHORE OIL AND GAS



SYSTEM

RISK CONTROLS

RISK ELEMENTS

PEOPLE

- **Culture that Supports Safety**
  - **1.** Definition of a Culture that Supports Safety
  - **2.** Elements of a Culture that Supports Safety
  - **3.** Assessment and Measurement of a Culture that Supports Safety
- **Human Resources**
  - **4.** Education and Training
  - **5.** Worker Empowerment

HUMAN-SYSTEMS INTEGRATION

- **Human-Systems Integration**
  - **6.** Integrated System Design
  - **7.** SEMS Implementation
  - **8.** Checklists, Procedures, and JSAs
  - **9.** Behaviors

SYSTEMS

- **Hardware and Design**
  - **10.** Barrier Identification
  - **11.** Barrier Integrity
  - **12.** Technology Enhancement
- **Regulatory Environment**
  - **13.** Barrier Verification
  - **14.** Inspections
  - **15.** Worker Certification

NATIONAL ACADEMIES *Sciences Engineering Medicine*

GULF RESEARCH PROGRAM

Moving forward into the future of the Gulf of Mexico

Questions?

Jim Pettigrew
jpettigrew@nas.edu

NATIONAL ACADEMIES *Sciences Engineering Medicine*
GULF RESEARCH PROGRAM

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

Texas A&M Engineering Experiment Station

Mary Kay O'Connor
Process Safety Center

78th Annual Instrumentation and Automation Symposium

Securing Industrial Control Systems

Implementing Zero Trust Architecture in OT Environments

That's the way we've always done it…

- *"The most damaging phrase in the language is 'We've always done it this way'."*
    - *Rear Admiral Grace Murray Hopper – Developer for COBOL coding language*
- How many times do we say this phrase to justify work processes and other actions? Is it safe just because "nothing bad happened before?"
- Alternative is Continuous Improvement
    - Turn the question around: **"Why do we do it this way?"**

Speaker profile

wood.

- Brad Mozisek
  - OPA COE Program Manager/Automation and Control Lead
  - Brad has over 15 years of experience in the Refining, Oil and Gas, Chemical, Offshore and Onshore industries. Brad currently manages Wood's Center of Excellence for OPA. This includes utilizing experience across multiple DCS systems to develop technical solutions including application libraries, sample architectures and technology stacks.

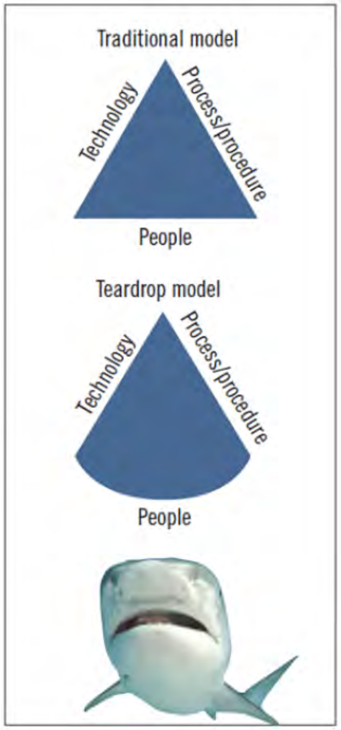
Implicit Trust to Zero Trust

Most common model in OT Today - Quick overview

- **Trusted Connections - Implicit Trust**
  - Perimeter based/Castle and Moat
- Rapidly changing threat base
  - Foundations for trusted Connections are not as stable as the past

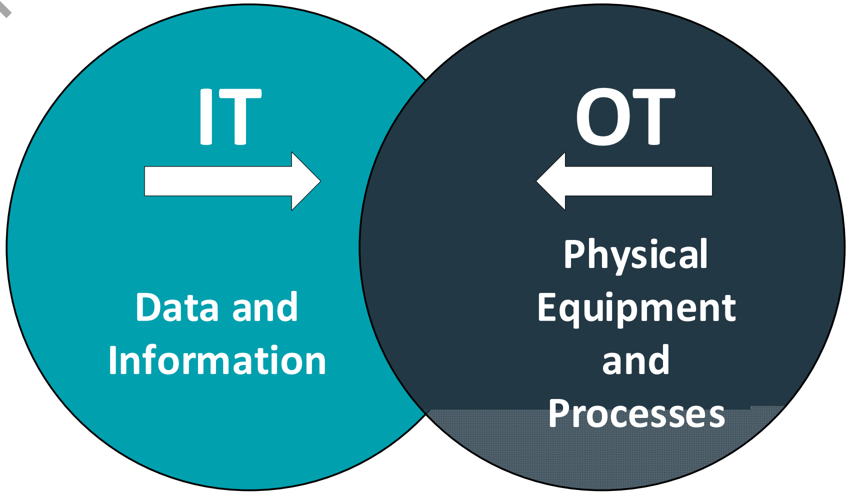
From Implicit trust to Zero Trust

- Zero Trust - Assuming no user or device trust by default
  - As technology advances, People may be the weakest link in security
- "Never Trust, Always Verify"
- Continual re-validation of credentials based on profiles, actions and other information.
  - Least privileged access at any given time.
- Figure:Brad Bonnette - Wood



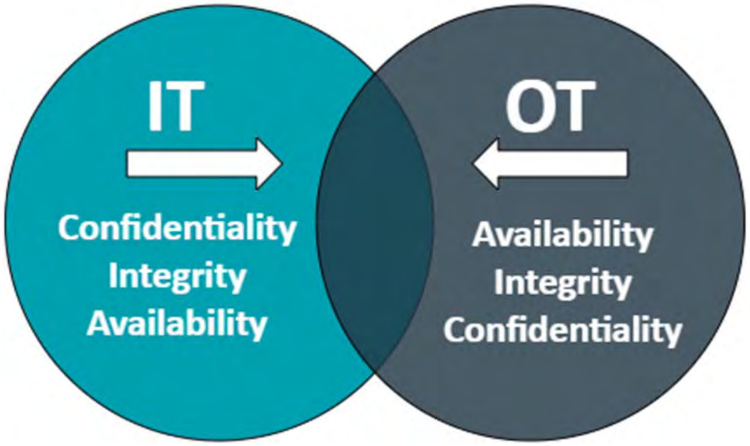
Bringing in IT and other Solutions to OT

- Not entirely new concepts - Online banking and other industries utilizes premises of ZTA today.
- Higher degree of implementation in more IT centric Areas



Bringing in IT and other Solutions to OT

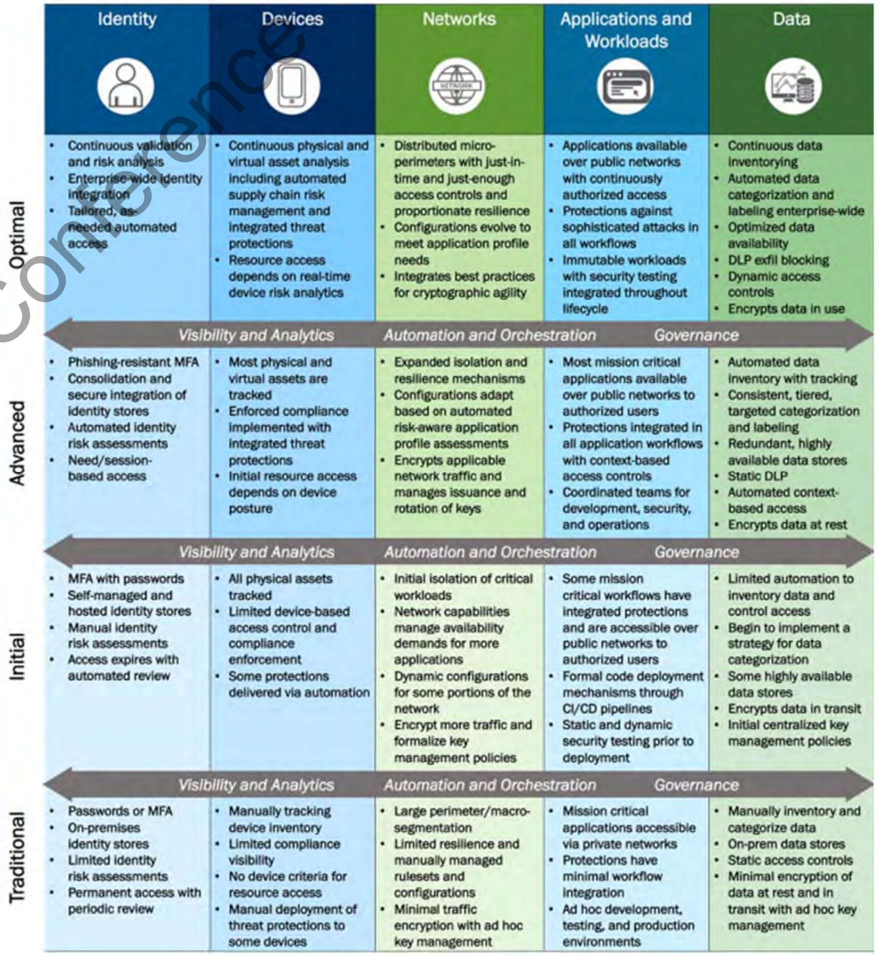
- CIA vs AIC models – Conflicting Interests to always keep in mind
  - Unlike purely digital domains, cyber-attacks in OT environments can have immediate physical consequences.
  - Compromised industrial systems can lead to equipment damage, production disruptions, and even safety hazards.



Long Journey – Not overnight trip

- CISA – Zero Trust Maturity Model – Version 2.0 – April 2023
- Similar to the safety journey - S84/61511
- Iterative

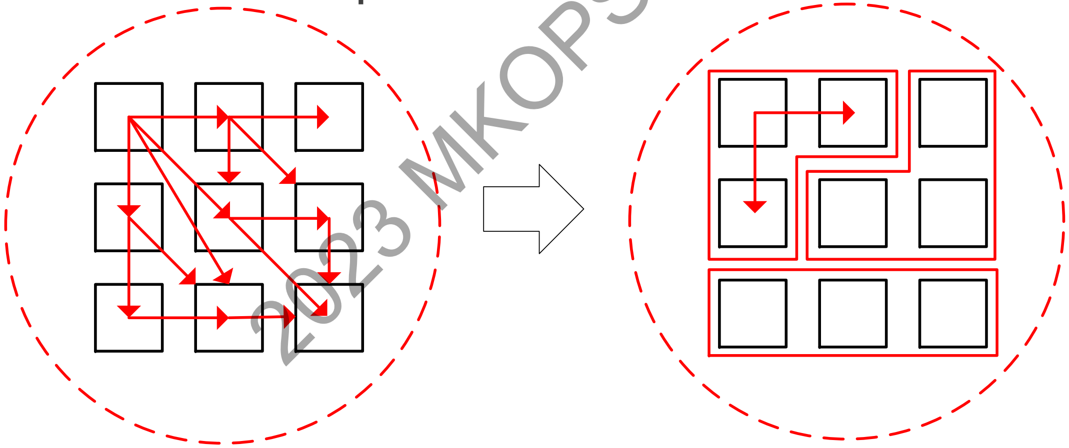
Figure: CISA Zero Trust Maturity Model Version 2.0, April 2023



	Identity	Devices	Networks	Applications and Workloads	Data
Optimal	Continuous validation and risk analysis Enterprise-wide identity integration Tailored, as-needed automated access	Continuous physical and virtual asset analysis including automated supply chain risk management and integrated threat protections Resource access depends on real-time device risk analytics	Distributed micro-perimeters with just-in-time and just-enough access controls and proportionate resilience Configurations evolve to meet application profile needs Integrates best practices for cryptographic agility	Applications available over public networks with continuously authorized access Protections against sophisticated attacks in all workflows Immutable workloads with security testing integrated throughout lifecycle	Continuous data inventorying Automated data categorization and labeling enterprise-wide Optimized data availability DLP exfil blocking Dynamic access controls Encrypts data in use
		Visibility and Analytics	Automation and Orchestration		Governance
Advanced	Phishing-resistant MFA Consolidation and secure integration of identity stores Automated identity risk assessments Need/session-based access	Most physical and virtual assets are tracked Enforced compliance implemented with integrated threat protections Initial resource access depends on device posture	Expanded isolation and resilience mechanisms Configurations adapt based on automated risk-aware application profile assessments Encrypts applicable network traffic and manages issuance and rotation of keys	Most mission critical applications available over public networks to authorized users Protections integrated in all application workflows with context-based access controls Coordinated teams for development, security, and operations	Automated data inventory with tracking Consistent, tiered, targeted categorization and labeling Redundant, highly available data stores Static DLP Automated context-based access Encrypts data at rest
		Visibility and Analytics	Automation and Orchestration		Governance
Initial	MFA with passwords Self-managed and hosted identity stores Manual identity risk assessments Access expires with automated review	All physical assets tracked Limited device-based access control and compliance enforcement Some protections delivered via automation	Initial isolation of critical workloads Network capabilities manage availability demands for more applications Dynamic configurations for some portions of the network Encrypt more traffic and formalize key management policies	Some mission critical workflows have integrated protections and are accessible over public networks to authorized users Formal code deployment mechanisms through CI/CD pipelines Static and dynamic security testing prior to deployment	Limited automation to inventory data and control access Begin to implement a strategy for data categorization Some highly available data stores Encrypts data in transit Initial centralized key management policies
		Visibility and Analytics	Automation and Orchestration		Governance
Traditional	Passwords or MFA On-premises identity stores Limited identity risk assessments Permanent access with periodic review	Manually tracking device inventory Limited compliance visibility No device criteria for resource access Manual deployment of threat protections to some devices	Large perimeter/macro-segmentation Limited resilience and manually managed rulesets and configurations Minimal traffic encryption with ad hoc key management	Mission critical applications accessible via private networks Protections have minimal workflow integration Ad hoc development, testing, and production environments	Manually inventory and categorize data On-prem data stores Static access controls Minimal encryption of data at rest and in transit with ad hoc key management

Granular security – least privilege

- Building point from IEC 62443 -
- Building on zones and conduits down to micro-segmentation
    - Self Contained attack protection – Block attacks before they spread



Best laid plans…

- Today's state of the art is tomorrow open attack vector
- ZTA will not prevent all threats, but continuous improvement can limit any potential damage to systems.
- Monitor and analyze network activity: Set up continuous monitoring of network traffic and user/device behavior, using tools like Security Information and Event Management (SIEM) systems or network traffic analysis software.
- Automate response and remediation: Develop automated response mechanisms to **quickly identify** and **remediate** security threats or policy violations

Moving Forward
Technology Adoption/Adaptation

How do we move forward?

- Incremental Journey with many milestones, not a single large jump.
  - Every step decreased risk – Refer back to CISA Zero Trust Security Model transitions.
- End users/Stakeholders need to continue to engage partnerships – Many existing players in the game today. Workshops along the journey.
  - Assessing Current state of Security
  - Auditing/analyzing OT risk vectors
  - Vendors and integrators need to continue innovate
    - Problem analysis to develop solutions
    - Not solution creation to find problems.
  - CHAZOPs

How do we move forward? – Technology Adoption

- Technology partners within system for secure access, Multi-factor Authentication (MFA, First steppingstone toward ZTA) and Intrusion detection
  - Many partners exist is this space today – Experts in bridging security gaps into the OT spaces
- Secure by Design technology adoption through standards-based technology and protocols
  - Open Process Automation Standards (O-PAS)
  - OPC-UA (adopting full encryption/security paths)
  - IEC 61499 – Event Based programming

O-PAS – Secure by Design

- Open (Not open source!) Standards allow for continuous improvement through new technologies – "Standard of Standards
    - Hardware solutions
    - Software solutions
    - Communication protocols
- Ability to incorporate latest technology to improve security.
- Allows integration with legacy systems while maintaining isolation for security.

Expanding segmentation within OT – Application and HMI

- Technology adoption – adaptation
- Expanding security focus from just systems basis
  - Further focus on application and HMI security for **Least Privileges** approach. Does not exist is most cases today.
    - Does HMI need full time write access to parameters?

Expanding segmentation within OT – Application and HMI

- Ex. Just in time authentication based on operator actions for changing PV or setpoint.
  - Was the request legitimate? Did the request come from a (currently) trust source – Trust needs to be constantly validated, including contextual needs.
    - Did the operator log in to an operator station, Is this a unit the operator is assigned to (We can already do this level)?
  - Secondary authentication with new technologies – robustness is a requirement to ensure reliability.
- **Must maintain operability** while balancing security needs

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

78th Annual Instrumentation and Automation Symposium

Greg Hardin, CFSE

- 50 years as a process engineer, instrument and controls engineer, functional safety practitioner
- Half of career with multi-national chemical firm, half with various engineering firms and one safety system manufacturer
- Senior Principal Specialist with aeSolutions in Houston

aeSolutions

greg.hardin@aesolutions.com

The Unrealized Potential of an Effective Safety Requirements Specification (SRS)

- It's a requirement of the ANSI/ISA-61511 and IEC-61511 standards
- The standards set out the required contents in some detail
- So, what's the problem?
- *It's completed after the fact*
- *It's not updated to reflect the final design*
- *It's filed away and forgotten*

IEC 61511-1

Edition 2.1 2017-08

FINAL VERSION

Functional safety – Safety instrumented systems for the process industry sector –
Part 1: Framework, definitions, system, hardware and application programming requirements

Why should you care?

If a project is following the 61511 standard then resources have been invested in creating the SRS. You want to obtain the maximum return on the investment.

Acronyms

- SRS, Safety Requirements Specification
- SIS, Safety Instrumented System
- SIF, Safety Instrumented Function
- IPL, Independent Protection Layer
- MRT, Mean Repair Time
- MTTR, Mean Time To Restore
- 61511, ANSI/ISA 61511-1-2018 (AKA: IEC 61511)

What's in an SRS?

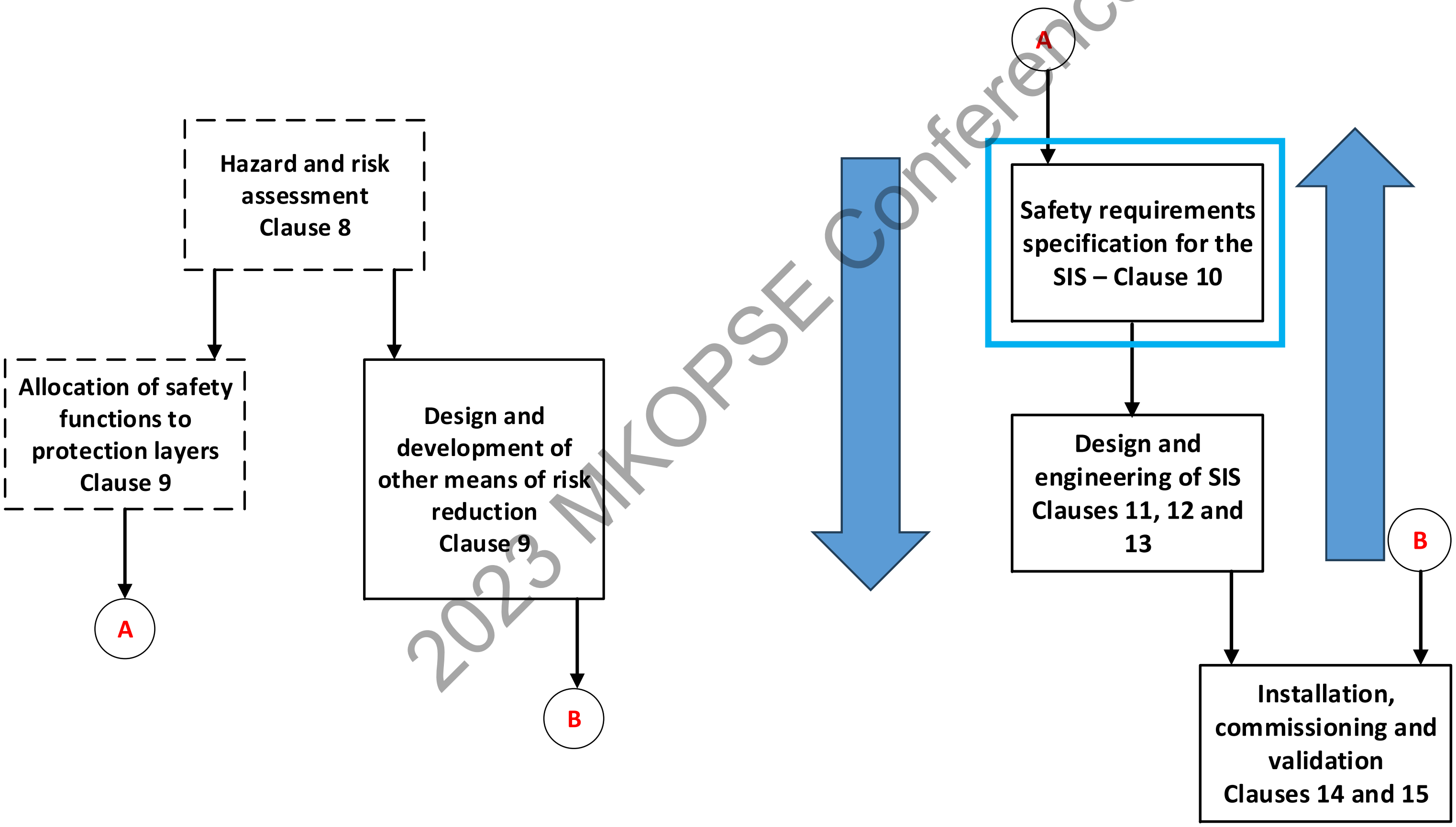
- The 2018 edition of the 61511standard lists 29 items that make up an SRS
- The standard does not require that all 29 items be present for every Safety Instrumented Function (SIF), but if any are omitted it is good practice to include an explanation of why
- The standard does not require that the SRS be a single document
- There is also an application program SRS (APSRS)

SRS contents

- SIF description
- field devices
- address common cause
- safe state of process
- concurrent safe states -> new hazard
- demands + demand rates
- proof test intervals
- proof test implementation
- response time
- required SIL, demand or continuous
- process measurements
- output actions
- outputs = fn(inputs)
- manual shutdown
- energize/de-energize
- reset
- spurious trip rate
- failure mode + response
- startup/shutdown
- SIS <-> other system interfaces

SRS contents (2)

- plant modes of operation
- application programming requirements
- bypass requirements
- actions in case of faults
- mean repair time
- dangerous combination of output states
- environmental conditions
- normal/abnormal process operating modes
- major accident survival



Hazard and risk assessment
Clause 8

Allocation of safety functions to protection layers
Clause 9

A

Design and development of other means of risk reduction
Clause 9

B

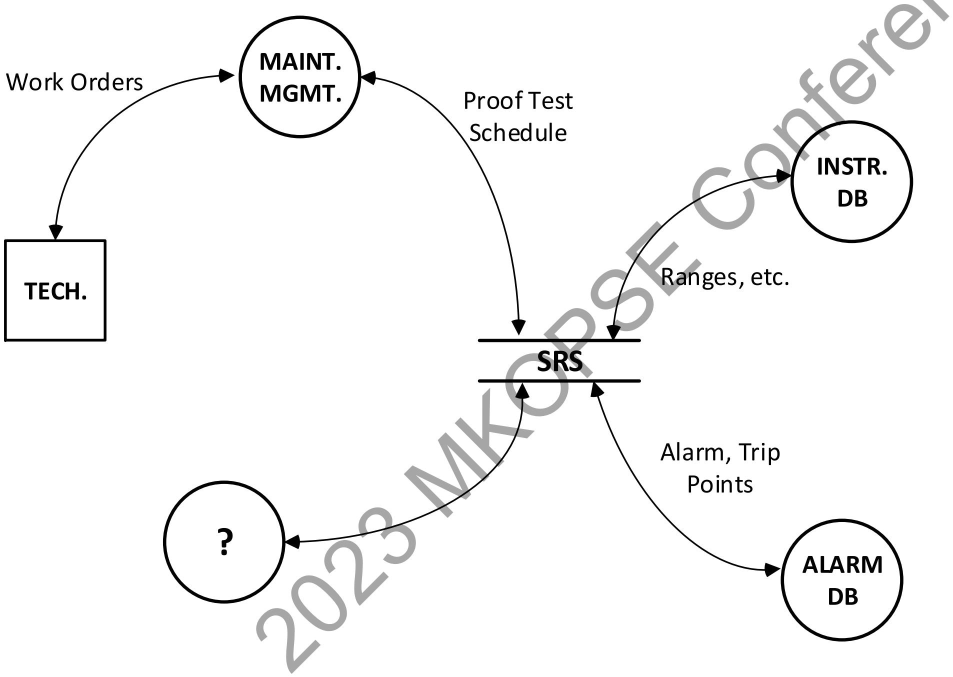
A

Safety requirements specification for the SIS – Clause 10

Design and engineering of SIS
Clauses 11, 12 and 13

B

Installation, commissioning and validation
Clauses 14 and 15


Work Orders
MAINT. MGMT.
Proof Test Schedule
INSTR. DB
TECH.
Ranges, etc.
SRS
Alarm, Trip Points
?
ALARM DB

Problematic Entries

- Process safety time
  - Can be difficult to determine
  - Can significantly impact SIF design
- Hazardous combinations of SIF outputs
- Systematic capability of field devices
- Mission time (overhaul interval) – not one of the required items in the SRS
- Valve leakage requirements, valve closing time

Suggestions

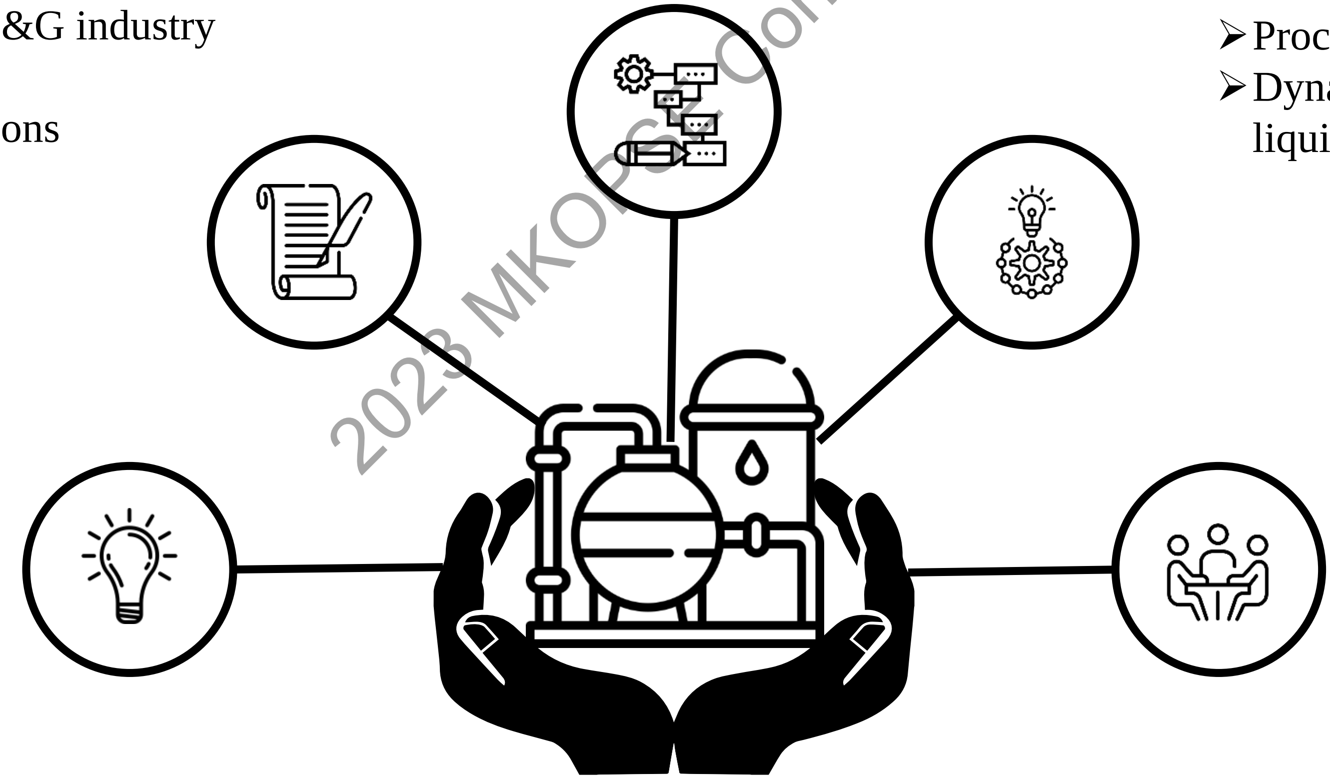
- Put information that applies to most SIFs implemented in a single logic solver in a master document
- Have datasheets for each SIF that document the SIF-specific items and refer to the master document for common items (e.g. what signal from a 4-20mA instrument signifies out of range)
- Depending on the number of SIS logic solvers consider a hierarchy of SRS documents – e.g. site-wide, process unit, single SIS
  - The goal is avoid duplicating data

Questions

Dynamic Risk Assessment Model to Minimize Overall Operational Risks (Oil and Gas Industry)

Master Thesis by Abdullah Alsulieman

Outline



Introduction

- Concepts/Definitions
- Problem statement
- Research aim
- Justification

Literature Review

- DRA categories
- DRA studies in O&G industry
- Review findings
- Approach limitations

Proposed Model

- Offline phase
  (Risk assessment)
- Online phase
  (Dynamic Risk assessment)

Application (case study)

- Process selection
- Process description
- Dynamic risk assessment of liquid carryover

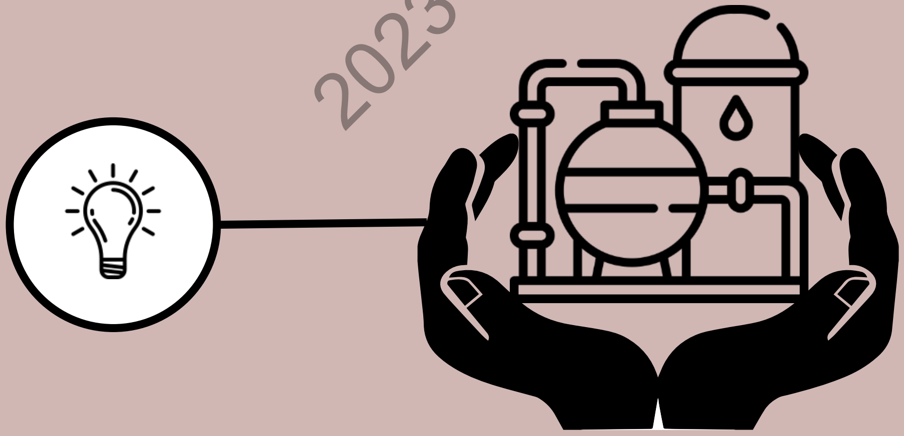
Discussion /Conclusion

- Results
- Limitations
- Research objectives

Outline

Introduction

- ➢Concepts/Definitions
- ➢Problem statement
- ➢Research aim
- ➢Justification



Key Concepts and Definitions

- What can happen in the future (Rausand & Haugen, 2020)
- Identify, analyze and evaluate
- Update estimated risk of a deteriorated process (Khan et al., 2016)

Problem Statement

Conventional Risk Assessment

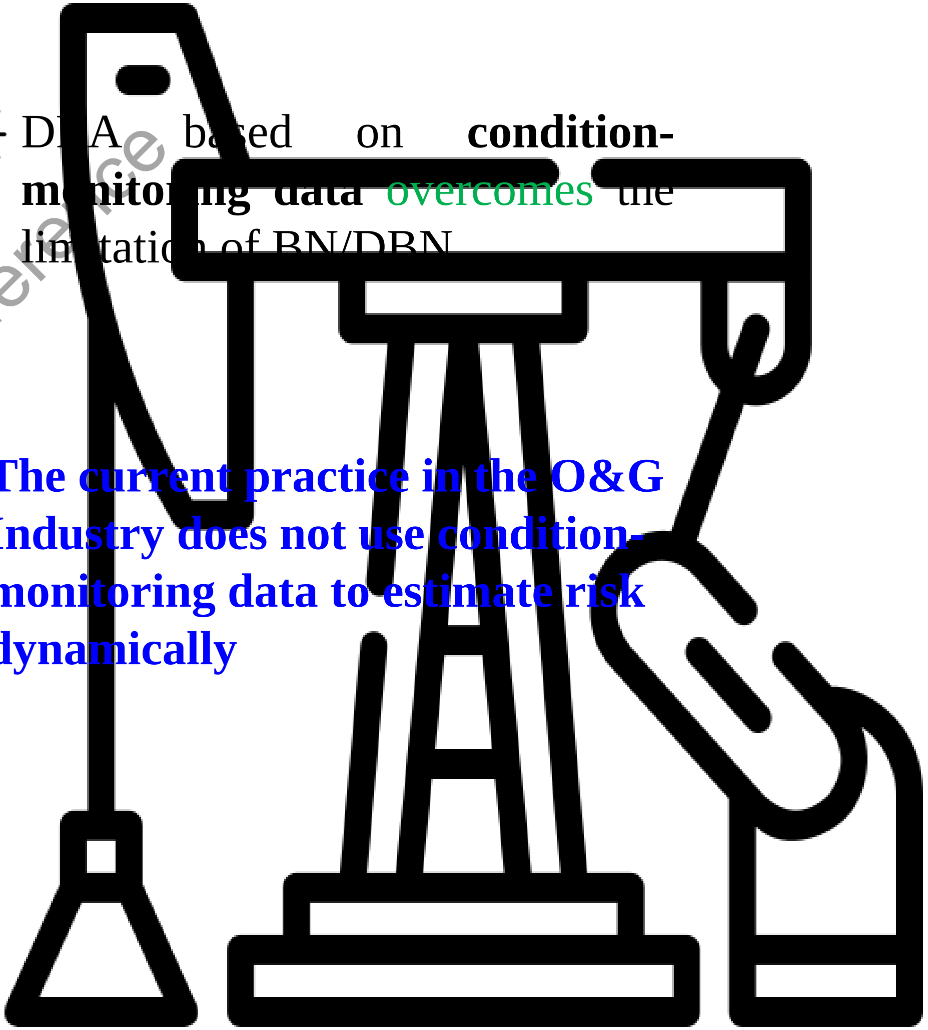
- Static in nature
- Do not consider changes in operations
- Often use generic failure data
- Can be overwhelming

(Zio, 2018)

Problem Statement

The existing DRA research in the O&G industry is mainly conducted based on: **Bayesian Network (BN)** or **Dynamic Bayesian Network (DBN)**

Require event-driven data to be updated, such as failure or accident data from similar systems



DRA based on **condition-monitoring data** overcomes the limitation of BN/DBN.

The current practice in the O&G Industry does not use condition-monitoring data to estimate risk dynamically

Research Aim

Aim **Apply a DRA technique to an O&G process unit based on condition-monitoring data.**

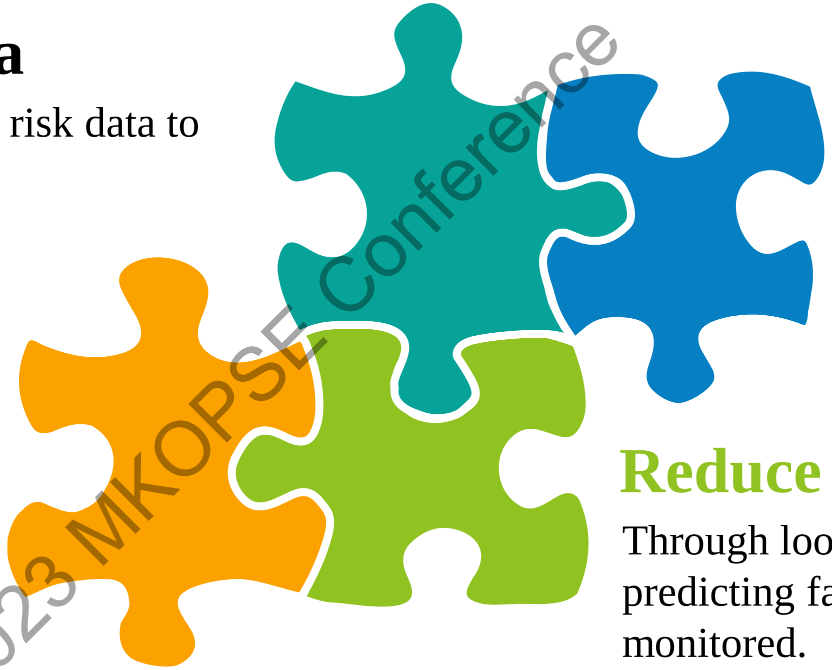
Objective-1 To contribute to the development and application of the DRA techniques in the O&G industry

Objective-2 To obtain the risk level of an accident scenario in real-time

Objective-3 To make informed decisions based on inputs from the DRA technique

Objective-4 To anticipate failures of process safety barriers

Justification



Obtain high certainty data

Operational personnel will have the right risk data to make informed decisions.

Implement the DRA at an oil and gas company

This study will contribute to the ongoing efforts to enhance the development and application of DRA techniques in the O&G industry by integrating conventional QRA methods with condition-monitoring data.

Optimize resources

Risk assessments can be time consuming; DRA will shift the resources to where they are needed the most.

Reduce operational risks

Through looking into the future and predicting failure of safety barriers being monitored.

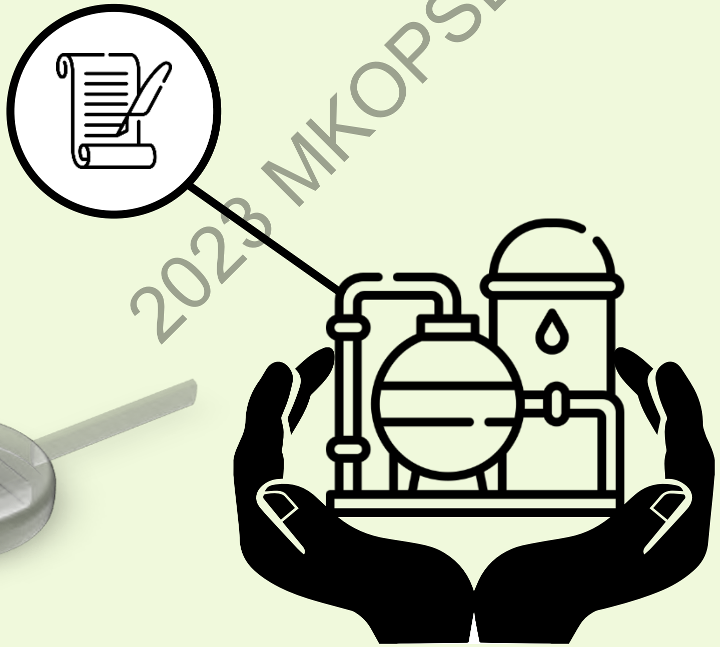
Outline

Literature Review

- DRA categories
- DRA studies in O&G industry
- Review findings
- Approach limitations

Introduction

- Concepts/Definitions
- Problem statement
- Research objectives
- Justification
- Limitation



DRA Categories

Data-based DRA

- Uses statistical failure data
    - *Counts of accidents, incidents, or near misses gathered from similar systems*
- Applies Bayesian theorem with conventional QRA
    - *FT, ET or BT*

Degradation-based DRA

- Employes condition monitoring data to overcome the constraints of the data-based DRA technique
- Focuses on accidents caused by degradation mechanisms such as wear, corrosion, and fracture formation

Process-based DRA

- Examines how process variables interact
- Risk rises when the monitored process parameters deviate from their ideal state
- Applies Bayesian network (BN) to identify dependencies

DRA Studies in the O&G Industry

Some existing DRA studies involving O&G process units include:

Cai et al. (2012)

Used BN methodology for QRA in offshore O&G

Bhandari et al. (2015)

Used BN for dynamic safety analysis in deep-water operations.

Khakzad et al. (2013)

Used BN for evaluating the safety of offshore drilling

Barua et al. (2016)

Converted DFT into DBN for risk assessment

L. Zhang et al. (2018)

Used DBNs in accident scenario analysis and dynamic quantitative risk assessment for managed pressure drilling safety.

Bijay et al. (2020)

Created a BN model to obtain the time dependent variations in kick effects using the real time failure probabilities of SB

Chen et al. (2020)

Developed a BN model of offshore drilling in order to minimize operational risks

Dimaio et al. (2021)

Proposed a multistate BN to model and assess the functional performance of safety barriers in oil and gas plants.

Literature Review Findings

- ☐ Many of the DRA techniques are not widely applied in the O&G industry
- ☐ DRA techniques are practical and valid in the O&G industry
- ☐ The DRA research in the O&G industry is mainly conducted based on:
  - Bayesian Networks (BNs)
  - Dynamic Bayesian Networks (DBNs)

DRA using condition-monitoring data has not been wildly applied within the O&G industry

To bridge the gap, we develop a Dynamic Risk Assessment model based on condition-monitoring data that can be utilized to predict failures, estimate risk in real-time, and support informed decision-making

Limitations of the Approach

Incapable of consequence assessment

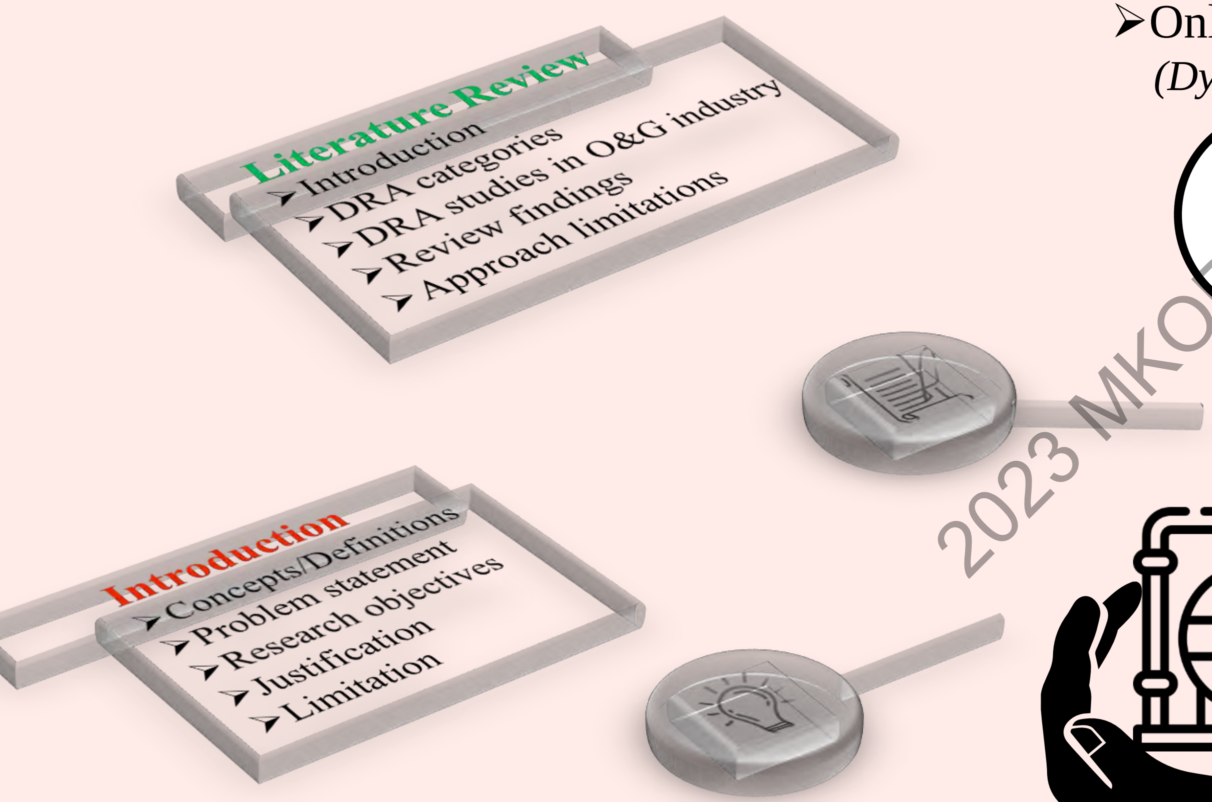
Ignores statistical failure data

May produce false positive or false negative readings

Computational issues

High expertise in operations and data analysis techniques

Outline



Introduction

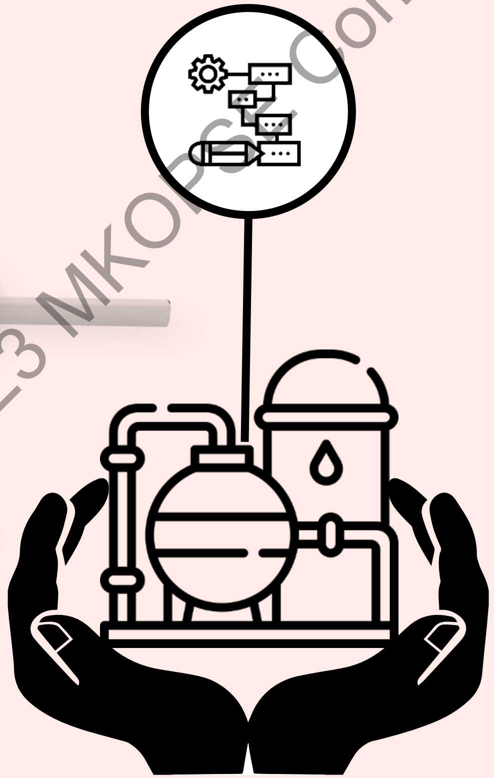
- Concepts/Definitions
- Problem statement
- Research objectives
- Justification
- Limitation

Literature Review

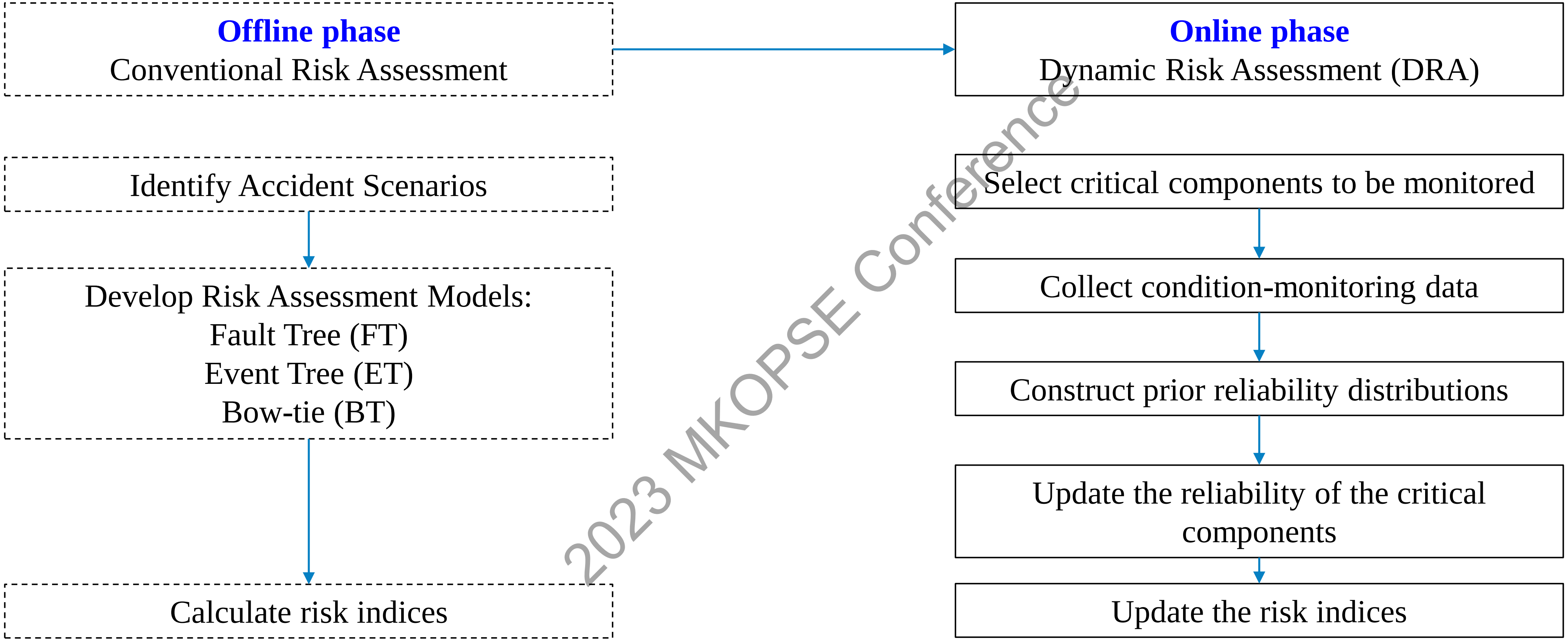
- Introduction
- DRA categories
- DRA studies in O&G industry
- Review findings
- Approach limitations

Proposed Model

- Offline phase
  (Risk assessment)
- Online phase
  (Dynamic Risk assessment)



Steps of the Proposed DRA Model



Offline phase
Conventional Risk Assessment

Identify Accident Scenarios

Develop Risk Assessment Models:
Fault Tree (FT)
Event Tree (ET)
Bow-tie (BT)

Calculate risk indices

Online phase
Dynamic Risk Assessment (DRA)

Select critical components to be monitored

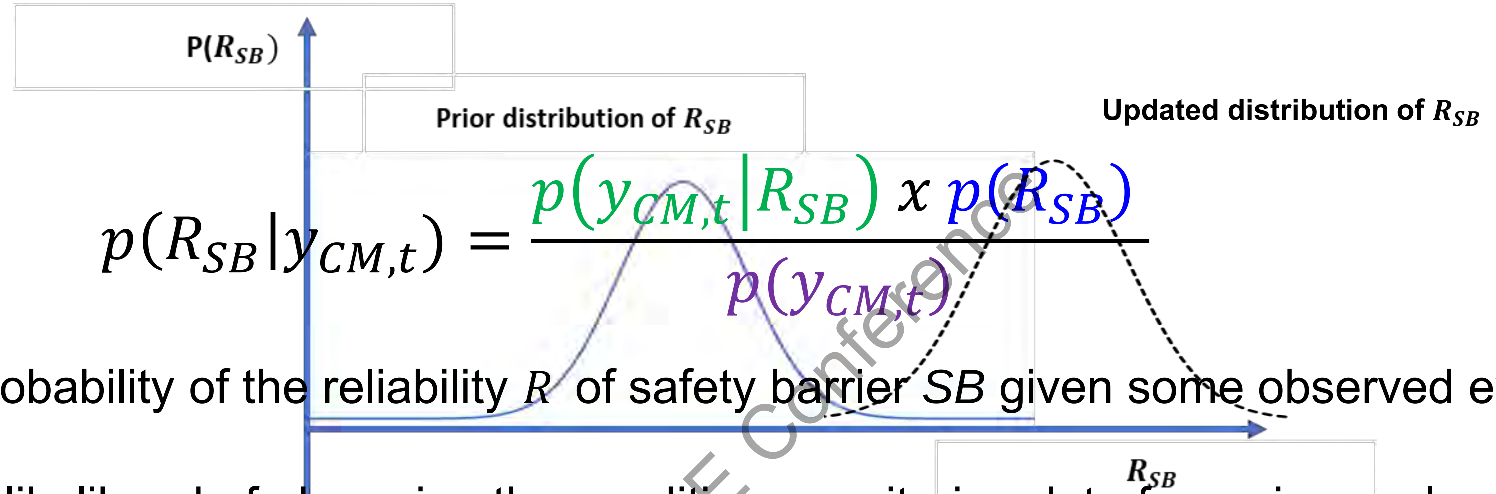
Collect condition-monitoring data

Construct prior reliability distributions

Update the reliability of the critical components

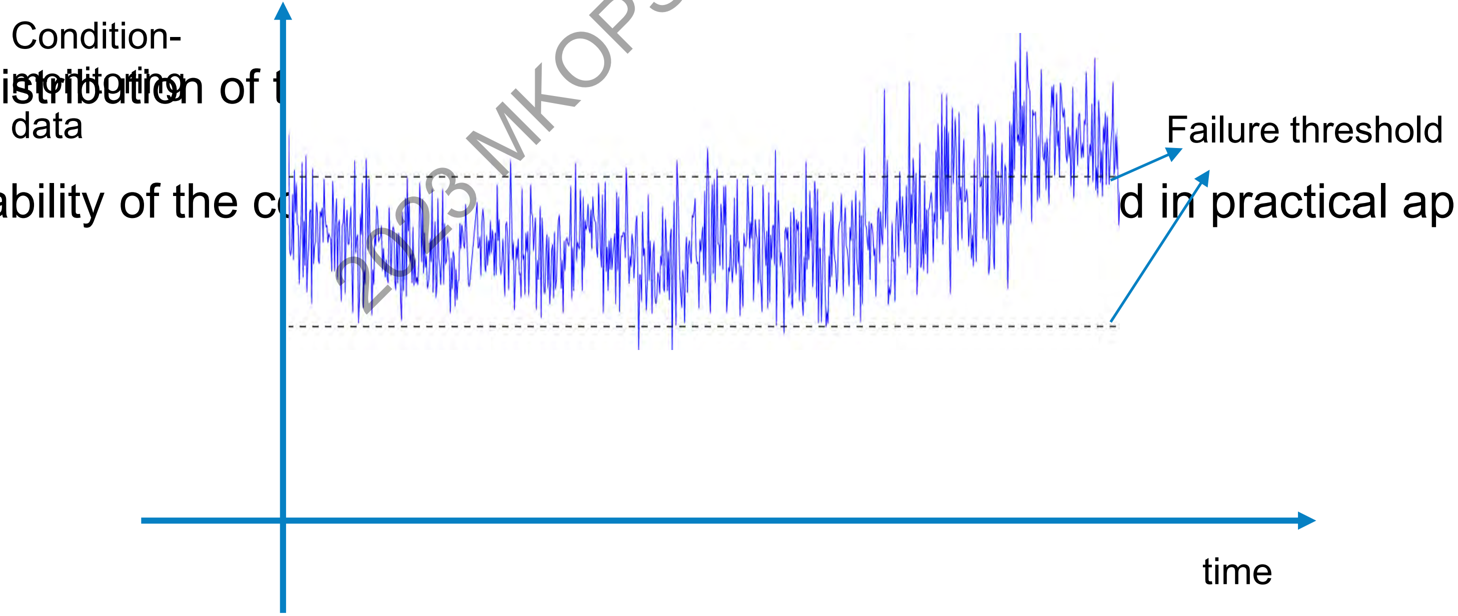
Update the risk indices

Online Phase



$$p(R_{SB}|y_{CM,t}) = \frac{p(y_{CM,t}|R_{SB})\ x\ p(R_{SB})}{p(y_{CM,t})}$$

- $p(R_{SB}|y_{CM,t})$ the probability of the reliability R of safety barrier *SB* given some observed evidence y_{CM}
- $p(y_{CM,t}|R_{SB})$ is the likelihood of observing the condition−monitoring data for a given value of R_{SB}
- $p(R_{SB})$ is the prior distribution of t
- $p(y_{CM,t})$ is the probability of the c d in practical application)



Online Phase

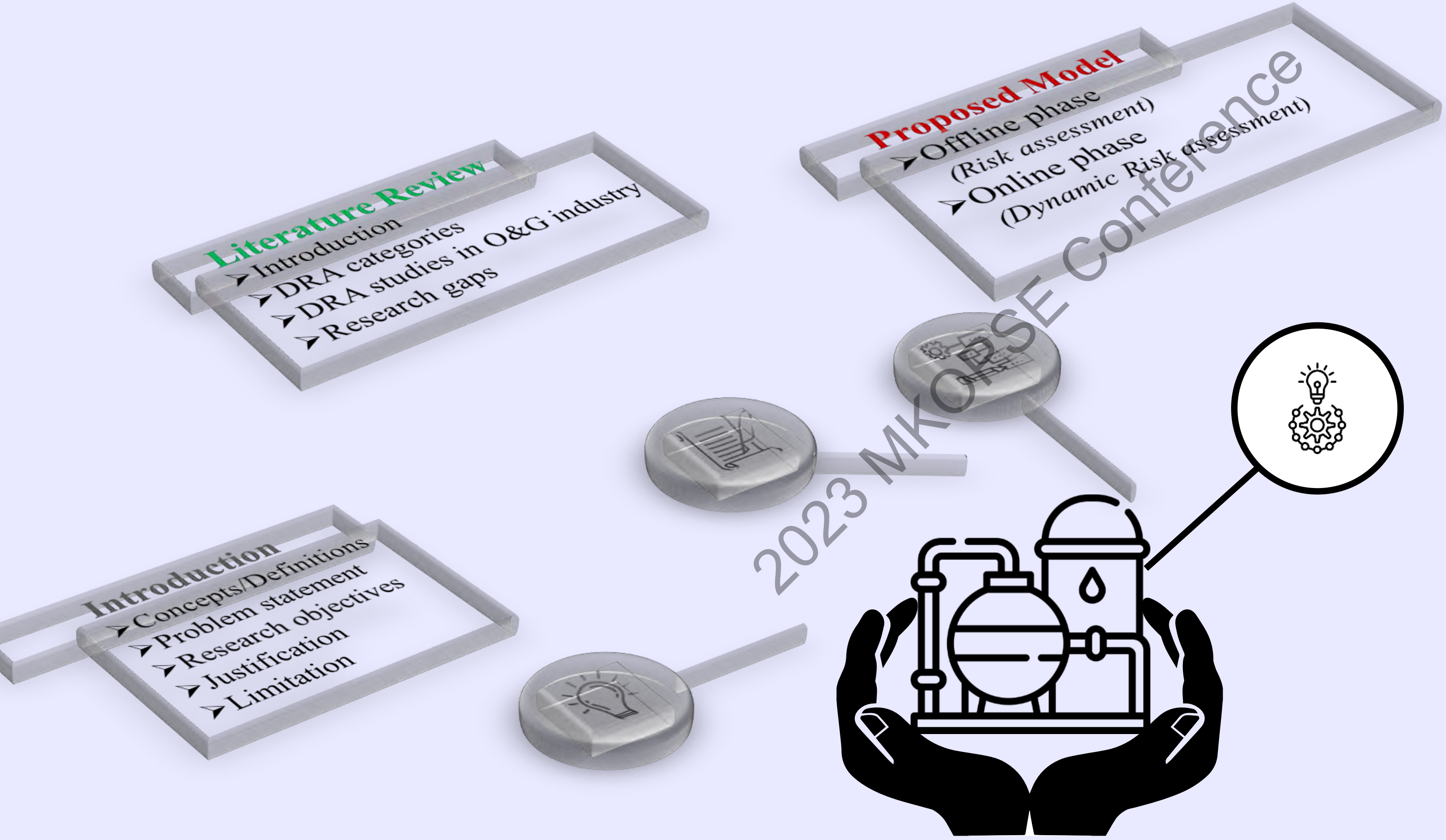
Algorithm 1. Dynamic reliability updating through Metropolis Sampling

```
Input: $y_{CM}, t, n_s$
Start: $p_{prop} = U(0,1), p_{prior} = p(R_{SB}), p^0 = mean\,(p_{prior}), k = 1$

Step 1: $p^{(k)} \longleftarrow$ Generate a sample from $p_{prop}$
Step 2: Calculate $p_{acc} = \min\left(1, \frac{p(y_{CM},t|p^{(k)})\,p_{prior}(P^{(K)})}{p(y_{CM},t|P^{(k-1)})\,p_{prior}(p^{(k-1)})}\right)$
Step 3: $r \longleftarrow$ Generate a sample from U(0.1)

Step 4:   $If\ r < p_{acc} : p^{(k)} \longleftarrow p^{(k)}$
          $Else : p^{(k)} \longleftarrow p^{(k-1)}$
Step 5: $k = k + 1$
          $If\ k = n_s : end$
          $Else : Go\ to\ step\ 1$
```

Outline



Introduction
- ➢Concepts/Definitions
- ➢Problem statement
- ➢Research objectives
- ➢Justification
- ➢Limitation

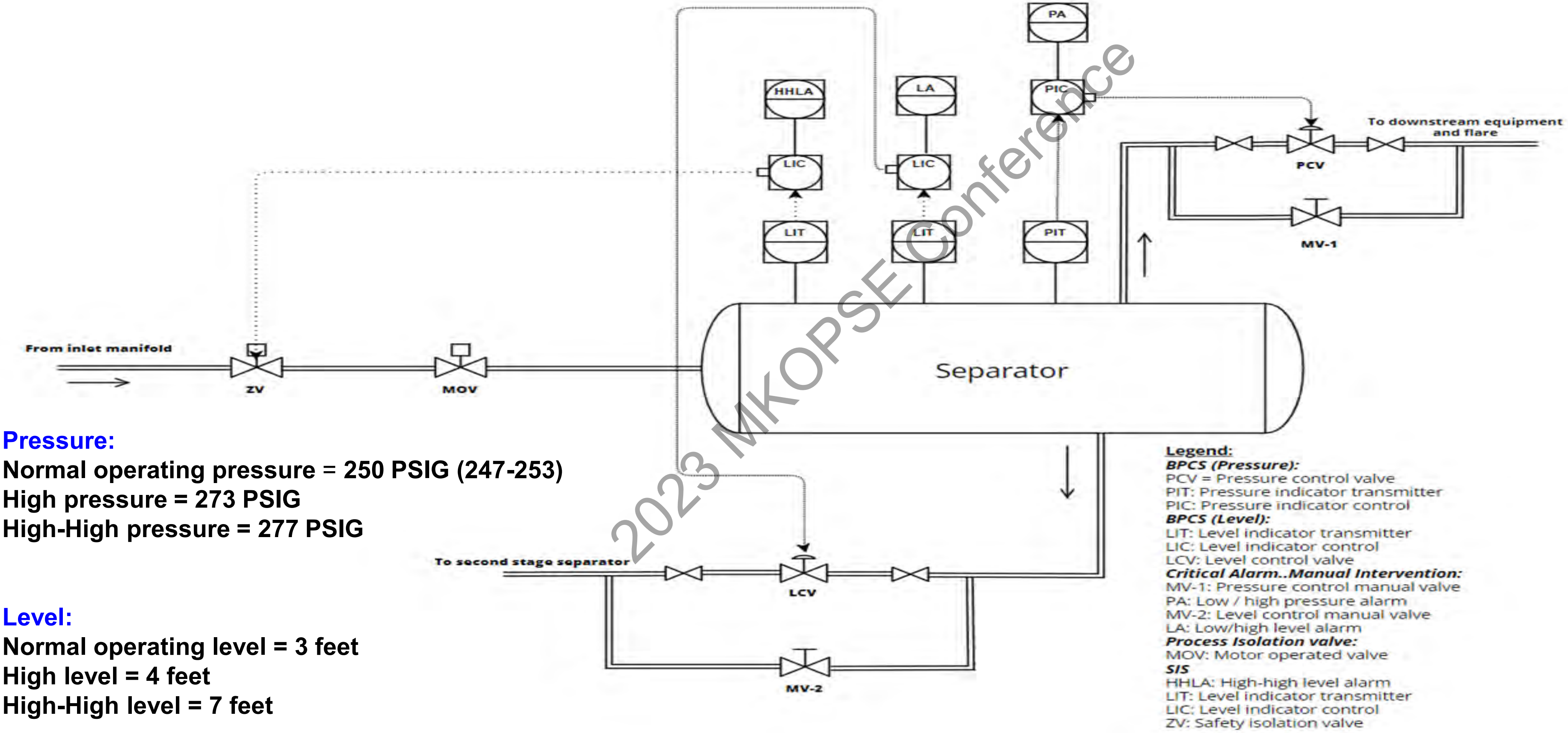
Literature Review
- ➢Introduction
- ➢DRA categories
- ➢DRA studies in O&G industry
- ➢Research gaps

Proposed Model
- ➢Offline phase
  (Risk assessment)
- ➢Online phase
  (Dynamic Risk assessment)

Application (case study)

- ➢Process selection
- ➢Process description
- ➢Dynamic risk assessment of liquid carryover

Application (Case Study)



Legend:
BPCS (Pressure):
PCV = Pressure control valve
PIT: Pressure indicator transmitter
PIC: Pressure indicator control
BPCS (Level):
LIT: Level indicator transmitter
LIC: Level indicator control
LCV: Level control valve
Critical Alarm..Manual Intervention:
MV-1: Pressure control manual valve
PA: Low / high pressure alarm
MV-2: Level control manual valve
LA: Low/high level alarm
Process Isolation valve:
MOV: Motor operated valve
SIS
HHLA: High-high level alarm
LIT: Level indicator transmitter
LIC: Level indicator control
ZV: Safety isolation valve

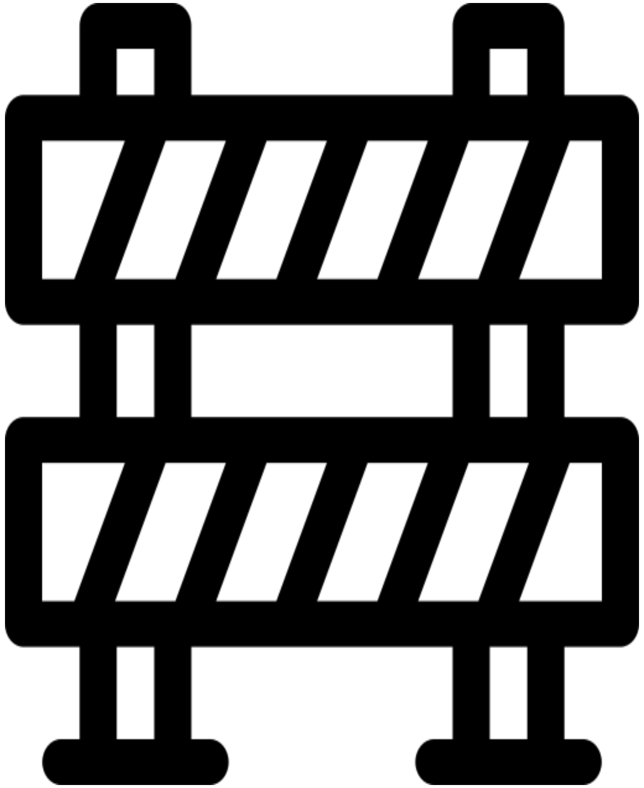
Pressure:
Normal operating pressure = 250 PSIG (247-253)
High pressure = 273 PSIG
High-High pressure = 277 PSIG

Level:
Normal operating level = 3 feet
High level = 4 feet
High-High level = 7 feet

Application (Case Study)

The liquid **carryover scenario** is **controlled** by the following safety barriers:

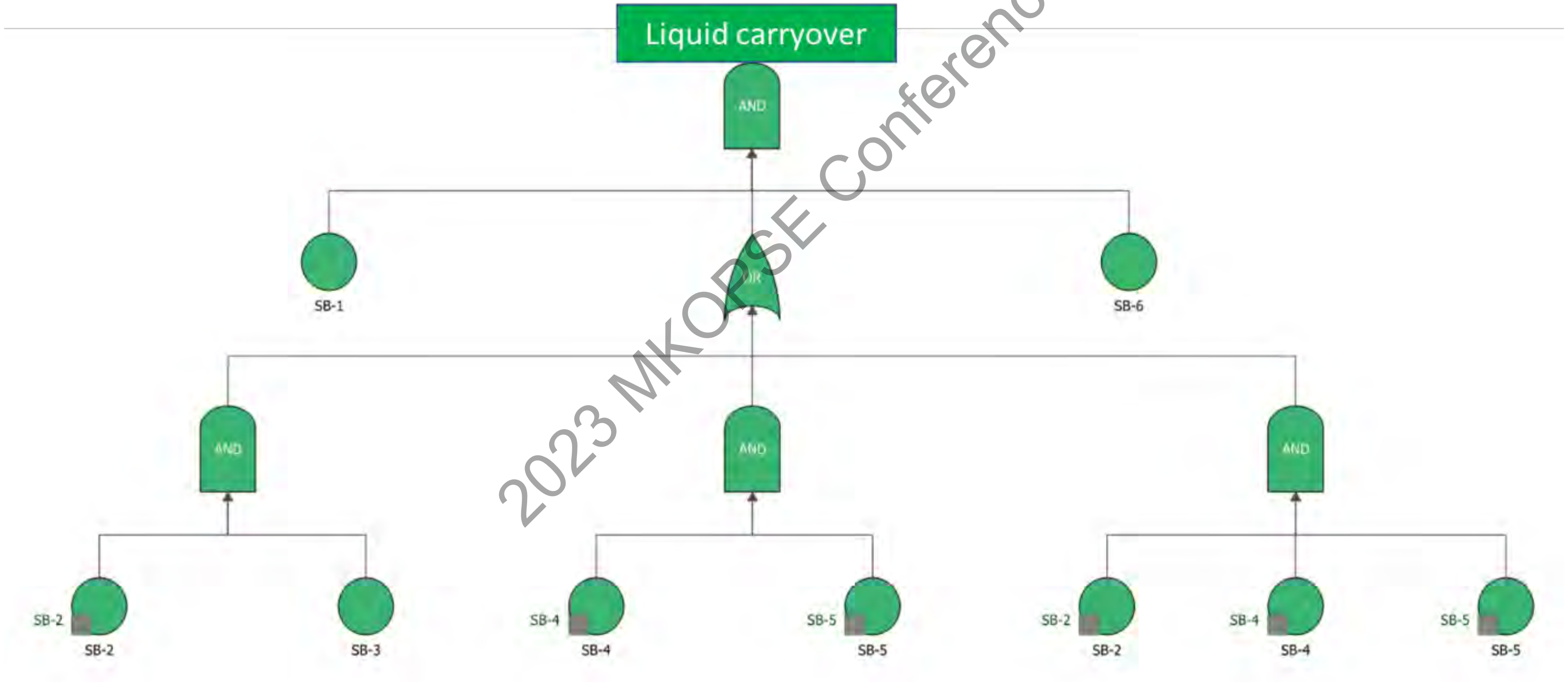
- *The first safety barrier (SB-1), a pressure control loop*
- *The second safety barrier (SB-2), high-level alarm*
- *The third and fourth safety barrier (SB-3 and SB-4), operator supervision and manual intervention, respectively.*
- *The fifth safety barrier (SB-5), motor-operated valve (MOV).*
- *The sixth safety barrier (SB-6), safety instrumented system (SIS)*



Offline phase

Risk Assessment – ***Offline***:

ReliaSoft (a reliability software) is a reliability software used to construct a Fault Tree

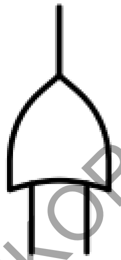


Risk Assessment – ***Offline:***

Using ReliaSoft, the minimal cut sets (failure scenarios) are as follows:

Minimal Cut Set #1

(SB-1) Pressure control loop AND
(SB-2) High-level alarm AND
(SB-3) Operator supervision AND
(SB-4) SIS



Minimal Cut Set #2

(SB-1) Pressure control loop AND
(SB-4) Pressure control manual valve AND
(SB-5) Motor-operated valve AND
(SB-6) SIS

Risk Assessment – *Offline*:

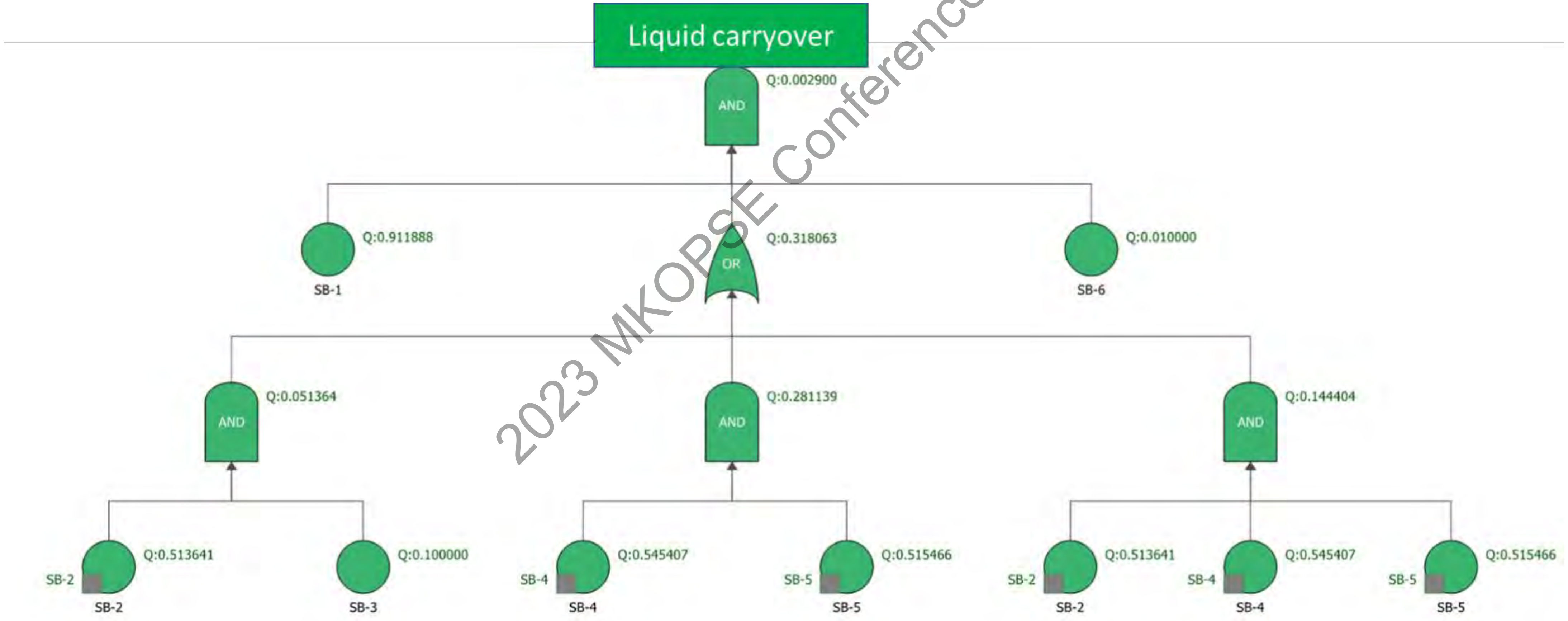
Next step is to assign failure probabilities to the basic events (e.g., SB-1, SB-2, …, SB-6).

The following assumptions are made:

- SBi are independent of each other
- SB-1, SB-2, SB-4 and SB-5 follow the exponential distribution function with a constant parameter λ.
- SB-3 and SB-6 have constant failure probabilities 0.1 and 0.01, respectively.

Risk Assessment – ***<u>Offline</u>***:

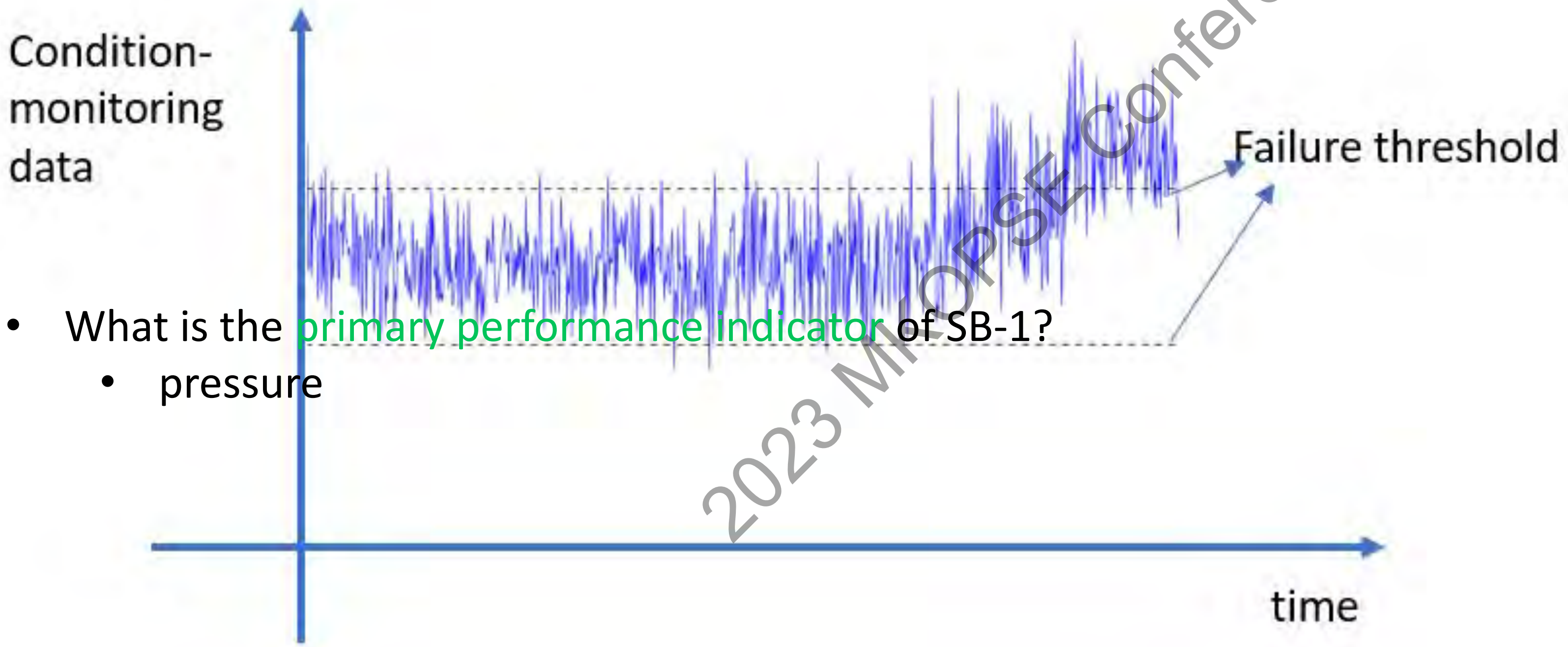
Using ReliaSoft, the risk of the top event at t = 3000 hours is **<u>0.0029</u>**



Online phase

Risk Assessment – *Online*:

Step 1: Select SB-1, pressure control loop, for monitoring

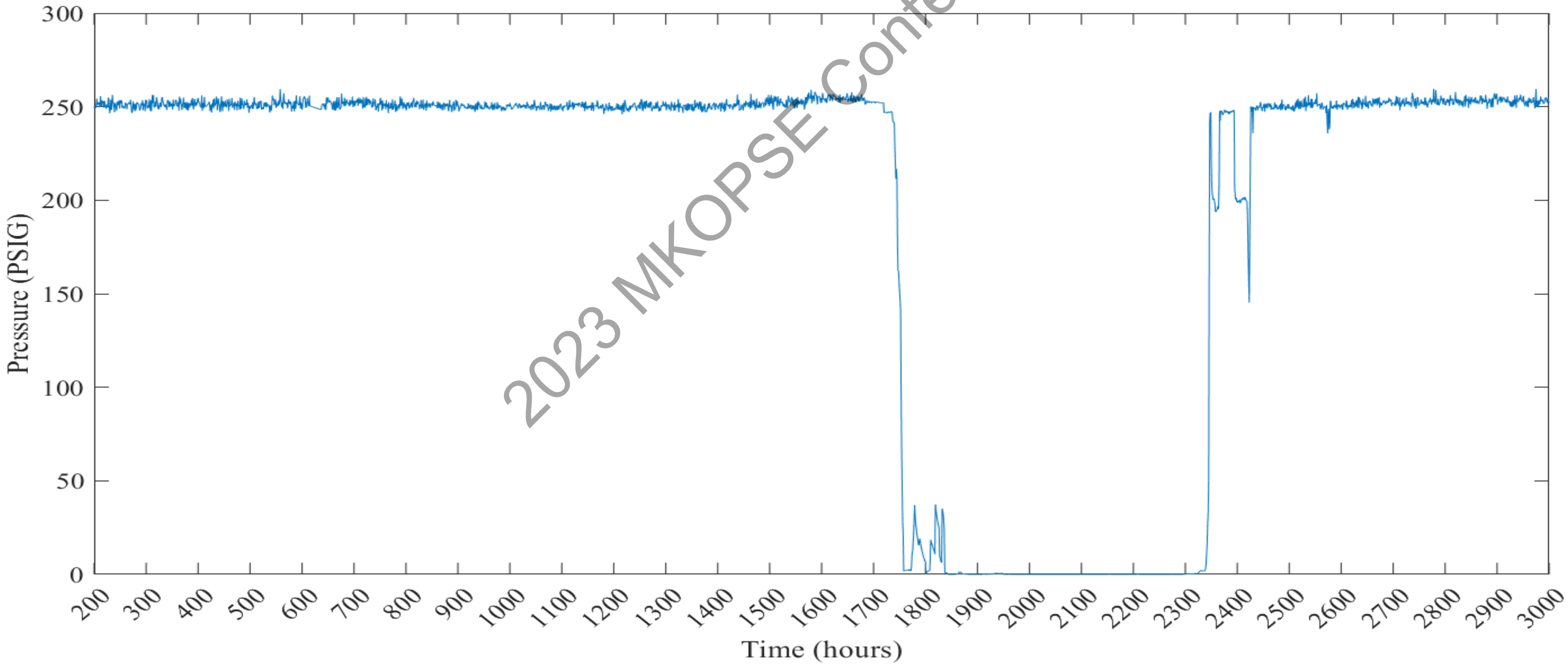


- What is the primary performance indicator of SB-1?
  - pressure

Risk Assessment – *Online*:

Step 1: Select SB-1, pressure control loop, for monitoring

Step 2: Collect condition-monitoring data



Risk Assessment – *Online:*

Step 1: Select SB-1, pressure control loop, for monitoring

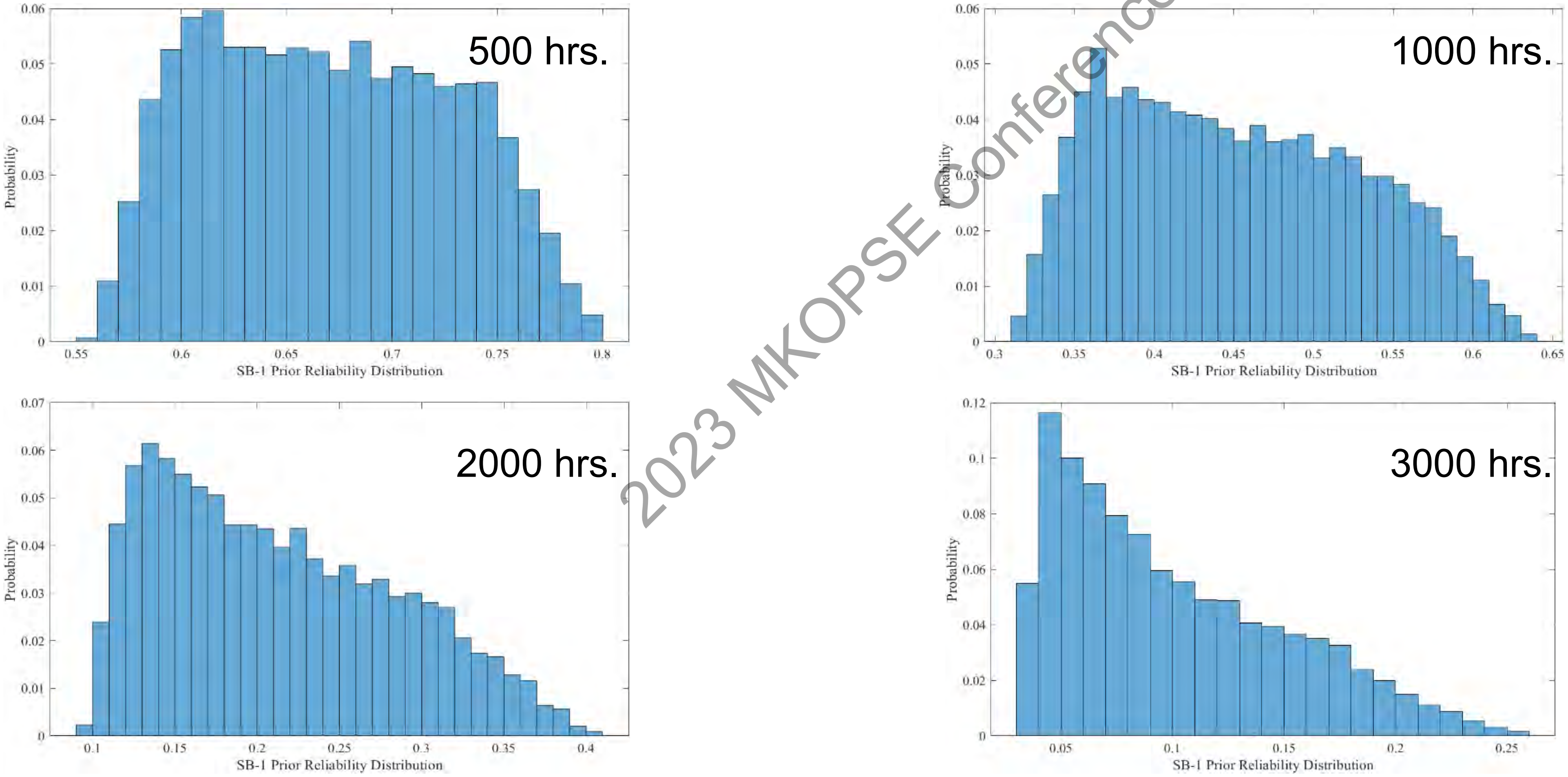
Step 2: Collect condition-monitoring data

Step 3: Construct prior reliability distribution of SB-1, $p(R_{SB1})$

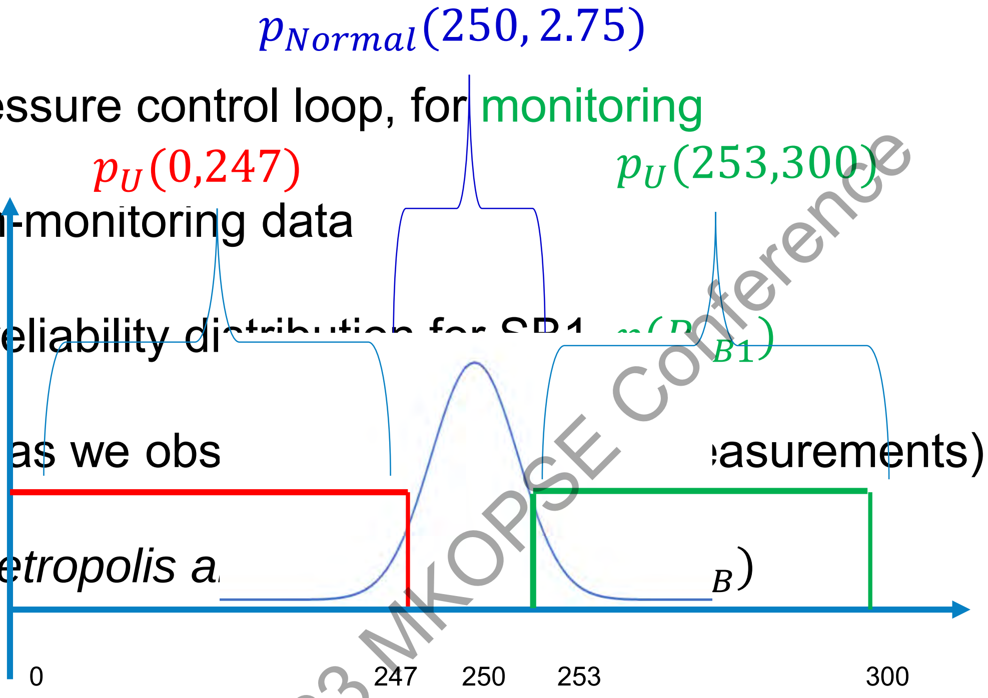
- $R = e^{-\lambda t}$, where $\lambda = [\text{Lower } \lambda, \text{upper } \lambda]$

Risk Assessment – *Online:*

The prior reliability distribution of SB-1, $p(R_{SB1})$, at t = 500, 1000, 2000 and 3000 hours:



Risk Assessment – *Online:*



Step 1: Select SB-1, pressure control loop, for monitoring

Step 2: Collect condition-monitoring data

Step 3: Construct prior reliability di $_{B1})$

Step 4: Update $p(R_{SB1})$ as we obs easurements)

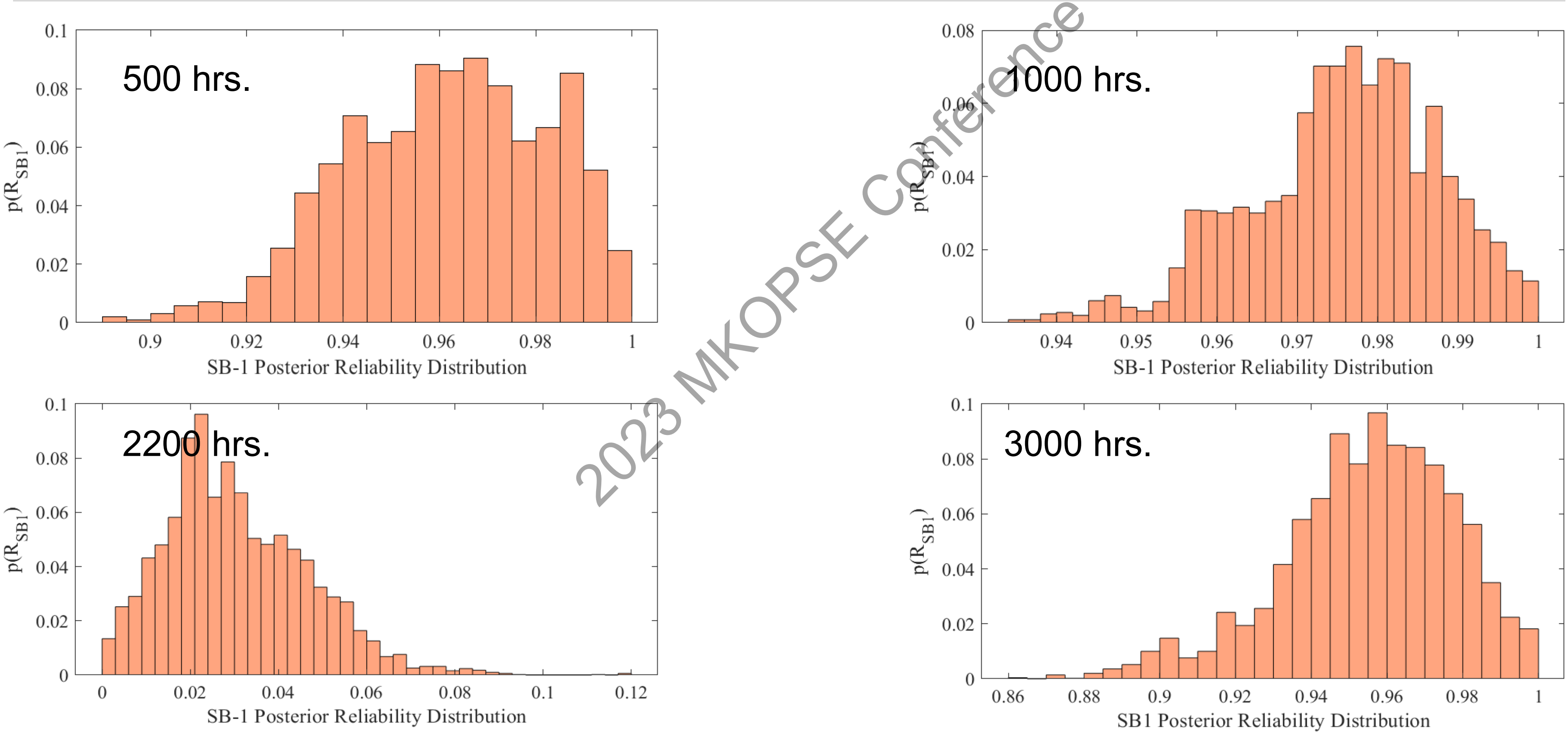
- *Apply the metropolis a* $_{B})$

- *Construct a likelihood function* $p(y_{CM,i}|R_{SB})$

$$p(y_{CM,i}|R_{SB}) = \mathrm{R_{SB}} \cdot \boxed{p_{Normal}(250, 2.75)} + \frac{1-R_{SB}}{2} \cdot \boxed{p_U(0, 247)} + \frac{1-R_{SB}}{2} \cdot \boxed{p_U(253, 300)}$$

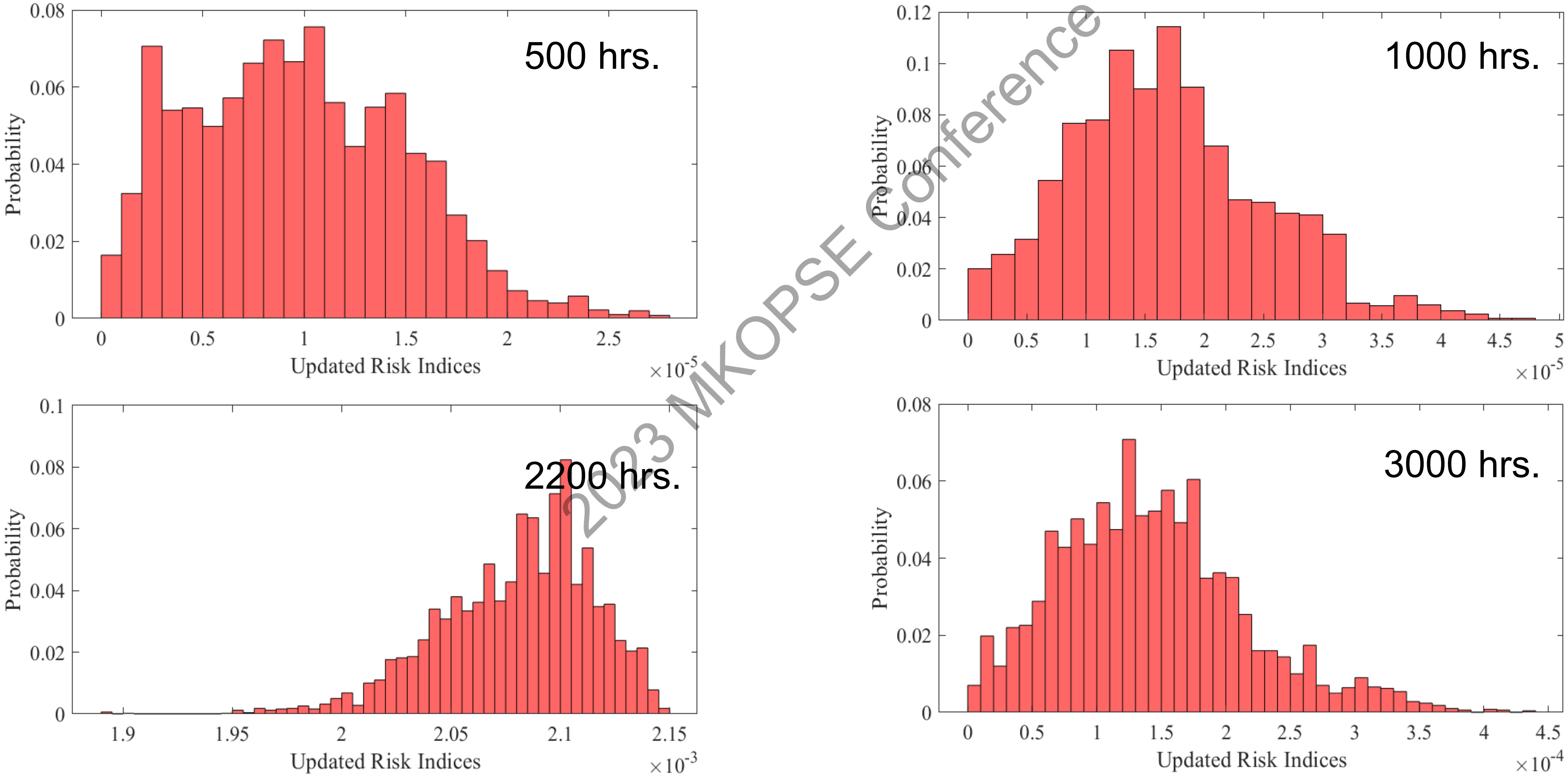
Risk Assessment – *Online:*

The posterior distribution of SB-1, $p(R_{SB}|y_{CM,t})$, at t = 500, 1000, 2200, 3000 hours:

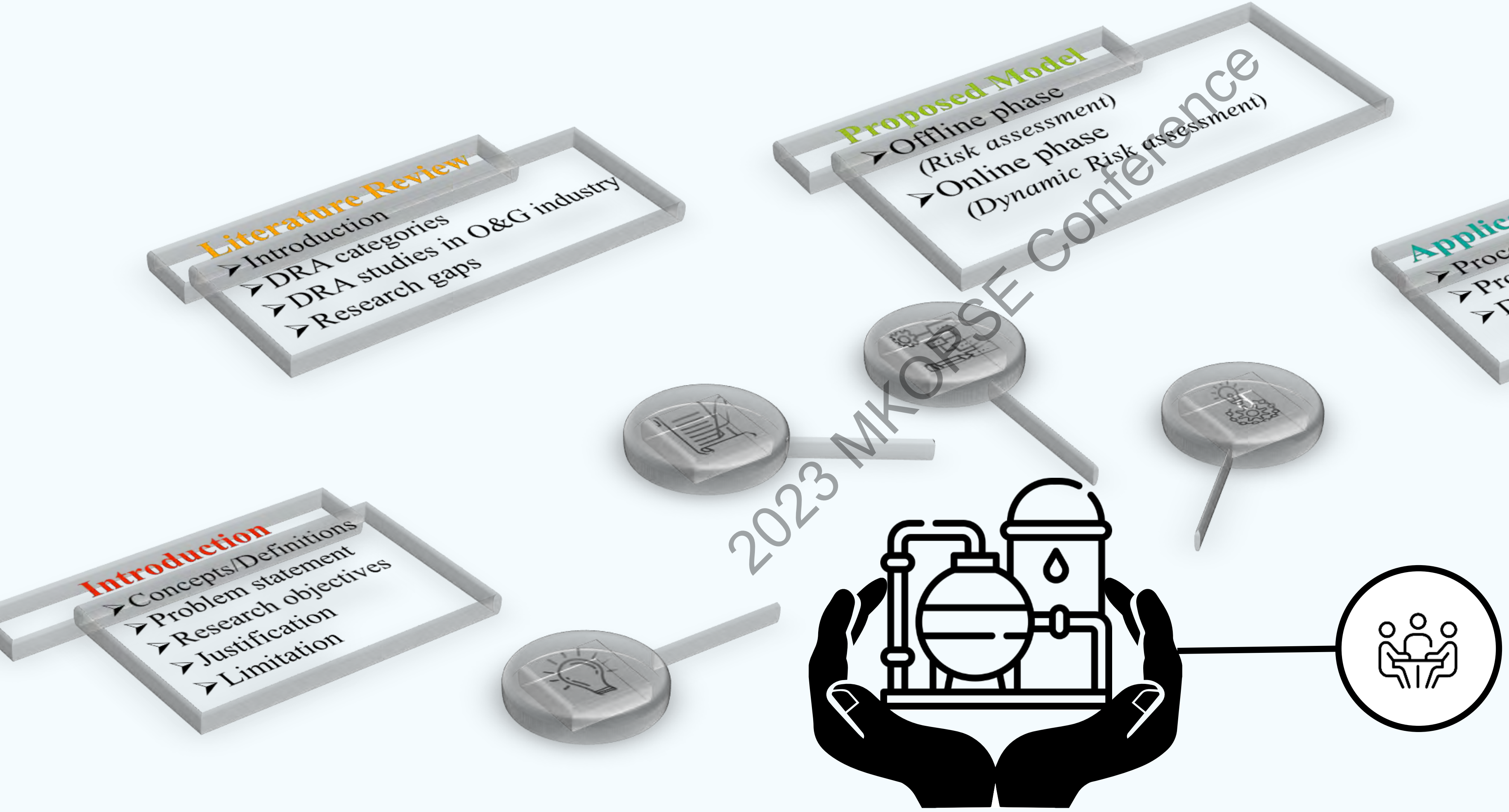


Risk Assessment – *Online:*

Substitute $p(R_{SB}|y_{CM,t})$ into $Risk = f(R_{SB1} x\ R_{SB2}\ x\ R_{SB3})$ to get risk indices distribution



Outline



Introduction

- ➢Concepts/Definitions
- ➢Problem statement
- ➢Research objectives
- ➢Justification
- ➢Limitation

Literature Review

- ➢Introduction
- ➢DRA categories
- ➢DRA studies in O&G industry
- ➢Research gaps

Proposed Model

- ➢Offline phase
  (*Risk assessment*)
- ➢Online phase
  (*Dynamic Risk assessment*)

Application (case study)

- ➢Process selection
- ➢Process description
- ➢Dynamic risk assessment of liquid carryover

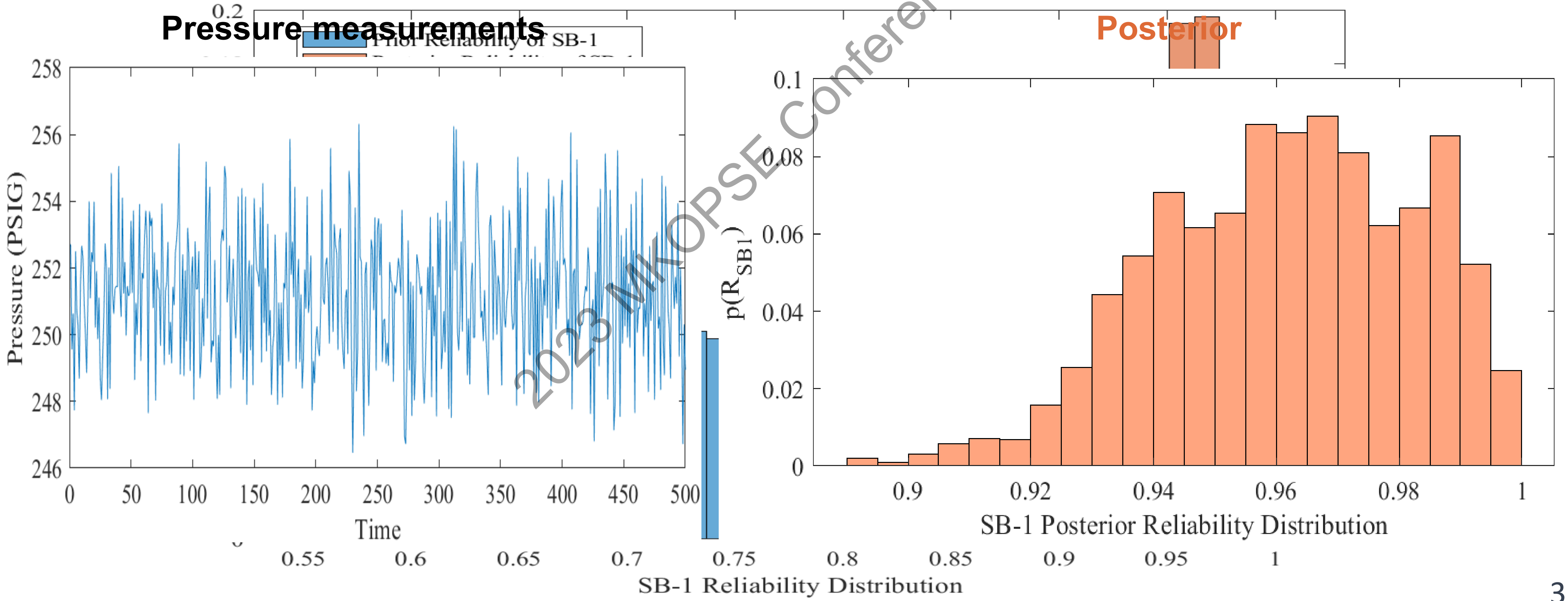
Discussion /Conclusion

- ➢Results
- ➢Research questions and answers
- ➢Conclusion and future work

Results and Discussion

At t = 500 hours

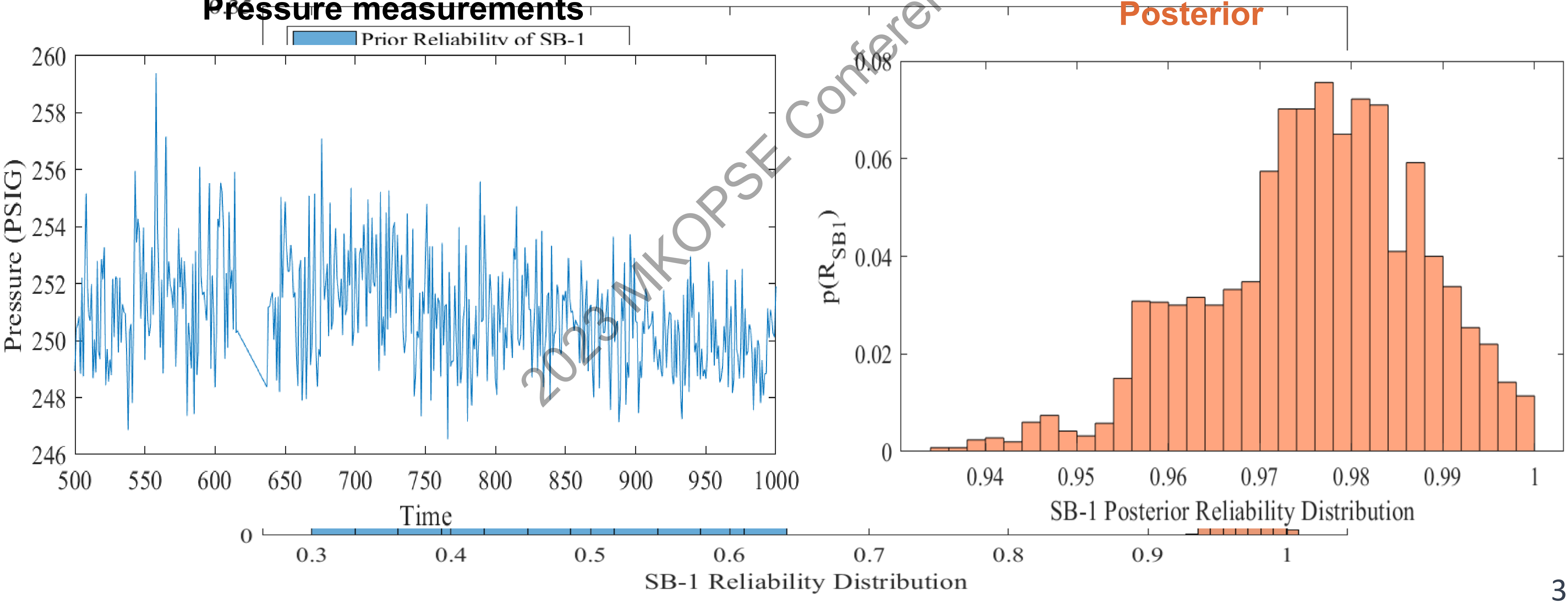
SB-1 prior reliability distribution vs. SB-1 posterior reliability distribution



Results and Discussion

At t = 1000 hours

SB-1 prior reliability distribution vs. SB-1 posterior reliability distribution



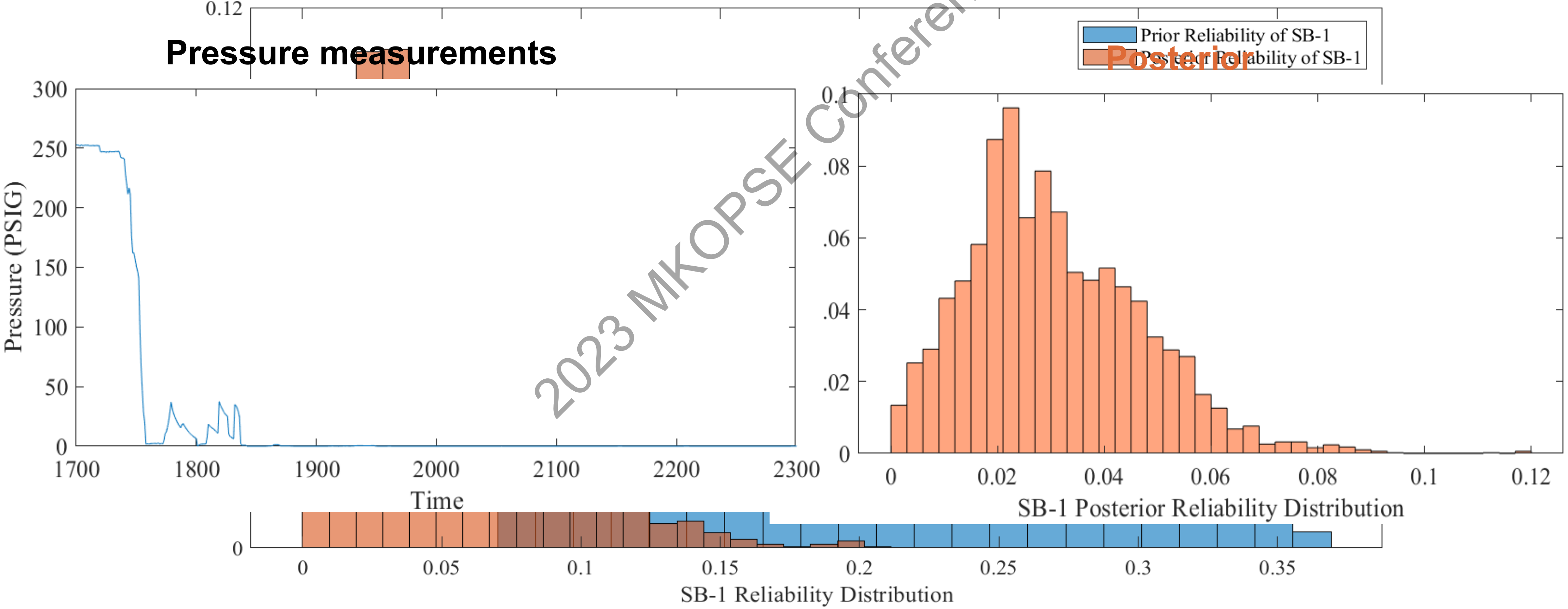
Pressure measurements

Posterior

Results and Discussion

At t = 2200 hours

SB-1 prior reliability distribution vs. SB-1 posterior reliability distribution



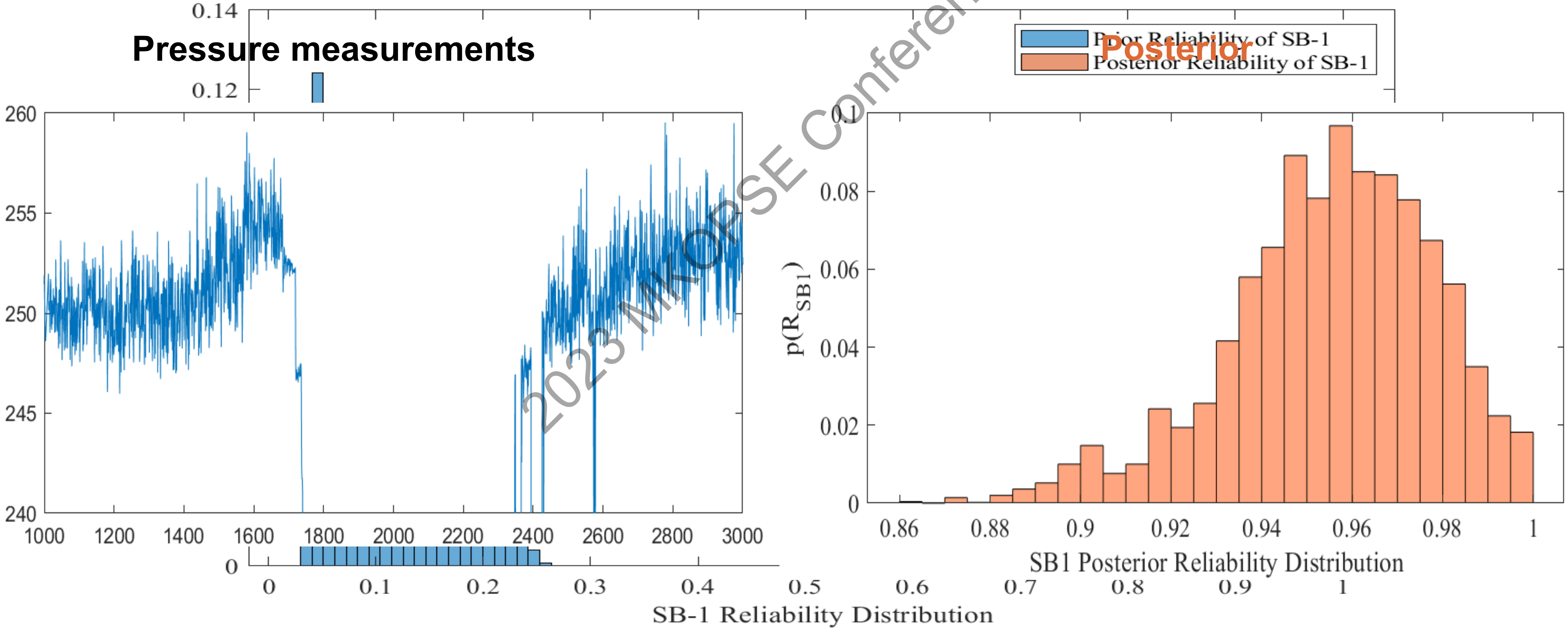
Pressure measurements

Posterior

Results and Discussion

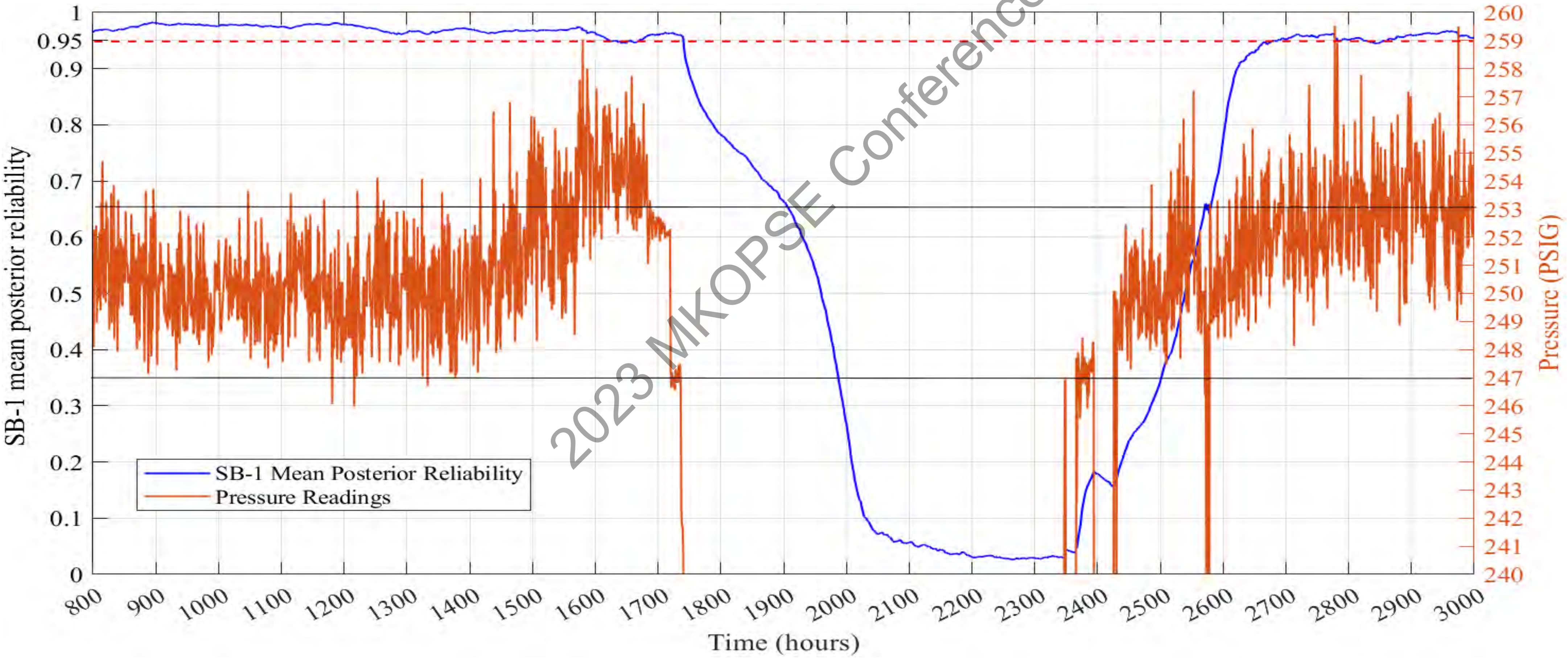
At t = 3000 hours

SB-1 prior reliability distribution vs. SB-1 posterior reliability distribution



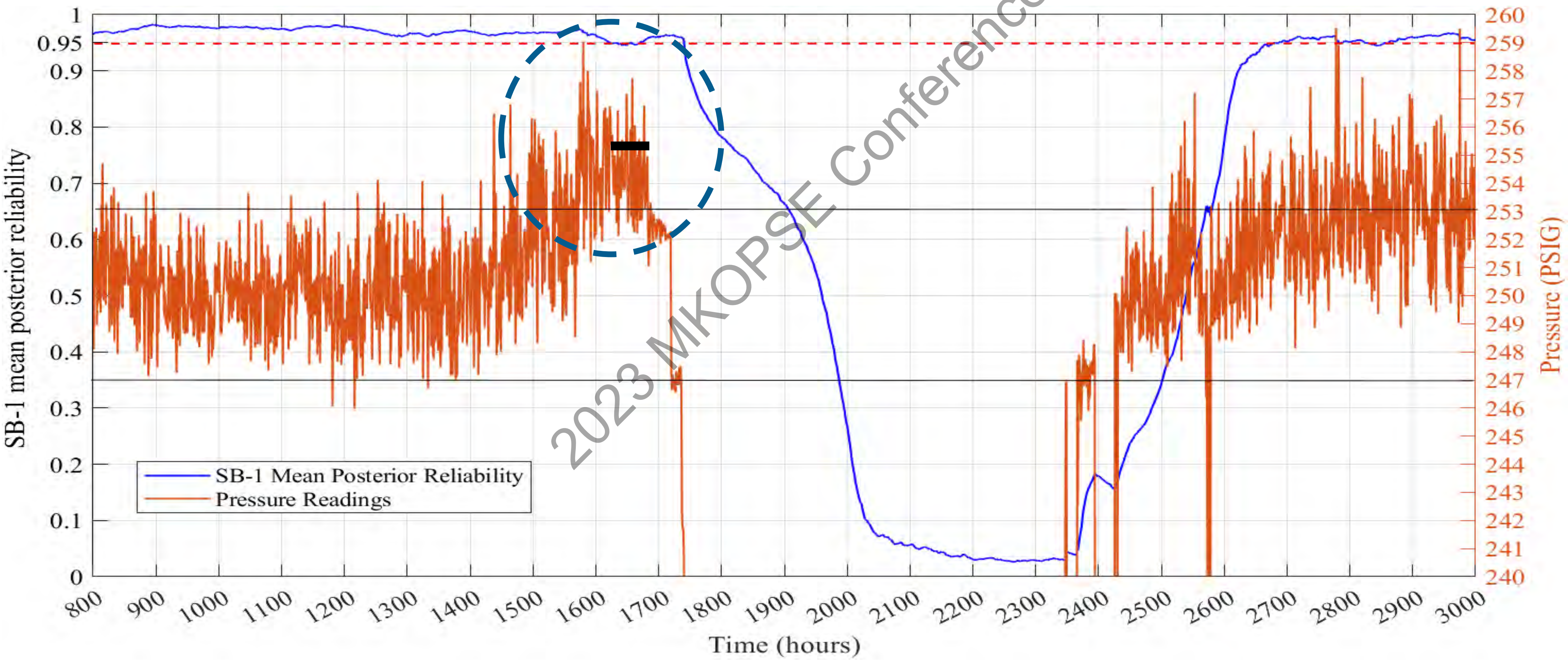
Results and Discussion

Furthermore, we correlate the mean posterior reliability of SB-1 with the pressure measurements:



Results and Discussion

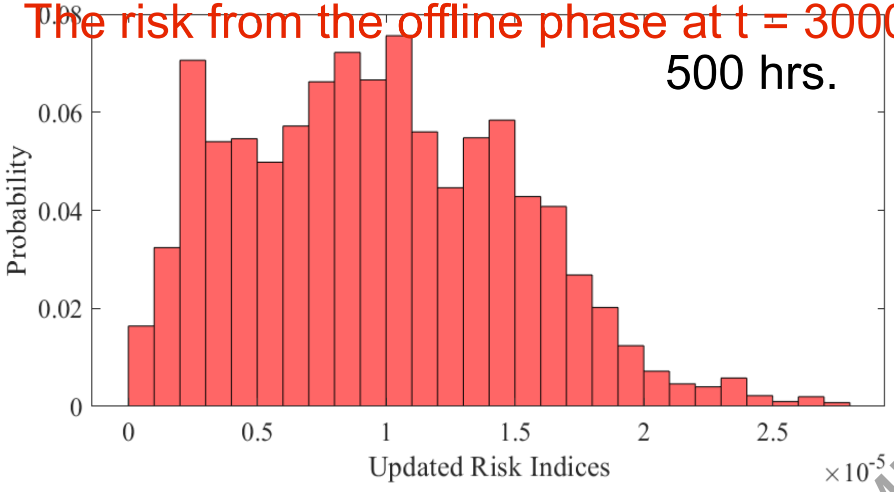
Furthermore, we correlate the mean posterior reliability of SB-1 with the pressure measurements:

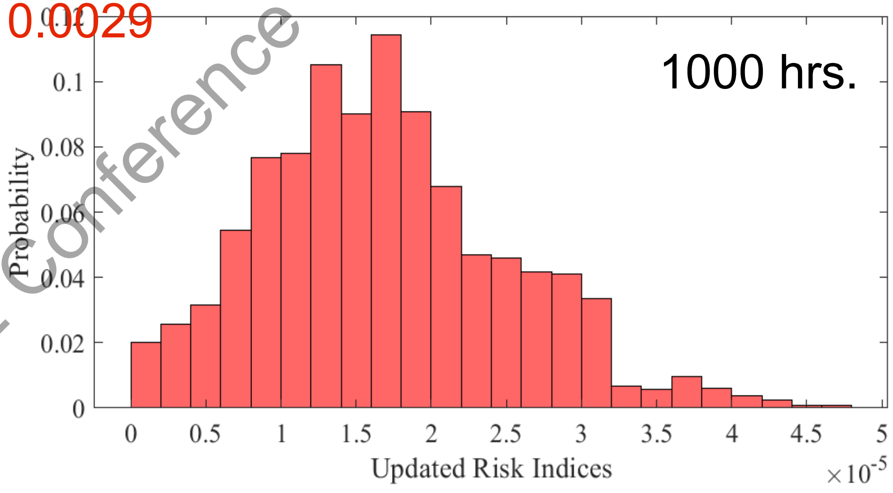


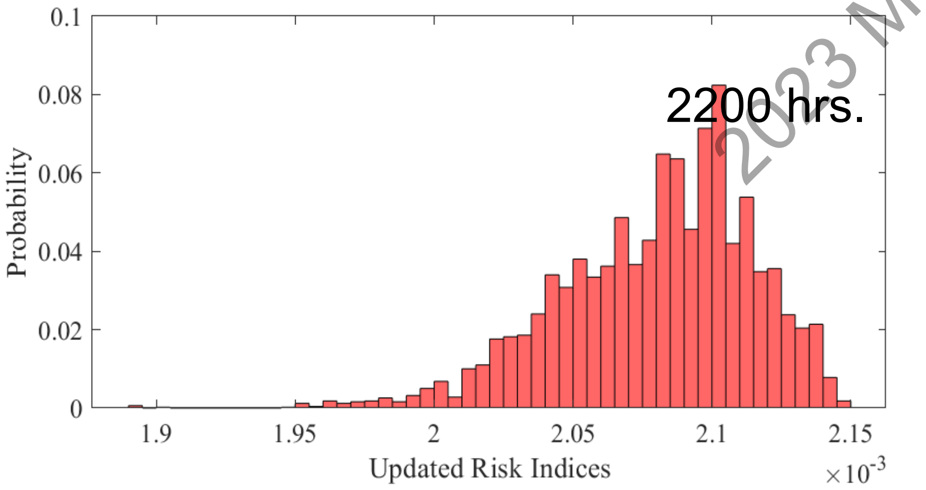
Results and Discussion

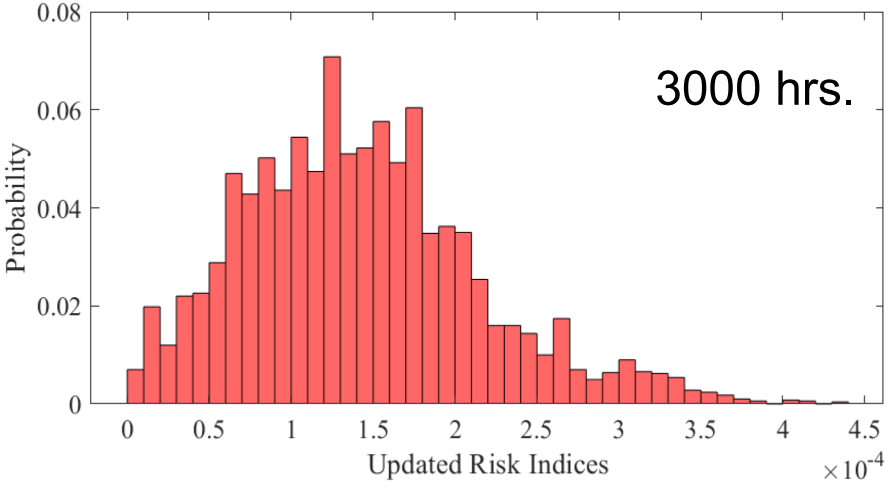
Risk of liquid carryover (offline phase vs. online phase)

The risk from the offline phase at t = 3000 hours is 0.0029









Results and Discussion

Offline phase (conventional QRA)	**Online phase (Our DRA model)**
✗ Does not capture operation changes nor time dependent failure probabilities	✓ Captures the time-dependent failure probabilities of critical components
✗ Unable to predict failures of critical components	✓ Predicts failures of critical components
✗ Requires an update to support decision-making	✓ Provides real-time data to improve decision-making
✗ Static, providing an outdated picture of risk	✓ Dynamic, enabling timely response to risk changes

Limitations of the Study

- Study and analyze the human errors as part of the model
- Incorporate inspection data into the model
- Select more than one critical component for monitoring
- Test the model on a different process within the O&G industry

Conclusion

Objective 1: To contribute to the development and application of the DRA techniques in the O&G industry

Our model applies a DRA technique involving a process from the O&G industry

Conclusion

Objective 1: To contribute to the development and application of the DRA techniques in the O&G industry

Objective 2: To obtain the risk level of an accident scenario in real-time

The model can provide evolving picture of risk level in real time.

Conclusion

Objective 1: To contribute to the development and application of the DRA techniques in the O&G industry

Objective 2: To obtain the risk level of an accident scenario in real-time

Objective 3: To make informed decisions based on inputs from the DRA technique

Decisions, concerning, for example production increase can be made based on inputs from this model.

Conclusion

Objective 1: To contribute to the development and application of the DRA techniques in the O&G industry

Objective 2: To obtain the risk level of an accident scenario in real-time

Objective 3: To make informed decisions based on inputs from the DRA technique

Objective 4: To anticipate failure of process safety barriers

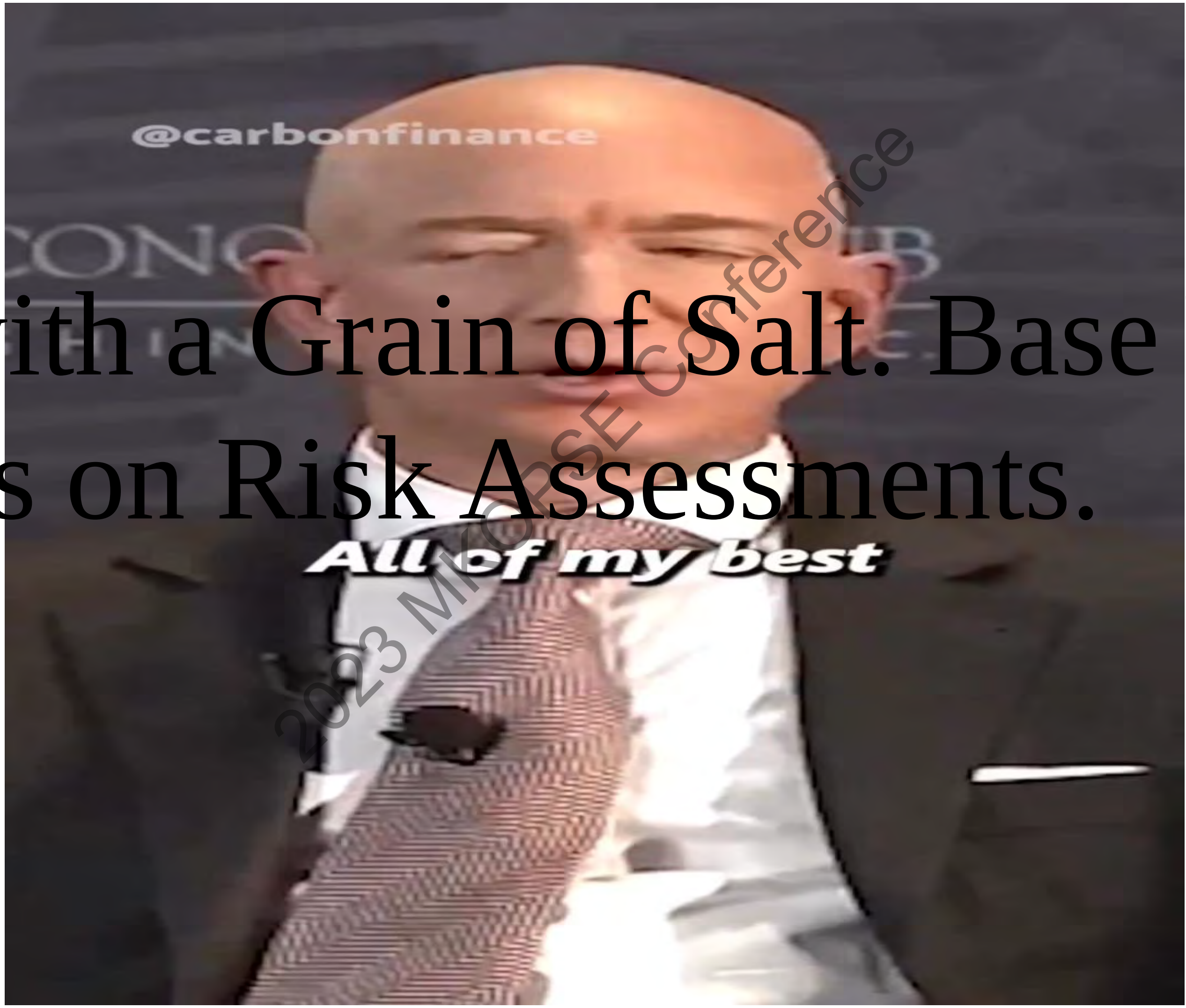
The model provides a window of 40 hours for maintenance/operation team to address and prevent SB-1 from failing.

Conclusion (achieving the Goal)

Goal

Apply a DRA technique to an O&G process unit by integrating conventional risk assessment with condition-monitoring data.

By realizing all 4 objectives, we can say that the goal of this study has been achieved.



Take it with a Grain of Salt. Base Your Decisions on Risk Assessments.

Thank you

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

*In Association with **IChemE***

October 11-13, 2023

Sponsored by aramco

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

26th Process Safety International Symposium

Application of Inherently Safe Principles to Projects

Presenter: Tim Hoff

ExxonMobil Technology and Engineering Company

Tim Hoff

- ExxonMobil Process Safety SME for Global Projects
- B.S. in ChemE from Purdue University (2001)
- Variety of roles within EM
  - Project Development, Process Design, and Execution/Start-up
  - Senior Operations Engineer for Alkylation and Light Ends Fractionation
  - Site Process Safety Engineer
  - Technical Process Safety Lead for Northeastern Operating Sites

What you don't have can't leak.

People who aren't there can't be killed.

- Trevor Kletz

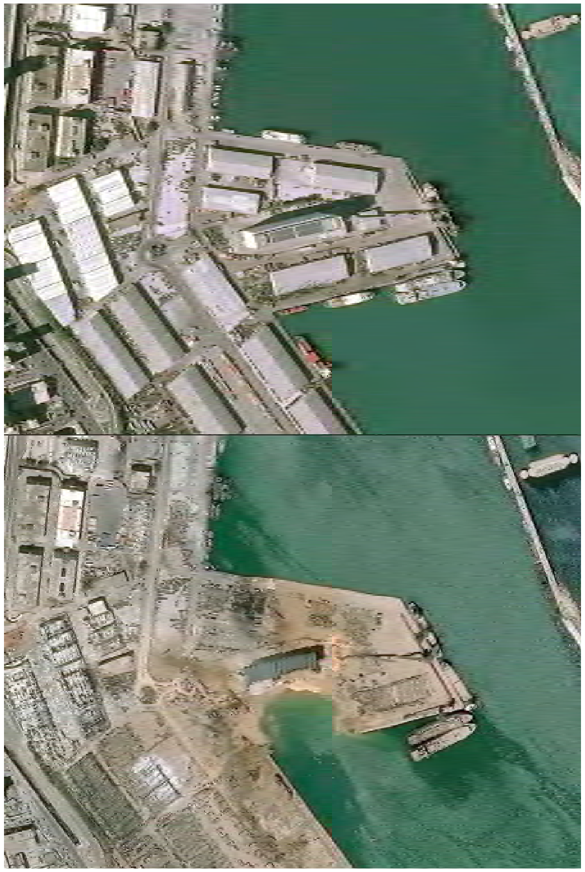
Bhopal Disaster - 1984

- Estimated 4k-20k fatalities due to exposure of highly toxic gas cloud of methyl isocyanate (MIC)
- Liquid MIC stored in three 18,000 US gal underground tanks
- Introduction of water to tank resulted in large production of vapor MIC to ATM via overpressure protection devices

Source: Wikipedia

Beirut Explosion - 2020

- At least 218 deaths from an explosion of 2,750 tons of ammonia nitrate that was being stored in a port warehouse
- Explosion was preceded by a large fire in the same warehouse
- Ammonia nitrate had been stored without safety precautions for 6 years after being confiscated by authorities



Source: New York Post

Aqaba Chlorine Leak - 2022

- At least 13 people killed after a 25 ton chlorine cylinder dropped from a crane and ruptured
- Wire rope sling of crane was rated for 8.5 tons
- Senior port officials had delegated critical safety tasks to untrained personnel

Source: Reuters

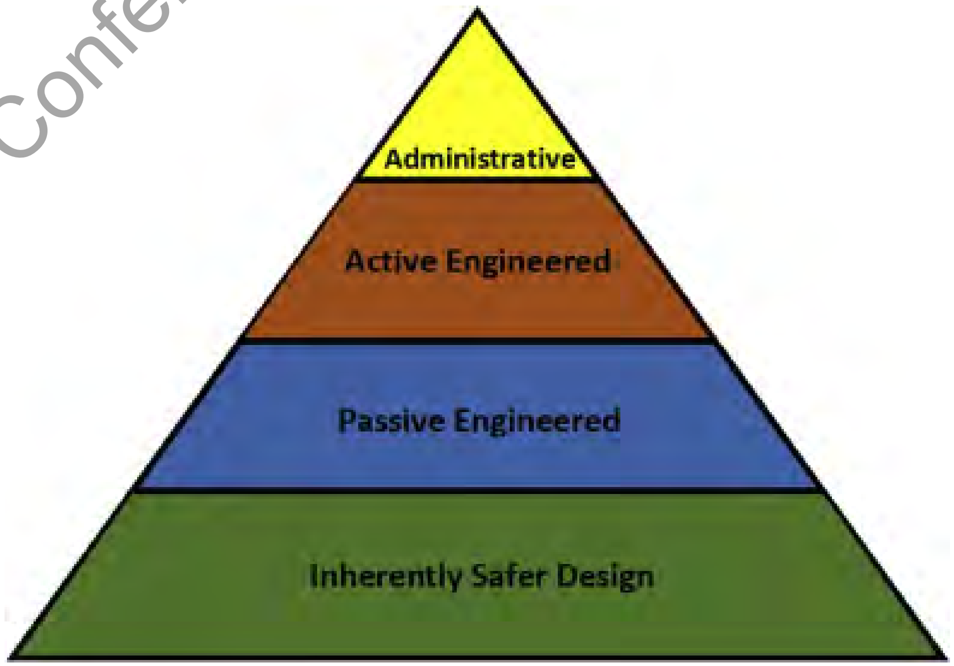
The public isn't responsible for hazards!!

Abnormal

Normal

What is Inherent Safety?

- Avoiding creation of hazards or minimizing hazards if design requires their inclusion
- Elimination or reduction of hazards is accomplished through application of the 4 common Inherent Safety Principles



Source: Methods in Chemical Process Safety, Volume 4

Inherent Safety Principles

- Substitution
    - Substitute more hazardous material with less hazardous one
- Reduction
    - Reduce inventory in storage and process vessels
- Attenuation
    - Reduce severity of processing/operating conditions
- Simplification
    - Simplify the process to reduce potential for operator error

Inherent Safety in Projects

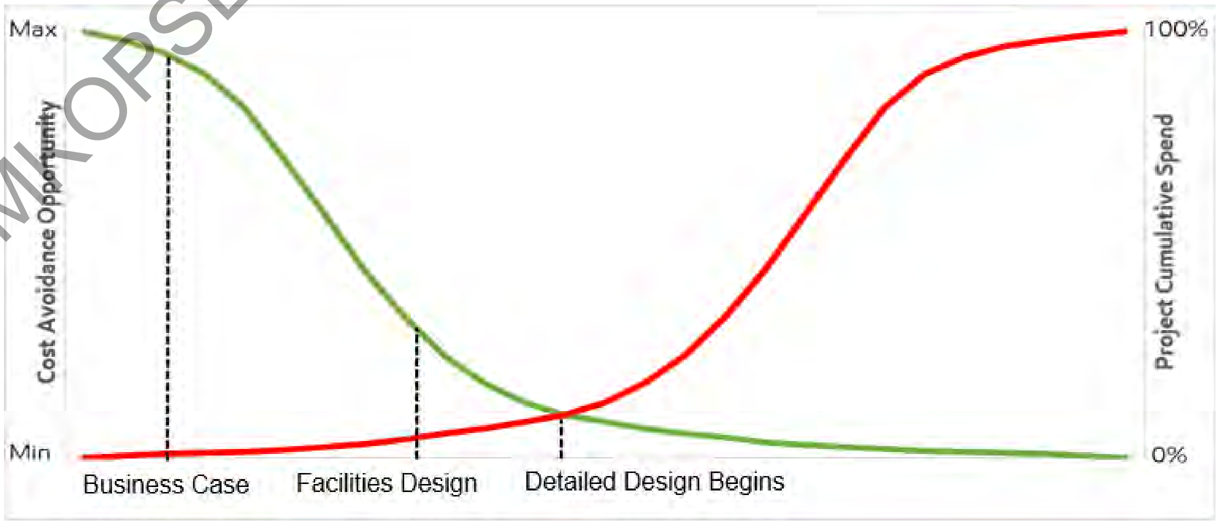
- Projects modify or introduce new hazards, altering an operating facility's risk profile
- Design philosophies might not recognize risks or new technologies/chemicals or changing risk philosophies over time
- Inherently Safest Design has a more substantial and permanent reduction in risk profile

Source: Mammoet.com

Inherent Safety Review and Timing

- Inherent Safety Reviews should be completed with a focus on a project's specific hazards and proposed design

- Early identification and review of hazards is critical to ensure inherently safest design has been considered



Inherent Safety Review Structure

- Formal review of the most representative design and hazard information available in early stages of project
  - Business Case review should focus on 'show stopper' hazards
  - Facilities Design review should focus on reduction of designed safeguards

- Effective review methodologies are "what-if" or checklist review
  - "What-if" is fit-for-purpose brainstorming approach
  - Checklist review requires development of questions in advance by experienced facilitator

Inherent Safety Review Participants

- Highly effective review is dependent on knowledge of the participants on the inherent hazards of the process or technology
- Team size should be based on complexity of process or technology
- Potential review members:
  - Process Safety Engineer
  - Process Technology Expert
  - Industrial Hygienist
  - Project Representative
  - Operations/Maintenance Representative

- *More details on Inherent Safety Reviews can be found in "CCPS: Guidelines for Hazard Evaluation Procedures", 3rd edition*

Inherent Safety Challenges in Projects

- Early application of Inherently Safest Technology may still incur a larger overall project cost
- Resolution of one risk can introduce another that requires further evaluation
- Inherently Safest Technology cannot be applied for logistical reasons

Source: The Hangover

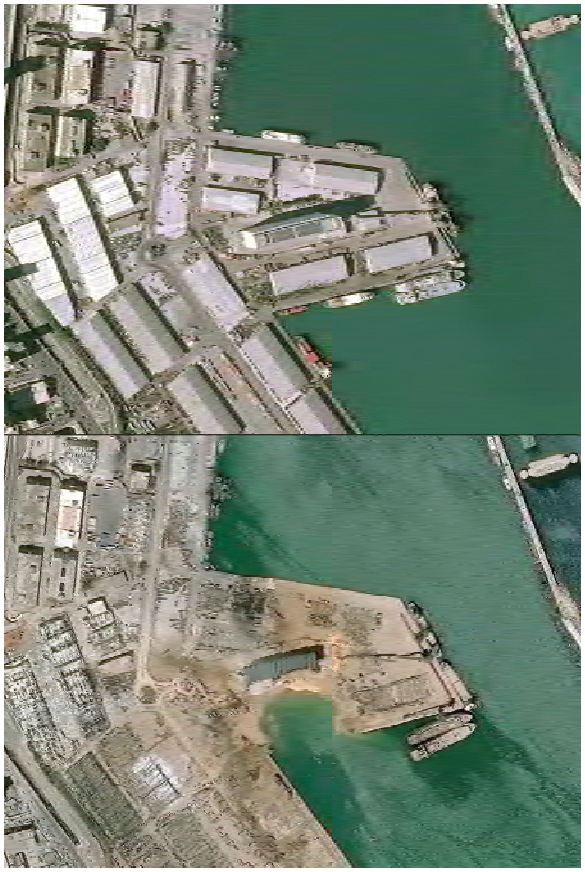
Inherent Safety Questions for Bhopal

- "What if a large volume of water is introduced into the MIC tank when closed relief system is unavailable?"
  - Was consideration given to reducing the tank sizes and liquid inventory of MIC?
  - Was consideration given to alternate process that makes MIC in-situ or doesn't require MIC at all?

Source: Wikipedia

Inherent Safety Questions for Beirut

- "What if there is a large uncontrolled fire in the warehouse?"
  - Was consideration given to storing ammonia nitrate in a fire-safe area?
  - Was consideration given to isolating ammonia nitrate from all other flammable material?



Source: New York Post

Inherent Safety Questions for Aqaba

- "What if one of the chlorine cylinders gets dropped from elevation and breaks?"
  - Was consideration given to an alternate means of cylinder transfer that didn't involve elevated lift?
  - Was consideration given to limiting size of cylinders to within weight limit of smallest sling?

Source: Reuters

Inherent Safety Summary

- Highly effective reduction in a project's risk profile can be achieved through timely application of Inherent Safety Principles
  - Impact on project cost and schedule is lessened the earlier hazards are identified and Inherent Safety Principles applied
- Application of Inherent Safety Principles can decrease the quantity of designed mechanical and procedural safeguards
- Inherently Safest Technology cannot always be applied, but hazard identification and review is key in aiding a project in their rationale of safeguards and meeting an operating site's endorsed risk profile


ANY
QUESTIONS

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with ***IChemE***

October 11-13, 2023

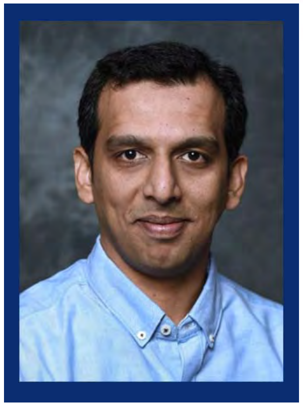
Sponsored by aramco

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

26th Process Safety International Symposium

"If you think safety is expensive…., try an accident"

- an old saying.



SreeRaj R Nair

Technical Safety Engineering Leader

Chevron Corporation

Harigopal Attal

Process Safety Management Consultant

HariAttalProcessSafety.com

- Steward process safety performance and governance, Global experience (23 years)
- Chartered Engineer (IET)
- PhD, MSc (Eng.), B.Tech

snair@chevron.com

- Process safety management, inherently safer design, Relief and flare system design (40 years)
- Professional Engineer (Texas)
- M.Chem Eng, B. Chem Eng

Hari@HariAttalProcessSafety.com

You have "safeguard" in place, sounds promising; have you tested it?

Act before it is too late !!

- Effective safeguards are critical for effective risk management
- Ensure safeguards are in place and effective throughout the lifecycle.

Agenda

- Basics of safeguards
- Why safeguards fail?
- Safeguard assurance

Safeguard centric risk management

Prevent things from going wrong to make sure things go right.

Establish
Sustain

Safeguards – a measure to protect from harm or damage

Initiating cause (latent conditions)

Preventive Safeguard

Event (Loss of control of energy)

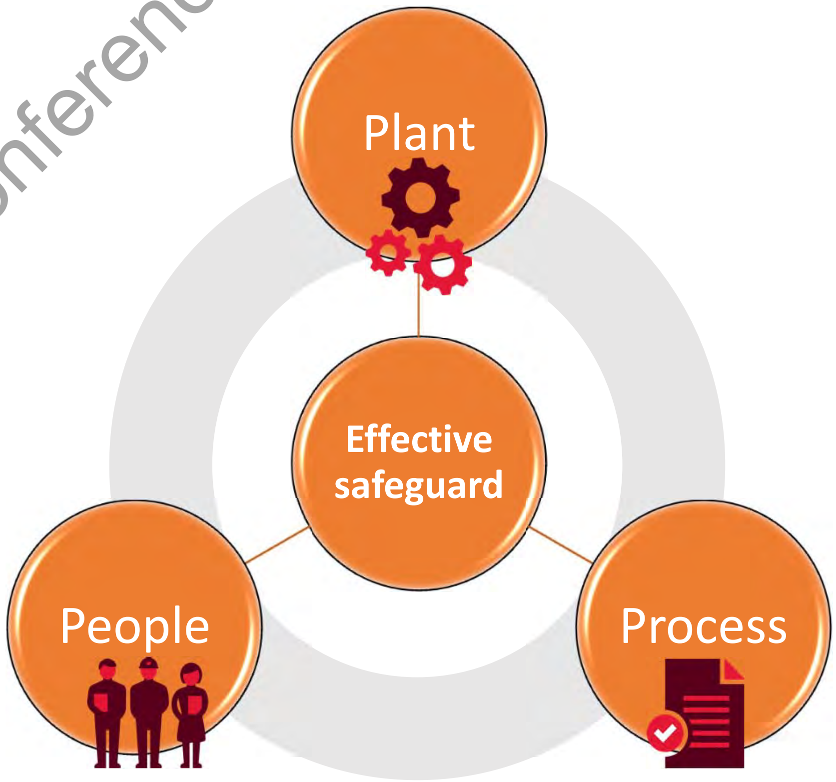
Mitigative Safeguard

Impact / losses (Consequences)

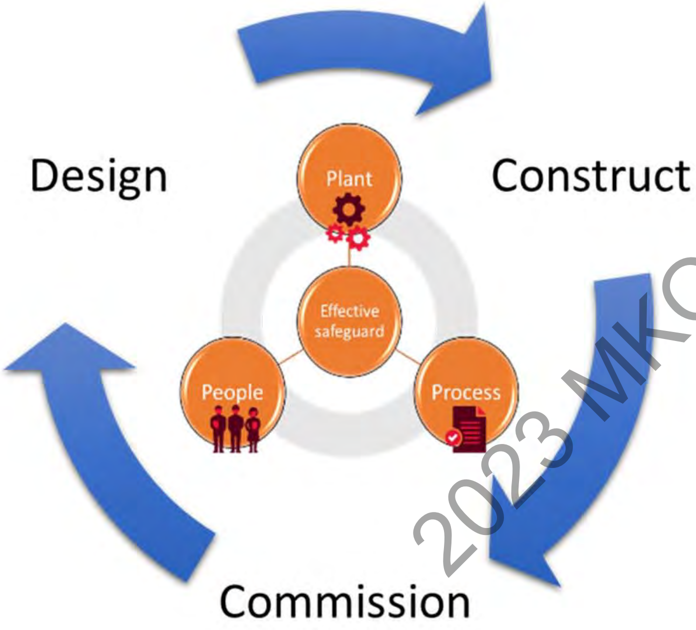
	Preventive safeguards	**Mitigative safeguards**
	prevent a loss of control over energy	reduce the severity, minimize impact
(i) leaks / hazardous material release	the primary equipment integrity management system, relief system.	Emergency shutdown, firewall, fire & gas detection, suppression system
(ii) vehicles and collision	Braking system, driver competence Alerts, Lane assist, electronic stability control	Seat belts, airbags

3Ps of Safeguard

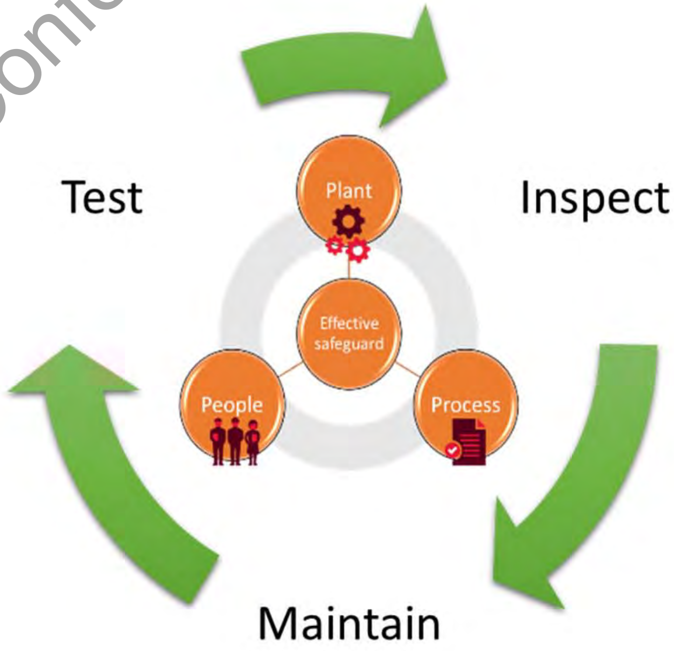
- **Plant** or the engineered devices and the physical barriers
- **Processes** or management systems to ensure that plant operations are safe and available when called for service.
- **People:** suitably qualified and experienced personnel to upkeep of the plant and the processes.



Safeguard – in place and effective

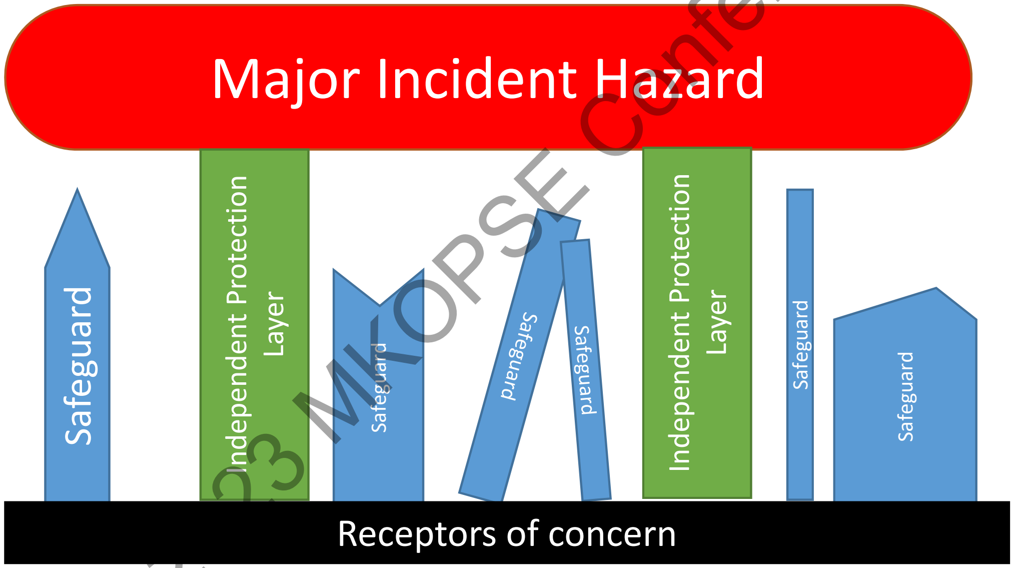


Project and design stage



Operational phase

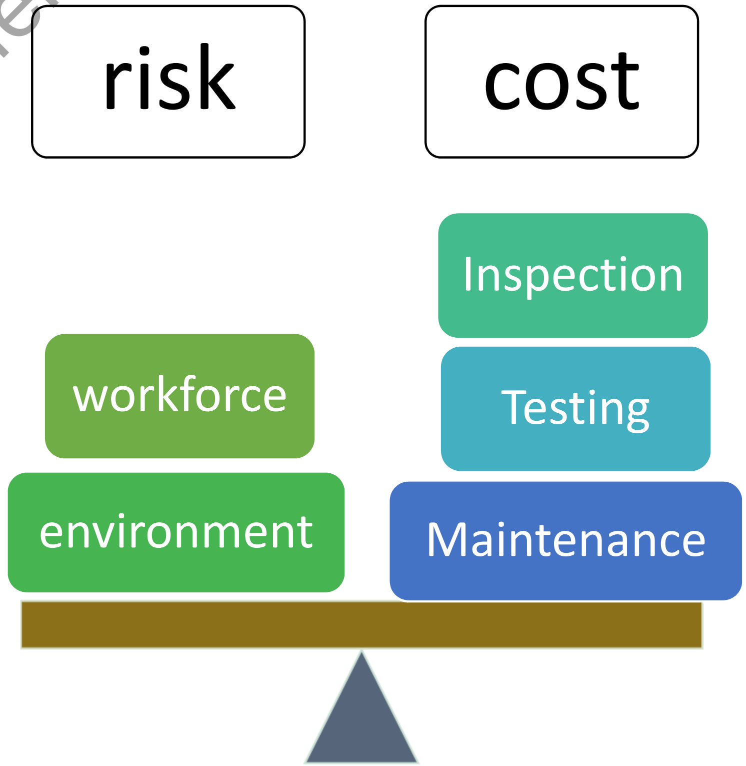
"All safeguards are not equally effective"



- Safeguard functionality
- Demand on the safeguard

"More is not necessarily safer"

- Resource (manhours, equipment, time) required for safeguard Inspection, Testing and Maintenance (ITPM).
- Safeguards should have functionality and workforce risk exposure from safeguard ITPM should be justified.



Safeguards should not create new hazards.

Why do safeguards fail?

Assurance and incident investigations

Typical findings:

- Safeguard not in place or
- Safeguard not effective

Failures:

- Engineering factors
- Human factors
- Life-cycle factors

Generally, major incidents occur due to the failure of more than one safeguard.

Failure reasons

Engineered safeguards

- Design aspects
  - Documentation, Risk-based
- Construction quality
- Commissioning
- Maintenance program inadequacy
- Inconsistency between records and what is in the field

Failure reasons

Human factors

- Competence of personnel
- Suitably qualified, experience, knowledge, skill
- Operational discipline

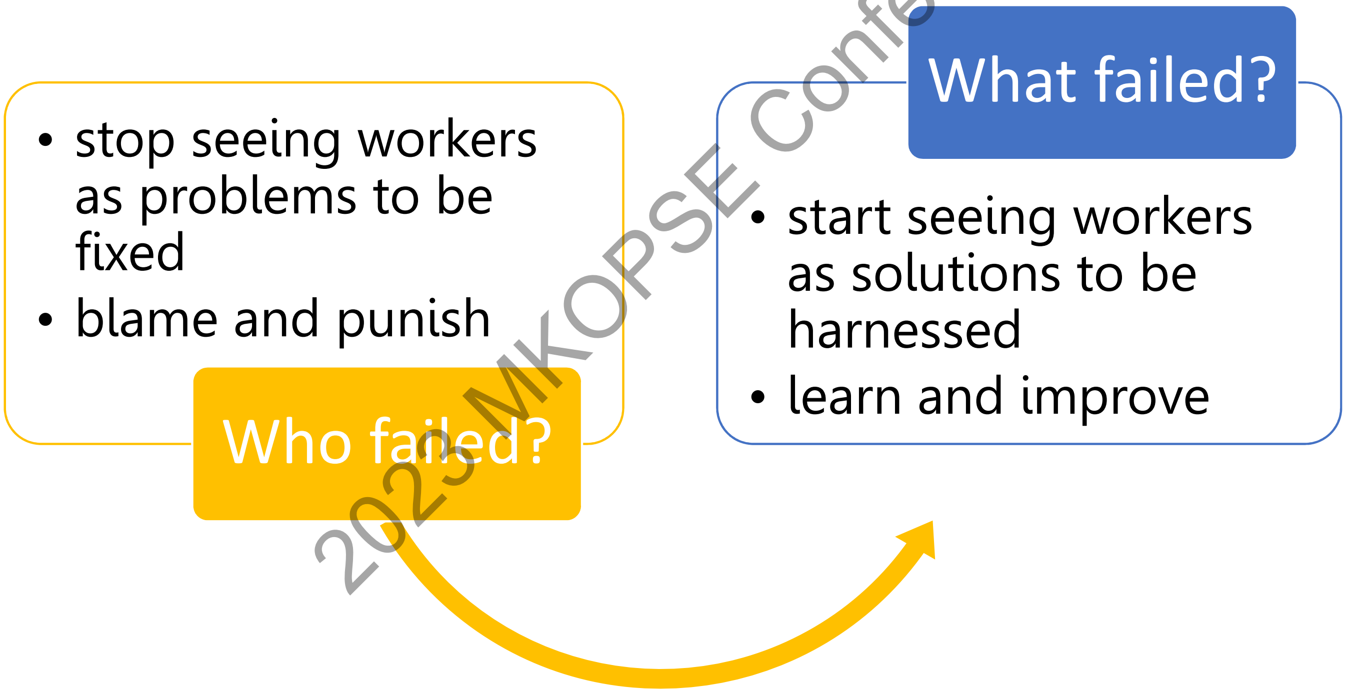
Life cycle considerations

- Changes on the demand during asset life
- Vendor support, life expectancy
- Spare part availability

Safeguard testing

- Is the safeguard(s) in place and match the design specifications and meet the design intent?
  - Does the design meet the RAGAGEP?
  - Is safeguard functional?
- Asset integrity, availability, reliability.
- Competency:
  - Understand the design intent and are knowledgeable on responding when safeguard is on demand.
  - Maintenance and functional testing requirements.
- Systemic, recurring issues identified and addressed?

'who?' to 'what?'



- stop seeing workers as problems to be fixed
- blame and punish

Who failed?

What failed?

- start seeing workers as solutions to be harnessed
- learn and improve

Key take aways

Effective safeguards are critical for risk management

- Establish and periodically review
    - Functionality, demand.
- Establish and maintain safeguard's 3Ps
    - People, Plant, and Process.
- Ensure safeguard is in place and effective throughout the lifecycle.
- Address change in demand.
- Consider inherently safer alternatives.

"Safety is not the absence of accidents, but the presence of safeguards"

Todd Conklin

Thank you

snair@chevron.com

Hari@HariAttalProcessSafety.com

Hierarchy of Safeguards

Strategic More reliable					Tactical Less Reliable		
Inherently Safer					Dependent on add-on Safeguards		
Elimination	**Substitution**	**Minimization**	**Moderation**	**Simplification**	**Passive**	**Active**	**Procedural**
No likelihood and no consequence	**Reduce hazard Severity**			**Reduce the likelihood of the hazard**	**Reduce the Likelihood or Severity of a hazard**		
	No Add-on Safety Systems				**By Add-on Safety Systems**		**Human Centric**
change the design or remove the need for hazardous material, equipment, activity	less dangerous material in a Process or Activity	smaller quantities of dangerous material inventory or limiting the hazardous activities	material in a less dangerous form or operating in less severe conditions	by designing processes, equipment, and procedures to eliminate opportunities for failures	available at all times but without the active functioning of the device	requires initiation during the event by active functioning of devices	by using administrative control procedures.

Hierarchy

Traditional Safety

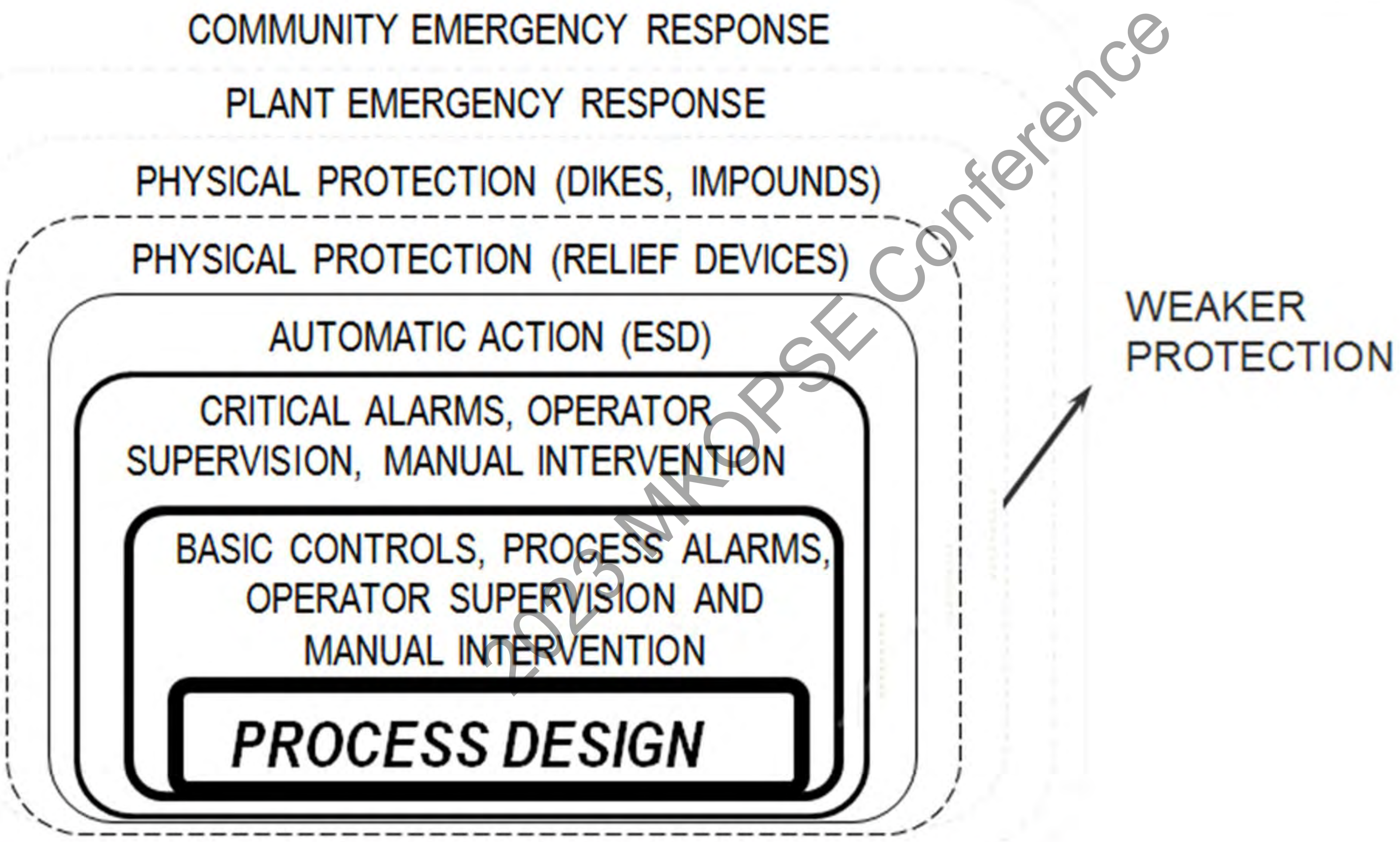
- Preventing things from going wrong
- Safety is the absence of accidents

Safeguard centric

- Making sure things go right
- Safety is the presence of safeguards

Inherent Safety

- Absence of safeguard
- Minimum demand on safeguard



COMMUNITY EMERGENCY RESPONSE

PLANT EMERGENCY RESPONSE

PHYSICAL PROTECTION (DIKES, IMPOUNDS)

PHYSICAL PROTECTION (RELIEF DEVICES)

AUTOMATIC ACTION (ESD)

CRITICAL ALARMS, OPERATOR SUPERVISION, MANUAL INTERVENTION

BASIC CONTROLS, PROCESS ALARMS, OPERATOR SUPERVISION AND MANUAL INTERVENTION

PROCESS DESIGN

WEAKER PROTECTION

References

1. Attal, H. and Ogbeifun, N., 2019. Inherent Safety as a driver for business success in the Oil & Gas Industry. Mary Kay O'Connor Process Safety Center; Texas &M University.
2. Laughland, Graeme, 2017, Practical experience with Deep Dive Assessments to identify key Major Accident Hazard risk factors on operational facilities, IChemE Symposium Series 162 HAZARDS 27
3. Manton, M. et. al., 2017, Standardisation of Bow Tie Methodology and Terminology via a CCPS/EI Book, IChemE HAZARDS 27
4. Leveson, Nancy, 2011, Risk Management in the Oil and Gas Industry, Testimony of Professor Leveson before the United States Senate Committee on Energy and Natural Resources
5. Paul Amyotte et al, 2018, CSB investigation reports and hierarchy of controls: Round 2, AIChE 14th GCPS
6. Todd Conklin, 2020, Pre-Accident Investigations – An Introduction to Organizational Safety.
7. US CSB Videos on incident investigation.

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

*In Association with **IChemE***

October 11-13, 2023

Sponsored by aramco

Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

26th Process Safety International Symposium

Jeff Marx, P.E., Quest Consultants Inc.

- Principal Engineer; 30 years at Quest
- BSME, OU; MSME, GaTech
- Consequence & risk analysis, facility siting, building siting
- Serving full petrochemical industry; LNG, LPG, H2, pipelines
- CANARY software

A Comparative Study: Transporting Hydrogen or Ammonia

Jeff Marx & Ben Ishii

Quest Consultants Inc.
Norman, OK
www.questconsult.com

QUEST CONSULTANTS

Purpose

- Hydrogen as a transportation fuel: increasingly popular topic
- Primary use is gaseous hydrogen in fuel cells
- Gradual build-out of hydrogen fueling infrastructure
  - Hydrogen generation & storage
  - Hydrogen transportation
  - Hydrogen storage & fueling
- Limitations in gaseous hydrogen (GH2) supply range/feasibility
- Proposals for alternate hydrogen carriers have emerged
  - Solids
  - Liquid hydrocarbons
  - Ammonia (NH_3)

Background and History

- 1766: Hydrogen identified as a discrete gas
- 1800: electrolysis
- 1800s
  - Early fuel cells (not vehicular)
  - Thermal reforming → town gas
- 1900s: hydrogen dirigibles
- 1931: methane reforming (produced H_2 from CH_4)
- 1950s/60s: NASA uses H_2 as propellant and in fuel cells
- 1970s-2000s: hydrogen-fueled vehicle research
- 2010s: Commercial hydrogen fuel cell passenger vehicles

Etienne Lenoir's "Hippomobile"

Hydrogen as a Vehicular Fuel

- Mostly hydrogen fuel cell electric vehicles (HFCEVs)
- Some internal combustion hydrogen engines
- Hydrogen market is mature…
  - Petrochemical applications
  - Industrial gases: generation, distribution
- Vehicular fueling infrastructure small but growing
  - Mostly compressed gaseous transports, storage
  - Some liquid hydrogen storage with regas/fueling
- Need extensive production, transportation, storage, fueling network

Ammonia as a Fuel?

- Ammonia is a mature market – fertilizers and others
- Direct combustion possible, but…
  - Energy density lower than other liquid fuels
  - Fuel storage technology different (in comparison)
  - Engines may need fuel spiking to maintain sufficient compression ratios
  - NO_x formation high
- Fuel cell use?
  - Ammonia is typically poisonous to fuel cells
  - Solid–oxide fuel cells (SOFC) show promise for NH_3 use
- Or…. Just use ammonia as a hydrogen carrier

Comparison Case

- Assume a hydrogen production and distribution network for vehicular fueling (HFCEVs)
- Beginning is hydrogen production
- End is gaseous fueling systems
- Consider four transportation options:
  1. Moderate pressure gaseous hydrogen
  2. High pressure gaseous hydrogen
  3. Liquid hydrogen
  4. Liquid ammonia

Comparison Cases

1. MP GH2 transport, tube trailer: (9) 40'x22"ID


Production
Compres-sion
Storage
Transport
Storage*
Fueling

2. HP GH2 transport: (75) Al/carbon fiber cylinders


Production
Compres-sion
Storage
Transport
Storage
Fueling

Comparison Cases

3. LH2 transport: 15,000 gallon vacuum-insulated vessel

Production
Liquefaction
Storage
Transport
Storage
Compression& Vaporization
Fueling

4. Ammonia transport: 12,600 gallon pressurized vessel

H_2 Production
NH_3 Synthesis
Storage
Transport
Storage
H_2 Reforming
Compression & Storage
Fueling

How to Evaluate?

- Technical feasibility? ✓
- Economic? Market demand analysis? ✖
- Life cycle analysis? ✖
- Energy balance? ✖

- "Hydrogen Logistics" ✓
- Consequence Analysis ✓
- Risk Analysis

Hydrogen Logistics

System	Transportation Type	Available Storage Volume [ft^3]	Total Mass Transported [lb]	KiloMoles Hydrogen Transported	Equivalent Tube Trailers
1	Moderate Pressure Gaseous Hydrogen (tube trailer)	950	779	175	1

Hydrogen Logistics

System	Transportation Type	Available Storage Volume [ft^3]	Total Mass Transported [lb]	KiloMoles Hydrogen Transported	Equivalent Tube Trailers
1	Moderate Pressure Gaseous Hydrogen (tube trailer)	950	779	175	1
2	High Pressure Gaseous Hydrogen (HP tube trailer)	848	1,512	340	1.94

Hydrogen Logistics

System	Transportation Type	Available Storage Volume [ft^3]	Total Mass Transported [lb]	KiloMoles Hydrogen Transported	Equivalent Tube Trailers
1	Moderate Pressure Gaseous Hydrogen (tube trailer)	950	779	175	1
2	High Pressure Gaseous Hydrogen (HP tube trailer)	848	1,512	340	1.94
3	Cryogenic Hydrogen	2,005	9,309	2,095	11.95

Hydrogen Logistics

System	Transportation Type	Available Storage Volume [ft^3]	Total Mass Transported [lb]	KiloMoles Hydrogen Transported	Equivalent Tube Trailers
1	Moderate Pressure Gaseous Hydrogen (tube trailer)	950	779	175	1
2	High Pressure Gaseous Hydrogen (HP tube trailer)	848	1,512	340	1.94
3	Cryogenic Hydrogen	2,005	9,309	2,095	11.95
4	Liquefied Ammonia	1,432	53,993	2,158	12.31

Consequence Analysis

- Definition: The use of mathematical models to predict the potential extent of specific hazard zones or effect zones that would result from specific accident event sequences
- Context is transportation of hydrogen (or hydrogen carrier)
  - Truck-based road transport
  - Vehicular accident causes a loss of containment
- Hazards introduced to the surrounding area

Consequence Analysis

- Tube trailers use 9/16" tubing, occasionally 1/2" tubing
- Liquid hydrogen trailers 1" or 1.5" piping
- Liquid ammonia trailers 2" or 3" piping
- How to evaluate on an equal basis?

♦ Set release hole size to 1/2"

♦ Assumed discharge from:

1. MPGH2: 1 of 9 tubes
2. HPGH2: 5 of 75 tubes
3. LH2: container
4. NH3: container

Consequence Analysis

- Hazard Definition
  - Gaseous hydrogen: flash fire, jet fire, VCE
  - Liquid hydrogen: cryogenic exposure, flash fire, jet fire, VCE
  - Ammonia: toxic vapor cloud

Hazard Type	Injury Level	Threshold of Fatality Level
Flammable Vapor Cloud	Extent of released gas mixed to the lower flammable limit (LFL) in air	
Thermal Radiation	1,600 Btu/hr-ft^2 for 30 second exposure; results in 2nd degree burns to unprotected skin	4,000 Btu/hr-ft^2 for 20-30 second exposure; potential fatality due to burns
Toxic Gas	Extent of released gas mixed to the AEGL-2 level, 10-minute exposure	Extent of released gas mixed to the AEGL-3 level, 10-minute exposure

CANARY by Quest®

Consequence Analysis Results

System	Transportation Type	Release Rate [lb/sec]	Event Duration	Distance to Threshold of Fatality [feet]	Distance to Injury [feet]
1	Moderate Pressure Gaseous Hydrogen (1 of 9 tubes)	1.074	> 4 minutes	35	40
2	High Pressure Gaseous Hydrogen (5 of 75 tubes)	1.53	< 3 minutes	55	60
3	Cryogenic Hydrogen	1.635	> 1 hour	80	80
4	Liquefied Ammonia	5.34	> 1 hour	1,050	3,500

Qualitative Risk Assessment

- Set MP GH2 (tube trailer) as basis

- HP GH2 Consequences approximately equal

- LH2 consequences slightly larger

- Ammonia consequences much larger

- Assuming an equal accident rate per mile, hydrogen options would have similar risk corridors, ammonia larger
- On a risk (probability) basis: LH2 < HPGH2 < MPGH2 < NH_3

Concluding Remarks

- Transport of GH2 seems to favor higher pressures
- Transport of LH2 slightly less risky, but more complicated
- Use of ammonia as a carrier reduces the probability of accident scenarios, but introduces significant toxic impacts and system complexity
- Conversion to, and reforming from, ammonia requires extra resources (equipment, energy, plot space…)
- Ammonia may or may not fit the needs of a given market

QUEST
CONSULTANTS

Thank You!

Jeff Marx, jdm@questconsult.com

Process Safety and Risk Management Services

Exponent®

MKOC 2023 - Explosion Workshop

Ali Rangwala, Ph.D.
Alfonso F. Ibarreta, Ph.D., PE, CFEI

Mary Kay O’Connor Process Safety Conference,
October 13, 2023

Ali Rangwala, Ph.D.

- Professor of Fire Protection Engineering at WPI, Worcester, MA
- Education
  - Ph.D. in Mechanical and Aerospace Engineering, University of California, San Diego
- Interests
  - Combustion
  - Industrial fire protection
  - Explosion protection
  - Combustible dust

Alfonso Ibarreta , Ph.D., PE, CFEI

- Managing Engineer at Exponent, Natick, MA
- Education
  - Ph.D. in Aerospace Engineering, University of Michigan
- Interests
  - Vapor cloud explosions
  - Explosion protection of process equipment
  - Combustible dust
- Memberships
  - NFPA Technical Committee on Explosion Protection Systems
  - Mechanical engineering representative at the Massachusetts Board of Fire Prevention Regulations

Presentation Outline (1/2)

- **PART I - Deflagration and Explosion Fundamentals**
  - Introduction to explosions and flammability (Dr. Ibarreta)
  - Case studies of gas explosions (Dr. Rangwala)
- **PART II – Closed Vessel Deflagrations**
  - Theory and calculations (Dr. Rangwala)
  - Explosion prevention methods (Dr. Ibarreta)

Presentation Outline (2/2)

- PART III – Vented Explosions
  - Analysis methods (Dr. Rangwala)
  - Explosion protection via deflagration venting (NFPA 68) (Dr. Ibarreta)

TYPES OF EXPLOSIONS

Definitions - I

- **Explosion:** The sudden conversion of potential energy (chemical or mechanical) into kinetic energy with the release of gas(es) under pressure. These gases then do mechanical work such as defeating their confining vessel or moving, changing, or shattering nearby materials. [NFPA 921]
- **Deflagration:** Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium.[NFPA 68]
- **Detonation:** Propagation of a combustion zone at a velocity greater than the speed of sound in the unreacted medium. [NFPA 921]

Definitions - II

- **Flammable Gas:** Any substance that exists in the gaseous state at normal atmospheric temperature and pressure and is capable of being ignited and burned when mixed with the proper proportion of air, oxygen, or other oxidizers. [NFPA 2]
- **Flammable Liquid:** A liquid with a closed-cup flash point below 100 °F (37.8 °C) and Reid vapor pressures not exceeding 40 psia at 100 °F (37.8 °C) [NFPA 30]
- **Explosive:** Any chemical compound, mixture, or device, the primary or common purpose of which is to function by explosion. [NFPA 495]

Explosions

- **Types of Explosions (NFPA 921)**
  - **Mechanical Explosion**
    - **Pressure vessel burst**
    - **Boiling Liquid Expanding Vapor Explosion (BLEVE)**
  - **Combustion Explosion**
    - **Flammable gases**
    - **Vapors of flammable liquids**
    - **Combustible dust**
  - Chemical Explosion
  - Electrical Explosion
  - Nuclear Explosion

Combustion Explosion

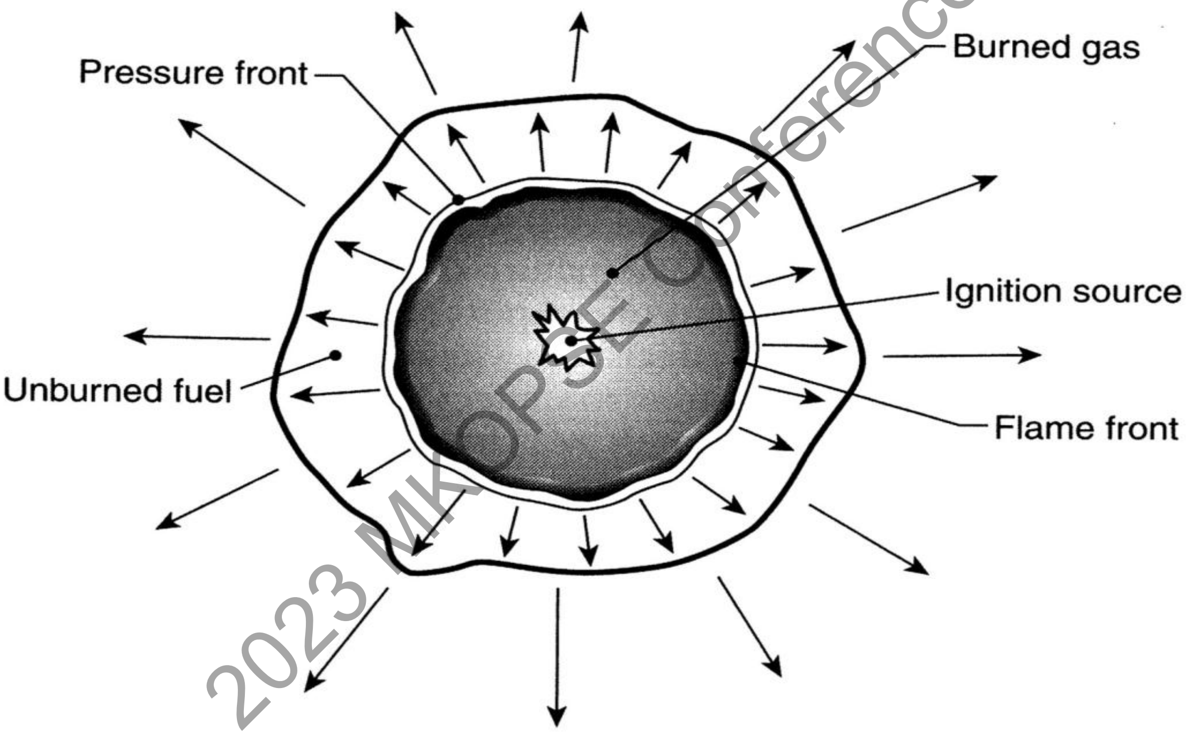
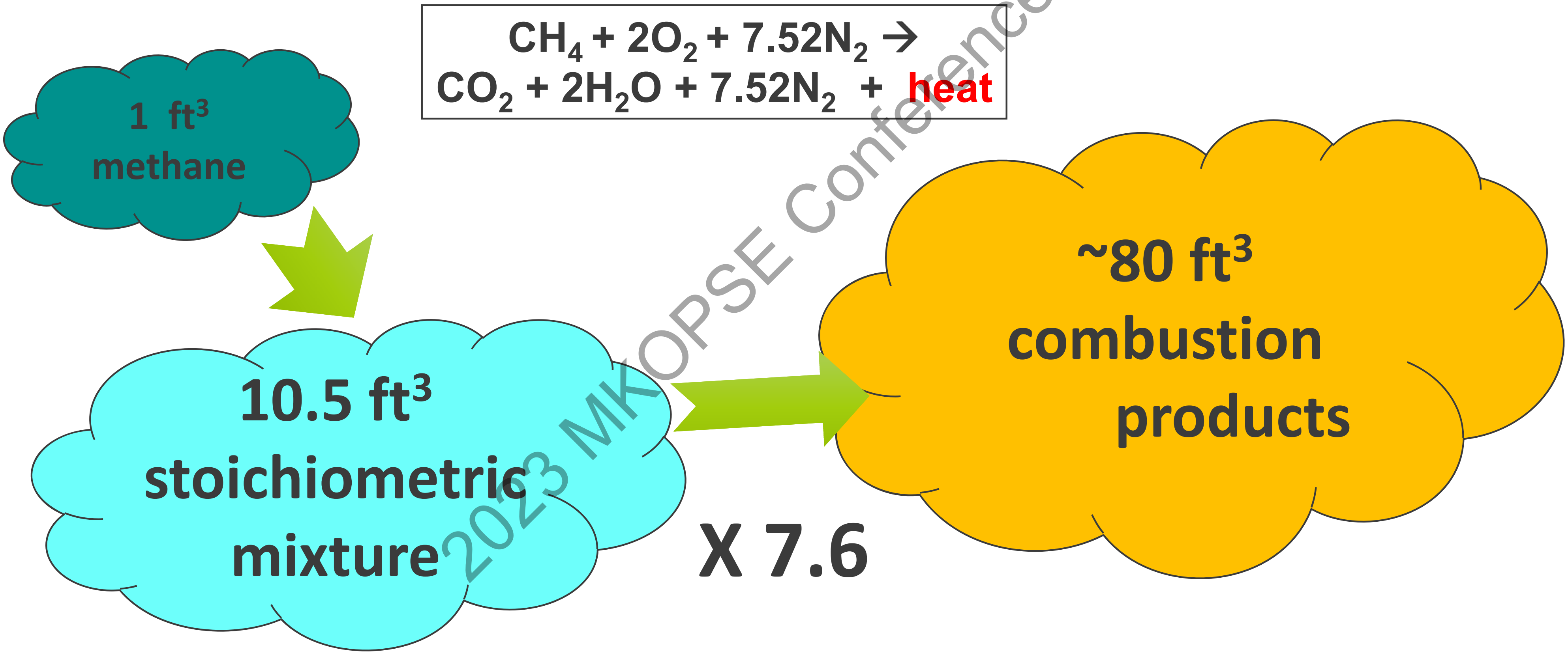


FIGURE 21.4.1.4(a) Idealized Propagating Flame and Pressure Fronts [After Harris (1983) p.3]

Source: NFPA 921 “Guide for Fire and Explosion Investigations”

Gas Expansion During Combustion Explosion



$CH_4 + 2O_2 + 7.52N_2 \rightarrow$
$CO_2 + 2H_2O + 7.52N_2$ + heat

1 ft^3 methane

10.5 ft^3 stoichiometric mixture

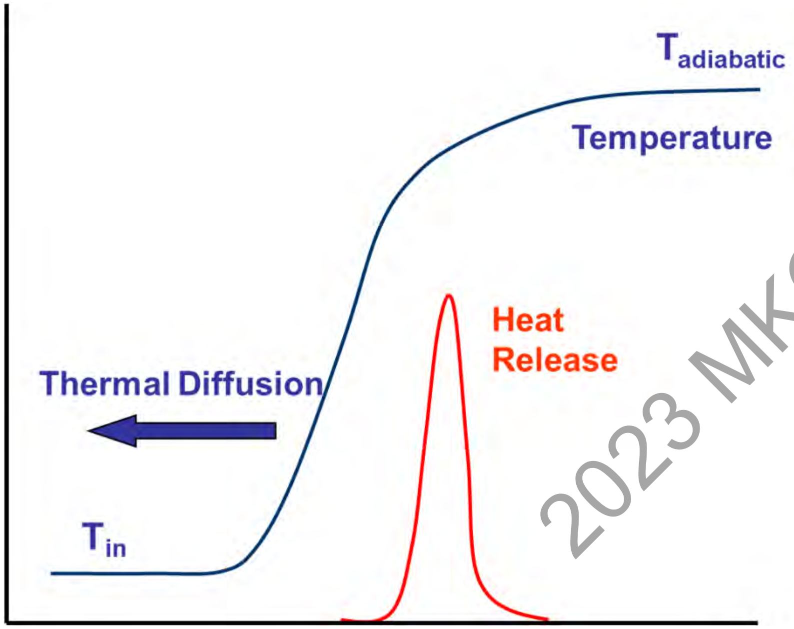
X 7.6

~80 ft^3 combustion products

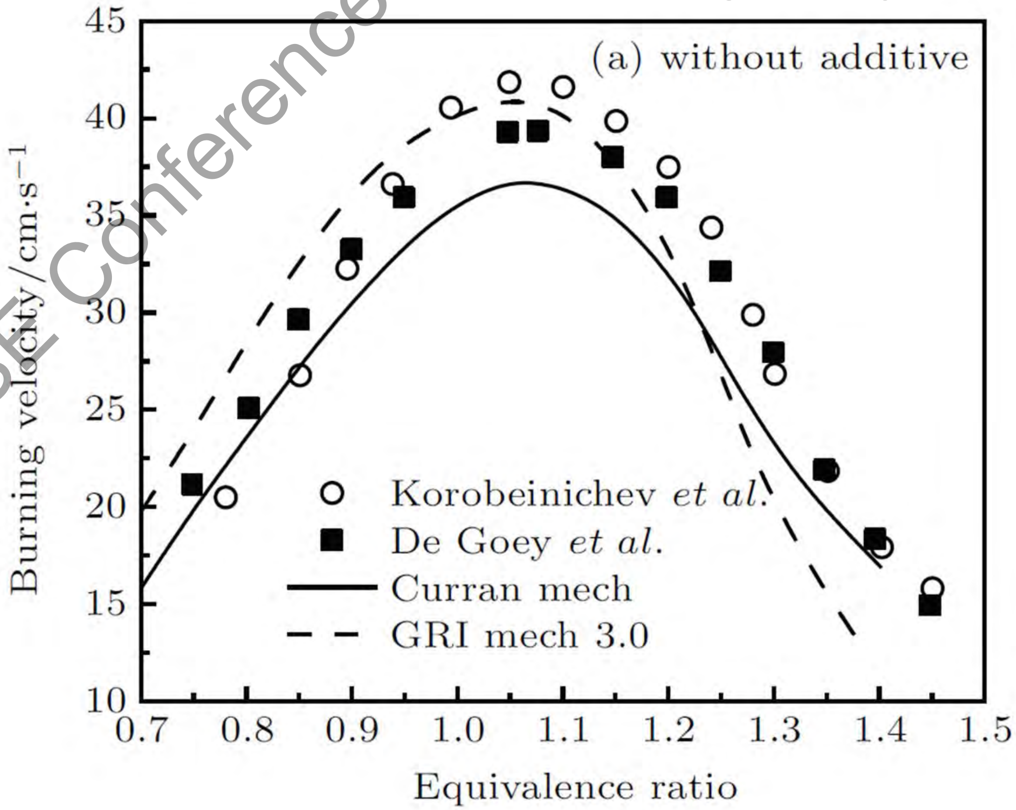
Flame Propagation and Burning Velocity

Premixed Flame Structure

$CH_4+2O_2 \rightarrow CO_2 + 2H_2O$

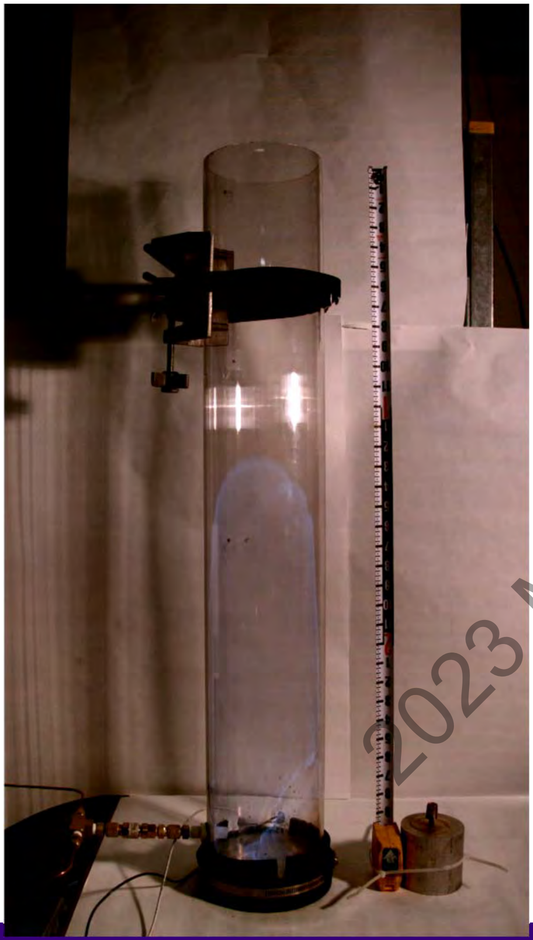


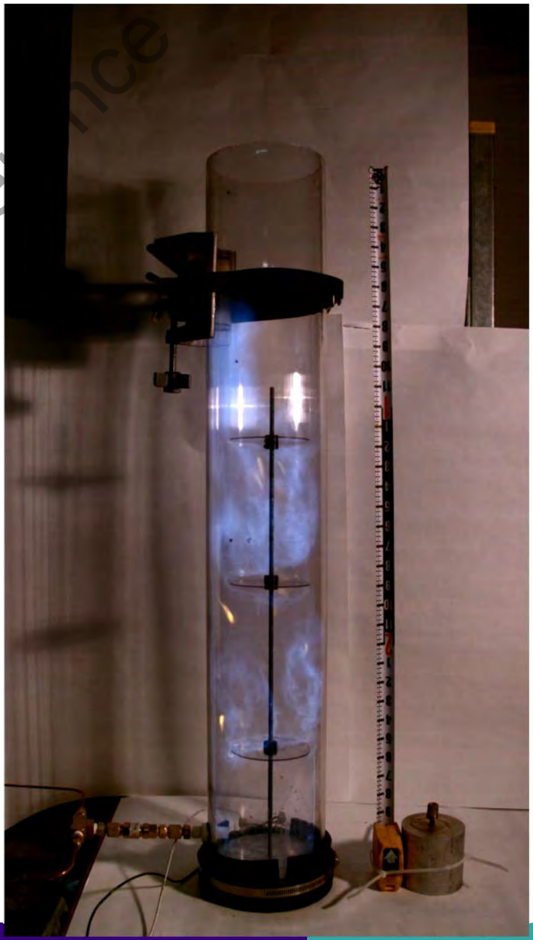
Methane/Air Flame Burning Velocity



Source: Yin et al. “Physical and chemical effects of phosphorus-containing compounds on laminar premixed flame” Chin. Phys. B Vol. 27, No. 9 (2018) 094701

Effect of Congestion – Propane / Air Flame





Tests performed by Exponent

Confined Deflagration

- Reaction wave propagates below speed of sound.
- Confinement required to generate significant overpressure.
- Relatively uniform pressure in an enclosure.

Photograph taken by Exponent

Vapor Cloud Explosion (VCE)

- Reaction wave propagates below speed of sound.
- Overpressure generated by congestion over large area.
- Pressure no longer uniform. Pressure pulse travels as a wave ahead of combustion front.

Tests performed by BakerRisk for the 2001 Explosion Research Cooperative

VCE Pressure Wave Propagation

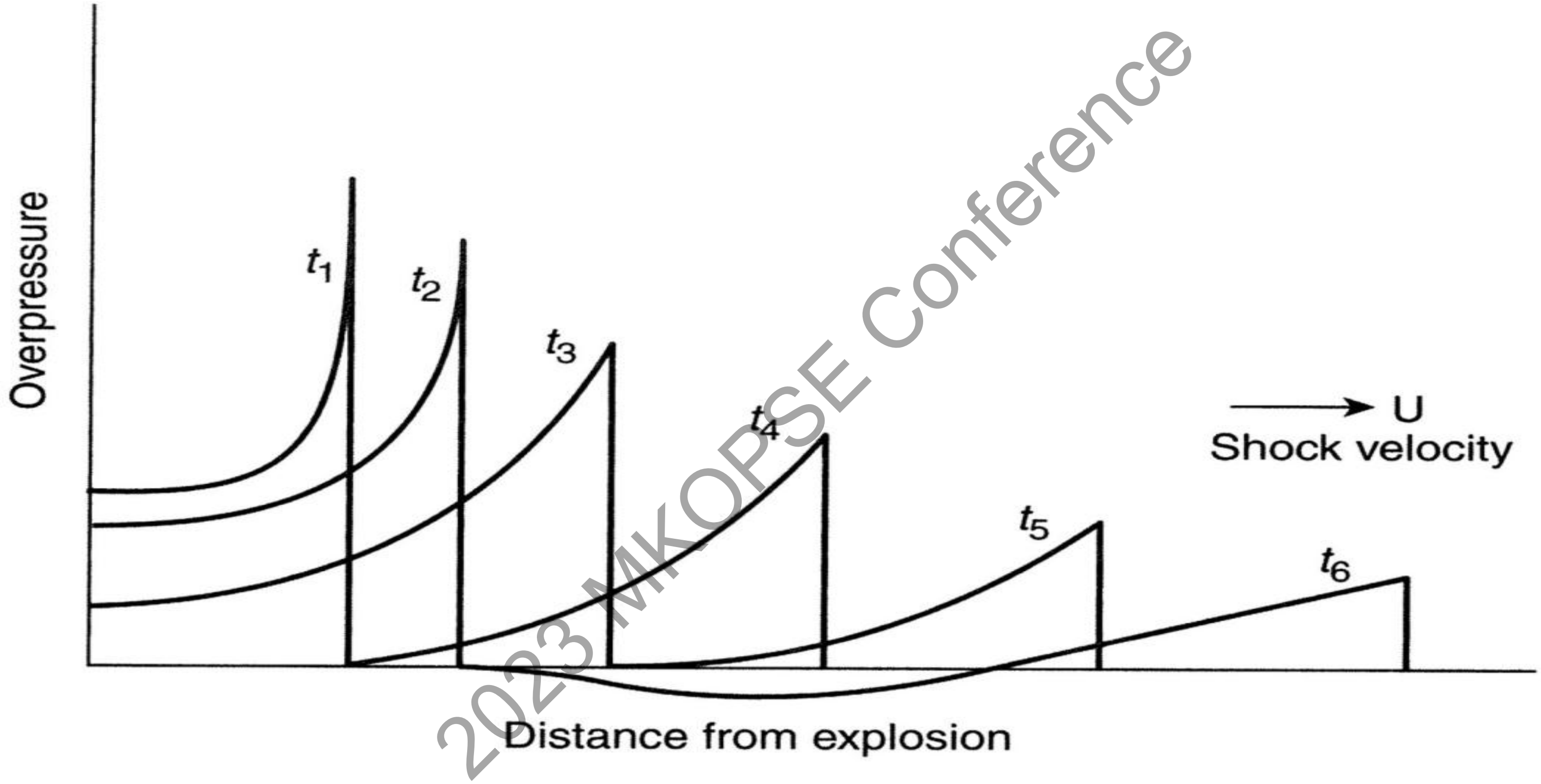


FIGURE 21.4.1.4.3 Typical Overpressure History at Locations Distant from Center of Explosion.

Source: NFPA 921 “Guide for Fire and Explosion Investigations”

Methane VCEs

Low Congestion

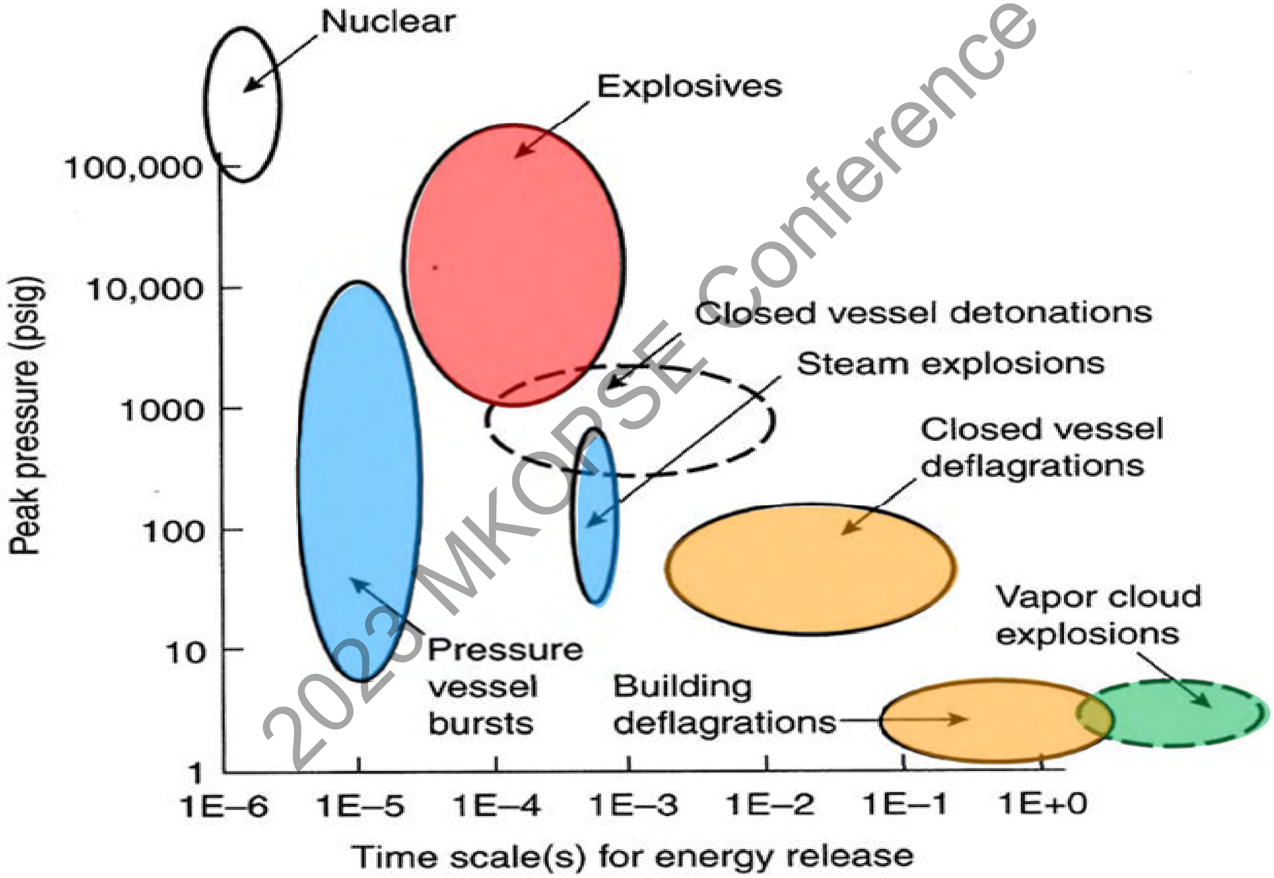
High Congestion

Tests performed by BakerRisk for the 2001 Explosion Research Cooperative

Detonation

- Reaction wave propagates above speed of sound
- Very high, localized pressure
- Localized shattering of objects

Vapor Cloud Explosion Pressure Scale Comparison



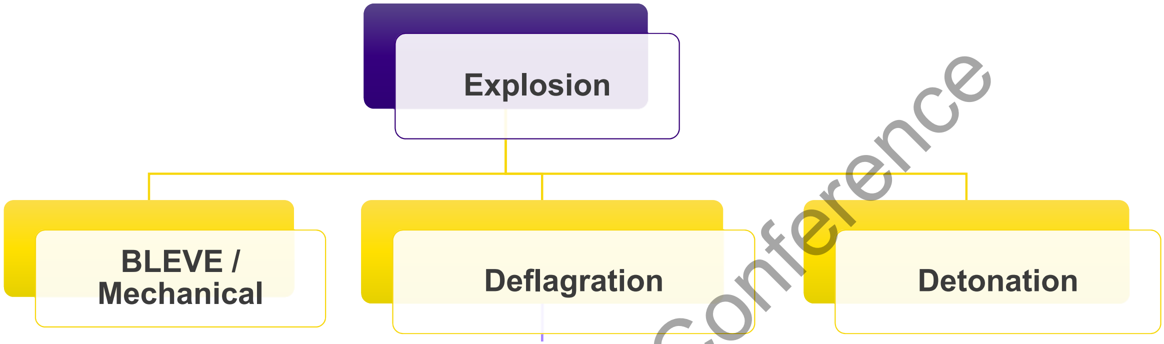
Exponent

Source: Robert Zalosh – NFPA "Fire Protection Handbook" 20th Ed., pg. 2-94

Analysis of Main Explosion Categories

- **P*V energy**

+ TNT Model



Explosion

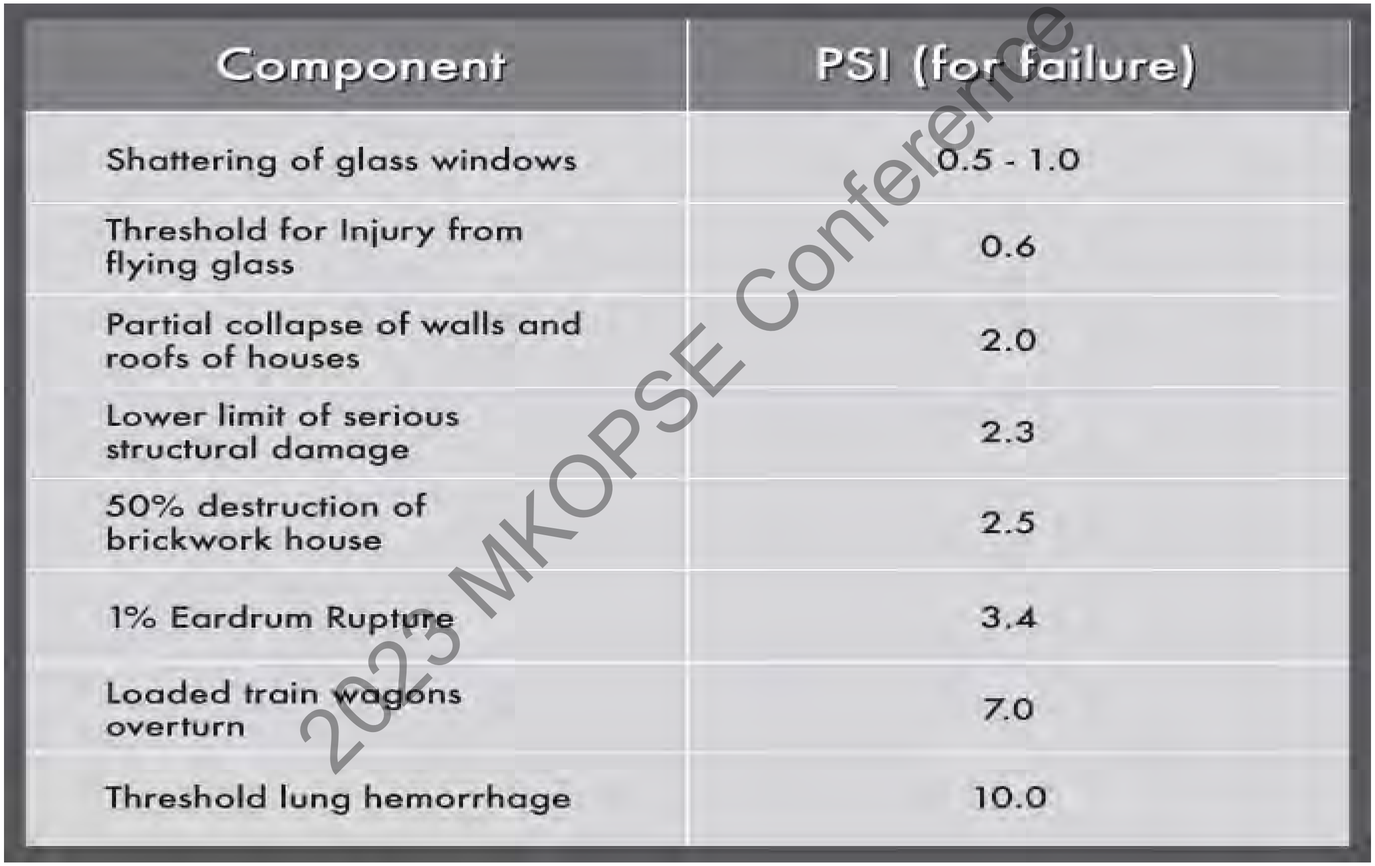
BLEVE / Mechanical

Deflagration

Detonation

- **TNT Model**

Damage Overpressures



Component	PSI (for failure)
Shattering of glass windows	0.5 - 1.0
Threshold for Injury from flying glass	0.6
Partial collapse of walls and roofs of houses	2.0
Lower limit of serious structural damage	2.3
50% destruction of brickwork house	2.5
1% Eardrum Rupture	3.4
Loaded train wagons overturn	7.0
Threshold lung hemorrhage	10.0

Source: NFPA 921 “Guide for Fire and Explosion Investigations”

FLAMMABILITY OF GASES

Fire Tetrahedron

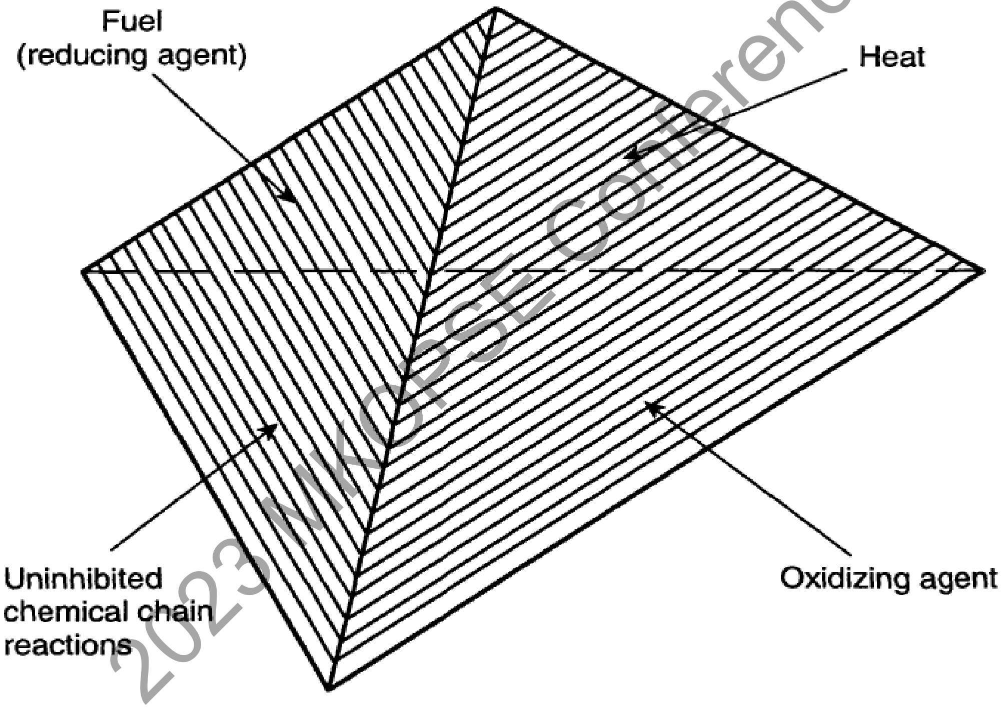
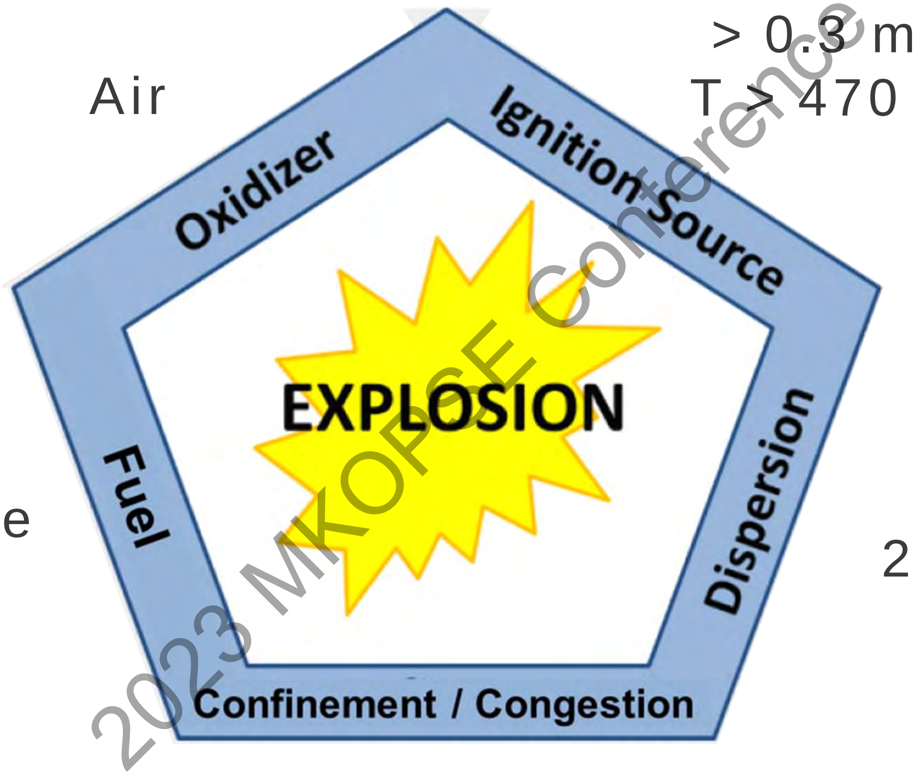


FIGURE 5.1.2 Fire Tetrahedron.

Source: NFPA 921 “Guide for Fire and Explosion Investigations”

Explosion Pentagon



Air

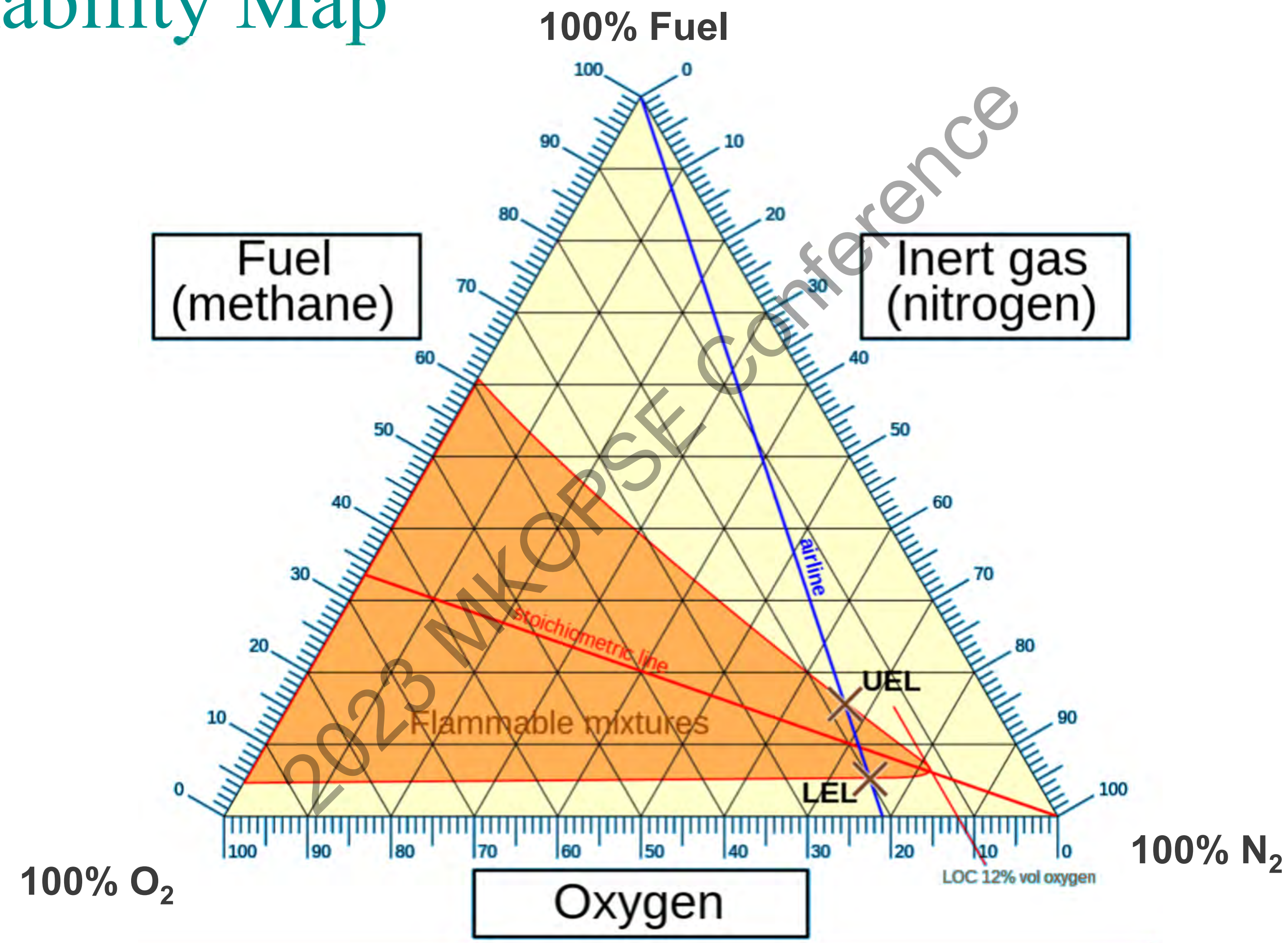
> 0.3 mJ
T > 470 °C

Propane

2 – 10 %

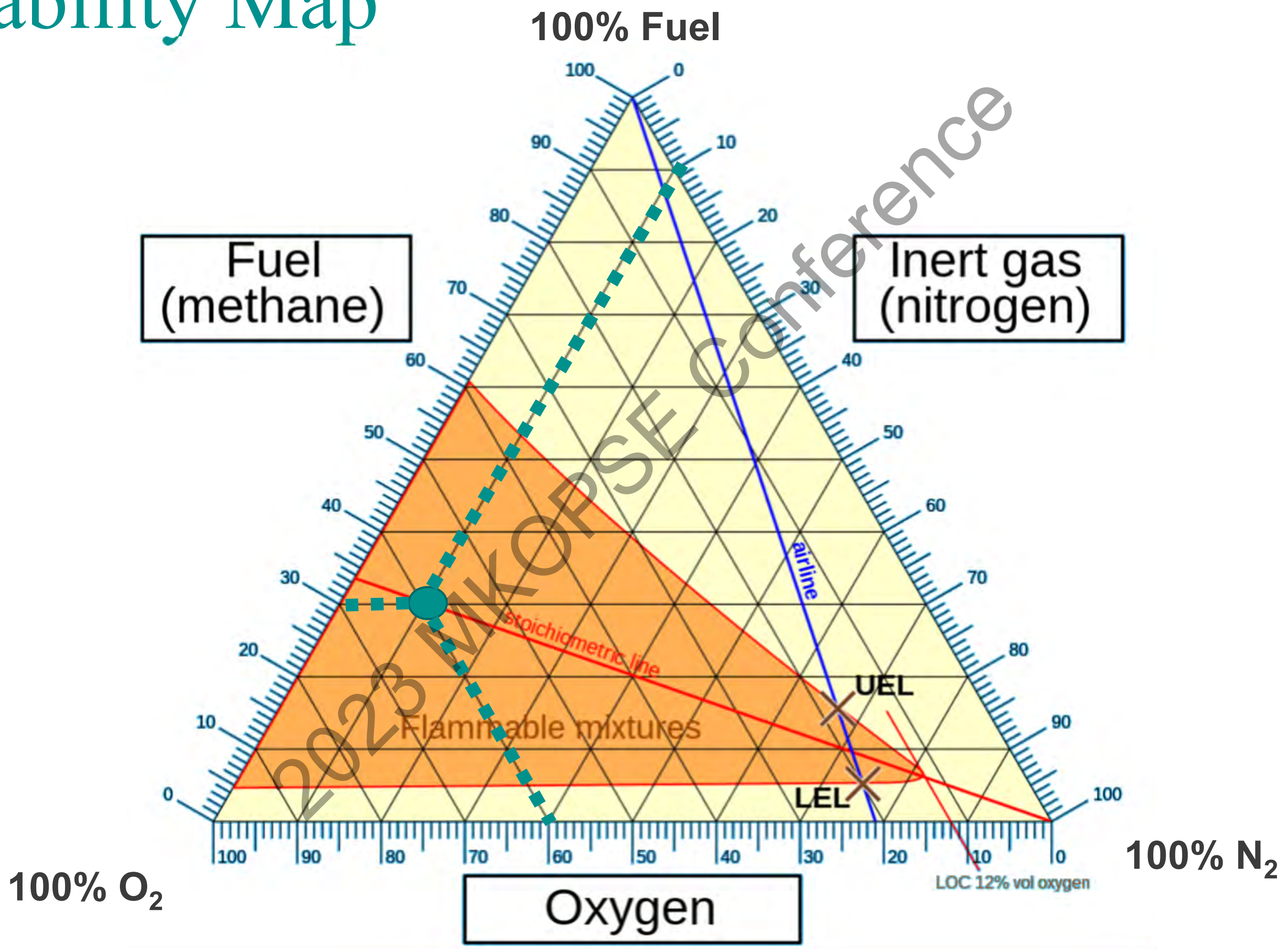
Equipment / Structures

Flammability Map



Source: https://commons.wikimedia.org/wiki/File:Flammability_diagram_methane.png

Flammability Map

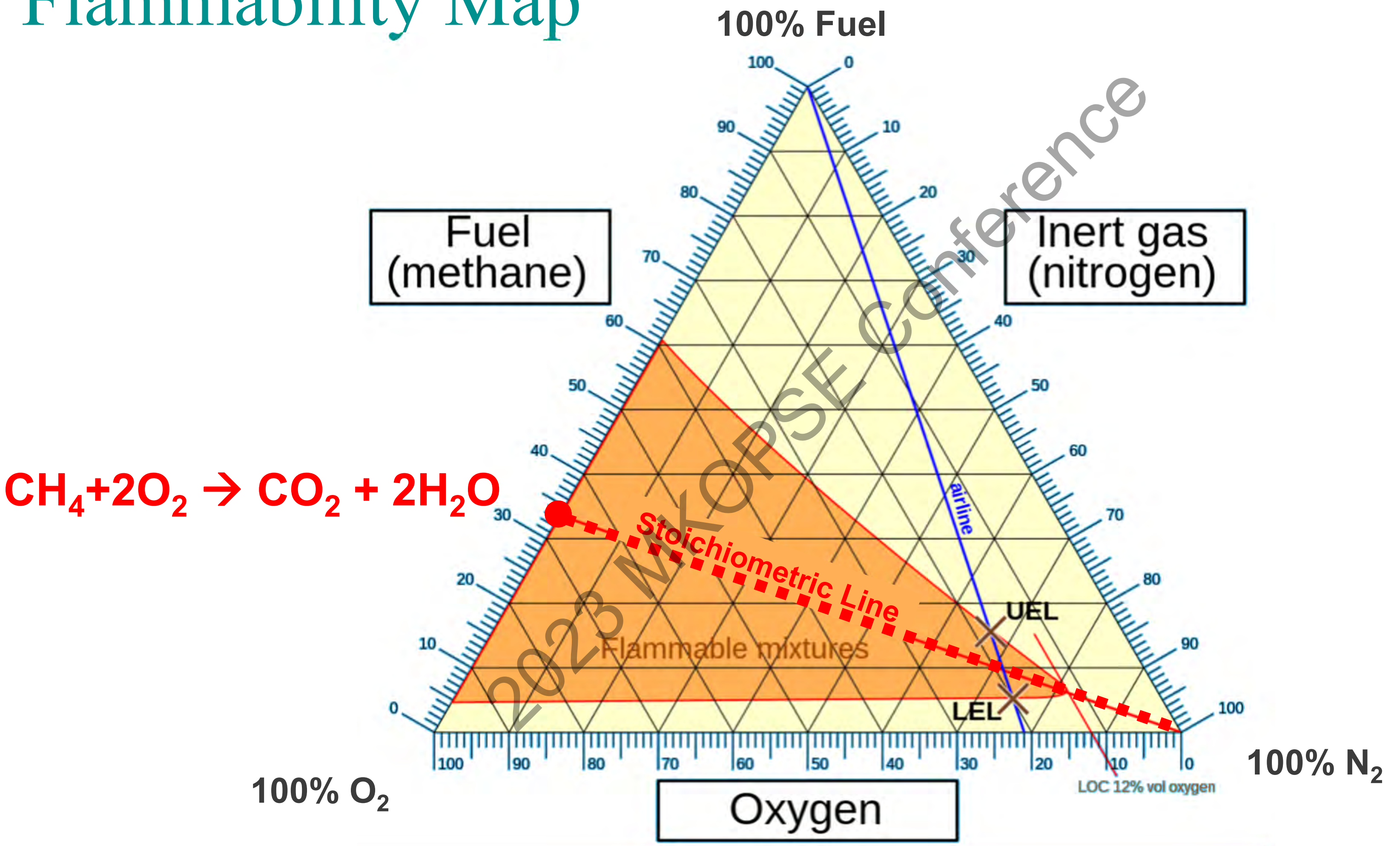


Point:

-
-
-

Source: https://commons.wikimedia.org/wiki/File:Flammability_diagram_methane.png

Flammability Map

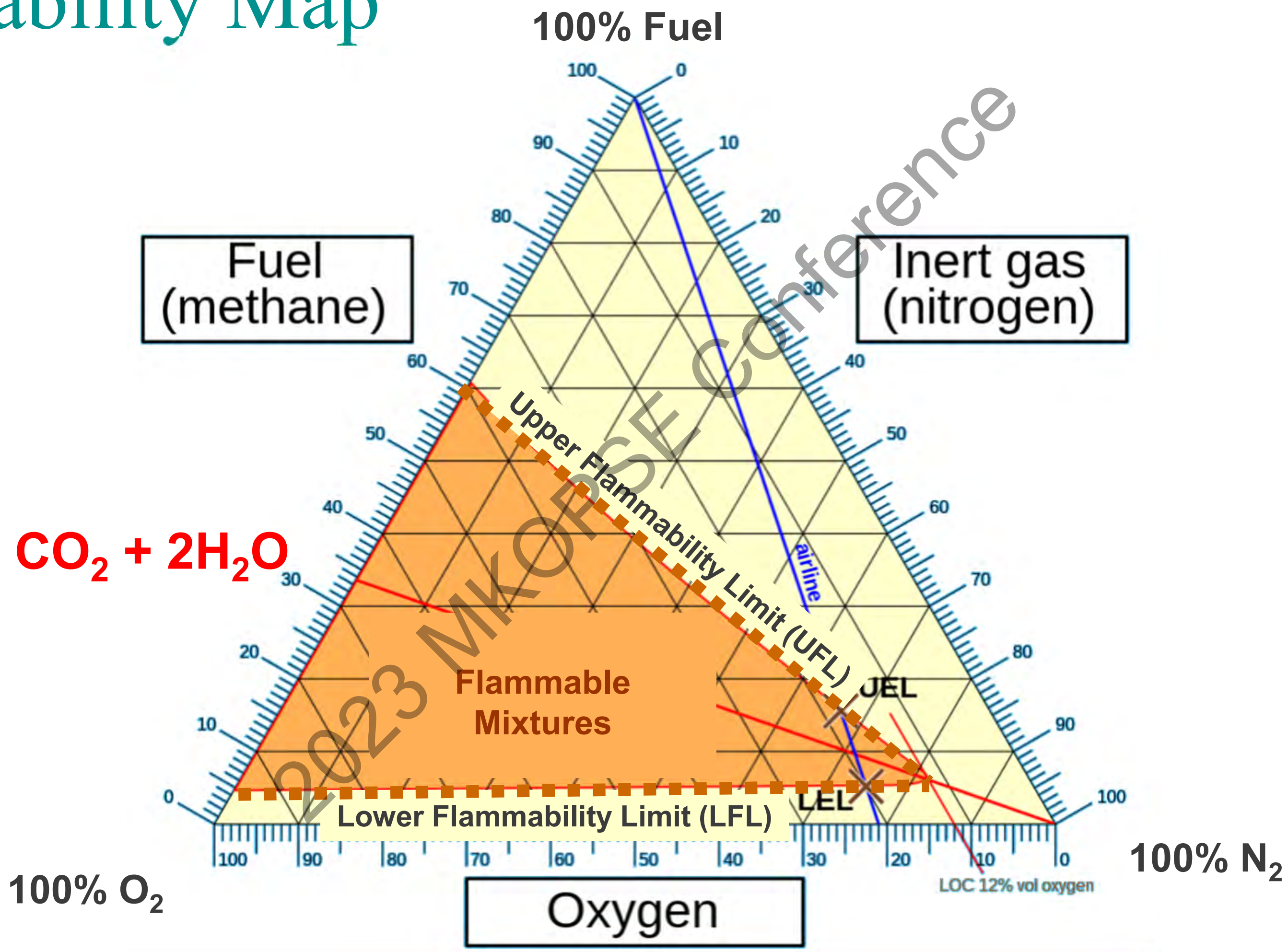


$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

Source: https://commons.wikimedia.org/wiki/File:Flammability_diagram_methane.png

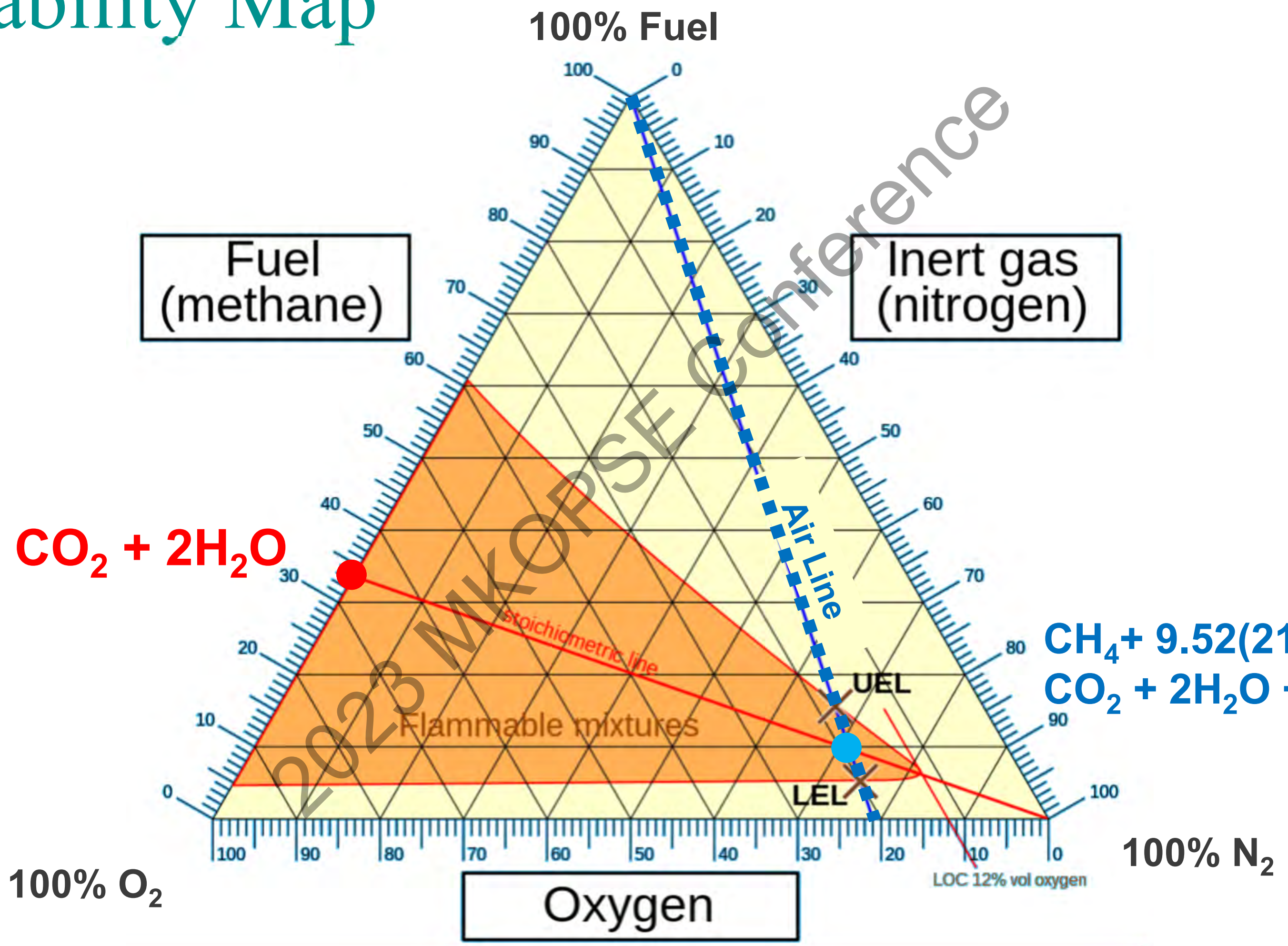
Flammability Map

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$



Source: https://commons.wikimedia.org/wiki/File:Flammability_diagram_methane.png

Flammability Map

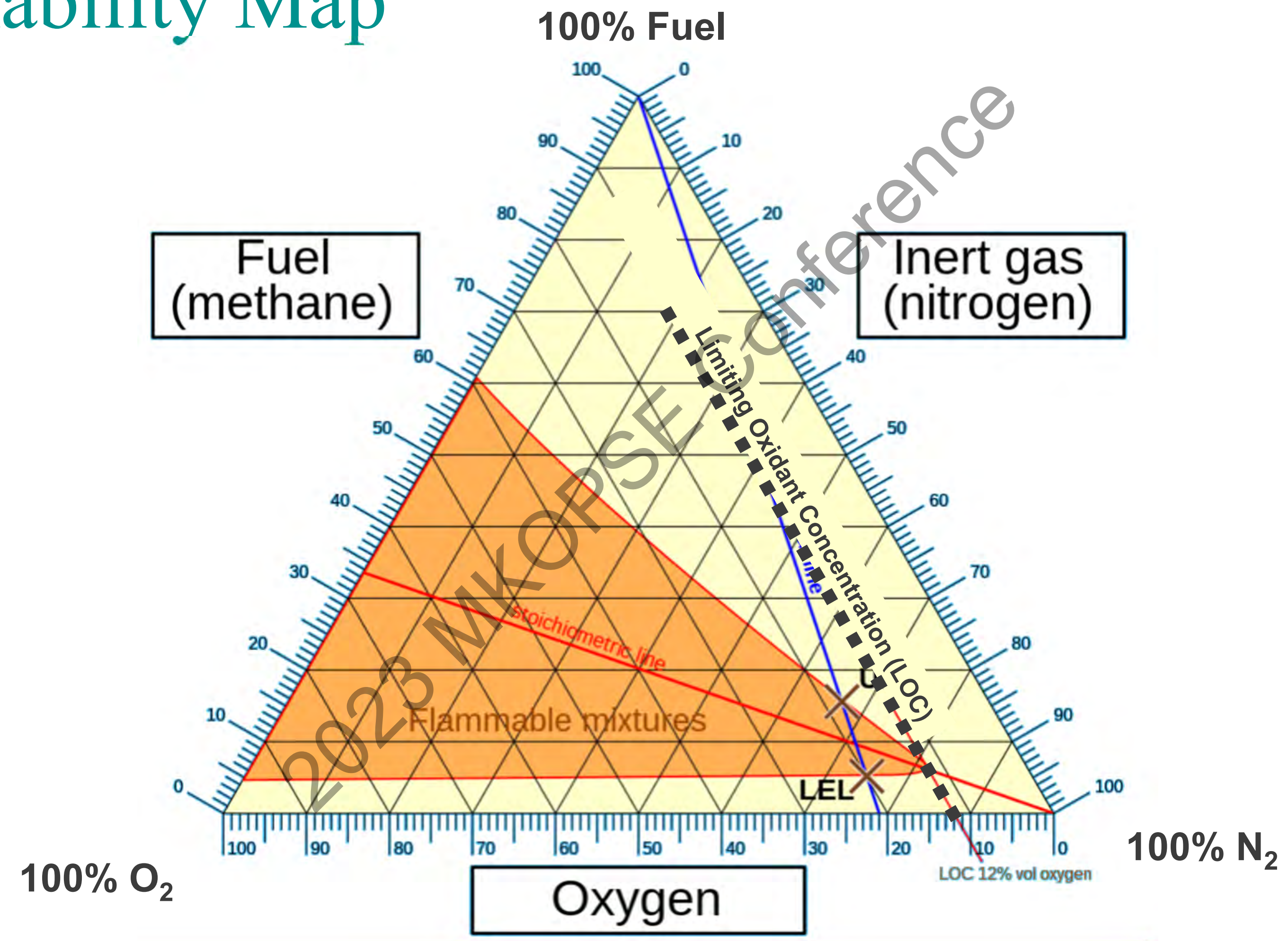


$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

$CH_4 + 9.52(21\%O_2 + 79\%N_2) \rightarrow$
$CO_2 + 2H_2O + 7.52N_2$

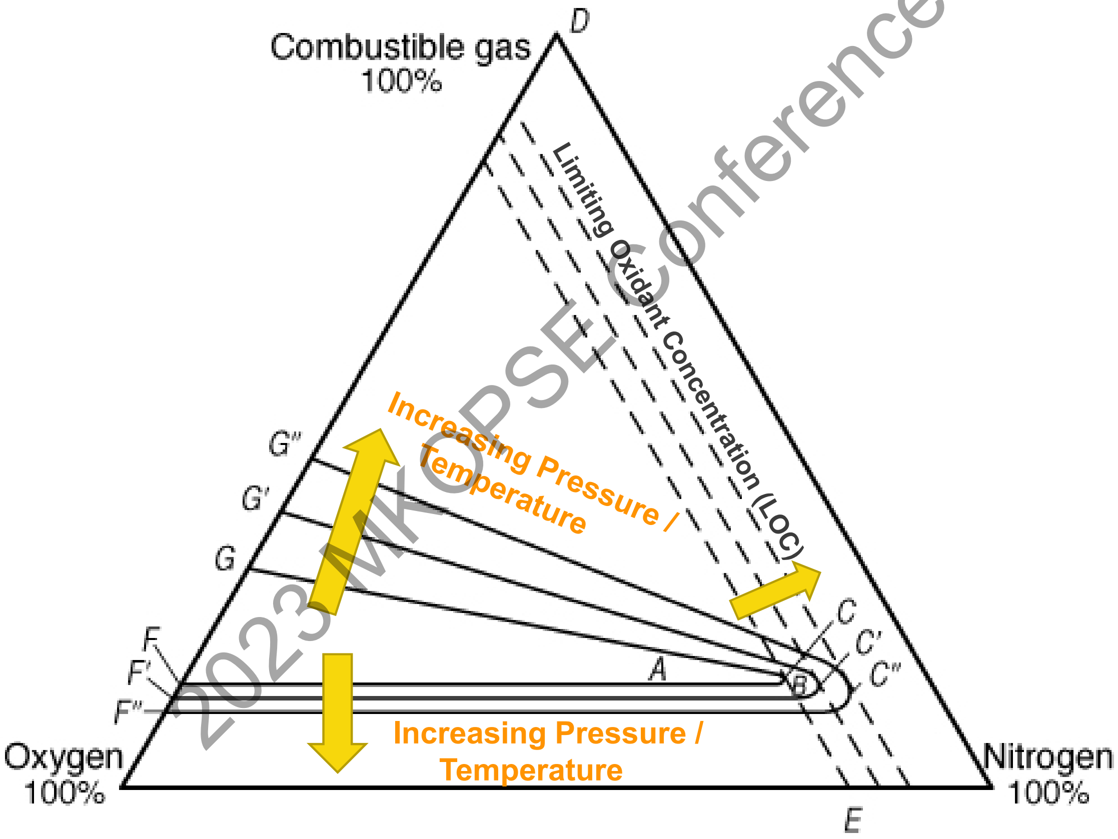
Source: https://commons.wikimedia.org/wiki/File:Flammability_diagram_methane.png

Flammability Map



Source: https://commons.wikimedia.org/wiki/File:Flammability_diagram_methane.png

Effect of Pressure / Temperature on Flammability



Source: NFPA 69 “Standard on Explosion Prevention Systems,” Appendix B

Flammability / Explosibility Parameters

- **Flammable Gases**
  - Laminar Burning Velocity
  - Lower and Upper Flammability Limits (LFL/UFL)
  - Limiting Oxidant (Oxygen) Concentration (LOC)
  - Minimum Ignition Energy (MIE)
  - Minimum AutoIgnition Temperature (MAIT)
  - Hot surface ignition temperature
- **Flammable Liquids (additional)**
  - Flash point
  - Vapor Pressure / Boiling Temperature

Minimum Ignition Energy (MIE)

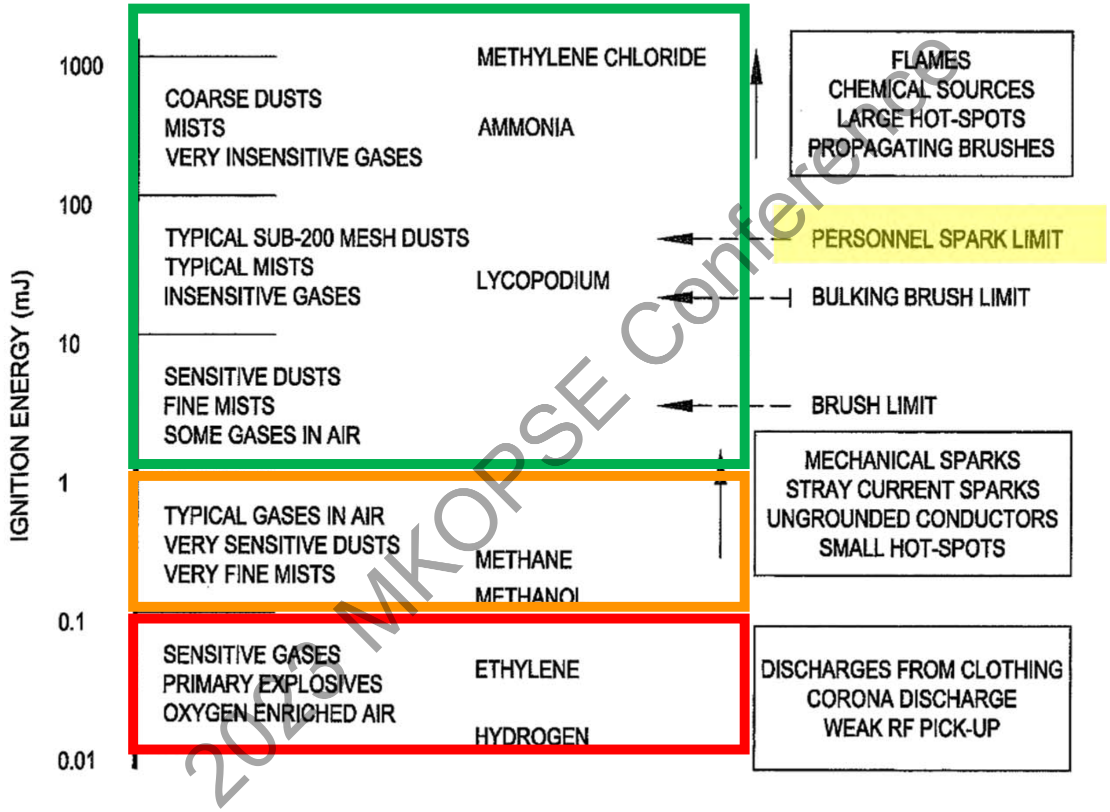


Figure 1.4. Ignition energies of various materials and types of ignition source that may ignite them (updated from Britton, 1999).

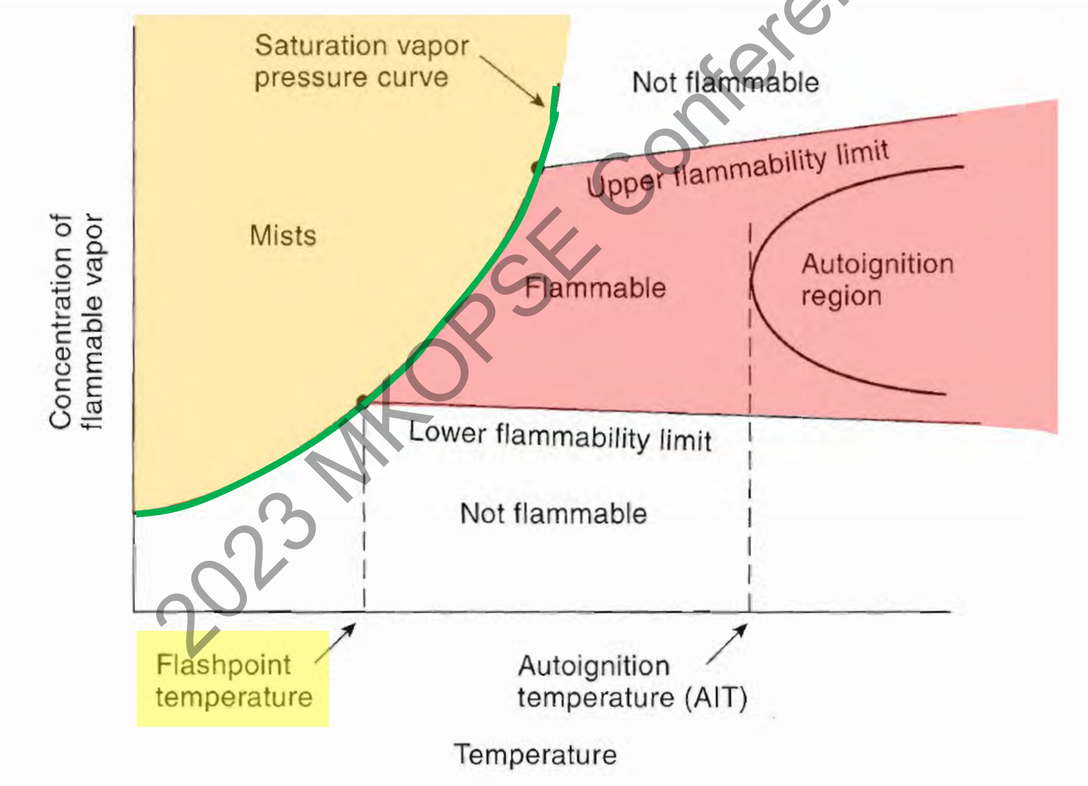
Source: CCPS “Guidelines for Determining the Probability of Ignition of a Released Flammable Mass”, Wiley, NY (2014)

Potential Ignition Sources

- Open flames and hot work
- High temperature sources
  - Hot surfaces
- Electrical sources
  - Powered equipment
  - Electrostatic accumulations
- Physical sources
  - Compression
  - Friction / impact
- Chemical sources
  - Catalytic materials
  - Pyrophoric materials

FLAMMABILITY OF LIQUIDS

Flammability Limits



Source: CCPS "Guidelines for Determining the Probability of Ignition of a Released Flammable Mass", Wiley, NY (2014)

Take a Break

Mechanical Explosion – Pressure Vessel Burst

Source: SAFENG

BLEVE

- Boiling Liquid Expanding Vapor Explosion (BLEVE)
- Portion of liquid evaporates and expands after vessel rupture, converting thermal energy to mechanical energy.

Source: https://www.slideshare.net/HARSHALKHODE1/bleve-52334425

Low Reactivity - Methane (2D Confinement and Low Congestion)

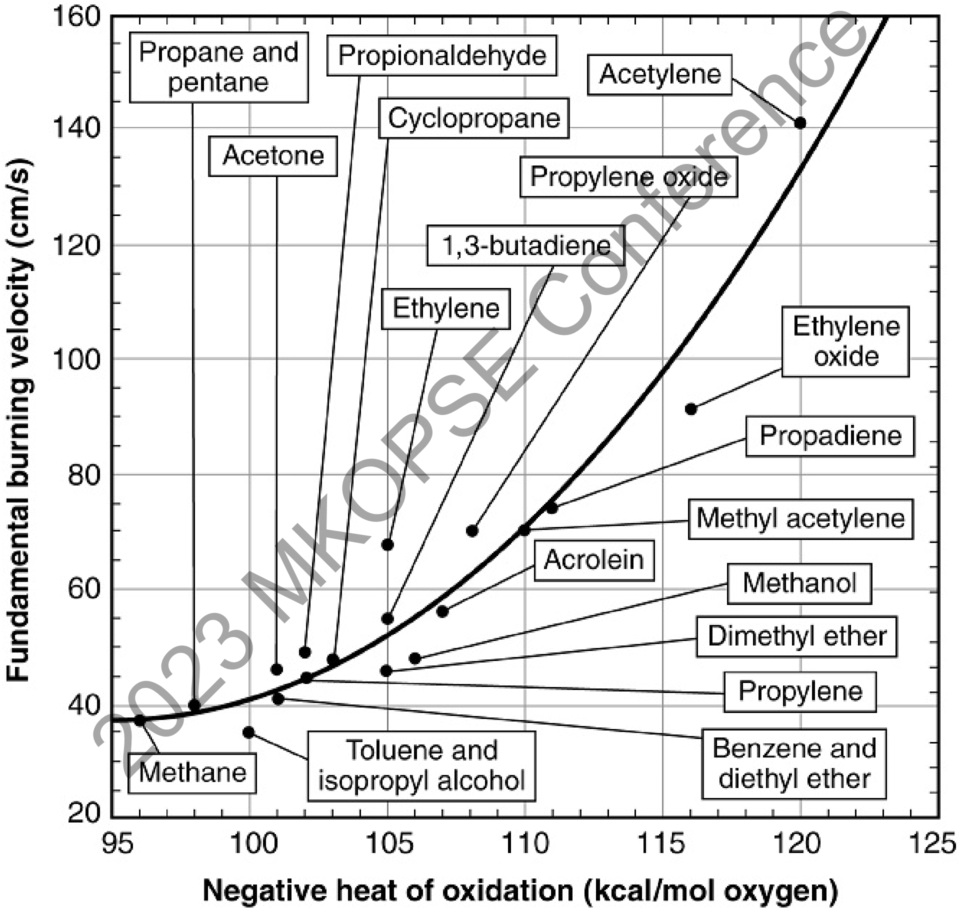
Tests performed by BakerRisk for the 2001 Explosion Research Cooperative

Low Reactivity - Methane (2D Confinement and High Congestion)

Tests performed by BakerRisk for the 2001 Explosion Research Cooperative

Detonation Example

Laminar Burning Velocities



Hydrogen

S_u = 286 cm/s

Source: Britton, L.G., "Using Heats of Oxidation to Evaluate Flammability Hazards," Process Safety Progress, Vol. 21, No. 1, 2000, pp. 1–24.

Minimum AutoIgnition Temperature (MAIT)

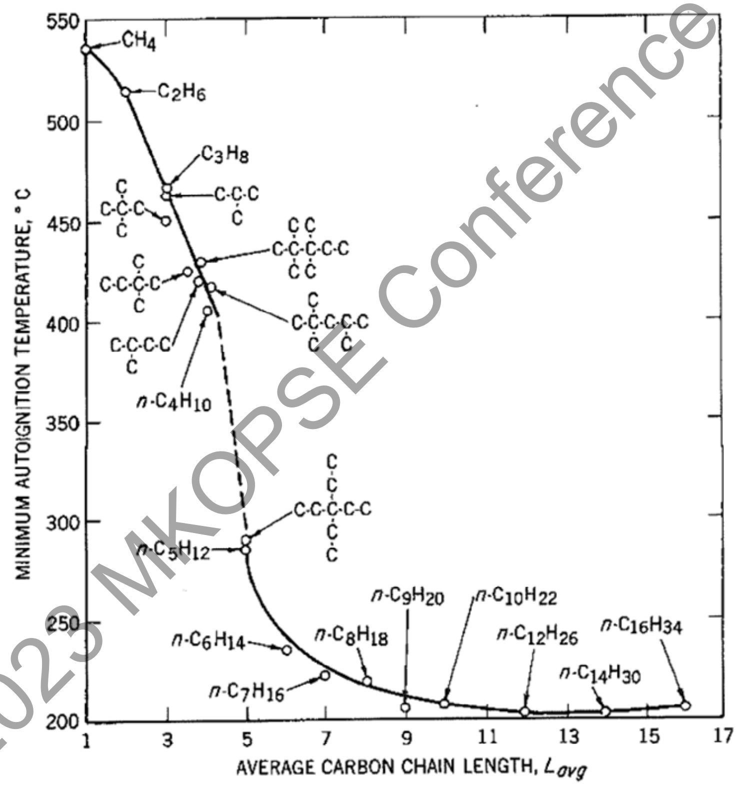
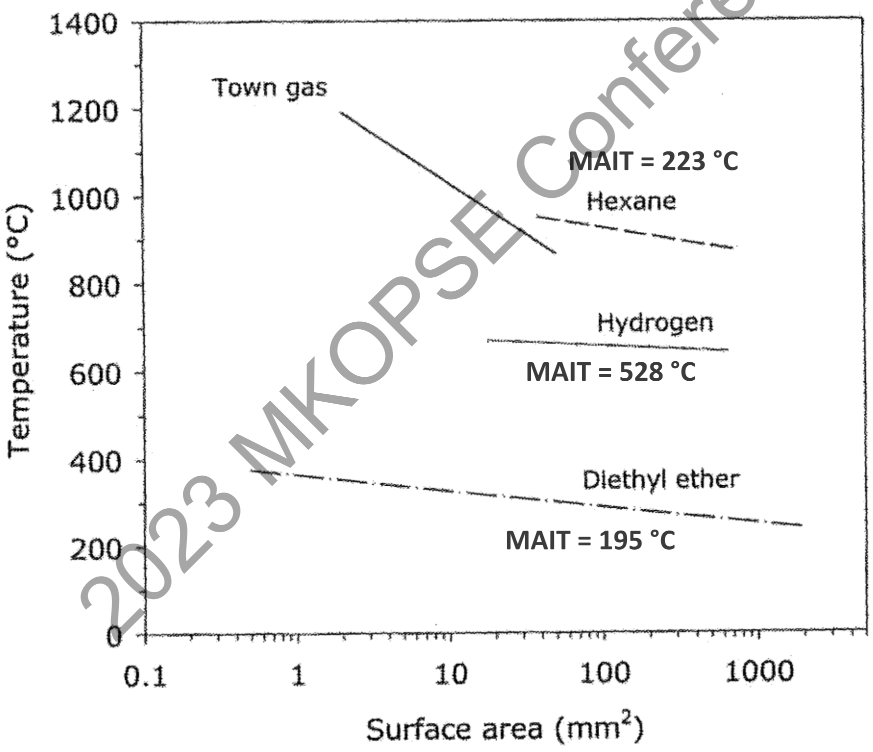


Figure 1.3. AIT as a function of chain length (Zabetakis, 1965).

Source: CCPS "Guidelines for Determining the Probability of Ignition of a Released Flammable Mass", Wiley, NY (2014)

Hot Surface Ignition Temperatures



Exponent

Source: CCPS “Guidelines for Determining the Probability of Ignition of a Released Flammable Mass”, Wiley, NY (2014)

Thank You

Any Questions

Exponent®

MKOC 2023 - Explosion Workshop

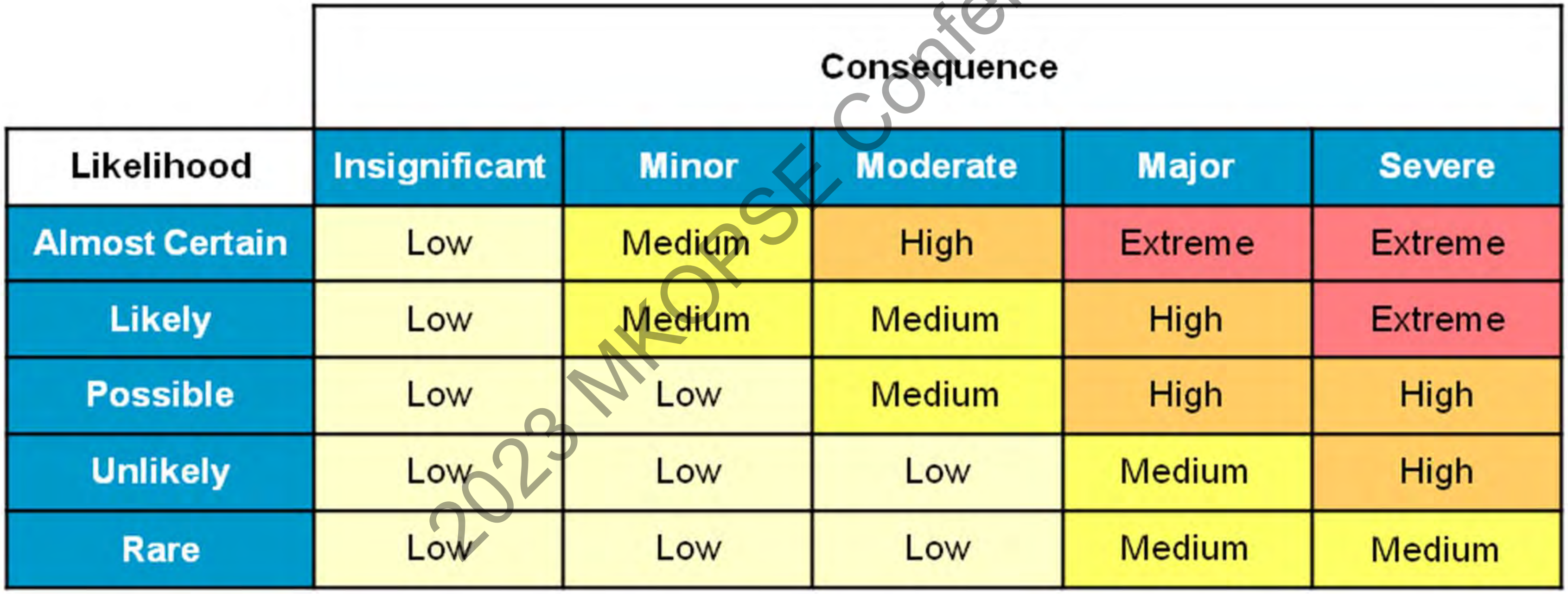
Ali Rangwala, Ph.D.
Alfonso F. Ibarreta, Ph.D., PE, CFEI

Mary Kay O’Connor Process Safety Conference,
October 13, 2023

EXPLOSION RISK MITIGATION

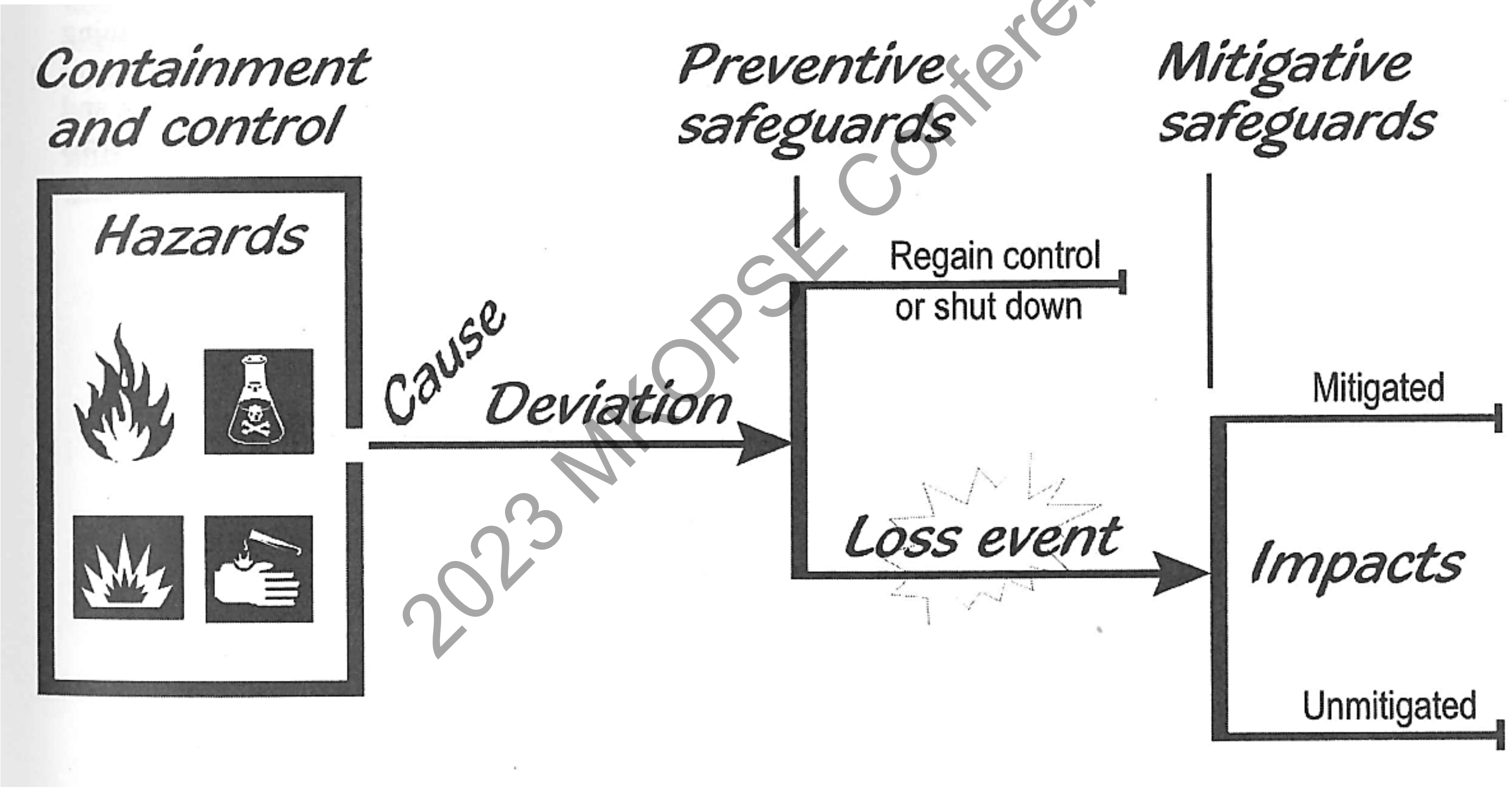
Minimizing Risk

- Risk = Likelihood x Consequence



	Consequence				
Likelihood	**Insignificant**	**Minor**	**Moderate**	**Major**	**Severe**
Almost Certain	Low	Medium	High	Extreme	Extreme
Likely	Low	Medium	Medium	High	Extreme
Possible	Low	Low	Medium	High	High
Unlikely	Low	Low	Low	Medium	High
Rare	Low	Low	Low	Medium	Medium

Safeguards



Source: CCPS “Guidelines for Hazard Evaluation Procedures” 3rd Ed. (2008)

EXPLOSION PREVENTION / PROTECTION

NFPA Standards - Explosion Protection of Equipment

- Ignition Control
- Oxidant Concentration Reduction
- Fuel Concentration Reduction
- Chemical Suppression
- Isolation
  - Active
  - Passive
- Pressure Containment

NFPA 69

Standard on Explosion Prevention Systems

- Explosion Venting

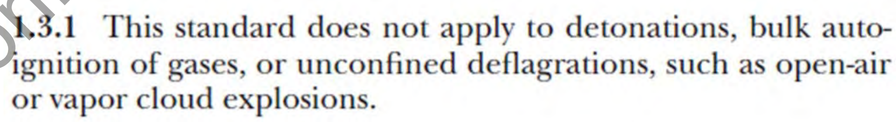
NFPA 68

Standard on Explosion Protection by Deflagration Venting

Deflagration vs. Detonation

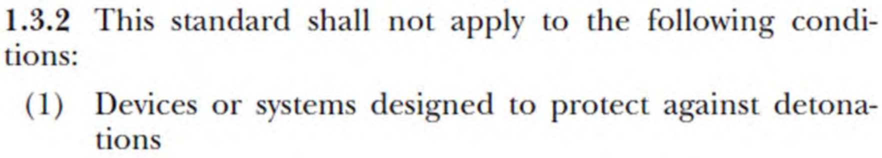
- Definitions (NFPA):
  - Deflagration: "Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium"
  - Detonation: "Propagation of a combustion zone at a velocity greater than the speed of sound in the unreacted medium."
- Explosion protection standards (NFPA 68 / 69) are not applicable to mitigation of detonations.
- NFPA 68 and NFPA 69 can still be used to prevent the occurrence of a deflagration and/or detonation.

NFPA 68



1.3.1 This standard does not apply to detonations, bulk autoignition of gases, or unconfined deflagrations, such as open-air or vapor cloud explosions.

NFPA 69



1.3.2 This standard shall not apply to the following conditions:

(1) Devices or systems designed to protect against detonations

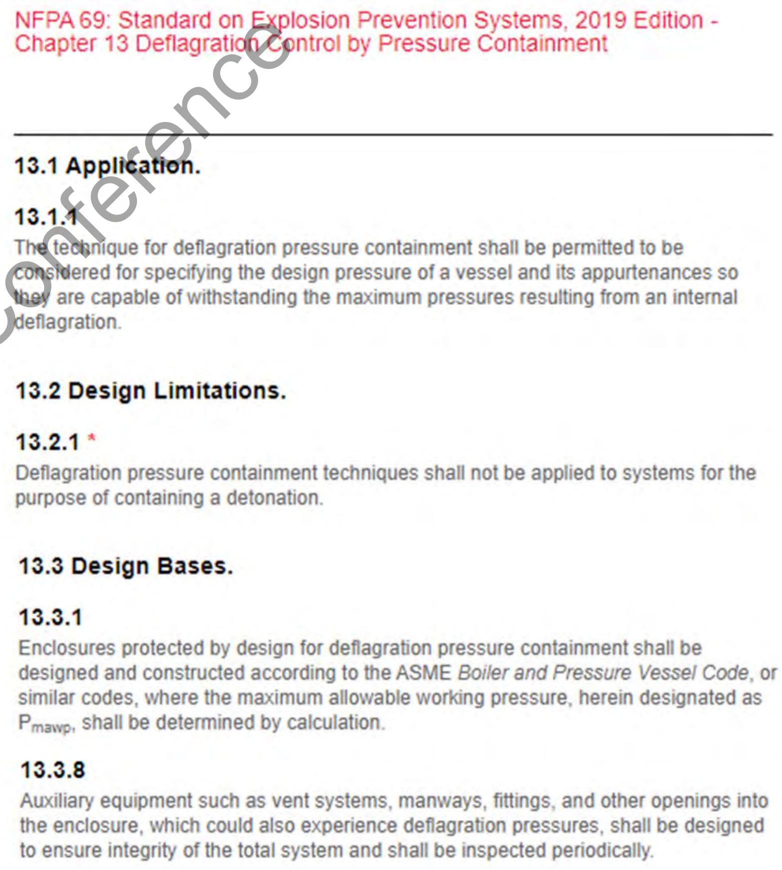
NFPA 69 Explosion Prevention Methods

- Prevention of deflagration ignition via:
  - **Chapter 7** – Deflagration Prevention by Oxidant Concentration Reduction
  - **Chapter 8** -- Deflagration Prevention by Combustible Concentration Reduction
  - **Chapter 9** – Predeflagration Detection and Control of Ignition Sources
- Prevention of deflagration propagation via:
  - **Chapter 11** – Deflagration Control by Active Isolation
  - **Chapter 12** – Deflagration Control by Passive Isolation
- Prevention of vessel rupture via:
  - **Chapter 10** – Deflagration Control by Suppression
  - **Chapter 13** – Deflagration Control by Pressure Containment
  - **Chapter 14** – Passive Explosion Suppression Using Expanded Mesh or Polymer Foam

PRESSURE CONTAINMENT

Strengthening System

- Chapter 13 of NFPA 69 provides requirements for strengthening the system (pressure containment).
- NFPA 69 is not applicable if deflagration transitions to a detonation.
- Enclosure would need to be designed and constructed in accordance with the *ASME Boiler and Pressure Vessel Code*, or similar codes.
- The vent system would also be subjected to overpressure and would need to be considered.



NFPA 69: Standard on Explosion Prevention Systems, 2019 Edition - Chapter 13 Deflagration Control by Pressure Containment

13.1 Application.

13.1.1

The technique for deflagration pressure containment shall be permitted to be considered for specifying the design pressure of a vessel and its appurtenances so they are capable of withstanding the maximum pressures resulting from an internal deflagration.

13.2 Design Limitations.

13.2.1 *

Deflagration pressure containment techniques shall not be applied to systems for the purpose of containing a detonation.

13.3 Design Bases.

13.3.1

Enclosures protected by design for deflagration pressure containment shall be designed and constructed according to the ASME *Boiler and Pressure Vessel Code*, or similar codes, where the maximum allowable working pressure, herein designated as P_{mawp}, shall be determined by calculation.

13.3.8

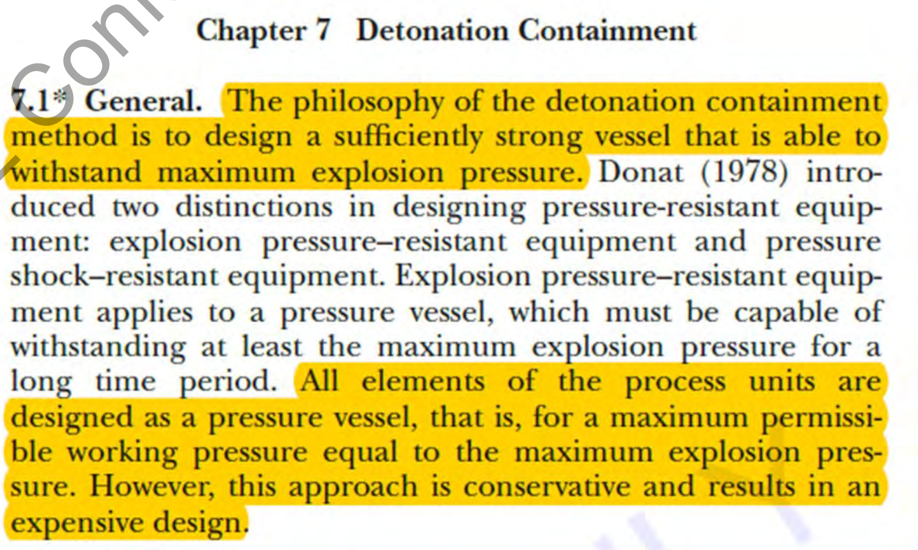
Auxiliary equipment such as vent systems, manways, fittings, and other openings into the enclosure, which could also experience deflagration pressures, shall be designed to ensure integrity of the total system and shall be inspected periodically.

Detonation Containment

- NFPA 68 / 69 standards do not apply.
- NFPA 67 applies, but is only a guideline at this time.
- Pipe must be strong enough and properly supported to withstand a detonation.
- All components must be able to withstand peak detonation overpressure.
- Additional engineering analysis is required to properly design such a system.

NFPA 67

Guide on Explosion Protection for Gaseous Mixtures in Pipe Systems



Chapter 7 Detonation Containment

7.1* General. The philosophy of the detonation containment method is to design a sufficiently strong vessel that is able to withstand maximum explosion pressure. Donat (1978) introduced two distinctions in designing pressure-resistant equipment: explosion pressure–resistant equipment and pressure shock–resistant equipment. Explosion pressure–resistant equipment applies to a pressure vessel, which must be capable of withstanding at least the maximum explosion pressure for a long time period. All elements of the process units are designed as a pressure vessel, that is, for a maximum permissible working pressure equal to the maximum explosion pressure. However, this approach is conservative and results in an expensive design.

Detonations in Pipes

- Normal deflagration pressures are in the < 10 barg range
- Detonations in straight open pipe can results in peak overpressures 15-20 barg
  - Higher overpressures possible at elbows and fittings (due to pressure wave reflections) and during a Deflagration-to-Detonation transition (DDT).

NFPA 68

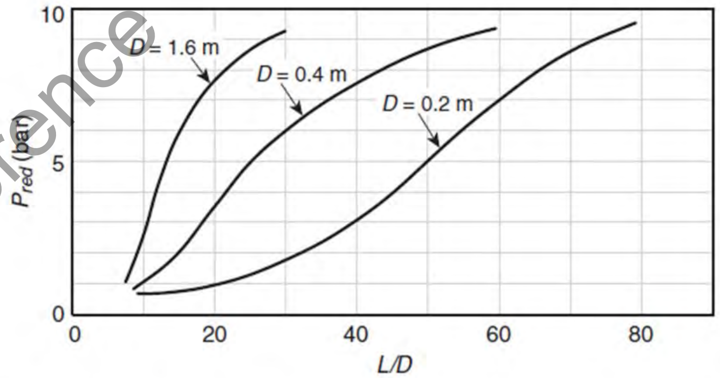


FIGURE 9.2.10.2.1.1 Maximum Pressure Developed During Deflagration of Propane/Air Mixtures Flowing at 2 m/s or Less in a Smooth, Straight Pipe Closed at One End.

NFPA 67

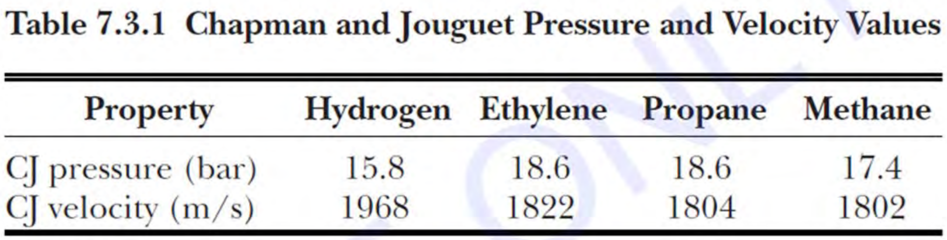
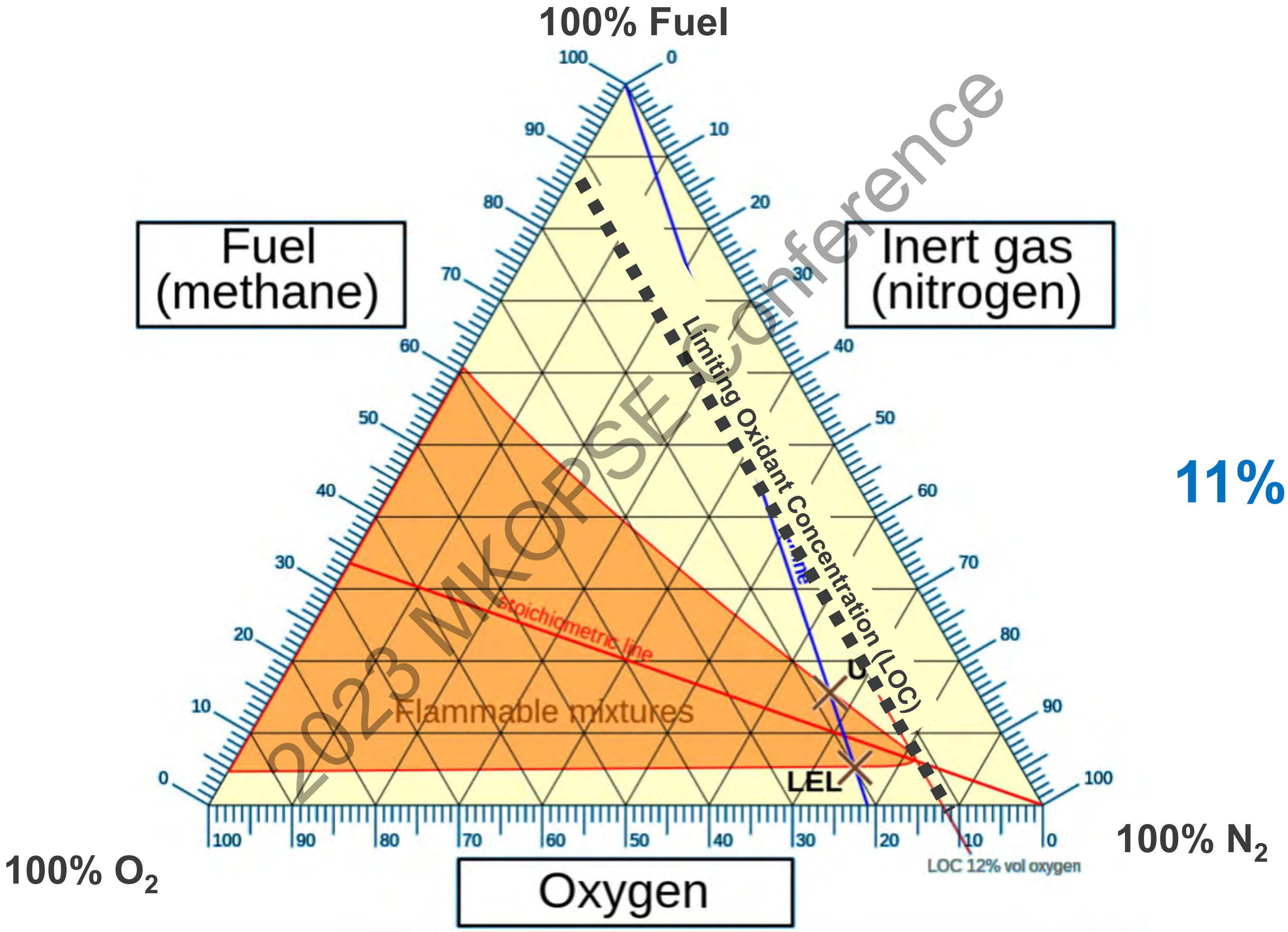


Table 7.3.1 Chapman and Jouguet Pressure and Velocity Values

Property	Hydrogen	Ethylene	Propane	Methane
CJ pressure (bar)	15.8	18.6	18.6	17.4
CJ velocity (m/s)	1968	1822	1804	1802

INERTING

Inerting - Limiting Oxygen Concentration (LOC)

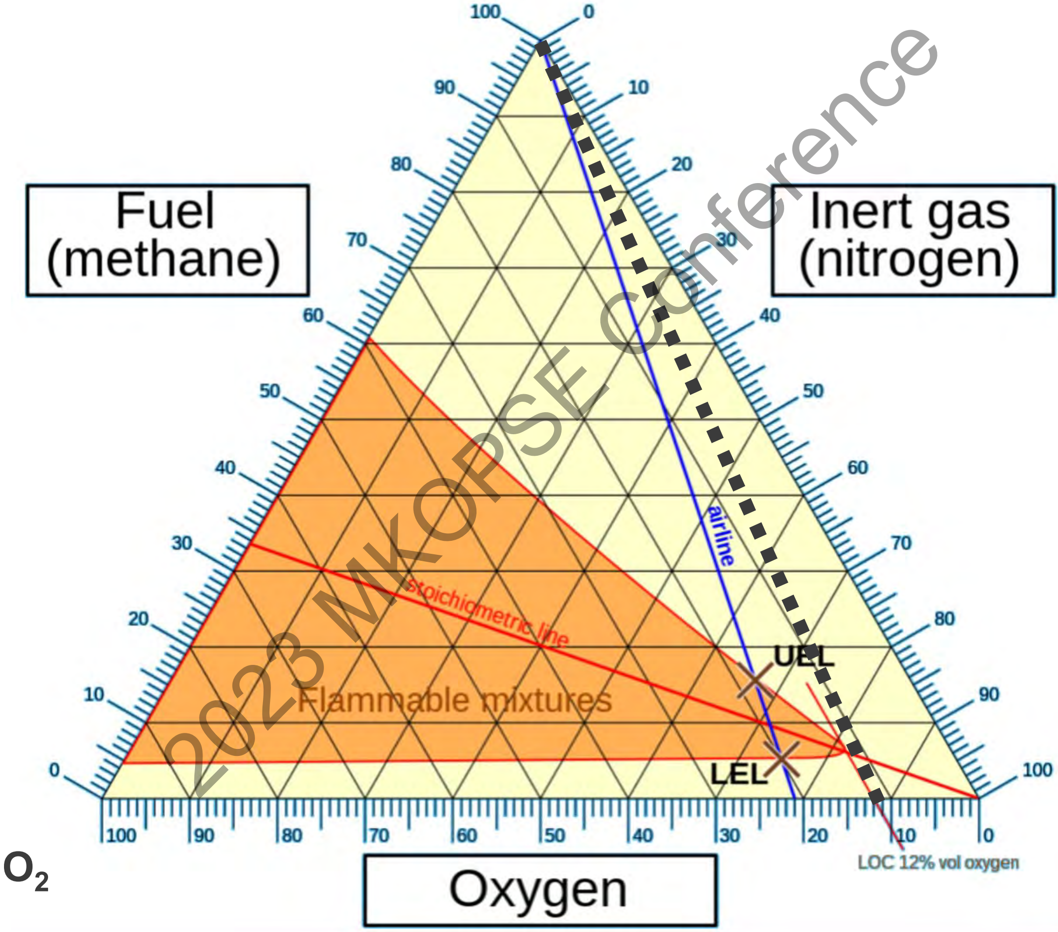


11% O_2

Source: https://commons.wikimedia.org/wiki/File:Flammability_diagram_methane.png

Inerting – N_2 Added to the Air

100% Fuel



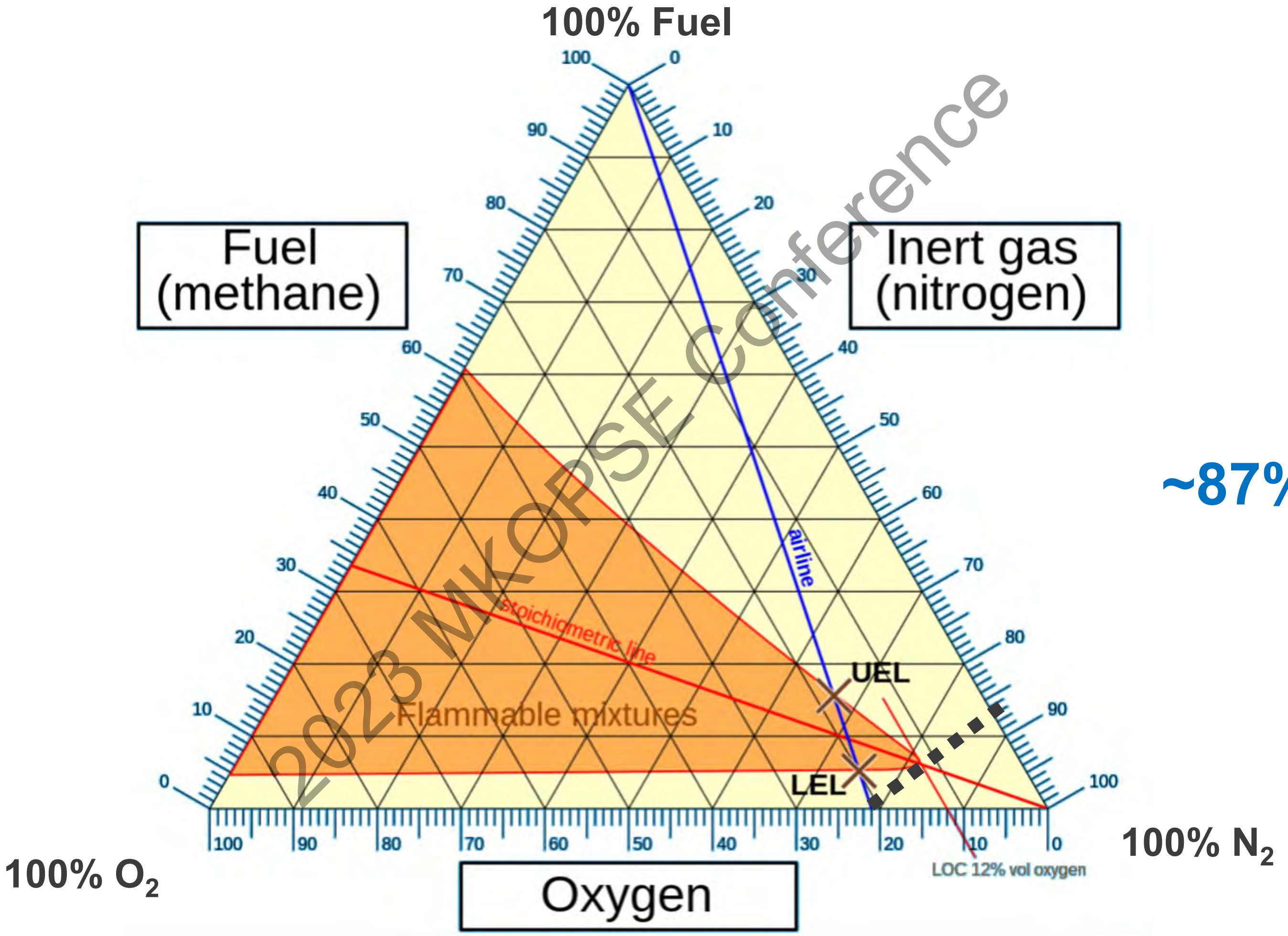
89% N_2

100% N_2

100% O_2

Source: https://commons.wikimedia.org/wiki/File:Flammability_diagram_methane.png

Inerting – N_2 Added to the Fuel



~87% N_2

Source: https://commons.wikimedia.org/wiki/File:Flammability_diagram_methane.png

Inerting Requirements – NFPA 69

7.7.2.5* One of the following requirements shall be met where the oxygen concentration is continuously monitored and controlled with safety interlocks:

(1) Where the LOC is greater than or equal to 5 percent, a safety margin of at least 2 volume percent below the worst credible case LOC shall be maintained.
(2) Where the LOC is less than 5 percent, the equipment shall be operated at no more than 60 percent of the LOC.

7.7.2.8* Where the oxygen concentration is not continuously monitored and controlled with safety interlocks, one of the following requirements shall be met:

(1) Where the LOC is greater than or equal to 7.5 percent, a safety margin of at least 4.5 volume percent below the worst credible case LOC shall be maintained.
(2) Where the LOC is less than 7.5 percent, the oxygen concentration shall be designed to operate at no more than 40 percent of the LOC.

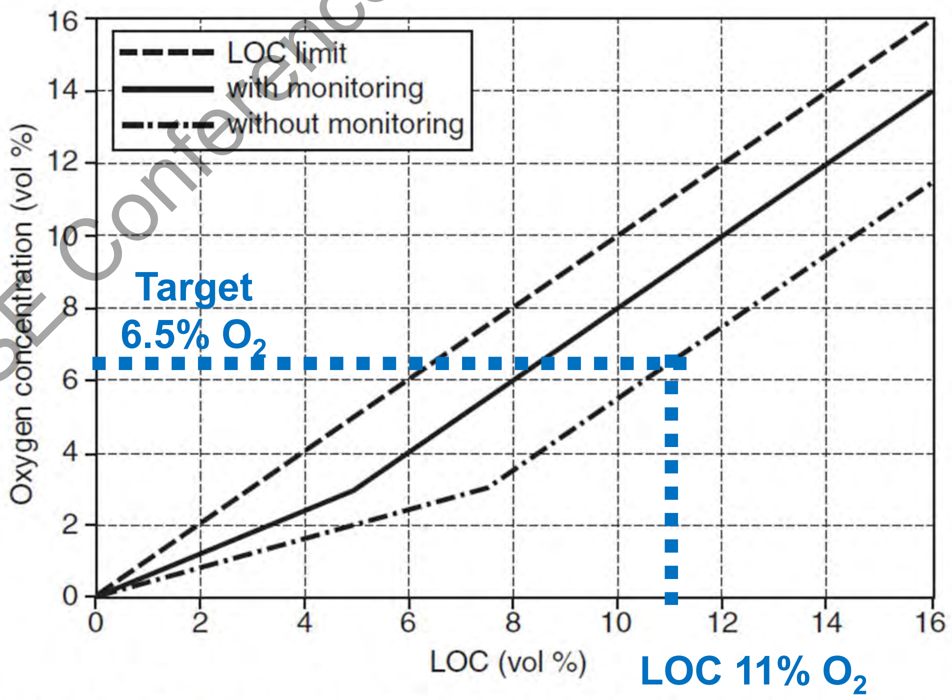


FIGURE A.7.7.2.8 Oxidant Control Limits as a Function of LOC.

Inerting Using Different Gases

Diluent	CO_2	N_2	Ar	He
Cp (J/K-mol)(1)	37.3	29.2	20.8	20.8
Methane LOC(2)	14.6%	12.1%	9.8%	N/A
Methane LOC(3)	13.1%	11.1%	N/A	N/A
CO LOC(3)	5.1%	5.1%	N/A	N/A
H_2 LOC(3)	4.6%	4.6%	N/A	N/A

(1) NIST Webbook (https://webbook.nist.gov/) – Fluid properties at 1 atm and 20ºC
(2) Irvin Glassman "Combustion" 3rd Ed, Academic Press (1996), Pg. 165
(3) NFPA 69 (2019), Appendix C

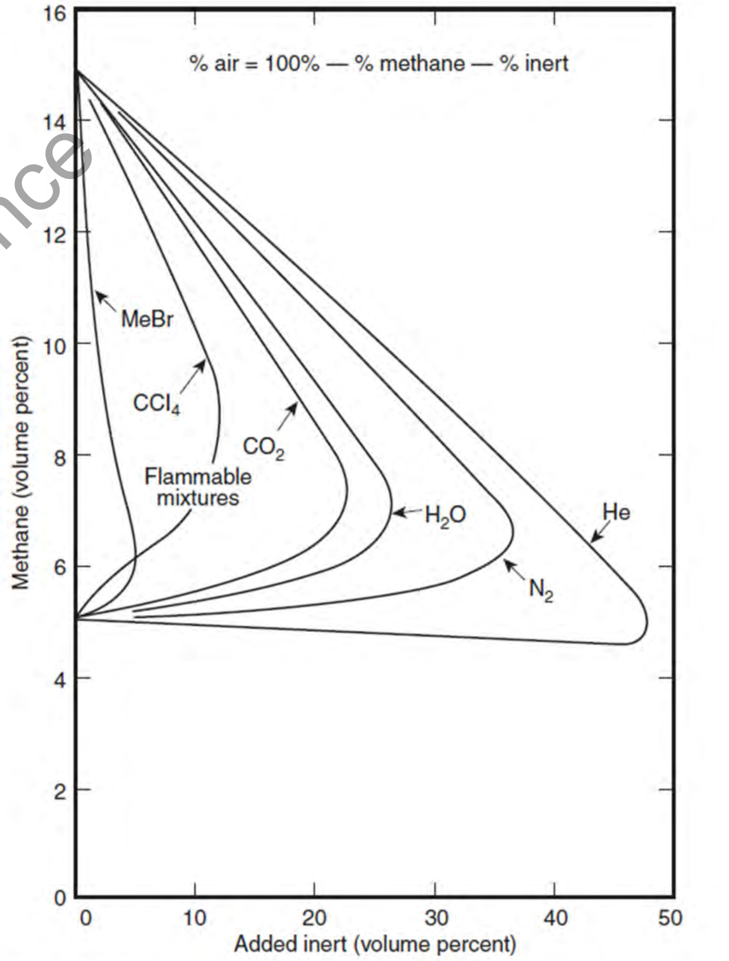
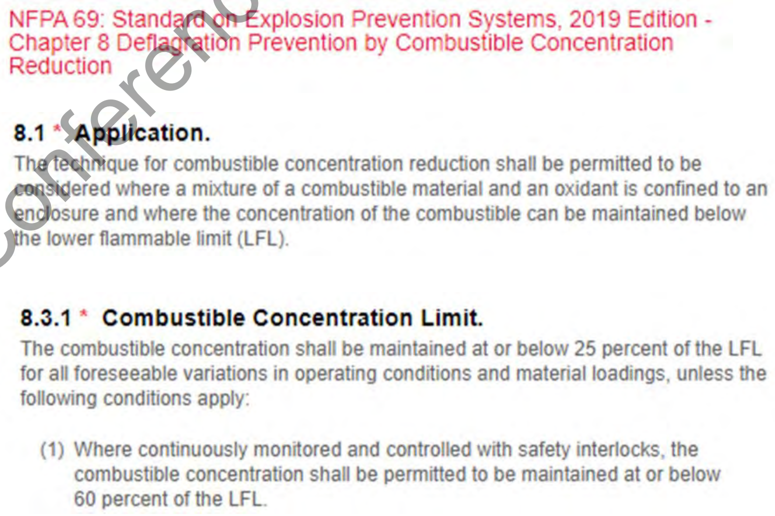


FIGURE B.3 Limits of Flammability of Methane–Inert Gas–Air Mixtures at 25°C (77°F) and Atmospheric Pressure.

DILUTION

Air Dilution

- Chapter 8 of NFPA 69 provides requirements for use of air dilution (combustible concentration reduction).
- NFPA 69 requires that fuel concentration be maintained:
  - < 25% LFL, or
  - < 60% LFL when concentration is continuously monitored and controlled.



NFPA 69: Standard on Explosion Prevention Systems, 2019 Edition - Chapter 8 Deflagration Prevention by Combustible Concentration Reduction

8.1 * Application.

The technique for combustible concentration reduction shall be permitted to be considered where a mixture of a combustible material and an oxidant is confined to an enclosure and where the concentration of the combustible can be maintained below the lower flammable limit (LFL).

8.3.1 * Combustible Concentration Limit.

The combustible concentration shall be maintained at or below 25 percent of the LFL for all foreseeable variations in operating conditions and material loadings, unless the following conditions apply:

(1) Where continuously monitored and controlled with safety interlocks, the combustible concentration shall be permitted to be maintained at or below 60 percent of the LFL.

EXPLOSION SUPPRESSION

Explosion Protection

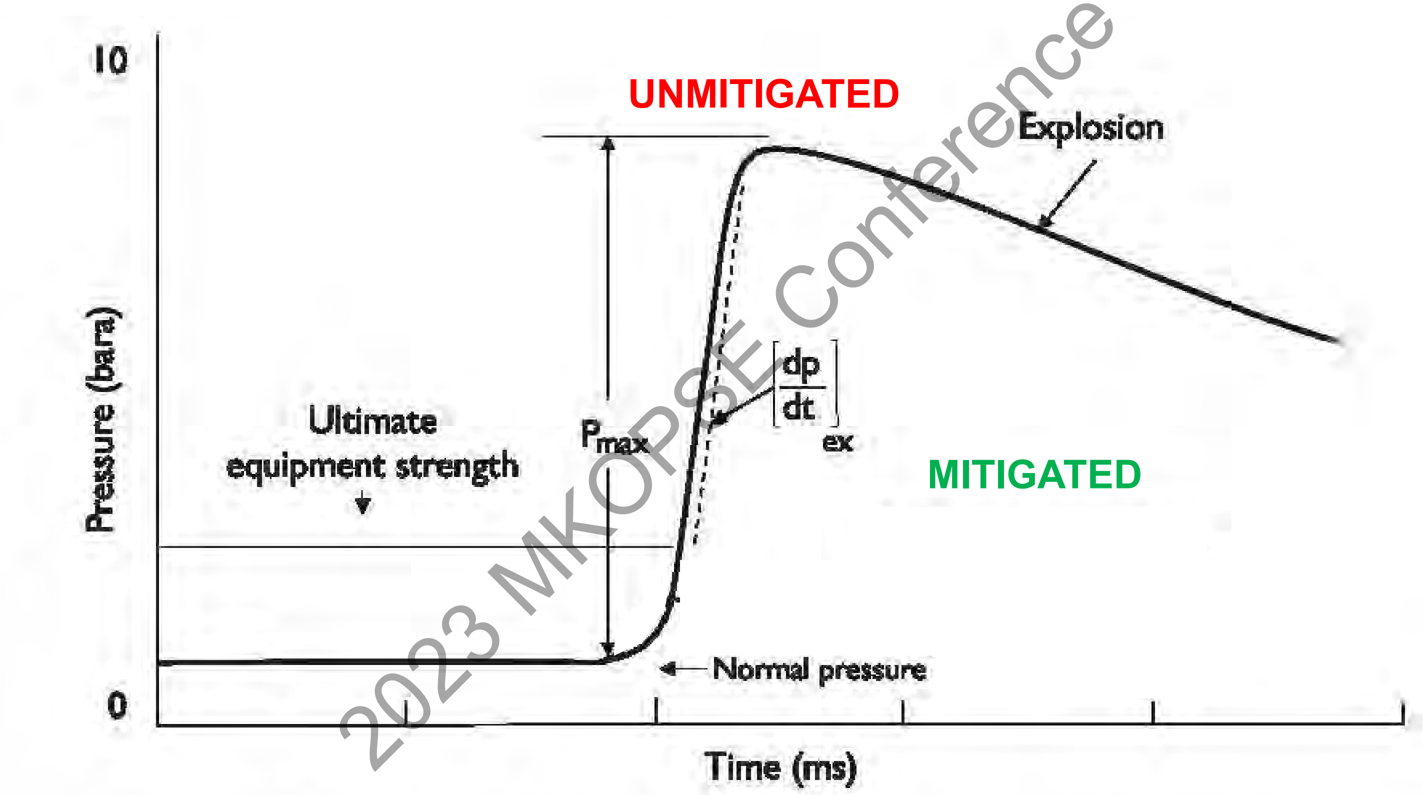


Figure 1: Pressure time histories of protected and unprotected explosions.

Figure Source: Chatrathi et al., Safety and Technology News, vol 10 (1) 1998.

Deflagration Suppression for Combustible Dust

- Detection of explosion
  - Pressure rise
  - Spark/flame detection
- Suppression
  - Fast injection of chemical suppressants
- Can typically minimize explosion overpressure to a few psi
- Often used when explosion venting is not feasible
- Typically more expensive than venting

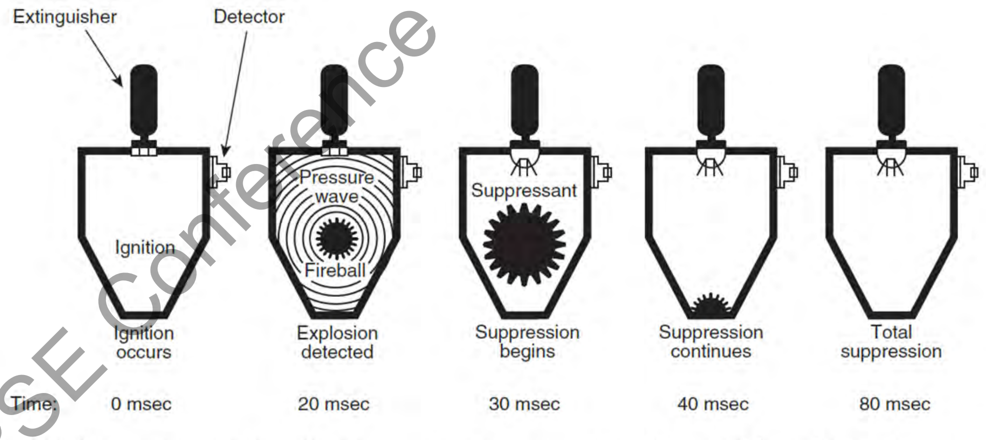
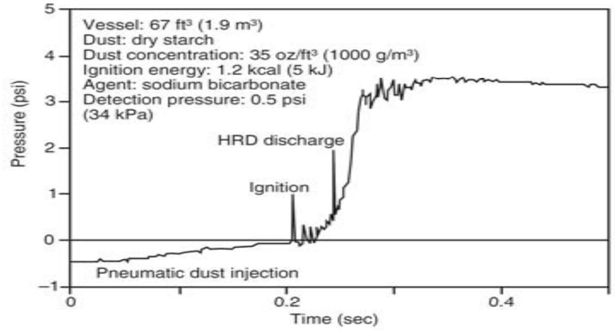


FIGURE B.5.1(a) **Deflagration Suppression Sequence of Starch in a 35 ft^3 (1 m^3) Vessel.**



Note: Pressures are gauge pressures.

FIGURE B.5.1(b) **Pressure Versus Time in a Suppressed Deflagration.**

Source: NFPA 654 “Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids”

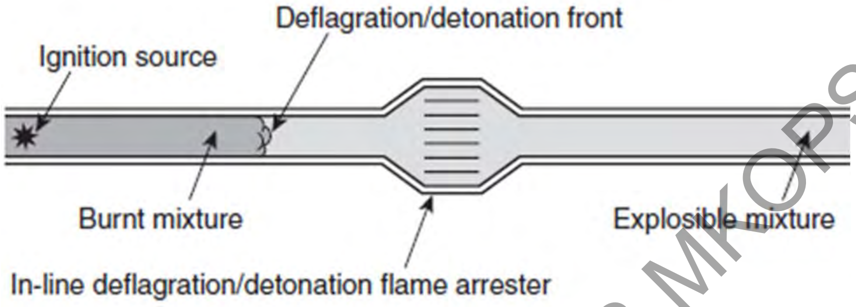
Deflagration Suppression – Slow Motion

Source: Fike Corporation

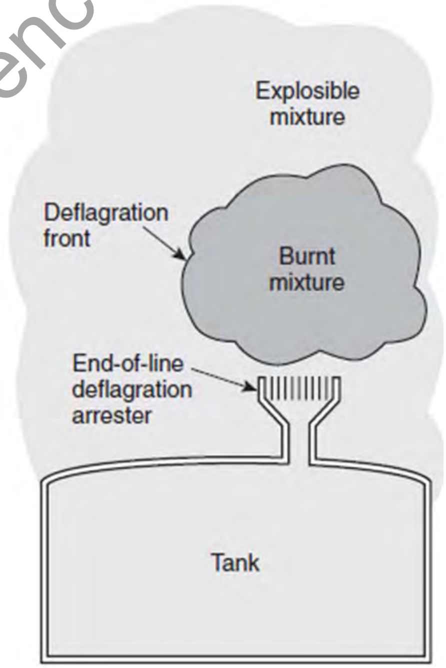
EXPLOSION ISOLATION

Types of flame arresters

- NFPA 69



In-line Flame arrester



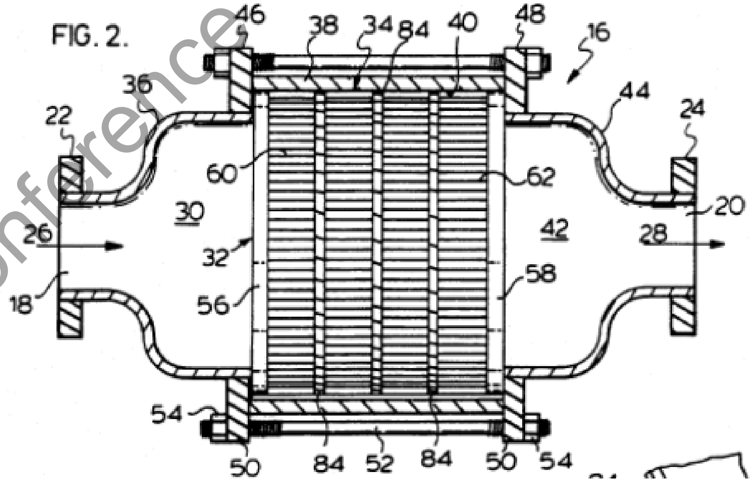
End-of-line Flame arrester

How do flame arresters work?

- **Quenching**
  - Flame arresters function by removing heat from a passing flame such that the temperature of the burning gases drops below the temperature required to sustain combustion, quenching the flame.

- Whether a flame can be quenched is dependent on:
  - The fuel / flame properties
  - The specific geometry of the flame path.
  - The physical properties of the arrester.
  - The flame speed approaching the flame arrester.

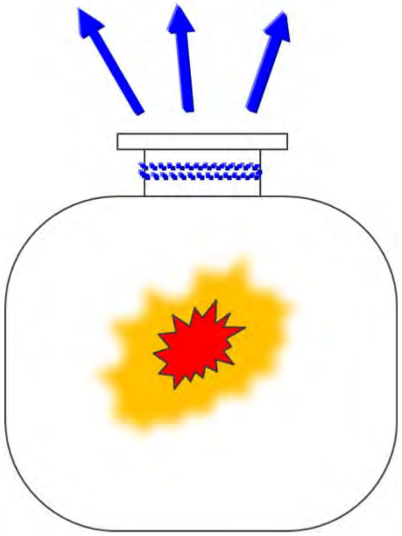
FIG. 2.



US Patent: US5415233A

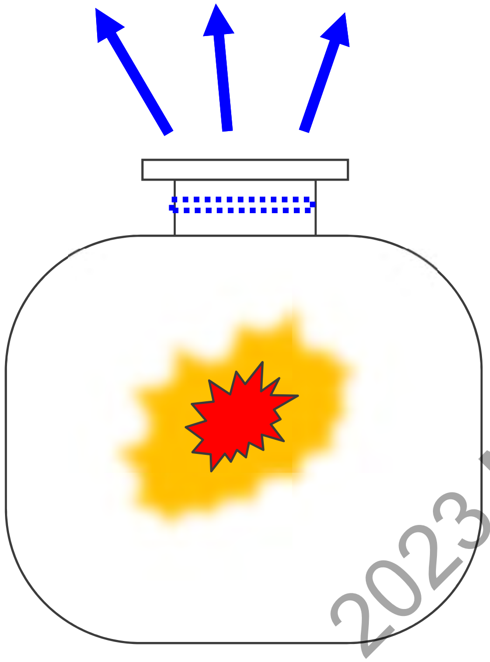
Active Explosion Isolation

Source: Rembe



EXPLOSION MITIGATION VIA DEFLAGRATION VENTING

Deflagration (Explosion) Venting – NFPA 68



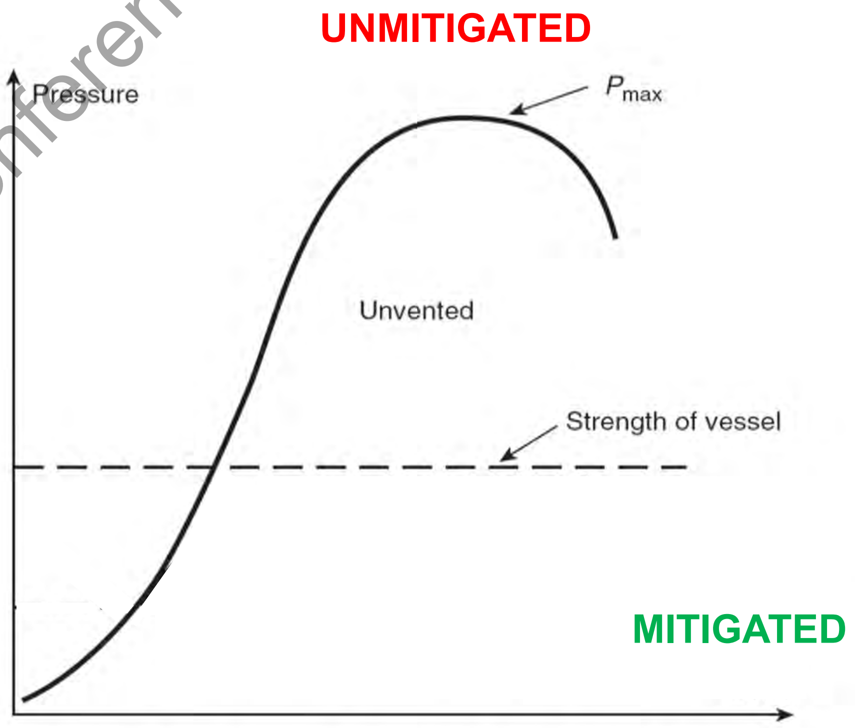


FIGURE B.4.1 Pressure–Time Graph of a Vented Deflagration.

Source: NFPA 654 (2020) "Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids"

Deflagration (Explosion) Venting – NFPA 68

- NFPA 68 provides equations for determining required explosion vent areas
- Vent reduces maximum overpressure
- Typically lower cost than explosion suppression systems
- Must vent to safe outdoor area
- Flame Arresting and Particulate Retention (Flameless) vents can be used indoors

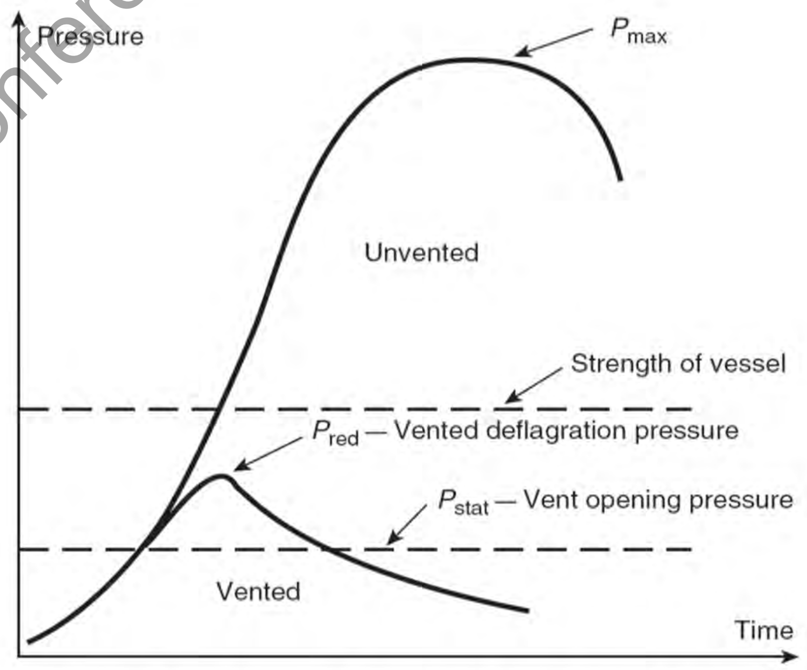


FIGURE B.4.1 Pressure–Time Graph of a Vented Deflagration.

Source: NFPA 68 “Standard for Explosion Protection by Deflagration Venting”


Take a
Break

Hierarchy of Hazard Control

- Elimination
- Substitution
- Engineering Controls
- Administrative Controls
- Personal Protective Equipment (PPE)

Preventive Safeguards

- Explosion prevention
- Instrumented protective system designed to bring system to safe state
- Operator response

Source: CCPS “Guidelines for Hazard Evaluation Procedures” 3rd Ed. (2008)

Mitigative Safeguards

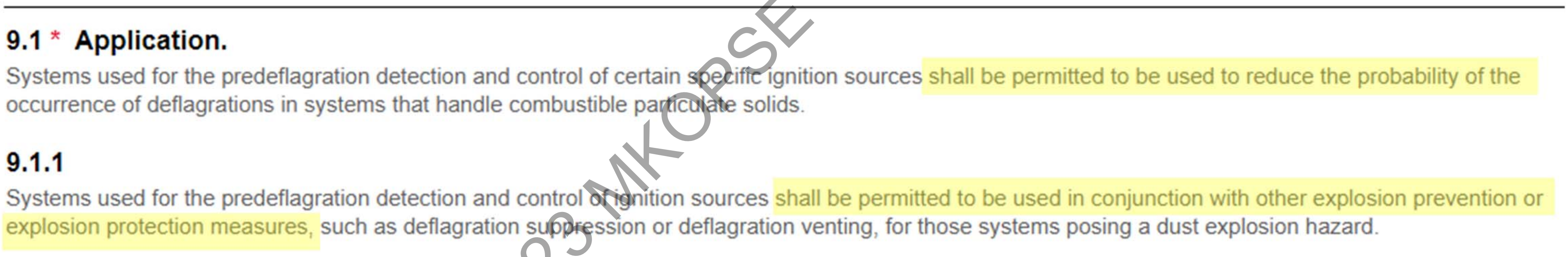
- Explosion protection via deflagration venting
- Secondary Containment
- Explosion blast barricades and blast-resistant construction
- Fire/release detection and warning systems
- Deluge, foam and vapor mitigation systems
- Fire resistant supports and structures
- PPE
- Emergency response and planning

Source: CCPS “Guidelines for Hazard Evaluation Procedures” 3rd Ed. (2008)

CONTROL OF IGNITION SOURCES

Ignition Source Control

NFPA 69: Standard on Explosion Prevention Systems, 2019 Edition - Chapter 9 Predeflagration Detection and Control of Ignition Sources



9.1 * Application.

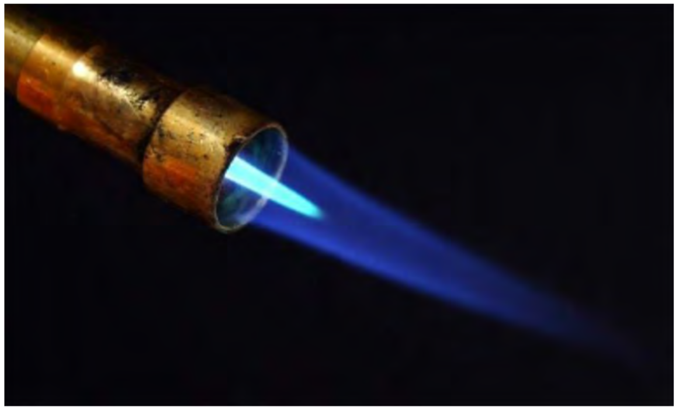
Systems used for the predeflagration detection and control of certain specific ignition sources shall be permitted to be used to reduce the probability of the occurrence of deflagrations in systems that handle combustible particulate solids.

9.1.1

Systems used for the predeflagration detection and control of ignition sources shall be permitted to be used in conjunction with other explosion prevention or explosion protection measures, such as deflagration suppression or deflagration venting, for those systems posing a dust explosion hazard.

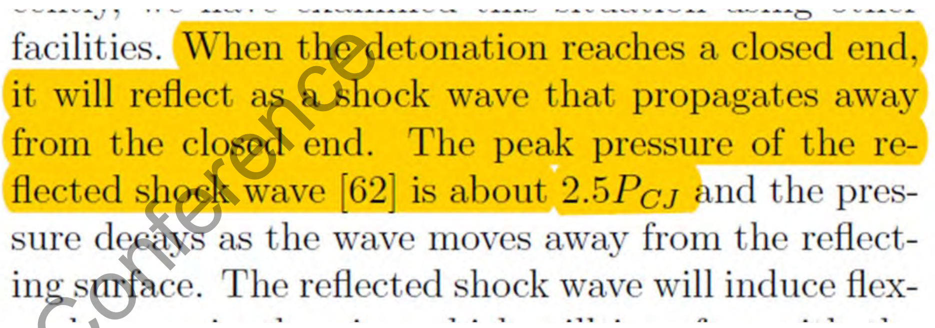
Metrics for Flames

- Laminar Burning Velocity
  - The laminar burning velocity is the speed of the flame front relative to the position of the unburned gas
- Maximum Experimental Safe Gap (MESG)
  - The MESG is the maximum gap between two parallel flat surfaces that prevents flame propagation across that gap under certain experimental conditions
  - The MESG is relied upon in the National Electric Code (NEC) to, in part, define flammable gases and vapors into four groups (A, B, C, D)
- Critical/Quenching Diameter
  - The quenching diameter is the maximum diameter of a round hole that would quench a slow moving flame

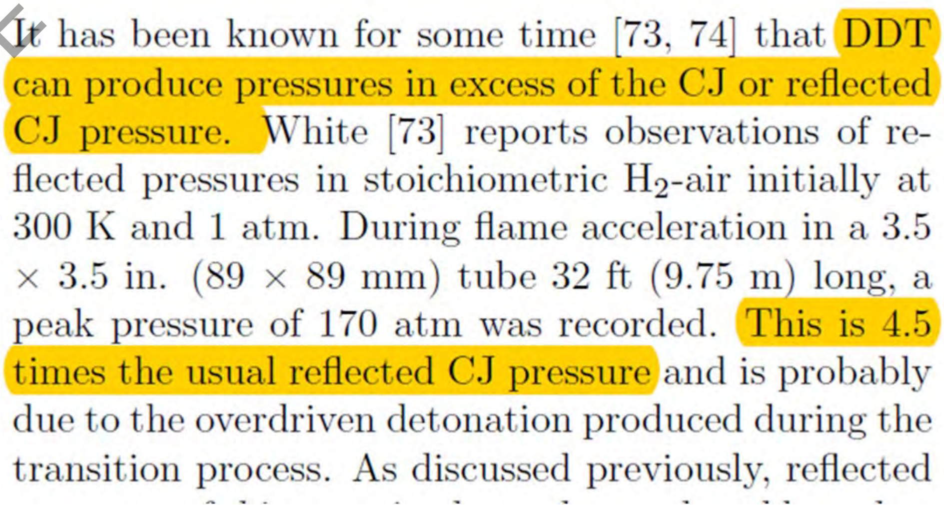


Detonation Pressures

- Reflected shocks at closed ends can result in peak pressures up to $2.5P_{CJ}$. (Chapman and Jouguet detonation pressure)
  - Elbows can also result in reflected pressure waves.
- A DDT can produce peak pressures up to $4.5P_{CJ}$.



facilities. When the detonation reaches a closed end, it will reflect as a shock wave that propagates away from the closed end. The peak pressure of the reflected shock wave [62] is about $2.5P_{CJ}$ and the pressure decays as the wave moves away from the reflecting surface. The reflected shock wave will induce flex-



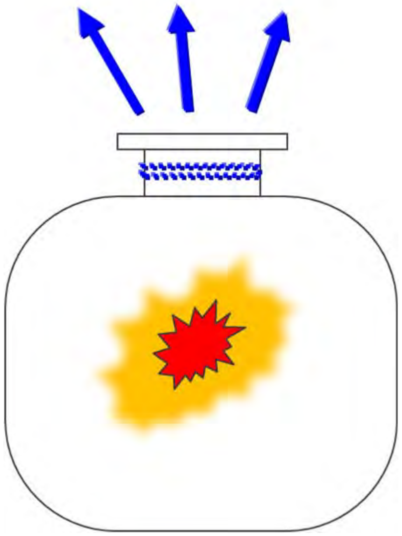
It has been known for some time [73, 74] that DDT can produce pressures in excess of the CJ or reflected CJ pressure. White [73] reports observations of reflected pressures in stoichiometric H_2-air initially at 300 K and 1 atm. During flame acceleration in a 3.5 × 3.5 in. (89 × 89 mm) tube 32 ft (9.75 m) long, a peak pressure of 170 atm was recorded. This is 4.5 times the usual reflected CJ pressure and is probably due to the overdriven detonation produced during the transition process. As discussed previously, reflected

Joseph E. Shepherd, Structural Response of Piping to Internal Gas Detonation, Journal of Pressure Vessel Technology, Vol. 131, Issue 3, 2009.

MKOC 2023 - Explosion Workshop

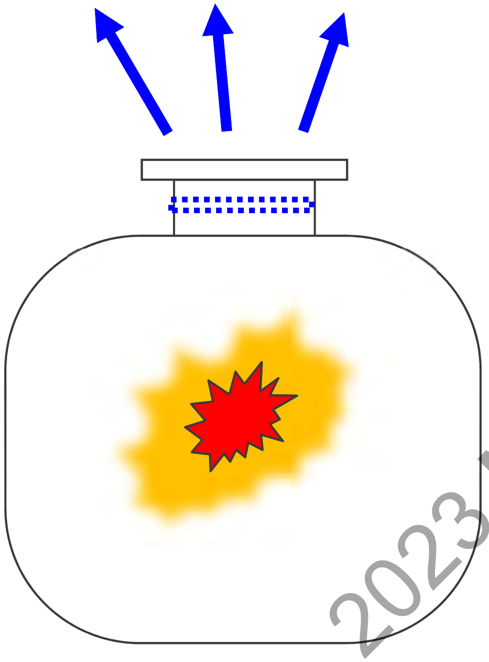
Ali Rangwala, Ph.D.
Alfonso F. Ibarreta, Ph.D., PE, CFEI

Mary Kay O'Connor Process Safety Conference,
October 13, 2023



EXPLOSION MITIGATION VIA DEFLAGRATION VENTING

Deflagration (Explosion) Venting – NFPA 68



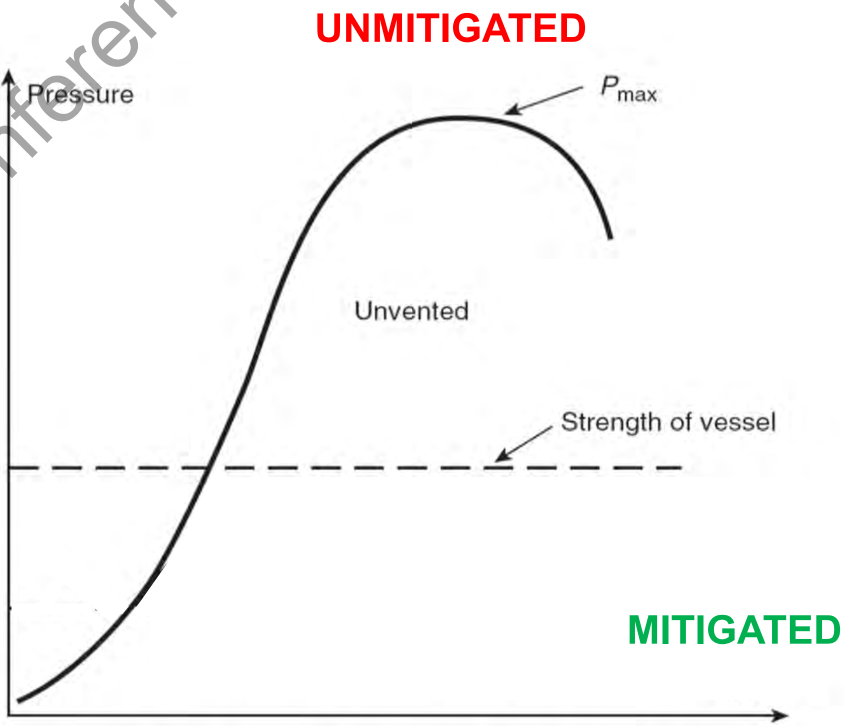


FIGURE B.4.1 Pressure–Time Graph of a Vented Deflagration.

Source: NFPA 654 (2020) “Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids”

Deflagration (Explosion) Venting – NFPA 68

- NFPA 68 provides equations for determining required explosion vent areas
- Vent reduces maximum overpressure
- Typically lower cost than explosion suppression systems
- Must vent to safe outdoor area
- Flame Arresting and Particulate Retention (Flameless) vents can be used indoors

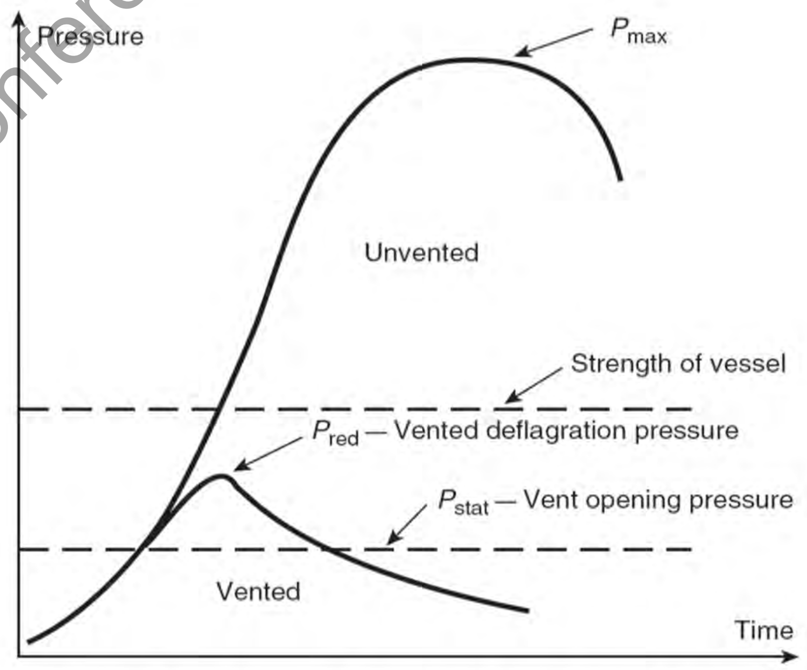


FIGURE B.4.1 Pressure–Time Graph of a Vented Deflagration.

Source: NFPA 68 "Standard for Explosion Protection by Deflagration Venting"

Vented Deflagrations – NFPA 68 - Gas Mixtures

NFPA 68: Standard on Explosion Protection by Deflagration Venting, 2023 Edition - Chapter 7 Venting Deflagrations of Gas Mixtures and Mists

▼ **Chapter 6 Fundamentals of Venting of Deflagrations**

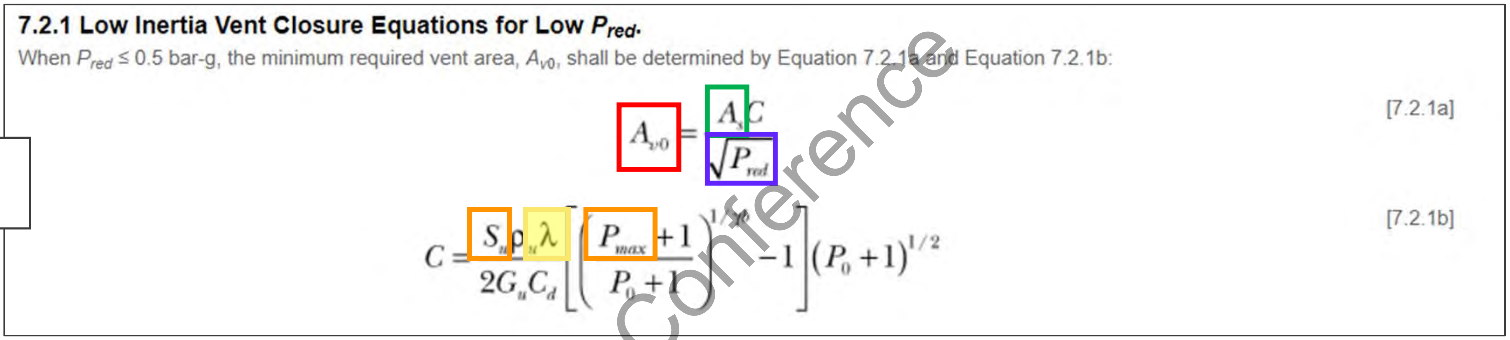
- *6.1 Basic Concepts.*
- *6.2 Mixtures.*
- *6.3 Enclosure Design and Support.*
- *6.4 Enclosure Length-to-Diameter Ratio and Vent Variables.*
- *6.5 Vent Closure Operation.*
- *6.6 Consequences of a Deflagration.*
- *6.7 Effects of Vent Inertia.*
- *6.8 Fireball Dimensions.*
- *6.9 Effects of Vent Discharge Ducts.*
- *6.10 Venting with Flame Arresting and Particulate Retention.*

▼ **Chapter 7 Venting Deflagrations of Gas Mixtures and Mists**

- *7.1 Introduction.*
- *7.2 Venting by Means of Low Inertia Vent Closures.*
- *7.3 Partial Volume Effects.*
- *7.4 Effects of Panel Inertia.*
- *7.5 Effects of Vent Ducts.*
- *7.6 Deflagration Venting of Enclosures Interconnected with Pipelines.*

NFPA 68 – 7.2 Low Inertia Vent Closures

$P_{red} < 0.5$ barg



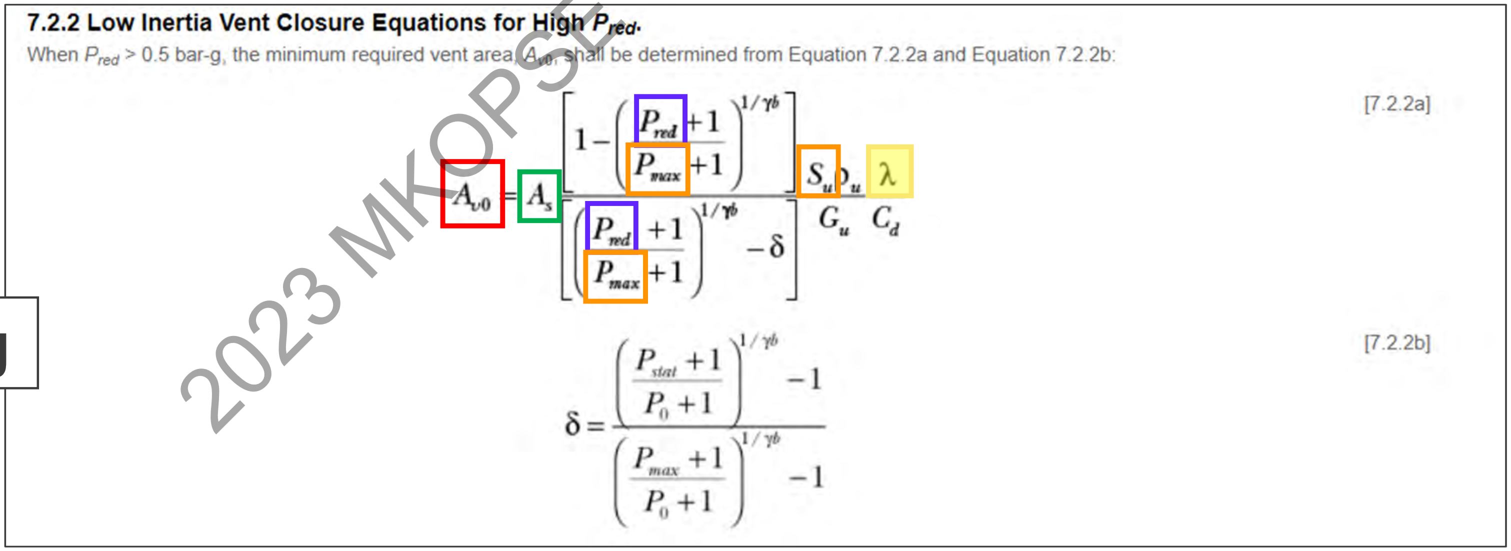
7.2.1 Low Inertia Vent Closure Equations for Low P_{red}.

When $P_{red} \leq 0.5$ bar-g, the minimum required vent area, A_{v0}, shall be determined by Equation 7.2.1a and Equation 7.2.1b:

$$A_{v0} = \frac{A_s C}{\sqrt{P_{red}}} \quad [7.2.1a]$$

$$C = \frac{S_u \rho_u \lambda}{2 G_u C_d}\left[\left(\frac{P_{max}+1}{P_0+1}\right)^{1/\gamma_b} - 1\right](P_0+1)^{1/2} \quad [7.2.1b]$$

$P_{red} > 0.5$ barg



7.2.2 Low Inertia Vent Closure Equations for High P_{red}.

When $P_{red} > 0.5$ bar-g, the minimum required vent area, A_{v0}, shall be determined from Equation 7.2.2a and Equation 7.2.2b:

$$A_{v0} = A_s \frac{\left[1-\left(\frac{P_{red}+1}{P_{max}+1}\right)^{1/\gamma_b}\right]}{\left[\left(\frac{P_{red}+1}{P_{max}+1}\right)^{1/\gamma_b} - \delta\right]} \frac{S_u \rho_u \lambda}{G_u C_d} \quad [7.2.2a]$$

$$\delta = \frac{\left(\frac{P_{stat}+1}{P_0+1}\right)^{1/\gamma_b} - 1}{\left(\frac{P_{max}+1}{P_0+1}\right)^{1/\gamma_b} - 1} \quad [7.2.2b]$$

NFPA 68 – 7.2.6 Turbulent Flame Enhancement Factor, λ

$$\lambda_0 = \varphi_1 \varphi_2$$

φ_1 **Enhancement due to flame-generated turbulence**

φ_2 **Enhancement due to vent-generated turbulence**

$$\varphi_1 = \begin{cases} 1, \ if \ \mathrm{Re}_f < 4000 \\ \left(\dfrac{\mathrm{Re}_f}{4000}\right)^{\theta}, \ if \ \mathrm{Re}_f \geq 4000 \end{cases}$$

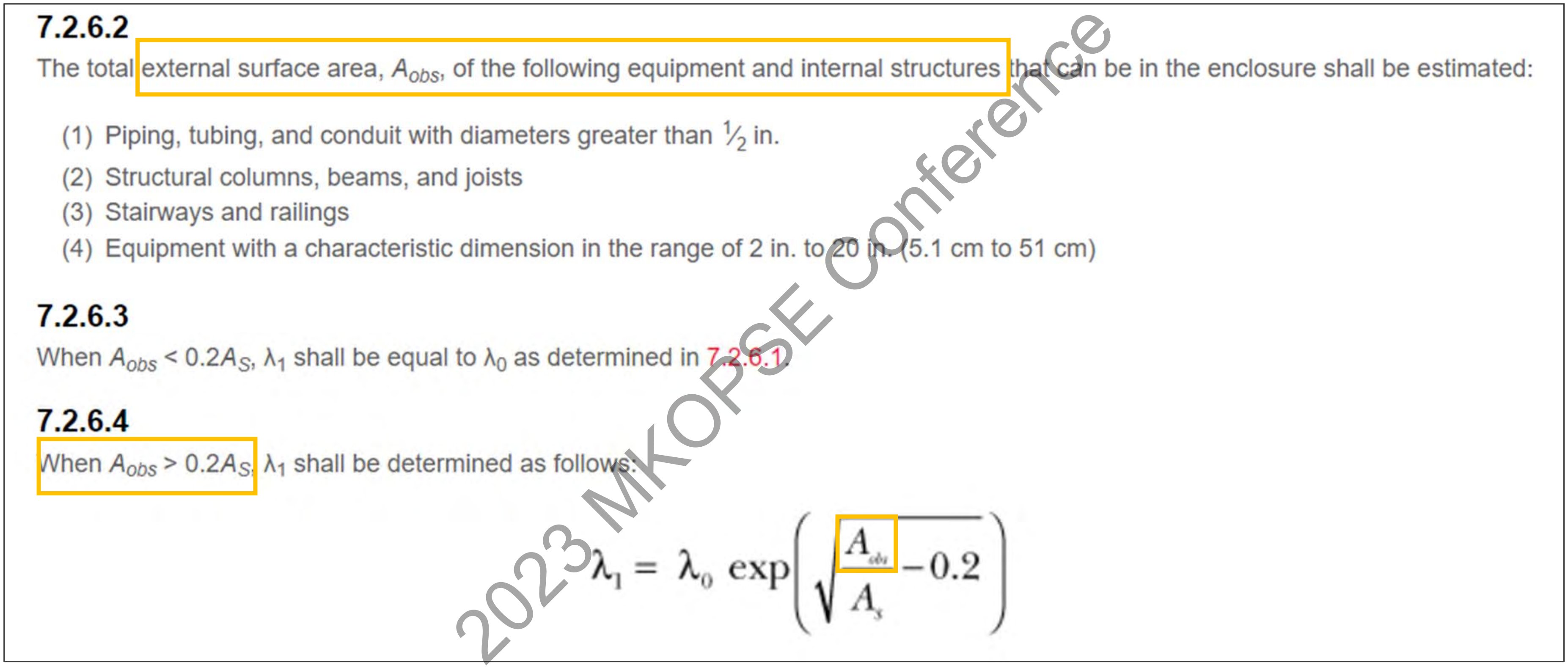
$$\mathrm{Re}_f = \frac{\rho_u \boxed{S_u} (D_{he}/2)}{\mu_u}$$

$$\varphi_2 = \max\left\{1, \beta_1 \left(\frac{\mathrm{Re}_v}{10^6}\right)^{\left(\frac{\beta_2}{\boxed{S_u}}\right)^{0.5}}\right\}$$

$$u_v = \min\left\{\sqrt{\frac{2\times10^5 \boxed{P_{red}}}{\rho_u}}, a_u\right\}$$

$$\mathrm{Re}_v = \frac{\rho_u u_v \boxed{(D_v} / 2)}{\mu_u}$$

NFPA 68 – 7.2.6.2 Obstacles



7.2.6.2

The total external surface area, A_{obs}, of the following equipment and internal structures that can be in the enclosure shall be estimated:

(1) Piping, tubing, and conduit with diameters greater than ½ in.
(2) Structural columns, beams, and joists
(3) Stairways and railings
(4) Equipment with a characteristic dimension in the range of 2 in. to 20 in. (5.1 cm to 51 cm)

7.2.6.3

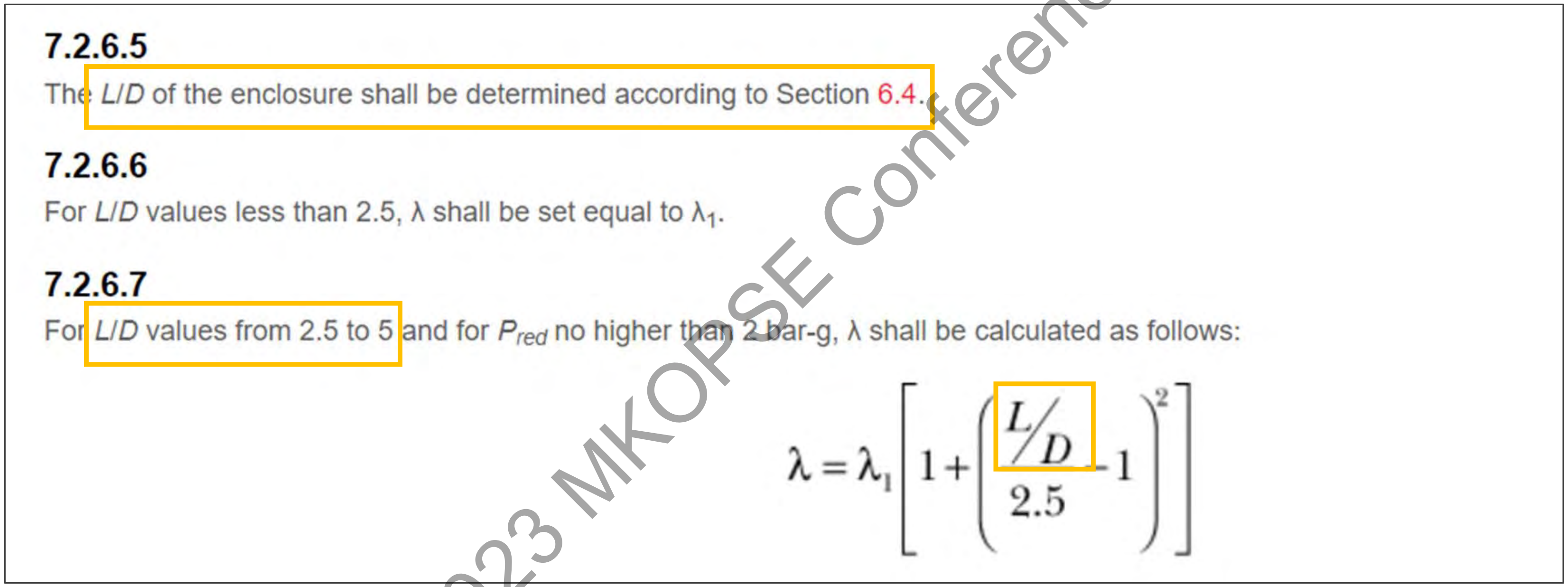
When $A_{obs} < 0.2A_S$, λ_1 shall be equal to λ_0 as determined in 7.2.6.1.

7.2.6.4

When $A_{obs} > 0.2A_S$, λ_1 shall be determined as follows:

$$\lambda_1 = \lambda_0 \exp\left(\sqrt{\frac{A_{obs}}{A_s} - 0.2}\right)$$

NFPA 68 – 7.2.6.5 Length to Diameter Ratio (L/D)



7.2.6.5

The *L/D* of the enclosure shall be determined according to Section 6.4.

7.2.6.6

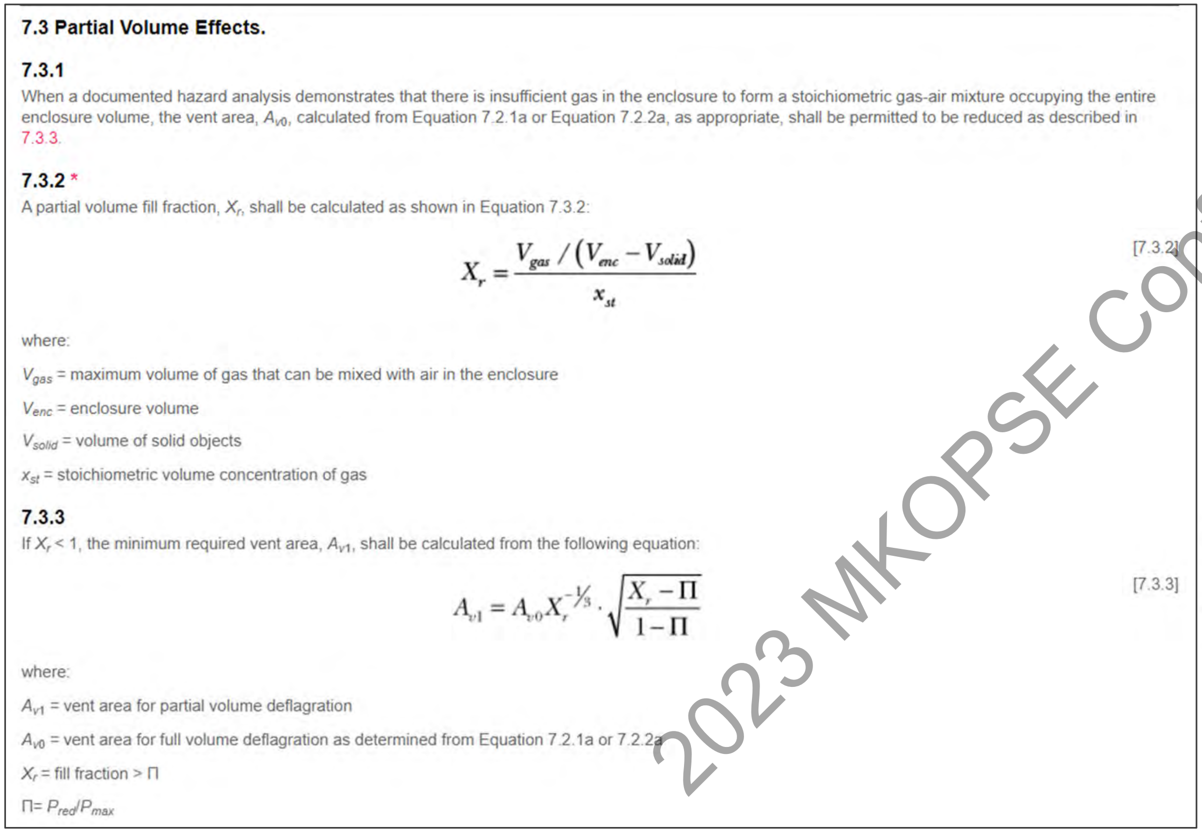
For *L/D* values less than 2.5, λ shall be set equal to λ_1.

7.2.6.7

For *L/D* values from 2.5 to 5 and for P_{red} no higher than 2 bar-g, λ shall be calculated as follows:

$$\lambda = \lambda_1 \left[1 + \left(\frac{L/D}{2.5} - 1 \right)^2 \right]$$

NFPA 68 – 7.3 Partial Volume Effects



7.3 Partial Volume Effects.

7.3.1

When a documented hazard analysis demonstrates that there is insufficient gas in the enclosure to form a stoichiometric gas-air mixture occupying the entire enclosure volume, the vent area, A_{v0}, calculated from Equation 7.2.1a or Equation 7.2.2a, as appropriate, shall be permitted to be reduced as described in 7.3.3.

7.3.2 *

A partial volume fill fraction, X_r, shall be calculated as shown in Equation 7.3.2:

$$X_r = \frac{V_{gas}/(V_{enc}-V_{solid})}{x_{st}}$$ [7.3.2]

where:

V_{gas} = maximum volume of gas that can be mixed with air in the enclosure

V_{enc} = enclosure volume

V_{solid} = volume of solid objects

x_{st} = stoichiometric volume concentration of gas

7.3.3

If $X_r < 1$, the minimum required vent area, A_{v1}, shall be calculated from the following equation:

$$A_{v1} = A_{v0} X_r^{-1/3} \cdot \sqrt{\frac{X_r - \Pi}{1-\Pi}}$$ [7.3.3]

where:

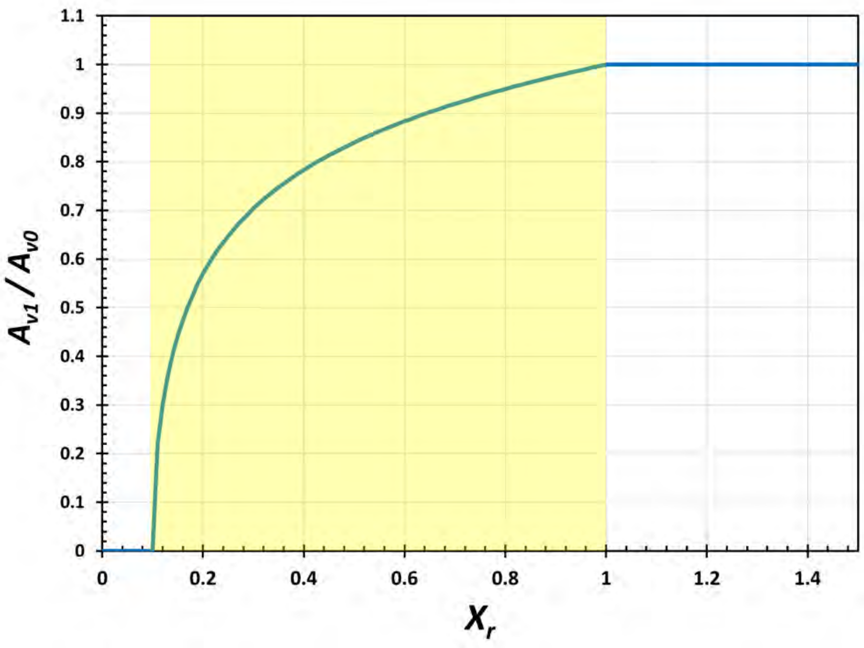
A_{v1} = vent area for partial volume deflagration

A_{v0} = vent area for full volume deflagration as determined from Equation 7.2.1a or 7.2.2a

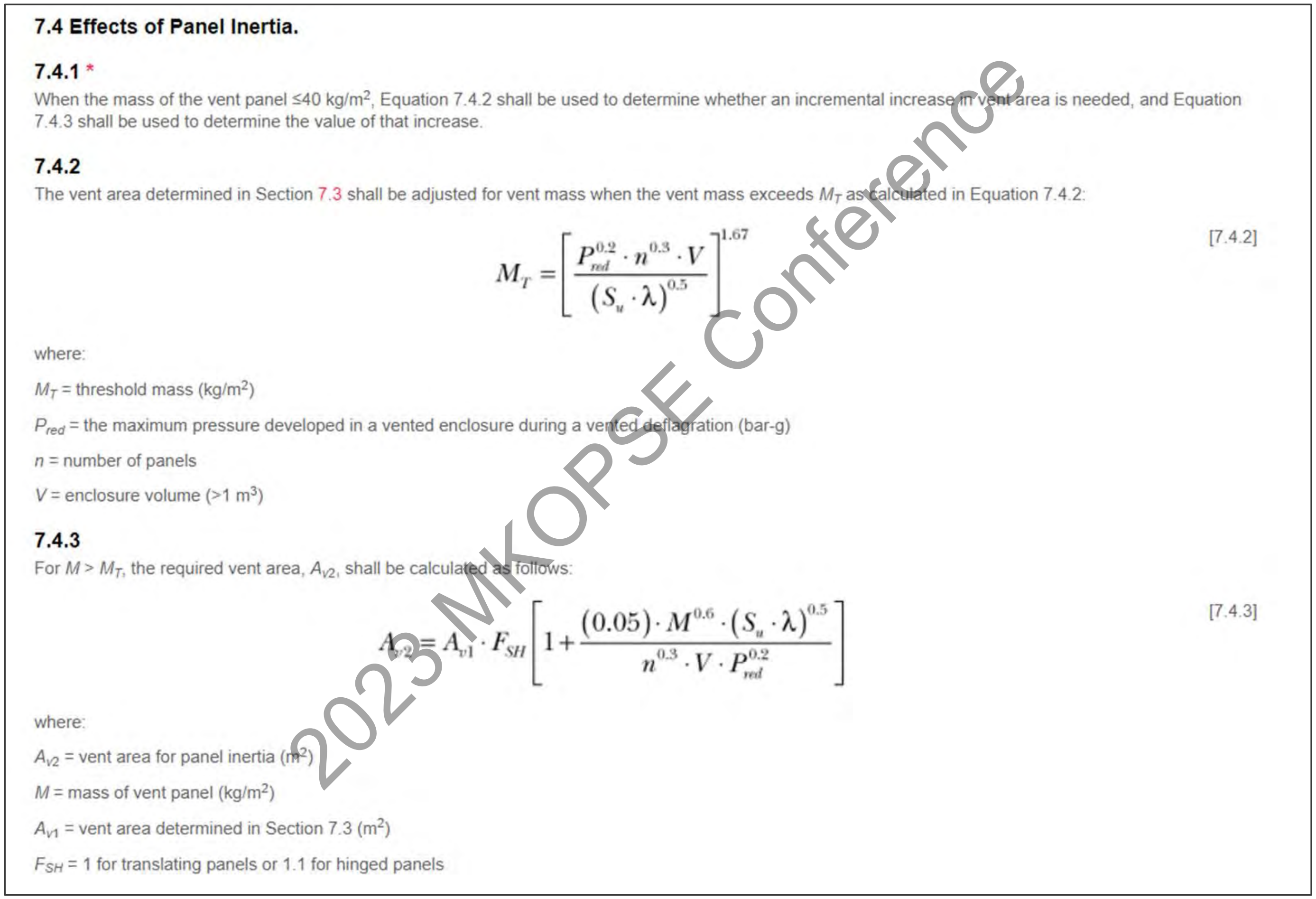
X_r = fill fraction > Π

$\Pi = P_{red}/P_{max}$

P_{red} = 0.5 barg
P_{max} = 5 barg
Π = 0.1



NFPA 68 – 7.4 Effect of Panel Inertia



7.4 Effects of Panel Inertia.

7.4.1 *

When the mass of the vent panel ≤40 kg/m^2, Equation 7.4.2 shall be used to determine whether an incremental increase in vent area is needed, and Equation 7.4.3 shall be used to determine the value of that increase.

7.4.2

The vent area determined in Section 7.3 shall be adjusted for vent mass when the vent mass exceeds M_T as calculated in Equation 7.4.2:

$$M_T = \left[\frac{P_{red}^{0.2} \cdot n^{0.3} \cdot V}{(S_u \cdot \lambda)^{0.5}}\right]^{1.67} \qquad [7.4.2]$$

where:

M_T = threshold mass (kg/m^2)

P_{red} = the maximum pressure developed in a vented enclosure during a vented deflagration (bar-g)

n = number of panels

V = enclosure volume (>1 m^3)

7.4.3

For $M > M_T$, the required vent area, A_{v2}, shall be calculated as follows:

$$A_{v2} = A_{v1} \cdot F_{SH}\left[1 + \frac{(0.05) \cdot M^{0.6} \cdot (S_u \cdot \lambda)^{0.5}}{n^{0.3} \cdot V \cdot P_{red}^{0.2}}\right] \qquad [7.4.3]$$

where:

A_{v2} = vent area for panel inertia (m^2)

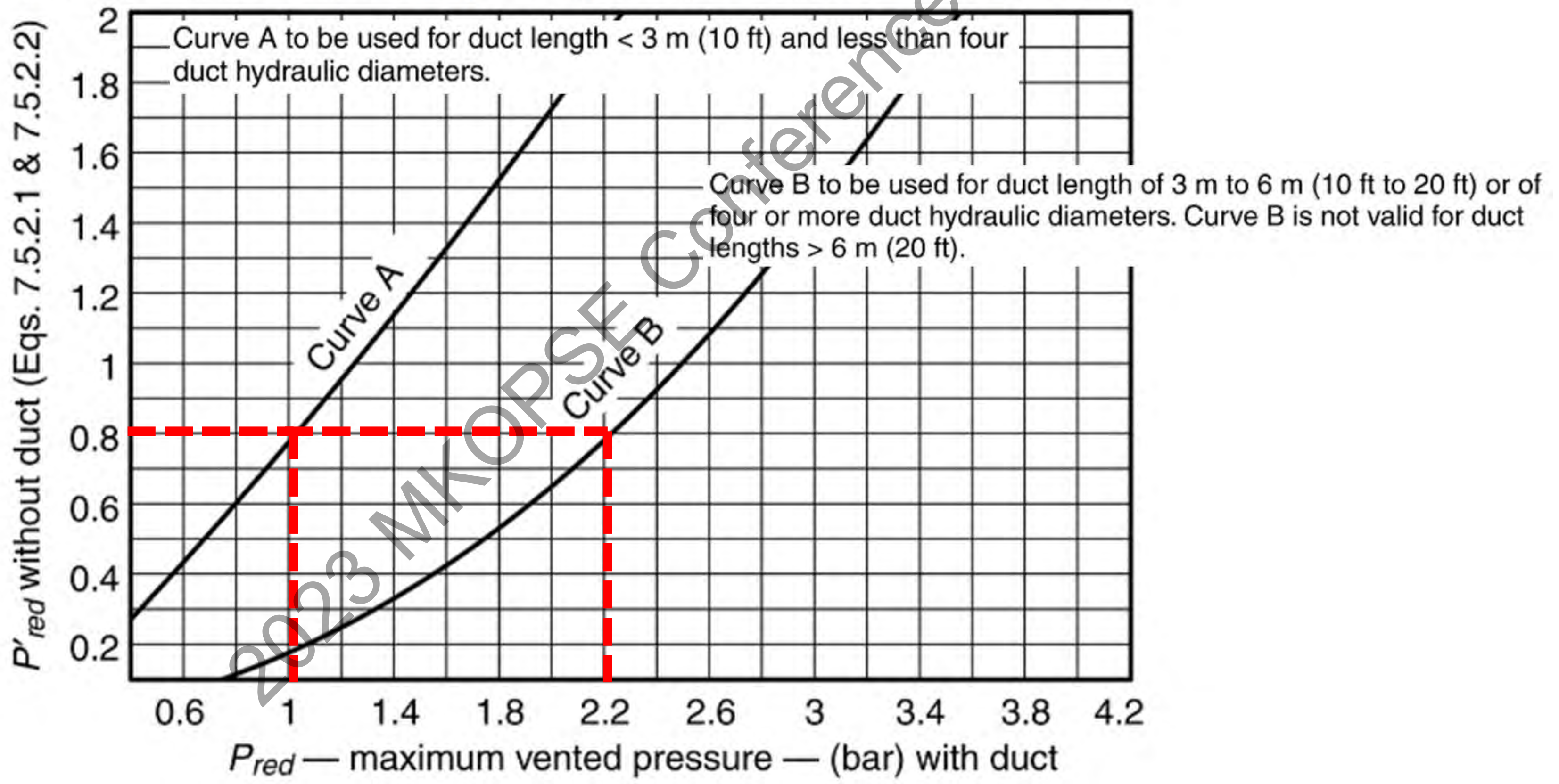
M = mass of vent panel (kg/m^2)

A_{v1} = vent area determined in Section 7.3 (m^2)

F_{SH} = 1 for translating panels or 1.1 for hinged panels

NFPA 68 – 7.5 Effect of Vent Ducts

Figure 7.5.2 Maximum Pressure Developed During Venting of Gas, with and Without Vent Ducts.



FIREBALL SIZE

Flameless Explosion Vents

Dust Explosion Venting
without REMBE® Q-Rohr®

with REMBE® Q-Rohr®

Source: Rembe

Explosion Venting Examples

Explosion Venting Examples

Empirical Correlations for Fireball Size

- NFPA 68 *Standard on Explosion Protection by Deflagration Venting*
- British Standard BS EN 14994 *Gas Explosion Venting Protective System*

Vented Deflagration Fireball Dimensions: NFPA 68 (2018)

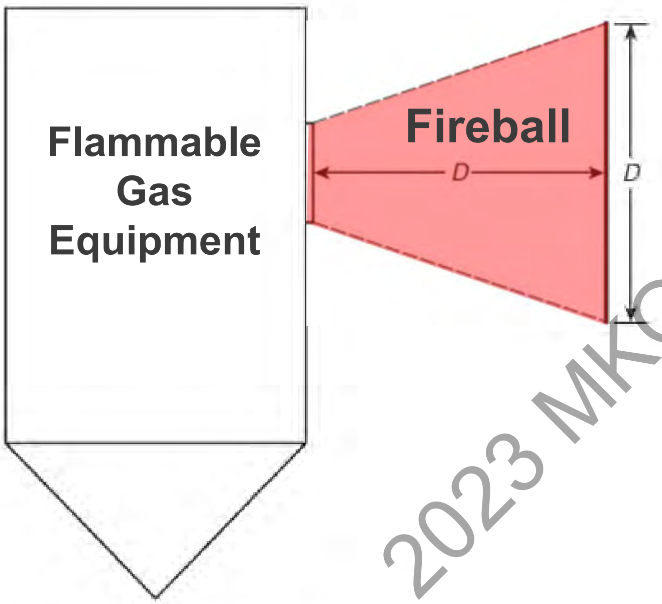


FIGURE 8.9.2.2 Fireball Dimensions.

Maximum Flammable Gas Fireball Travel Distance:

$$D = 3.1 \cdot \left(\frac{V}{n} \right)^{0.402}$$

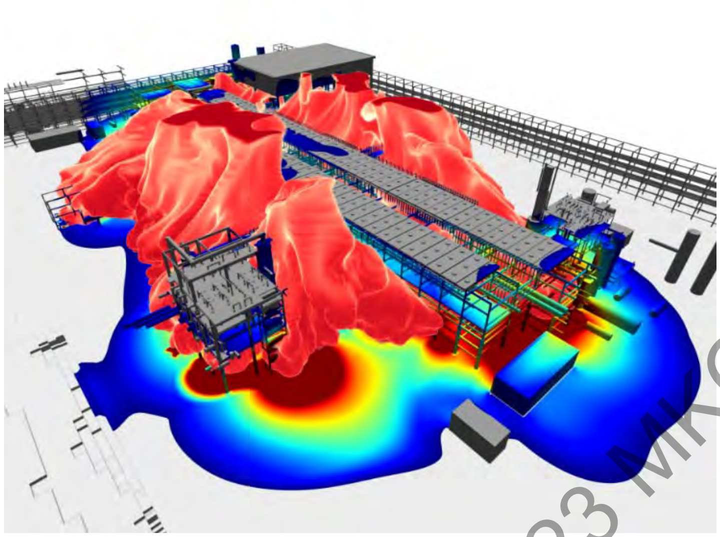
where:
D = axial distance (front-centerline) from vent (m)
V = volume of vented enclosure (m^3)
n = number of evenly distributed vents

EN 14494 uses $D=5\ V^{1/3}$

Empirical Equation Limitations

- Based on a number of limited experiments
- Depend on only:
  - Enclosure volume
  - Number of vents
  - Metal dust (yes/no)
- Do not take into account:
  - Fuel reactivity (S_u)
  - Vent activation pressure (P_{stat})
  - Maximum vented explosion overpressure (P_{red})
  - Vent geometry
  - Fuel concentration

FLACS / DUSTEX CFD Models

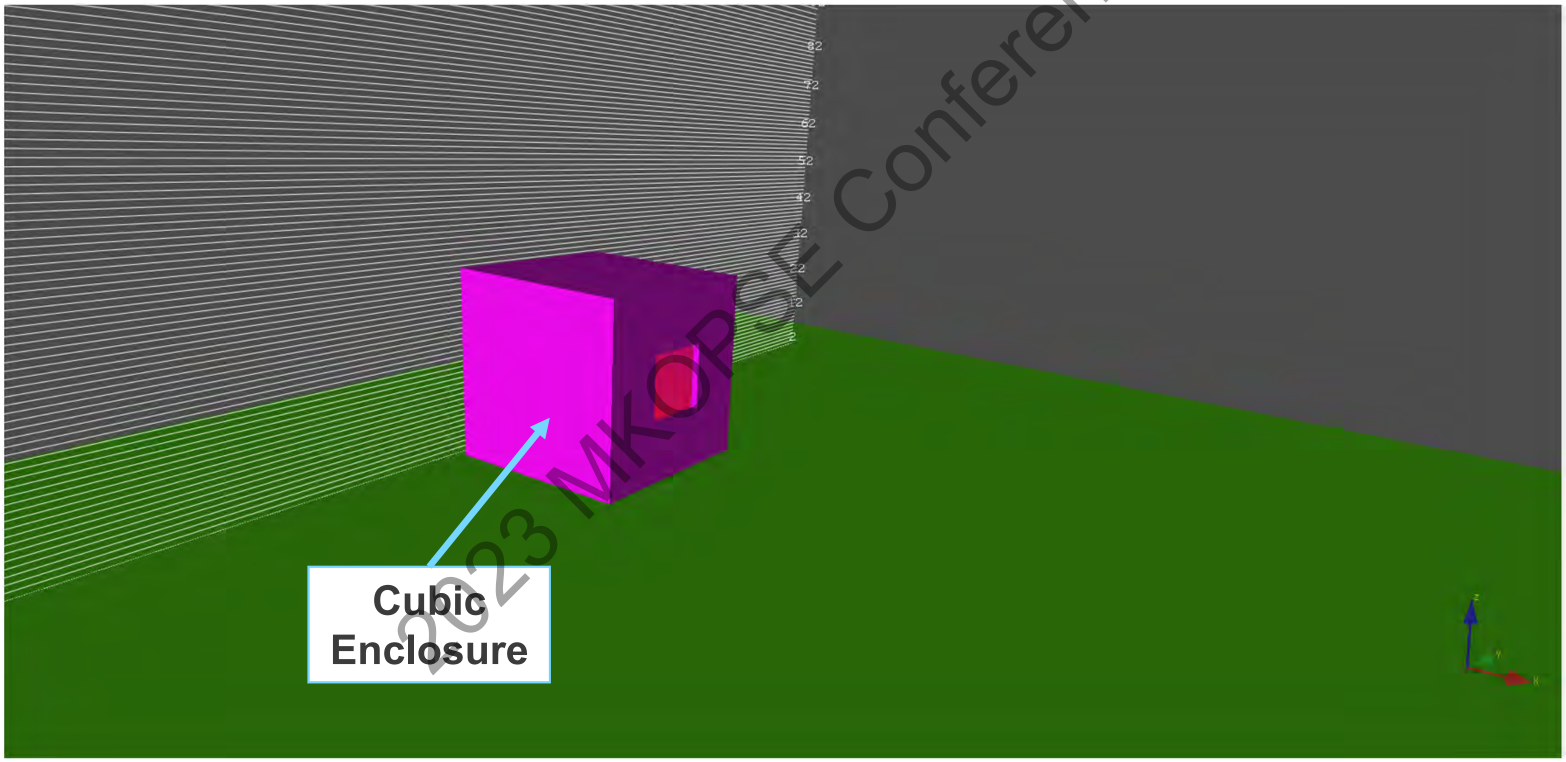


- FLACS is a Computational Fluid Dynamics (CFD) software developed by Gexcon to model vapor dispersion and gas explosion events
- DUSTEX is a FLACS module developed to model combustible dust deflagrations and explosions

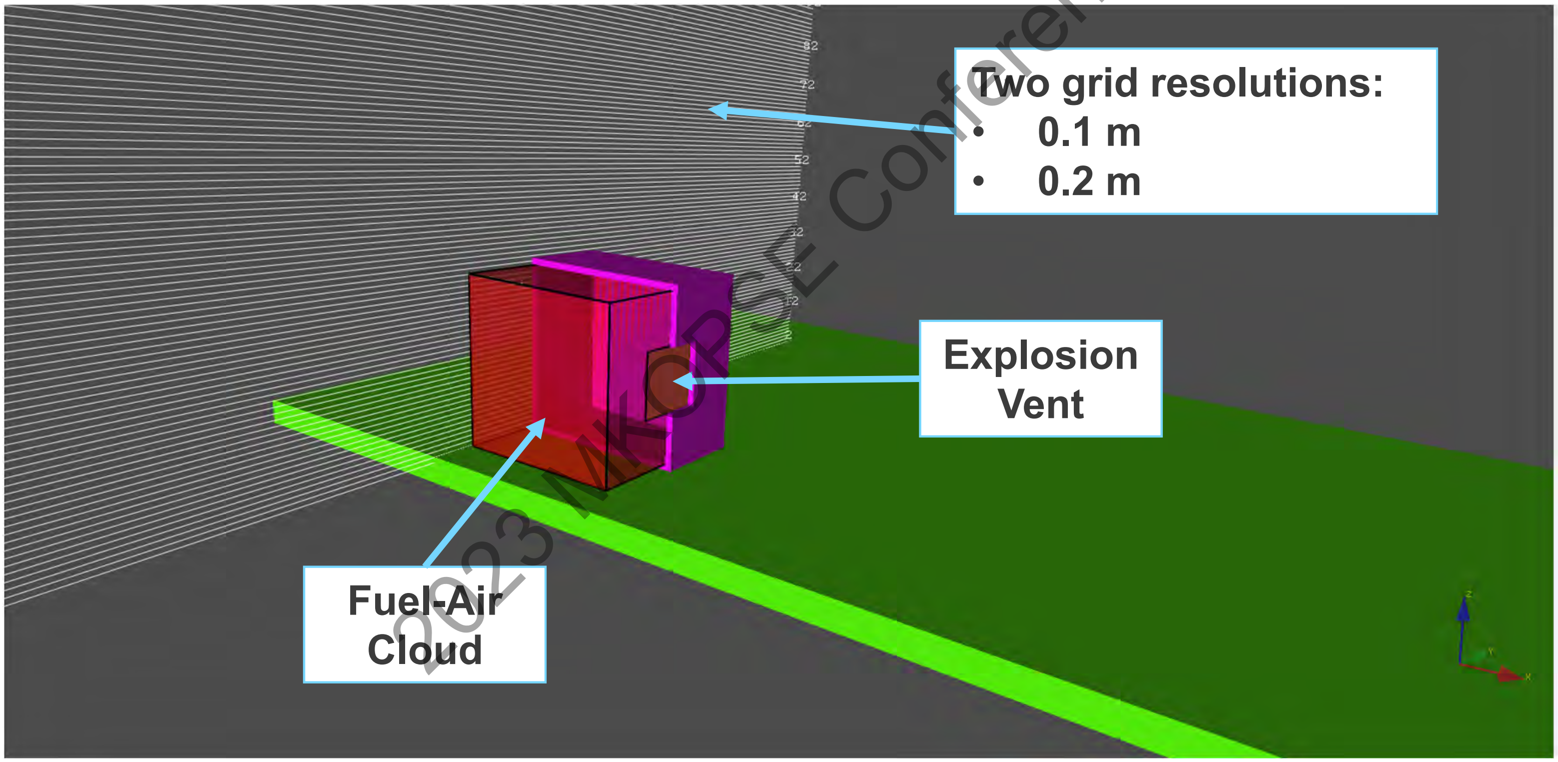
FLACS

GEXCON

CFD Modeling of Explosion Venting - Geometry



CFD Modeling of Explosion Venting - Geometry



Two grid resolutions:
- 0.1 m
- 0.2 m

Explosion Vent

Fuel-Air Cloud

Scenario Matrix

Fuel	Methane	Propane	Ethylene
Concentration	Phi = 1.0	Phi = 0.7 Phi = 1.0 Phi = 1.4	Phi = 1.0
Fuel[1] S_u	38 cm/s	45 cm/s	74 cm/s
Enclosure Volume	4 – 1,000 m^3	4 – 1,000 m^3	4 – 1,000 m^3
Vent Size	0.2 – 16 m^2	0.2 – 16 m^2	0.2 – 16 m^2
Vent Activation Pressure	0.1 barg	0.1 – 0.2 barg	0.1 barg
# of scenarios	7	24	7

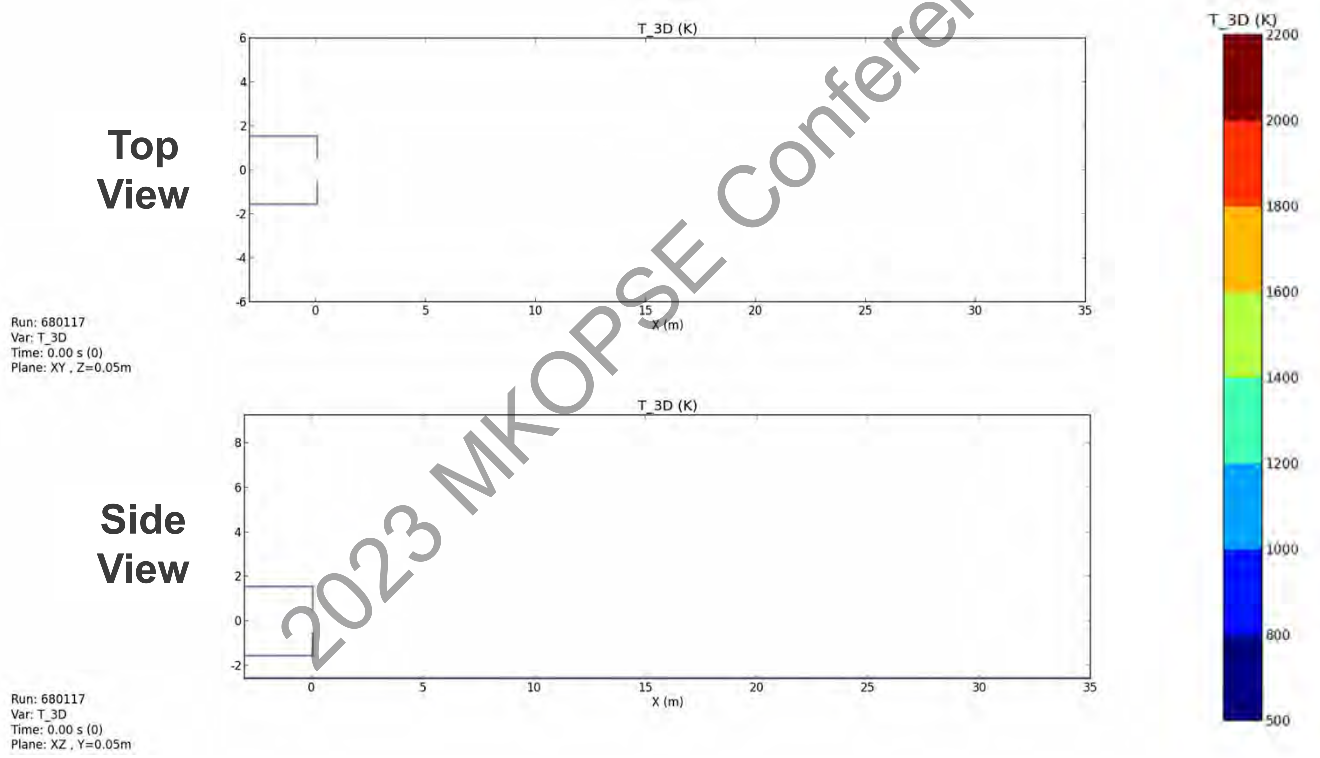
[1] Default values in FLACS libraries

Propane Explosion Venting Example

Propane
Phi = 1
3m x 3m x 3m

Top View

Side View



Temperature Contours
500 K – 2200 K

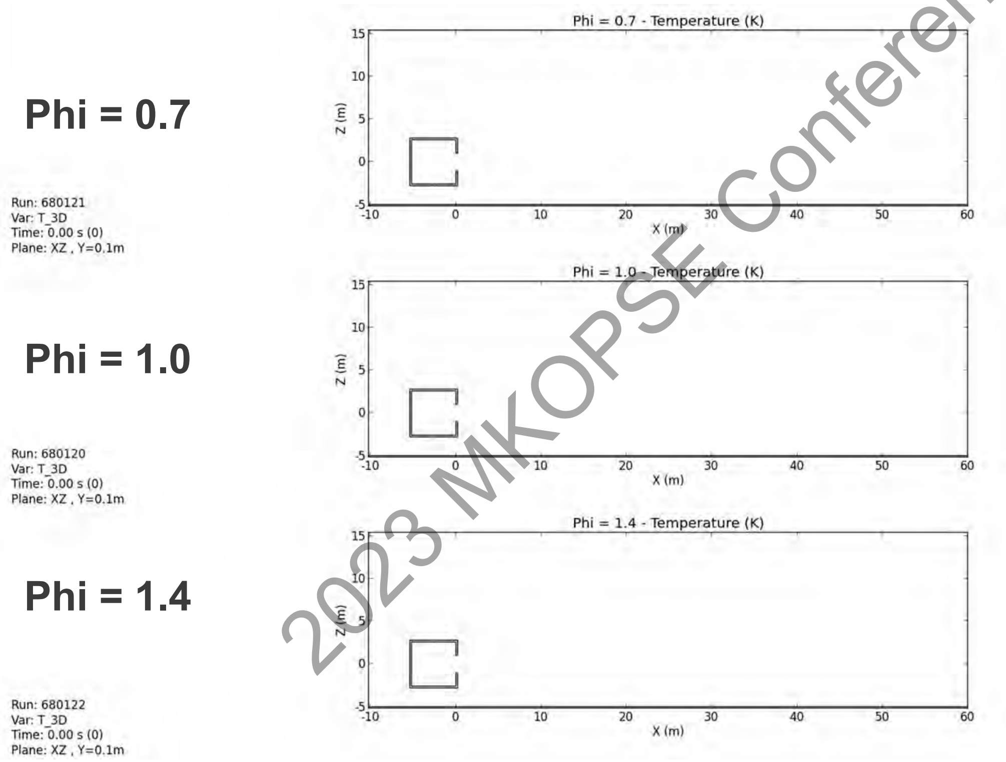
Propane – Effect of Equivalence Ratio

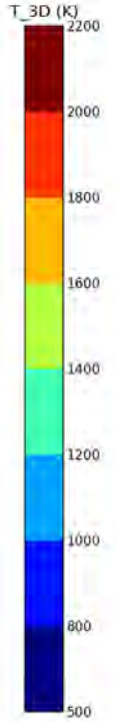
Propane
5.2m x 5.2m x 5.2m

Phi = 0.7

Phi = 1.0

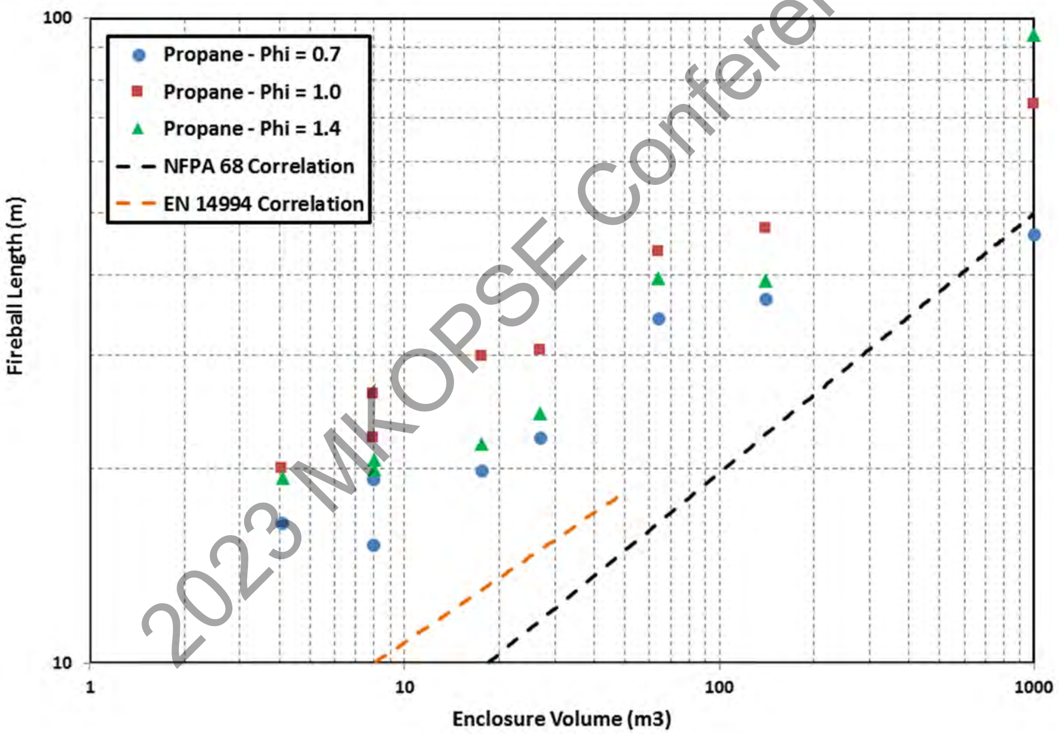
Phi = 1.4





Temperature Contours
500 K – 2200 K

Gas Explosion Venting Fireball – CFD Results



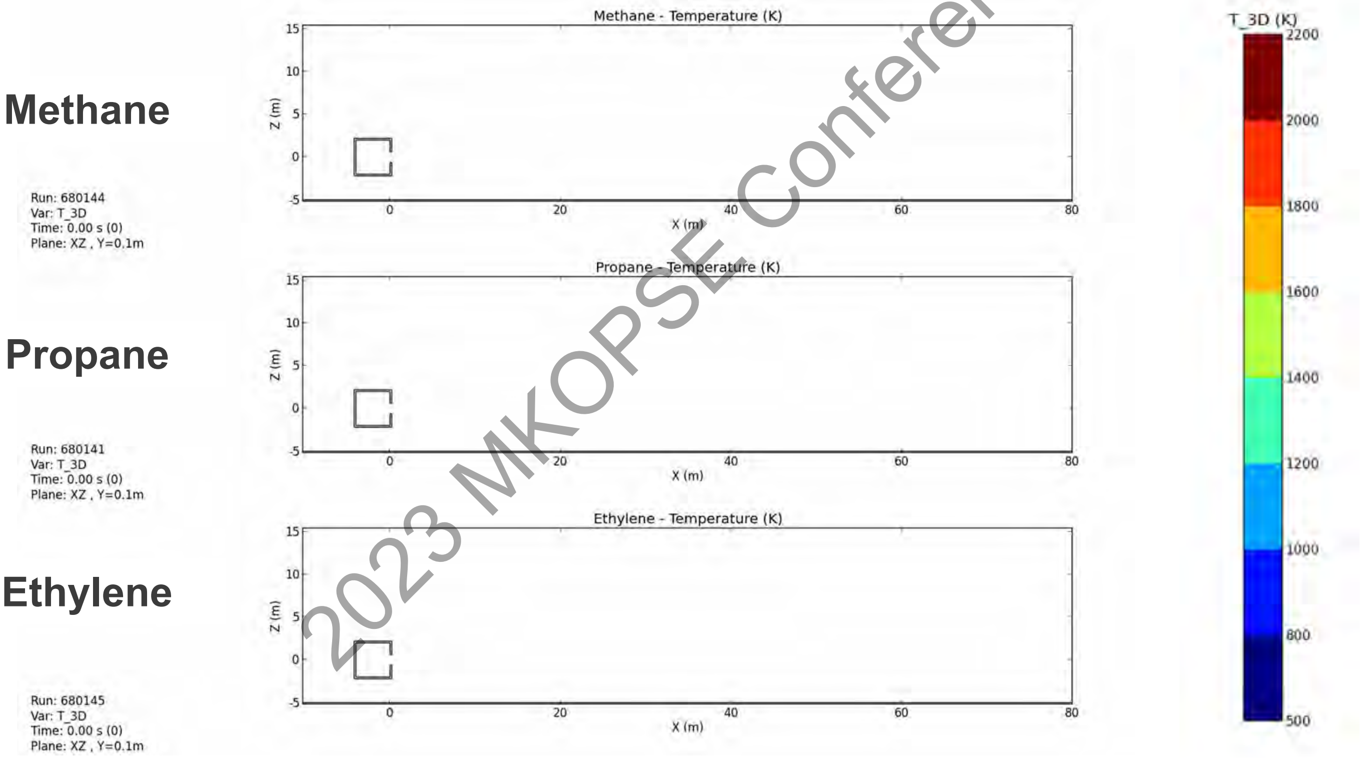
Effect of Fuel Type – Small Volume

Phi = 1.0
4m x 4m x 4m

Methane

Propane

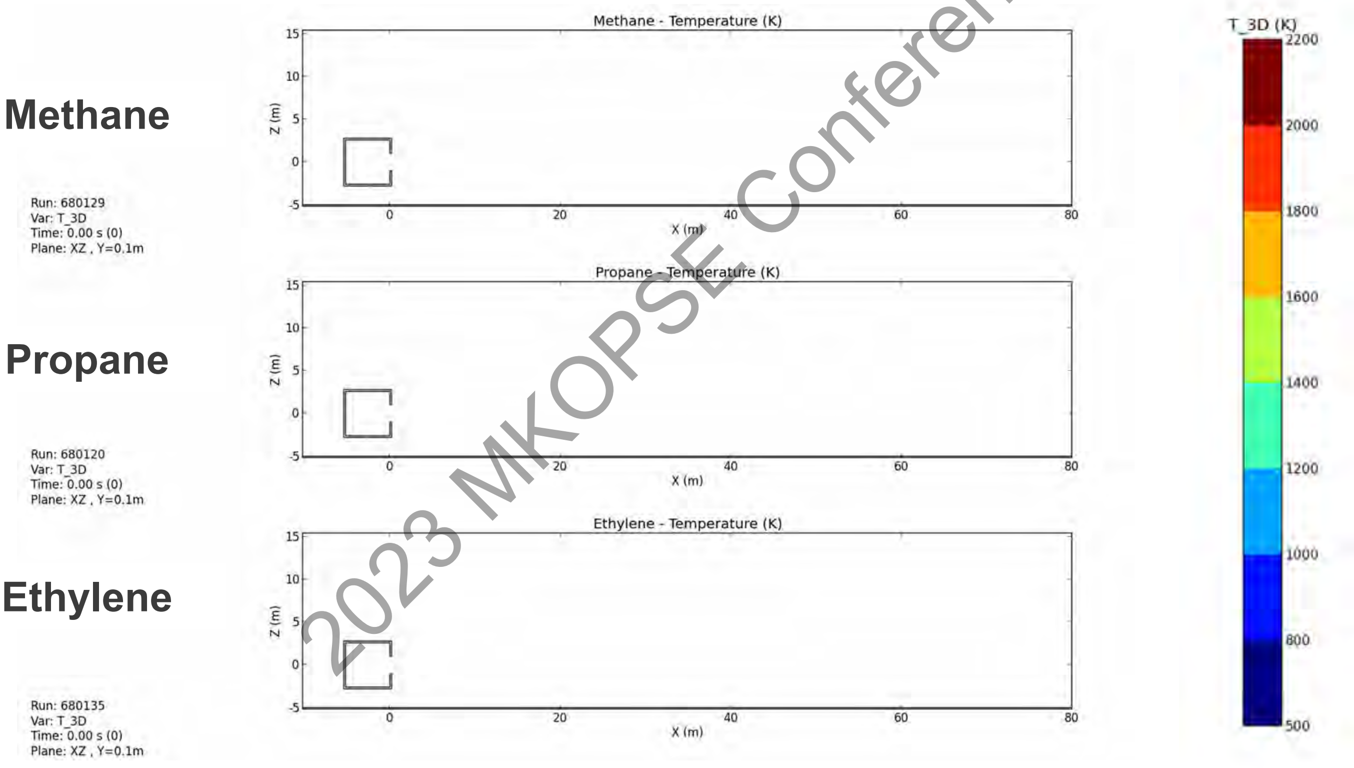
Ethylene



Temperature Contours
500 K – 2200 K

Effect of Fuel Type – Large Volume

Phi = 1.0
5.2m x 5.2m x 5.2m



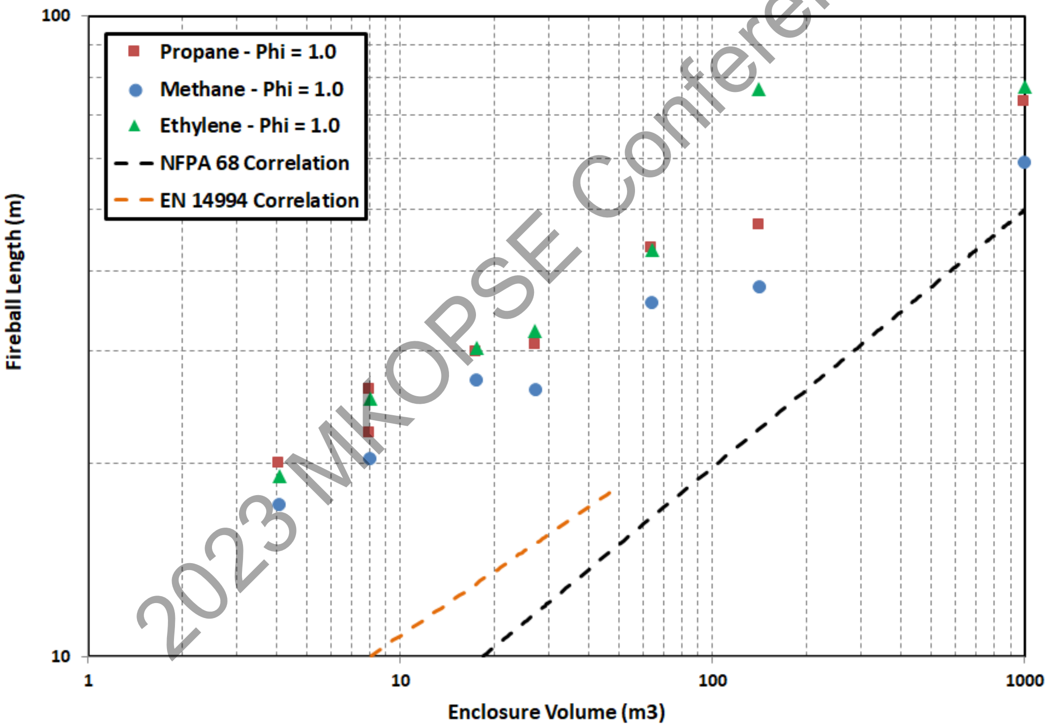
Methane

Propane

Ethylene

Temperature Contours
500 K – 2200 K

Gas Explosion Venting Fireball – CFD Results



Conclusions – Flammable Gas

- Stoichiometric, or near-stoichiometric, conditions pose a worst-case scenario for explosion venting fireball lengths.
- Relatively-poor agreement was obtained between gas deflagration venting simulation fireball length data and the empirical correlations.
  - Sizes calculated using the FLACS CFD model are up to a factor 2 to 3 larger than the estimates obtained using the standard correlations.
- A dependency of the fireball size on flammable gas species has been identified with propane and ethylene leading to larger fireballs.
  - Further analysis is required to determine the relative role of the expansion ratio and flame speed on the fireball dimensions

Explosion Venting Examples

kent

Risk Assessment: How to avoid slipping, tripping, and falling over the numbers

Will Sharpe

2023 MKOPSC

kentplc.com

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

26th Process Safety International Symposium

Frank Hart

DNV

- Mathematical Modeller (DNV) since 2019
- Previously
  - Risk consultant (Risktec Solutions)
  - Software engineer (Tessella, now CapGemini)
  - Research associate (School of Physics, University of Bath)

Model improvements and validation for buried CO2 pipeline ruptures

Introduction

- Dense phase pipeline transport
- Necessary for reducing CO_2 emissions during energy transition
- Especially for buried pipelines, modelling these is not easy
- Various attempts to better assess potential hazards

6" buried CO_2 pipeline rupture at DNV Spadeadam

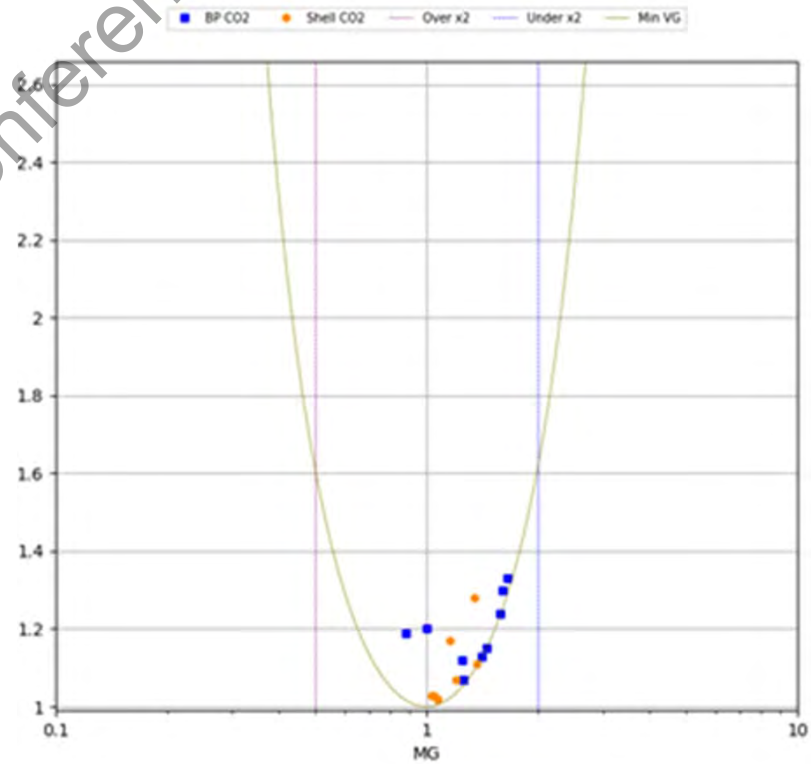
Introduction

- The hazards of CO_2 pipeline transport are registering with the public and politicians
- Some high profile failures
- Current hazard zones demonstrably inadequate

Crater from a 24" pipeline rupture near Satartia in 2020

Modelling and Phast 8.71 CO_2 Validation

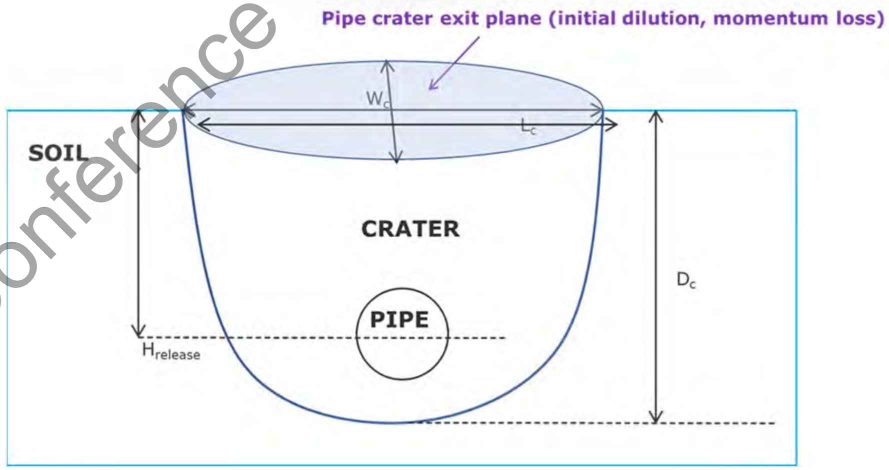
- Use the widely-used Phast UDM dispersion model
- Existing validation for small-medium scale above ground releases
- Specific to buried pipelines…
  - 'Crater' model
  - Thermodynamic model extension - solid phase CO_2

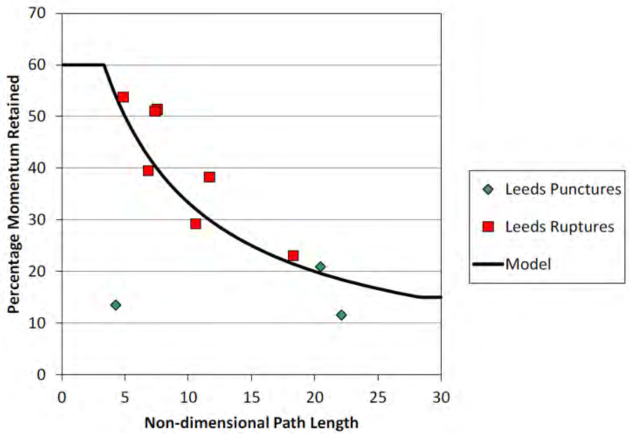


Validation against CO2PIPETRANS dispersion experiments

Crater modelling

- Crater dimensions
- Post-expansion source has additional air entrainment and reduced velocity
- Based on a small number of idealised CFD simulations
- Velocity appears too high for standard jet-based dispersion models

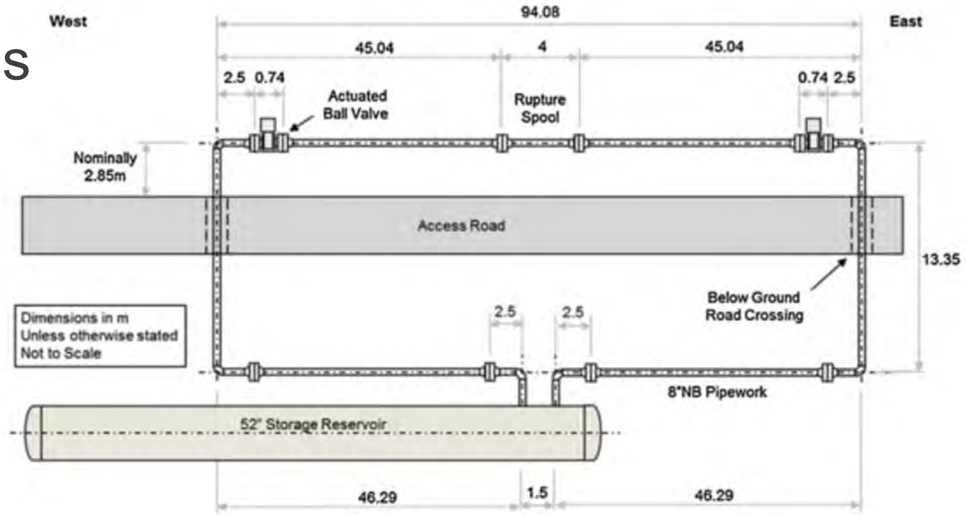




Crater model schematic (top), and correlation for momentum against 'path length' (bottom)

COSHER experiments

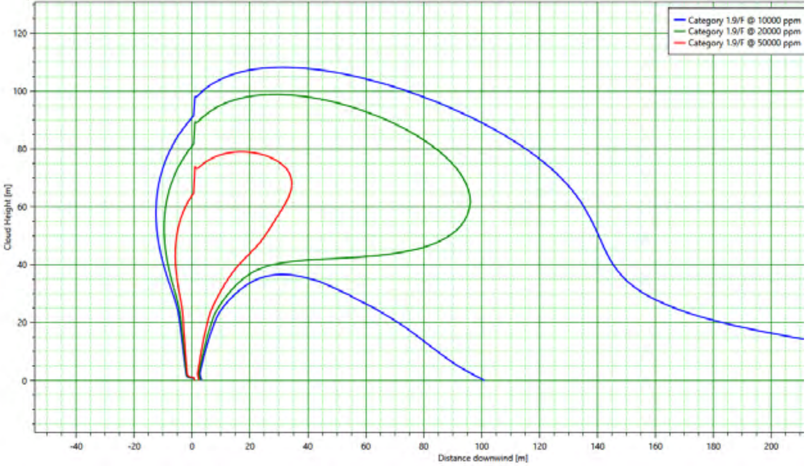
- Carried out at DNV Spadeadam test site in the UK
- Two punctures from buried 6" CO_2 pipelines (1.9/F and 4.7/D weather)
- Complex release geometry – requires some simplifying assumptions for source term
- Limited publicly available data



COSHER experiments – equipment layout

COSHER Validation (v8.71)

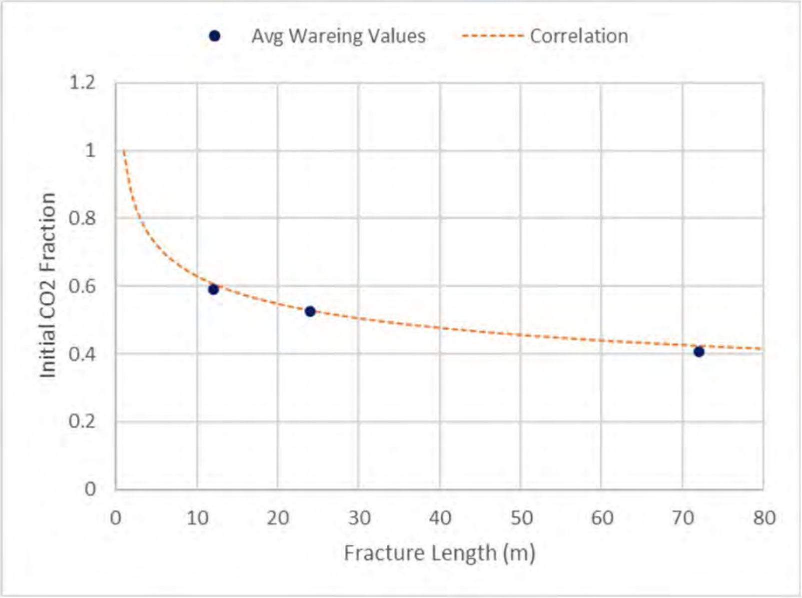
- Visible comparison of experiment vs prediction sufficient to show issues
- Experiment shows…
    - No evidence of an elevated plume
    - 'Pancake' shaped cloud around the release
- Primary cause was velocity out of the crater



COSHER 2 (low windspeed) release at 120s

Improved crater model

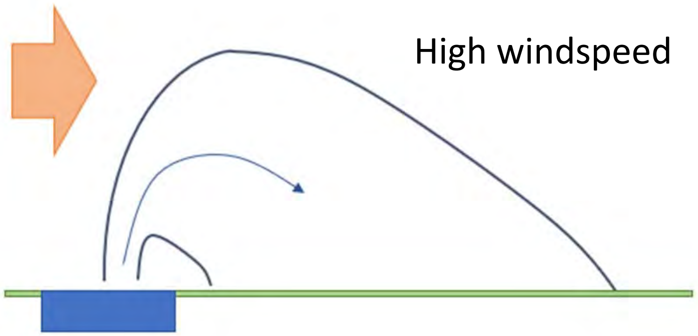
- Simplified model derived – flow area defined by crater width
- Implies generally larger areas and much reduced velocities (esp. for small L_f)
- Air entrainment correlation based on full set of CFD simulations
- Full bore ruptures only



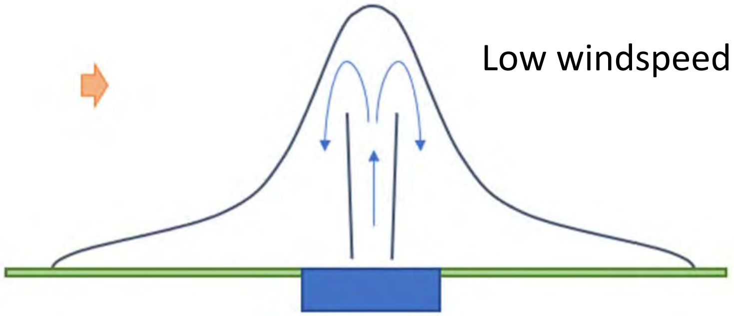
Modified Air entrainment correlation

CO_2 dispersion in contrasting wind conditions

- Plume trajectory bent over by wind
- No re-entrainment, no upwind spreading
- Suitably handled by UDM

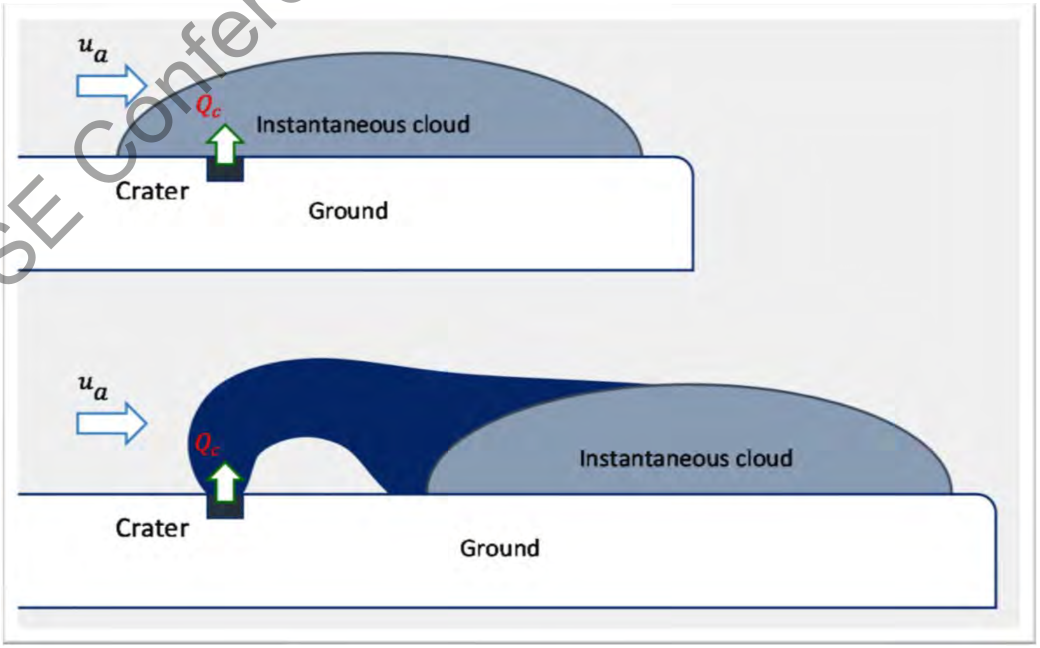


- Low impact on trajectory, results in 'fountain' behaviour
- Circular spreading at ground level
- Not well handled by standard UDM



'Gas Blanket' model

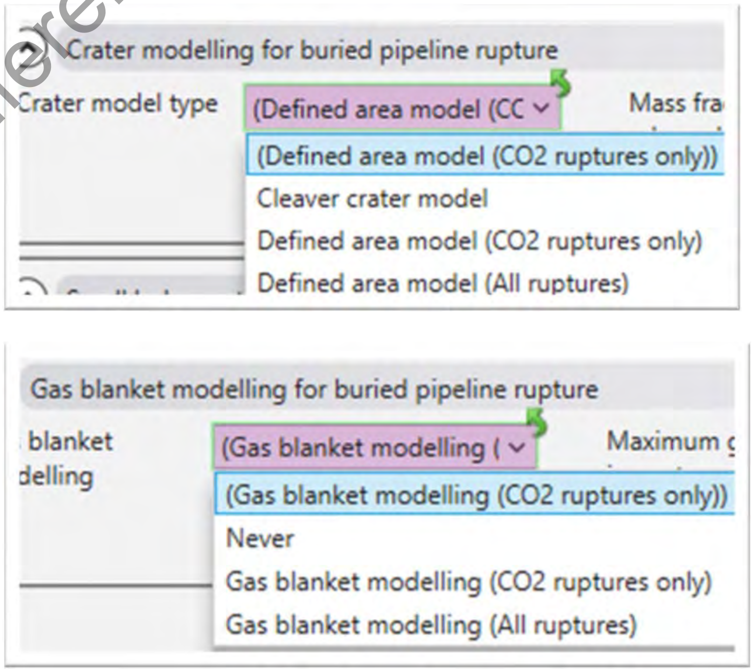
- Requires the initial jet-based plume to touch down at > 45° impact angle
- Represents the release as an instantaneous release
- Fed by a time-varying crater source
- Eventually the instantaneous cloud drifts and uncovers the crater
- Any remaining source treated as normal vertical jet



Gas blanket modelling

Phast v8.9

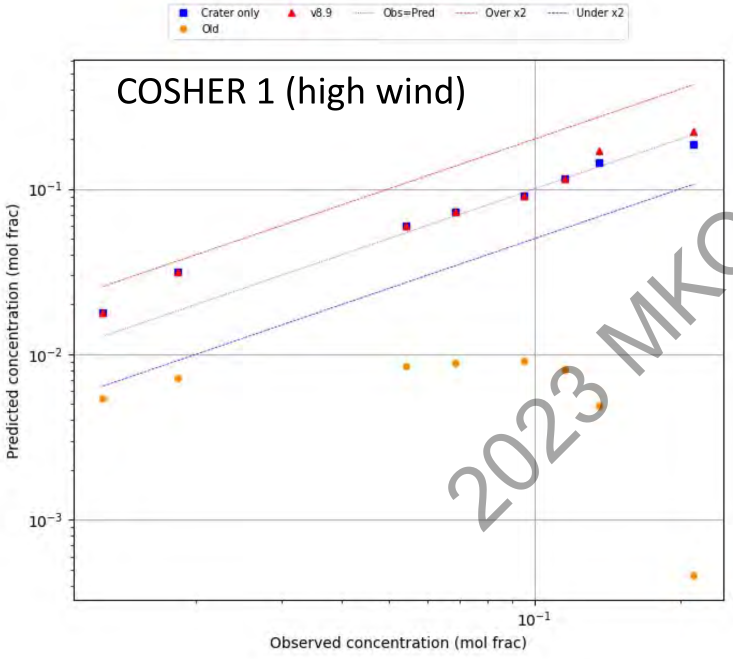
- Separate options for crater modelling and gas blanket modelling
- Options for both…
  - Original (v8.71) models
  - Improved models for pure CO_2 only (default)
  - Improved models for all materials

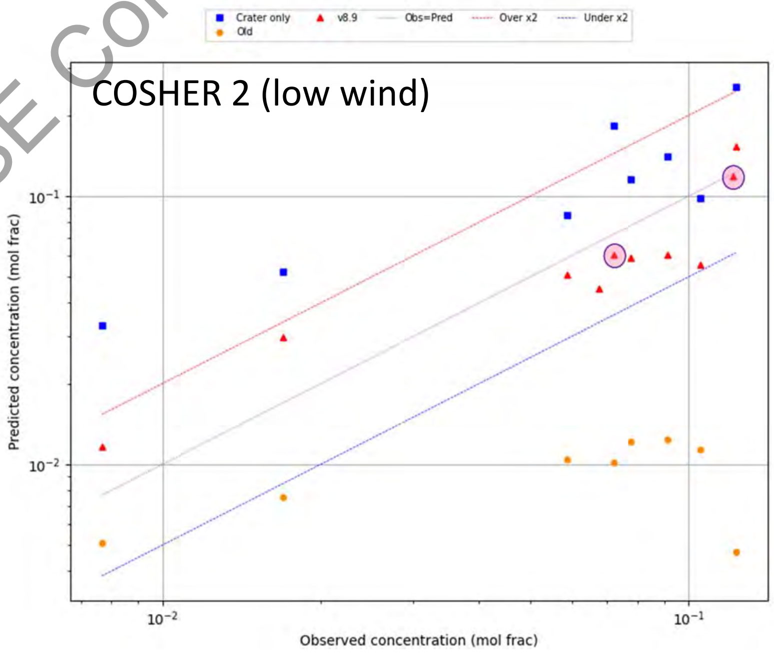


Phast parameters controlling improved modelling

COSHER Validation –8.9 vs .871 models

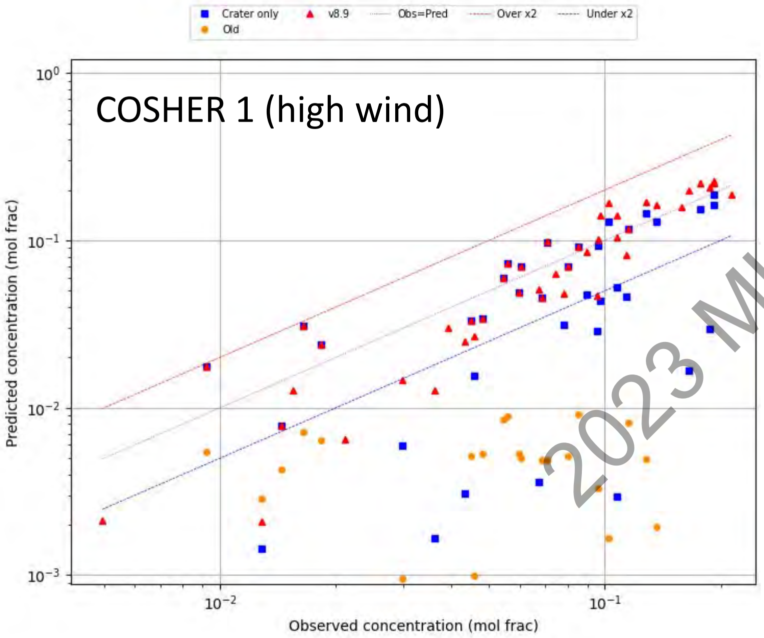
Arcwise maximum concentrations – observed vs predicted

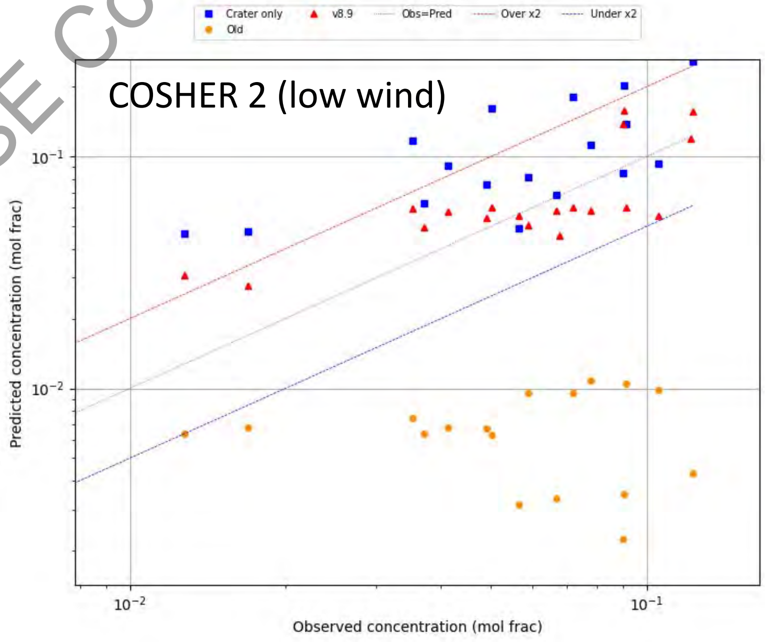




COSHER Validation

Pointwise maximum concentrations – observed vs predicted





COSHER Validation

- Improved crater model alone. Vastly improved downwind ground level concentrations
- With gas blanket model (esp. for low windspeed cases):
  - Additional improvement in downwind concentrations
  - Major improvement in crosswind and upwind concentrations

	COSHER 1	COSHER 2	Overall
Phast 8.71			
MG	12.41	5.94	8.59
VG	>1000	46.41	557
Phast 8.9 (Crater only)			
MG	0.89	0.51	0.67
VG	1.06	1.94	1.43
Phast 8.9			
MG	0.86	1.09	0.98
VG	1.06	1.15	1.11

Geometric mean and variance for arcwise maximum concentrations

Further work and limitations

- Lack of available data suitable for development / validation is a critical issue
- Inability to measure the post-crater cloud makes life difficult
- Do the crater changes make sense for other materials?
- Scalability?
- What about punctures?

Proposed JIP for CO_2 Dispersion

Carbon dioxide pipeline risk assessment

Plans for a programme of CO_2 dispersion experiments and model development

Simon Gant*, Zoe Chaplin, Martin Thomson Health and Safety Executive (HSE), Buxton, UK
Dan Allason, Ann Halford, Karen Warhurst, Mike Acton, Mike Harper, Jan Stene, Gabriele Ferrara, DNV
Jo Miles, Sarah Bragg, Joel Howard, Matthew Turner, DSTL, UK
Matthew Hort, Frances Beckett, Met Office, UK
Tom Spicer, University of Arkansas, USA
Jon Lang, Ed Sullivan, National Chemical Emergency Centre, Ricardo, UK

Carbon Capture and Storage Association (CCSA), Health and Safety Technical Working Group Meeting, London, UK
31 August 2023

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

26th Process Safety International Symposium

Frank Hart

- Mathematical Modeller (DNV) since 2019
- Previously
  - Risk consultant (Risktec Solutions)
  - Software engineer (Tessella, now CapGemini)
  - Research associate (School of Physics, University of Bath)

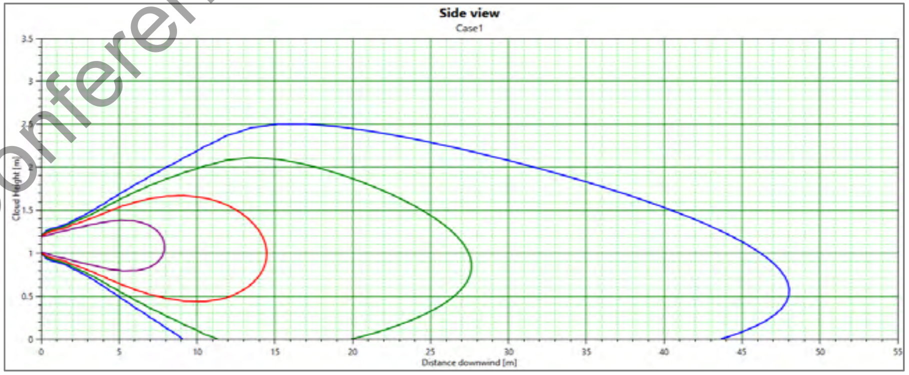
Review and Validation of Phast Dispersion Model required for LNG Siting Applications in the US

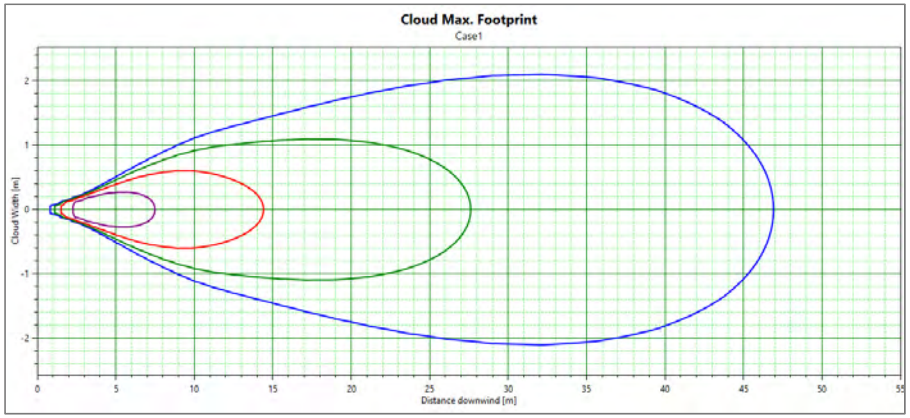
Introduction

- PHMSA require an exclusion zone around LNG facilities
  - Regulation 49 CFR 193
- This to be calculated using 'approved' models.
- Phast 6.7 was approved in 2011
- Model improvements, architectural changes, Phast 6.7 end-of-life argued for an updated approved version
- A petition was submitted to approve Phast 8.4

Phast - UDM

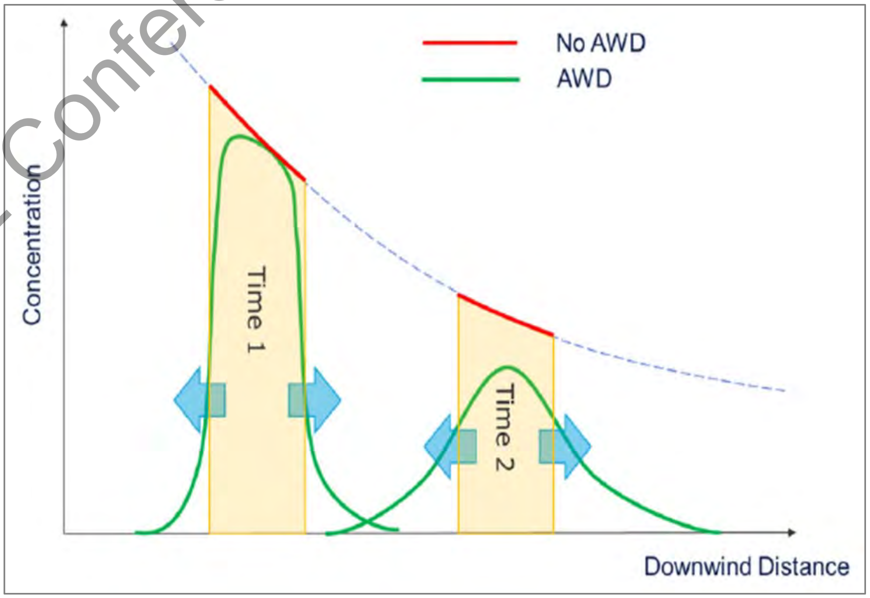
- Integral model comprising linked DAEs
- Combined jet, heavy-gas and passive models
- Imposes similarity concentration profile
- Finite duration, time-varying and instantaneous
- Droplets and rainout





Changes since v6.7

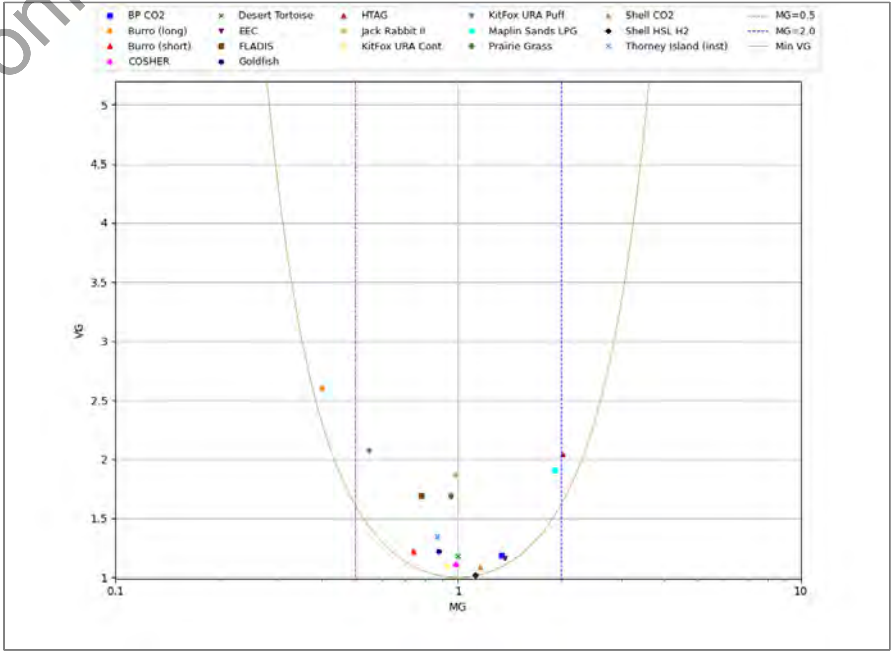
- Many changes including:
  - Pools
  - Cloud-pool linking
  - AWD
  - Instantaneous expansion
  - Improved solver



Existing validation set

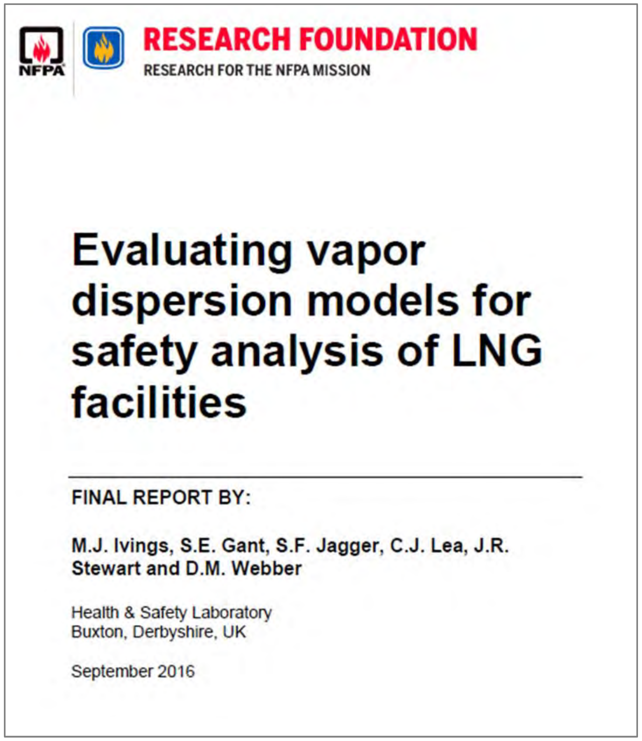
- Extensive validation set with each release
- Includes most PHMSA experiments
- Generally good agreement with experiment
- All available as .psux files on request

Arc-wise concentration



PHMSA Model Evaluation Protocol

- Submission based on 2016 MEP
- Updated experimental database
- 'Change-log' report
  - Scientific Assessment
  - Verification
  - Validation
- External expert reviewer



RESEARCH FOUNDATION
RESEARCH FOR THE NFPA MISSION

Evaluating vapor dispersion models for safety analysis of LNG facilities

FINAL REPORT BY:

M.J. Ivings, S.E. Gant, S.F. Jagger, C.J. Lea, J.R. Stewart and D.M. Webber

Health & Safety Laboratory
Buxton, Derbyshire, UK

September 2016

MEP Changes (since Phast 6.7)

- Method for arc-wise concentrations
  - Maximum prediction at arc sensor locations
- Updated experimental data:
  - Full review of data set
  - Errors corrected
  - Point-wise concentrations added
  - Some post-ignition points removed
- Additional physical & statistical measures

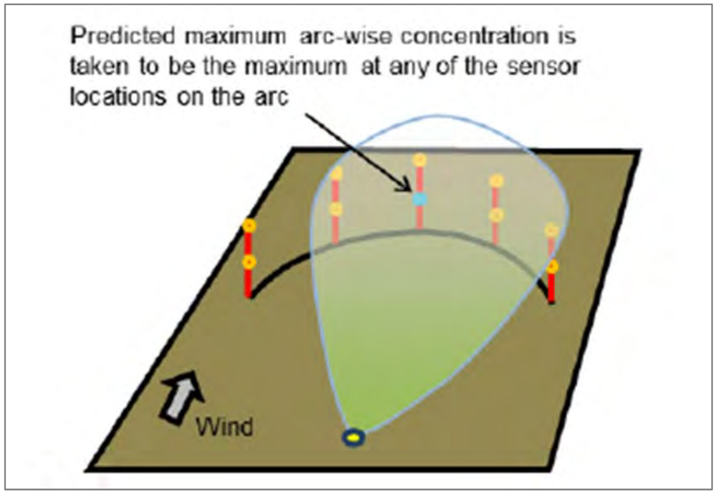


Image: 2016 MEP

Validation Experiments

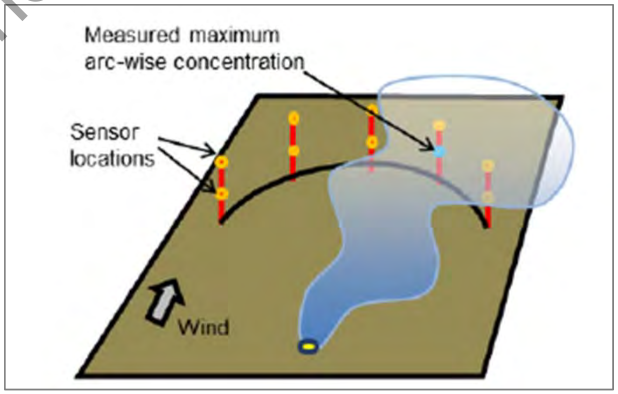
- 17 Experiments
  - No obstructions
  - 12 field experiments
  - 5 wind-tunnel
- Burro & Coyote
  - Short and long time averages
  - Each assessed separately

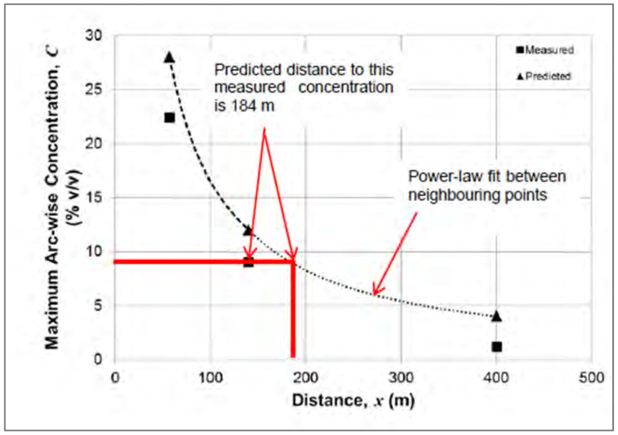
Experiment	Trial	Type	Material	Notes
Maplin Sands	27 34 35	Field	LNG	
Burro	3 7 8 9	Field	LNG	Short and long time averaged concentrations available
Coyote	3 5 6	Field	LNG	Short and long time averaged concentrations available
Thorney Island	45 47	Field	Freon & N_2	
CHRC	A	Wind tunnel	CO_2	
BA-Hamburg	DA0120 DAT223	Wind tunnel	SF_6	
BA-TNO	TUV01 FLS	Wind tunnel	SF_6	

Assessment Results

- 4 physical comparison parameters
  - Maximum arc-wise gas concentration
  - Maximum point-wise gas concentration
  - Distance to measured gas concentration
  - Width (calculated - not presented here)

- 9 statistical performance measures
  - Not all relevant for each parameter

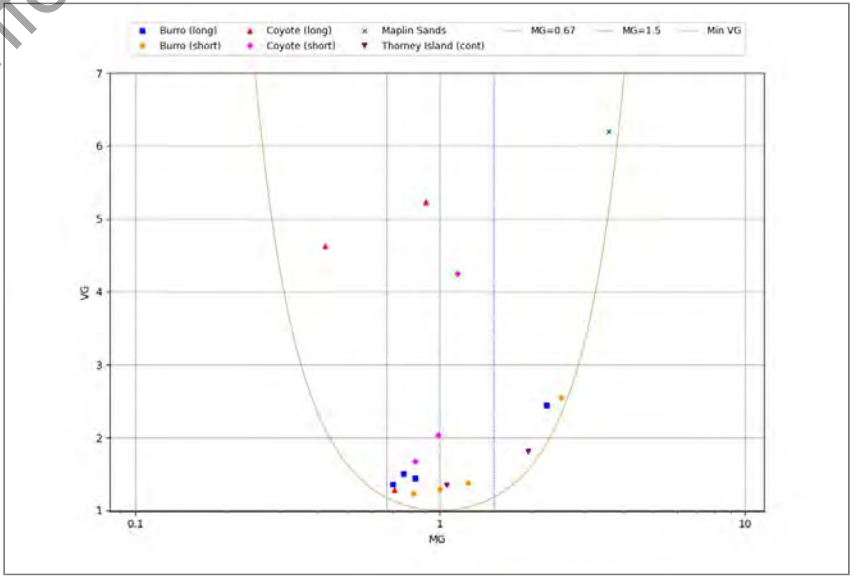




Images: 2016 MEP

Arc-wise Concentration (Field)

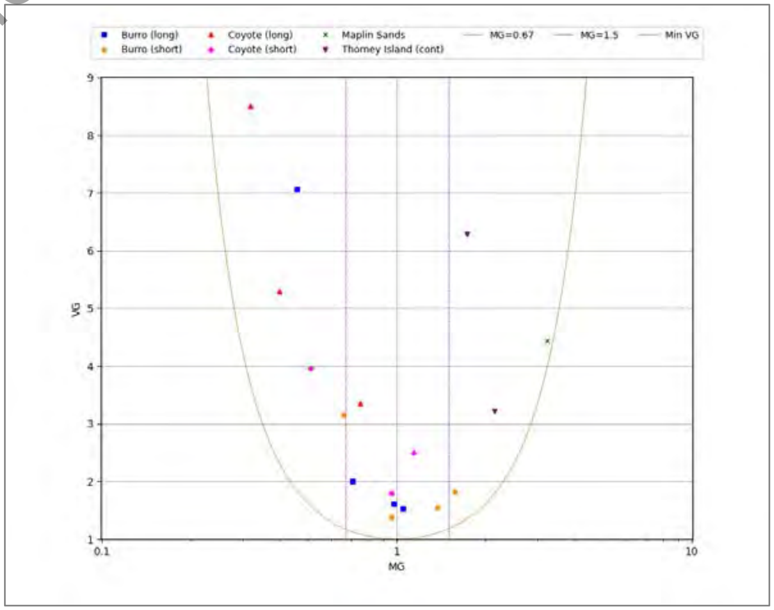
- Most within PHMSA scrutiny range
- Coyote 6 (over), TI45, BU08 (under)
- Maplin Sands high underprediction
  - Consistent feature
  - Return to this shortly



$$MG = exp\left\langle \ln\left(\frac{C_m}{C_p}\right) \right\rangle \qquad VG = exp\left\langle \left[\ln\left(\frac{C_m}{C_p}\right)\right]^2 \right\rangle$$

Point-wise Concentration (Field)

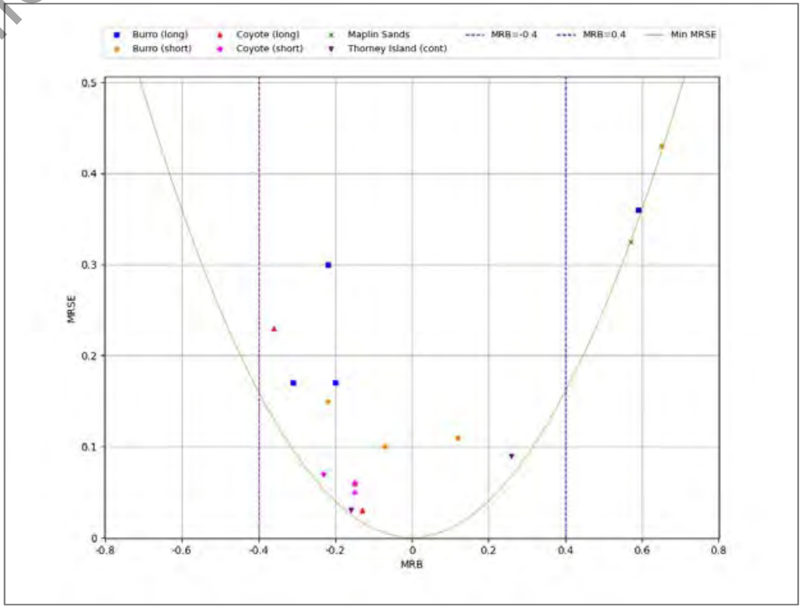
- More scatter
- Burro & Coyote (short) mainly within PHMSA scrutiny range
- Coyote (long) overprediction
- Thorney island underprediction
- Maplin Sands high underprediction



$$MG = exp\left\langle \ln\left(\frac{C_m}{C_p}\right)\right\rangle \qquad VG = exp\left\langle \left[\ln\left(\frac{C_m}{C_p}\right)\right]^2\right\rangle$$

Distance to arc-wise concentration (Field)

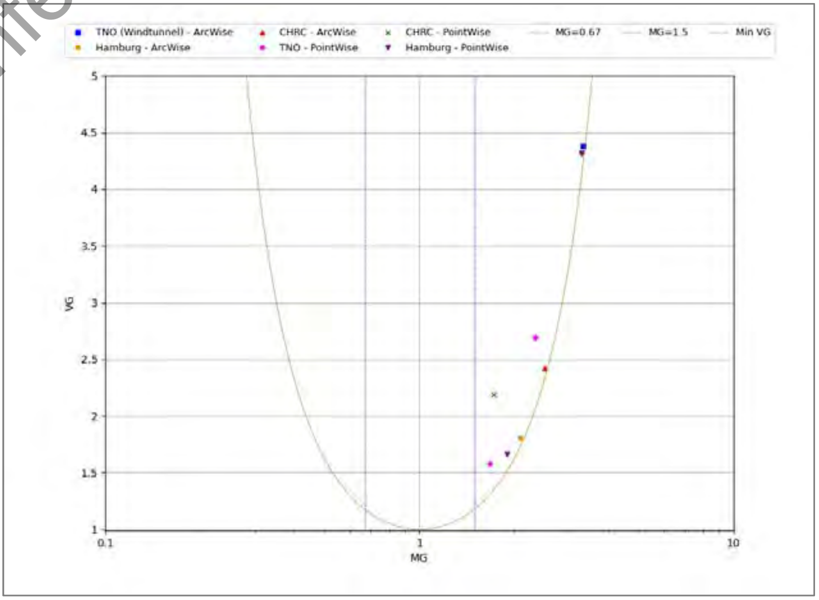
- Largely within PHMSA scrutiny range
- Slight trend to overpredict (MRB < 0)
- Burro 8 underprediction
- Maplin Sands high underprediction



$$MRB = \left\langle \frac{C_m - C_p}{\frac{1}{2}(C_p + C_m)} \right\rangle \qquad MRSE = \left\langle \frac{(C_p - C_m)^2}{\frac{1}{4}(C_p + C_m)^2} \right\rangle$$

Wind-tunnel cases

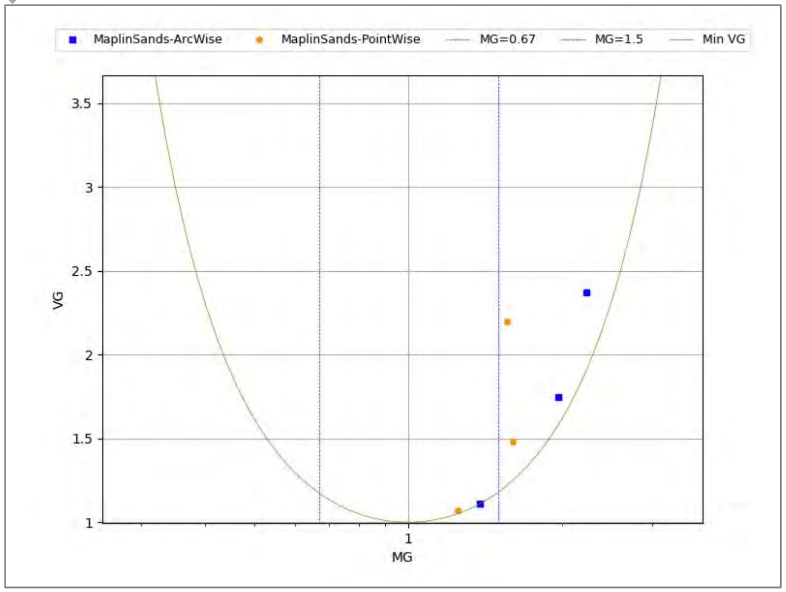
- Consistent underprediction
- Possibly due to field-scaling
  - UDM used field not wind tunnel scale
- Sensitive to roughness
  - Improved alignment with reduced SR
- Improves on Phast 6.7 results



$$MG = exp\left\langle \ln\left(\frac{C_m}{C_p}\right) \right\rangle \qquad VG = exp\left\langle \left[\ln\left(\frac{C_m}{C_p}\right)\right]^2 \right\rangle$$

Uncertainties

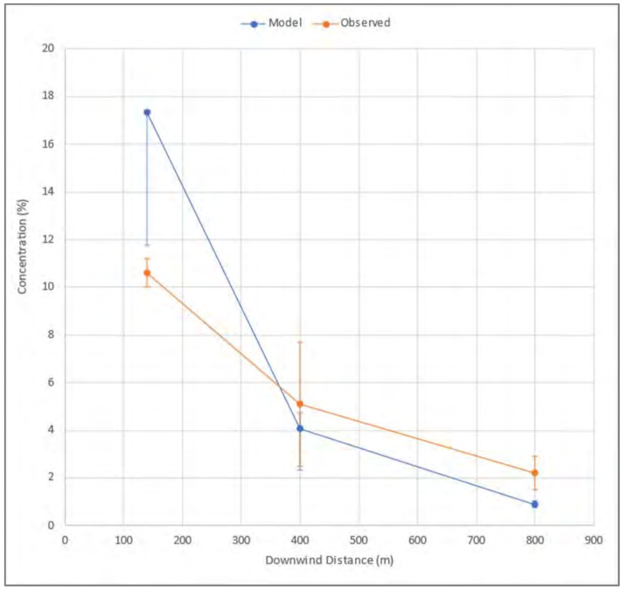
- Maplin Sands
  - Thin clouds, poor spatial resolution
  - Sensitivity - sensors at y=0 (5-10° change)
  - Much improved alignment
- Burro, Coyote
  - Cases with peak concentrations at arc edges
  - Terrain impact & bifurcation in Burro 8



$$MG = exp\left\langle \ln\left(\frac{C_m}{C_p}\right) \right\rangle \qquad VG = exp\left\langle \left[\ln\left(\frac{C_m}{C_p}\right)\right]^2 \right\rangle$$

Sensitivities

- Sensitivity study
  - 7 cases
  - Between 1 and 8 individual parameters
- Some significant variations
  - Burro 9 (long) arc-wise shown
  - High surface roughness at lower bound
  - Different parameters at higher bound
  - Factor >2 between low/high at 400m



Summary

- PHMSA approval process outlined
  - Detailed submission due to >10 years since Phast 6.7
  - More rigorous: 2016 MEP and v12 validation database
  - Validates well, particularly for field trials
  - Uncertainties around Maplin Sands well understood

- Phast 8.4 approved April 2023
  - Identical conditions to Phast 6.7
  - Uncertainty factor of 2 for LFL distances (i.e. use ½ LFL)
  - www.regulations.gov docket PHMSA-2021-0041

Acknowedgements

- Anay Luketa (Sandia National Laboratories)
- Thach Nguyen (PHMSA)

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

26th Process Safety International Symposium

Texas A&M Engineering Experiment Station

Mary Kay O'Connor Process Safety Center

Title: Data-Driven Model for Multiphase Leak Detection Using Dimensional Analysis Technique

List of Content

1 Self Introduction:

Name: Mohammad Azizur Rahman

Designation: Associate Professor (TAMU Qatar)

Research focus:
Multiphase flow, Flow assurance, Cuttings transport, Leak Detection, Gas kick, carbon capture and storage, Geothermal energy, Ionic liquid, reservoir characterization, Statistical Analysis, Machine Learning Application in Oil and Gas Industries, and Aphron-based drilling fluid.

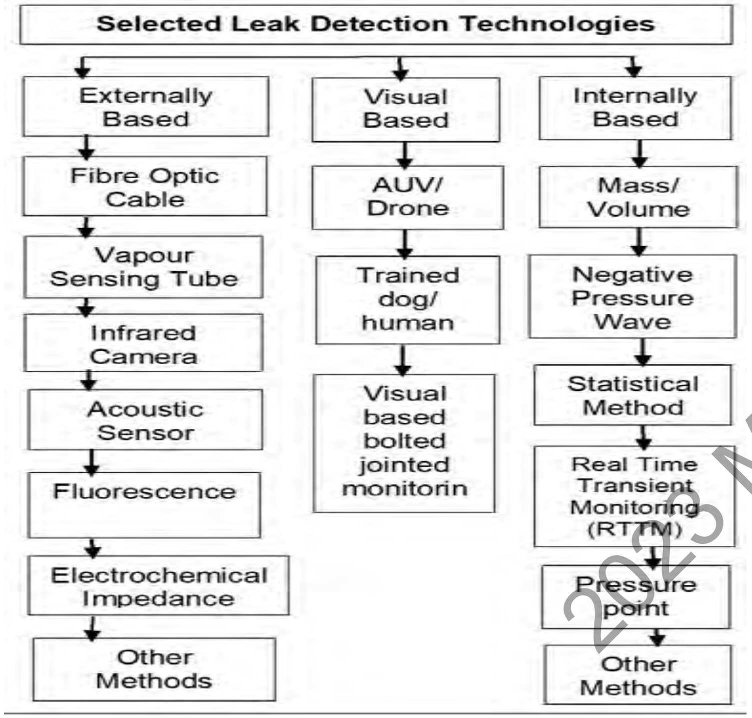
https://scholar.google.com/citations?hl=en&user=PYRtlBIAAAAJ&view_op=list_works&sortby=pubdate

Introduction:

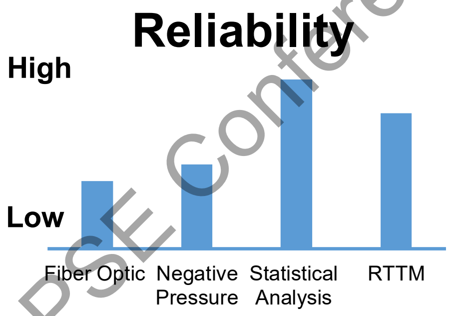
Introduction: Why study leak detection?

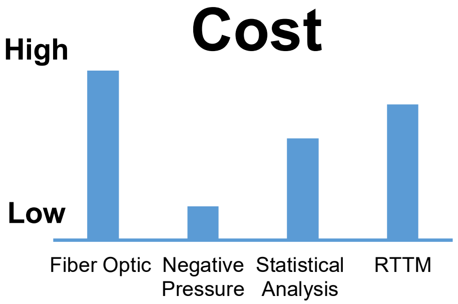
- Leaks may occur in the existing pipelines although designed with quality construction and appropriate regulations.
- Huge economic impact.
- Failure can have an adverse impact on life, the economy, the environment, and corporate reputation.

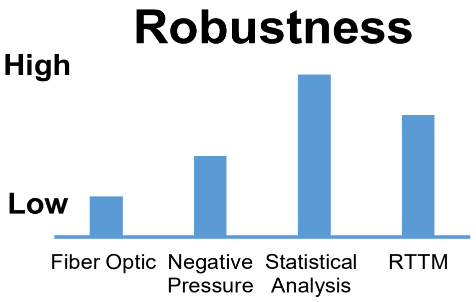
Introduction: Different types of leak detection.



(Adegboye et al., 2019; Zhang et al., 2013)







- In this study we focus on Internally based methods i.e. physics based mechanistic correlation and data-driven non-dimensional correlation.
- These methods generally have high reliability, robustness and lower cost.

Literature review:

List of literature for mechanistic Correlation:

Fluids used	Model used	Leak in terms of	Focus	Key remarks	Reference
Gas-liquid	Beggs and Brill's two phase correlation	Inlet and outlet total flow rate	Subsea pipelines	Higher leak size improves leak detection. Compressible liquid inhibits leak detection.	(Gajbhiye and Kam, 2008)
Gas-Oil	Beggs and Brill's two phase correlation	Change in inlet pressure, change in outlet flow rate	Deepwater operations	Outlet flowrate was more favourable as compared to inlet pressure. Longer distance, larger opening size, and compressible phase are favorable.	(Kam, 2010b)
Liquid	Probabilistic approach	Mass-imbalance	Pipeline	Able to detect leak location and leak size	(Rougier, 2005)
Water	Steady and un-steady state approach.	Pressure	Pressurized pipe system.	Higher pressure improves leak detection in a steady state as compared to an un-steady state condition.	(Ferrante et al., 2014)
Two-phase flow	Combination of numerical and analytical approach.	Pressure, Heat transfer	Wellbore	Deviated wells loses more heat to the formation as compared to the vertical wells because of higher residence time.	(Hasan et al., 1998)
Natural Gas	New mathematical model using a multi-rate test.	Flow rate and Pressure	Pipeline	Two leaks in a pipeline is detected instead of one leak.	(Rui et al., 2017)

Literature gap:

- The number of mechanistic correlations available for multiphase flow is still very limited.
- Most of the correlations (e.g. Kam 2010, Gajbhiye et al. 2008) assumes that me know leak parameters. However, in actual conditions most of the times we do not have sensors at the leak locations.
- Multiphase correlations are complex and time taking.

List of literature for Dimensional Analysis (DA):

Fluids used	Flow geometry	Key remarks	Reference
Gas-liquid	Pipe flow	A model was proposed to scale up or scale down pressue drop and liquid hold up based on DA	(Al-Sarkhi et al., 2016)
Gas-liquid	Stratified pipe flow	DA helped to scale up lab scale result to large scale facility.	(Farokhpoor et al., 2020)
Solid-liquid	Annulus pipe flow	Non-dimensional correlation for pressure drop was developed for a wide range of operating parameters and validated with independent literature data.	(Barooah et al., 2022)
Solid-liquid	Annulus pipe flow	Non-dimensional correlation was validated with literature data and used to predict volume fraction during cuttings transport.	(Khaled et al., 2021)

Key notes:

- DA has been used successfully in multiphase flow to predict and scale up lab scale data to larger scale.
- DA usually consist of simpler calculations which can be done without numerical analysis.
- Use of DA for leak detection in pipeline cannot be found in literature.

Objective:

Objective:

- Develop a physics-based mechanistic model for pipeline leak detection.
- Perform Dimensional Analysis to develop a non-dimensional model using the validated data points from the mechanistic model.
- Validate the non-dimensional model with independent literature data.

Methodology for model development:

Development of mechanistic Correlation:

Material balance equations:

$$m_{tin} = m_{tleak} + m_{tout}$$

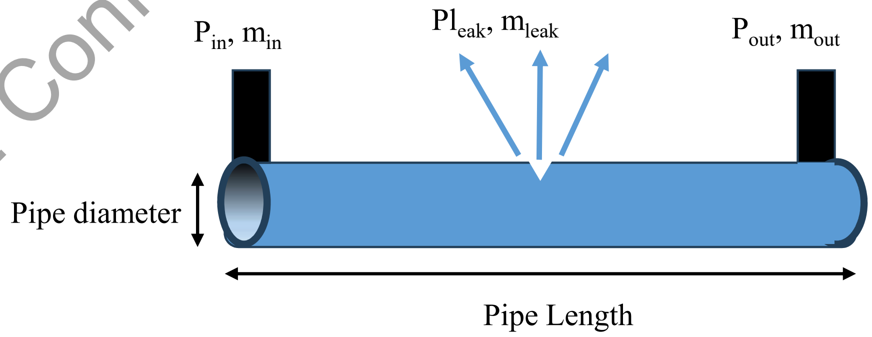
$$m_{gin} = m_{gleak} + m_{gout}$$

$$m_{Lin} = m_{Lleak} + m_{Lout}$$

$$f_{gin} = \frac{q_{gin}}{q_{tin}} = \frac{q_{gin}}{q_{gin} + q_{Lin}} = 1 - f_{Lin}$$

$$f_{gout} = \frac{q_{gout}}{q_{tout}} = \frac{q_{gout}}{q_{gout} + q_{Lout}} = 1 - f_{Lout}$$

$$f_{gout} = 1 - f_{Lout}$$



Where q is the volume flow rate, m is the mass flow rate, f is the fraction of gas, and t, g, L, in, out and Leak are the subscripts for total, gas, liquid, inlet, outlet, and leak.

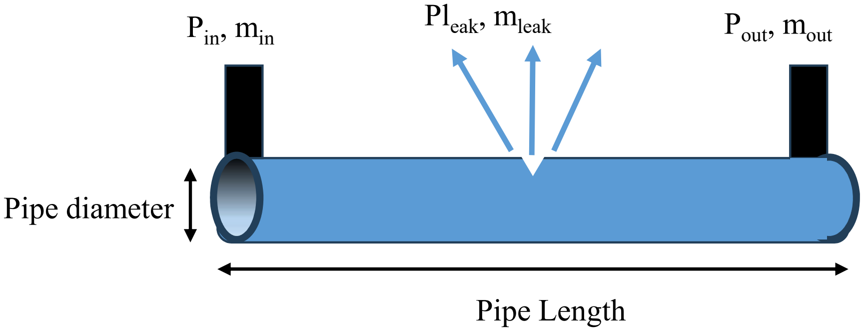
Development of mechanistic Correlation:

Pressure at any node is determined by:

$$\mathrm{P}^{\mathrm{i}+1} = \mathrm{P}^{\mathrm{i}} + \left(\frac{dP}{dx}\right)\Delta L$$

A leak which is regarded as a sink term can be described as the fluid loss due to the difference between the pressures inside and outside the pipe at the leak.

$$\mathrm{P}_{\mathrm{leak}} - \mathrm{P}_{\mathrm{sur}} = \frac{\rho_m \, q_{tLeak}^2}{C_d^2 \left(\frac{\pi d_{Leak}^2}{4}\right)^2}$$



Where,

A_{Leak} = cross-sectional area of leak opening
d_{Leak} = leak equivalent diameter
ρ_m = mixture density at that point
C_d = Leak coefficient

$\rho_m = \rho_g f_g + \rho_L f_L$

New methodology for the leak detection correlation

Pressure drop is calculated using the Beggs and brill model:

$$\frac{dP}{dx} = \frac{f_{tp}\rho_m\,(q_t/A)\,(q_t/A)^2}{gD}$$

Where f_{tp} is the friction factor during two-phase flow which is expressed as:

$$f_{tp} = f_n\left(\frac{f_{tp}}{f_n}\right)$$

$$\frac{f_{tp}}{f_n} = 2.2\left(\frac{f_L}{y_L^2}\right) - 1.2 \text{ if } 1 < \left(\frac{f_L}{y_L^2}\right) < 1.2$$

Otherwise,

$$\frac{f_{tp}}{f_n} = \exp\left[\frac{\ln\left(\frac{f_L}{y_L^2}\right)}{-0.0523 + 3.182\ln\left(\frac{f_L}{y_L^2}\right) - 0.8725\ln\left(\frac{f_L}{y_L^2}\right)^2 + 0.01853\ln\left(\frac{f_L}{y_L^2}\right)^4}\right]$$

Advantage:

- Most commonly used correlation for horizontal flow and circular pipe.
- Identifies the flow regime and liquid hold up, which helps to calculate the mixture velocity and density.
- Can be corrected for different inclination.
- Performs better for horizontal flow as compared to Hagedorn and Brown, Duns and Ros, Fancher and Brown, etc.
- Used in many commercial softwares such as Pipesim.

New methodology for the leak detection correlation

f_n is the fanning friction factor which is found by the Colebrook eq.

$$\frac{1}{\sqrt{f_n}} = -4\log[\frac{-5.0452.}{N_{re}}\log\left(\frac{7.149}{N_{re}}\right)^{0.8981}]$$

N_{re} is the Reynolds number, which is defined as:

$$N_{re} = (\frac{\left(\frac{qt}{A}\right)\rho_m D}{\mu_L f_L + \mu_g f_g})$$

μ_L and μ_g are the liquid and gas viscosities.

The liquid hold up for distributed flow is given by:

$$y = a(\frac{f_L^b}{N_{re}^c})$$

$$P_{leak} - P_{sur} = \frac{\rho_m\, q_{tLeak}^2}{C_d^2 \left(\frac{\pi d_{Leak}^2}{4}\right)^2}$$

As we have three unknowns (i.e., ρ_m, qt, d_{Leak}^2) and only two eq. (Leak eq. and Beggs and brill correlation) , therefore an iterative process is required to solve.

Methodology for leak detection

Steps:

- First, an initial value of total leak flow rate (q_{tleak}) is assumed, and leak pressure (P_{leak}) is calculated for different values of d_{leak}.

- Subsequently, an iterative method is employed to determine total flow rate at the pipe inlet (q_{tin}) in the upstream section, ensuring the desired value of inlet pressure P_{in} is achieved.

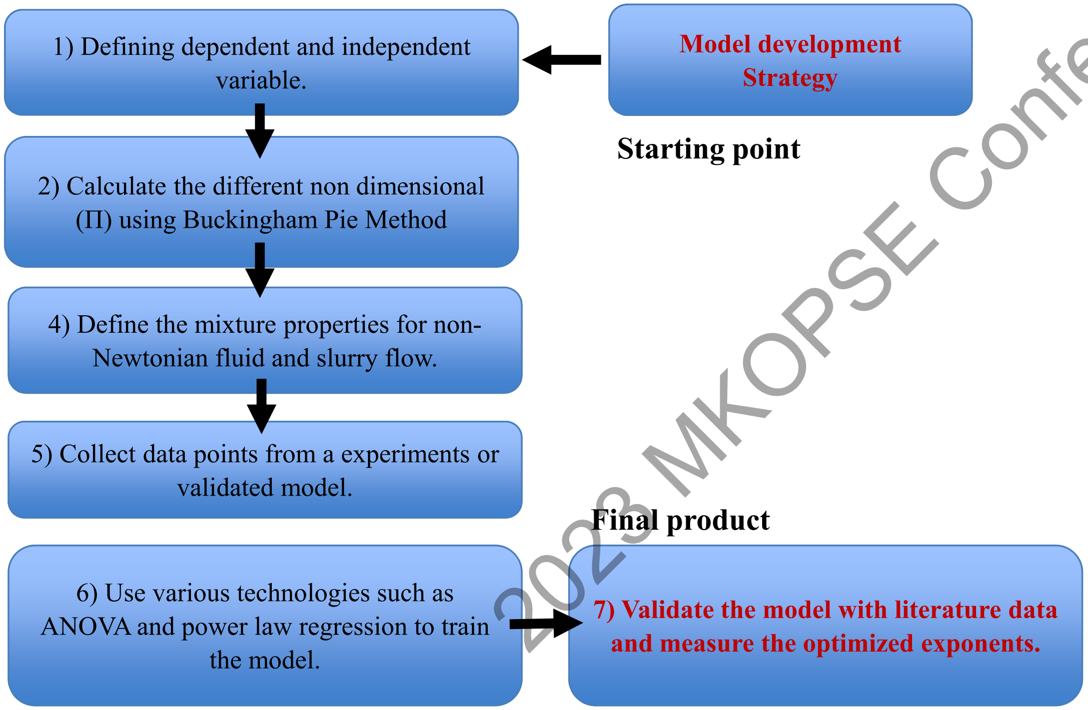
- Next, using another iterative method, total flow rate at the outlet q_{tout} is calculated for the downstream section while maintaining the desired constraint on outlet pressure P_{out}.

- As changing q_{tout} impacts q_{tleak} and thereby P_{leak}, the process iterates once again to find a new value of q_{tin} that maintains the desired $P_{in.}$

- This iterative process continues until optimized values of q_{tin}, q_{tout}, and q_{tleak} are obtained. During the entire process it needs to be ensured that the mass balance and pressure constraints are conserved.

This is be done either by developing macros in excel or in MATLAB

Methodology: Dimensional Analysis



Model development Strategy

Starting point

1) Defining dependent and independent variable.

2) Calculate the different non dimensional (Π) using Buckingham Pie Method

4) Define the mixture properties for non-Newtonian fluid and slurry flow.

5) Collect data points from a experiments or validated model.

6) Use various technologies such as ANOVA and power law regression to train the model.

Final product

7) Validate the model with literature data and measure the optimized exponents.

Flowline of the model development strategy

Advantage

1. It gives us insight into what parameters could be ignored or treated approximately.
2. Upscale our correlations by testing it with a larger experimental data set which can be translated to different lab scale and field scale.
3. Develop non-dimensional flow regime map based on the non-dimensional numbers and surface operating conditions.

Methodology: Dimensional Analysis

Buckingham-Pi Theorem

1. Total n parameters can be grouped into n-m independent π groups expressed as: $\Pi_1 = f(\Pi_2, \Pi_3, \ldots \Pi_{n-m})$
    1. n = Total number of dependent and independent variables
    2. m = Minimum number dimensions required to characterize all the n parameters

Defining dependent and independent variable

- **Dependent variable**
    - Leak Pressure or
    - Leak flow rate or
    - Leak location
- **Independent Variable**
    - 1) Mixture viscosity
    - 2) Mixture density difference
    - 2) Pipe length
    - 3) Leak diameter
    - 4) Pipe diameter
    - 5) Change in total mass flow rate

Buckingham-Pi Theorem Methodology

Defining dependent and independent variable

Parameter	**Symbol**	**Unit**	**Dimension**
Mixture viscosity	(μ_m)	Kg/ms	M/LT
Mixture density difference	$\Delta\rho_m$	Kg/m^3	M/L^3
Pipe length	L	m	L
Leak diameter	d_{leak}	m	L
Pipe diameter	D	m	L
Change in total mass flow rate	Δm	Kg/s	M/T
Leak pressure	P_{leak}	Pa	M/LT^2

(Busch et. al 2019)

6. Buckingham-Pi Theorem Methodology

Methodology: Dimensional Analysis

Defining dependent and independent variable

- Set of fundamental dimensions are selected: [M, L, T] = 3
- Total number of parameters = n = 7
- Repeated parameters = R = 3
  - Pipe diameter
  - Change in mixture density
  - Change in mass flow rate
- By Applying Buckingham pi theorem
  Non dimensionless number = 7-3=4

Buckingham-Pi Theorem Methodology

Methodology: Dimensional Analysis

Calculate the different non dimensional Π terms

- $\Pi_2 = \frac{\mu_m D}{\Delta m} \frac{\rho_{inlet}}{\rho_{outlet}}$
- $\Pi_3 = \frac{L}{D}$
- $\Pi_4 = \frac{d_m}{D}$
- $\Pi_1 = \frac{P_{leak} D^5 \Delta\rho_m}{\Delta m^2}$

General Form:

$$\boldsymbol{\Pi_1 = a1\, \Pi_2^{a2} \Pi_3^{a3} \Pi_4^{a4}}$$

Input parameters	**Output parameter**
Pipe Diameter (m)	Leak pressure (Pa)
Leak diameter (m)	
Liquid volume fraction at inlet, cLi	
Liquid volume fraction at outlet, cLO	
Change in total inlet and outlet mass flow rate (%)	

The values of the different exponents have to be calculated by experimental fit or regression method.

Results and Discussion:

Results and Discussion: Statistical Analysis

Range of parameters for model development

Operating parameters	Range (field units)	SI units
Pipe Diameter, D (inch)	1 inch to 5 inch	0.0762 - 0.172 m
leak diameter, dm (inch)	0.2 inch to 3 inch	0.0127 - 0.0762 m
Liquid outlet fraction, cL	0.3 – 0.628	
Pipe length (feet)	2000 – 10000 feet	600 – 6500 m
Mixture viscosity	0.1126 – 0.0017 cP	1.227×10^{-4} - 1.7×10^{-6} PaS
Mixture density (kg/m3)	295 – 560 kg/m3	18.4162 – 34.95 lb/ft^3
Leak location (m)	91 – 460 m	91 – 460 m
Inlet total mass flow rate (kg/s)	14 – 28 kg/s	31 – 62 lb/s
Outlet total mass flow rate (kg/s)	3 – 10 kg/s	6.6 - 22

Only the inlet and outlet parameters are selected that effect the leak pressure.

$$\mathrm{P_{leak}} - \mathrm{P_{sur}} = \frac{\rho_m \, q_{tLeak}^2}{C_d^2 \left(\frac{\pi d_{Leak}}{4}\right)^2}$$

Results and Discussion: Statistical Analysis

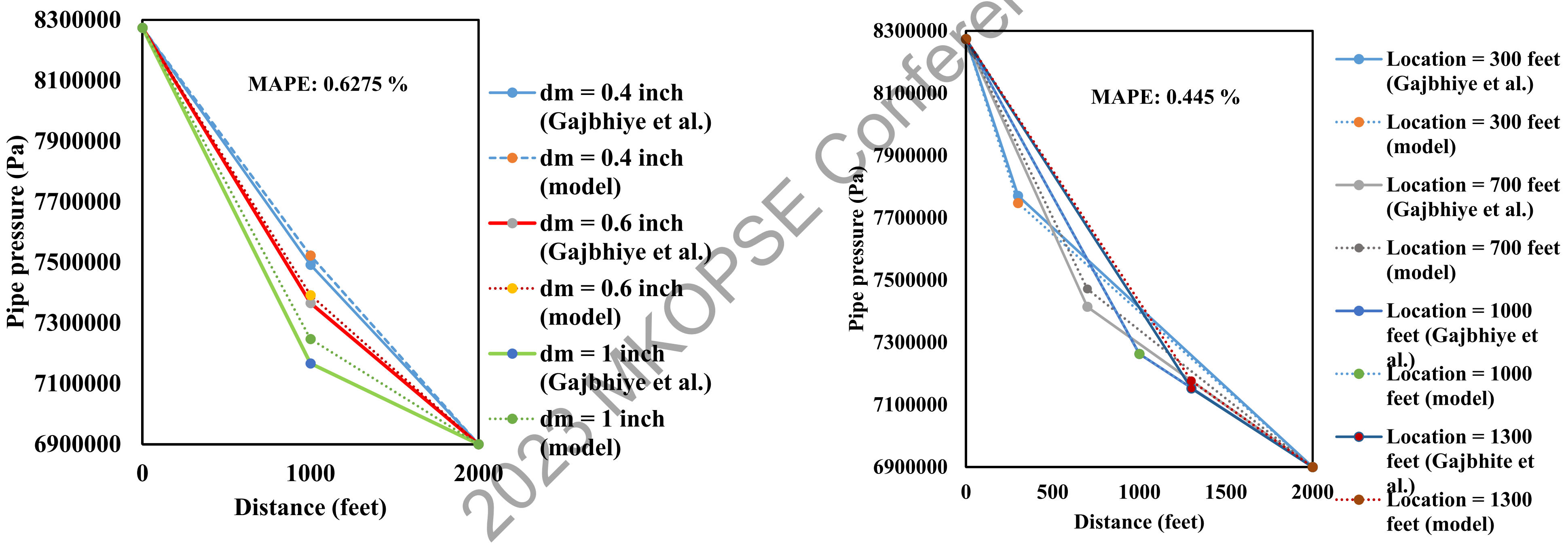
Correlation analysis

	Mixture viscosity	Mixture density (outlet)	Mixture density (inlet)	Pipe Length	Pipe Diameter, D	leak diameter	cLi	cLo	change in mass flow rate
Mixture viscosity	1								
Mixture density (outlet)	-0.312	1							
Mixture density (inlet)	4.167E-15	8.28E-15	1						
Pipe Length (feet)	0.198	0.279	0	1					
Pipe Diameter, D (inch)	0.1490	0.209	6.03E-16	-0.133	1				
leak diameter, dm (inch)	0.410	-0.184	3.81E-15	-0.366	0.572	1			
cLi	3.43E-15	8.18E-15	1	0	7.021E-17	3.15E-15	1		
cLo	-0.312	1	1.78E-15	0.279	0.209	-0.184	1.24E-15	1	
change in mass flow rate	-0.312	0.571	7.76E-16	0.474	-0.377	-0.480	6.59E-16	0.571	1

cLin and cLout is dependent on the inlet and outlet mixture density, therefore these parameters can be excluded

The ANOVA analysis shows that the input parameters are statistically significant and the correlation analysis suggest that the input parameters are statistically independent.

Results and Discussion: Validation of mechanistic model

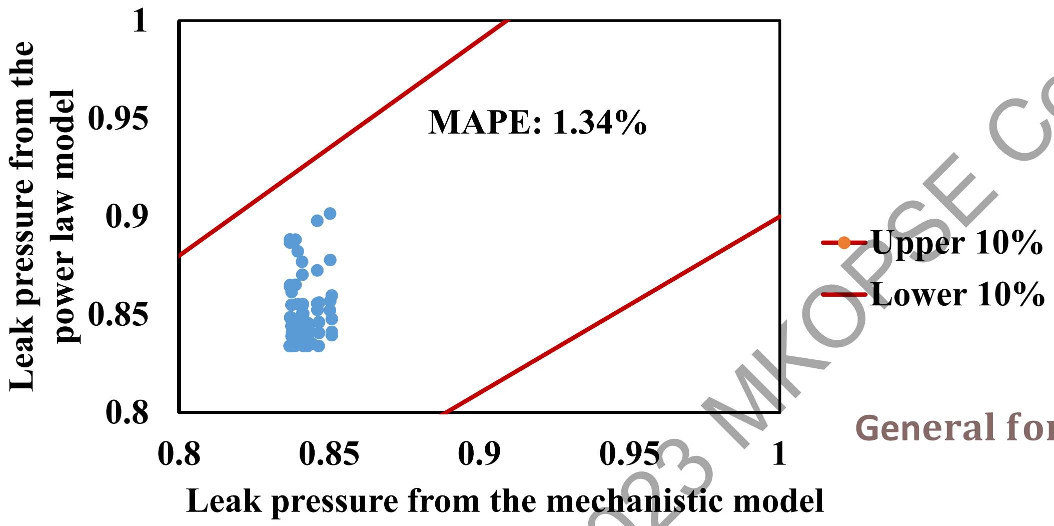


Validation for effect of pipe pressure

Validation for effect of leak location

Validation of mechanistic model for pipe pressure

Results and Discussion: Training and Optimization of non-dimensional model with mechanistic model



General form: $\Pi_1 = a\, \Pi_2^b \Pi_3^c \Pi_4^d$

Model optimization is showing a good agreement with Mechanistic model with a MAPE of 1.34%.

Optimized Exponents	
a1	37.9228
a2	1.152
a3	1.732
a4	-0.354

Non-dimensional parameters

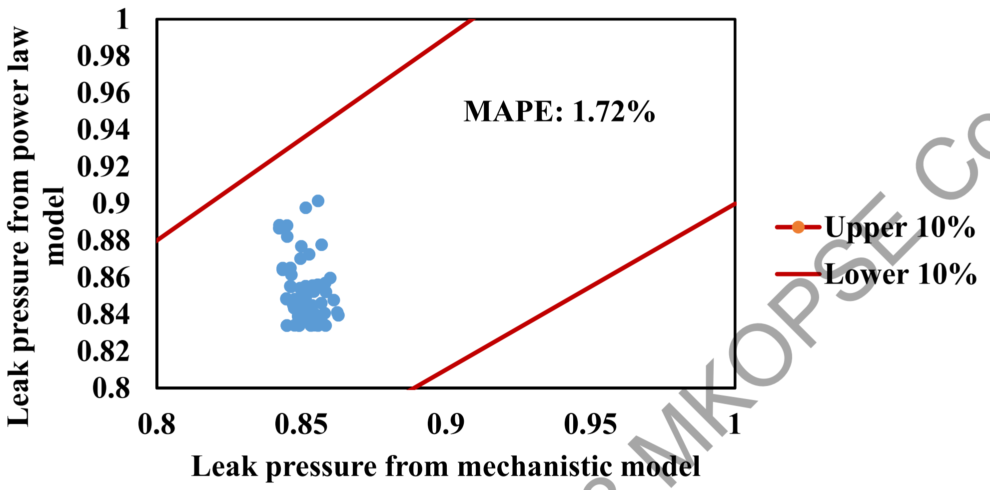
$$\Pi_1 = \frac{P_{leak}}{P_i - P_0}$$

$$\Pi_2 = \frac{\mu_m D}{\Delta m} \frac{\rho_{inlet}}{\rho_{outlet}}$$

$$\Pi_3 = \frac{L}{D}$$

$$\Pi_4 = \frac{d_m}{D}$$

Results and Discussion: Validation of the non-dimensional model.



Validation of leak pressure of the power law model with Gajbhiye et al. 2008

Final form of the non-dimensional correlation:

$$\frac{P_{leak}}{P_i - P_0} = 37.922\left(\frac{\mu_m D}{m_t}\,\frac{\rho_{inlet}}{\rho_{outlet}}\right)^{1.152} \mathrm{X}\ \frac{L}{D}^{1.732} \ \mathrm{X}\ \frac{d_m}{D}^{-0.354}$$

Conclusion:

- This study Introduced an innovative mechanistic model for multiphase flow pipeline leak detection that achieved excellent predictability with a MAPE of only 0.63% through validation against independent literature data.
- A non-dimensional model was developed with impressive validation, MAPE of 1.34% and 1.72% with the mechanistic model and literature data.
- The non-dimensional model is particularly valuable for lengthy pipelines where dedicated sensors at leak locations are often lacking.
- This model offers user-friendly, real-time applicability during daily operations, in contrast to complex and time-consuming models.

Future work:

- It should be noted that the accuracy of the developed model can decrease when the range of operating parameters is too much out of the range provided in Table 3.
- Furthermore, it was identified that the accuracy of the model reduces a little when the leak location is more than 10,000 feet from the inlet section.
- Therefore, in future work, we plan to collect data points from a wide variety of experimental, modelling, and independent literature to train and validate the non-dimensional model.

Nomenclature:

m	Mass flow rate
f	Volume fraction
q	Volume flow rate
P	Pressure
dP	Pressure difference
ΔL	Length increment
ρ	Density
C_d	Leak coefficient
A	Cross-sectional area
D	Diameter
D	Pipe diameter
L	Pipe length
cL	Volume fraction of liquid
μ	Viscosity
$\Delta\rho$	Density difference between the inlet and outlet section
Δm	Change in mass flow rate between the inlet and outlet section
μ	Viscosity
Π	Non-dimensional parameter

Subscripts

t	Total
g	Gas
L	Liquid
in	Inlet
out	Outlet
leak	Leak
sur	Surrounding
m	Mixture

Relevant References:

Ahn, B., Kim, J., & Choi, B. (2019). Artificial intelligence-based machine learning considering flow and temperature of the pipeline for leak early detection using acoustic emission. *Engineering Fracture Mechanics*, *210*, 381–392.

Al-Sarkhi, A., Duc, V., Sarica, C., & Pereryra, E. (2016). Upscaling modeling using dimensional analysis in gas–liquid annular and stratified flows. *Journal of Petroleum Science and Engineering*, *137*, 240–249.

Barooah, A., Khan, M. S., Khaled, M. S., Manikonda, K., Rahman, M. A., Hassan, I., Hasan, R., Maheshwari, P., & Hascakir, B. (2022). Development of pressure gradient correlation for slurry flow using dimensional analysis. *Journal of Natural Gas Science and Engineering*, *104*(April), 104660. https://doi.org/10.1016/j.jngse.2022.104660.

Buckingham, E. (1914). On physically similar systems; illustrations of the use of dimensional equations. *Physical Review*, *4*(4), 345.

Busch, A., Islam, A., Martins, D., & Engie, E. (2016). Cuttings Transport Modeling - Part 1 : Specification of Benchmark. *SPE Drilling & Completion*, *33*(02), 1–32.

Busch, A., Werner, B., Johansen, S. T., & Industry, S. (2020). *Cuttings Transport Modeling — Part 2 : Dimensional Analysis and Scaling*. *March*, 69–87.

Economides, M. J., Hill, A. D., & Ehlig-Economides, C. (1994). Petroleum Production Systems; PTR Prentice Hall Inc. *Englewood Cliffs, NJ*.

Farokhpoor, R., Liu, L., Langsholt, M., Hald, K., Amundsen, J., & Lawrence, C. (2020). Dimensional analysis and scaling in two-phase gas–liquid stratified pipe flow–Methodology evaluation. *International Journal of Multiphase Flow*, *122*. https://doi.org/10.1016/j.ijmultiphaseflow.2019.103139

Relevant References:

Gajbhiye, R. N., & Kam, S. I. (2008a). Leak detection in subsea pipeline: a mechanistic modeling approach with fixed pressure boundaries. *Offshore Technology Conference*.

Hasan, A. R., Kabir, C. S., & Wang, X. (1998). Wellbore two-phase flow and heat transfer during transient testing. *SPE Journal*, *3*(02), 174–180.

Kam, S. I. (2010a). Mechanistic modeling of pipeline leak detection at fixed inlet rate. *Journal of Petroleum Science and Engineering*, *70*(3–4), 145–156.

Khaled, M. S., Khan, M. S., Ferroudji, H., Barooah, A., Rahman, M. A., Hassan, I., & Hasan, A. R. (2021). Dimensionless data-driven model for optimizing hole cleaning efficiency in daily drilling operations. *Journal of Natural Gas Science and Engineering*, *96*(October), 104315. https://doi.org/10.1016/j.jngse.2021.104315.

Rougier, J. (2005). Probabilistic leak detection in pipelines using the mass imbalance approach. *Journal of Hydraulic Research*, *43*(5), 556–566.

Rui, Z., Han, G., Zhang, H., Wang, S., Pu, H., & Ling, K. (2017). A new model to evaluate two leak points in a gas pipeline. *Journal of Natural Gas Science and Engineering*, *46*, 491–497.

THANK YOU

مؤسسة قطر
Qatar Foundation

TEXAS A&M
UNIVERSITY at QATAR

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

78th Annual Instrumentation and Automation Symposium

Safety and Security Impact of Emerging Technologies

How standards address the needs of owner operators

Speaker profile

- Howard Elton
  - BSChE University of Houston
  - Process Control, Automation, SIS, Instrument Systems, across a broad range of industries and process technologies (as an end user)
  - Now consulting with ProLytX as a Principal Technical Consultant for Functional Safety.

ProLytX
ENGINEERING IT

Dominant Themes in Industrial Control

- Wireless Everything
- "Levels" Are History - No More Purdue Models
- More Data from Everything – Right Now, and..
- Data Must Flow Freely In Every Direction - Everything Open And Common
- More Data From The SIS
- Ethernet Only – no proprietary networks
- Smart Everything – People??

Objectives of this Presentation

- Describe the nature of these emerging technologies
- Unpack the issues, challenges, and opportunities
- How Standards/Committees are addressing these issues

Emerging Technologies in Industrial Controls

ethernet-apl™
advanced physical layer

ISA International Society of Automation

FIELDCOMM GROUP™
Connecting the World of Process Automation

ODVA

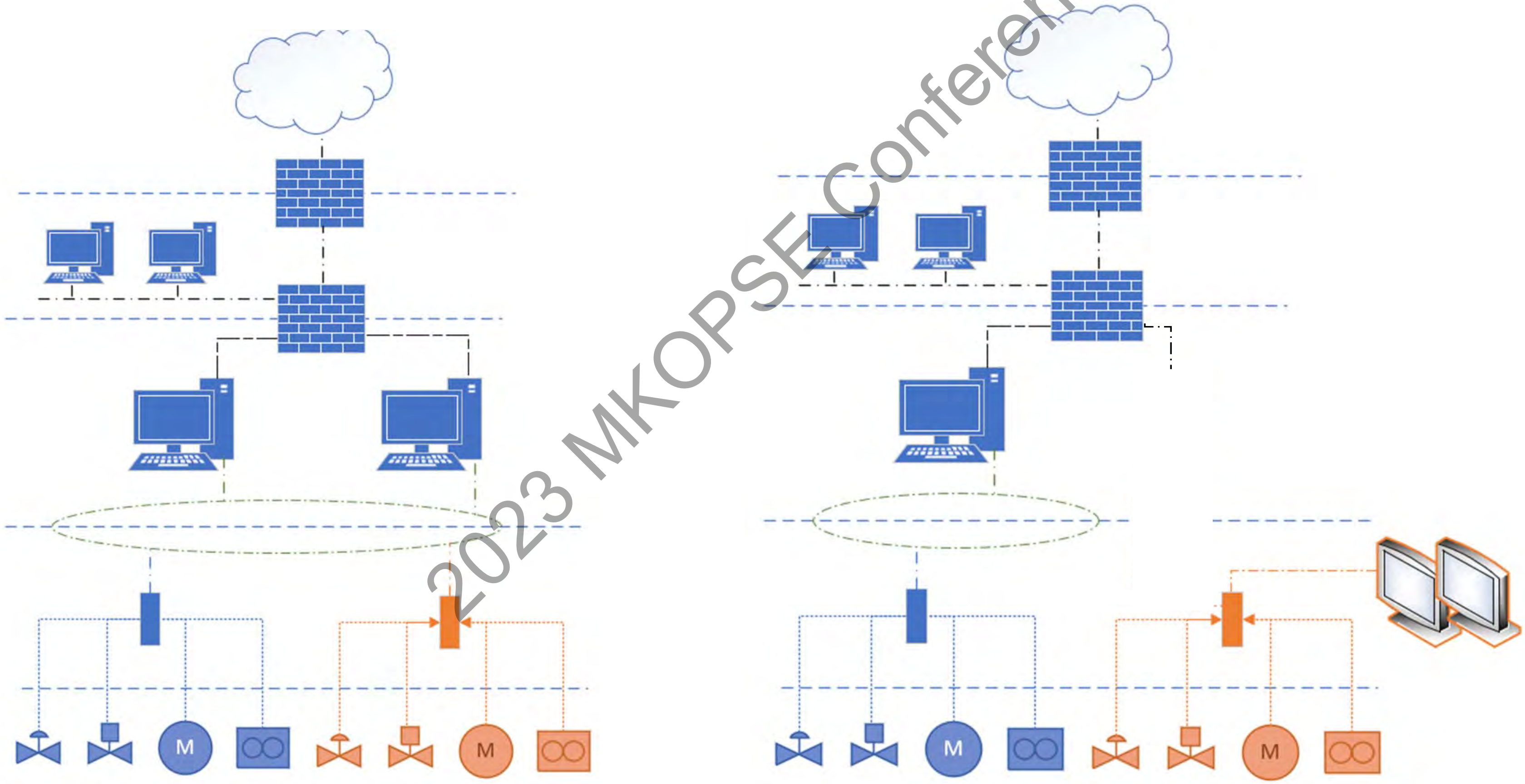
THE OPEN GROUP
OPEN PROCESS AUTOMATION™
FORUM

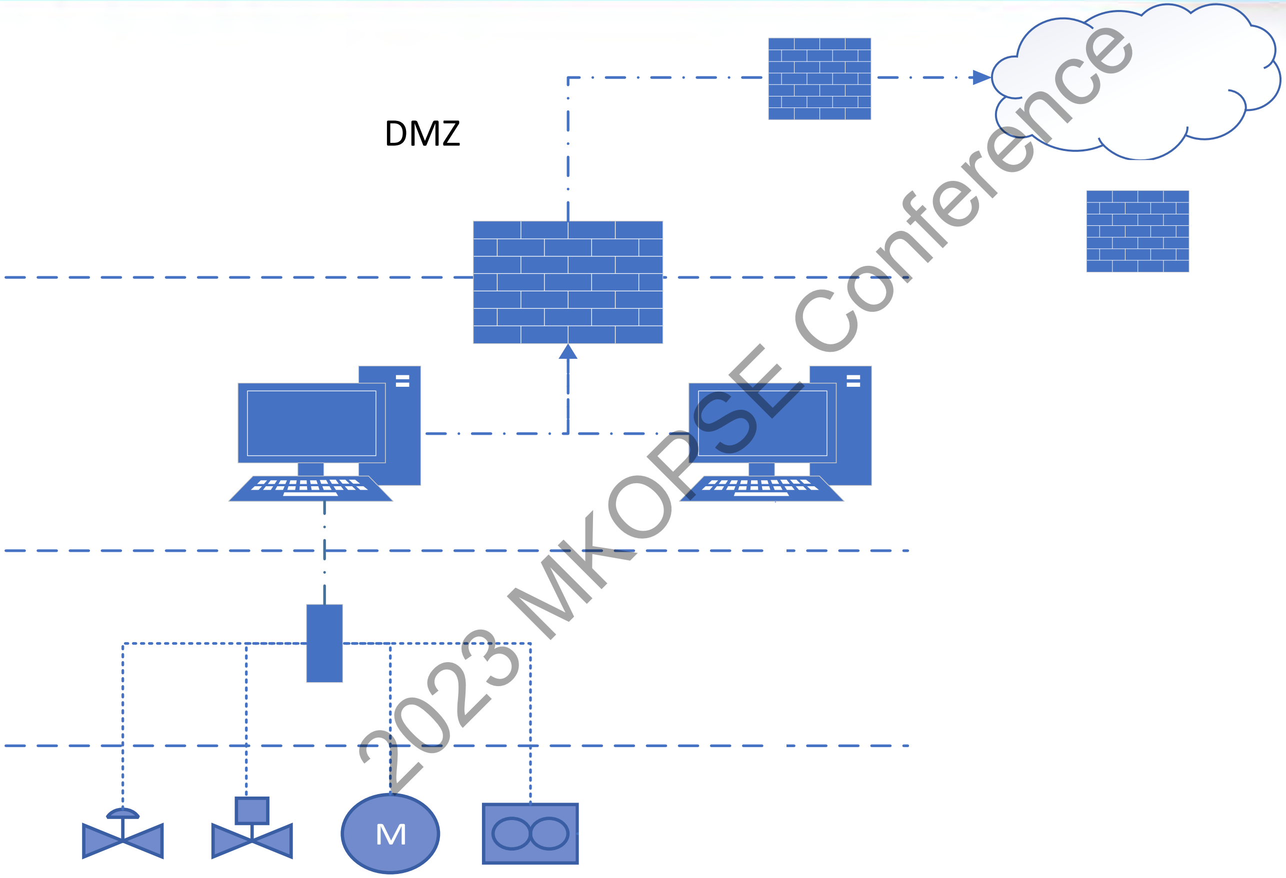
ISA International Society of Automation

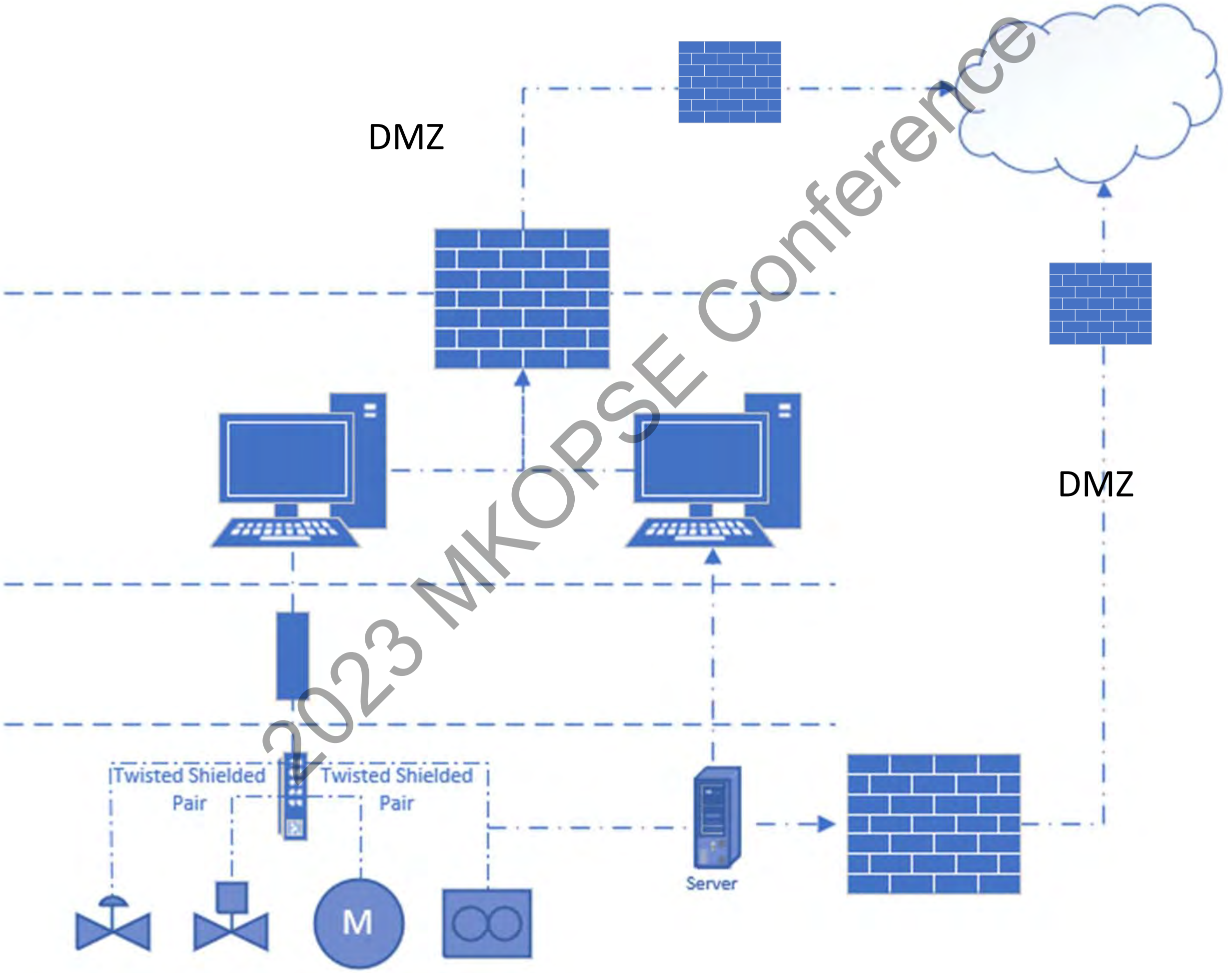
SIS Performance Management
And Data Analysis
WG10

OPC® FOUNDATION
The Industrial Interoperability Standard™

The "Open Future" - Issues facing Owner/Operators

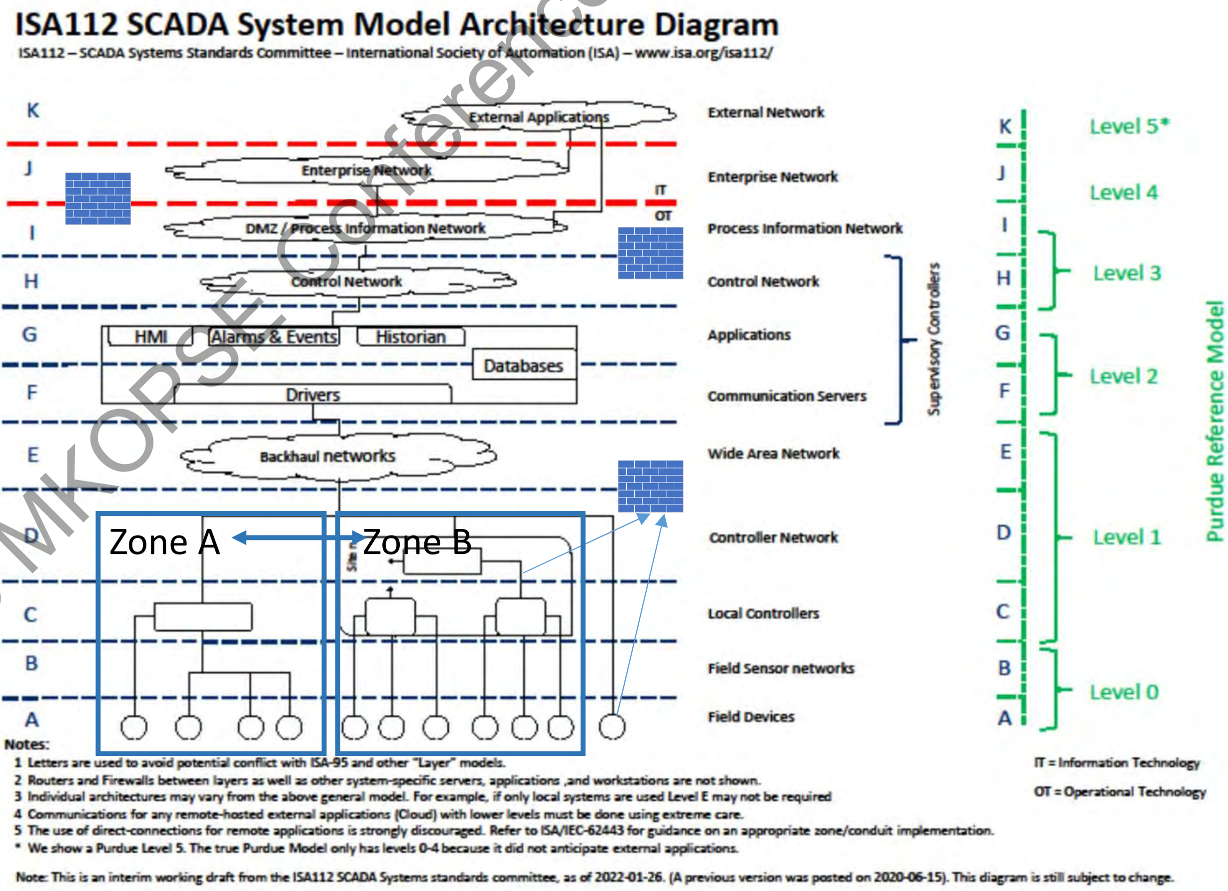



DMZ
M


DMZ
DMZ
Twisted Shielded Pair
Twisted Shielded Pair
M
Server

Impact to Cybersecurity

- Purdue or not Purdue
- Functional Model is timeless and indispensable
- Cyber now lives at all levels, embedded



ISA112 SCADA System Model Architecture Diagram

ISA112 – SCADA Systems Standards Committee – International Society of Automation (ISA) – www.isa.org/isa112/

Notes:
1 Letters are used to avoid potential conflict with ISA-95 and other "Layer" models.
2 Routers and Firewalls between layers as well as other system-specific servers, applications ,and workstations are not shown.
3 Individual architectures may vary from the above general model. For example, if only local systems are used Level E may not be required
4 Communications for any remote-hosted external applications (Cloud) with lower levels must be done using extreme care.
5 The use of direct-connections for remote applications is strongly discouraged. Refer to ISA/IEC-62443 for guidance on an appropriate zone/conduit implementation.
* We show a Purdue Level 5. The true Purdue Model only has levels 0-4 because it did not anticipate external applications.

IT = Information Technology
OT = Operational Technology

Note: This is an interim working draft from the ISA112 SCADA Systems standards committee, as of 2022-01-26. (A previous version was posted on 2020-06-15). This diagram is still subject to change.

Impact to Programs, Policy and Organization

ISA61511
TüV – Exida
Certifications
Functional Safety
Policy

ISA108
Intelligent Device
Management
Policy, Practice

ISA62443
Cyber Policy
Training and
Certifications

System Lifecycle Planning
Digital Transformation
Industry 4.0 Roadmap

Converging Standards

- ISA 108
- Namur and FieldComm Group/ODVA/IEEE
- OPAF
- OPC Group
- ISA84 Working Groups 9 & 10
- ISA112
- ISA62443 Cybersecurity Standards

Key Issues Presented to Owner Operators

Safety
Security

Policy
Competency

$$$ Benefits

Marketplace
Technologies

Emerging
Standards

Trustworthy
Partners

Roadmaps
Obsolescence
Integration

Question and Comments

HOWARD P. ELTON
Principal Technical Consultant | ProLytX
281-910-9137 | howard.elton@prolytx.com
16430 Park Ten Place, Suite 550
Houston, TX 77084
www.prolytx.com

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

Swiss Cheese
Why the Holes Line Up?

Rajender Dahiya, CSP, MIChemE
Professional Process Safety Engineer
Energy Risk Consulting
AIG

26th Process Safety International Symposium

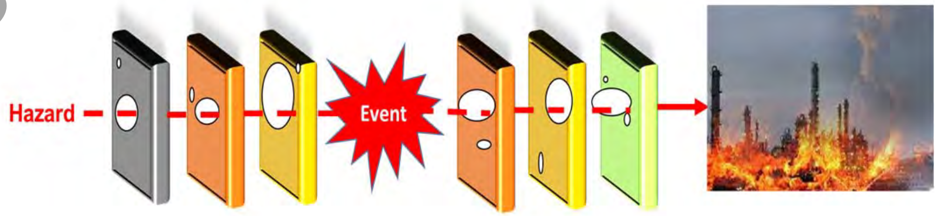
About Rajender

- >28 years experience in Oil, Chemicals, Insurance
- Expertise – Process safety, fire protection and risk management
- Professional Qualifications, Certifications
  - B. Sc, BE – Fire Engineering
  - Professional Process Safety Engineer (PPSE) – IChemE UK
  - Certified Safety Professional (CSP) – BCSP USA
- Membership
  - MIChemE
  - Sr. Member – AIChE
  - Professional Member – ASSP
- Presenting in national and local conferences
  - AIChE-GCPS, MKOPSC (Texas A&M) ASSP, CSSE….
- Volunteering
  - Subcommittee member – Peer Reviewer, Published 4 books recently – AIChE
  - *A yoga and meditation volunteer teacher*

Rajender Dahiya, CSP, MIChemE
Professional Process Safety Engineer
Energy Risk Consulting
AIG

Context

- We know that all incidents are preventable
- But major incidents keep occurring
- Causes and consequences are comparable
- This means…
  - there are problems, and
  - each problem has its solution
- So…It is simple
  - either we do not know the problem
  - or it is not getting fixed

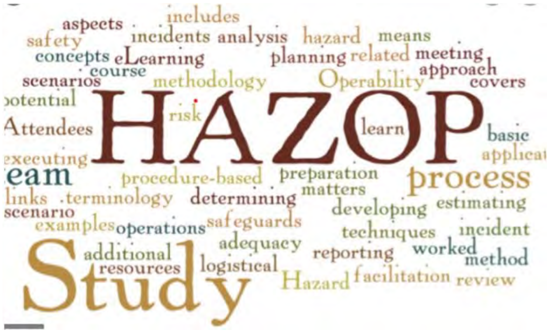


Root Causes of Incidents

Management failure to identify the hazard and manage risk	**Hazard Identification and Risk Assessment (HIRA)**
Management failure to maintain the integrity and availability of safety critical systems	**Operating and Maintenance Programs**
Management failure to learn from incidents	**Learning from Incidents**

What we normally do

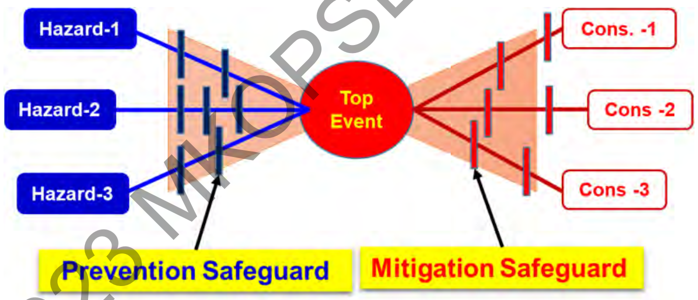
✓ HIRA done
(HAZID, PHA, LOPA…….)



Source: [CCPS - Center for Chemical Process Safety]()

HAZID: Hazard Identification
PHA: Process hazard analysis
HIRA: Hazard identification and risk assessment
HAZOP: Hazard & Operability Study
LOPA: Layers of Protection Analysis

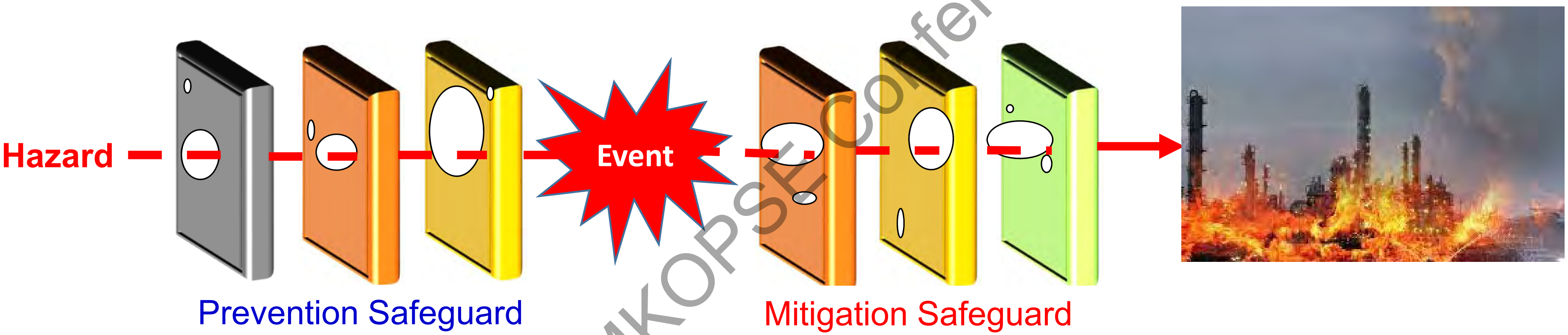
✓ multiple safeguards installed



✓ management systems in place

- Corporate Policies Standards
- Design Standards
- Inspection & Maintenance
- Operating Procedures
- Emergency Response
- Training Competency Culture
- KPIs Audit

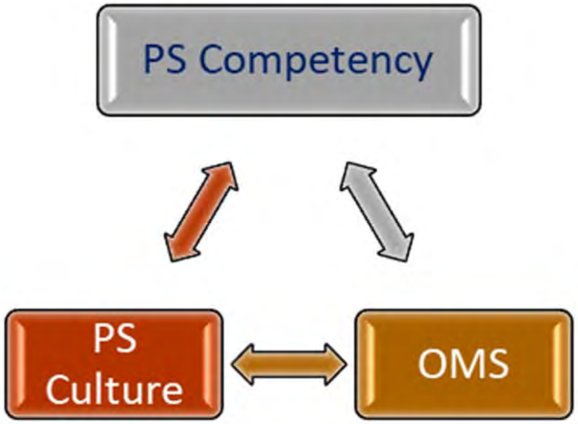
Holes Developed & Aligned – Incident



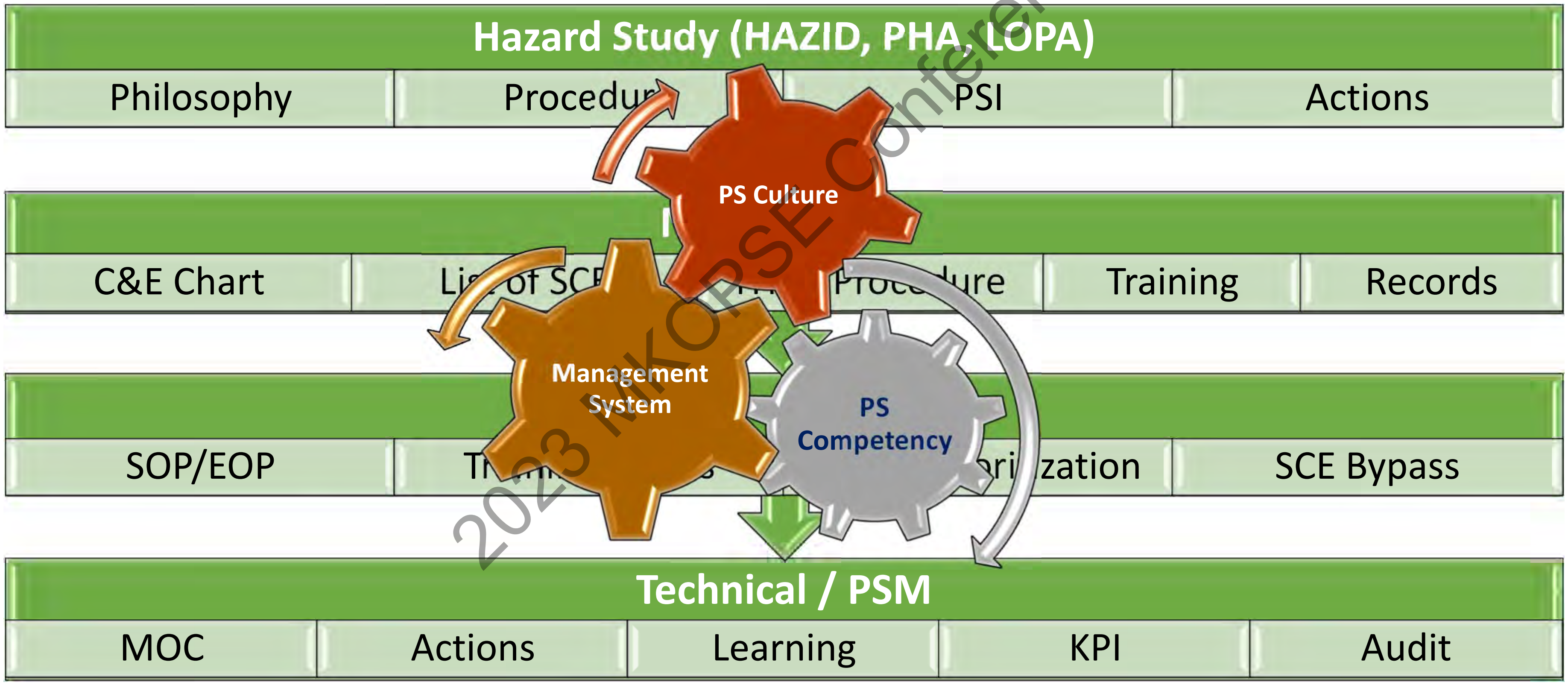
- The holes depicts MS weaknesses
- Several warning signs, weak signals, near misses, small incidents may have been neglected or not addressed adequately

Most Common Causes / Gaps

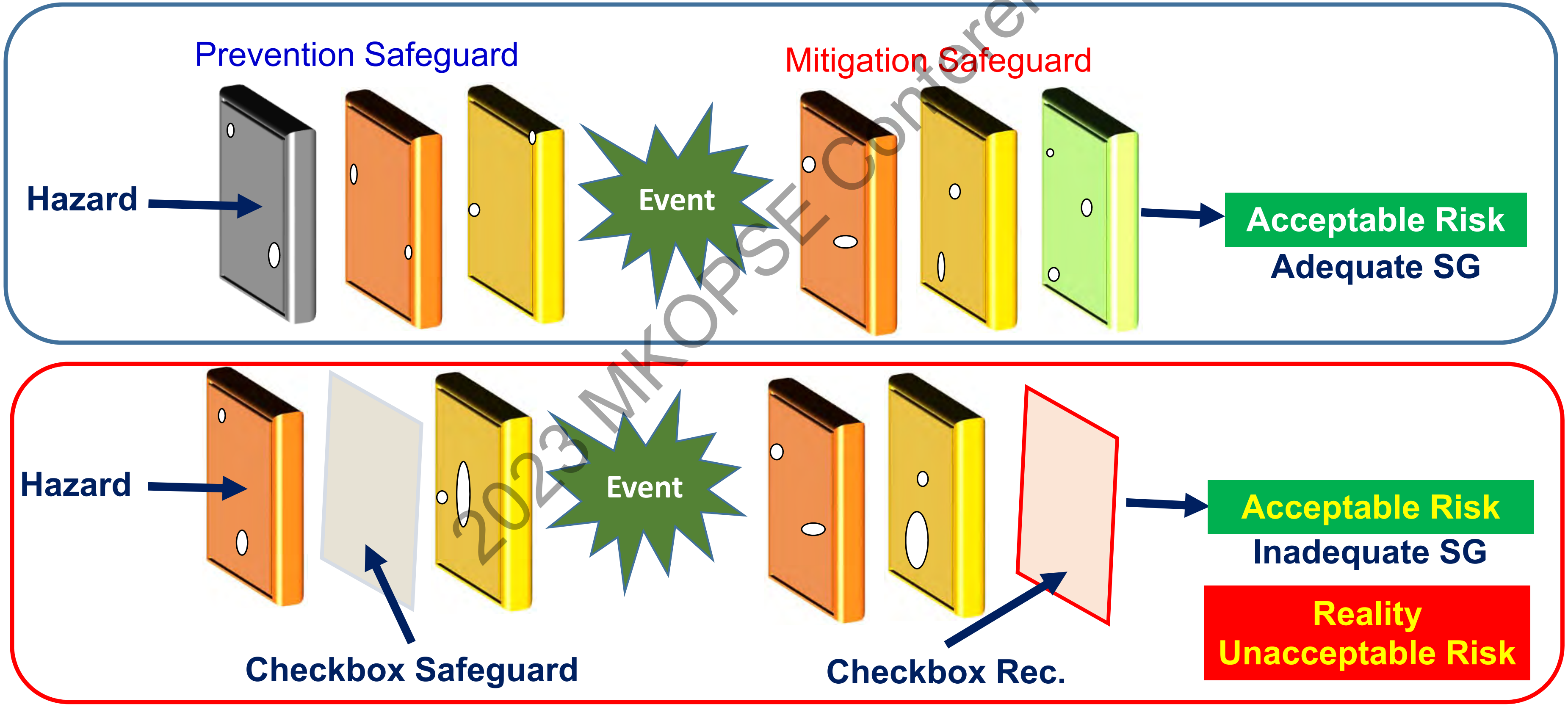
- HIRA
- Actions Management
- Inspection Testing and Preventive maintenance (ITPM)
- Operator procedures and training
- Safety system bypass
- Incident investigation and learning
- Key Performance Indicators (KPIs)
- Audit



Journey – How the Holes are Created and ……



HIRA Quality – Good vs. Poor



Prevention Safeguard

Mitigation Safeguard

Hazard

Event

Acceptable Risk

Adequate SG

Hazard

Event

Acceptable Risk

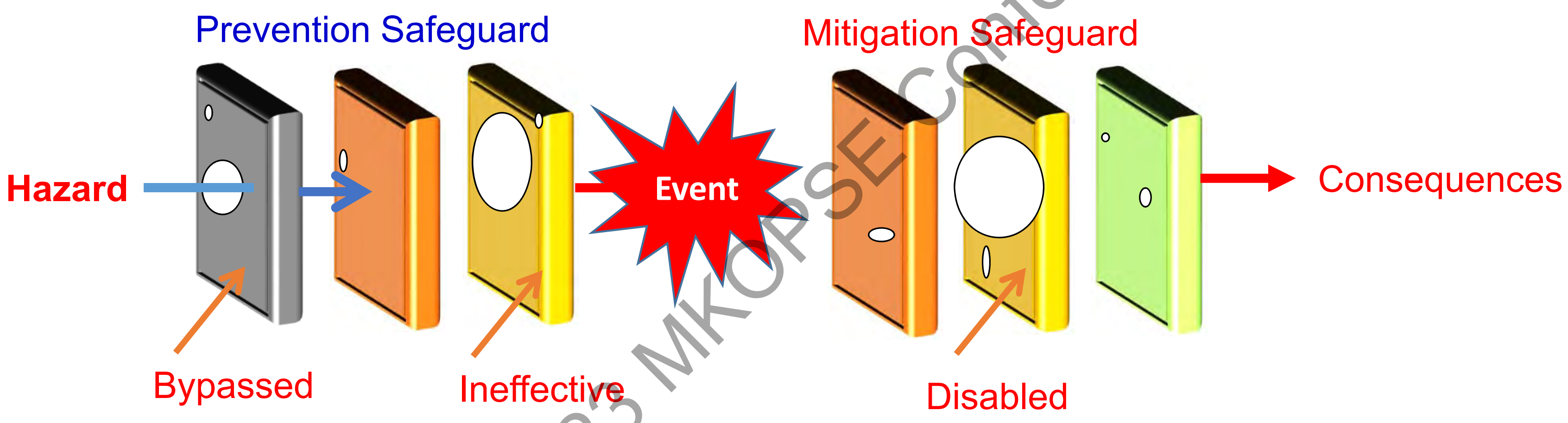
Inadequate SG

Reality
Unacceptable Risk

Checkbox Safeguard

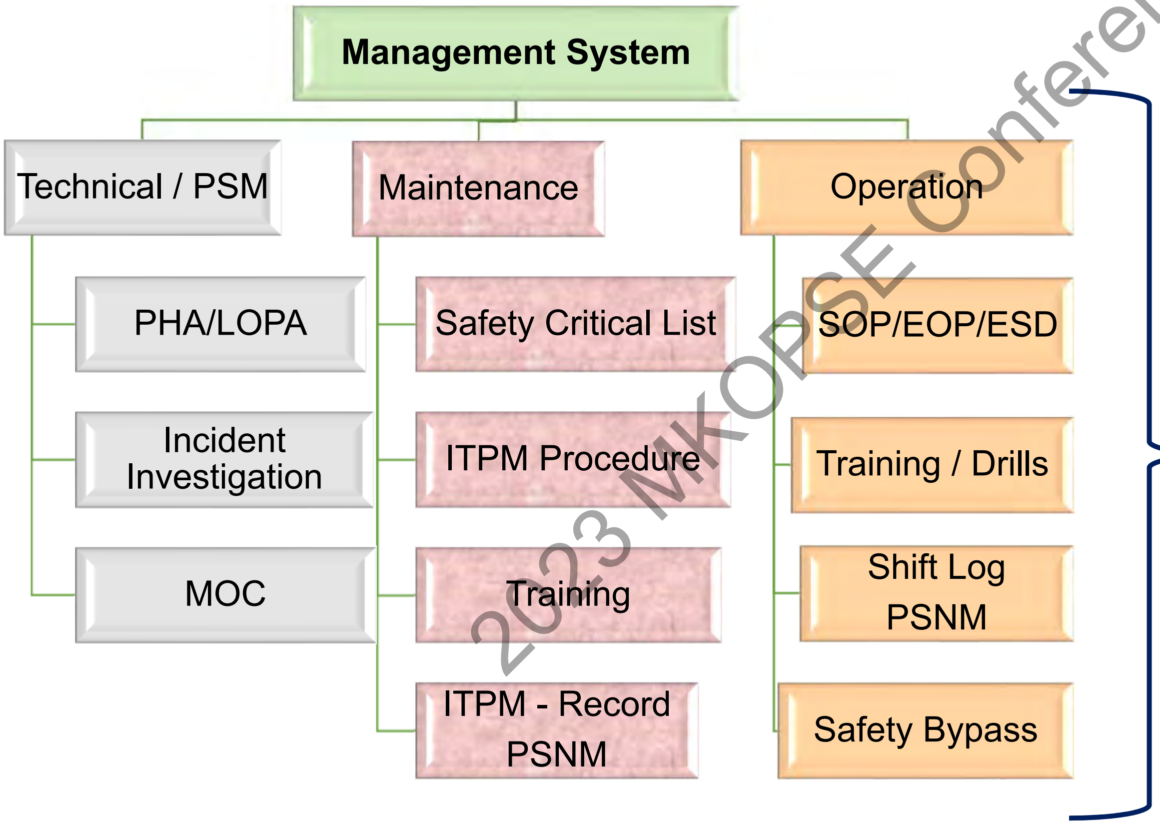
Checkbox Rec.

Operation Stage



Knowingly or Unknowingly the plant is operated with UNACCEPTABLE risk

Management System Weakness - Example

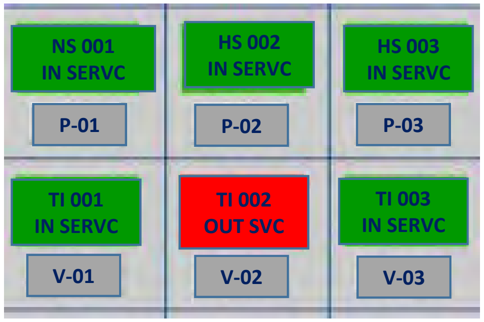


Management System

Technical / PSM
- PHA/LOPA
- Incident Investigation
- MOC

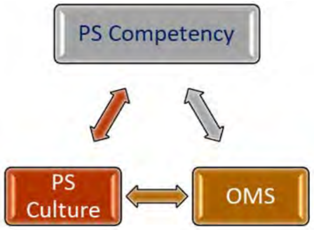
Maintenance
- Safety Critical List
- ITPM Procedure
- Training
- ITPM - Record PSNM

Operation
- SOP/EOP/ESD
- Training / Drills
- Shift Log PSNM
- Safety Bypass

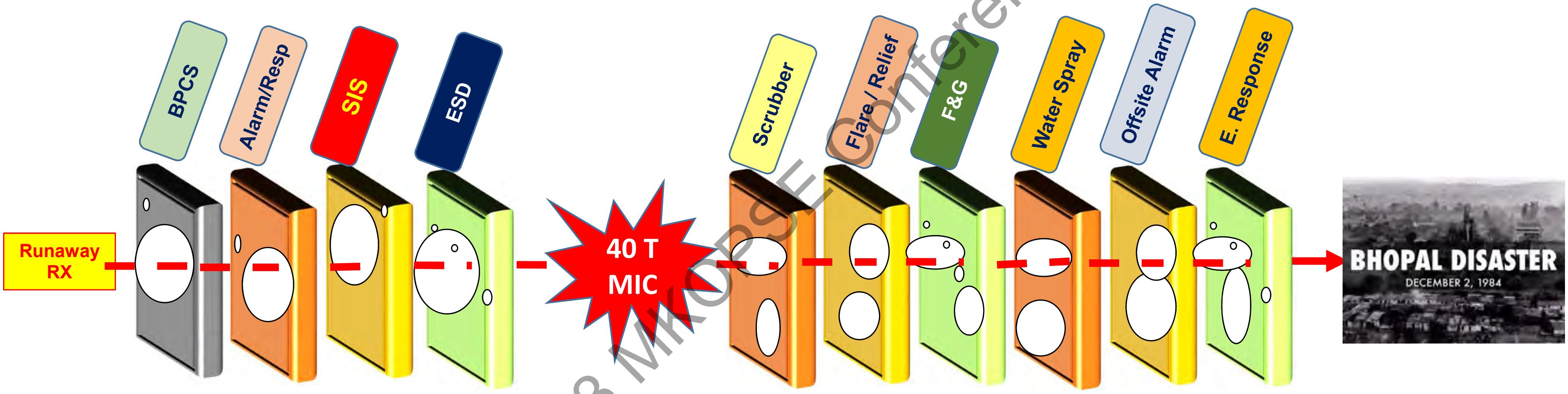


🟩 NS 001 IN SERVC	🟩 HS 002 IN SERVC	🟩 HS 003 IN SERVC
P-01	P-02	P-03
🟩 TI 001 IN SERVC	🟥 TI 002 OUT SVC	🟩 TI 003 IN SERVC
V-01	V-02	V-03

- Program Audit
- Key Performance Indicator



Bhopal Incident (1984) – What is Different Now?



- Several precursors, neglected
- Leaders, managers, employees, union, public, media were aware about this risk

Truth
None of these 10 Safeguards Failed

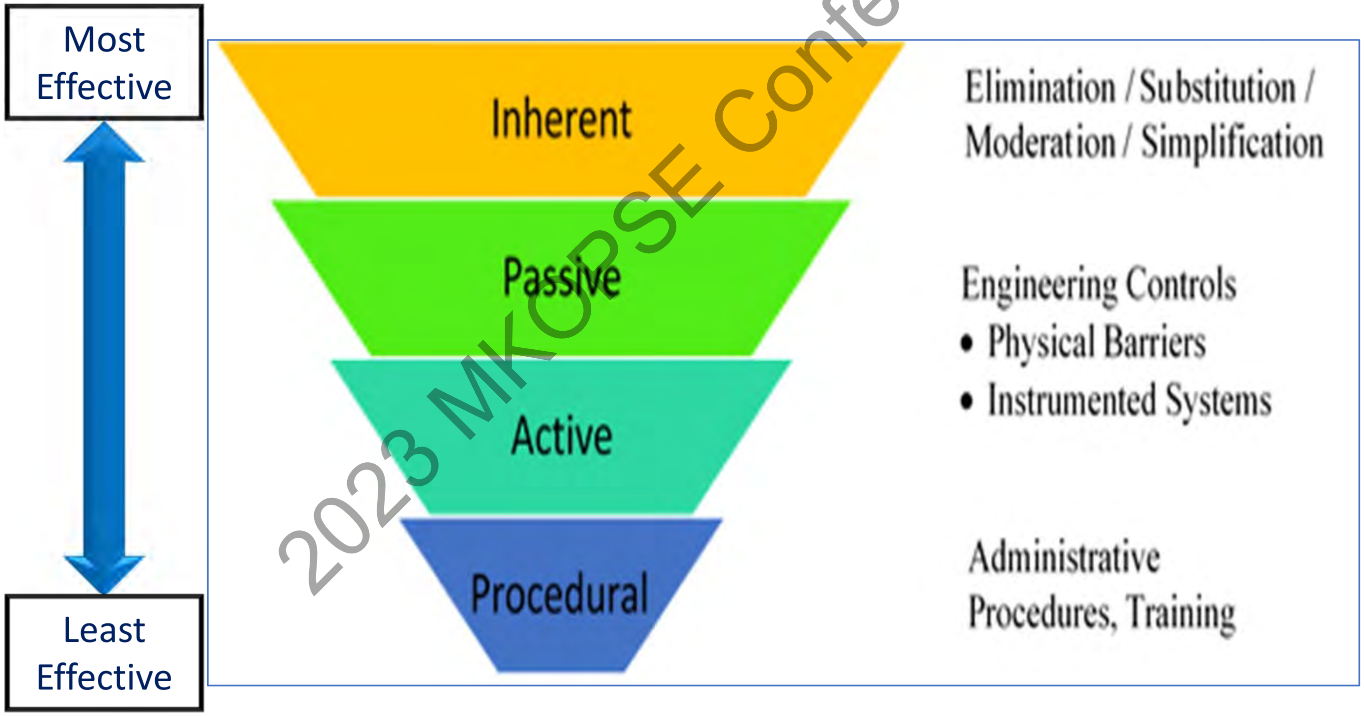
Anything different now?
Similar gaps causing an incident

Next Step

Proactive
&
Reactive

Hierarchy of Process Risk Management (CCPS)

Safety in Design



Most Effective

Least Effective

Inherent

Passive

Active

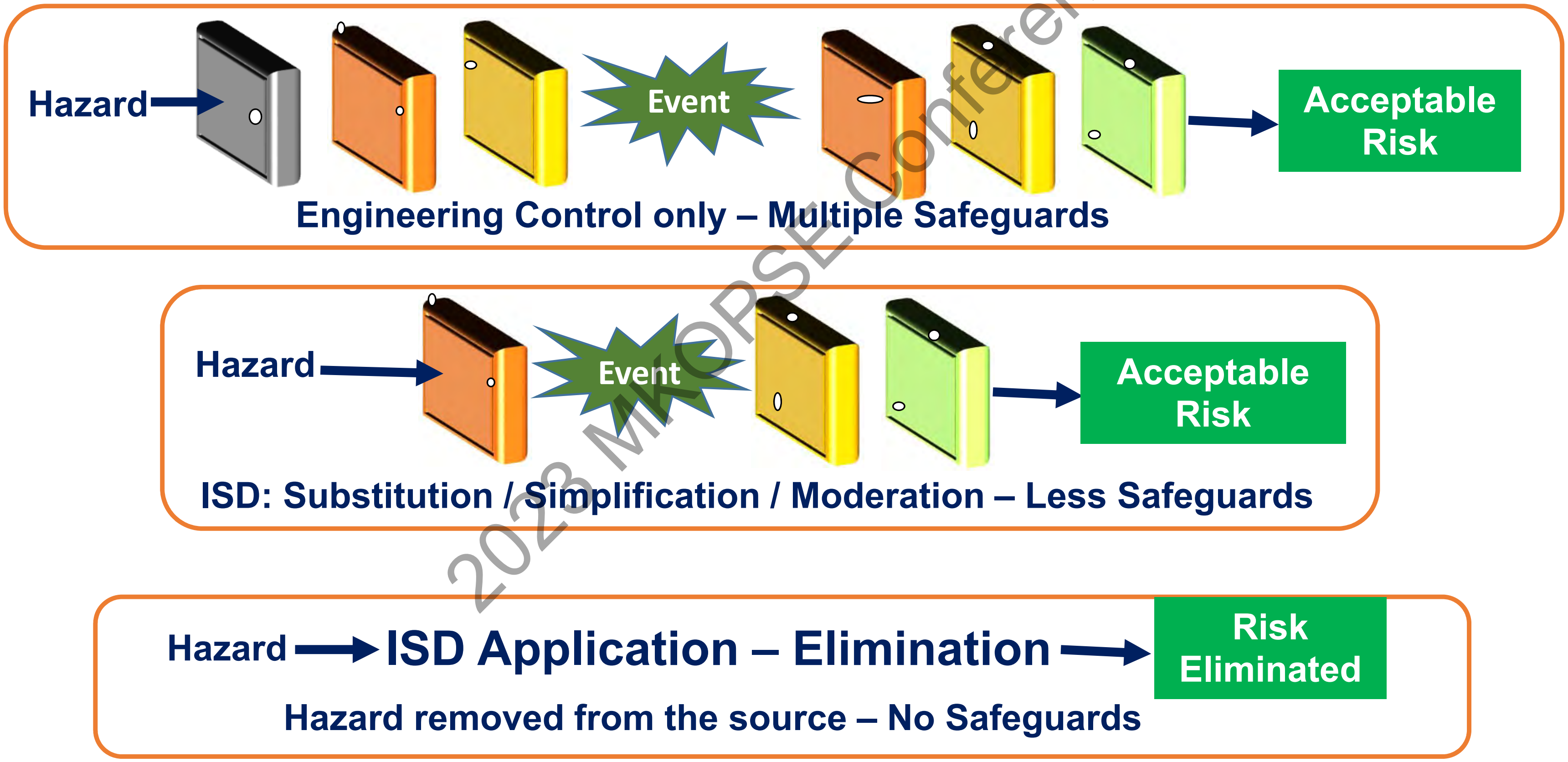
Procedural

Elimination / Substitution / Moderation / Simplification

Engineering Controls
- Physical Barriers
- Instrumented Systems

Administrative Procedures, Training

Industry Practices vs Industry Best Practices



Hazard → → **Acceptable Risk**

Engineering Control only – Multiple Safeguards

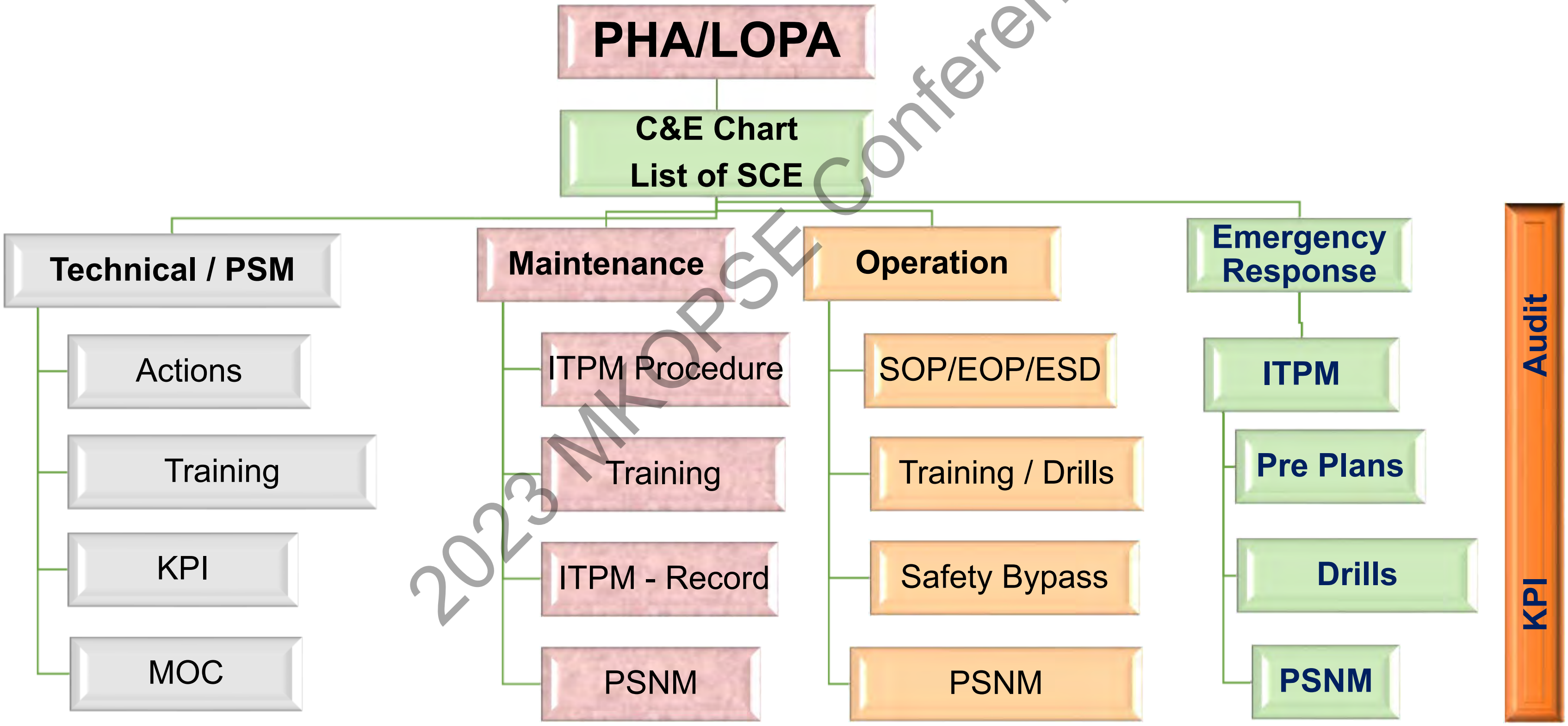
Hazard → → **Acceptable Risk**

ISD: Substitution / Simplification / Moderation – Less Safeguards

Hazard → **ISD Application – Elimination** → **Risk Eliminated**

Hazard removed from the source – No Safeguards

Integrity & Availability – Best Practices



PHA/LOPA

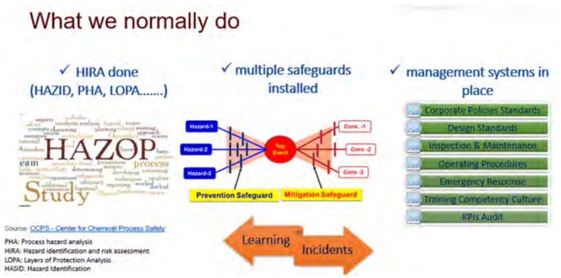
C&E Chart
List of SCE

- **Technical / PSM**
  - Actions
  - Training
  - KPI
  - MOC
- **Maintenance**
  - ITPM Procedure
  - Training
  - ITPM - Record
  - PSNM
- **Operation**
  - SOP/EOP/ESD
  - Training / Drills
  - Safety Bypass
  - PSNM
- **Emergency Response**
  - **ITPM**
  - **Pre Plans**
  - **Drills**
  - **PSNM**

Audit

KPI

Actions Management – Gaps & Best Practices



What we normally do

✓ HIRA done
(HAZID, PHA, LOPA.......)

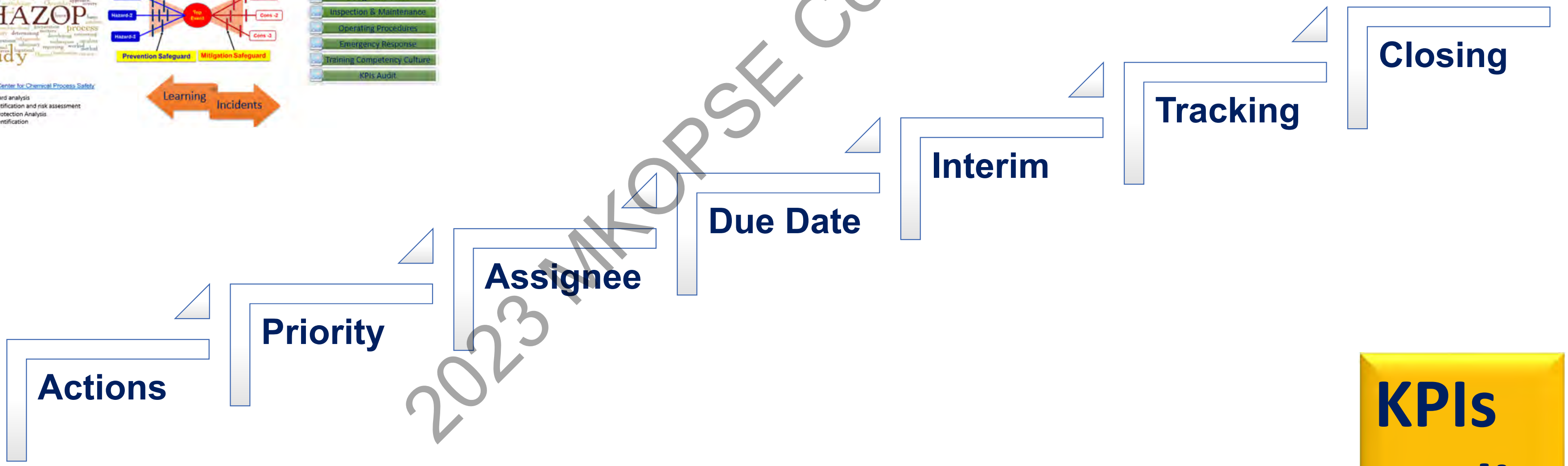
✓ multiple safeguards installed

✓ management systems in place

- Corporate Policies Standards
- Design Standards
- Inspection & Maintenance
- Operating Procedures
- Emergency Response
- Training Competency Culture
- KPIs Audit

Source: CCPS - Center for Chemical Process Safety

PHA: Process hazard analysis
HIRA: Hazard identification and risk assessment
LOPA: Layers of Protection Analysis
HASID: Hazard Identification



Actions

Priority

Assignee

Due Date

Interim

Tracking

Closing

KPIs Audit

Learning from Incidents

- Defined / reported / KPIs
- Walk the talk, meeting

- Potential consequences
- Real root causes

- Rec. address the root causes

- Action priority, review and verification

- One pager
- Company wide

- Not defined / reported

- Actual consequences
- Not to the root cause

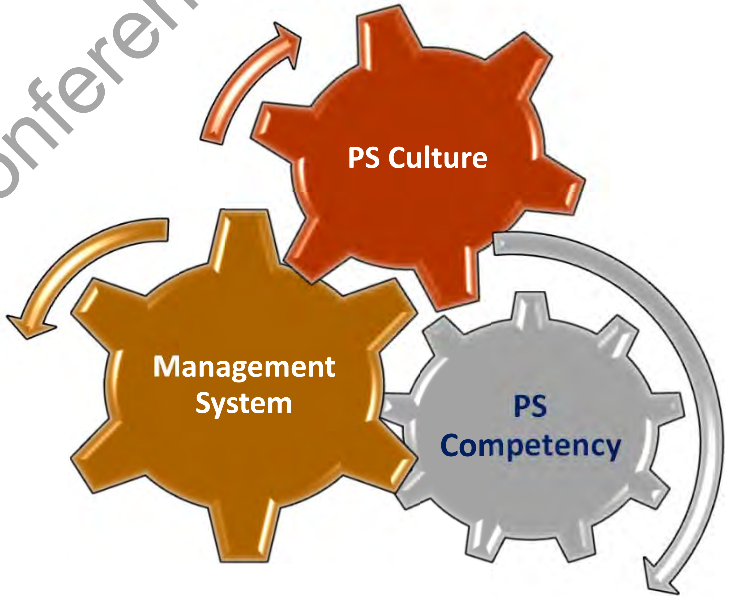
- Generic, easy to fix

- Not trackable

- Local fix

What Matters……. Learning & Takeaway

- Quality
- Consistency
- User friendly
- Simplicity
- Fit for purpose
- KPIs Audit

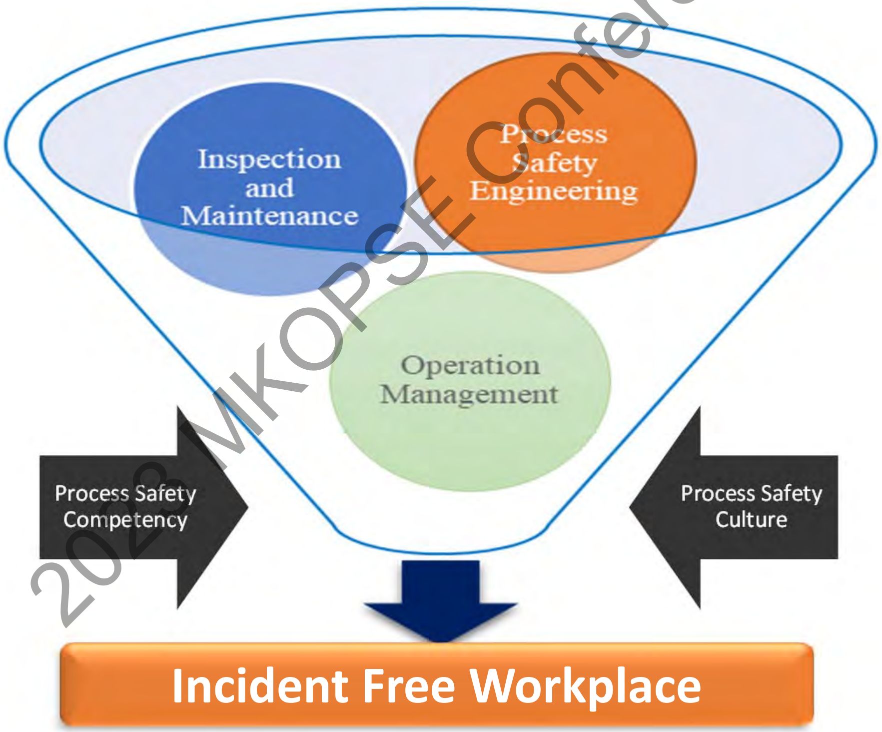


Corporate Design Operation

Summary

- FACT All incidents are preventable, but incidents keep repeating with severe consequences
- We know that whatever may be the causes, if hazard is identified and multiple safety systems work as designed, then the catastrophe could be avoided altogether, or be much less severe consequences
- Root causes of process incidents are deep rooted in the company's operating management systems, corporate process safety culture and competency of the employees – deep dive is MUST.
- Irrespective of the process hazards, the owner/operator is responsible for ensuring that safety critical equipment and systems are designed and maintained to prevent any accident – PSM covered or Not
- Process safety competency is more important for leaders than the employees.
- Inherently safer techniques are applicable for the facility lifecycle.
- Check Box Must Go Away

Conclusion


Inspection and Maintenance
Process Safety Engineering
Operation Management
Process Safety Competency
Process Safety Culture
Incident Free Workplace

Thank You

Rajender Dahiya, CSP, PPSE-MIChemE
Senior Technical Services Manager – Loss Control
AIG, Houston, Texas USA

Cell: +1 832 627 9918
Rajender.Dahiya@aig.com

2023 MKOPSE Conference

The information, suggestions and recommendations contained herein are for general informational purposes only. This information has been compiled from sources believed to be reliable. Risk Consulting Services do not address every possible loss potential, law, rule, regulation, practice or procedure. No warranty, guarantee, or representation, either expressed or implied, is made as to the correctness or sufficiency of any such service. Reliance upon, or compliance with, any recommendation in no way guarantees any result, including without limitation the fulfillment of your obligations under your insurance policy or as may otherwise be required by any laws, rules or regulations. No responsibility is assumed for the discovery and/or elimination of any hazards that could cause accidents, injury or damage. The information contained herein should not be construed as financial, accounting, tax or legal advice and does not create an attorney-client relationship.

American International Group, Inc. (AIG) is a leading global insurance organization. AIG member companies provide a wide range of property casualty insurance, life insurance, retirement solutions and other financial services to customers in approximately 70 countries and jurisdictions. These diverse offerings include products and services that help businesses and individuals protect their assets, manage risks and provide for retirement security. AIG common stock is listed on the New York Stock Exchange.

Additional information about AIG can be found at www.aig.com | YouTube: www.youtube.com/aig | Twitter: @AIGinsurance www.twitter.com/AIGinsurance | LinkedIn: www.linkedin.com/company/aig. These references with additional information about AIG have been provided as a convenience, and the information contained on such websites is not incorporated by reference herein.

AIG is the marketing name for the worldwide property-casualty, life and retirement and general insurance operations of American International Group, Inc. For additional information, please visit our website at www.aig.com. All products and services are written or provided by subsidiaries or affiliates of American International Group, Inc. Products or services may not be available in all countries and jurisdictions, and coverage is subject to underwriting requirements and actual policy language. Non-insurance products and services may be provided by independent third parties. Certain property-casualty coverages may be provided by a surplus lines insurer. Surplus lines insurers do not generally participate in state guaranty funds, and insureds are therefore not protected by such funds.

Copyright © 2023 American International Group, Inc. All rights reserved

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

TEES

Texas A&M Engineering Experiment Station

Mary Kay O'Connor Process Safety Center

26th Process Safety International Symposium

Objective

- *Unlocking the Future of Control Systems, where precision meets uncertainty, and adaptability is paramount.*
- *Augmentation of safety-critical decision making with systems-based real-time operation to proactively reduce process safety losses.*

Challenges

Dynamic Environments | *Uncertainty* | *Struggles of conventional control*

Risk-Informed Model Predictive Control (R-MPC)

- ***Bayesian-informed Control****: Bayesian updates to leverage uncertainty as an asset, enhancing control system adaptability*
- ***Real-Time Tolerance adjustment****: Allowing control system to adjust tolerances in response to changing conditions, ensuring resilience and responsiveness*
- ***Safety-centric strategy****: Prioritizing safety and performance by actively monitoring and managing risk throughout the system operation*

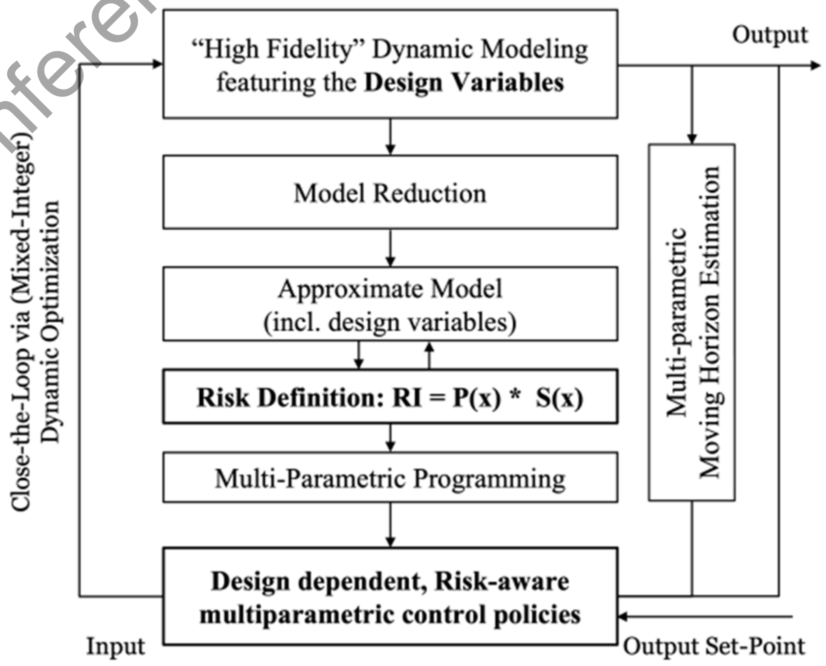
Literature Review

The inspiration for this work was drawn from:

"Ali, M., Cai, X., Khan, F. I., Pistikopoulos, E. N., & Tian, Y. (2023). Dynamic risk-based process design and operational optimization via multi-parametric programming. Digital Chemical Engineering, 7, 100096"

The proposed framework by the authors in this work includes:

- High-fidelity modelling of process and safety system
- Dynamic risk modelling as functions of process variables
- Design-dependent risk-aware control policies via multi-parametric policies



"High Fidelity" Dynamic Modeling featuring the **Design Variables**

Model Reduction

Approximate Model (incl. design variables)

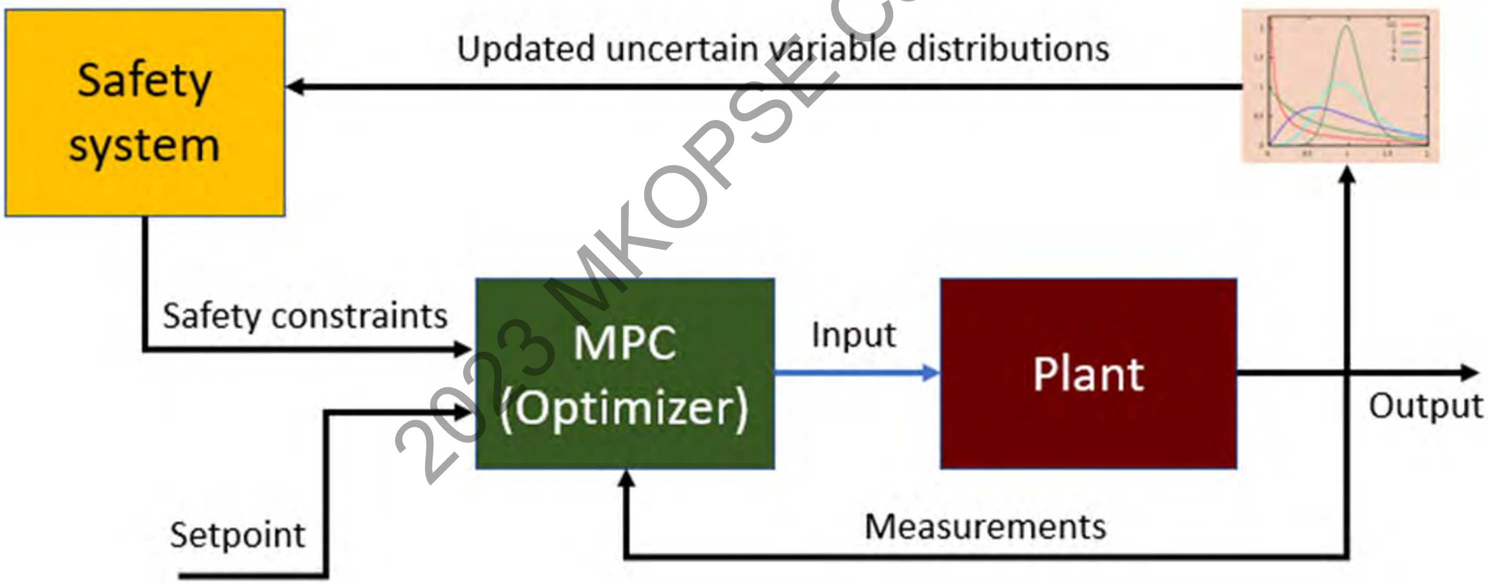
Risk Definition: RI = P(x) * S(x)

Multi-Parametric Programming

Design dependent, Risk-aware multiparametric control policies

Research Objectives

The primary objective of this project is to design a controller that prioritizes the **probabilistic nature of risk**, employing **Bayesian inference methods for continuous risk updates within a rolling time horizon**, all while operating within a chance-constrained programming framework.



Safety system

Updated uncertain variable distributions

Safety constraints

MPC (Optimizer)

Input

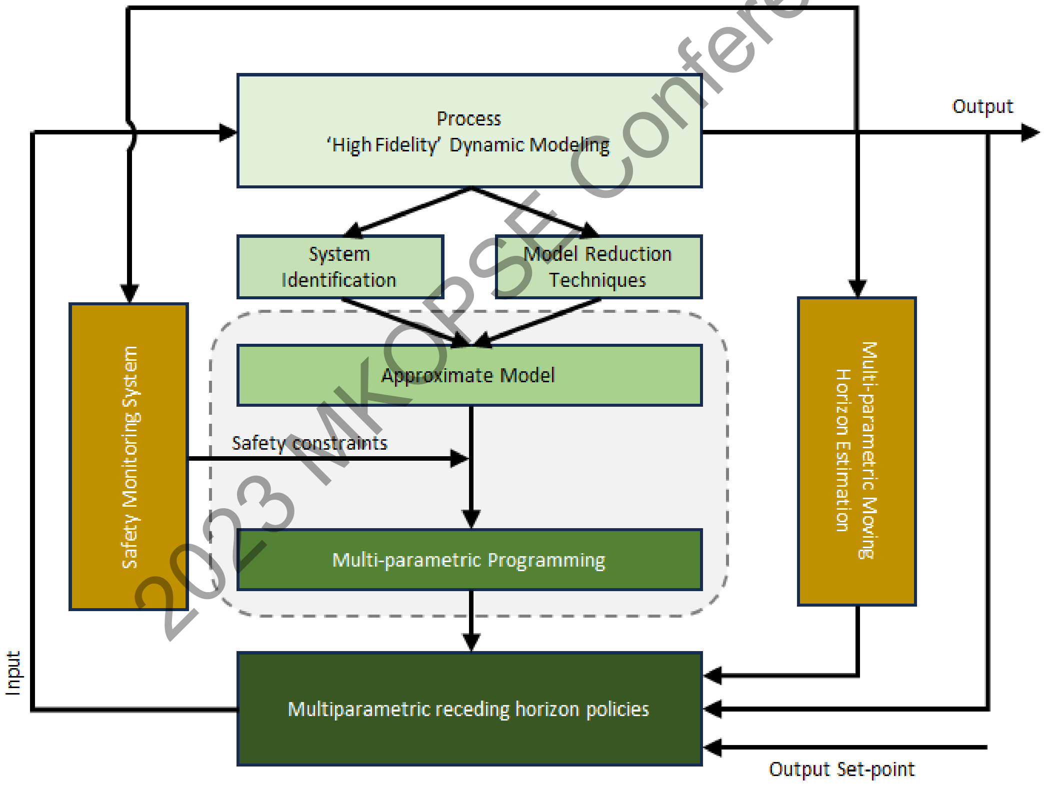
Plant

Output

Setpoint

Measurements

PAROC Framework



Formulation

$$\min J = \underbrace{x_N^T P x_N + \sum_{k=1}^{OH-1} (y_k - y_k^R)^T QR_k (y_k - y_k^R) + \sum_{k=1}^{CH-1} (u_k - u_k^R)^T R_k (u_k - u_k^R)}_{\textit{Control losses}} + \underbrace{f(x_k)}_{\textit{Safety losses}}$$

s.t.

$$\left.\begin{aligned} x_{k+1} &= Ax_k + Bu_k + C[d_k; De] \\ y_k &= Dx_k + Eu_k \end{aligned}\right\} \textit{Linear process model}$$

$$\Pr(a^T x_k \geq T) \leq \beta_k \qquad \textit{Violation-allowance constraint (risk)}$$

$$\underline{x} \leq x_k \leq \bar{x}\,;\, \underline{y} \leq y_k \leq \bar{y}\,;\, \underline{u} \leq u_k \leq \bar{u}\,;\, \underline{De} \leq De_k \leq \overline{De} \qquad \textit{Process bounds}$$

$$\beta_{k+1} = L(x_k, x_{k-1}, x_{k-2}, \ldots, x_0) * \beta_k \qquad \textit{Bayesian update step}$$

Where T is the maximum limit for violation of the constraint, L is the likelihood function for Bayesian update

Chance-constrained Programming

- Probability constraints in the optimization framework are converted to their deterministic approximates via chance-constrained programming.
- Only Gaussian probability distributions are considered in the current scope of applications.
- Deterministically approximated via reliability index methodology.

Probabilistic constraint	**Deterministic approximate**
$\Pr(a^T x_k \geq T) \leq \beta_k$	$a^T x_k \geq T + z.\sigma$

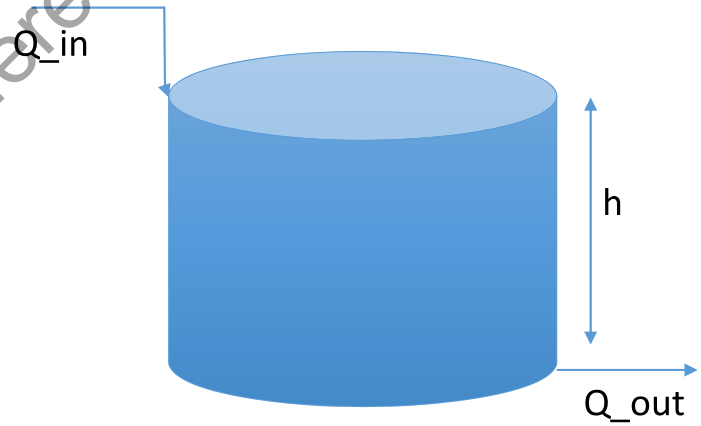
Where,

- z is the reliability index calculated from the inverse cumulative distribution ($z = \varphi^{-1}(\beta_k)$)
- σ is the standard deviation associated with the probability distribution observed in the uncertainties.

Case-study: Tank level control

Objective:

Control the level of the tank while adapting to changing levels of uncertainty in real-time



$$\frac{dh}{dt} = \frac{Q_{in} - Q_{out}}{A}$$

$$Q_{out} = \mathrm{k} * \mathrm{h}$$

State Space Model	
State Variables	Level in the tank (h)
Input Variable	Q_in
Disturbance	Uncertainty (w)
Design	Cross-sectional area (A)

Case-study: Formulation

$$\min J = \sum_{k=1}^{OH-1} (x_k - x_{sp})^2 + INLF(x_k)$$

$$h_{k+1} = \left(1 - \frac{kT_s}{A}\right) h_k + \left(\frac{T_s}{A}\right) Q_{in\_k} + \left(\frac{T_s}{A}\right) w_k$$

$$P(x_k \geq x_{max}) \leq \epsilon_t \ \rightarrow \ P((x_k - x_{max}) \geq 0) \leq \epsilon_t$$

$$0 \leq x_k \leq x_{max}$$

$$\min J = \sum_{k=1}^{OH-1} (x_k - x_{sp})^2 + INLF(x_k)$$

$$h_{k+1} = \left(1 - \frac{kT_s}{A}\right) h_k + \left(\frac{T_s}{A}\right) Q_{in\_k} + \left(\frac{T_s}{A}\right) w_k$$

$$x_k \geq x_{max} + \varphi^{-1}(\epsilon_t).\sigma$$

$$0 \leq x_k \leq x_{max}$$

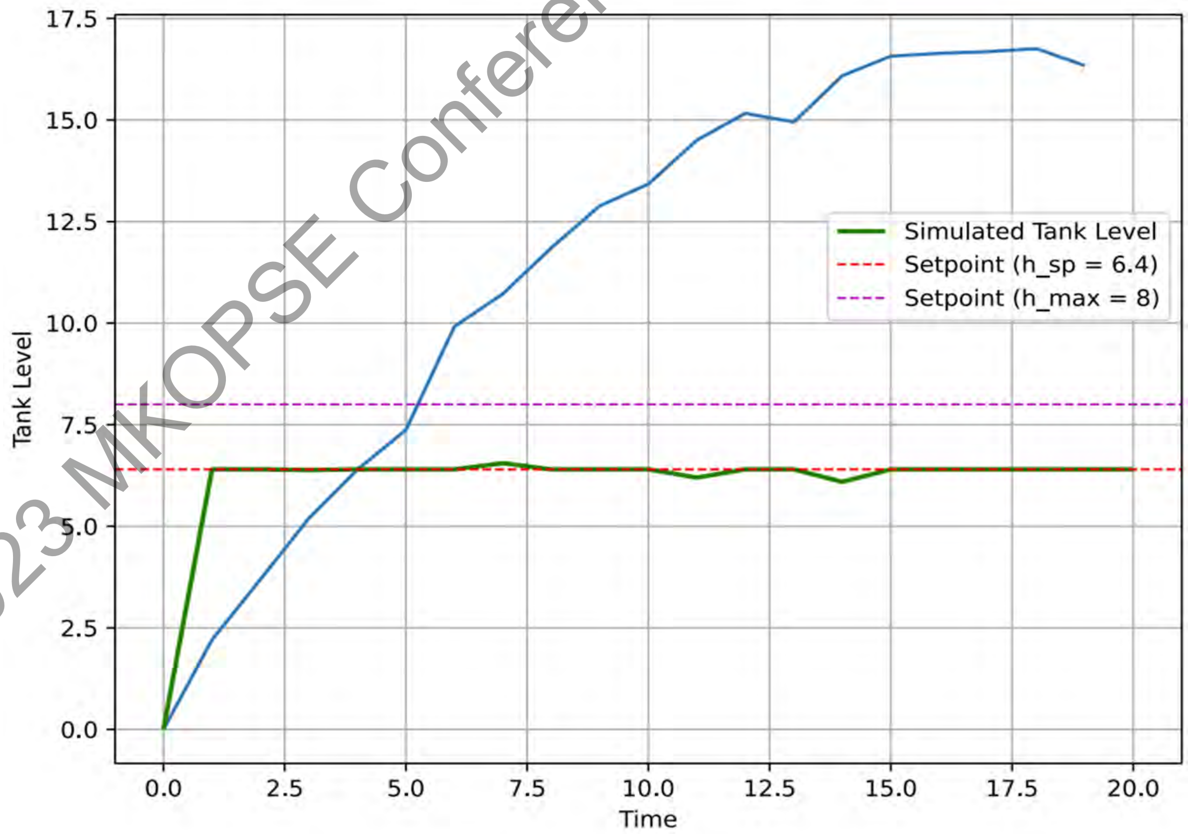
Updating probability tolerance on rolling horizon basis:

$$P((x_k - x_{max}) \geq 0)_{posterior} = L(x_k, x_{k-1}, x_{k-2}, \ldots, x_0).\, P((x_k - x_{max}) \geq 0)_{prior}$$

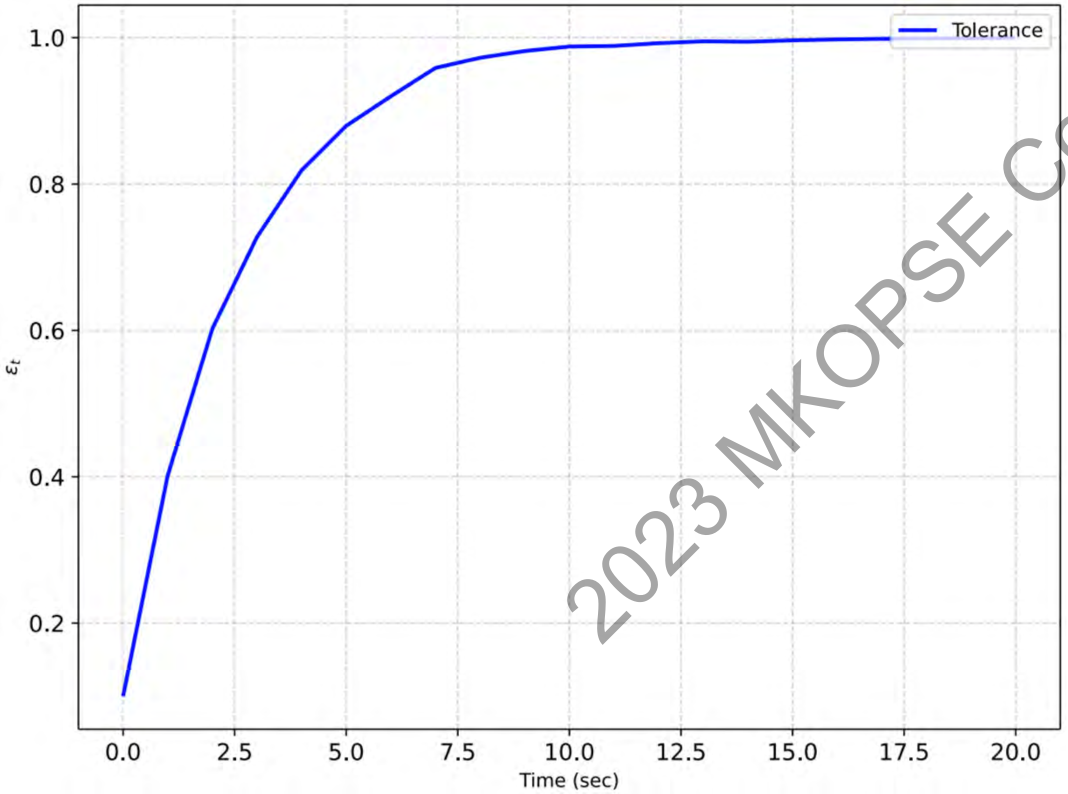
$$\epsilon_{t+1} = L(x_k, x_{k-1}, x_{k-2}, \ldots, x_0).\, \epsilon_t$$

Results & Conclusions

- Level in the tank is being maintained with R-MPC by adjusting the input flowrate



Results & Conclusions



Permissive Constraint Approach:
The increasing epsilon trend reflects a deliberate move towards a more permissive constraint strategy, prioritizing system performance over strict constraint adherence.

Enhanced Adaptability:
The control system's increasing epsilon allows it to adapt more effectively to changing conditions, disturbances, and setpoint variations while managing the risk of occasional constraint violations.

Thank you!

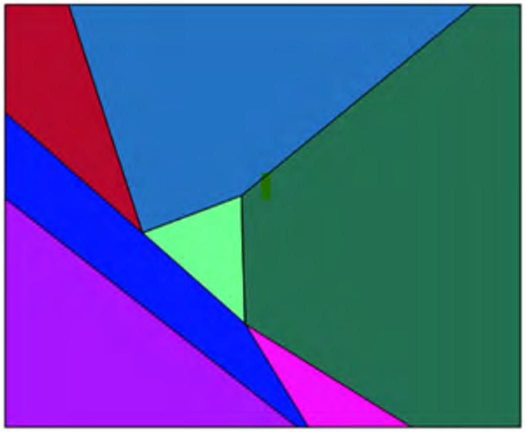
Additional slides: Multi-Parametric programming

$$z(\theta) = min_x\ f(x,\theta)$$

s.t. $g(x,\theta) \leq 0$

$h(x,\theta) = 0$

$$x^*(\theta) = \begin{cases} x^1(\theta), if\ \theta \in CR1 \\ x^2(\theta), if\ \theta \in CR2 \\ . \\ . \\ x^v(\theta), if\ \theta \in CRv \end{cases}$$



$\theta \in \Theta$

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

Hazard Recognition of Proton Exchange Membrane (PEM) Hydrogen Production and Storage Installation

26th Process Safety International Symposium

Speaker profile

- **Mohd Fadly Adnan** - Process Safety Staff Engineer/ Manager at PETRONAS Group Technical Solution with 15 years experience in Oil and Gas sector.
- Providing process safety consultancy to PETRONAS Project and Operating Unit (OPU)/Asset.
- Experienced in LNG sector as Operation Lead Engineer (Process/Utility) and Technical Authority for Process Safety at Group Technical Solution (GTS) under Technical Delivery Excellence (TDEx).

Background

- Touted as Fuel of the future – Emerging green Hydrogen production facilities
- Inherent hazard needs to be recognized, assess, and mitigated
- PETRONAS H_2 project - safety analysis and hazard identification in a typical Proton Exchange Membrane (PEM) Hydrogen production/storage through qualitative (HAZID, HAZOP) and quantitative assessment (Dispersion Modelling) which influenced some of the design criteria consideration.

Recognizing inherent hazard of H_2

Flammability

Flammable range between 4% to 75% by volume in air

Minimum ignition energy (MIE) of 0.02 mJ, which is among the lowest compared to typical hydrocarbons.

Wide detonation range (20-65 vol%). High laminar burning velocity – deflagration, explosion

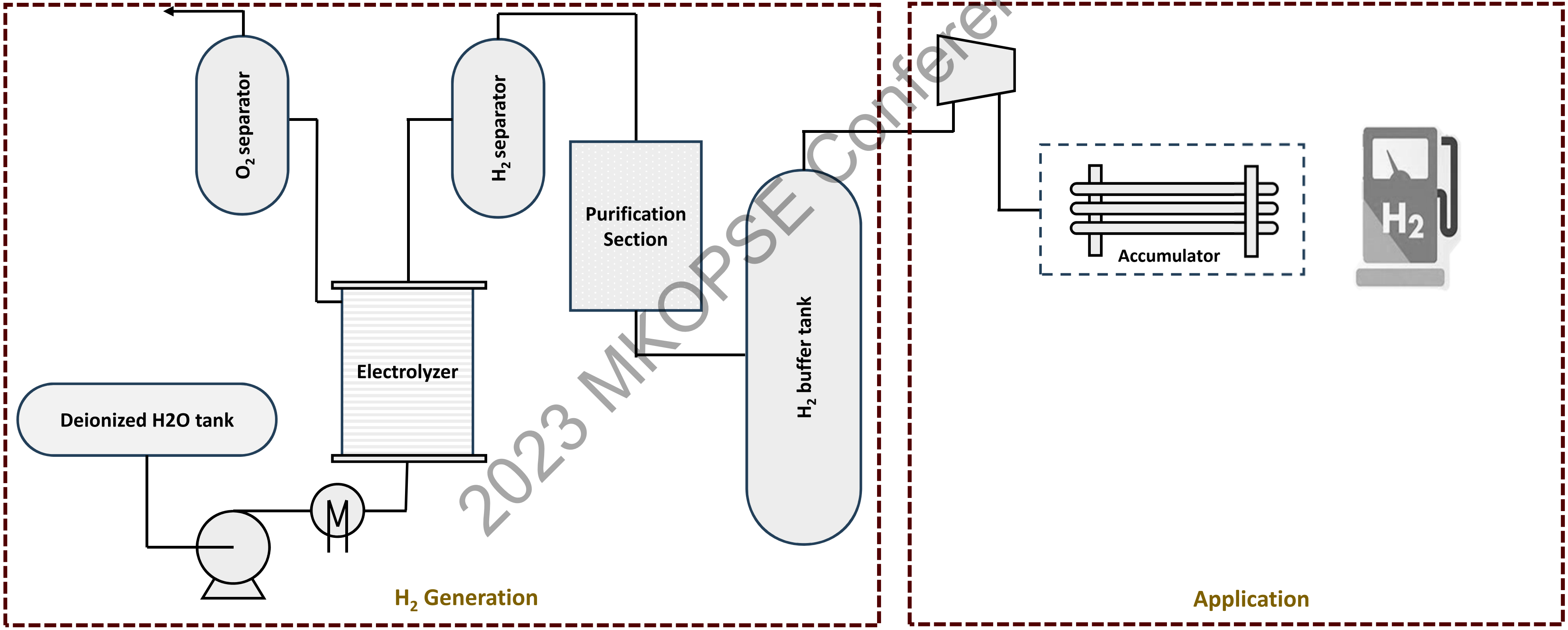
Behaviour

Small size of molecules – can easily leak, permeate through metal

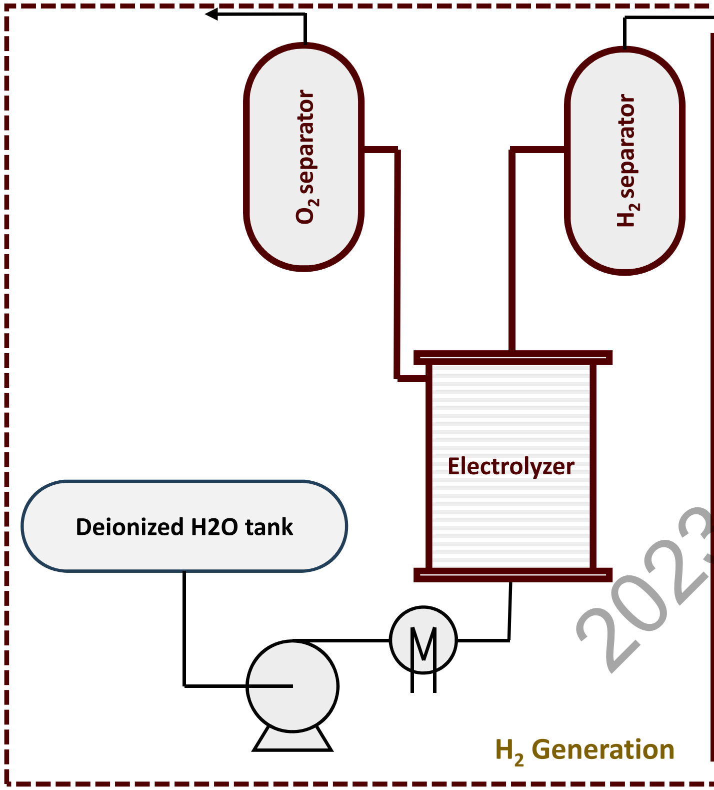
Fire almost invisible during daylight, can burn undetected

Buoyant nature – potential trapped at high point enclosure area

Recognizing component in typical H2 electrolyzer



Recognizing threats - Qualitative



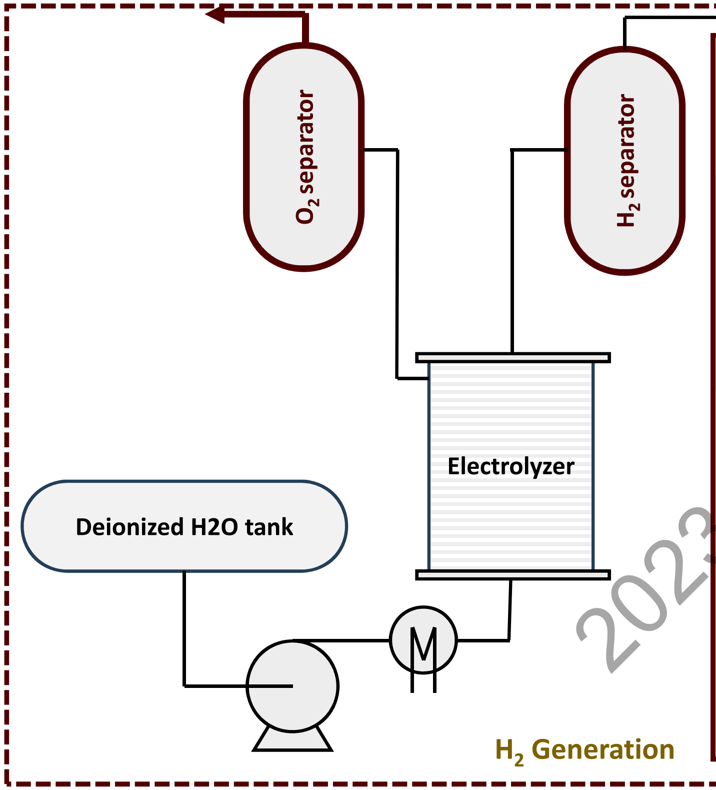
H_2/O_2 crossover mixing

H_2 ⟷ O_2

- Membrane damage
  - High temperature
    - Loss of feedwater – Pump failure
    - Loss of chilled water

- High temperature trip protection
- Low flow protection/pump trip interlock
- O2 analyzer in H2 stream – Limiting concentration
- H2 in O2 analyzer

Recognizing threats - Qualitative



Safe venting

- Proximity of H2 and O2 venting location
- Ignition source – lightning strike, static

- Separation of vent point outlet for H_2 and O_2 system
- Lightning Protection System within vicinity
- Grounding, bonding, vent design specification

Recognizing threats - Qualitative

Failure of equipment integrity

• Overpressure
  • Blocked outlet of compressor, H2 generator
• Over temperature
  • Failure of heating element in De-Oxo and Dryer
	• High pressure alarm and trip protection
	• Pressure Safety Valve (PSV)
	• High temperature trip protection

Recognizing threats - Quantitative

Fire and explosion impact

- H_2 release – ventilation, early detection of gas/flame
- Jet Fire threat – Isolate and depressurize
- Sensitive receptor – Endurance time, fire/blast wall

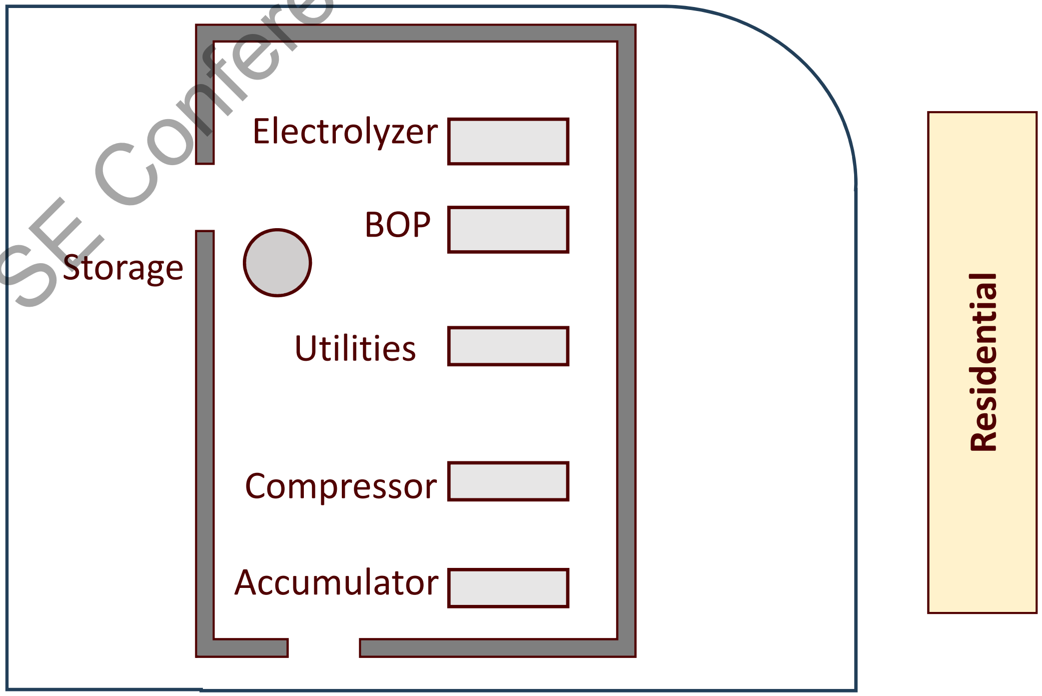
Key information output

- Jet flame length, thermal radiation and fire duration
- Unignited release radius
- Explosion radius and side-on peak overpressure

Recognizing threats – Case Study

Basis

- Highest pressure component – compressor (900 barg)
- Representative hole size (1% of flow area – 1" ID)*
- Inventory – 5 kg

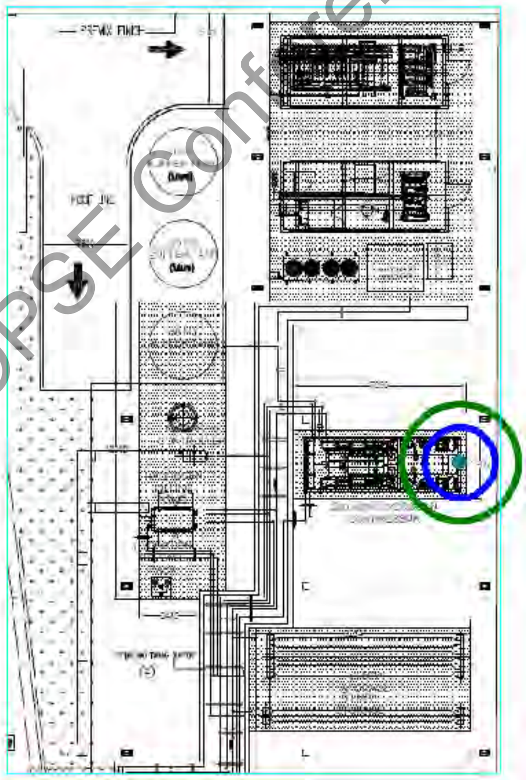


Site Layout Representation (not to be scaled)

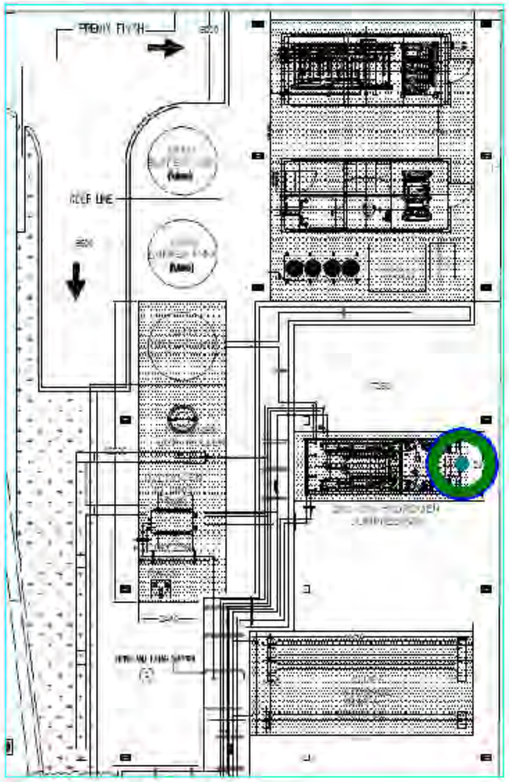
*NFPA 2, 2020

Recognizing threats – Case Study

- Results:
  - Dispersion to LFL – 1.5 meter
  - Jet Fire radiation ellipse – 1.2 meter
  - Jet Flame length – 1 meter
- Full rupture fire duration is only <1 second even though the impact radius is large

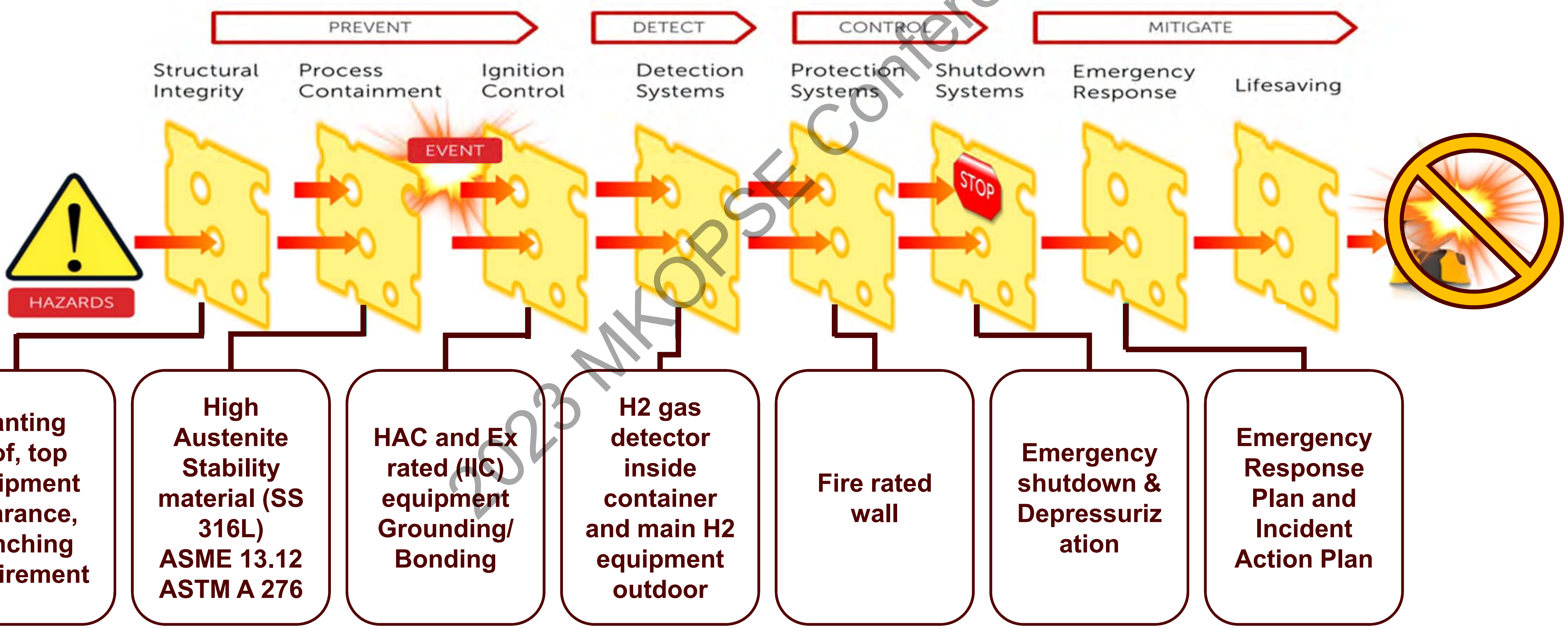


Dispersion



Jet Fire

Post Hazard recognition – "Design-It-Right"



- Slanting roof, top equipment clearance, trenching requirement
- High Austenite Stability material (SS 316L) ASME 13.12 ASTM A 276
- HAC and Ex rated (IIC) equipment Grounding/ Bonding
- H2 gas detector inside container and main H2 equipment outdoor
- Fire rated wall
- Emergency shutdown & Depressurization
- Emergency Response Plan and Incident Action Plan

Thank You

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

*In Association with **IChemE***

October 11-13, 2023

Sponsored by aramco

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

78th Annual Instrumentation and Automation Symposium

Speaker profile

- Gregory K. McMillan is a retired Senior Fellow from Solutia
- Control Magazine "Engineer of the Year" award in 1994
- Control Magazine "Automation Hall of Fame" inductee in 2001
- InTech Magazine "Most Influential Innovators" award in 2003
- International Society of Automation "Life Achievement" award in 2011
- Author of more than 30 books and 400 articles
  - https://blog.isa.org/author/greg-mcmillan
  - https://www.controlglobal.com/blogs/controltalkblog

Control Strategies to Improve Reactor Performance

Advances in Reactor Measurement and Control

By Gregory K. McMillan

Written from a practical perspective, *Advances in Reactor Measurement and Control* underscores how control system design can address the different process responses and fundamental characteristics of the major types of reactors in the process industry.

This book enables the reader to learn what measurements, control strategies, controller features and tuning parameters will achieve process objectives for a given type of reactor. No prior education or experience in process engineering or control theory is needed. This book starts with the fundamentals and principles needed to become proficient in getting the best reactor and control system performance. The practitioner will be able to design, implement and support straightforward configurations based on the type of process and equipment.

McMillan—the author of more than 20 books, including several ISA best sellers, Process Automation Hall of Fame inductee and the recipient of the ISA Life Achievement Award—educates through a practitioner's experience and perspective, outlining the general concepts and details, from the field to the control room, for the control and optimization of batch and continuous reactors.

"Taking a practitioner's approach, I believe, is unique," McMillan says. "The concepts in this book are developed to help the reader understand the fundamental differences in reactor applications and improve the performance of nearly all types of reactors. This book is unique in providing readily configurable practical solutions for batch and fluidized bed reactors besides the more traditional continuous stirred tank reactors."

According to McMillan, the book's practical value is reinforced through its:

- Simple presentation of the characteristics and implications of each of the dynamic responses needed to achieve the necessary efficiency, capacity, quality, and safety in operation.
- Clear explanation of the PID features and tuning and control loops needed for addressing the lack of smoothing in dead time dominant processes and the lack of negative feedback in integrating and runaway processes.

The material in this book represents knowledge from leading participants in the ISA Mentor program, Brian Hrankowsky and Héctor Torres, reflecting decades of experience in the pharmaceutical and chemical industry, respectively.

International Society of Automation
67 T.W. Alexander Drive
P.O. Box 12277
Research Triangle Park, NC 27709
PHONE +1 919-549-8411
FAX +1 919-549-8288
EMAIL info@isa.org
www.isa.org

ISBN: 978-0-87664-089-0

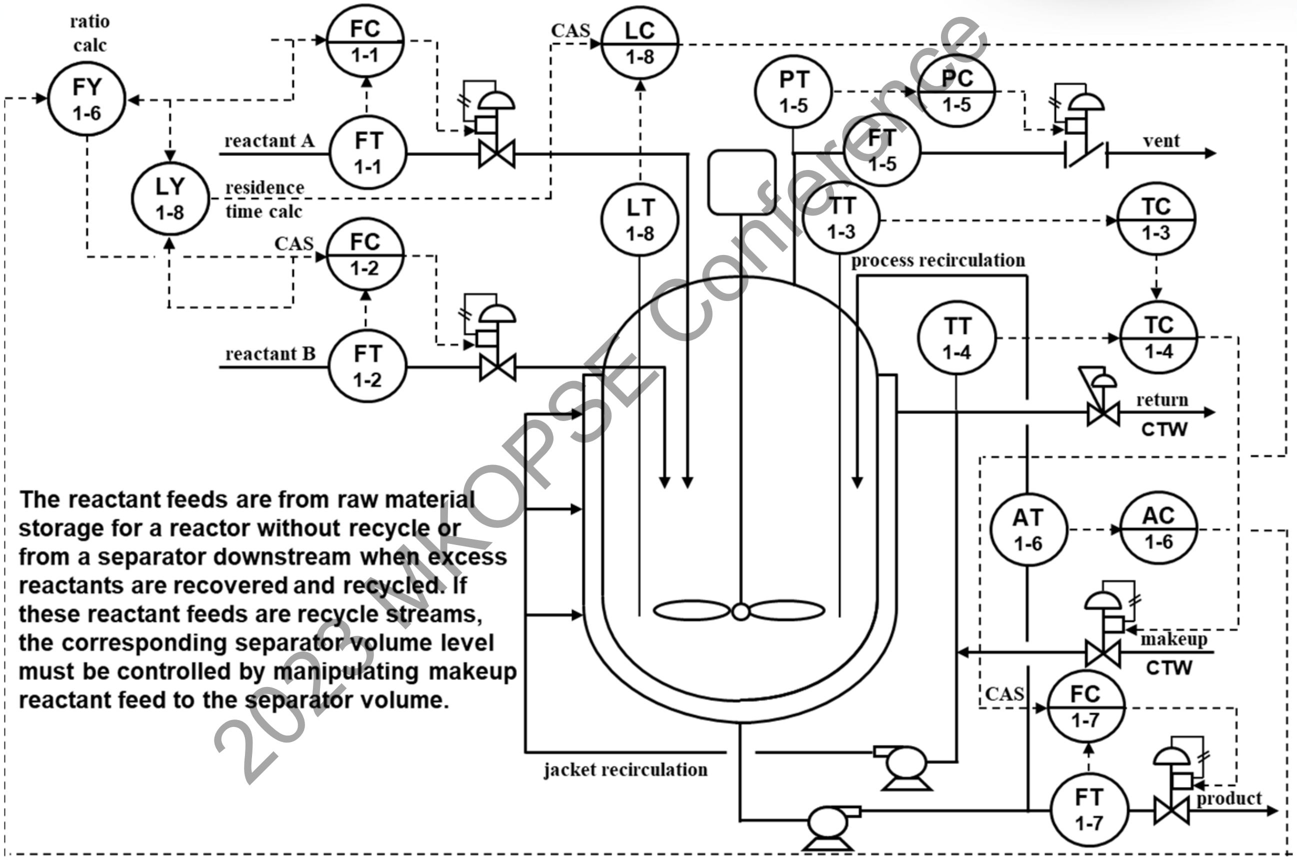
Gregory K. McMillan Advances in Reactor Measurement and Control

Advances in Reactor Measurement and Control

By Gregory K. McMillan

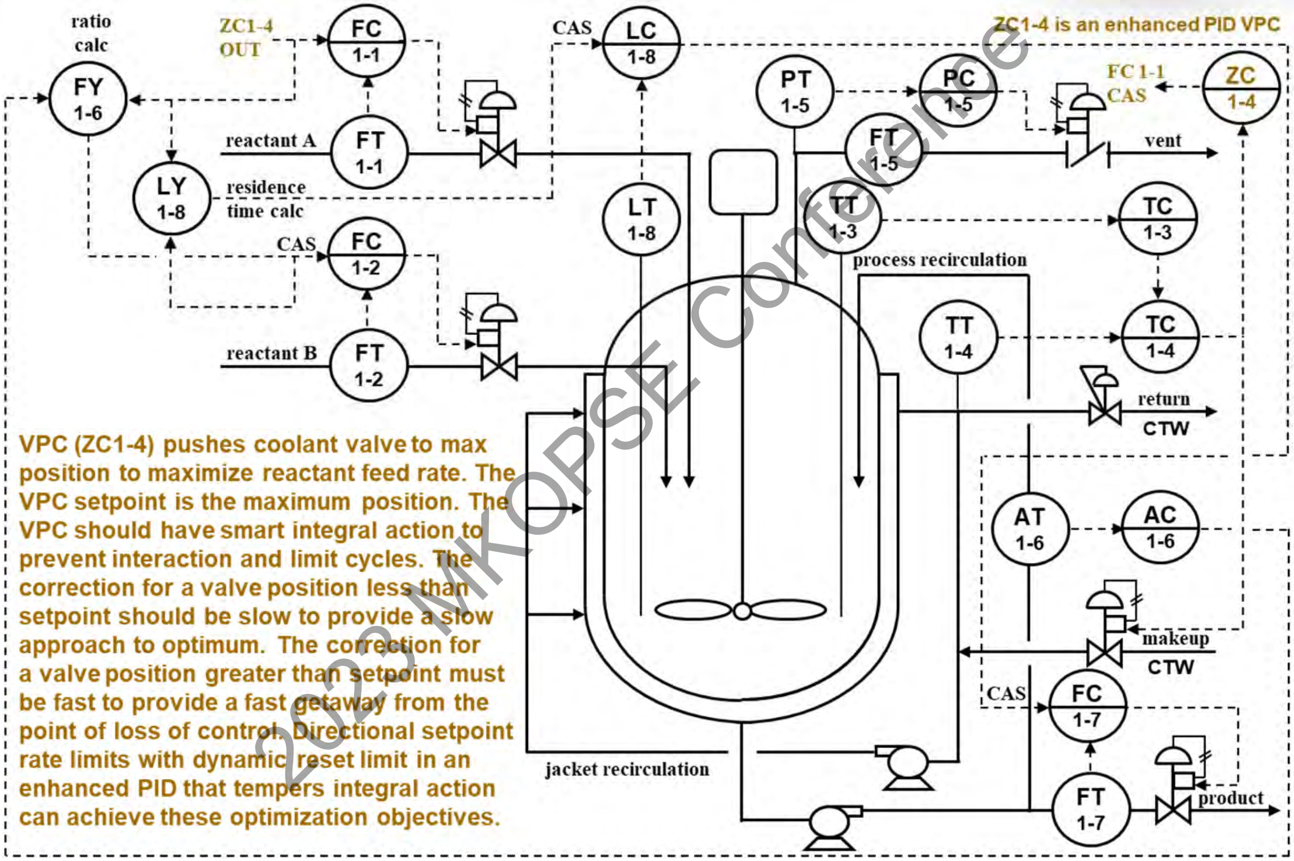
Setting the Standard for Automation™

About 20 free copies will be available to give out to presentation attendees



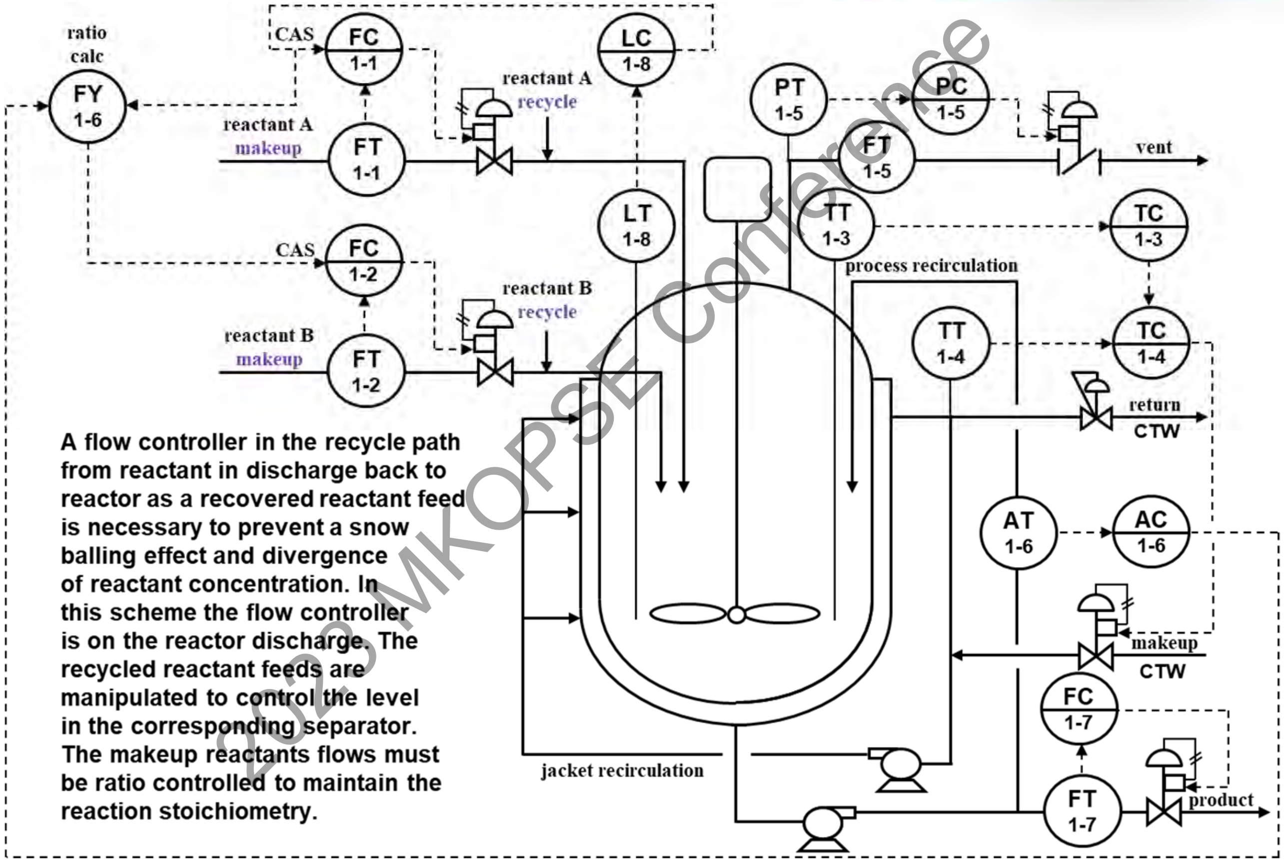
The reactant feeds are from raw material storage for a reactor without recycle or from a separator downstream when excess reactants are recovered and recycled. If these reactant feeds are recycle streams, the corresponding separator volume level must be controlled by manipulating makeup reactant feed to the separator volume.

For a liquid reactor, level control sets reaction time via residence time, temperature control sets reaction rate via energy, and composition control enforces the stoichiometric ratio.



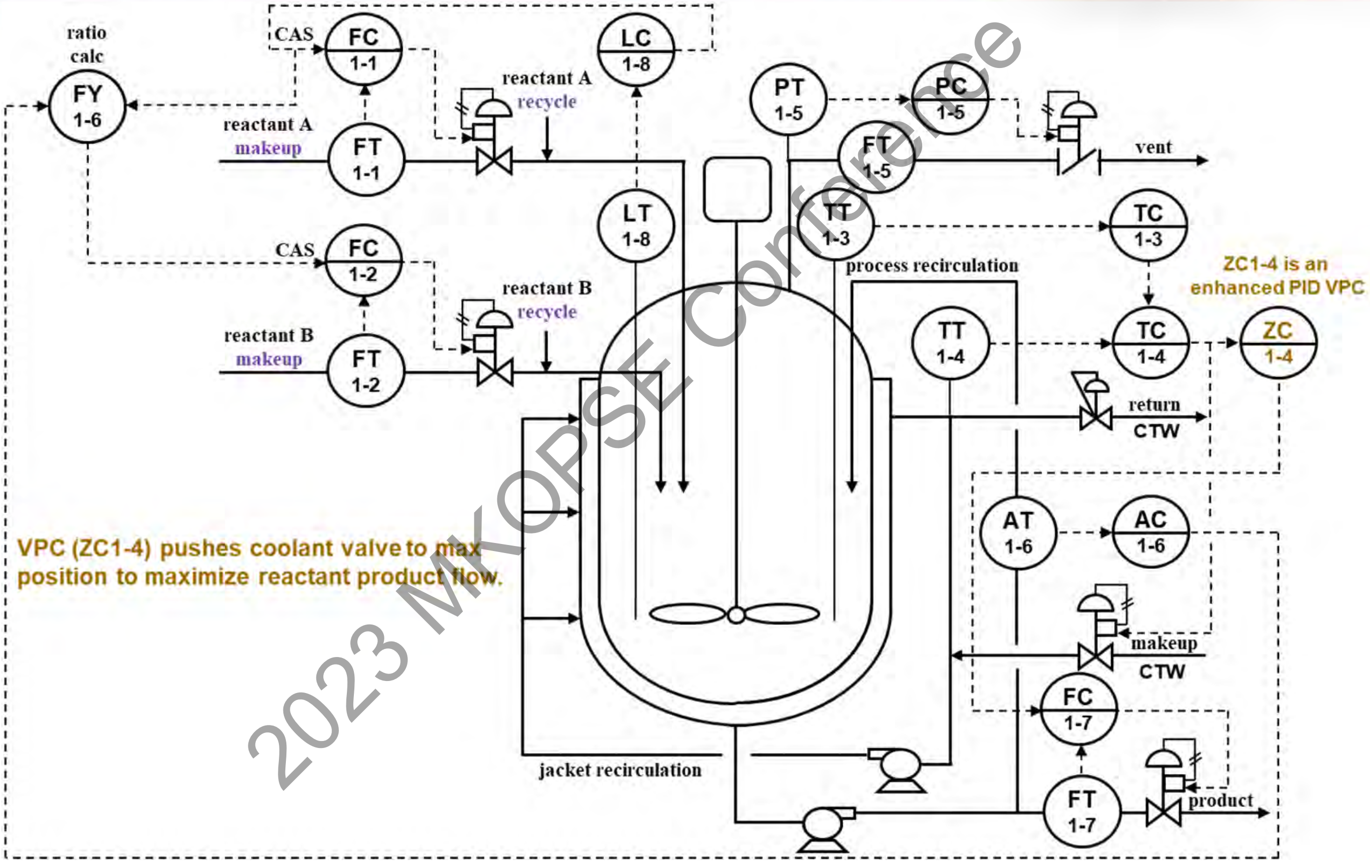
VPC (ZC1-4) pushes coolant valve to max position to maximize reactant feed rate. The VPC setpoint is the maximum position. The VPC should have smart integral action to prevent interaction and limit cycles. The correction for a valve position less than setpoint should be slow to provide a slow approach to optimum. The correction for a valve position greater than setpoint must be fast to provide a fast getaway from the point of loss of control. Directional setpoint rate limits with dynamic reset limit in an enhanced PID that tempers integral action can achieve these optimization objectives.

For a liquid reactor, the production rate can be maximized by a VPC (ZC1-4) that increases reactant feed till the jacket temperature valve reaches maximum position.



A flow controller in the recycle path from reactant in discharge back to reactor as a recovered reactant feed is necessary to prevent a snow balling effect and divergence of reactant concentration. In this scheme the flow controller is on the reactor discharge. The recycled reactant feeds are manipulated to control the level in the corresponding separator. The makeup reactants flows must be ratio controlled to maintain the reaction stoichiometry.

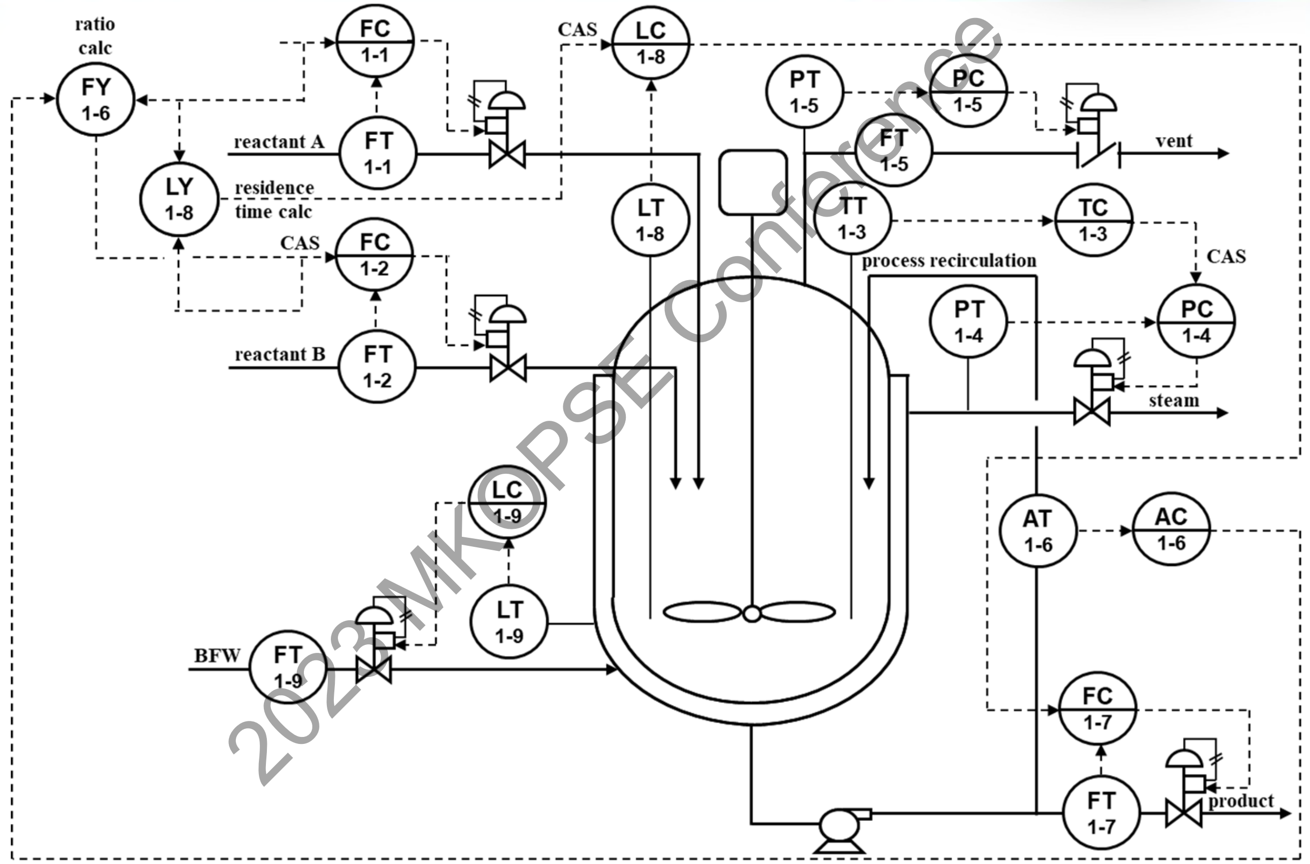
For a liquid reactor with recycle of recovered reactants set by downstream separator level controllers, the makeup reactant flows must be ratioed to maintain stoichiometry.



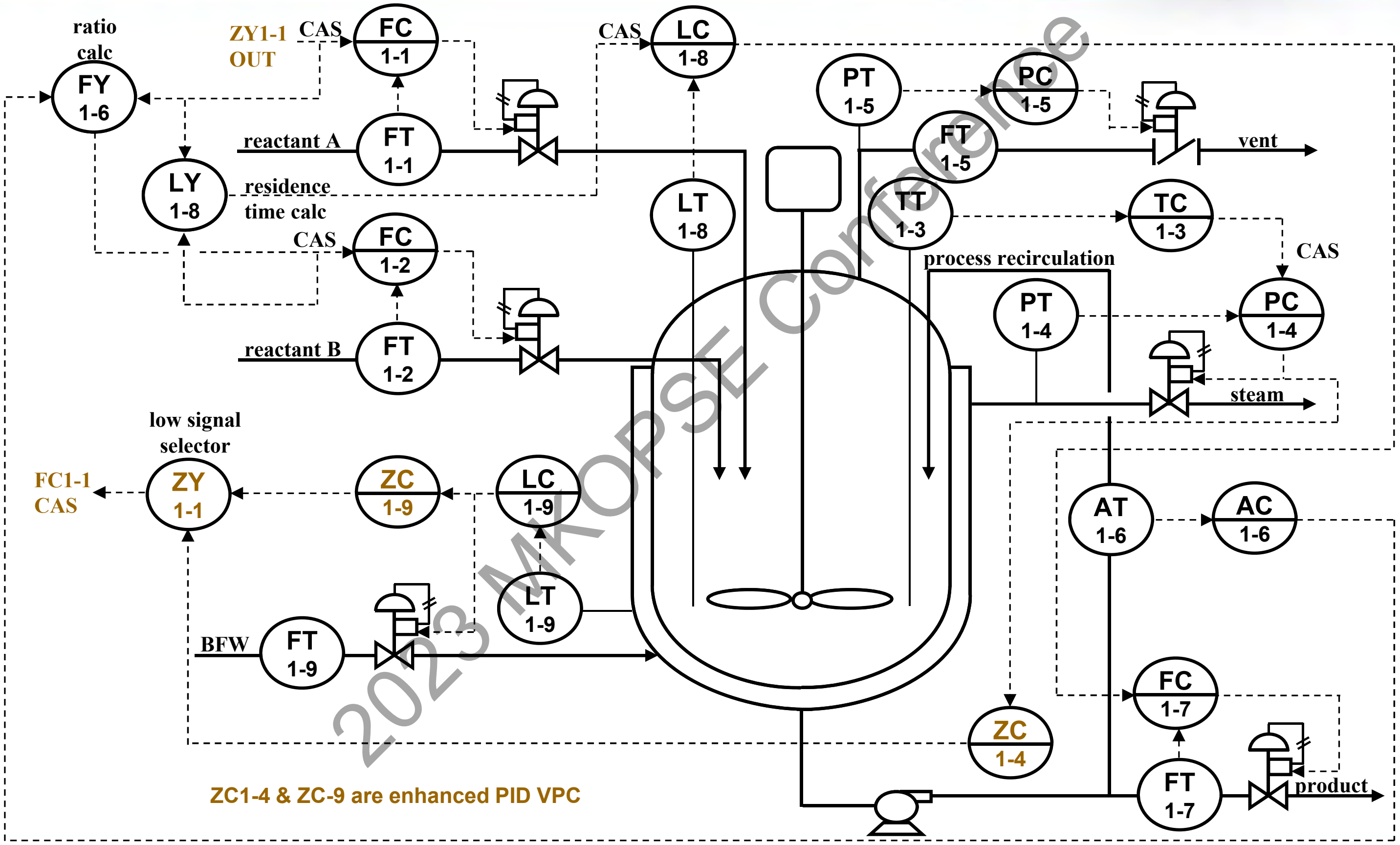
ZC1-4 is an enhanced PID VPC

VPC (ZC1-4) pushes coolant valve to max position to maximize reactant product flow.

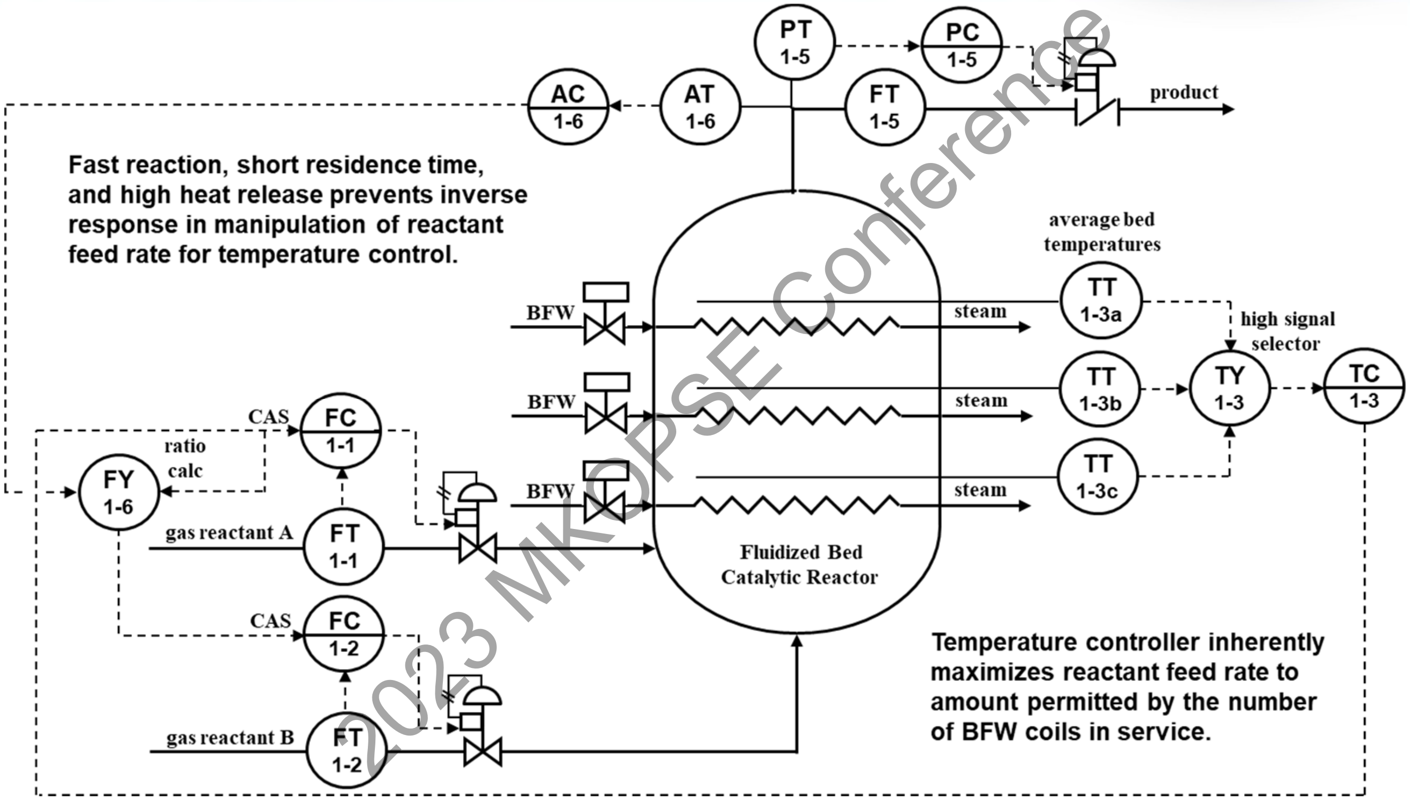
For a liquid reactor with recycle of recovered reactants set by downstream separator level controllers, the production rate can be maximized by VPC setting discharge flow.



For a high temperature liquid reactor, coolant is replaced with the boiling of water to provide a constant temperature heat sink that helps stabilize highly exothermic reactions.



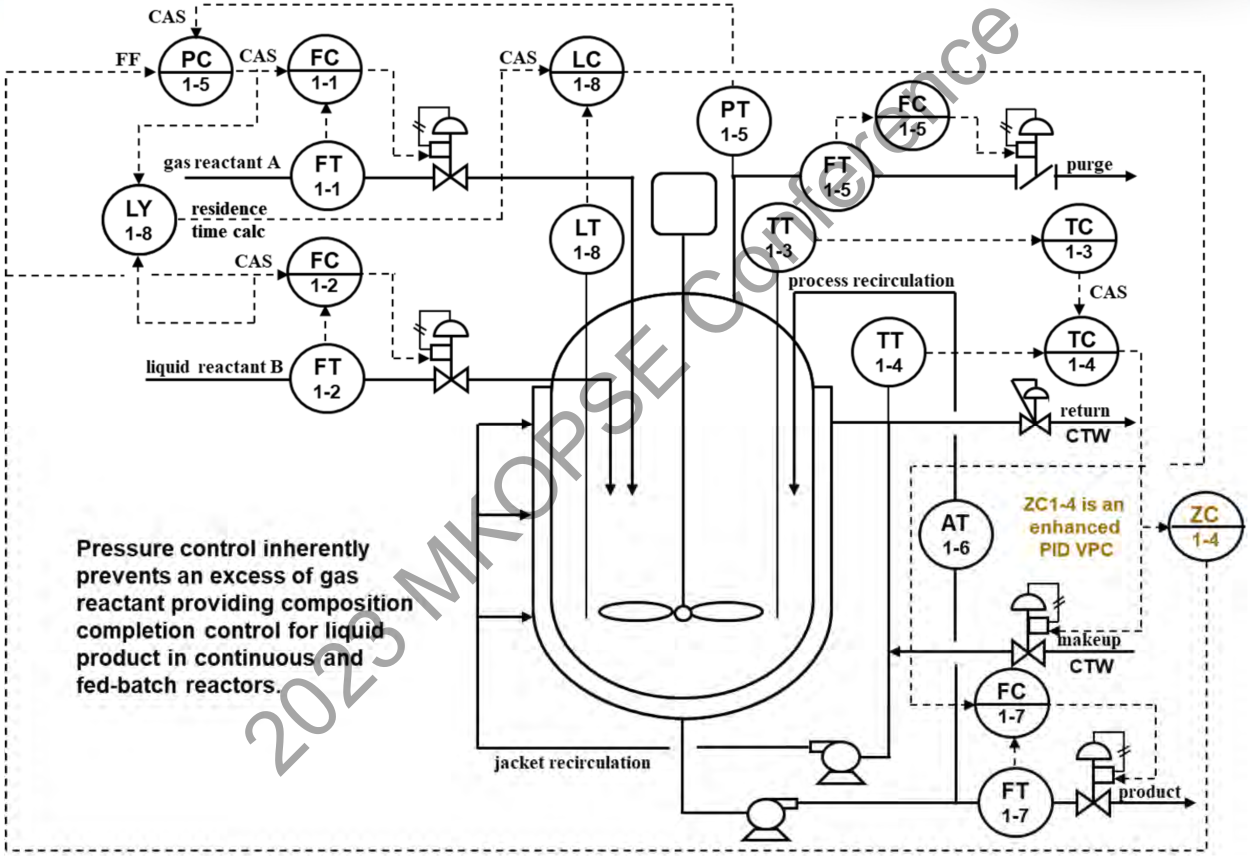
For a high temperature liquid reactor, the production rate can be maximized by a VPC that increases reactant feed till the BFW or steam valve reach maximum position.



Fast reaction, short residence time, and high heat release prevents inverse response in manipulation of reactant feed rate for temperature control.

Temperature controller inherently maximizes reactant feed rate to amount permitted by the number of BFW coils in service.

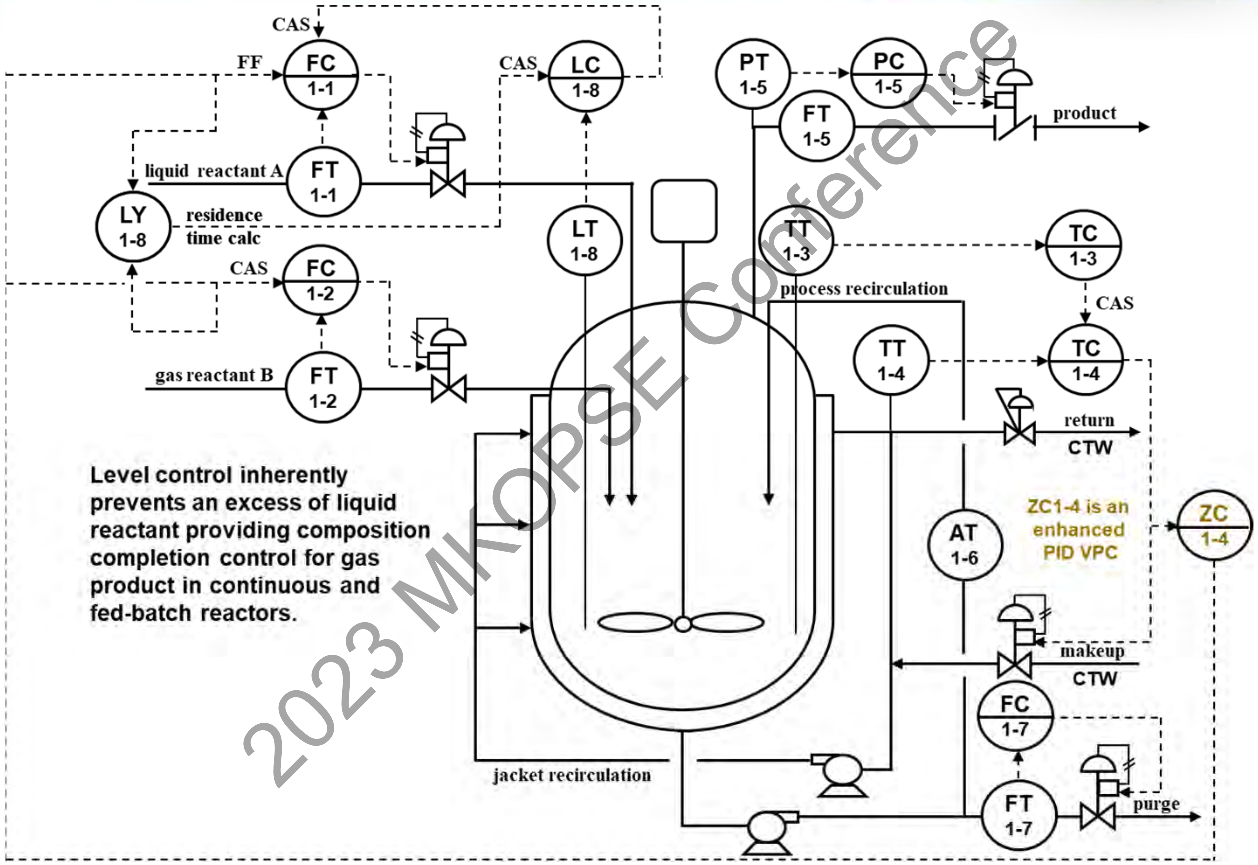
An enhanced PID using an at-line analyzer or inferential measurement for concentration control sets the gas reactant flow ratio, a pressure controller sets reaction time, and a temperature control system maximizes reaction rate by setting gas feed rate.



ZC1-4 is an enhanced PID VPC

Pressure control inherently prevents an excess of gas reactant providing composition completion control for liquid product in continuous and fed-batch reactors.

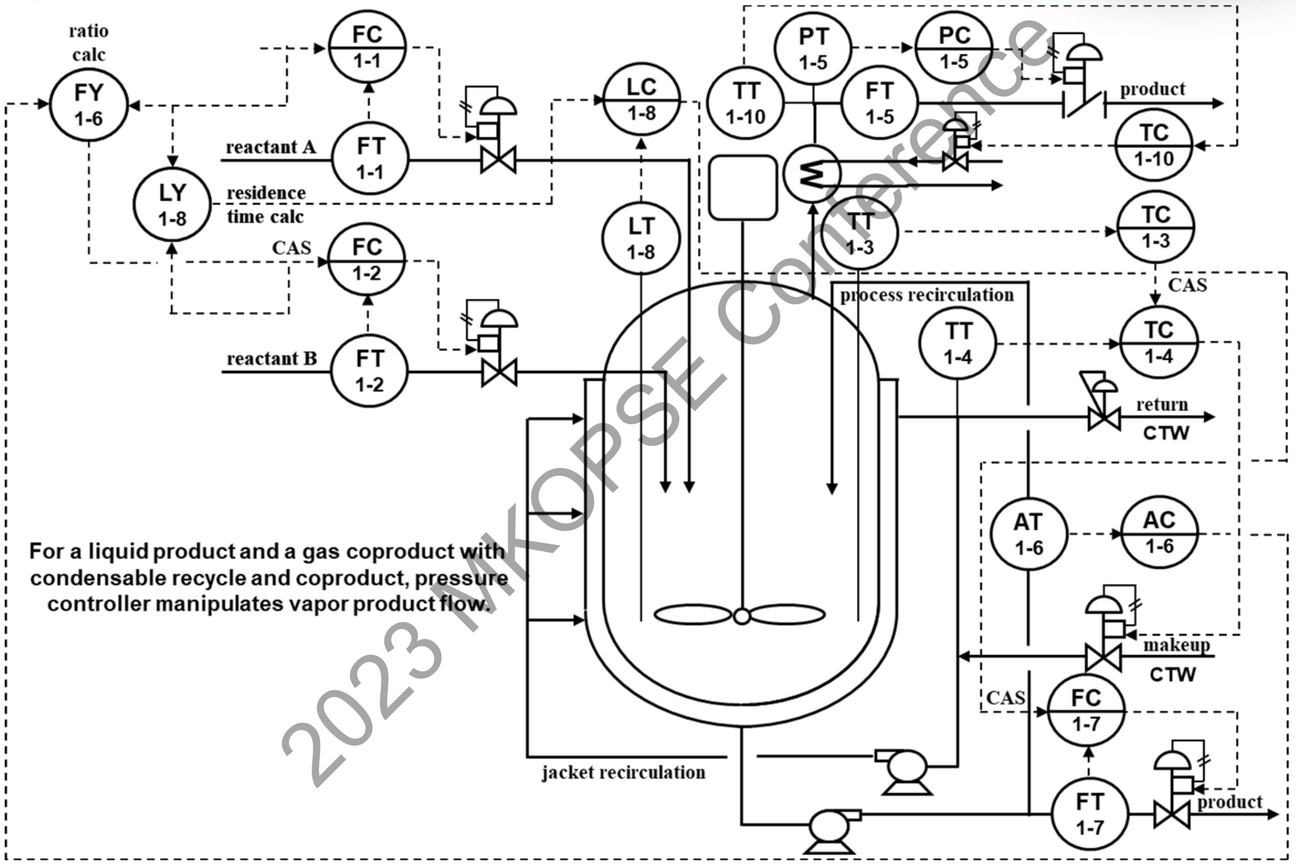
For a liquid and gas reactants, and a liquid product, pressure control maintains continuous composition completion control and level control maintains the liquid inventory.



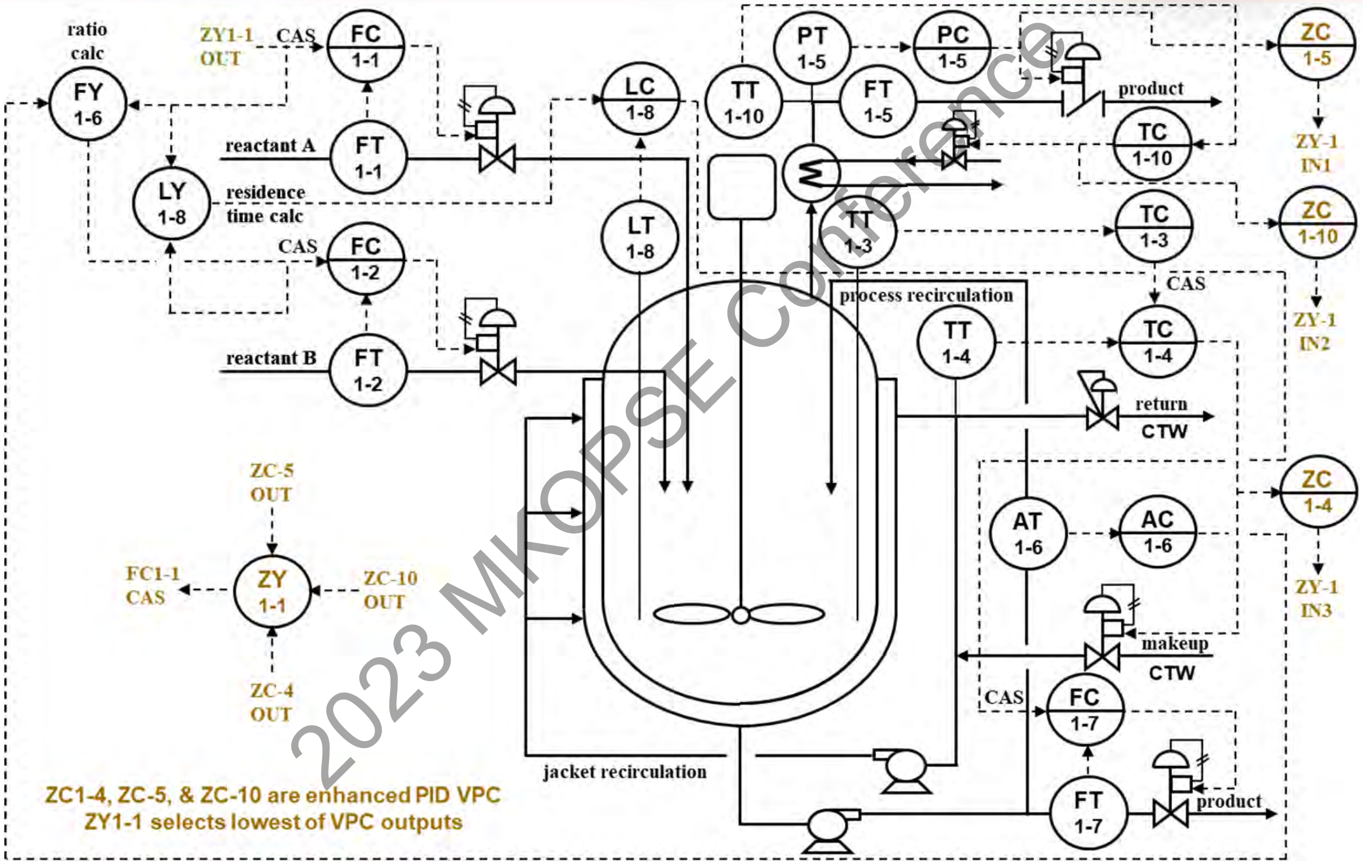
Level control inherently prevents an excess of liquid reactant providing composition completion control for gas product in continuous and fed-batch reactors.

ZC1-4 is an enhanced PID VPC

For a liquid and gas reactants, and a gas product, level control maintains continuous composition completion control and pressure control maintains the gas inventory.

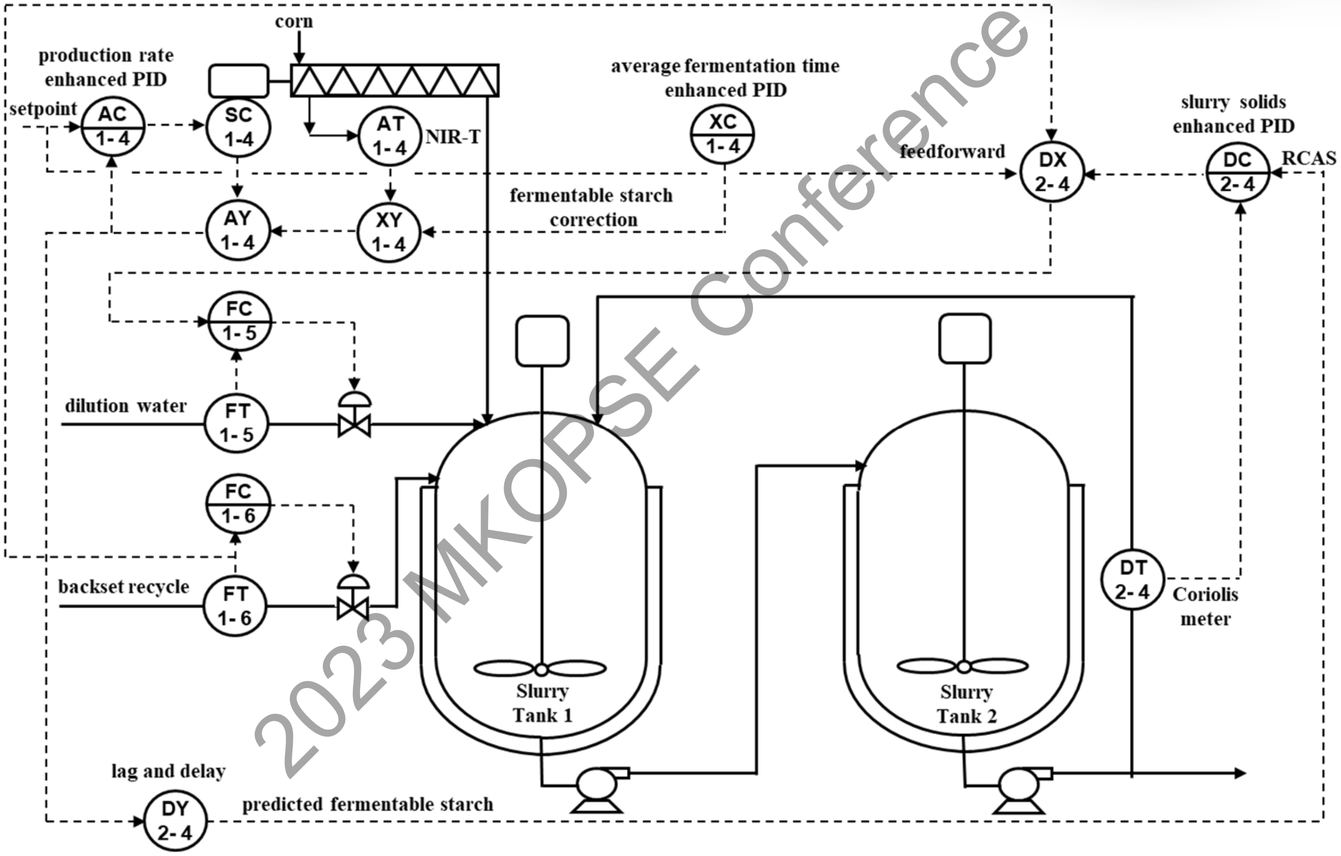


For a liquid product and a gas co-product with condensable recycle and co-product, a reactor pressure controller manipulates vapor product flow.

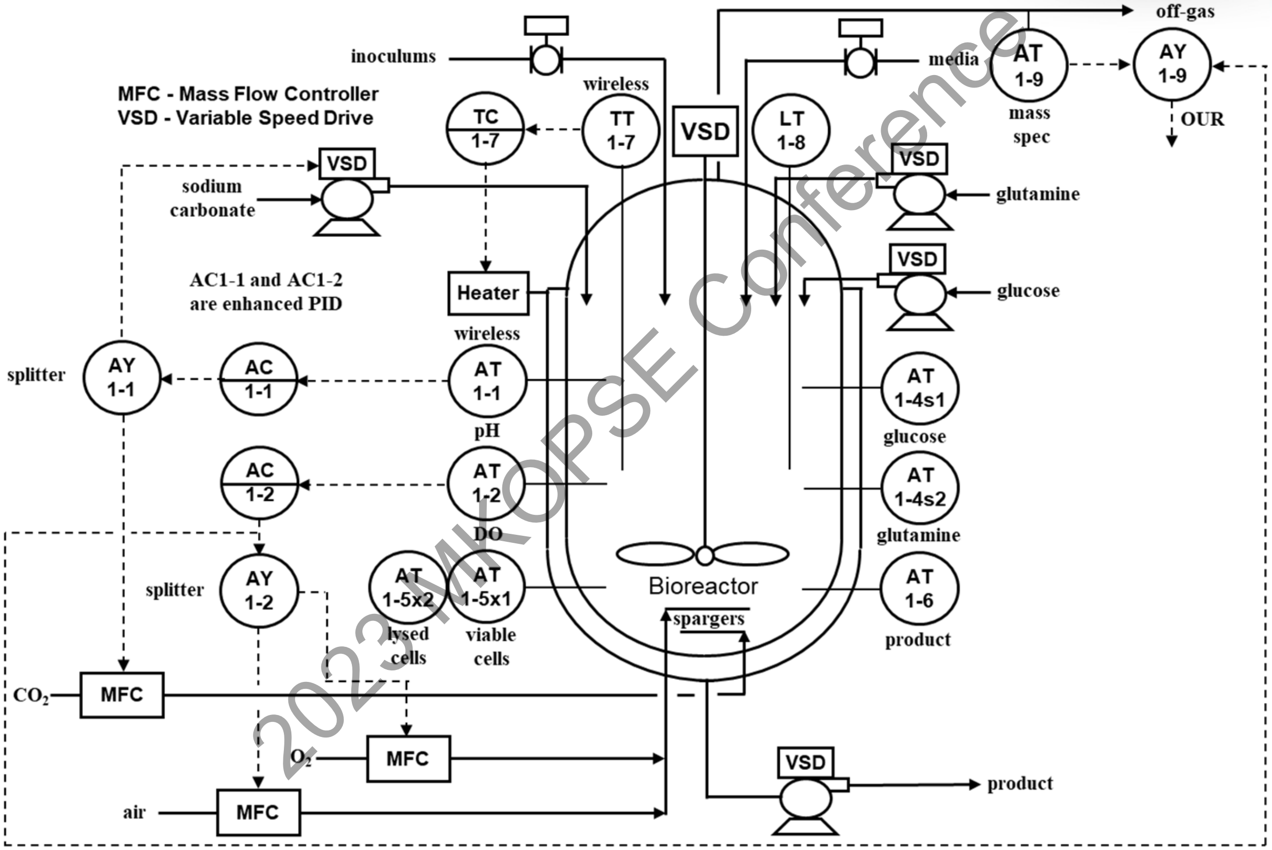


ZC1-4, ZC-5, & ZC-10 are enhanced PID VPC
ZY1-1 selects lowest of VPC outputs

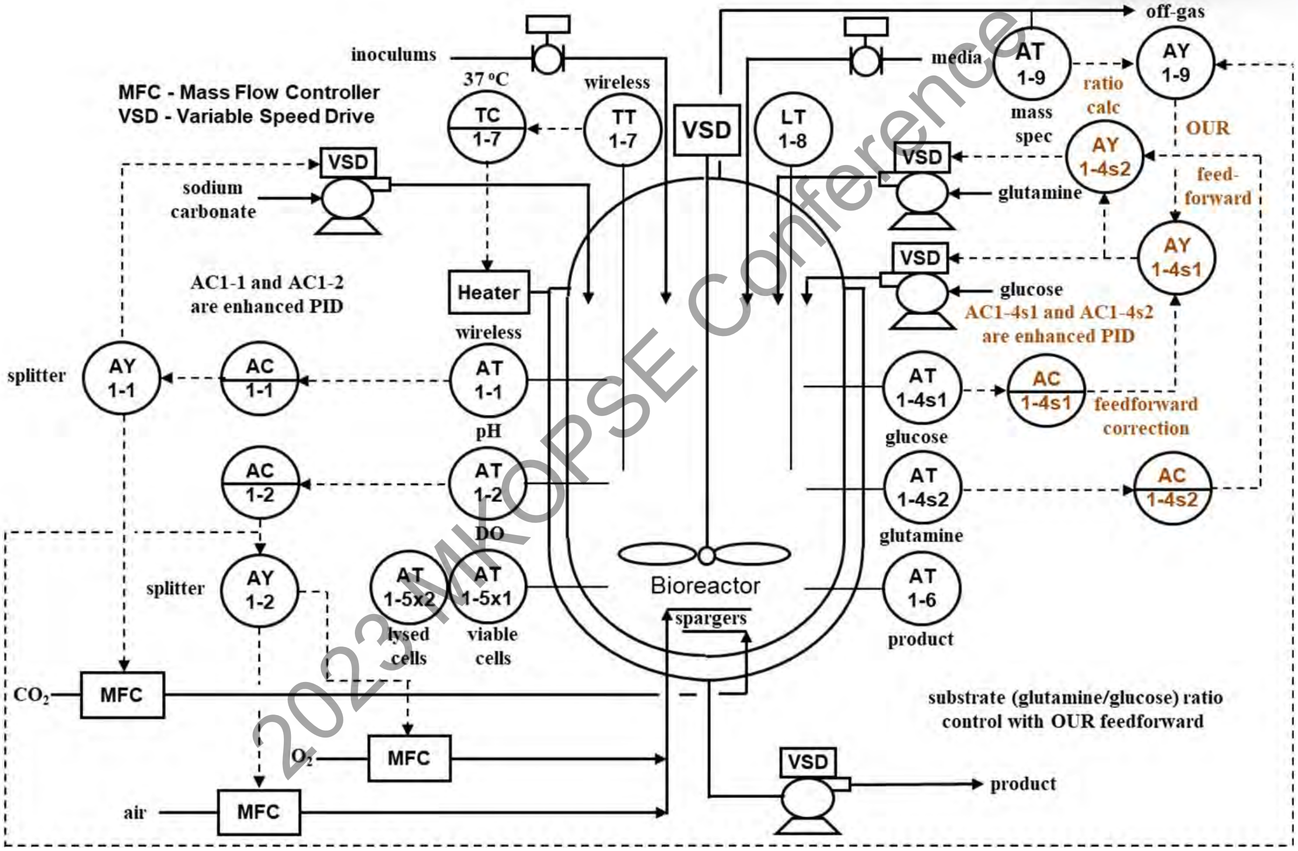
For a liquid product and a gas co-product, the production rate can be maximized by a VPC that increases reactant feed till the coolant valves and gas product valve reach maximum position



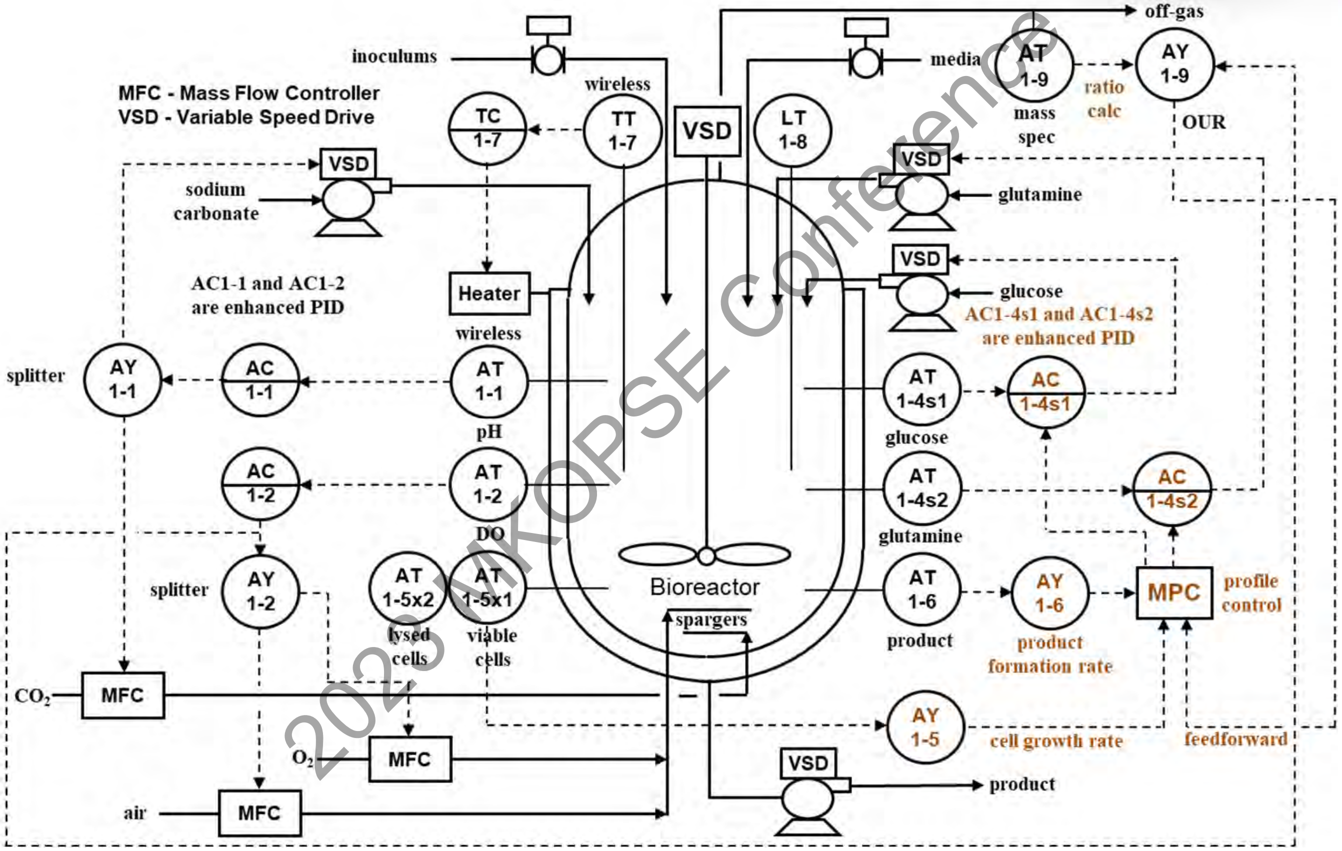
Ethanol plant yield can be increased by the use of an at-line corn analyzer
and enhanced PID to optimize corn feed rate, slurry solids concentration, and batch time.



Mammalian bioreactors have all of the process control of bacterial reactors, but with more complex DO and pH loops with decoupling and smarter split ranged control.



Online and at-line analyzers enable substrate concentration control with glutamine feed ratioed to glucose.
An OUR feedforward anticipates changes in glucose utilization rate.



Growth rate and product formation rate from the rate of change of actual or inferential measurements can provide fed-batch profile control by the manipulation of glucose and glutamine.

Coriolis Meters and Completion Control

- For well mixed reactors the largest sources of improper reactant concentration leading to excess reactant are errors in reactant flow measurement and changes in reactant composition. Note that a deficiency in one reactant concentration creates an excess of another reactant. Coriolis meters can be used to provide the greatest mass flow measurement precision and rangeability with density correction for any changes in reactant feed concentration. Consequently, Coriolis meters on reactant feeds eliminate most of the sources of reactant unbalances if the mass flow ratios are correct and coordinate to maintain reaction stoichiometry
- If density of the excess reactant is significantly different than the density of the other components in the reactor, a Coriolis meter in the recirculation line can provide an inline inferential measurement of the excess reactant concentration. Inline composition measurements by means of sensors in a vessel or pipeline provide a measurement in a few seconds whereas at-line analyzers with sample systems can have 30 or more minutes of dead time due to sample and analyzer cycle times. An enhanced PID is essential to deal with these cycle times.
- Completion control seeks to provide for both batch and continuous reactors a complete conversion of all the reactants and consequently no excess accumulation of a reactant in a particular phase. If the reactants are in different phases and the product is a single phase, inventory control can be used for reaction completion control. The product must be a gas, liquid, or solids with no recycle or co-products in the other phases.

Key PID Features for Valve Position Control

Feature	Function	Advantage 1	Advantage 2
Up Down SP Velocity Limits (Directional Move Suppression)	Limit VPC Action Speed Based on Direction	Prevent Running Out of Valve	Minimize Disruption to Process
External Reset Feedback (Dynamic Reset Limit)	Limit VPC Action Speed to Process Response	Direction Velocity Limits	Prevent Burst of Oscillations
Adaptive Tuning	Automatically Identify and Schedule Tuning	Eliminate Manual Tuning	Compensation of Nonlinearity
Feedforward	Preemptively Set VPC Out for Upset	Prevent Running Out of Valve	Minimize Disruption
Enhanced PID (PIDPlus)	Suspend Integral Action until PV Update	Eliminate Limit Cycles from Stiction & Backlash	Minimize Oscillations from Interaction & Delay

For much more on how valve position control (VPC) is used for optimization of unit operations checkout the Control magazine article "Don't Over Look PID in APC"

https://www.controlglobal.com/control/distributed-control/article/11380959/control-valves-dont-over-look-pid-in-apc

2022 Mary Kay O'Connor Safety & Risk Conference

Health to Human is Safety to System: Making Safety Second Nature

In Association with IChemE and C-RISE

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

Process Safety Health: How Should We Approach Metrics and Monitoring?

October 5-7, 2022

Speaker profile

Dave Drerup
CEO

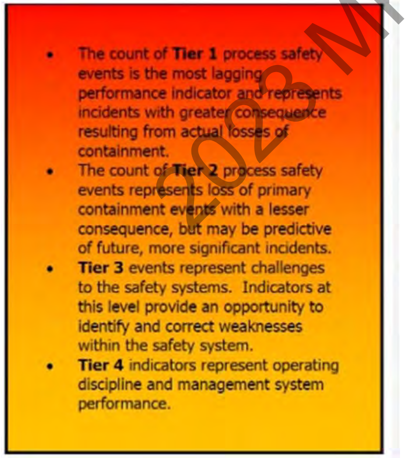
- Dave Drerup
- Operational Sustainability, LLC
- 29 Years in the Industry
- Field of Expertise: Process Safety, Mechanical Integrity, EH&S, Operational Excellence, IT Consulting
- Industry Involvement/Recognition: API Code Committees, AFPM, CCPS, Contribute to CCPS Publications

Process Safety Metrics

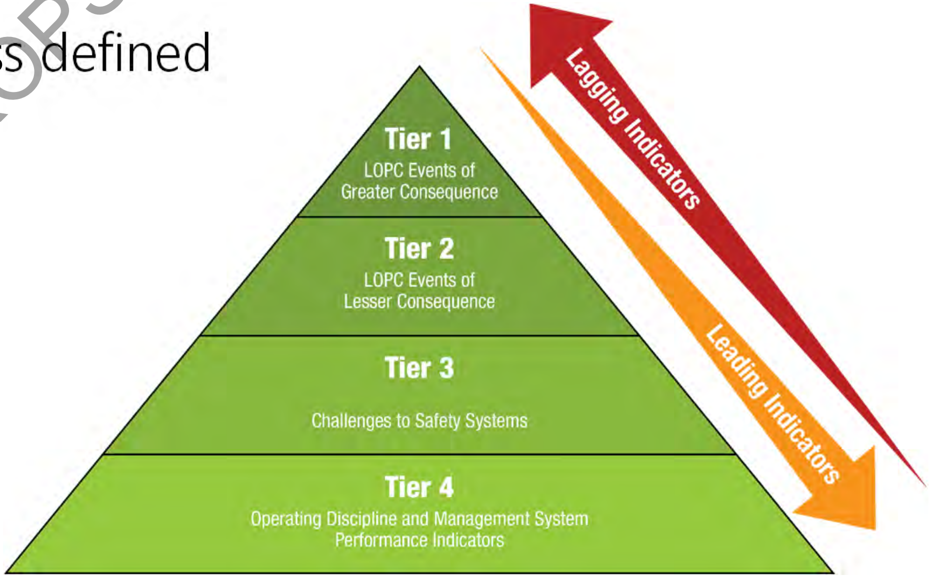
- Reporting and management system standards and guidelines
  - Good news … They exist
  - Bad news … There are lots of them
- Can be subjective and open for local or organizational interpretation
- Benchmarking efforts is challenging
  - AFPM, Phillip Townsend & Assoc., API 754…
- Leading indicators are more difficult

API-754

- Example: API RP-754 – Process safety indicators for the refining and petrochemical industries
- Helps assure accurate assessment of incidents for individual sites
- Drives consistency allowing Tier 1 & 2 comparison across an enterprise and with peers
- Leaves leading indicators less defined

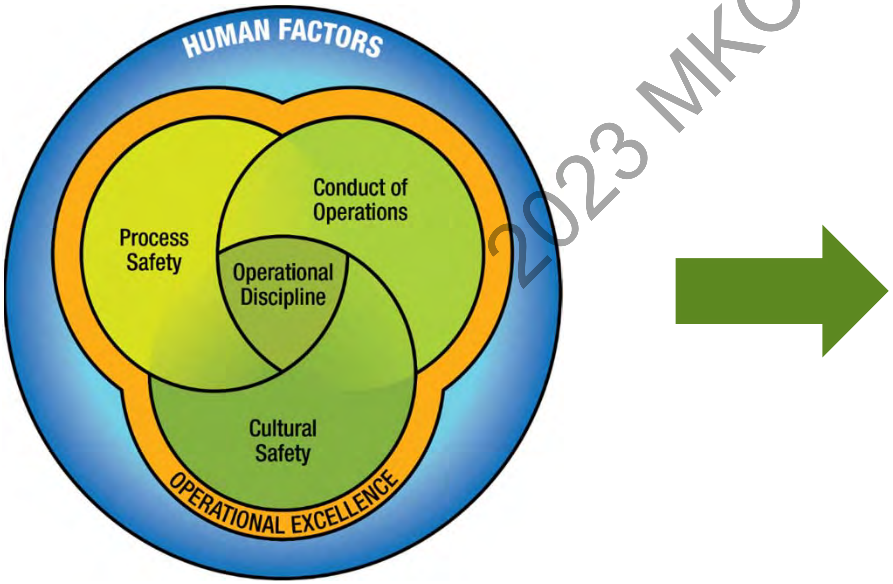


- The count of **Tier 1** process safety events is the most lagging performance indicator and represents incidents with greater consequence resulting from actual losses of containment.
- The count of **Tier 2** process safety events represents loss of primary containment events with a lesser consequence, but may be predictive of future, more significant incidents.
- **Tier 3** events represent challenges to the safety systems. Indicators at this level provide an opportunity to identify and correct weaknesses within the safety system.
- **Tier 4** indicators represent operating discipline and management system performance.



Why ESG Matters in Process Safety

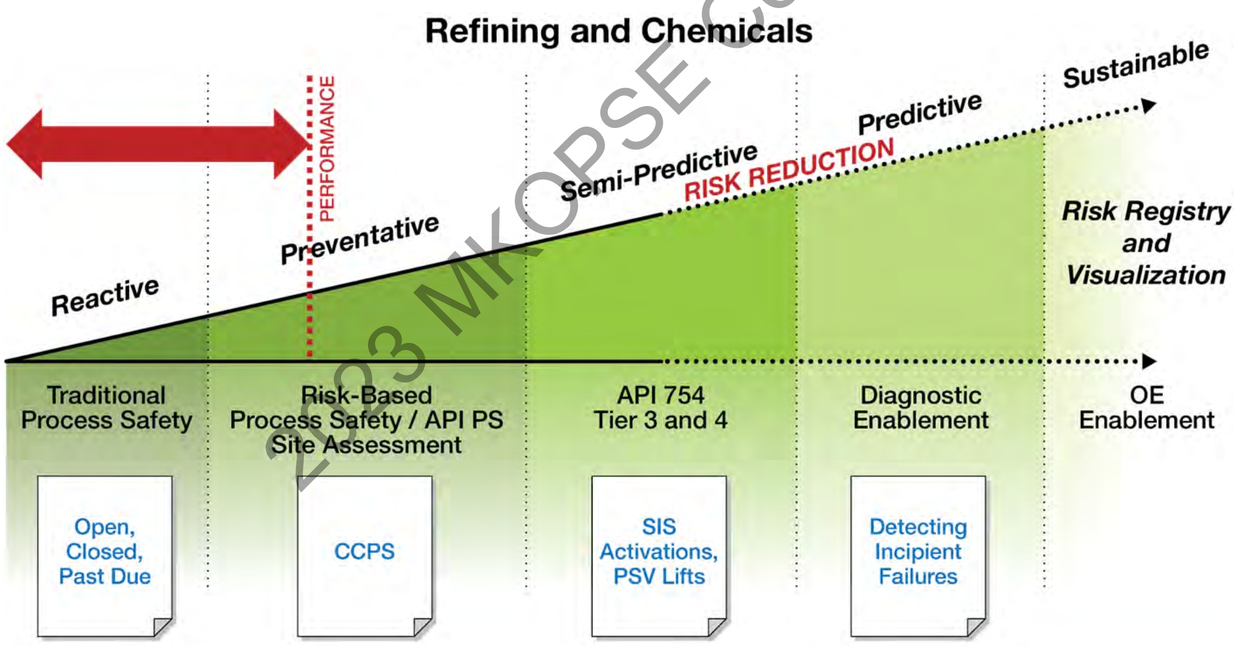
- Societal Expectations on performance tied to privilege to operate
- Risk-Based Process Safety Brings in Conduct of Operations
- API 754 Tier 4 – "G" is in the management system performance
- Tier 4 also requires "Operational Discipline"
- Develop useful metrics for Tier 4 and enact "Orchestration"



CCPS Vision 20/20

Metric Maturity / Opportunity

- Advancing to predictive / sustainable levels of performance maturity depends upon leading indicators



Process Safety Metrics: *"Leading is arguably lagging. Process Safety [today] is inherently reactive,"* per the Baker Panel Report.

Challenges

What is Process Safety Health?
A holistic, continuous monitoring methodology covering all process safety functional reporting areas to provide a clear picture of an organization's overall health.

- No IT strategy for process safety
- "Application / Data Silos" – can't aggregate, identify, and manage total risk
- Many data sets generating many reports
- Solutions need to incorporate asset-based intelligence, not just process workflows
- We aren't AI-enabled

To meet the need, companies will need to undergo significant re-architecting of their existing Process Safety IT portfolio.

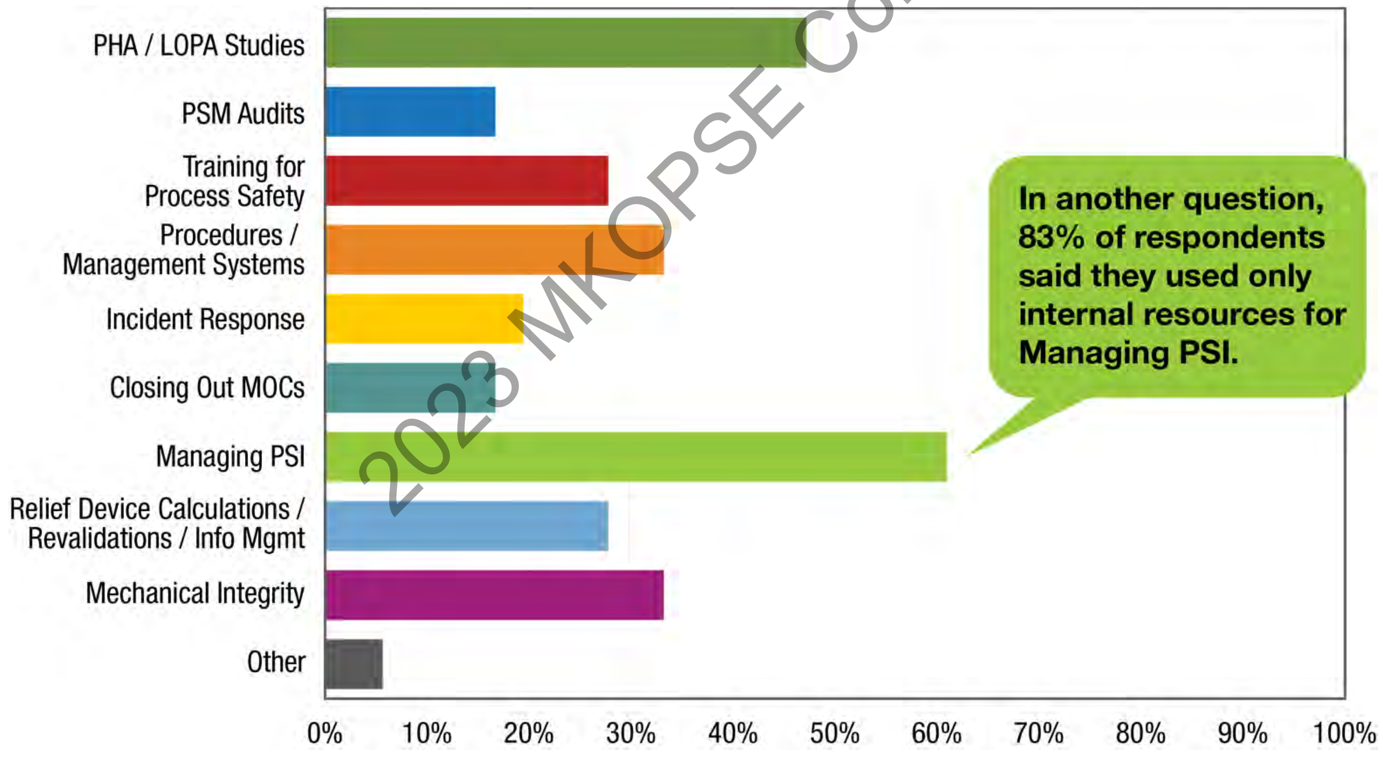
Challenges: Application Proliferation

Audit, Incident Investigation, Corrective & Preventative Actions (CAPA)	→	Basic EHS compliance starting point focusing on safety with EHS vendors
PHA, MOC, PSSR, Organizational Change	→	Core PSM focus
Mechanical Integrity	→	Inspection and EAM software focus area
PSI, Relief Devices	→	Engineering content vendors
Procedural Automation	→	Boutique vendors
Training, LMS, Competency Management	→	LMS vendors
LOPA, SIS, Alarm Management	→	Safety lifecycle vendors
Work Permitting	→	EHS vendors

OS PSM market research indicated that nearly two-thirds of respondents from companies with more than 2500 employees were operating in basic, siloed IT systems to manage process safety.

Which Elements Are Most Challenging Today?

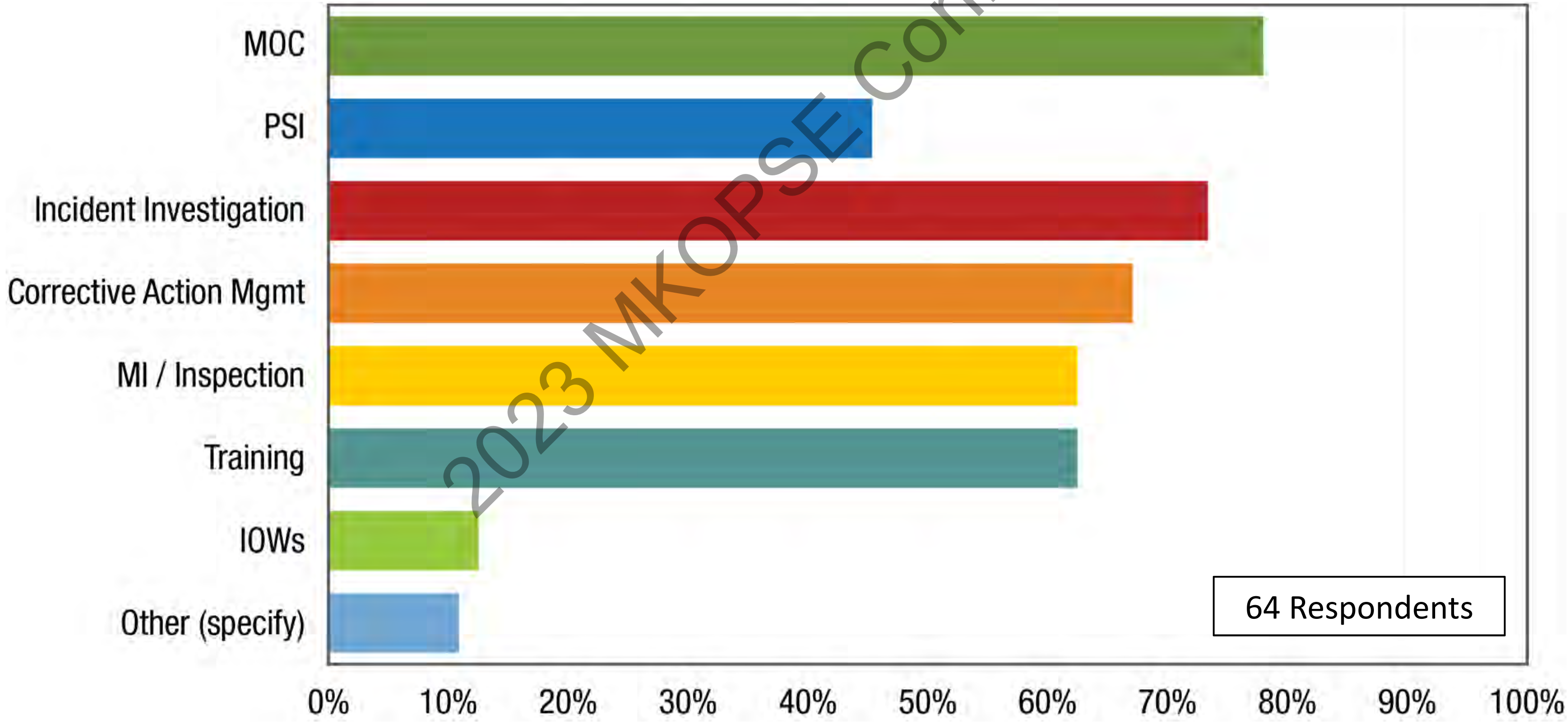
- In your opinion, what elements of Process Safety are the hardest to provide adequate resources for, whether internal or external?
  (check all that apply)



In another question, 83% of respondents said they used only internal resources for Managing PSI.

PSM IT Portfolio

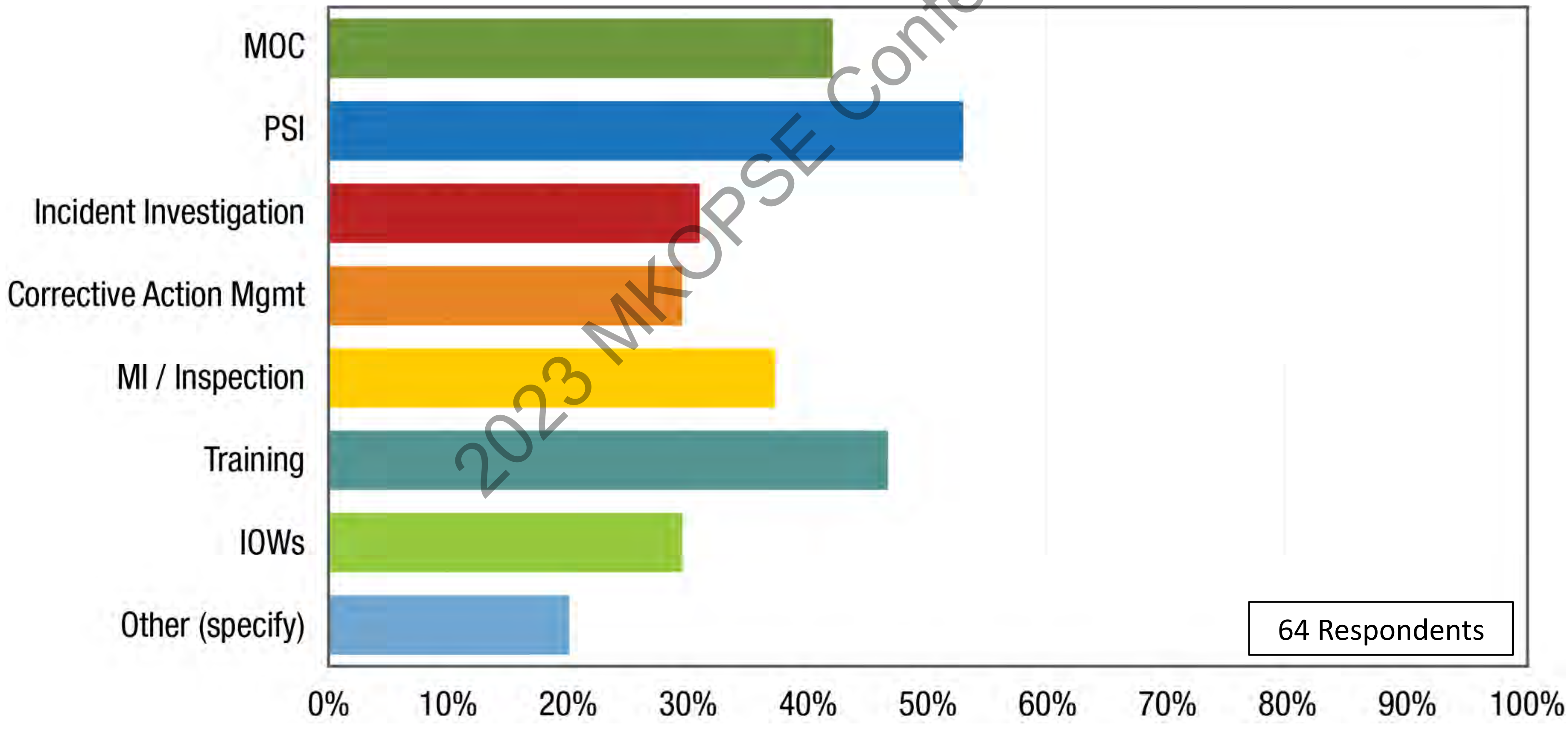
- What Process Safety processes currently use significant automation and/or technology in your organization? (check all that apply)



64 Respondents

Challenges: Survey – PSM IT Investment

- Thinking about your own facility or organization, do you anticipate an increasing need for automation of these processes **within the next 3 years**?



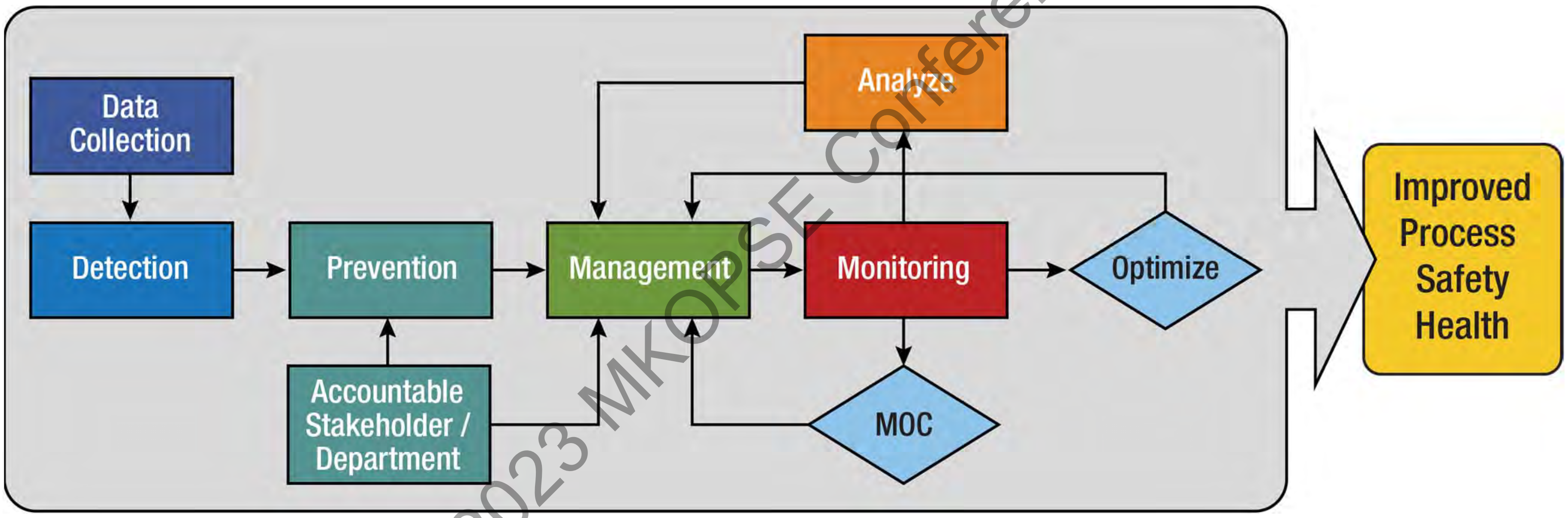
Need a Digital "Strategy" for PSM

Process Safety Framework

Strategy to Enable Holistic PSM / Dynamic Risk Management

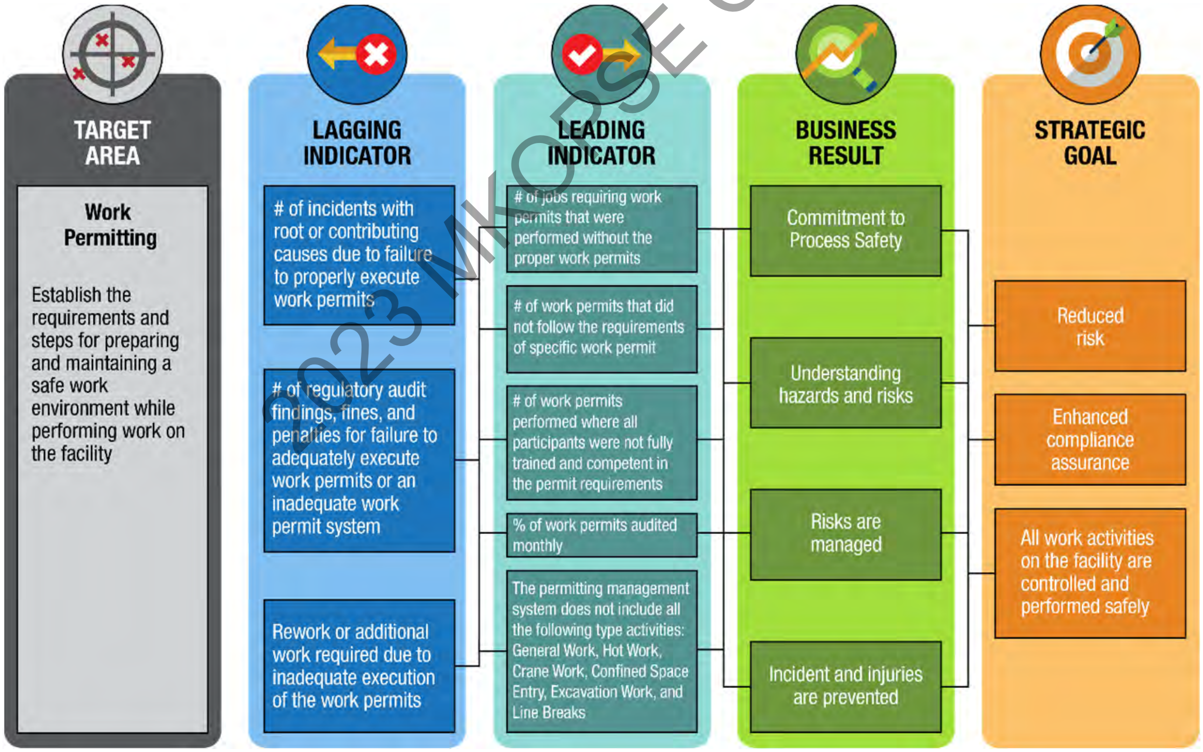
Phase 1	**"Basic PSM"** **CAPA, Incident, Process Risk / PHA**
Phase 2	**"Intermediate PSM"** **MOC, PSSR, Document Management, Training, LOPA, Audit**
Phase 3	**"Advanced PSM"** **Inspection, Organizational Change, Relief Device Management, Task Management, CoW / LOTO**
Phase 4	**"Mature PSM"** **IOWs, RBI, Alarms, SIS, Procedures, PSI, Competency, Production Loss**

Process Safety Health



Path Forward: Define Metrics

- Identify indicators tied to quantifying performance risks and risks to achieving Strategic / ESG goals / targets
- Ensure the metrics drive and support the desired actions and culture
- Establish sustainable methods to consistently providing auditable metrics



TARGET AREA

Work Permitting

Establish the requirements and steps for preparing and maintaining a safe work environment while performing work on the facility

LAGGING INDICATOR

# of incidents with root or contributing causes due to failure to properly execute work permits

# of regulatory audit findings, fines, and penalties for failure to adequately execute work permits or an inadequate work permit system

Rework or additional work required due to inadequate execution of the work permits

LEADING INDICATOR

# of jobs requiring work permits that were performed without the proper work permits

# of work permits that did not follow the requirements of specific work permit

# of work permits performed where all participants were not fully trained and competent in the permit requirements

% of work permits audited monthly

The permitting management system does not include all the following type activities: General Work, Hot Work, Crane Work, Confined Space Entry, Excavation Work, and Line Breaks

BUSINESS RESULT

Commitment to Process Safety

Understanding hazards and risks

Risks are managed

Incident and injuries are prevented

STRATEGIC GOAL

Reduced risk

Enhanced compliance assurance

All work activities on the facility are controlled and performed safely

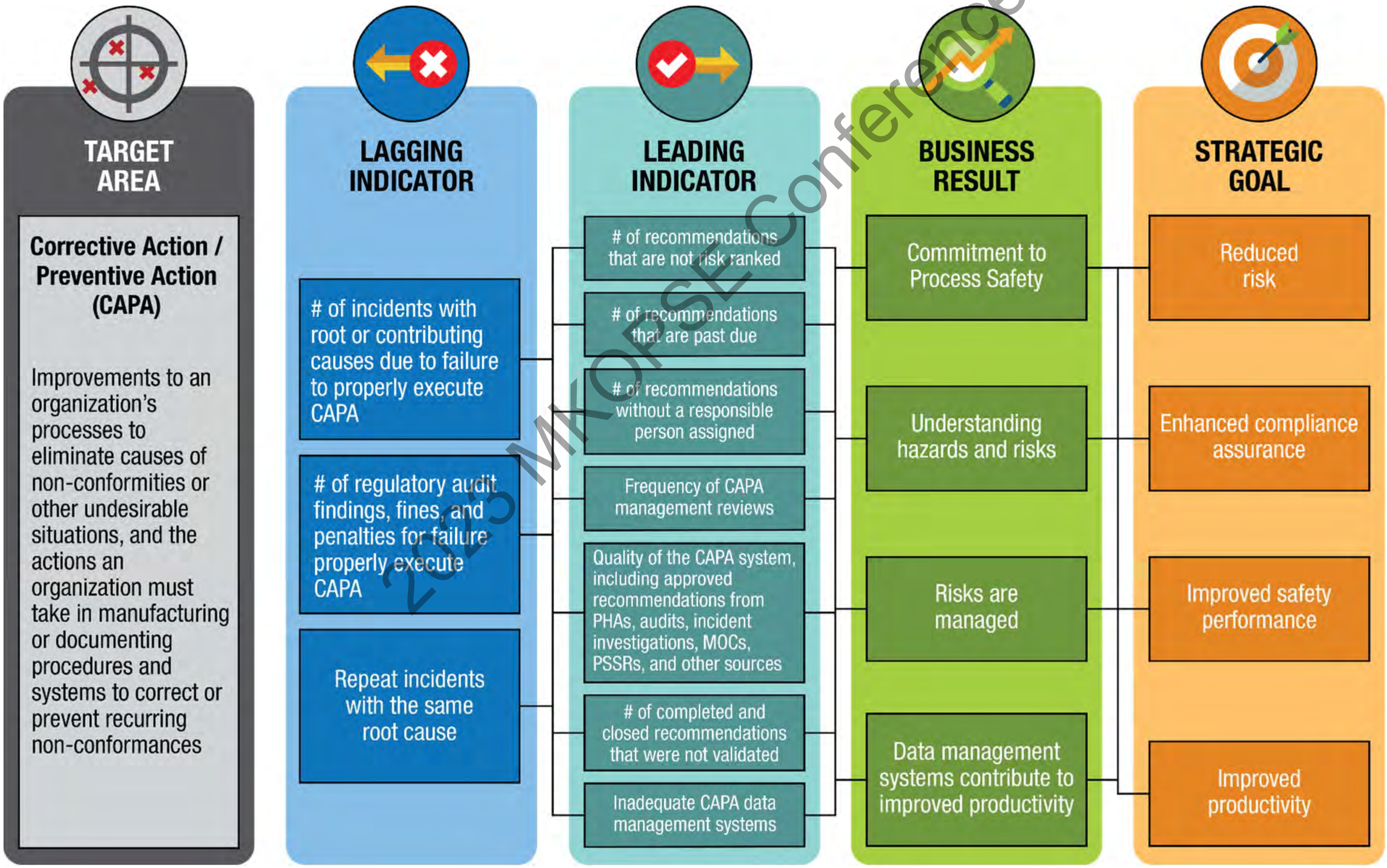
Create Indicators

Control Theme	Indicator	Implementation
Maintenance and Inspections	Number of overdue BMI inspections	○
	Number of watch list items	○
	Number of alarm points built and monitored by the Power Optimization Center	○
	Number of operational rounds performed	○
	Routine maintenance spend (fixed and variable)	○
	Capital spend	○
	Failures detected by the POC and during rounds	◒
	Reliability and Availability (GADS)	○
Management of Change Process	Number of individuals trained on MOC process and categories	○
	Number of changes	◒
Leadership Behaviors	Number of issues reviewed in leadership meetings	◒
	Number of issues acted on in the leadership meetings	◒
	Number of leadership communication on issues and strategy	○
Staff Competence and Task Understanding	Number of personal development plans developed by the staff in a specified period of time	●
	Number of positions with a defined minimum hiring or transfer qualification	◒
	Number of tailgate discussions	◒
	Time since last review of succession planning at plant level w/ SUPT	○
	Number of failures due to operator error	●
Operating, Start-up, and Shutdown Procedures	Procedures that have a defined review process	○
	Procedure review frequency	○
	Number of inconsistent operations	●

LEGEND

Leading Indicator	□
Lagging Indicator	🟩
Easy to Implement	○
Moderate to Implement	◒
Difficult to Implement	●

Target Metrics



TARGET AREA

Corrective Action / Preventive Action (CAPA)

Improvements to an organization's processes to eliminate causes of non-conformities or other undesirable situations, and the actions an organization must take in manufacturing or documenting procedures and systems to correct or prevent recurring non-conformances

LAGGING INDICATOR

- # of incidents with root or contributing causes due to failure to properly execute CAPA
- # of regulatory audit findings, fines, and penalties for failure properly execute CAPA
- Repeat incidents with the same root cause

LEADING INDICATOR

- # of recommendations that are not risk ranked
- # of recommendations that are past due
- # of recommendations without a responsible person assigned
- Frequency of CAPA management reviews
- Quality of the CAPA system, including approved recommendations from PHAs, audits, incident investigations, MOCs, PSSRs, and other sources
- # of completed and closed recommendations that were not validated
- Inadequate CAPA data management systems

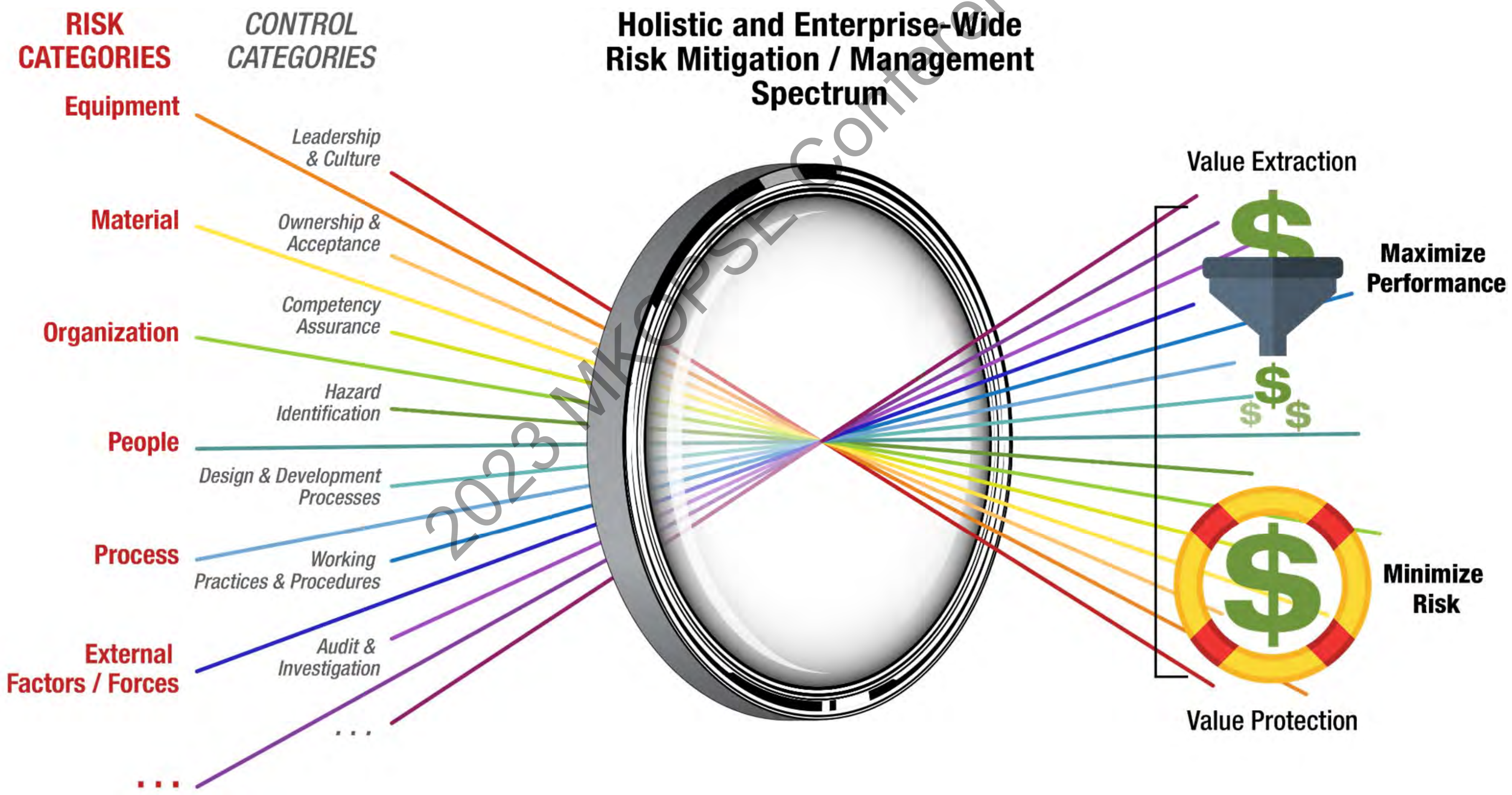
BUSINESS RESULT

- Commitment to Process Safety
- Understanding hazards and risks
- Risks are managed
- Data management systems contribute to improved productivity

STRATEGIC GOAL

- Reduced risk
- Enhanced compliance assurance
- Improved safety performance
- Improved productivity

Shift from "Safety" to "Risk Management"



RISK CATEGORIES
- **Equipment**
- **Material**
- **Organization**
- **People**
- **Process**
- **External Factors / Forces**
- **. . .**

CONTROL CATEGORIES
- *Leadership & Culture*
- *Ownership & Acceptance*
- *Competency Assurance*
- *Hazard Identification*
- *Design & Development Processes*
- *Working Practices & Procedures*
- *Audit & Investigation*
- *. . .*

Holistic and Enterprise-Wide Risk Mitigation / Management Spectrum

Value Extraction

Maximize Performance

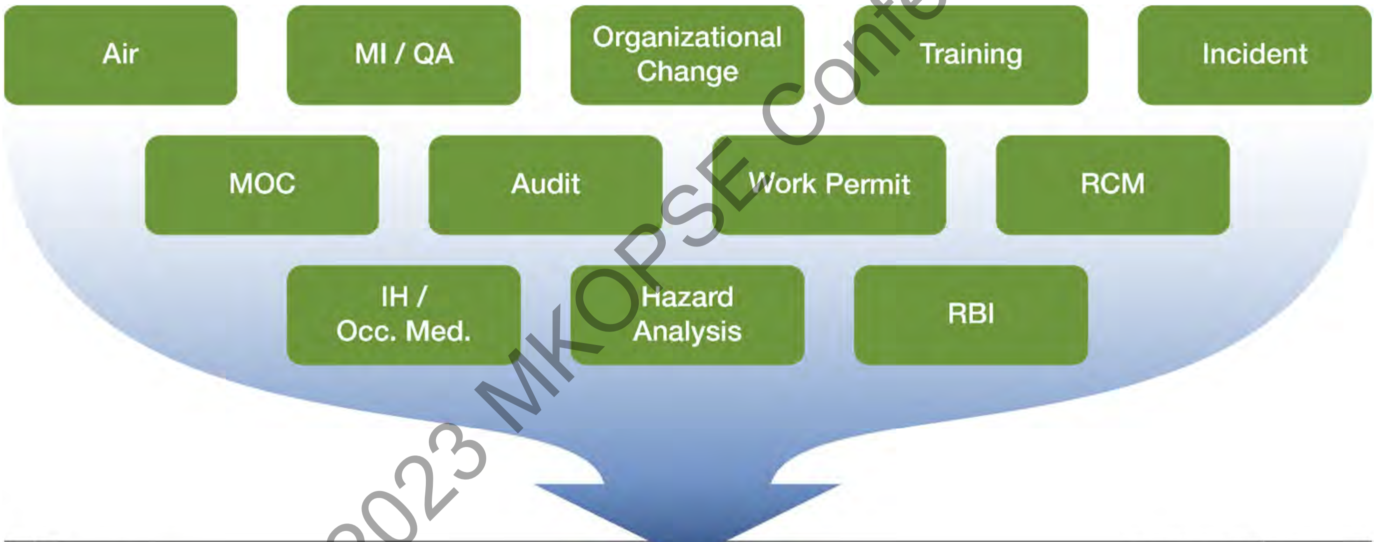
Minimize Risk

Value Protection

Path Forward: Operational Risk

Path Forward: Enterprise Risk

- Manage all risks in a single environment with ***common risk categorization***, including **risks to achieving committed ESG targets.**



ENTERPRISE RISK DASHBOARD

Entity	Type	Category	Risk #	Event/Scenario	Discipline	Risk Status	Unmitigated Risk	Mitigated Risk	# of Mitigation Steps
HOU-FCCU	Asset Risk	Equipment Failure	20-RSK-0031	Runs between 5 year T/A intervals	Inspection, Reliability	Closed	6	8	1
HOU-Maintenance Admin	Asset Risk	Equipment Failure	20-RSK-0032	Run regen to regen (6-8 months)	Inspection, Reliability	Closed	5	6	2
HOU-Reformer	Asset Risk	Equipment Failure	20-RSK-0033	Runs between 5 year T/A intervals	Inspection, Reliability	Closed	3	5	1
Houston Plant (HOU)	Facility Risk	Natural Disaster (Hurricane, Earthquakes)	20-RSK-0034	Infrastructure damage, plant damage, loss of containments leading to spill and consequence fire and explosion or contamination (wash up on shore), facilities possible.	Environmental, Asset Integrity	Managing Recommendations	5	6	2

Artificial Intelligence

- Where are We Today?
  - Are We AI Enabled?
  - Do we have Data Scientists?
- What Problems are Worth Solving?
- What are Some Practical Examples?
- How good is your data?
  - Do you have enough data?
- What are Limitations / Challenges
  - Be Careful of Data Virtualization
  - Create a "Console"

Conclusion

- How easy is it for you to roll-up all elements of your PSM program digitally?
  - Do you have a single source of truth or do you have architectural limitations?
  - Do you need to aggregate and are you able to leverage data virtualization?
- Do you have a clearly defined sets of metrics?
- Do you have a sense of how to detect potential deviations that may lead to incidents?
- What is your risk tolerance and are you operating withing that constraint?
- What's your strategy for Process Safety Digitalization?

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

Application of Natural Language Processing for Spill Reduction in an Exploration and Production Company

26th Process Safety International Symposium

Speaker profile

- Jamison Chang, Risk Lead with Oxy
- 10 years' experience in process risk management in Upstream and CCUS segment
- B.S. in Chemical Engineering at Texas A&M University

Outline

- Spill Reduction Initiatives
- Process Safety Indicators
- Natural Language Processing
- Results

Spill Reduction Initiatives

- Why
  - Protect People and the Environment
  - Maintain production
- How
  - Identify bad actors, root causes
  - Predictive and proactive replacements

Process Safety Indicators

- API 754
- Spills may be Tier 1 or Tier 2 events
- Learn from events to mitigate higher-level consequences
- Corrective actions to improve performance

Challenges

- Limited time and resources
  - Focus on higher-level consequences (e.g. Tier 1 PSEs)
- Data quality
  - Limited time for detailed reporting of spills
  - Free-text inputs
- Lagging indicators

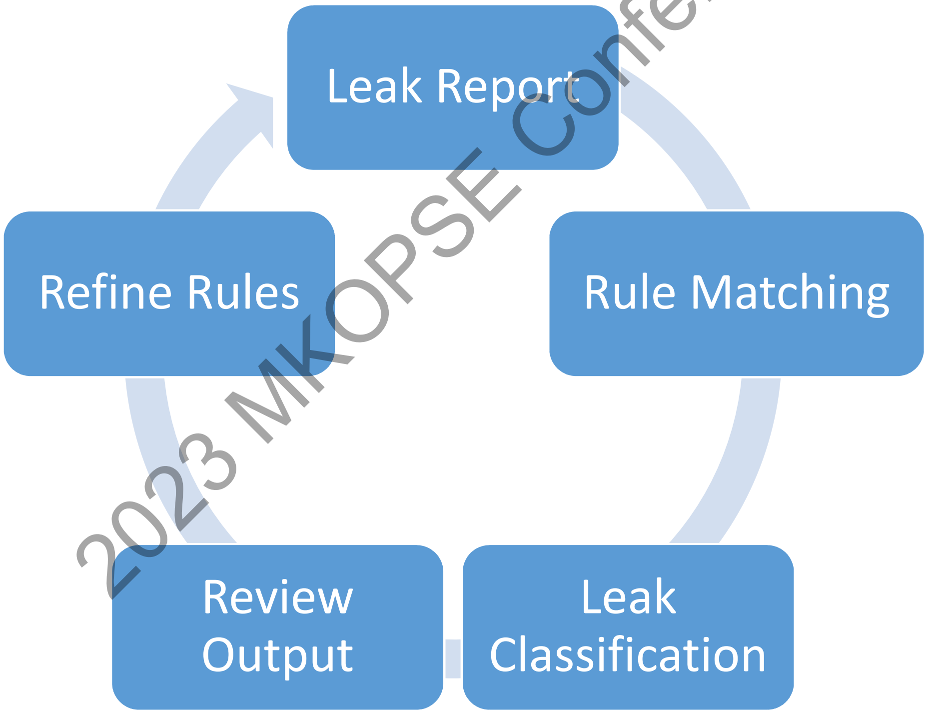
Natural Language Processing

- In computer science, NLP is the task of designing a system to take human text as input and "understand" some feature from it
- Entity extraction: From a text, identify the span related to a particular entity (e.g. leaks, dates, people, organization, etc)
- Two main approaches: Rule-based and machine learning
  - Rule-based: from a given set of rules to identify a leak we let the system find the span of the text where it matches any of the rules given
  - Machine learning: rules are learned from the data
  - There are pros and cons to both approaches

MI KPI Classification

- Goal: Identify leaks that can help focus mechanical integrity programs
- Challenges
  - Manual review of data
  - Look for keywords in different columns
- Opportunity to speed up data review and have timely results
  - Live data -> more accurate snapshot of MI performance

Leak Classification – MI KPIs



Leak Report

Rule Matching

Leak Classification

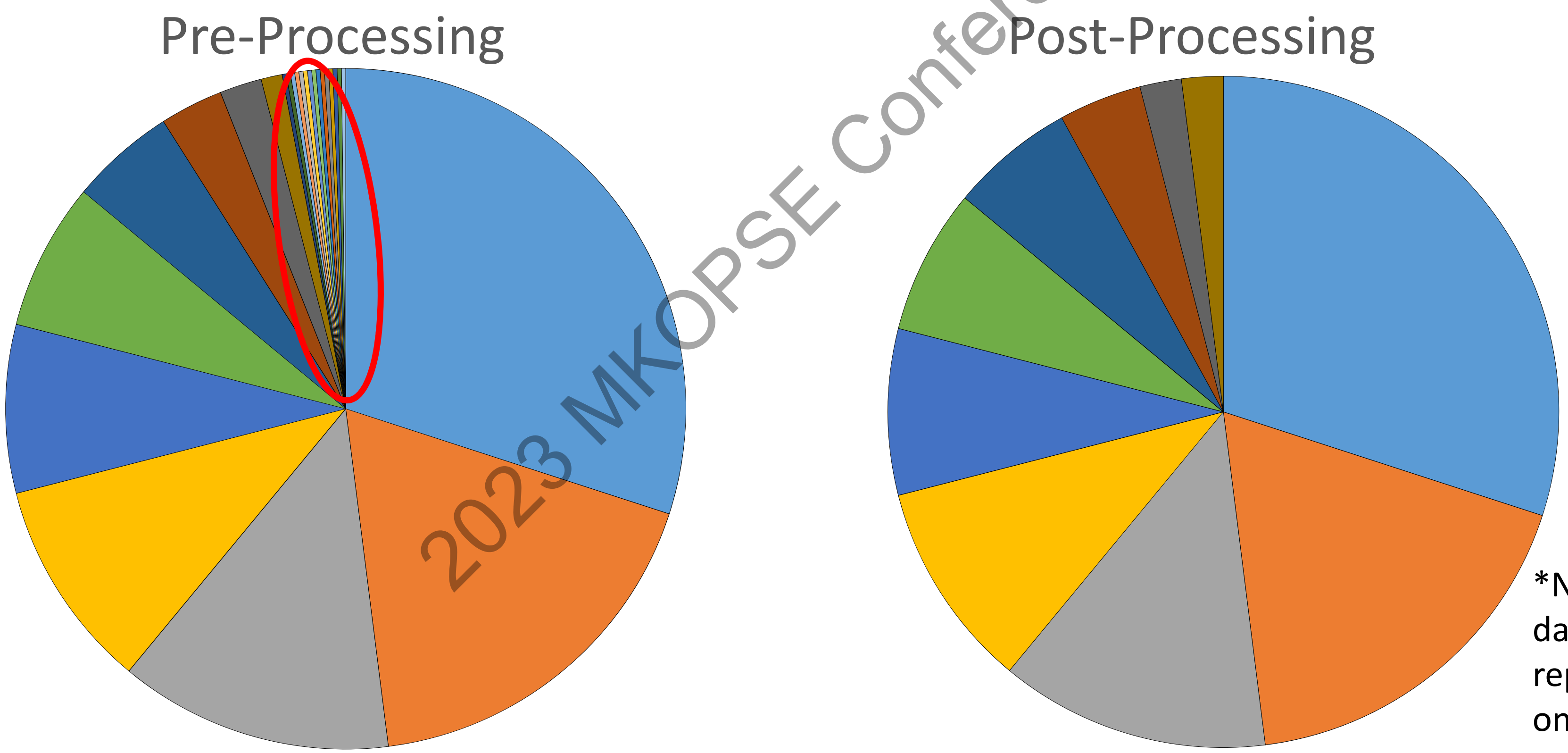
Review Output

Refine Rules

Results – MI KPI Classification

- Rule Based Approach
- Model had 90+% accuracy
  - Compared results with last 3 years of data
- Benefits
  - Save man-hours
  - Focus time on analysis
  - Expand ability to trend data, especially historical data

Cause of Leak – Rule Based Approach



*Not actual data, for visual representation only

Cause of Leak Prediction – Machine Learning

- Problem: original leak report may not always have "cause of leak" identified
  - User may not know the cause or did not include
- Solution: Prediction based on other data in the report
  - Provide sample set
    - Either fully trained model or a few shot pre-trained model
  - Evaluate if model can determine a pattern
- Goals
  - More accurate analysis of trends by "filling in blanks"
  - Ability to validate previous user inputs

Natural Language Processing

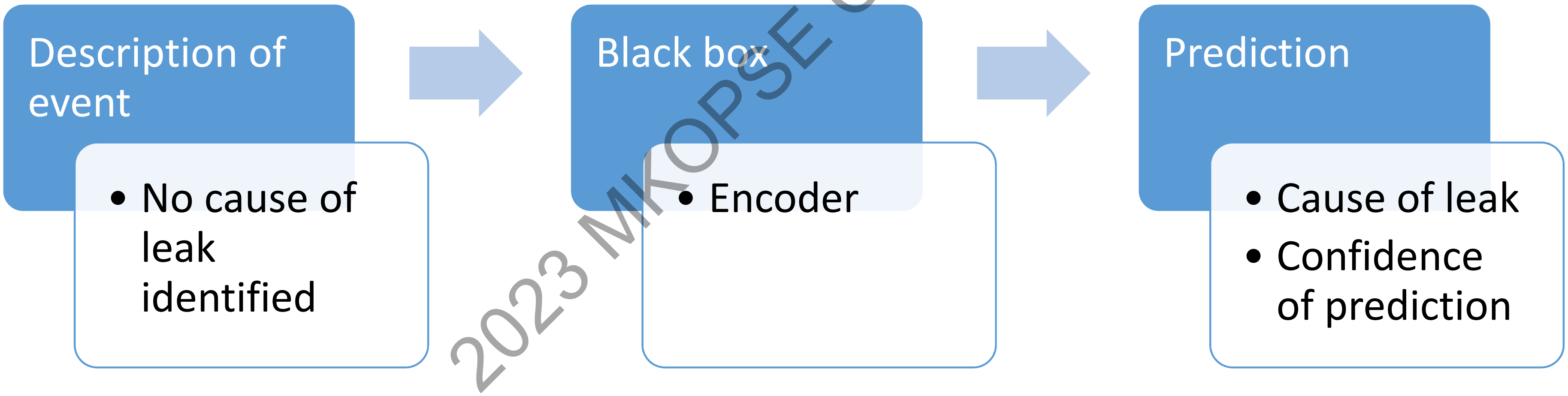
Training Example – cause of leak defined

- Description of event
- Equipment type
- Service type

Black Box

- Transformer model
    - Encoder-decoder
- Type of neural network
    - Architecture behind ChatGPT

Natural Language Processing



Description of event
- No cause of leak identified

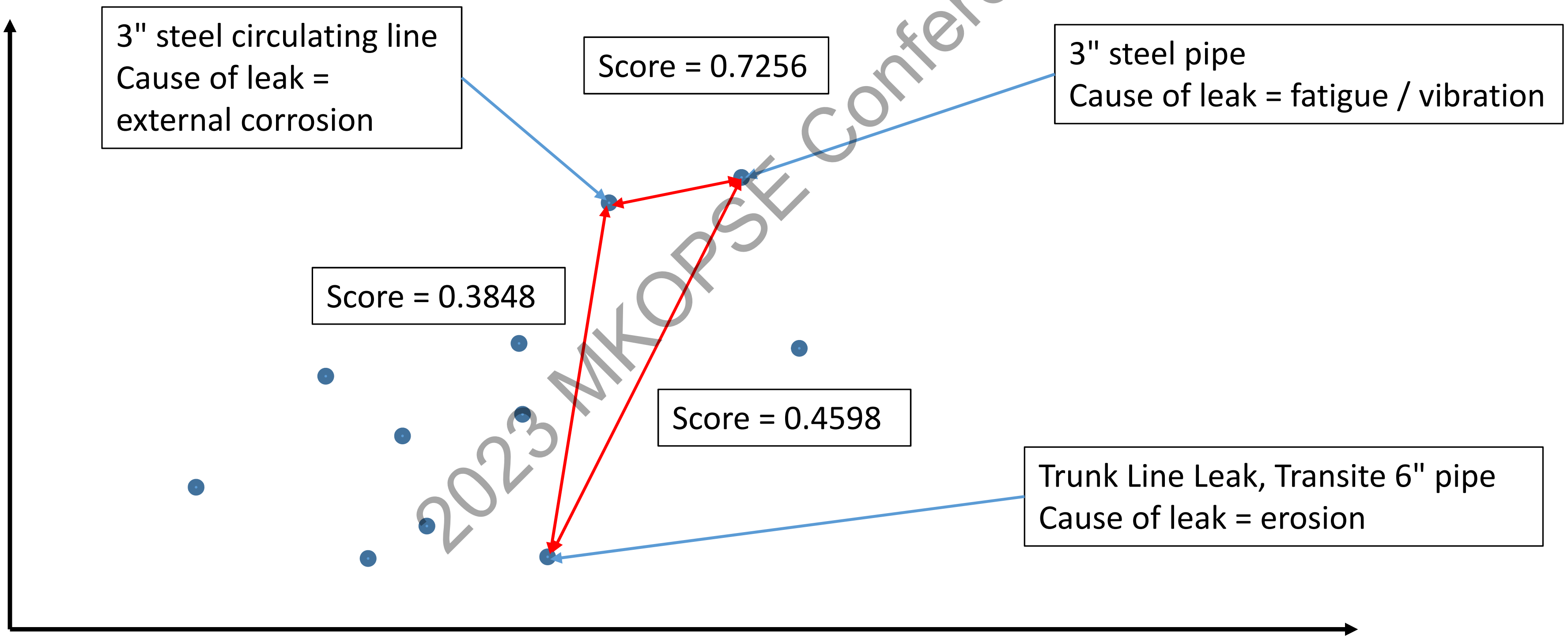
Black box
- Encoder

Prediction
- Cause of leak
- Confidence of prediction

A Simple Machine Learning Approach

- Inputs would be leak report data (or any text)
- Assumption: Similar text inform common causes.
  - For a given corpus of text, if we've seen a similar text before, we may tag similarly.
- Goal: Given a new set of leak report data, without the cause of leak defined, find most "similar" set of data with semantically similar information to assign a cause of leak

Machine Learning Approach



3" steel circulating line
Cause of leak = external corrosion

Score = 0.7256

3" steel pipe
Cause of leak = fatigue / vibration

Score = 0.3848

Score = 0.4598

Trunk Line Leak, Transite 6" pipe
Cause of leak = erosion

Results - Cause of leak prediction

- Model with 54% accuracy out of 837 training cases
- Bias towards most common causes
- Advantage: using purely semantically similar sentences to assign the most probable cause
- Next steps: Model can be refined by using additional information from leak report to enrich the sentence we are encoding

Example Results

Cause	Long_Text	Best_Guess	Score	Correct
SEAL/PACKING	PACKING ON STUFFING BOX, BACKHOE/VAC TRUCK.	SEAL/PACKING	0.88	TRUE
INTERNAL CORROSION	2" Steel nipple	FATIGUE/VIBRATION	0.49	FALSE

Final Thoughts on Machine Learning Models

- These days, people use either public OpenAI models or models hosted on Azure or AWS; however, we should never disregard data privacy as a major security concern
- We used completely open-source locally hosted models to ensure data privacy; particularly when top state of the art models are not worth using when information is low to begin with
- Smaller models can perform just as well, and have full control of where data resides

Opportunities

- Focus on larger data set (e.g. Tier 2 events)
    - More representative data to analyze
- Communicate lessons learned more widely
- Quicker, more up-to-date analysis
- Improve data quality for human review (e.g. RCFA)

Future applications

- PSE classification – tier 1 / 2 / 3 / 4
- Tie with spill volumes data

Acknowledgments

- Co-author: Jesus Martinez, Senior Analytics Engineer

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with ***IChemE***

October 11-13, 2023

Sponsored by aramco

TEES
Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

26th Process Safety International Symposium

Fire Behaviour of Liquid Solvents by Cone Calorimeter

Gianmaria Pio*, Benedetta A. De Liso, Ernesto Salzano

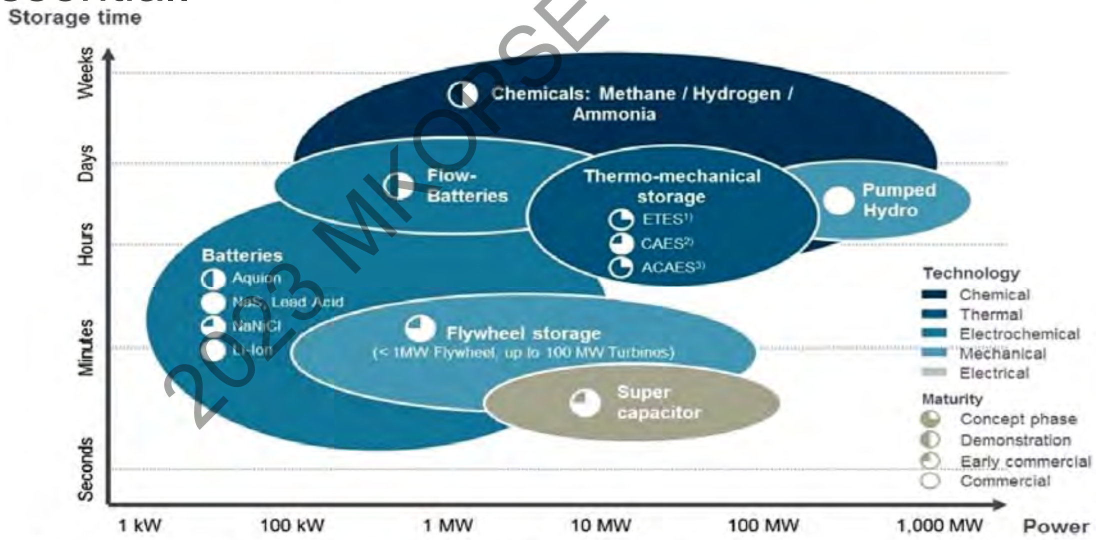
Department of Civil, Chemical, Environmental and Materials Engineering – University of Bologna (IT)

gianmaria.pio@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Introduction: Electrification in Chemical Industry

The energy transition is promoting the integration of storage systems in large-scale traditional processes, making the development of energy storage technologies essential.



1) Electro-Thermal Energy Storage 2) Compressed Air Energy Storage 3) Adiabatic Compressed Air Energy Storage

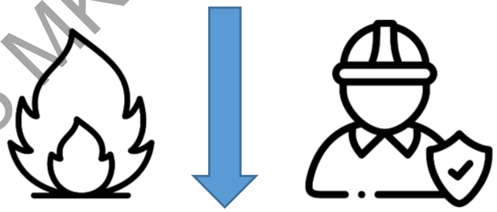
Valera-Medina et al. (2018) 10.1016/j.pecs.2018.07.001 0360-1285

Introduction: New Challenges in Fire Safety

Several energy storage technologies using non-aqueous solvents have been recently developed, introducing new challenges in industrial safety.

Among possible scenarios, runaway and pool fire are of concern.

Different parameters have a significant impact on fire-related phenomena and thus macroscopic properties.

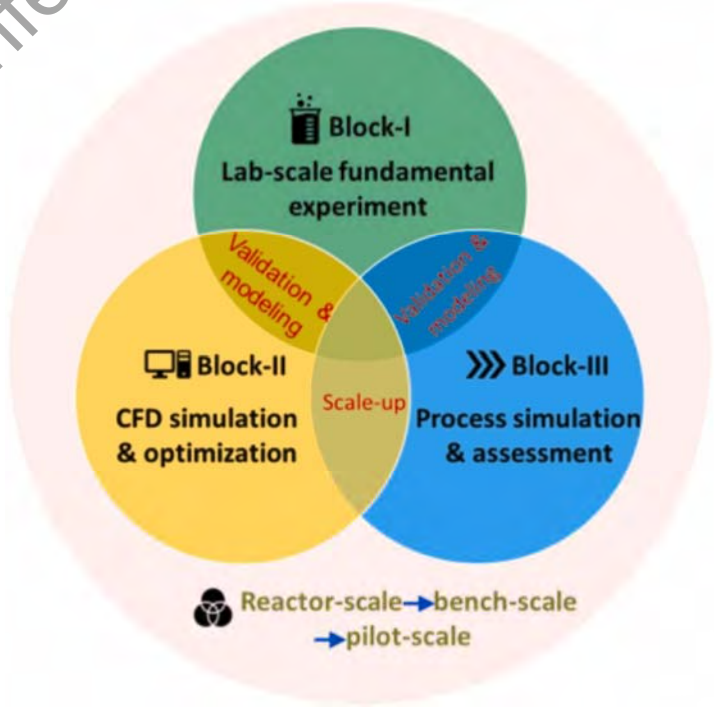


Standardized procedures to determine the safety parameters are essential

Valera-Medina et al. (2018) 10.1016/j.pecs.2018.07.001 0360-1285

Introduction: New Challenges in Fire Safety

- The need for sustainable technologies introduced alternative solvents, requiring the characterization of physic-chemical behaviour under fire conditions.
- The experimental approach shall be preferred to characterize innovative solutions
- The experimental systems shall be selected to allow a robust validation of numerical models

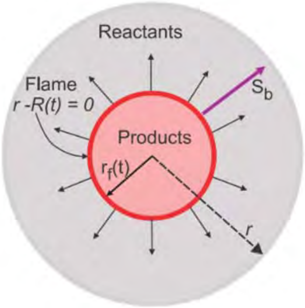


Ouyang et al. (2022) 10.1016/j.cep.2022.109164

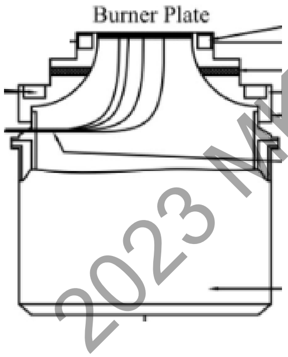
Introduction: New Challenges in Fire Safety

The overall reactivity and the composition of exhaust gases shall be considered as the main targets for an experimental campaign.

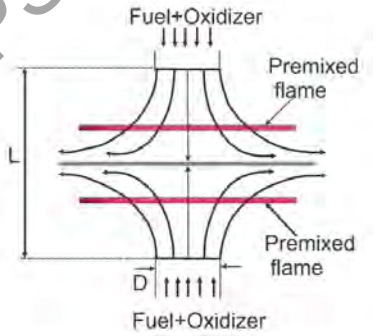
Spherical Vessel



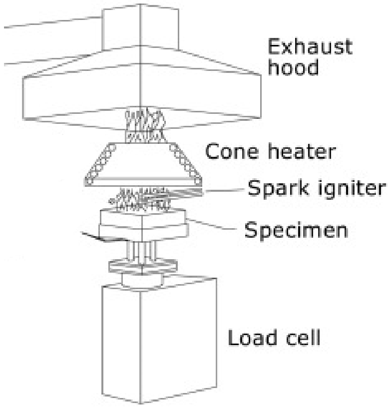
Heat Flux Burner



Counter Flow Flame



Cone Calorimeter



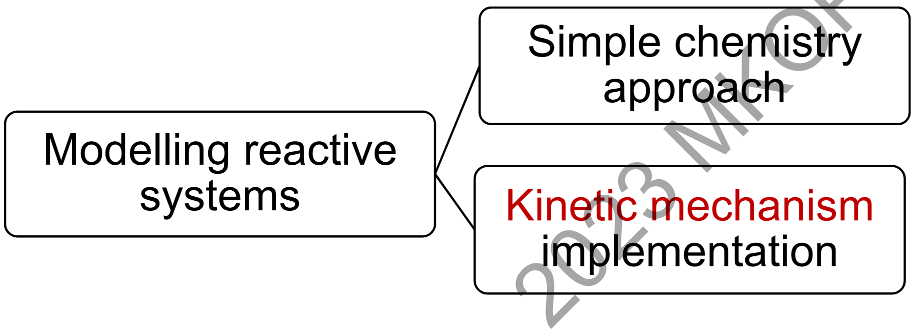
Evaporation needed

Standardized for solids

Konnov et al. (2018) 10.1016/j.pecs.2018.05.003; Babrauskas (2002) 10.1016/B978-0-12-824045-8.00002-2

Introduction: New Challenges in Fire Safety

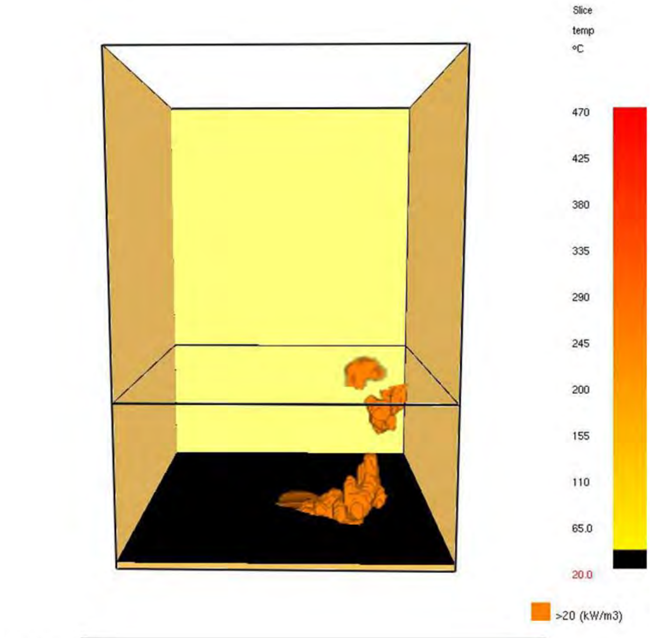
The data potentially obtained from experimental campaigns can be compared with numerical estimations deriving from computational fluid dynamics having different chemical submodels.



Modelling reactive systems

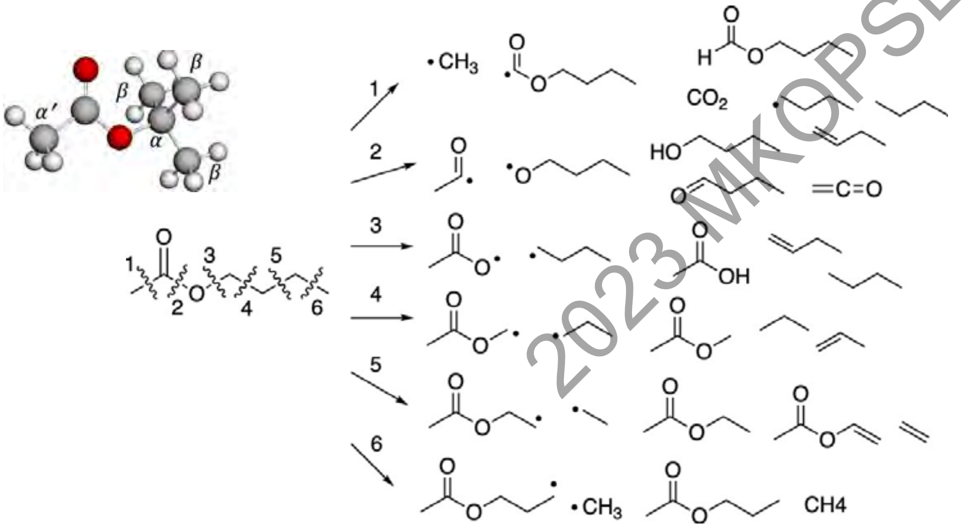
Simple chemistry approach

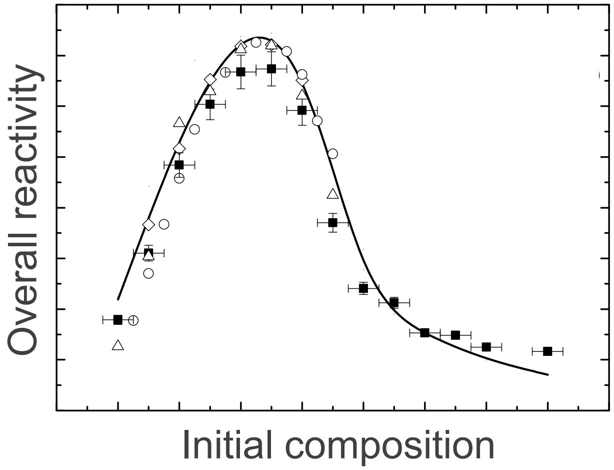
Kinetic mechanism implementation



Introduction: New Challenges in Fire Safety

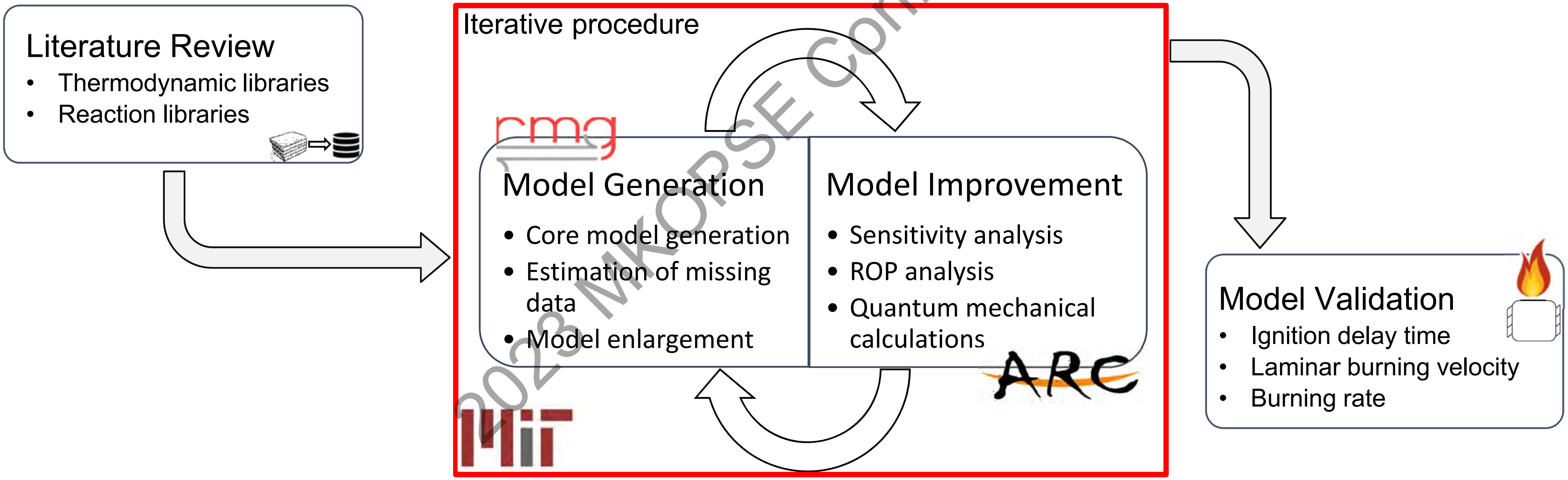
The use of a detailed kinetic mechanism allows for the identification of possible products, the quantification of the reactivity, and the exhaust composition in a wide range of temperature, pressure, and composition.





Dong et al. (2023) 10.1021/acs.jpca.2c07545

Introduction: New Challenges in Fire Safety



Literature Review
- Thermodynamic libraries
- Reaction libraries

Iterative procedure

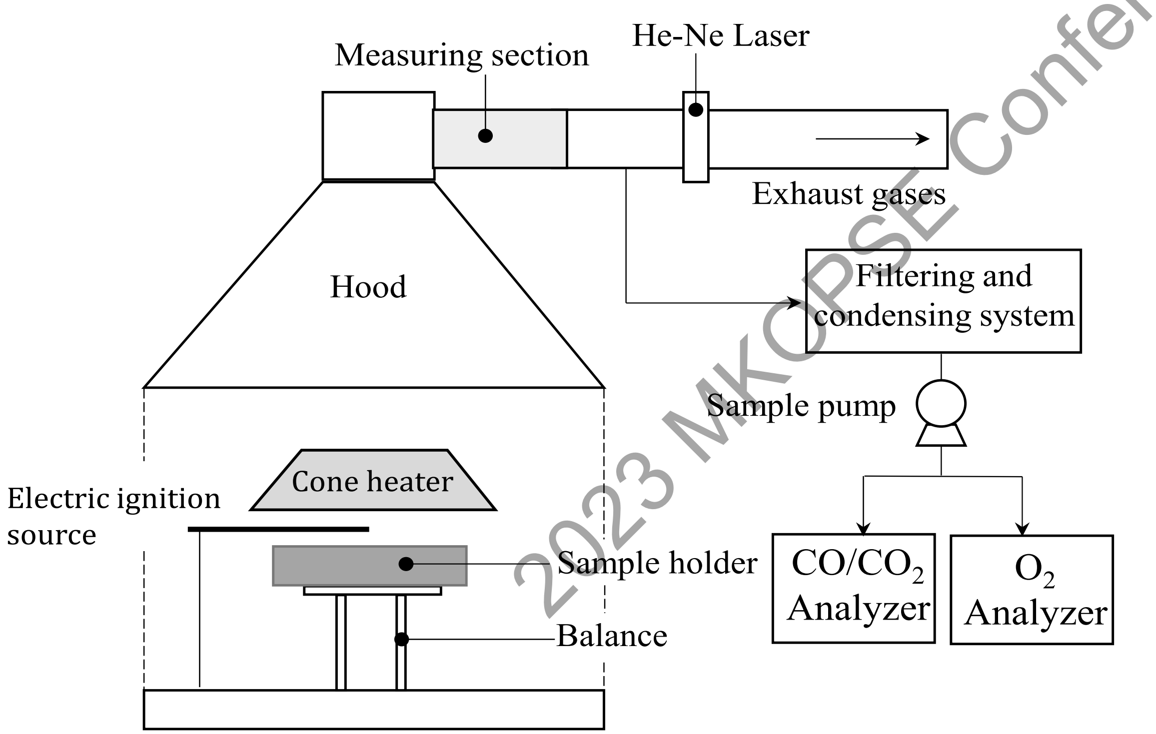
Model Generation
- Core model generation
- Estimation of missing data
- Model enlargement

Model Improvement
- Sensitivity analysis
- ROP analysis
- Quantum mechanical calculations

Model Validation
- Ignition delay time
- Laminar burning velocity
- Burning rate

Pio et al. (2022) 10.1016/j.combustflame.2022.112080

Methodology: Cone calorimeter



Direct output

- Heat flux [kW/m^2]
- Ignition time and extinction time [s]
- Specific extinction area [m^2/kg]
- CO_2 yield [kg/kg]
- CO yield [kg/kg]
- Heat release rate [kW/m^2]
- Smoke production rate [m^2/s]
- Mass loss, Mass loss rate [g, g/s]
- Effective heat of combustion [MJ/kg]
- Total oxygen consumption [g]

Methodology: Tested Materials and Conditions

Component	T_a [°C]	T_F [°C]	T_B [°C]	k_L [W/(mK)]	ρ_L [g/m^3]
Acetonitrile	523.9	5.5	81.6	0.120	777
Ethyl Acetate	426.7	-4.0	77.2	0.193	894
Lactic Acid	> 400	110.0	216.0	0.144	1200
Hexane	224.0	-23.0	68.9	0.203	656

- Autoignition temperature (T_a)
- Flash point temperature (T_F)
- Bubble point temperature (T_B)
- Thermal conductivity (k_L)
- Density of the liquid solvent (ρ_L)

Sample surface [m^2]	0.01
Sample thickness [m]	0.01
Distance from cone heater [m]	0.025
Heat flux [kW/m^2]	7 – 50
Initial mass [kg]	0.050 – 0.055
Cone heater orientation	Horizontal

Methodology: Derived Parameters

Heat Release Rate = HRR

Peak of Heat Release Rate = pHRR

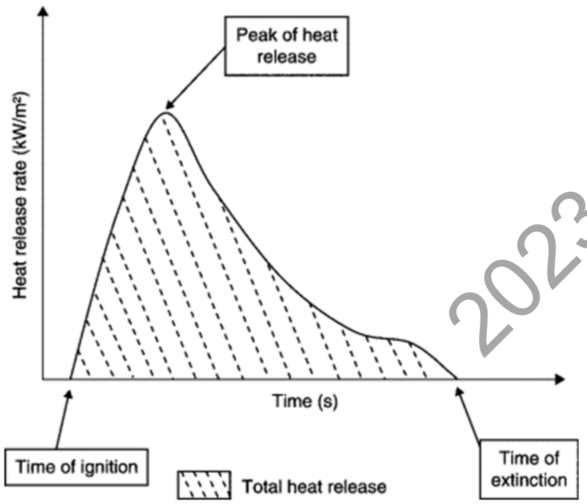
Time of Peak in Heat Release Rate = tpHRR

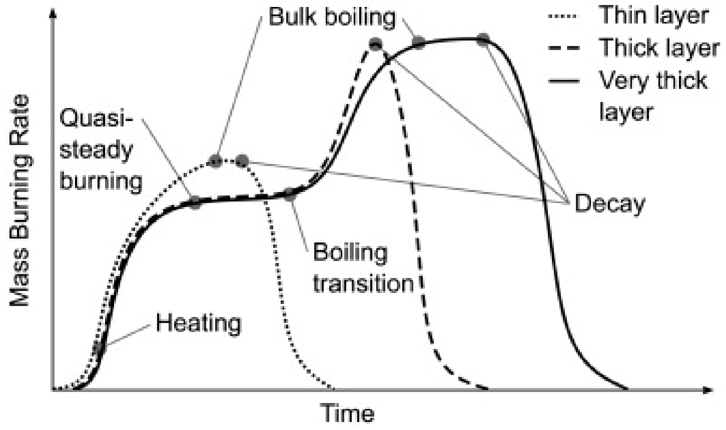
Mass Loss Rate = MLR

Peak in Mass Loss Rate = pMLR

Overall Reaction Rate = ORR = $\frac{MLR}{Area \cdot Density}$

Peak in Overall Reaction Rate = pORR

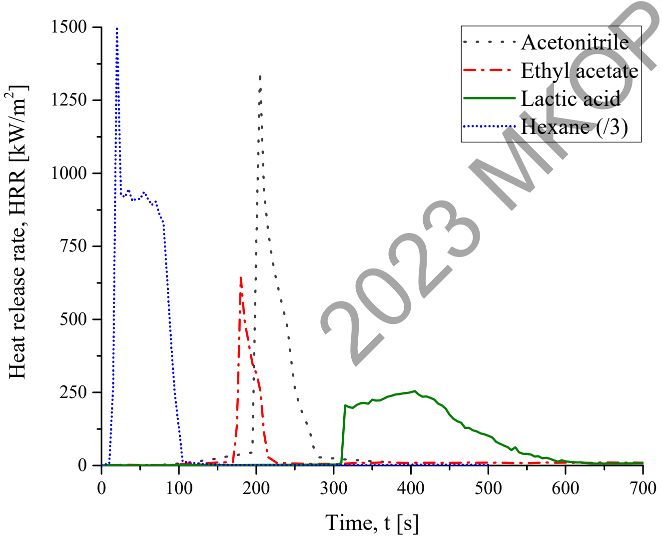


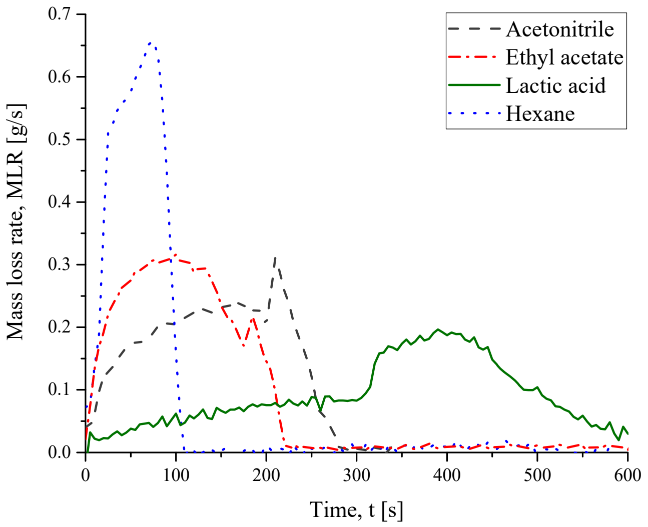


Dewaghe et al. (2011) 10.1533/9780857091390.3.718; DiDomizio et al. (2021) 10.1016/j.firesaf.2021.103449

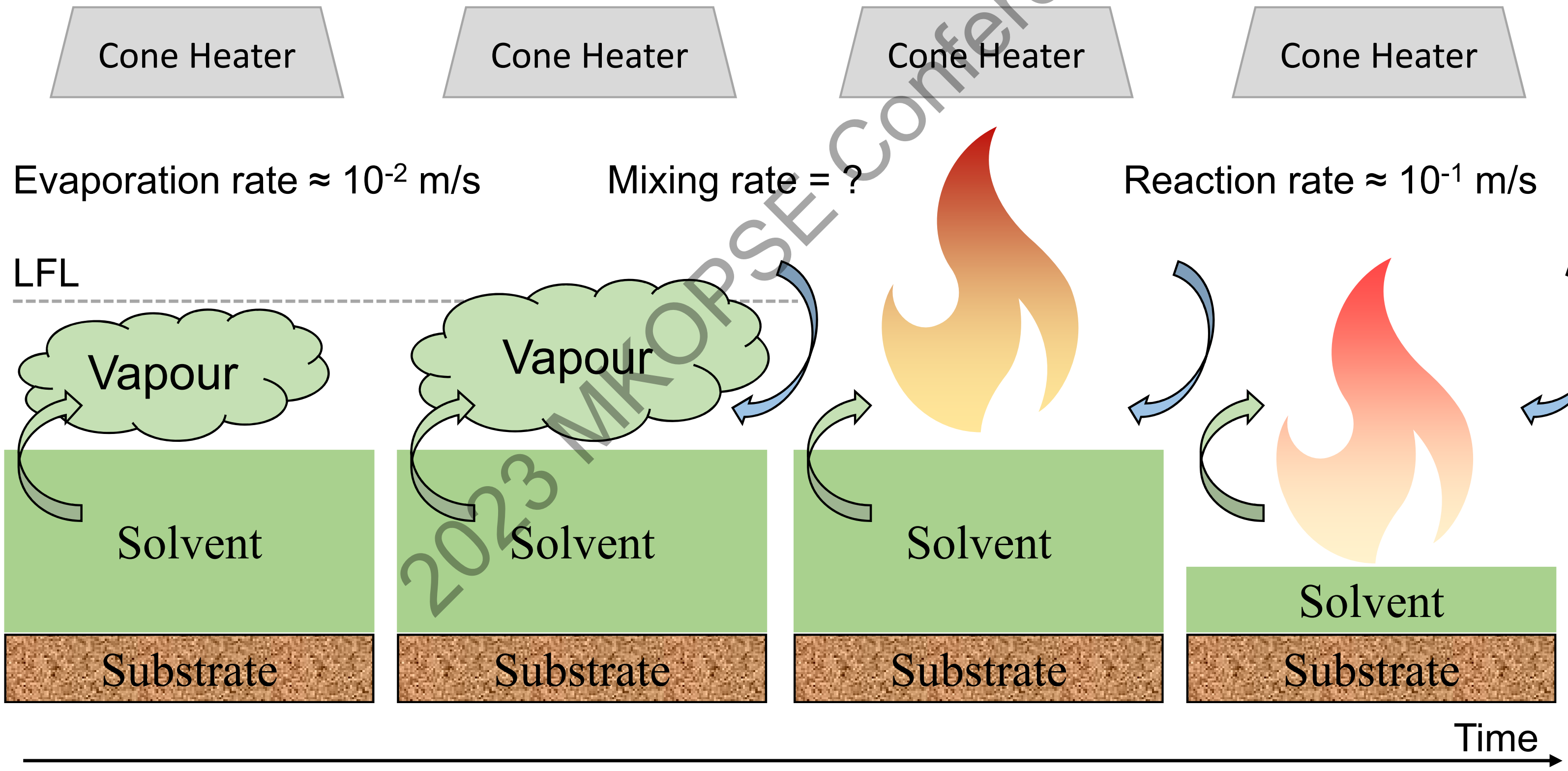
Results: Base Case Scenario (25 kW/m^2)

- ☐ Hexane and ethyl acetate show a thin layer behaviour with different heating time
- ☐ Acetronitrile has a thick behaviour and lactic acid a very thick
- ☐ Mass decay does not correspond to the peak of Heat Release Rate





Results: Observed Stages and Characteristic Time



Results: Heat Flux and Observation Time

According to the obtained characteristic times and pORR, mixing is identified as the rate-determining step

Heat Flux [kW/m²]

$t_{ignition}$ = 250 s	7	15	25	35	50
Acetonitrile	🟩	🟩	🟨	🟥	🟥
Ethyl acetate	🟩	🟩	🟥	🟥	🟥
Lactic acid	🟩	🟩	🟩	🟩	🟥
Hexane	🟨	🟨	🟥	🟥	🟥

🟩 No flame

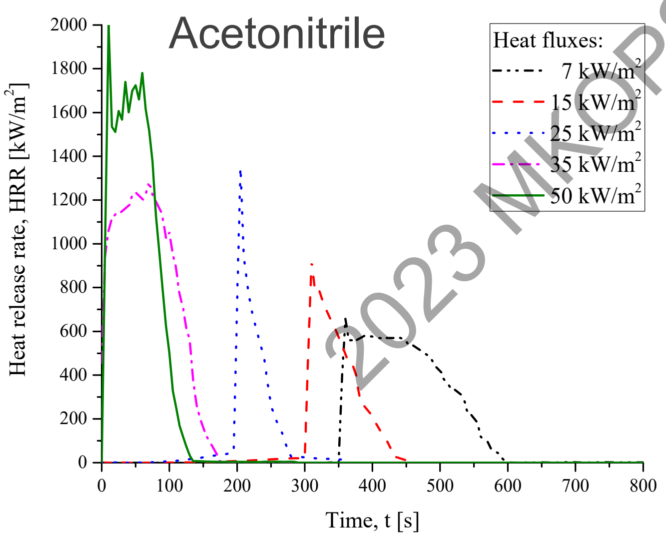
🟨 Ignitability

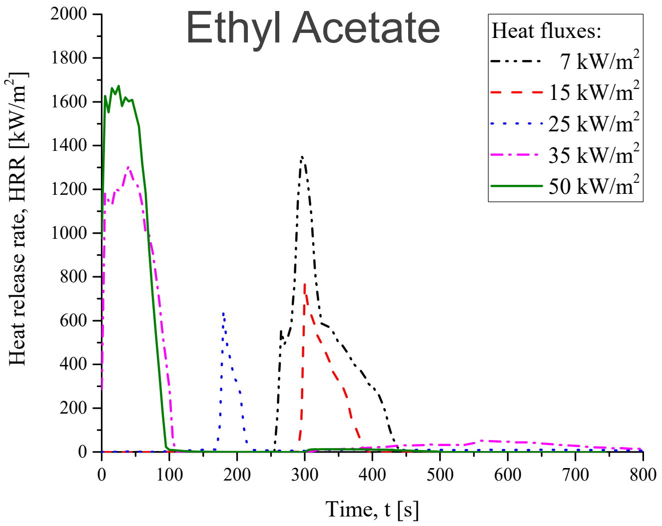
🟥 Flammability

Component	Heat flux [kW/m²]	pORR ($\cdot 10^{-5}$) [m/s]
Acetonitrile	7	0.98
	15	1.41
	25	1.82
	35	3.89
	50	4.68
Ethyl Acetate	7	1.56
	15	1.76
	25	1.14
	35	3.38
	50	3.20

Results: The Effects of Heat Flux

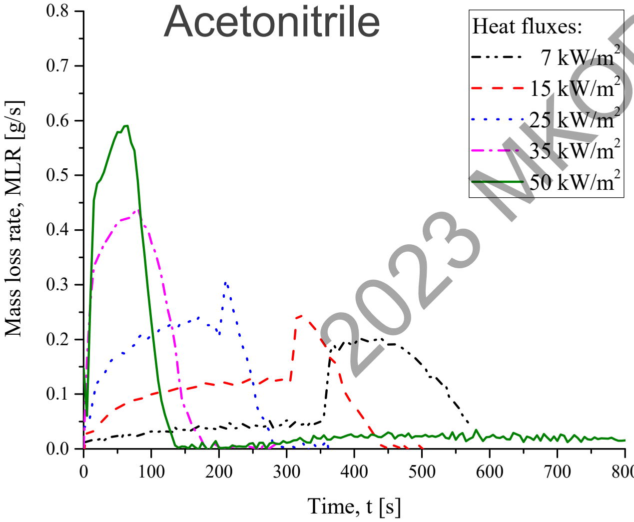
- Increasing the heat flux, Acetonitrile shows a decrease in tpHRR and pHRR
- Ethyl acetate at 7 kW/m² is affected by the given ignition (ignitability)

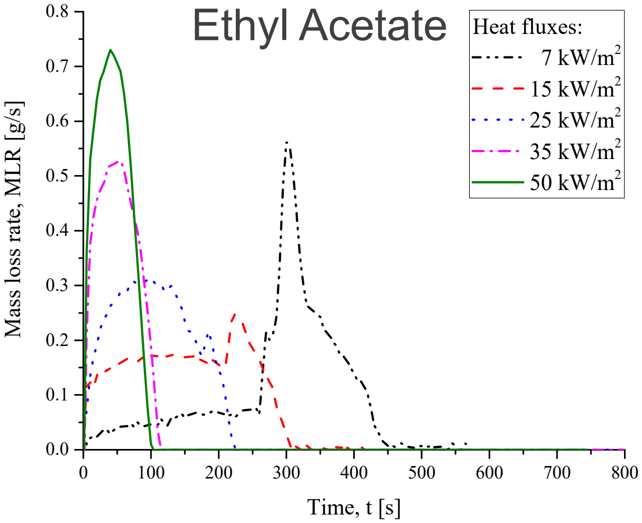




Results: The Effects of Heat Flux

- ☐ The heat flux provided affects the liquid behaviour (from thin to thick layer)
- ☐ Uncomplete conversion can be observed for acetonitrile only





Conclusions & Future Developments

- Experimental determination of the flame characteristics of liquid solvents
- Assessment of the chemical and visible features of a solvent-derived flames
- Comparison of safety performances of different solvents exposed to fire and under a wide range of boundary conditions (e.g., heat flux, distance, thickness)
- Identification of the most critical conditions and phenomena characterizing the analysed scenario
- Realization of a robust and standardized procedure to characterize the sustainability of solvents

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Gianmaria Pio
gianmaria.pio@unibo.it

Department of Civil, Chemical, Environmental, and Materials Engineering – DICAM

Member of Laboratory of Industrial Safety & Environmental Sustainability – LISES
https://site.unibo.it/lises/en

LISES – Laboratory of Industrial Safety & Environmental Sustainability

The staff of the laboratory of industrial safety and environmental sustainability is engaged in edge-cutting research on chemical and process safety, risk assessment and management, sustainability assessment and environmental managment of industrial processes, also addressing the development of new technologies.

Acknowledgments

Authors gratefully acknowledge the Italian Ministry of University and Research (MIUR) for the financial support through the project "Dipartimenti di Eccellenza 2018-2022" and the National Recovery and Resilience plan (PNRR), Extended Partnership PE2: NEST – Network 4 Energy Sustainable Transition", Spoke 6: Energy Storage - - T6.4.4 Safety, LCA and sustainability studies of energy storage systems and processes.

MiUr

Ministero dell'Istruzione, dell'Università e della Ricerca

Piano Nazionale
di Ripresa e Resilienza

#NEXTGENERATIONITALIA

Process Safety Culture in Research Centers.
Road Map Toward Enhancement

[Abstract]

Hesham K. Al-Subait

Abstract Summary

Process Safety Culture in Research Centers. Road Map Toward Enhancement

Process Safety culture enhancement in a research center requires a systematic and comprehensive approach to ensure that all aspects of the organization's operations are aligned with its safety goals. Here are some steps to enhance process safety culture in a research center:

1. **Assessment**: Conduct a process safety culture assessment to identify strengths and weaknesses in the existing safety culture of the organization. The assessment can be used to identify areas requiring improvement in communication, training, and workforce involvement in safety issues.

2. **Leadership commitment**: The management of the research center should demonstrate their commitment to process safety culture improvement and encourage employee participation in safety-related activities.

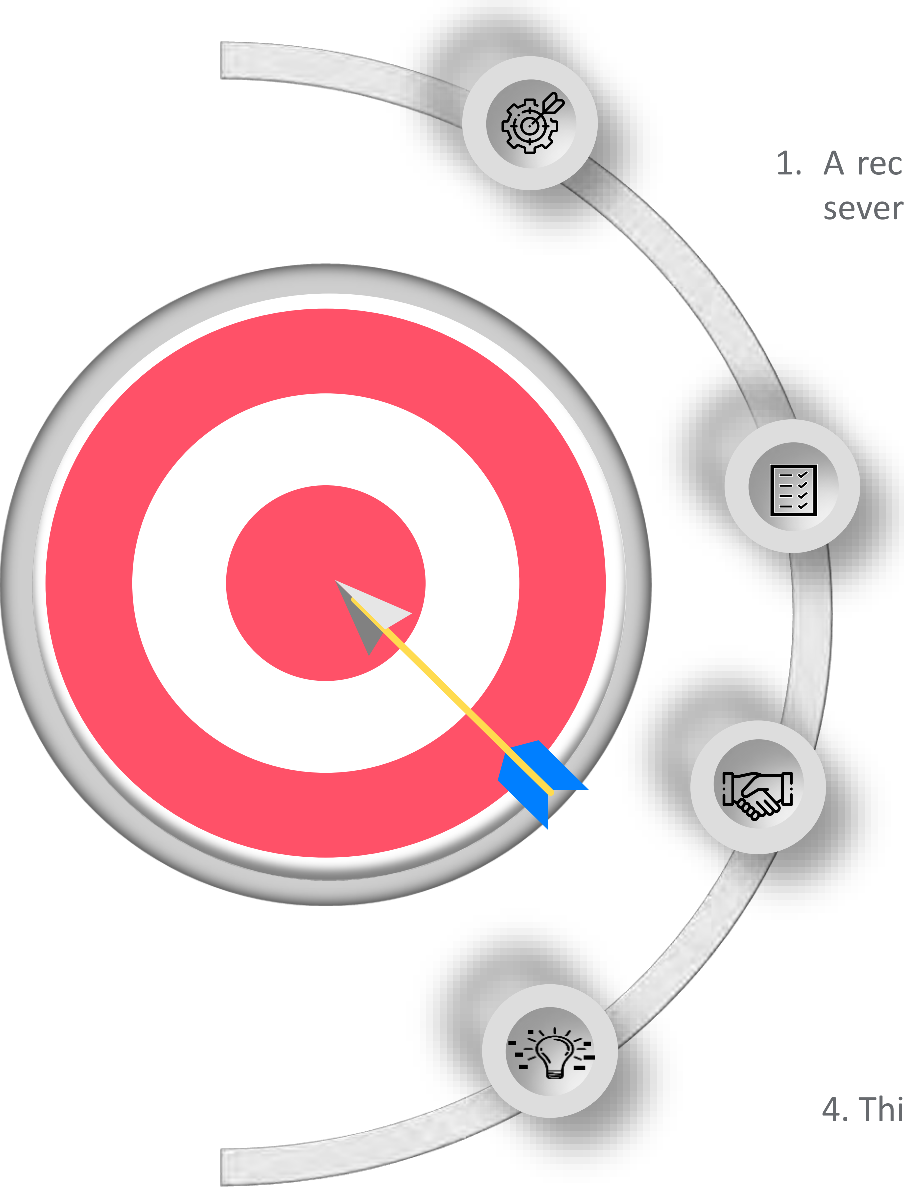
3. **Employee involvement**: Encourage employees to be more involved in the safety management process by including them in decision-making processes, hazard identification, and risk assessments.

4. **Training and Development**: Train employees in process safety management principles and ensure that they understand the importance of safety in the workplace. Refresher training can be conducted on a regular basis to help maintain the culture of safety.

5. **Two Way Communication**: Ensure that employees receive clear and concise safety-related information. Consider ways to use posters, meetings, and email communications to emphasize safety culture to employees.

6**. Continuous improvement**: Establish systems to track progress and identify opportunities for improvement in process safety culture. Regularly engage stakeholders, review data, conduct audits, and conduct periodic assessments to identify areas that need attention.

Why do we need PS Culture Enhancement?



1. A recent in-depth internal analysis-2019 / and 2020 SMS internal review has revealed several PS improvement opportunities namely around:
    - the level of engagement and commitment of employees to HSE,
    - the need to enhance PS core competencies,
    - the need to focus on pro-active risk discovery and mitigation,
    - the need to enhance the current SMSs/OEs audit mechanism and
    - increasing the ownership by all of our SMS .

2. Despite substantial improvement in PS overall performance between 2019 and 2020 led by STTF team , recent incidents and near misses have generated a sense of urgency to steeply increase risk management effectiveness across the Dept.

3. As part of Major Safety Goals established in the Safety Annual Letter for 2021, Strengthen of Safety Culture as an overall has been targeted by implementing a series of activities and communications across the department to reinforce our unmistakable commitment to safety and excellence.

4. This has resulted in deciding to form a Major Safety Enhancement Culture Committee sponsored by Head of the Organization.

Expected Outcome

Assessing the key PS risk from operating, maintaining and modifying existing Assets (Pilot Plants, Labs, Facilities, etc.)

Development of specific Mitigation Plans following targeted in-depth risk assessments

Increase ownership on SMS Expectations in SMS Element Champions and Process Owners

Support the implementation of risk management in the field through an appropriate set of tools and KPIs.

Support the delivery of enhanced competencies and functional SMS ownership and understanding, and skills on process safety throughout the department and leadership in particular.

أرامكو السعودية
saudi aramco

Process Safety Management in the Semiconductor Industry

Samsung Austin Semiconductor is a world-class technology leader with 25 years of storied history in the Central Texas area.
We're breaking barriers with help from outstanding employees.

Bio: Mike Stone

- BS Chemical Engineering from the South Dakota School of Mines and Technology
- 10 years Halliburton
  - Wireline Field Engineer
  - Performance Development Coordinator
  - Logistics Manager
- 6 months Upstream Brewing
  - Brewer and expert beer taster
- 4 years Green Plains
  - PSM Engineering Manager
- 2 years Samsung
  - Sr. Engineer PSM/ RMP

By the Numbers

Samsung Austin Semiconductor saw massive growth in 2022. These numbers are just a snapshot of the impact we're having on the community.

- Received Zero Waste to Landfill Gold level validation for recycling or reusing 97% of waste
- Powered by 100% renewable energy

- Investment in Austin facility since 1996

- Plus 9,935 additional workforce (includes on-site vendors, partners and contractors)

- Total economic impact in Central Texas in 2022 (includes Taylor construction site)

- $400,000 in charitable giving by employees
- $1.5 million in corporate giving

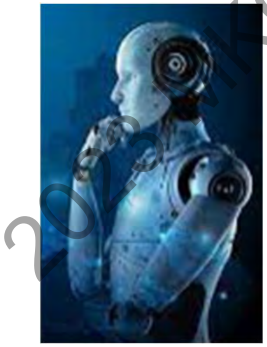
SOCIAL IMPACT REPORT 2022

SAMSUNG
AUSTIN SEMICONDUCTOR

What is a semiconductor chip?

S I A SEMICONDUCTOR INDUSTRY ASSOCIATION

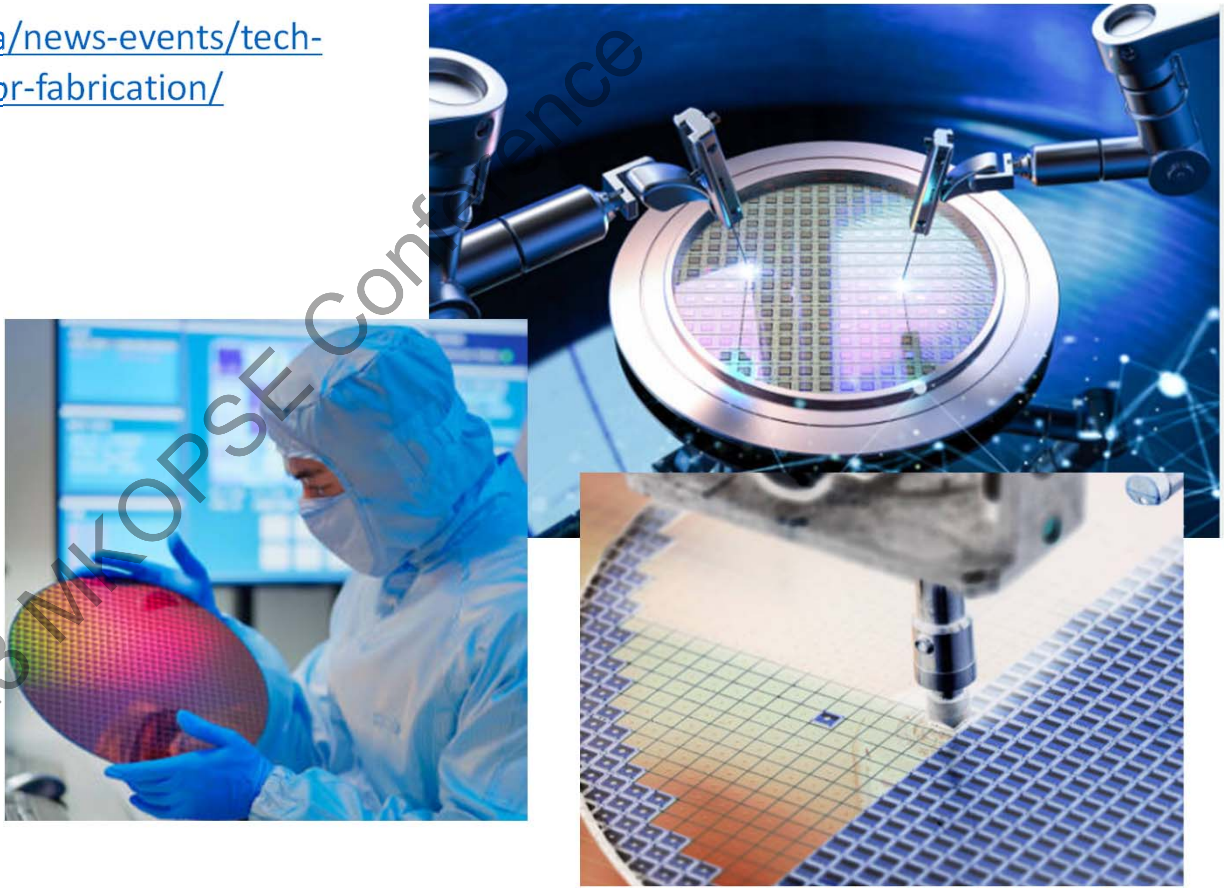
“Semiconductors are the brains of modern electronics, enabling advances in medical devices and health care, communications, computing, defense, transportation. Clean energy, and technologies of the future such as artificial intelligence, quantum computing, and advanced wireless networks.”



Semiconductor Chip Manufacturing in 8 Simple Steps

https://semiconductor.samsung.com/emea/news-events/tech-blog/a-short-introduction-to-semiconductor-fabrication/

1. Build the silicon wafer
2. Imprinting the Integrated Circuit
3. The Etching Process
4. The Thin Film Process
5. The Metal Interconnect Process
6. The EDS Process
7. Packaging
8. Testing

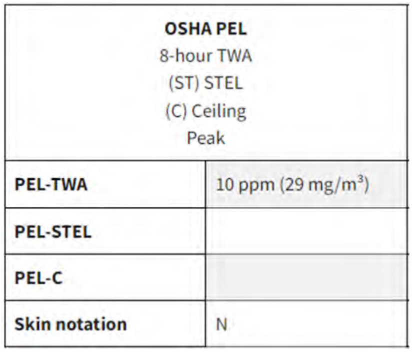


Incidents in the Semiconductor Industry

2011 Intel Chandler, Arizona

- Leak of Nitrogen Trifluoride
- 43 treatments and 12 hospitalizations
- Result of an O-ring failing in the gas exhaust system

https://bit-tech.net/news/tech/cpus/intel-chemical-leak/1/



OSHA PEL 8-hour TWA (ST) STEL (C) Ceiling Peak	
PEL-TWA	10 ppm (29 mg/m^3)
PEL-STEL	
PEL-C	
Skin notation	N

Incidents in the Semiconductor Industry

2013 SK Hynix Wuxi, China

- 1 minor injury
- Halted production of half the foundry for 6 months
- Result of installation of new equipment
- $1 billion in damages

https://www.computerworld.com/

Incidents in the Semiconductor Industry

2013 Samsung Hwaseong, South Korea

- 1 fatality
- 10 L diluted HF acid leaked
- Likely resulted from a damaged gasket

https://theseoultimes.com

Process Safety Management

“Process safety management (PSM) is addressed in specific standards for the general and construction industries. OSHA's standard emphasizes the management of hazards associated with highly hazardous chemicals and establishes a comprehensive management program that integrates technologies, procedures, and management practices.” – OSHA

14 Elements

- Employee Participation
- Process Safety Information
- Process Hazard Analysis
- Operating Procedures
- Training
- Contractors
- Pre-Startup Safety Review
- Mechanical Integrity
- Hot Work
- Management of Change
- Incident Investigation
- Emergency Planning and response
- Compliance Audits
- Trade Secrets

PSM Boundary in Manufacturing

Chemical Manufacturing

Oil and Gas

PSM Boundary in the Semiconductor Industry

- Specifically challenging that the standard was not written to include unique processes used within the semi-conductor industry.
- Small quantities of the chemical used after the bulk distribution system.
- Highly specialized tools with built in controls and interlocks to prevent potential incidents.
- Fast paced manufacturing environment with processes that are installed and uninstalled within a relatively short time period due to new process designs.
- Limited experience with PSM applicability within the industry.
- Various interpretations of PSM coverage applicability.
- Tool level coverage creates a significant financial and resource allocation burden that could cripple operations.

Jim Testo, CSP, CIH
Ashley Moll

Process Safety Management & the Semi-Conductor Industry

Greystone Risk Management - https://sesha.org/wp-content/uploads/2019/11/Greystone-PSM-Presentation.pdf

GREYSTONE

Azko-Nobel Chemicals – Limits of a Process 1997

In this case, the company does not dispute it has a covered process, as defined by 29 CFR 1910.119. However, what is disputed is the limits or the boundaries of the process downstream from the equipment the company stipulates is part of the covered process. The company contends that interconnected equipment downstream from what it stipulates as the covered process should not be included in the boundaries of the covered process. The company contends there is no circumstance, i.e. deviations, upsets, releases, etc., which might occur downstream (outside) from the stipulated covered process, which could affect a catastrophic release of HHC in the upstream stipulated covered process. Therefore, the company contends that since there is no potential for a catastrophic release of a HHC, those downstream aspects should be considered as being outside the limits or boundaries and should not be considered as part of the covered process.

It is OSHA's position that this issue can be resolved through the following analysis: Employers must determine:

1) the extent of process(es) by utilizing the definition of process [1910.119(b)] which includes any vessels which are connected and separate vessels located such that a HHC could be involved in a potential release. Engineering and administrative controls required by the PSM standard to prevent catastrophic release of a covered HHC may not be used to determine the extent of a process as defined in paragraph 1910.119(b). This interpretation is predicated on the assumption that an event such as an explosion will take place in the process notwithstanding such controls;

2) determine whether the process contains at any particular time a threshold quantity (TQ) or greater amount of a PSM HHC. If so, the process is covered by the PSM standard; and

3) consider each aspect of the process as defined to determine the extent of PSM coverage for each particular aspect. Aspects of the process which contain a HHC would be covered by all PSM elements, such as information, process hazard analysis and mechanical integrity. Aspects which do not contain HHC, but are interconnected or located nearby are part of the process. Such aspects may or may not be covered by the PSM standard based on whether the particular aspects could cause a HHC release or interfere with mitigating the consequences if there was a HHC release. If the particular aspects do not contain a HHC but could cause a HHC release or interfere with mitigating the consequences of a HHC release, then based on the employers analysis, various elements of PSM would apply to these aspects;

If based on this analysis, it is determined that interconnected equipment downstream from the stipulated covered process cannot cause a HHC release or interfere with the mitigation of the consequences of a HHC release, and the equipment does not itself contain a TQ or greater amount of a HHC, then such equipment could safely be considered outside the limits or boundaries of the covered process.

OSHA intends that the PHA be an objective verification to ensure that the process, as determined by the employer (using steps including #l through #3 above) is managed in accordance with the requirements of the PSM Standard.

Paragraph 1910.119(l) process safety management of changes are anticipated over the service life of the process. Aspects of the process impacted by a change must be reevaluated to determine the extent to which they are covered by the PSM standard. Of concern is that aspects could be removed from further consideration by an earlier evaluation of the process if the extent of the process was determined other than described above. As a consequence of a change, an overlooked aspect could contribute to the cause of a catastrophic release or interfere with mitigating the consequences if there was a HHC release.

Azko-Nobel Chemicals – Limits of a Process 1997

Employers must:

- Determine the extent of the process such that a HHC that could be involved in a potential release
  - Administrative and Engineering Controls can't be used to make the determination
- Determine if the process has a TQ or greater of PSM HHC
  - If so, it is covered by PSM
- Consider each aspect of the process to determine the extent of the PSM coverage

AkzoNobel

Based on the above determination:

- The interconnected equipment downstream cannot cause a HHC release or
- Interfere with the mitigation of the consequences of ta HHC relase
- The equipment itself does not contain a TQ or greater of amount of HHC
- Not PSM
- Verified by conducting a PHA

Key Take Aways

- Making Semiconductor chips is a long, complicated, expensive and hazardous process
- OSHA regulates many of the chemicals used in Semiconductor manufacturing
- Each employer should determine the PSM boundary for their process
- OSHA responded to Azko-Nobel Chemicals and laid out the rules for determining the PSM boundary
  - Determine where the process no longer has a HHC TQ
  - Confirm the boundary with a PHA

Thank you!

2023 Mary Kay O'Connor Safety & Risk Conference

Safe and Sustainable Energy Transition

In Association with IChemE and C-RISE

October 11-13, 2023

Texas A&M Engineering Experiment Station
Mary Kay O'Connor
Process Safety Center

Session 82: Safety First: Innovative Advanced Analytical and Automation Solutions For Improving Safety

Doug White
Emerson Automation Solutions

26th Process Safety International Symposium

Doug White (doug.white@emerson.com)

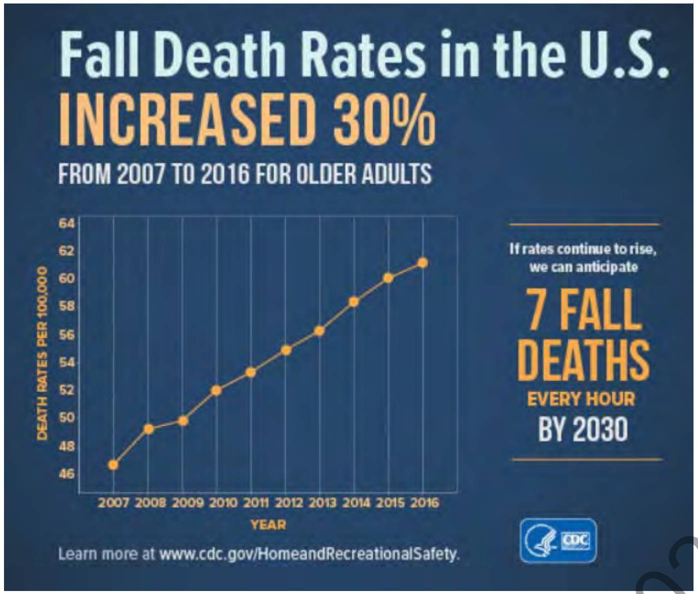
Principal Consultant

Emerson Automation Solutions

Background: Many years of experience designing, justifying, installing and commissioning advanced real time modeling, optimization, digitalization and automation applications in the process industries and assessing their impact on safety, sustainability and profitability.

EMERSON

Safety Moment: Safety on the Stairs



- Most of us use stairs everyday at home and work without thinking about the risk.
  - Falls are the most common incident reported at both home and work.
  - Over 1 million Americans are treated for fall-related injuries every year.
  - Estimated medical costs for falls in 2015 was $50B
- Take care to stay safe on the stairs:
  - Use the handrail
  - Avoid distractions like texting, conversation or reading
  - Walk, not run
  - Take one step at a time
  - Get help or use the elevator if moving things
  - Wear good footwear
  - Clear up spills when observed

Emerson At-A-Glance

(Continuing Operations)

COMPANY PROFILE

Emerson is a global leader in automation technology and software. We help customers in critical industries, like energy, chemical, power and renewables, life sciences and factory automation operate more sustainably while improving productivity, energy security and reliability.

BUSINESS SEGMENTS

SOFTWARE AND CONTROL	AspenTech Control Systems & Software
INTELLIGENT DEVICES	Measurement & Analytical Final Control Discrete Automation Safety & Productivity

66 YEARS

CONSECUTIVE YEARS OF INCREASED DIVIDENDS

SUSTAINABILITY MARKET PRESENCE

~70%
Sales tied to sustainability enabling technologies

65%
Of 2022 electric vehicles produced using Emerson solutions

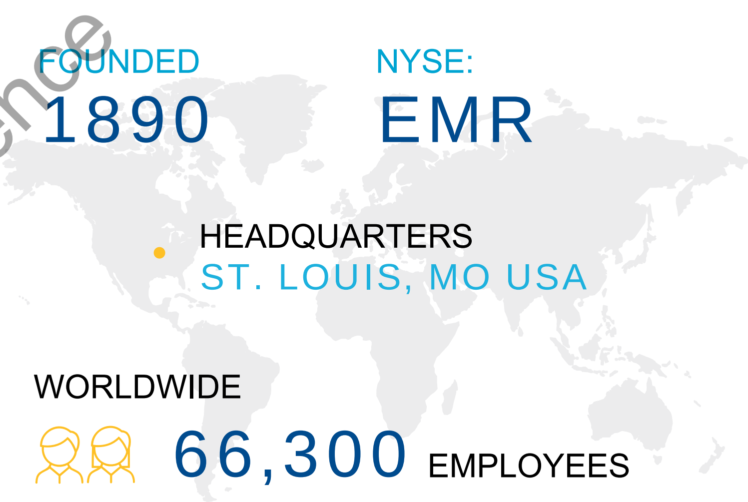
24 of Top 25
Life sciences companies use Emerson technology

60,000
Wind turbines controlled with Emerson systems

9 of Top 10
Semiconductor manufacturers use Emerson technology

$13.8 BILLION

GLOBAL NET SALES FY 2022



FOUNDED
1890

NYSE:
EMR

HEADQUARTERS
ST. LOUIS, MO USA

WORLDWIDE

66,300 EMPLOYEES

130 MANUFACTURING LOCATIONS

2022 RECOGNITIONS

TOP 50 EMPLOYERS
Woman Engineer Magazine

WORLD'S BEST EMPLOYERS
Forbes Magazine

INDUSTRIAL IOT COMPANY OF THE YEAR
IoT Breakthrough

CSB Video Of Philadelphia Refinery Explosion and Fire

Agenda

1 Introduction

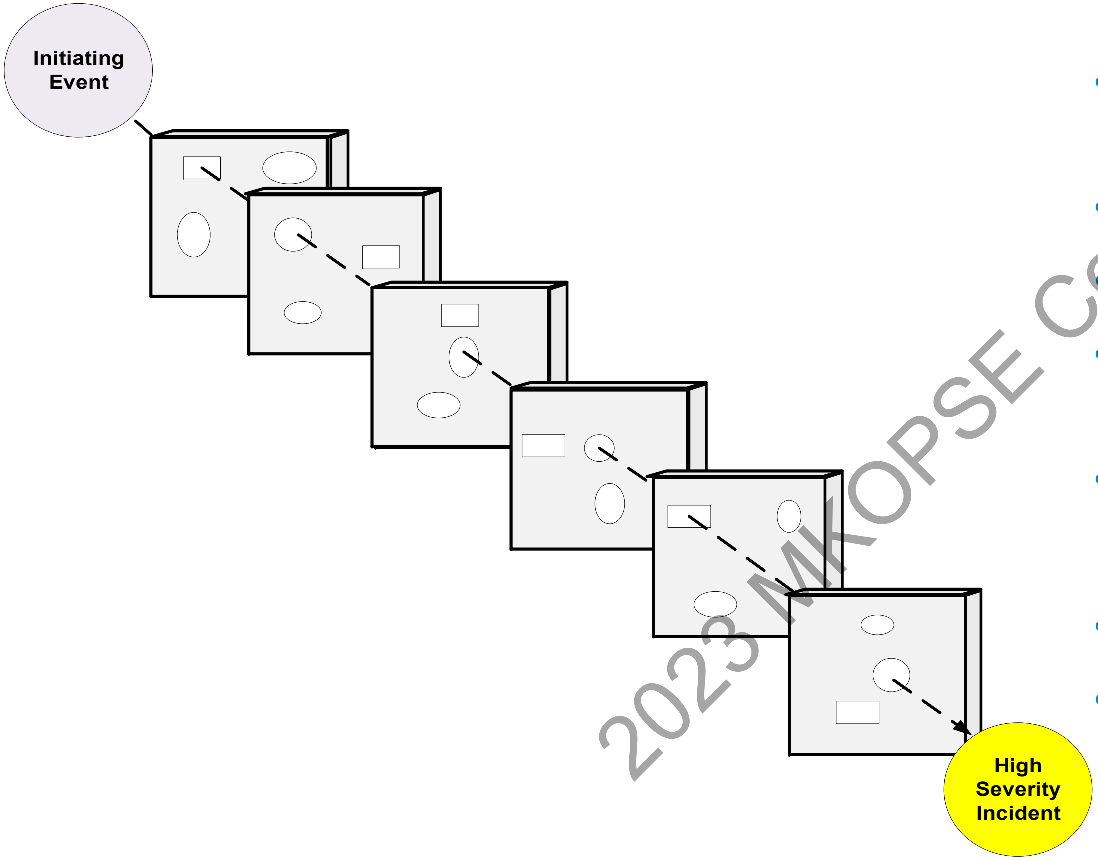
2 What Does The Data Tell Us?

3 How Can Recent Technology Advances Improve Safety?

4 What To Do Next?

5 Summary And Questions

Process Safety Risk Mitigation – Initial Layers of Protection



- Basic Process Chemistry and Components
- Process Design
- Staff Training and Procedures
- Equipment Maintenance and Monitoring Practices
- Basic Process Control Systems
  - Alarm Management
- Safety Shutdown Systems
- Relief Systems

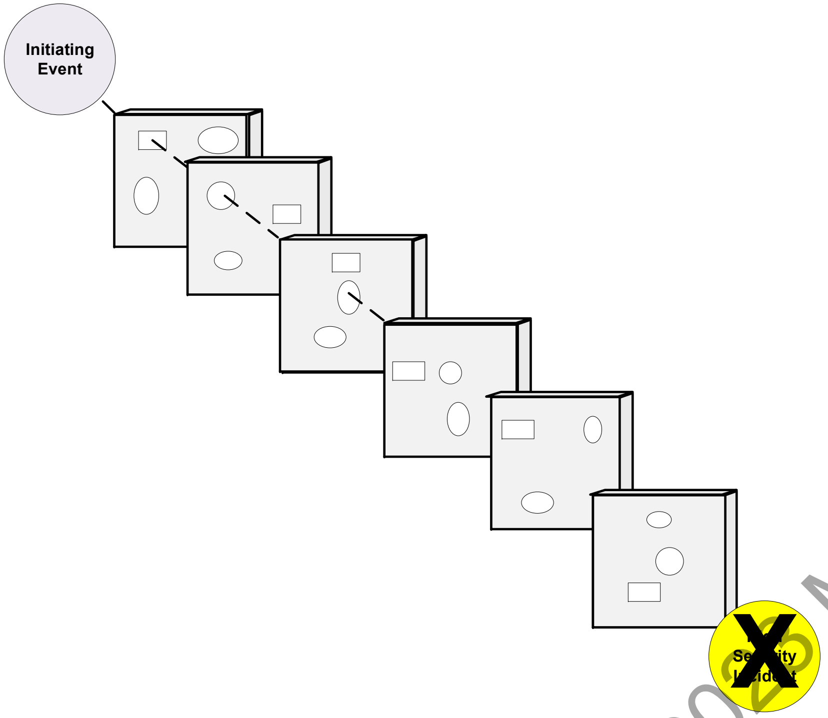
How Can New Advanced Analytical and Automation Solutions Help?

- **Major Gulf Coast Refinery - "Device diagnostic software (AMS) is key…we identified a problem with a boiler control transmitter that avoided an estimated production impact of $5 million, as well as potential equipment damage."**

- **Major Onshore Oil & Gas Processor – Implemented measurements and data analytics on key pumps. Analytics detected anomalous relationship between changes in pump intake pressure, motor amps and motor temperature and alerted maintenance – difficult to detect manually. Avoided a pump failure that could have created a safety incident and production losses.**

- **A European refiner operated four similar and parallel amine trains. They retrofitted real-time corrosion monitoring at key locations. It was determined that one of the four had *dramatically* higher corrosion rates which might have led to a safety incident and production losses prior to the next scheduled turnaround. Amine unit feed redistribution was implemented and the corrosion rate was brought under control.**

Advanced Analytical and Automation Solutions - Process Safety Risk Mitigation – Components Impacted



- Basic Process Chemistry and Components
- *Process Design*
- *Staff Training and Procedures*
- *Equipment Maintenance and Monitoring Practices*
- *Basic Process Control Systems*
  - *Alarm Systems*
- *Safety Shutdown Systems*
- *Relief Systems*

Advanced Analytical and Automation Solutions provide additional risk mitigation

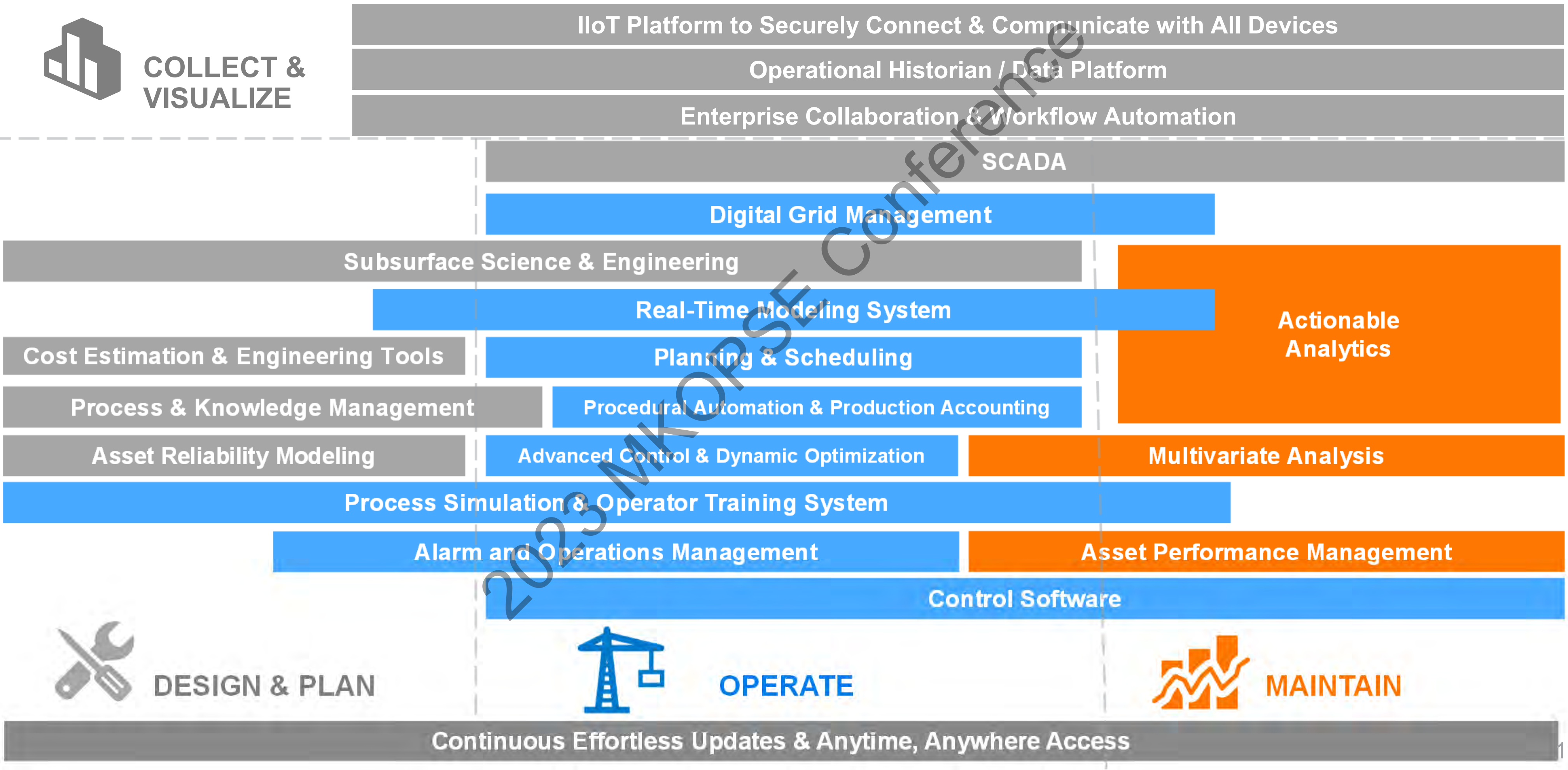
What Is Meant By Advanced Analytical and Automation Solutions?

DESIGN ←→ **OPERATE** ←→ **MAINTAIN**

Connected Enterprise	*Integrated operations across the corporation connected to business outcomes*
Optimized Operations	*Drive towards autonomous self-optimizing operations and maintenance*
Intelligent Field	*Results-oriented pervasive sensing and intelligent devices*

Safer Operation **More Sustainable** **Increased Profitability** **Improved Reliability**

Advanced Automation/Industrial Software /Analytics Capabilities That Support Safety Across the Facility Lifecycle



COLLECT & VISUALIZE

IIoT Platform to Securely Connect & Communicate with All Devices

Operational Historian / Data Platform

Enterprise Collaboration & Workflow Automation

SCADA

Digital Grid Management

Subsurface Science & Engineering

Actionable Analytics

Real-Time Modeling System

Cost Estimation & Engineering Tools

Planning & Scheduling

Process & Knowledge Management

Procedural Automation & Production Accounting

Asset Reliability Modeling

Advanced Control & Dynamic Optimization

Multivariate Analysis

Process Simulation & Operator Training System

Alarm and Operations Management

Asset Performance Management

Control Software

DESIGN & PLAN

OPERATE

MAINTAIN

Continuous Effortless Updates & Anytime, Anywhere Access

Refining And Chemical Plant Life Cycle: How Can Advanced Automation And Software Technology Help Improve Safety Through The Plant’s Life Cycle?

Techno-economic Safety Design

Maintain Safe Operation

Meet Regulatory Requirements

Process Modification Evaluation

- Evaluate Potential Safety Issues Through Design Decisions Regarding New Processes Or Products
- Model Fire Environments

Process & Equipment Design

- Accelerate Effective But Safe Scale-up Of New Processes
- Sizing Overpressure Systems Including PRV’s And Flare Systems
- Low Pressure Storage Tank Safety Modeling

Production Planning For Safe Operation

- Operator Training Simulation
- Optimize Feedstock Selection
- Set Process Targets
- Optimize Predictive Maintenance

Process Operation And Maintenance

- Accurate Warnings Of Potential Equipment Failures
- Reduce Personnel Exposure To Hazardous Conditions
- Procedural Automation Of Manual Operations
- Alarm System Management And Optimization
- Maintain “Integrity Operating Windows” Through Real Time Monitoring
- Digital Twin Modeling For Safety

Enterprise Optimization

- Asset Safety Monitoring Available Throughout The Corporation
- Consolidate Disparate Data Into Actionable Desktop User Interface
- Automate Regulatory Report Generation

Safety Incident – Possible Impact

Safety Incident

Personnel Impact

- SIF (Serious Injuries/ Fatalities)
- OSHA Recordables
- OSHA Lost Time Injury

Environmental Impact

- Tier 1, Tier 2 - LOPC Events
- EPA, State and Local Reportable Events
- NOV – Notice of Violations – Fines

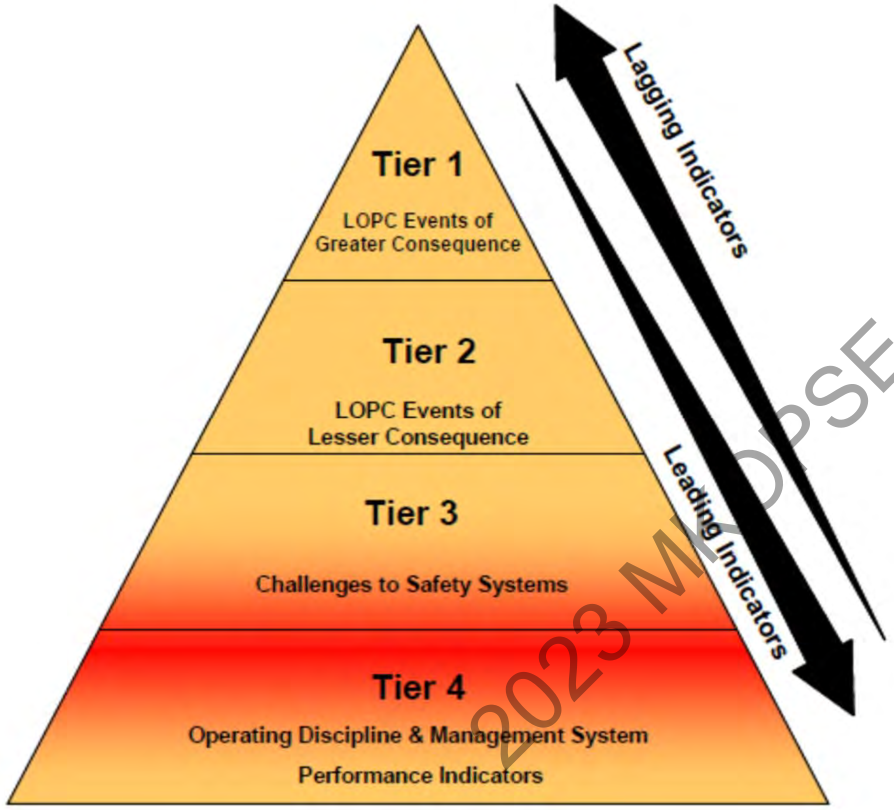
Community Impact

- Evacuation alert
- SIP – Shelter in Place alert
- Road Closures
- Media Headlines and Coverage

Financial Impact

- Direct Losses
- Production Losses
- Civil Suits
- High Loss Insurance Rates

Safety Event Classification - API RP 754



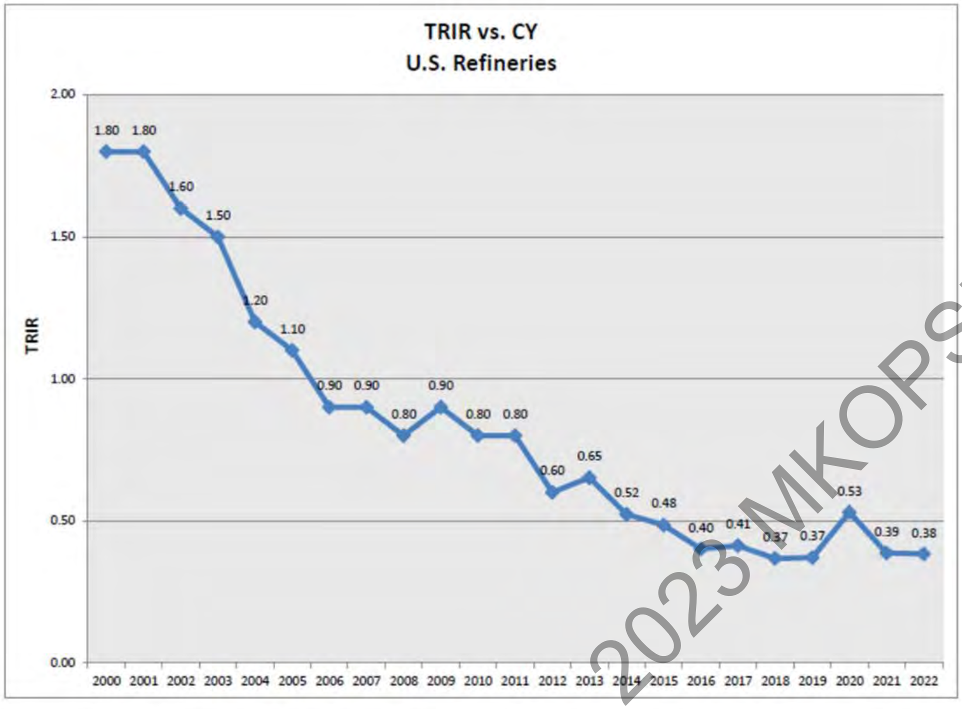
- In 2010, AFPM and API jointly created the Advanced Process Safety Program (APS)

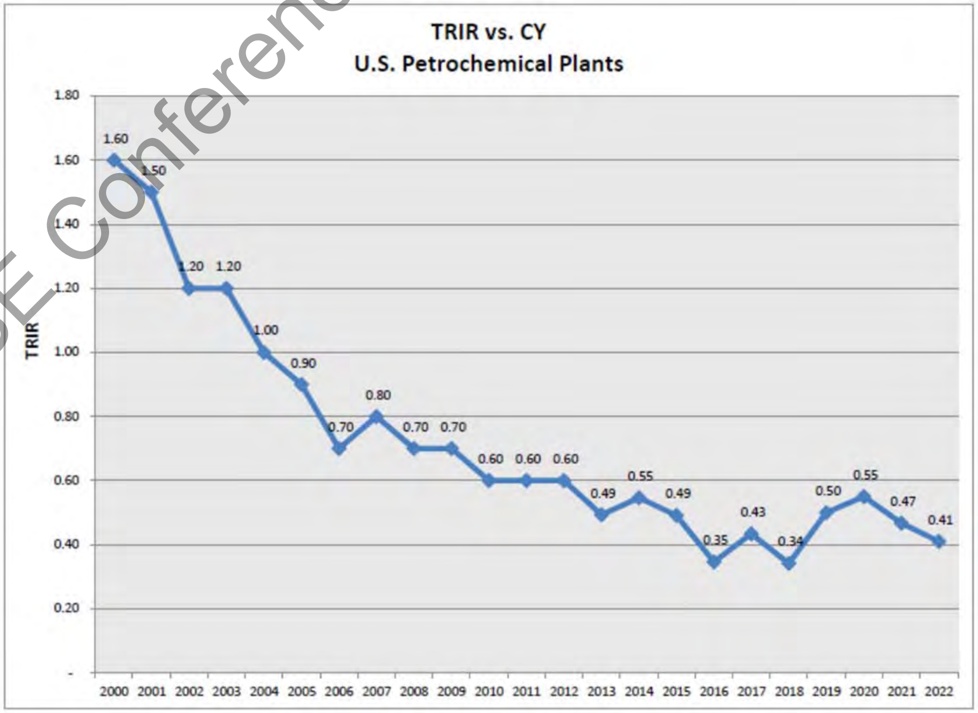
- Consistent data collection (voluntary) on all safety events (big and small) from virtually all the US refining industry and the majority of the petrochemical industry

- Two sub-groups – Occupational Safety (Safety and Health Committee) and Process Safety (Process Safety Workgroup)

What Does the Data Tell Us?

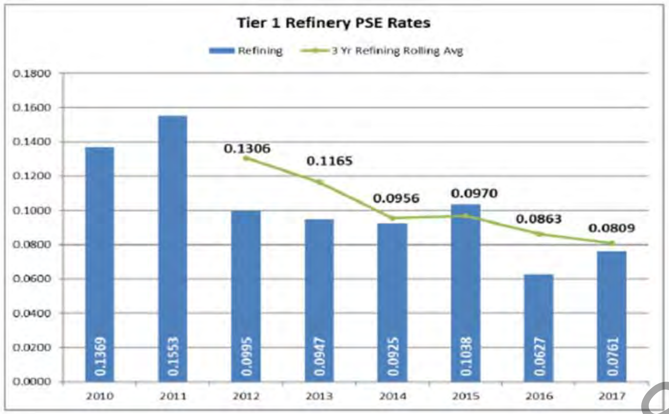
Occupational Safety

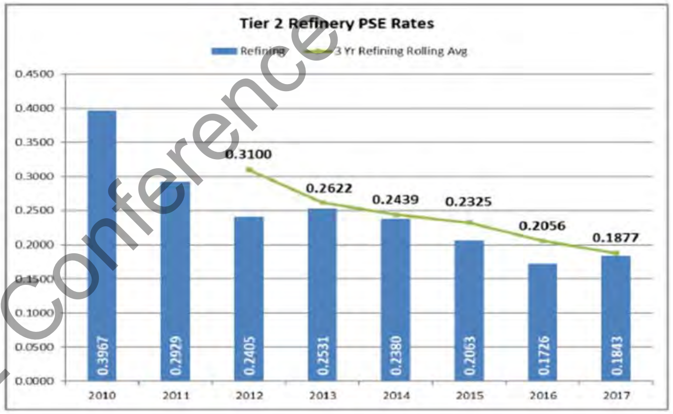


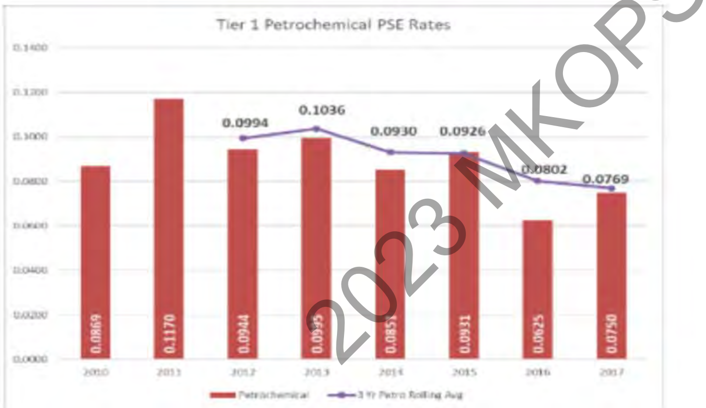


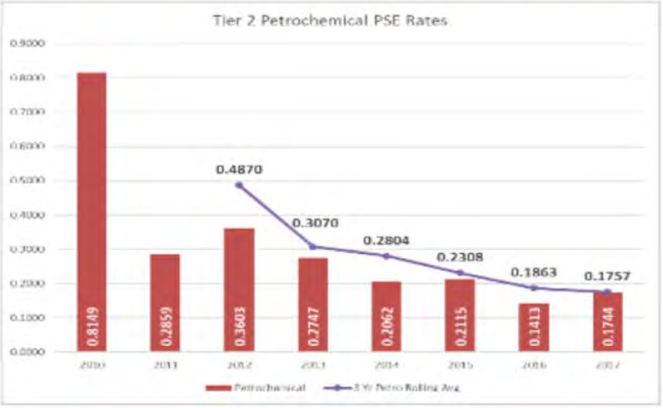
Source: 2022AFPM Occupational Injury and Illness Report

Process Safety - API 754 Tier 1 and Tier 2 Incidence









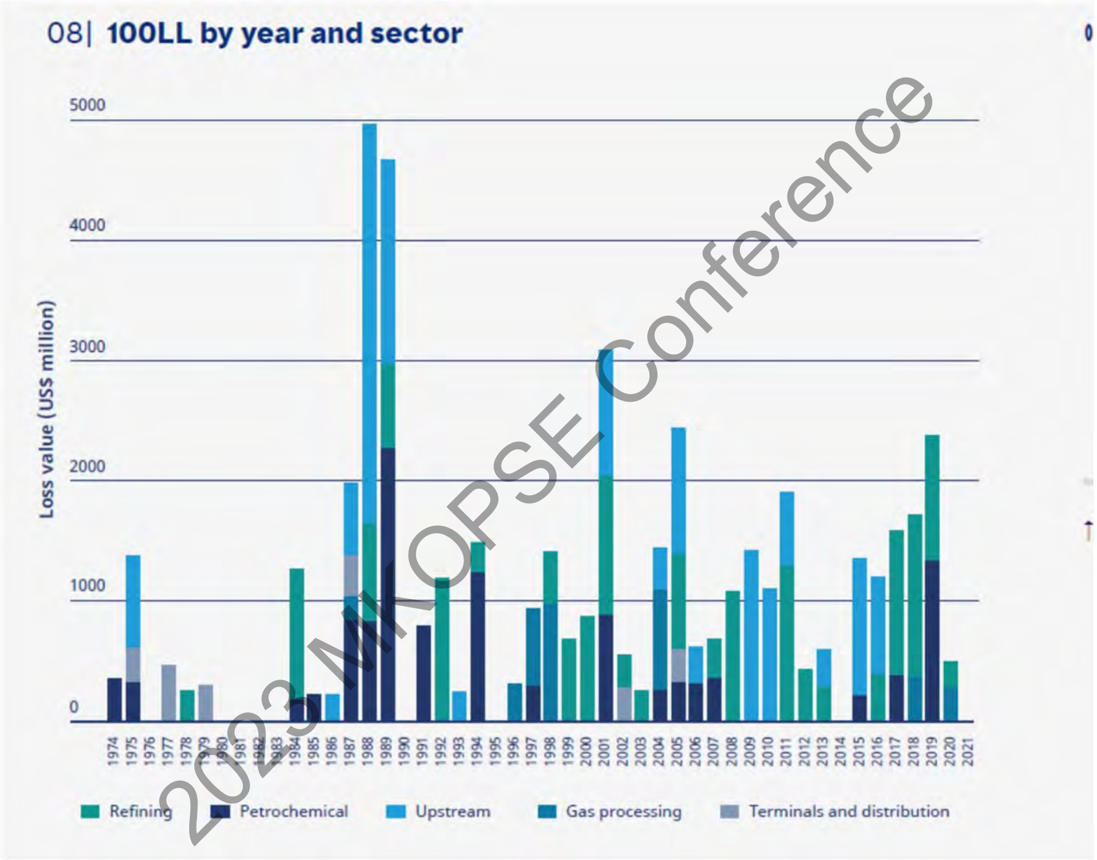
Source: AFPM Webinar; Advancing Process Safety; Nov 13, 2018

Most Common Locations For LOPC Incidents

Where do Tier 1 and Tier 2 Incidents Occur?

Source: AFPM Focused Learning Report 2020

Hydrocarbon Industry Property Damage Loss History



Production Losses Are Additional!

Source: Marsh & McLennan; Large Property Damage Losses in the Hydrocarbon Industry 27th edition

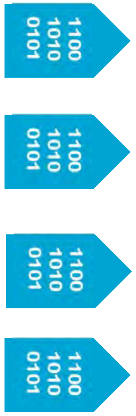
How Can Recent Technology Advances Improve Safety?

What Is Required For Advanced Analytics and Advanced Automation?

It starts with:

Data

Connectivity



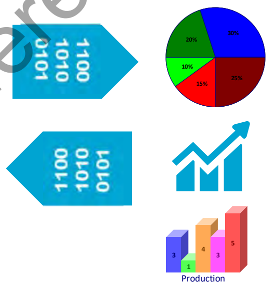
Storage

Cloud
Application
Platform
Data Storage

Or/ And

Server

Analytics



User Interface

You can measure and collect data from almost anything

You can send the data anywhere

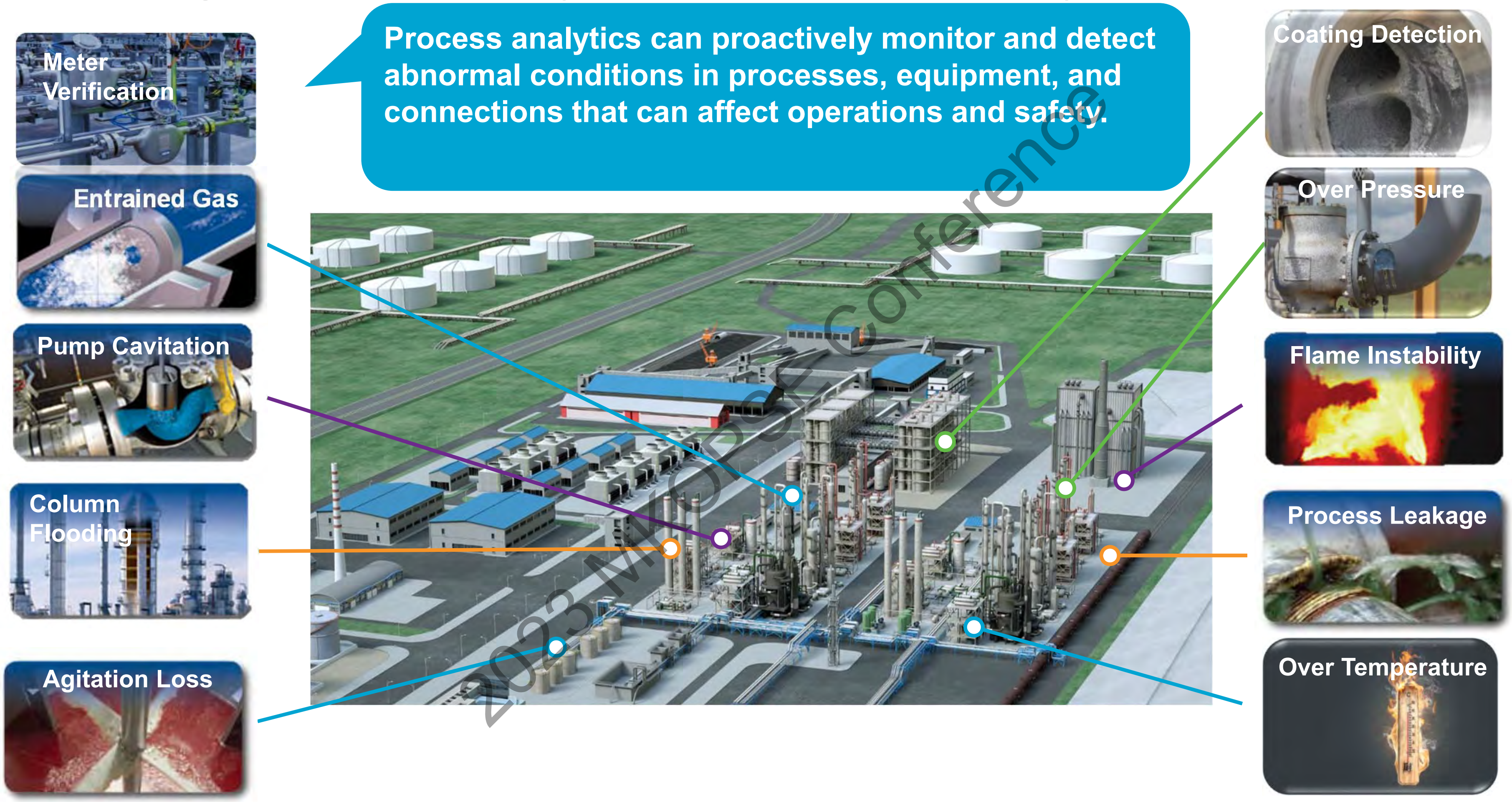
You can store all data with fast/ cheap access

Sophisticated analytics algorithms for model development easier to implement

Convenient User Interfaces

Improving Process Safety with Advanced Analytics

Process analytics can proactively monitor and detect abnormal conditions in processes, equipment, and connections that can affect operations and safety.



Tier 1 and Tier 2 Safety Events Frequency

Top Causes of Tier 1 and Tier 2 Safety Events

48% due to piping

13% due to tanks

10% due to pumps

6% heat exchangers

2% due to fired heaters

4% due to pressure vessels

Solutions

Piping
Real time corrosion monitoring

Tanks
Complete tank safety systems including tank overfill protection

Pumps
Leak Detection and condition monitoring

Heat exchangers
Condition monitoring to detect problems

Fired heater
BMS compliant with new API standards.

Fire and leak monitoring
Ambient toxic gas detection and alarming

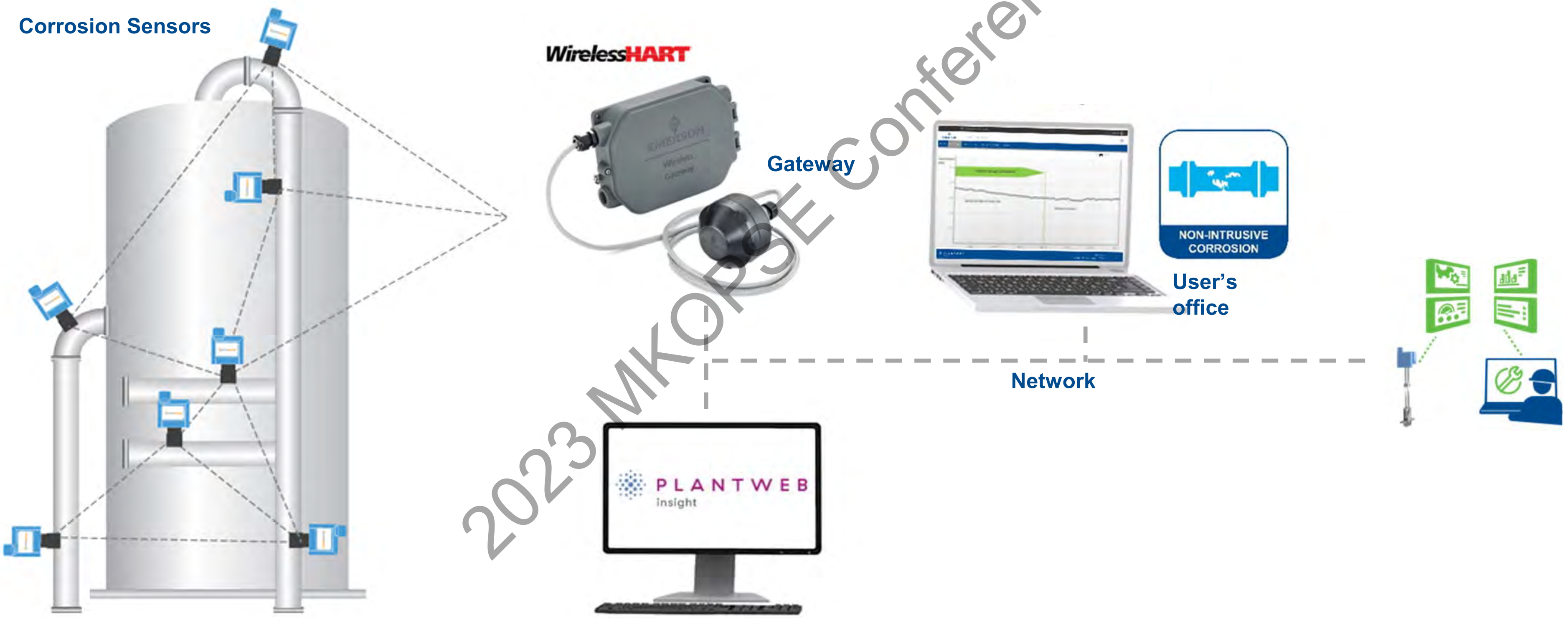
Corrosion Example - Continuous Integrity Monitoring Delivers Real Time Asset Health Data Directly to Desk

Field Data

Data Connectivity and Transfer

Analytical Software

User Interface



Corrosion Sensors

Gateway

User's office

Network

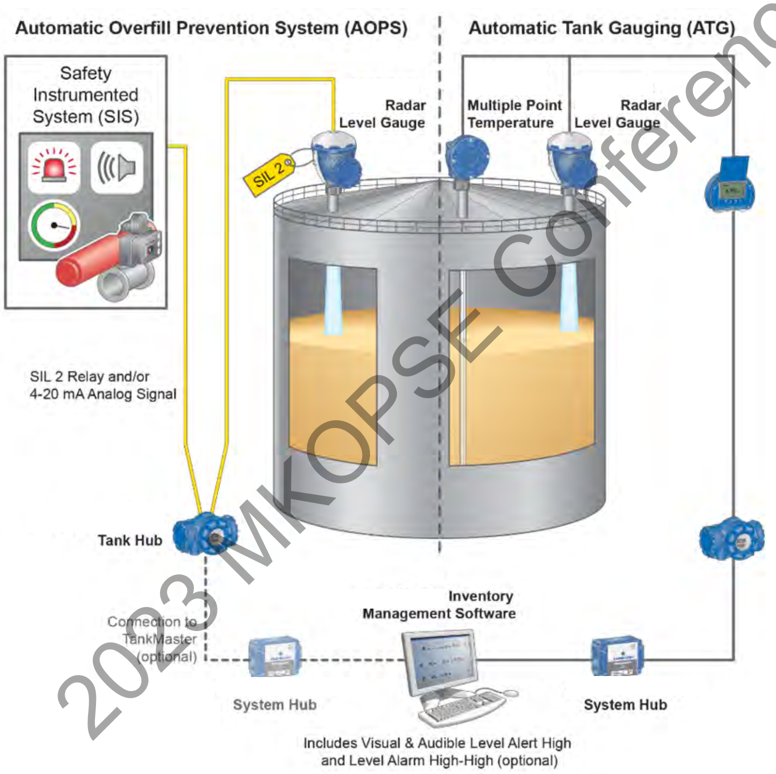
Server

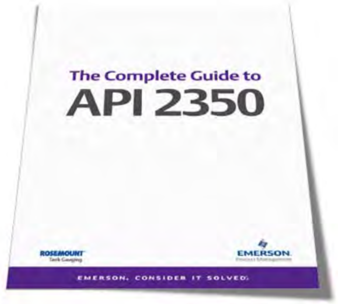
Tank Safety Solutions

One Overfill Statistically Occurs Every 3300 Filling Operations

One Overfill Every 10 Years for Group of 10 Tanks Filled 3x / Month

Source: Marsh and McLennan 2015




The Complete Guide to
API 2350

Independent Protection Layers

Serves as a Second Independent Layer of Defense Should the Basic Control System Fail

2-in-1 Functionality

Overfill Prevention and Level Measurement Using One Tank Nozzle

Comply with Regulations

API 2350 and IEC 61511 Compliant for Automatic and Manual Systems

Remote Proof-Testing

Safe and Fully Integrated Remote Partial Proof-Tests

Reduce Unplanned Shutdowns with Flame Instability Detection

Production Challenges

- Ultra low NOx burners were constantly on the verge of flame-out
- Variation in fuel BTU content causes flame instability
- Lack of insight to flame instability risked fired heater shutdowns and explosion risk in case of flame-out
- Traditional optical scanners are very expensive

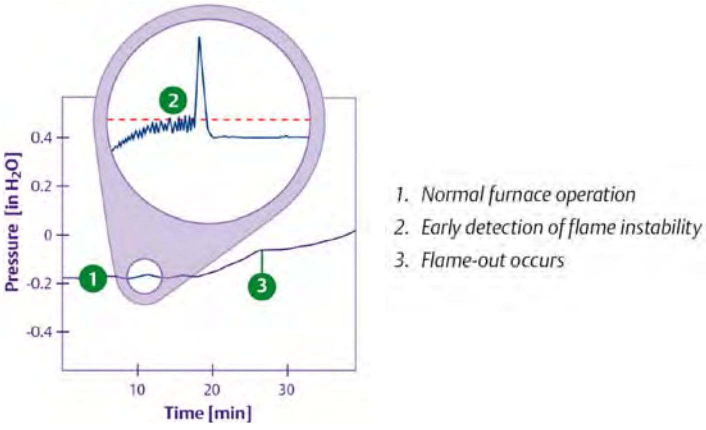
Value Enabler

Rosemount 3051S Pressure Transmitter with Process Intelligence Diagnostics

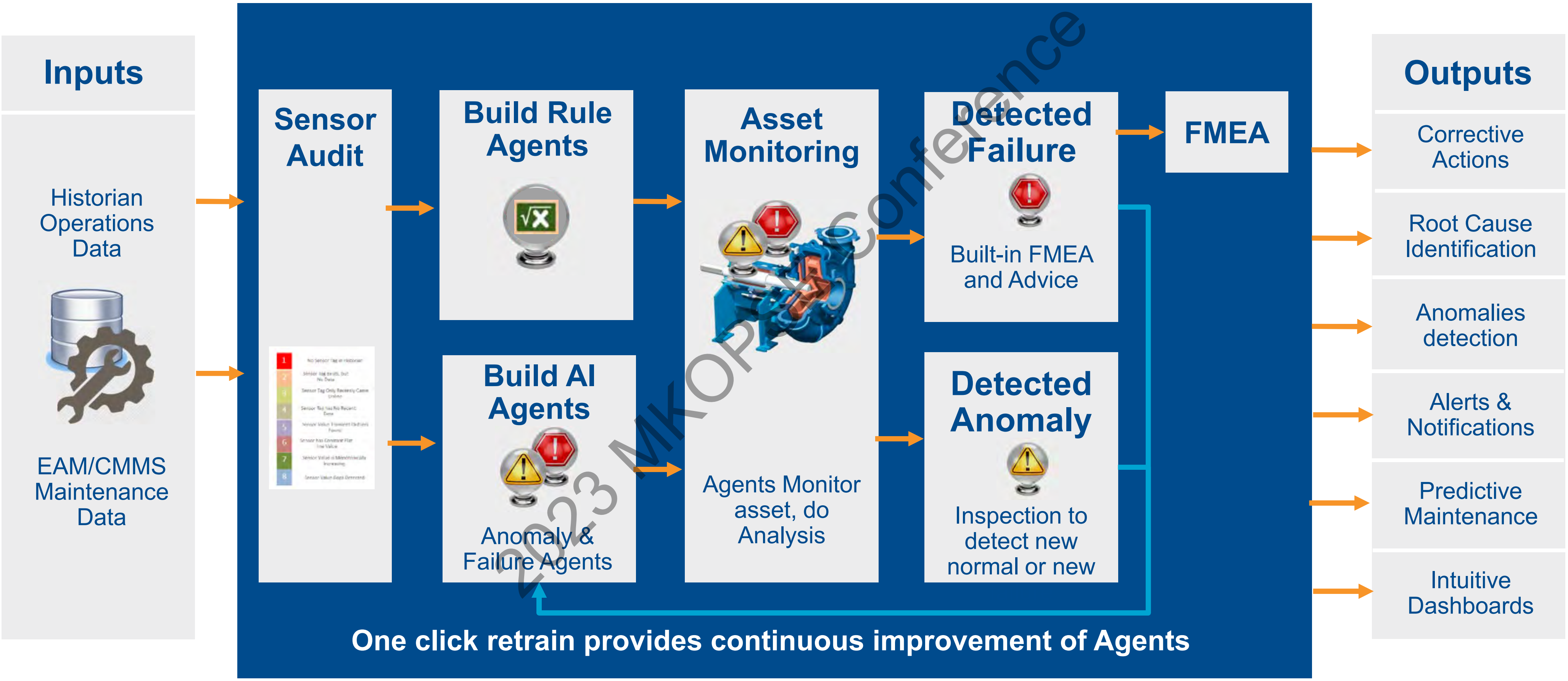
- Measure draft pressure in the firebox of the process heater at 22 times per second
- Statistical Process Monitoring (SPM) technology calculates standard deviation and mean of draft pressure
- Deviation from baseline is an indication of flame instability

Impact on Operations

- Eliminating shutdowns saved $1M per event
- 70% lower cost than optical system
- Reduced safety risk



AI Based Asset Fault Predictive Technology



Inputs

Historian Operations Data

EAM/CMMS Maintenance Data

Sensor Audit

Build Rule Agents

Build AI Agents

Anomaly & Failure Agents

Asset Monitoring

Agents Monitor asset, do Analysis

Detected Failure

Built-in FMEA and Advice

Detected Anomaly

Inspection to detect new normal or new

FMEA

One click retrain provides continuous improvement of Agents

Outputs

Corrective Actions

Root Cause Identification

Anomalies detection

Alerts & Notifications

Predictive Maintenance

Intuitive Dashboards

Protective Autonomous Agent Fault Prediction - Lead Time Examples

Industry	Asset Type	Failure	Days Lead Time	Industry	Asset Type	Failure	Days Lead Time
Mining	De-Water/Thickener	High Torque	30	Transportation	Locomotive Engines	Hydro Loss-of-Engine	47
Transportation	Locomotive Engines	Crankcase Bearings	25	Midstream O&G	Pipeline Pump	Main Bearing Failure	21
Chemicals	Hyper-Compressors	Plunger Displacement	47	Downstream O&G	H2 Comressor	Valve Failure	30
Pharma	Freeze Driers	Pass-thur Leakage	21	Water/Wastewater	Generator (CH4)	Cracked Head	14
Refining	Charge Pumps	Bearings Seals	30	Midstream O&G	ESP's	Cavitation Fails Motor	30
Refining	Compressors	Impeller/Bearings/Seals	14	Transportation	Locomotive Engines	Crankshaft Fatigue	63
Mining	Slurry Pumps	Motor Burn-out	30	Chemicals	Quench Oil Tower	Fouling	26
LNG	Compressors	V-cone Flow Element	63	Chemicals	Compressors	Liquid Carry-over	5-60
Upstream	ESP's	Casing Leaks	26	Chemicals	Compressors	Cylinder Noise	4-34
Pharma	Chillers	Tube Leaks	5-60	Chemicals	Compressors	Valve Contamination	30
Upstream Drilling	Draw-works	Motor Fail	4-34	Chemicals	Furnace	Coil Plugging	48
Upstream	ESP's	Gas-lock	30	Downstream O&G	H2 Compressors	Liquid Carry-over Issues	45-80
Pulp & Paper	Kiln	Overheating/Fires	48	Downstream O&G	Compressor	3rd-stage Valve Fail	56
Forest Products	Drying System	Blower Thermal Flash	45-80	Downstream O&G	Charge Pumps	Feed Density Changes	120
Pulp & Paper	Pulp Refiner	Catastrophic Blade Fail	56	Downstream O&G	Incinerator	Flame-out Analysis	1000+
Pharma	Chiller	Motor Failure	30	Downstream O&G	Feed Pumps	Bearing Failures	40+
Upstream	Top-Drive	Lube Motor Failure	25	Downstream O&G	Feed Pumps	Alignmnent Issues	40+

Reducing Hazardous Exposure - Range of Wireless Measurement Products to Replace Manual Checks

Pressure

Temperature

Level

Discrete

Vibration

Toxic Gas

Corrosion

What To Do Next?

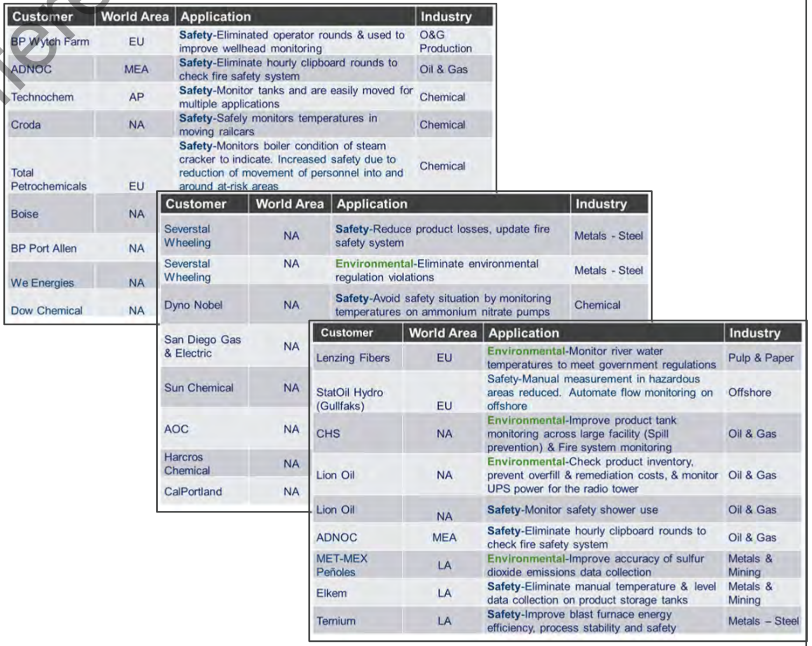
What Is The Next Step? – Safety Assessment Workshops

- Structured COLLABORATIVE process to build consensus on top priorities and safety impact
- Engagement from multiple disciplines at the plant and headquarters
- Experienced external consultants can facilitate session and provide outside expertise

Summary

- **Current Status in Refining and Petrochemical**
  - **Occupational Safety – Significant decrease in incident rate previously but leveling off in recent years**
  - **Process Safety – Still a significant number of incidents of high significance**
- **New Advanced Analytical and Automation technologies have the potential to provide early detection of potential safety incidents and to mitigate the consequences**

Catalog Client Safety Solutions



Customer	World Area	Application	Industry
BP Wytch Farm	EU	**Safety**-Eliminated operator rounds & used to improve wellhead monitoring	O&G Production
ADNOC	MEA	**Safety**-Eliminate hourly clipboard rounds to check fire safety system	Oil & Gas
Technochem	AP	**Safety**-Monitor tanks and are easily moved for multiple applications	Chemical
Croda	NA	**Safety**-Safely monitors temperatures in moving railcars	Chemical
Total Petrochemicals	EU	**Safety**-Monitors boiler condition of steam cracker to indicate. Increased safety due to reduction of movement of personnel into and around at-risk areas	Chemical
Boise	NA		
BP Port Allen	NA		
We Energies	NA		
Dow Chemical	NA		

Customer	World Area	Application	Industry
Severstal Wheeling	NA	**Safety**-Reduce product losses, update fire safety system	Metals - Steel
Severstal Wheeling	NA	**Environmental**-Eliminate environmental regulation violations	Metals - Steel
Dyno Nobel	NA	**Safety**-Avoid safety situation by monitoring temperatures on ammonium nitrate pumps	Chemical
San Diego Gas & Electric	NA		
Sun Chemical	NA		
AOC	NA		
Harcros Chemical	NA		
CalPortland	NA		

Customer	World Area	Application	Industry
Lenzing Fibers	EU	**Environmental**-Monitor river water temperatures to meet government regulations	Pulp & Paper
StatOil Hydro (Gullfaks)	EU	Safety-Manual measurement in hazardous areas reduced. Automate flow monitoring on offshore	Offshore
CHS	NA	**Environmental**-Improve product tank monitoring across large facility (Spill prevention) & Fire system monitoring	Oil & Gas
Lion Oil	NA	**Environmental**-Check product inventory, prevent overfill & remediation costs, & monitor UPS power for the radio tower	Oil & Gas
Lion Oil	NA	**Safety**-Monitor safety shower use	Oil & Gas
ADNOC	MEA	**Safety**-Eliminate hourly clipboard rounds to check fire safety system	Oil & Gas
MET-MEX Peñoles	LA	**Environmental**-Improve accuracy of sulfur dioxide emissions data collection	Metals & Mining
Elkem	LA	**Safety**-Eliminate manual temperature & level data collection on product storage tanks	Metals & Mining
Ternium	LA	**Safety**-Improve blast furnace energy efficiency, process stability and safety	Metals – Steel

EMERSON

Thank You!
Questions?

doug.white@emerson.com

A new index encompassing water-energy-food nexus and the risks associated with the production of protein

by

Dr. Tabassum Abbasi[1,2]

[2]Institute for Energy Systems, University of Edinburgh, Edinburgh , UK

[3]Sustainability Cluster,

University of Petroleum and Energy Studies, Dehradun, India

THE UNIVERSITY *of* EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM fellowship

UPES
UNIVERSITY OF TOMORROW

The food-water-energy-climate nexus impacted by the production of animal protein, and the associated risks

- Among the risks posed to the very existence of planet earth, one of the major ones is global warming and other forms of pollution caused in the course of producing animal protein from livestock

The food system underpinning the world's current dietary patterns is responsible for around 21–37 % of total (GHG) emissions.

FAO report, 2020

THE UNIVERSITY *of* EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM fellowship

UPES

The livestock sector utilizes and impacts 30% of the non-polar terrestrial surface on the planet.

The meat and dairy industries create 7.1 gigatons of greenhouses gases annually—that's 14.5% of total man-made emissions.

THE UNIVERSITY of EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL

Women in STEM fellowship

UPES

Raising, maintaining and utilizing livestock contribute about 18% of total anthropogenic greenhouse gas emission, second only to the top global warming sector: energy.

Image courtesy https://beef.unl.edu

The water used by the livestock sector is more than 8% of the global human water use.

The global share of water used for industry, drinking and servicing is just 0.1%.

- 500-2000 litres to produce a 1 Kg of potato, wheat, rice, or soybeans
- 43000 litres to produce one 1 Kg of beef.

THE UNIVERSITY *of* EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM fellowship

UPES
UNIVERSITY OF TOMORROW

Large quantities of energy and grain is required to produce meat as compared to other forms of food.

Livestock in USA consume more than 7 times as much grain as is consumed directly by the entire American population.

- The impact of livestock production on degradation of land and soil erosion is equally severe.

The prognosis

- The demand for livestock—and consequently livestock production—is going to increase sharply and is expected to reach 465 million tonnes, or double the 2000 figure, by 2050 .

Protein shortage

- The world is getting more and more short on plant protein

- But it is facing an even greater shortage of animal protein

- There have been concerted attempts to reduce the footprints of the conventional livestock production processes but the limit of that goal seems to have reached within both technological as well as socio-economic constraints.

- This has left us with only one option: finding alternative sources of animal protein.

THE UNIVERSITY *of* EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM fellowship

UPES

The sustainability weighed protein production index (SWePPI)

- SWePPI aims to provide a tool with which risks of global warming and pollution are incorporated into the gains in terms of per unit mass of protein obtainable from a source.
- With the resulting index one can compare different options of protein production and learn how much risk each carries.
- The index also brings out the energy-water-food nexus as the driver of global warming and other forms of eco-degradation caused by different sources of animal protein.

Methodology

Parameter selection

Global warming potential (GWP)

Land use(LU)

Water use(WU)

Protein content(P)

Vitamin content (I and B)

Fuzzy inference system development

To develop the index, 729 rules were used

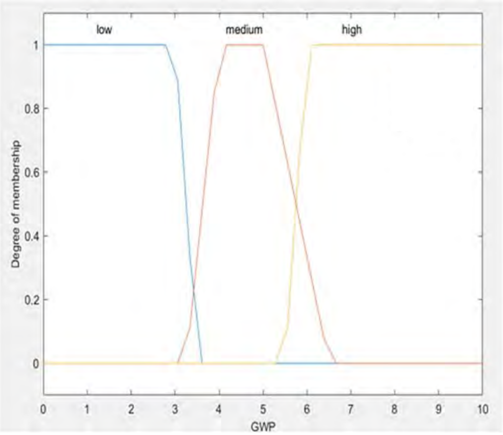
Optimization using evolutionary algorithms

To determine the optimal weights of a simplified weighted index

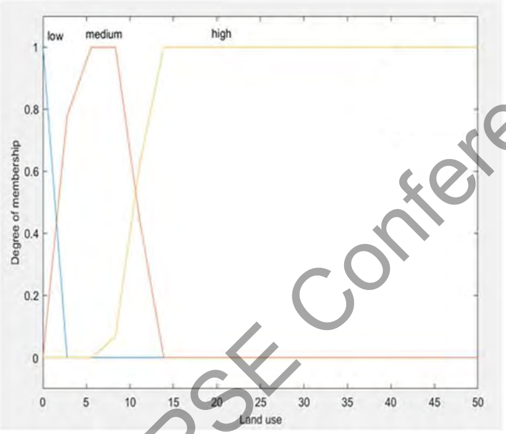
The food protein production index

The best algorithm was selected based on minimum error between the simplified index and fuzzy index. The optimized weights from the algorithm was deployed in the simplified weighted index

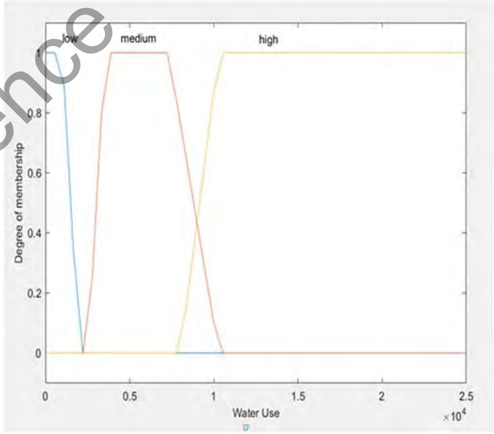
The fuzzy membership functions



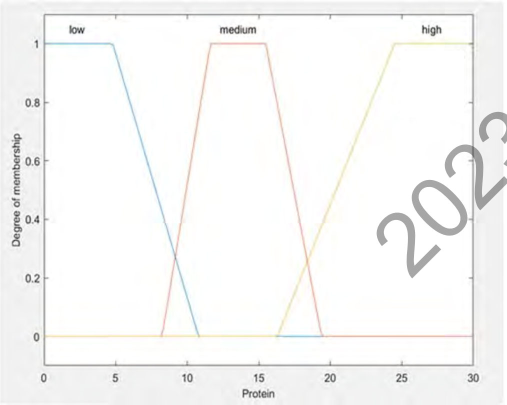
GWP



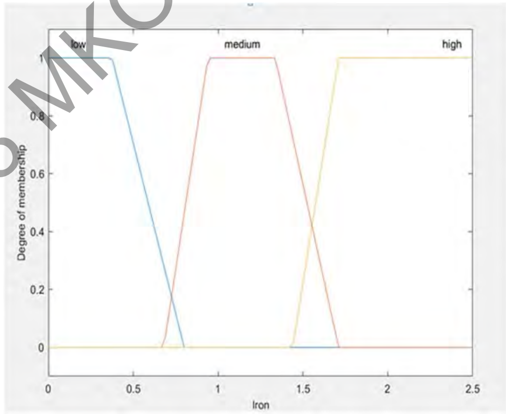
Land use



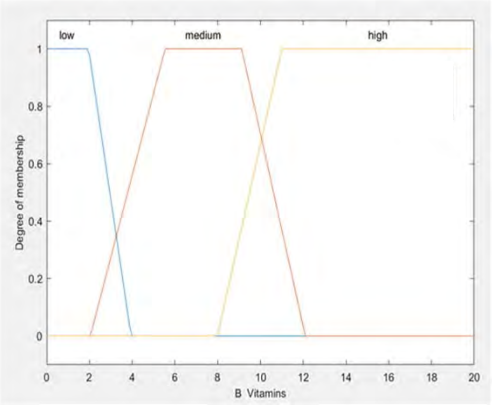
Water use



Protein content



Iron content

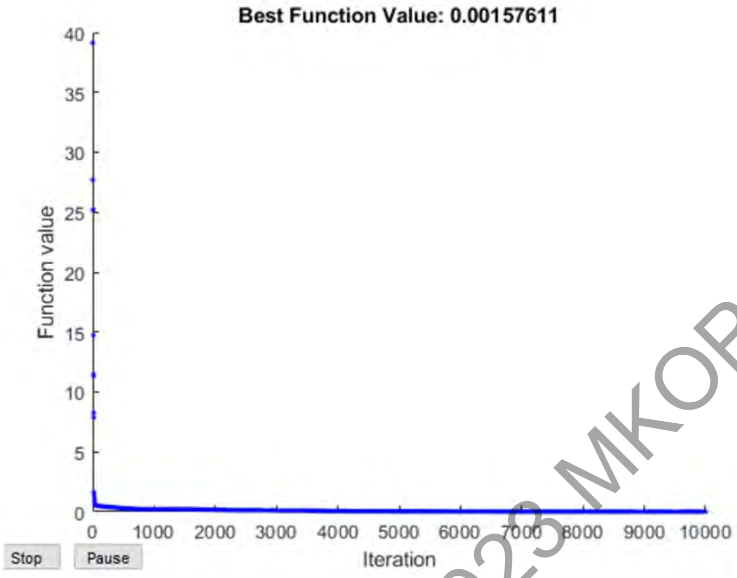


B-vitamins content

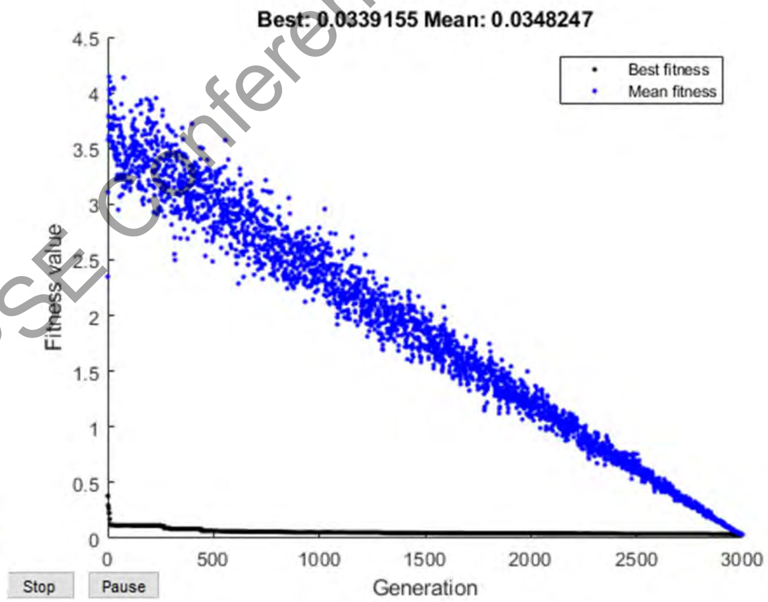
Results

Animal Protein Source	GWP from farm to regional distribution centre (kg CO_2 eq/kg produce or bone free meat)	Land use (m^2*year/kg food eaten)	Water (m^3/ton)	Protein content per 100 g edible portion (g)	Iron content per 100 g edible portion (mg)	B Vitamins per 100 g edible portion (mg)	Fuzzy food sustainability index
Milk	1.39	1.7	1020	3.66	0.2	1.47	11.85
Eggs	3.39	4.5	3265	19	2.16	2.18	46.79
Beef	28.73	53	15415	21.45	2.96	13.86	12.34
Pork	5.85	24	5988	22	0.49	6.63	12.14
Chicken	4.12	8.7	4325	10.64	0.7	10.38	21.95
Mealworm	2.7	3.6	2.5	19.24	2.18	8.88	86.20

Performance of the PSO and GA algorithms in optimizing the weights of the PSI

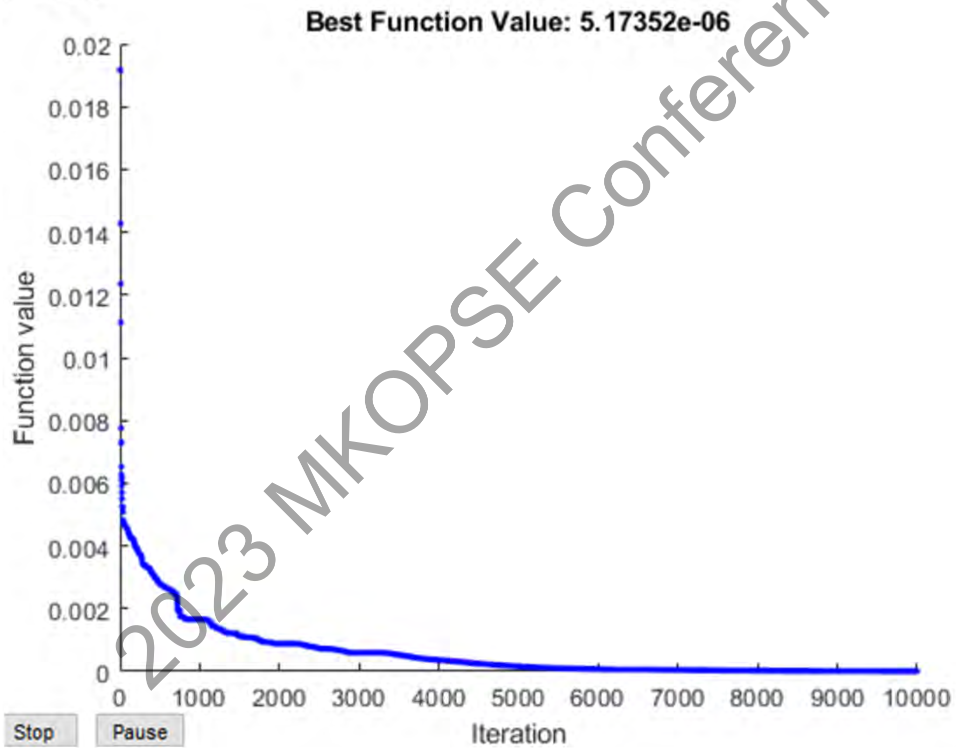


Performance of the Particle Swarm Optimization algorithm in optimizing weights of the PSI



Performance of the Genetic Algorithm in optimizing weights of the PSI

Performance of the particle swarm algorithm in optimizing weights of the PSI



Comparison of the linear indexes derived using GA and PSO

$PSI_{PSO}=7.66*GWP-3.00*LU-0.01*WU+3.81*P-5.95*I+1.81*B$

Animal Protein Source	Fuzzy food sustainability index	PSO derived linear food sustainability index (PSO-FSI)	GA derived linear food sustainability index (GA-FSI)
Milk	11.85	11.85	3.66
Eggs	46.79	46.79	47.71
Beef	12.34	12.34	12.25
Pork	12.14	12.14	12.51
Chicken	21.95	21.95	22.67
Mealworm	86.20	86.20	85.52

GWP: Global warming potential from farm to regional distribution center,
LU: Land use, WU: Water use, P: Protein content, I: Iron content, B: B-vitamins content

THE UNIVERSITY of EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM fellowship

UPES

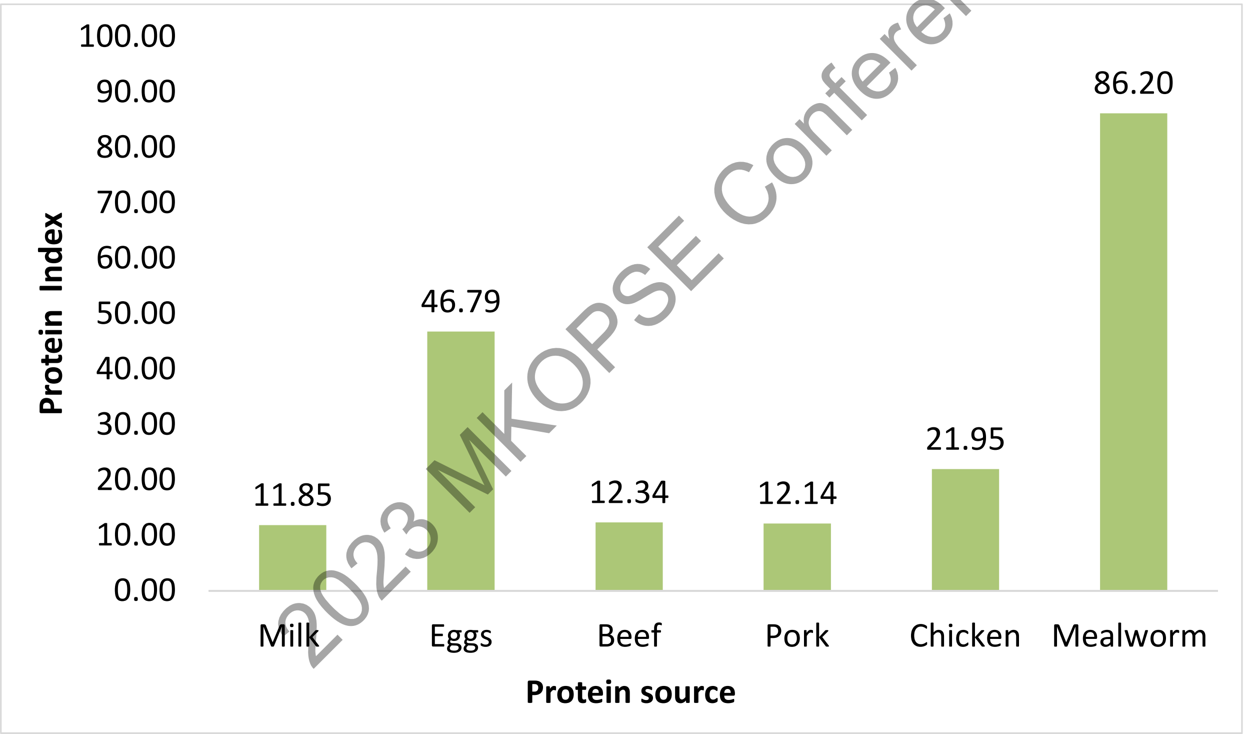
Index score	Interpretation
0 - 30	Low sustainability
30 - 60	Average sustainability
60 -80	Good sustainability
80 - 100	Excellent sustainability

THE UNIVERSITY of EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM
fellowship

UPES

Index scores for various sources of animal protein



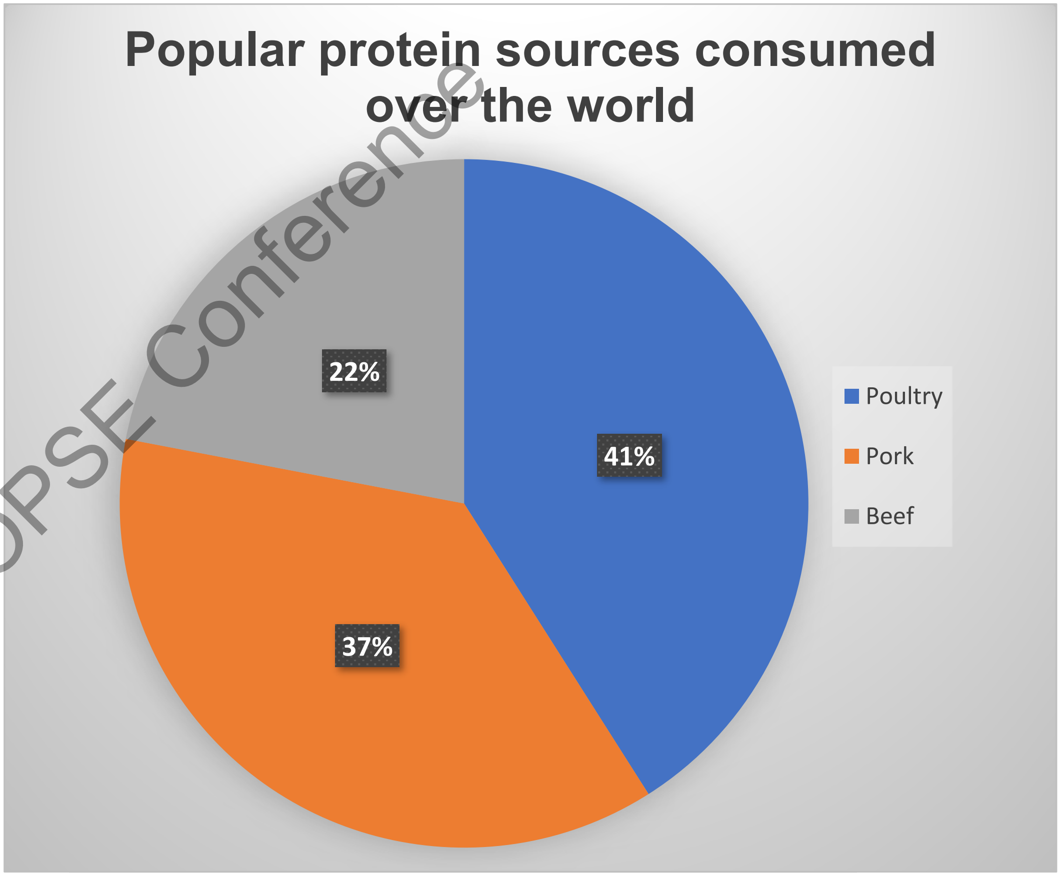
THE UNIVERSITY of EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM fellowship

UPES

- By a recent estimate (Shahbandeh, 2023) poultry is the most widely eaten animal meat in the world (41%), followed by pork (37%) and beef (22%).

- On the scale of animal protein in general, fish and other aquatic sources contribute the most (33%), followed by poultry (28%), pork (25%) and beef (15%).



THE UNIVERSITY *of* EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM fellowship

UPES
UNIVERSITY OF TOMORROW

- Other sources of animal protein are also consumed in different regions such as bush meat, frogs, reptiles, and dogs but their proportion in global human diet is negligible.

- This shows that from among millions of genera of animals, humankind depends mostly on just 3 genera for its meat intake, and a few more for its overall animal protein intake.

- And production of all these sources of animal protein is imposing on the world great risk of global warming, pollution, and ecosystem collapse.

https://www.mashed.com

Women in STEM
fellowship

Minilivestock: a veritable treasure trove

- One of the potentially most diverse, nutritious, and eco-friendly sources of animal protein is small invertebrates, mainly insects.
- If this sounds incredulous, and possibly revolting, to hear, permit me to real off these facts:
- During all but a few hundred years of its 4 million year presence on earth, Homo sapiens has been an insect-eater, or entomophagous.
- It is even said that it was due to certain proteins present abundantly in insects, which are lean in higher animals, that human brain could evolve much faster and better than it otherwise have.

THE UNIVERSITY *of* EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM fellowship

UPES

Due to certain socio-religious factors entomophagy was gradually abandoned in most areas of the world.

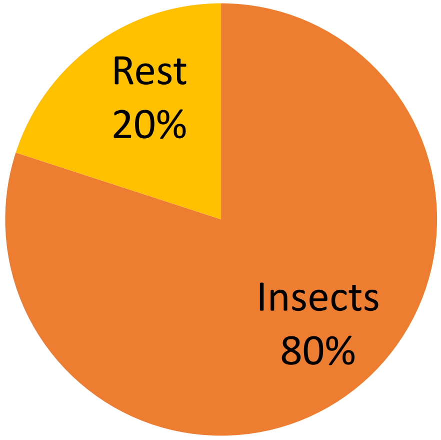
Yet it not only survives but thrives in certain regions, mainly in South-East Asia, Latin America, and parts of Africa.


Insect lollipops, Germany


Chaprah – red ant Chutney , *Chattisgarh, India*

Key factors which make insects — or minilivestok — potentially better source of animal protein than conventional Livestock

- For every kilogram of vegetation consumed, more animal protein is generated by minilivestock than by conventional livestock.
- Meat production, in particular, consumes great energy as it takes 10 times more plant nutrients to produce meat than equivalent quantities of insect protein.



Animal Kingdom

- Minilivestock is able to transform phytomass into zoomass much more efficiently than conventional livestock .
- A substantial contribution to this energy efficiency comes from higher edible weight fraction of insects. For example 80% of a cricket is edible as compared to 58% of chicken and 40% of beef.
- Insects are poikilothermic—they can change their body temperatures to match that of the surroundings. Due to this, the insects have to spend much less part of their food energy and nutrients in maintaining their body temperature than the warm-blooded livestock have to. This further enhances the overall energy efficiency of insect-based protein production.

- Unlike conventional livestock, insects can be reared on a myriad of biodegradable waste. For practically every substance of organic origin, there are one or more species of insects specialized in feeding upon it.

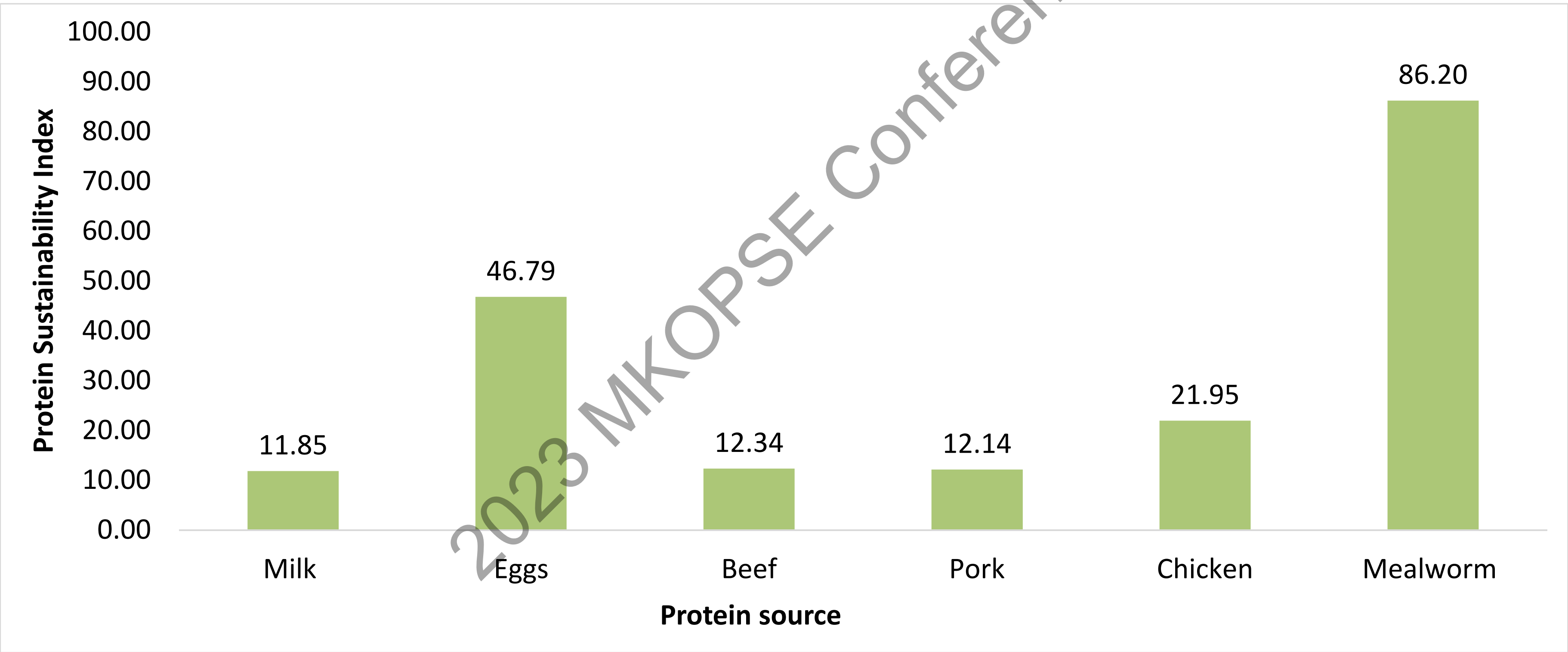
- If an organic waste happens to carry the risk of pathogens and contaminants—such as manure—the insects reared on it may not be directly utilizable for human consumption but can be made to contribute, with due quality control, indirectly to human diet by use as poultry or fish feed.

- In this manner insects can reduce the demand on foodgrain for livestock feed and free that much extra foodgrain for human consumption. In turn they may either reduce, or add value to the very substantial water use that is involved in grain production (especially rice).

- The significance of this aspect can be gauged from the fact that 60 percent of the total cost of raising farm animals is incurred on the feed of which a major portion comes from foodgrain.

- In the USA about 91% of the estimated 27.1 million tons of cereal, legume, and vegetable protein that is otherwise fit for human nutrition, is fed to livestock every year. In return only 5.3 million tons of animal protein is obtained.

Back to the sustainability score of various protein sources



So would you like to try meal worms in your next meal?

OR

?

THE UNIVERSITY *of* EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM fellowship

UPES
UNIVERSITY OF TOMORROW

Thank you

THE UNIVERSITY of EDINBURGH
Institute for Energy Systems

BRITISH COUNCIL
Women in STEM fellowship

UPES
UNIVERSITY OF TOMORROW

Greater reproductive thrust

Insects have much higher fecundity and much faster growth rate