University of Sheffield

Congres
Process Safety
May 14, 2025 - Dordrecht

Fiona Macleod
Professor of Process Safety
School of Chemical, Materials and Biological Engineering
University of Sheffield

WHAT UNI? STUDENT CHOICE Awards 2024 **UNIVERSITY OF THE YEAR**

victrex

ICI

EASTMAN

Hovione

bp

JM

龍蟒佰利聯
LOMON BILLIONS

Fiona Macleod

Managing Director Lynemouth Power at EPUKI

England, United Kingdom · Contact info

500+ connections

EP UK Investments Ltd

University of Cambridge

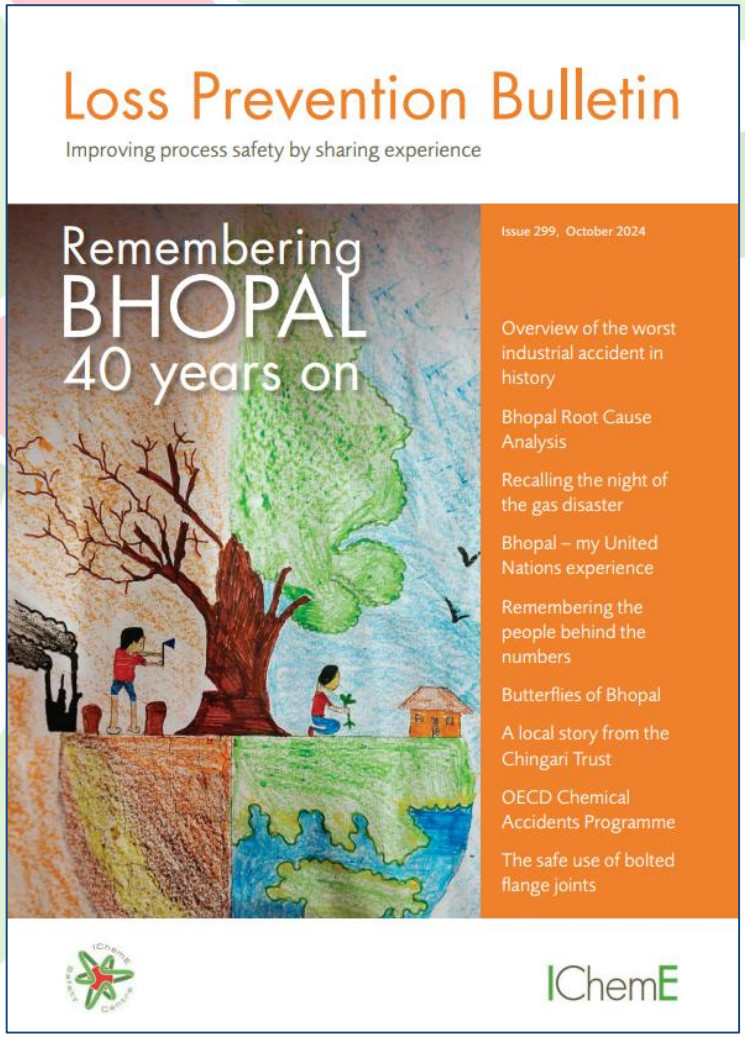
Open to | Add profile section | More

University of Sheffield

Chemical, Materials and Biological Engineering

Process Safety and Loss Prevention

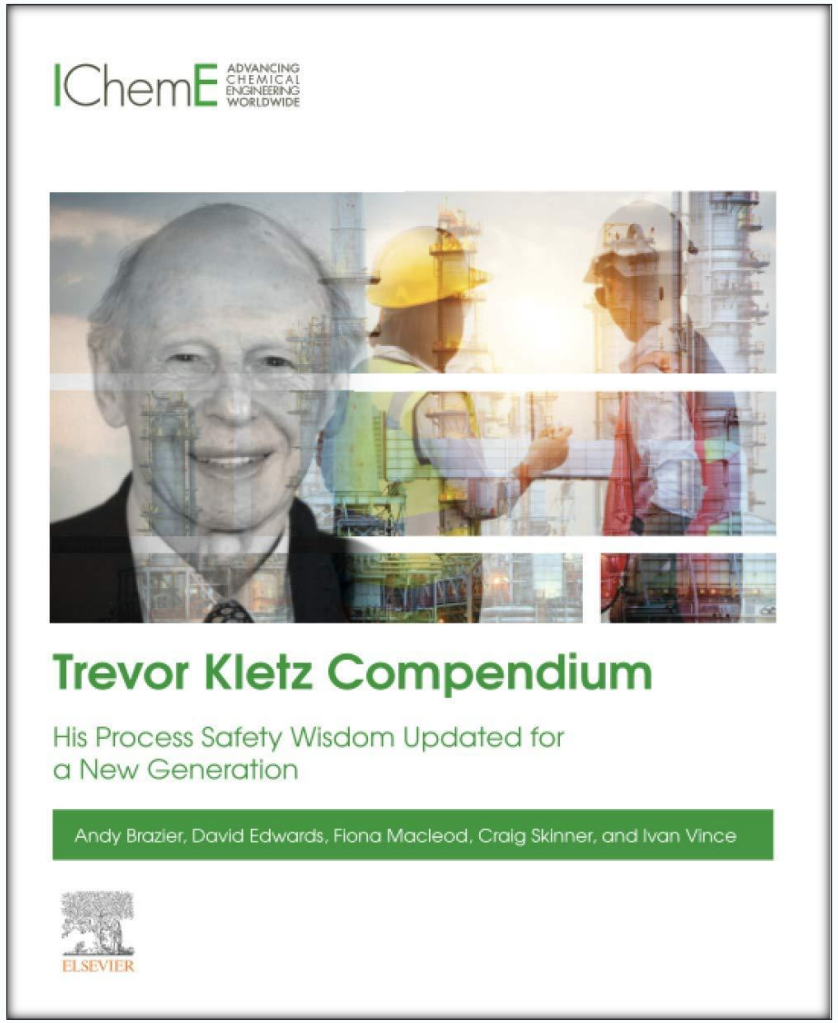
WHAT UNI? STUDENT CHOICE Awards 2024 UNIVERSITY OF THE YEAR

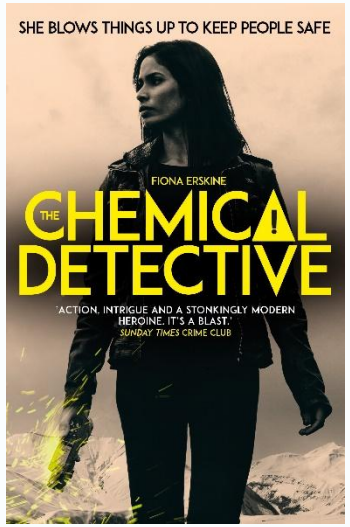


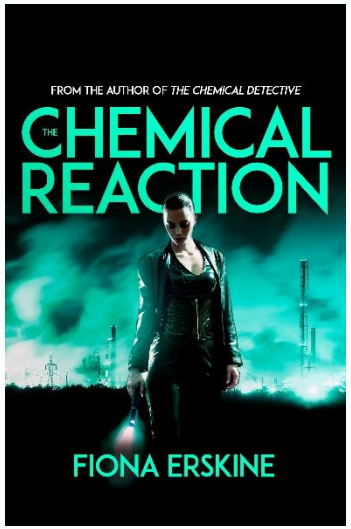
IChemE Safety Centre

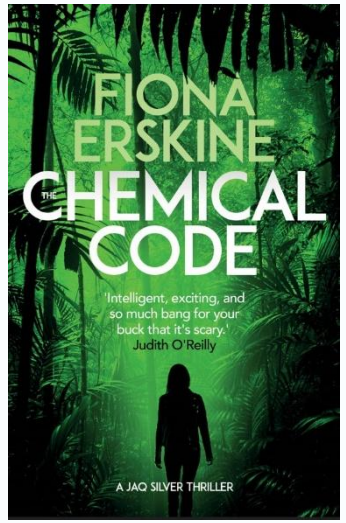
Fiona Macleod
Chief Technical Officer

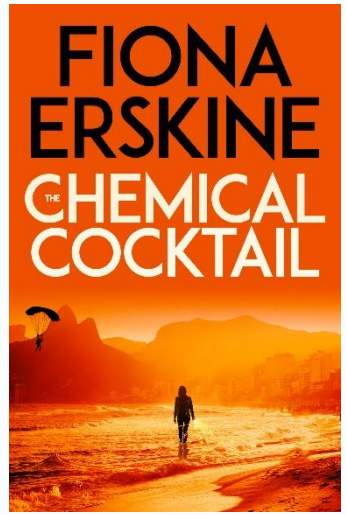
Engineer by day, writer by night

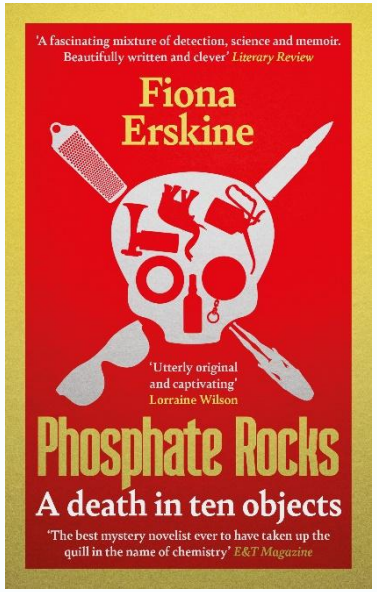


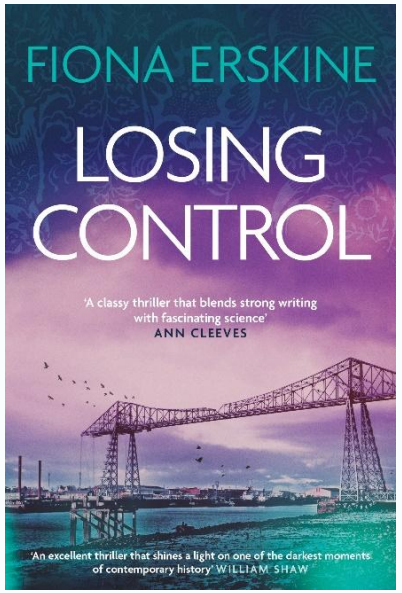










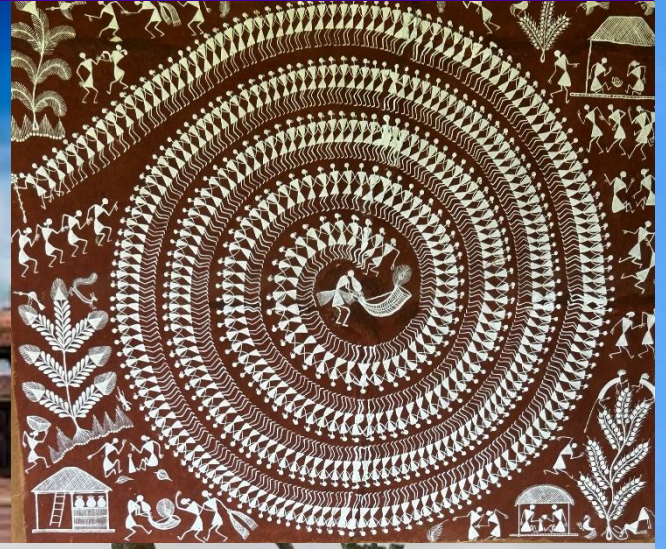


University of Sheffield

University of Sheffield

Bhopal 40 Years on

What Have We Learned?



Bhopal, 40 years on

The Tragedy

When?	3 December 1984
Where?	Bhopal, Madhya Pradesh, India
What?	~27 tonnes of toxic gas released
Who?	Thousands killed Hundreds of thousands injured

Toxic gas release – How did it happen?

How?

Runaway reaction

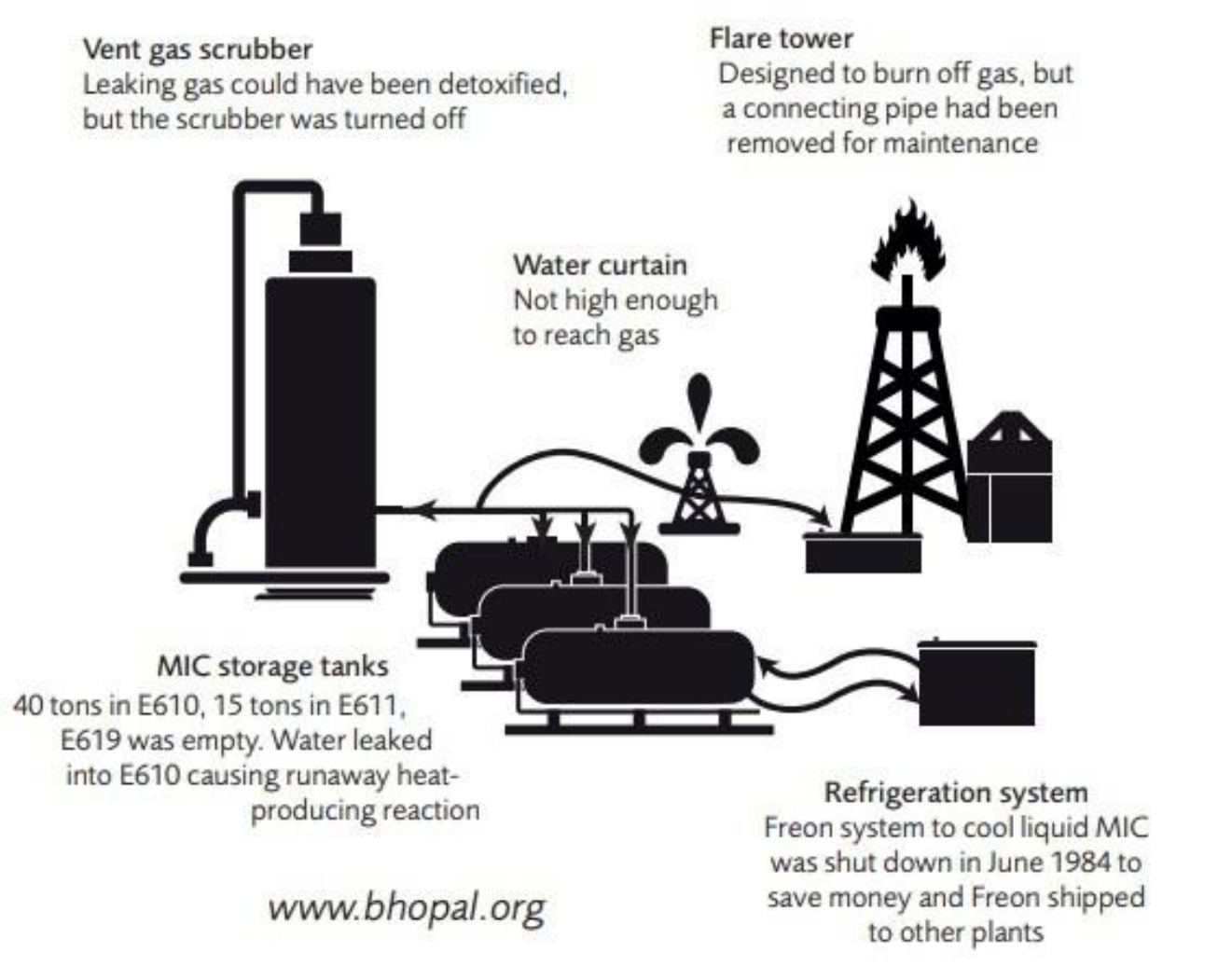
Methyl Isocyanate (MIC) + H_20 + Fe

Why?

Five theories

Failure of emergency response

- Flare
- Scrubber
- Water Curtain
- Spare tank
- Refrigeration
- Community Alarm
- Community Response Plan



How did water enter the MIC tank?

1. The MIC slow degradation theory
2. The filter washing theory
3. The sabotage theory
4. The nitrogen mix up theory
5. Rethinking Bhopal

The Investigations

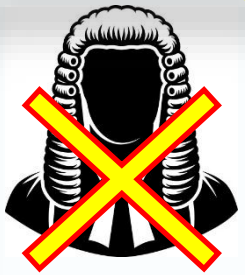
BHOPAL METHYL ISOCYANATE INCIDENT

INVESTIGATION TEAM

REPORT

MARCH, 1985

UNION CARBIDE CORPORATION
DANBURY, CONNECTICUT



Judge NK Singh Inquiry

INVESTIGATION OF LARGE-MAGNITUDE INCIDENTS: BHOPAL AS A CASE STUDY

Ashok S. Kalelkar
Arthur D. Little, Inc.
Cambridge, Massachusetts, USA

Presented At
The Institution of Chemical Engineers Conference On
Preventing Major Chemical Accidents

London, England

May 1988

REPORT ON SCIENTIFIC STUDIES ON THE FACTORS RELATED TO BHOPAL TOXIC GAS LEAKAGE

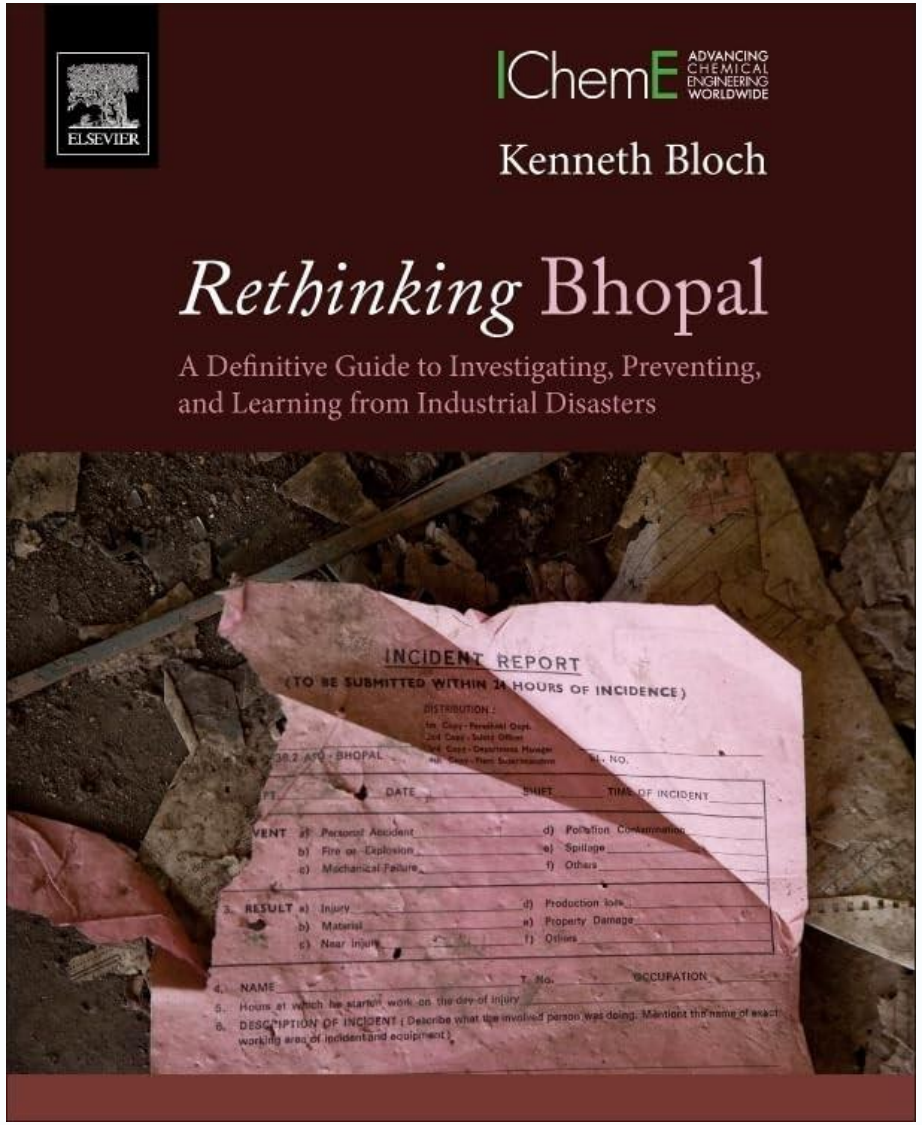
This Report results from Studies

by

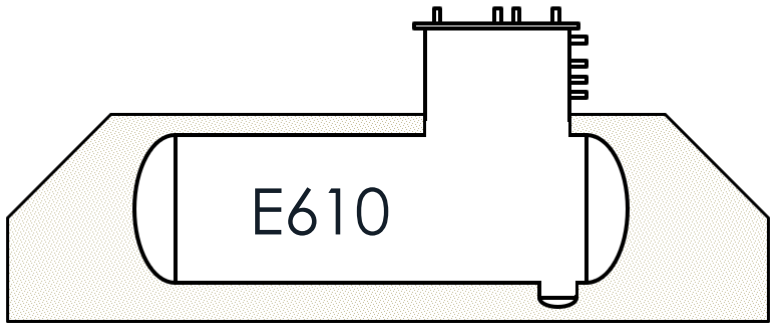
Dr. S. Varadarajan
Dr. L.K. Doraiswamy
Dr. N.R. Ayyangar
Dr. C.S.P. Iyer
Dr. A.A. Khan
Dr. A.K. Lahiri
Mr. K.V. Munumdar
Dr. R.A. Mashelkar
Dr. R.B. Mitra
Dr. O.G.B. Nambiar
Mr. V. Ramachandran
Mr. V.D. Sahasrabudhe
Dr. S. Sivaram
Dr. M. Sriram
Dr. G. Thyagarajan
Dr. R.S. Venkataraman

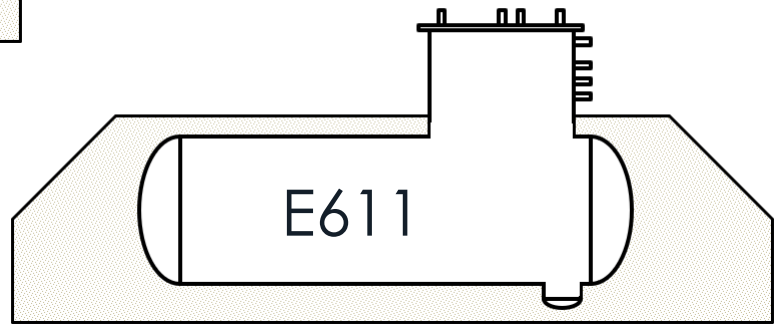
CSIR

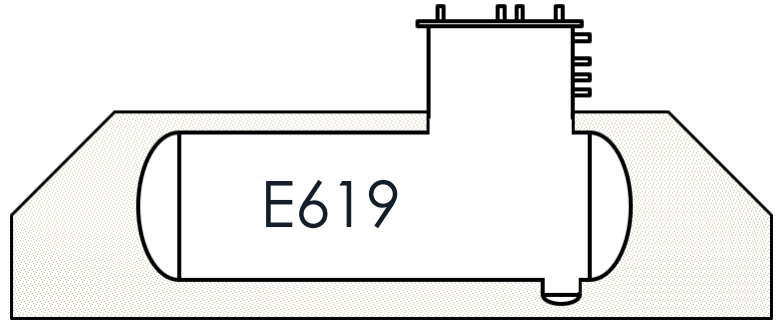
DECEMBER, 1985



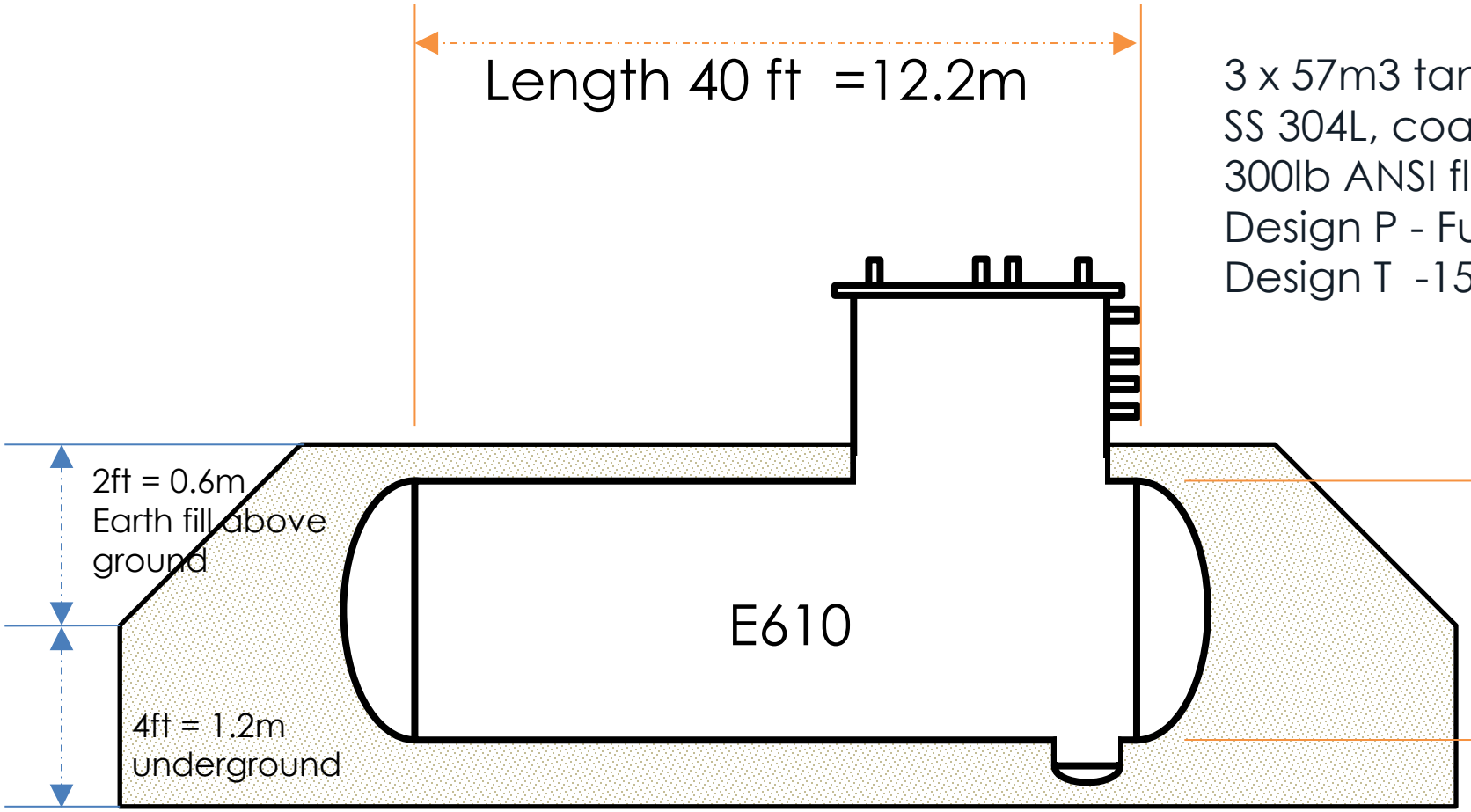
Methyl Isocyanate (MIC) Storage Tanks







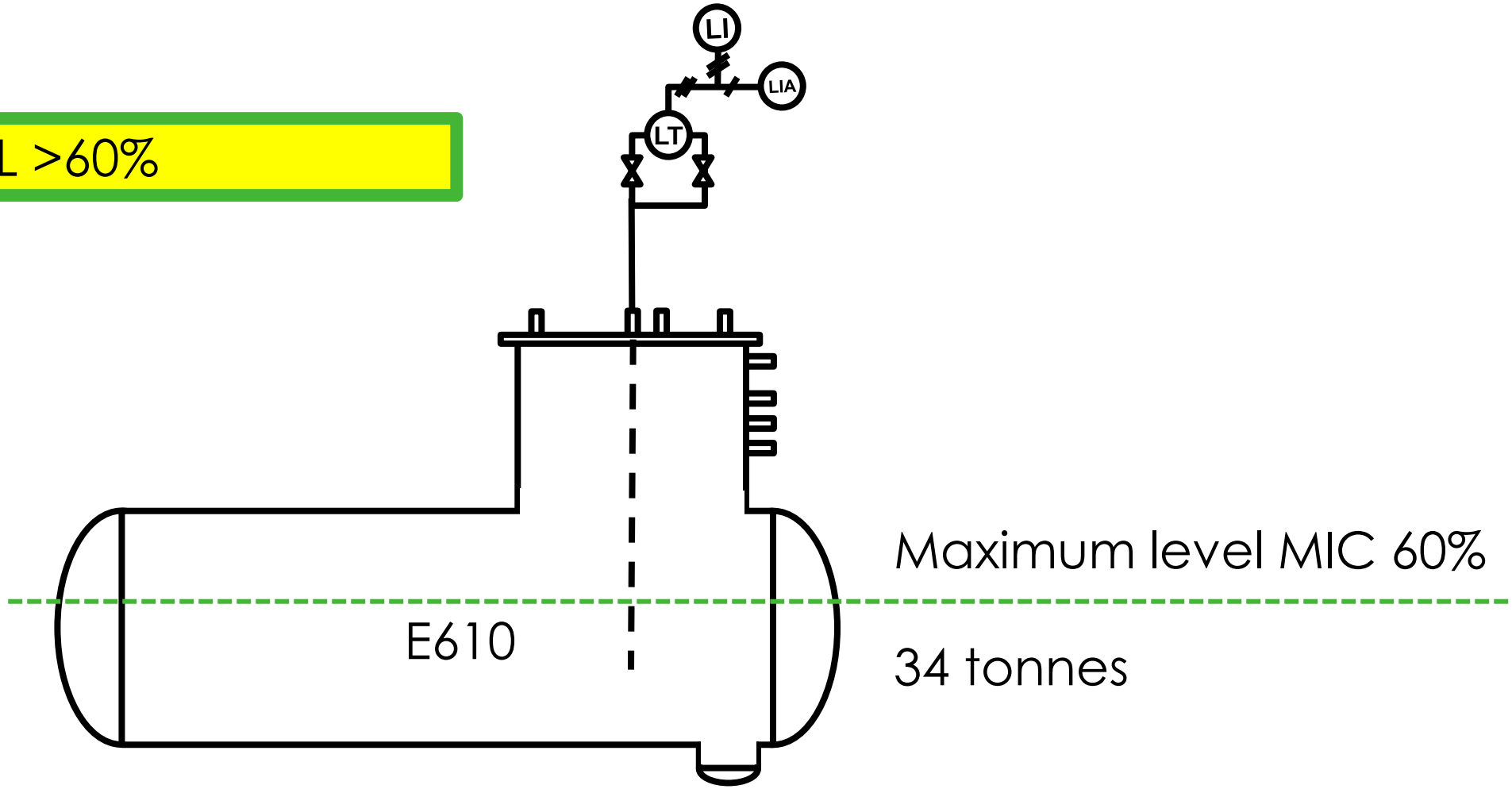
3 x MIC Storage Tanks



3 x 57m3 tanks (15,000 gallons)
SS 304L, coated, cathodic protection
300lb ANSI flanges
Design P - Full vacuum to 40 psig (2.75 barg)
Design T -15° to 121°C

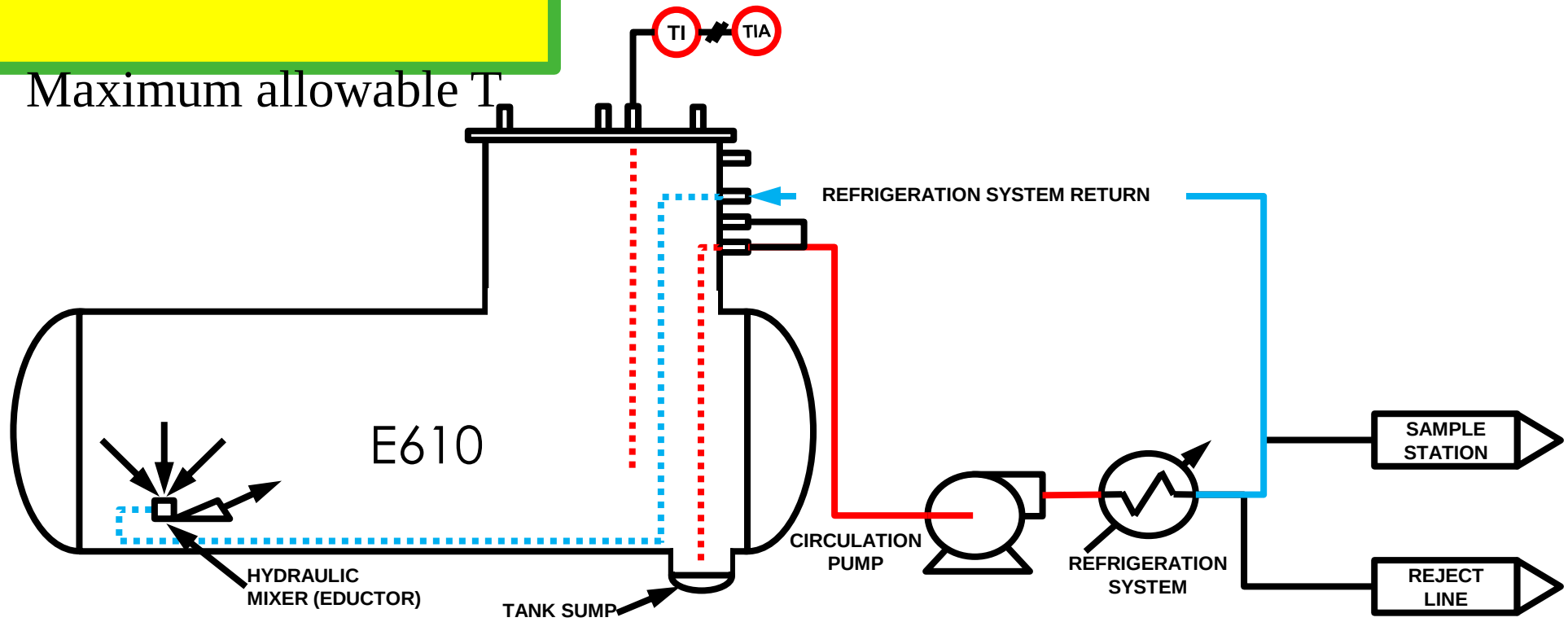
E610 – Level Indication

20% < L >60%

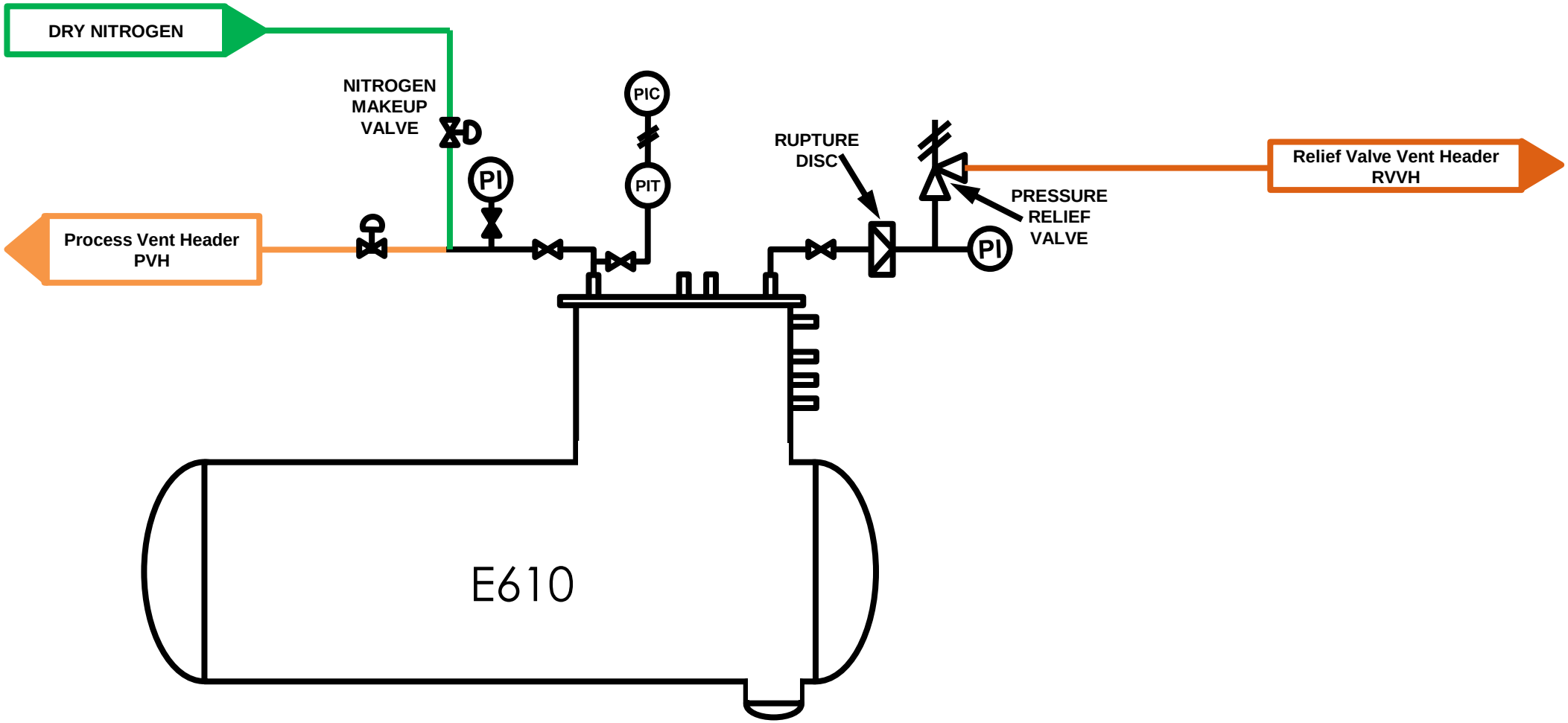


E610 – Temperature Control

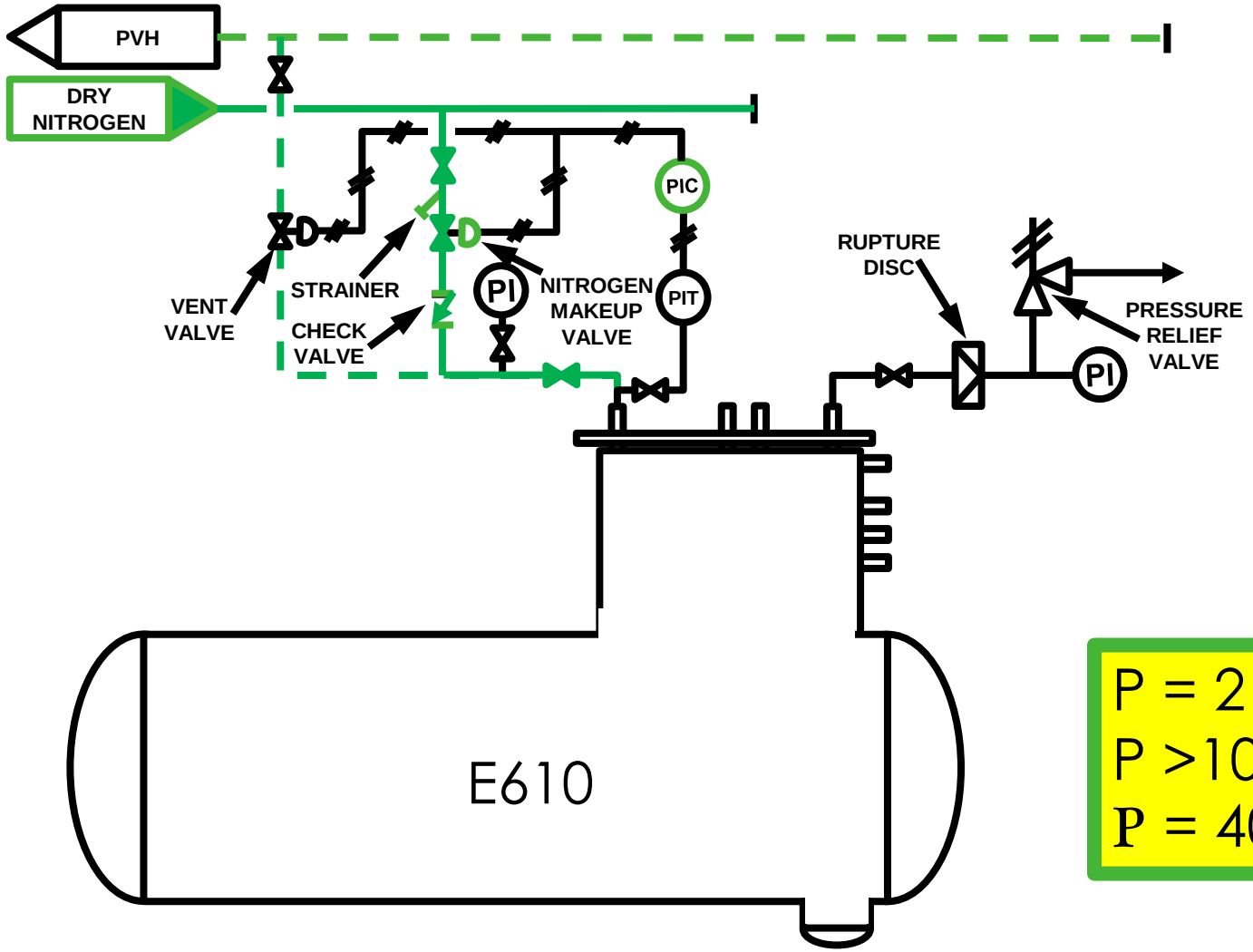
T = 0°C Design Storage T
T >11°C High Temperature Alarm
T = 15°C Maximum allowable T



E610 – Pressure Control

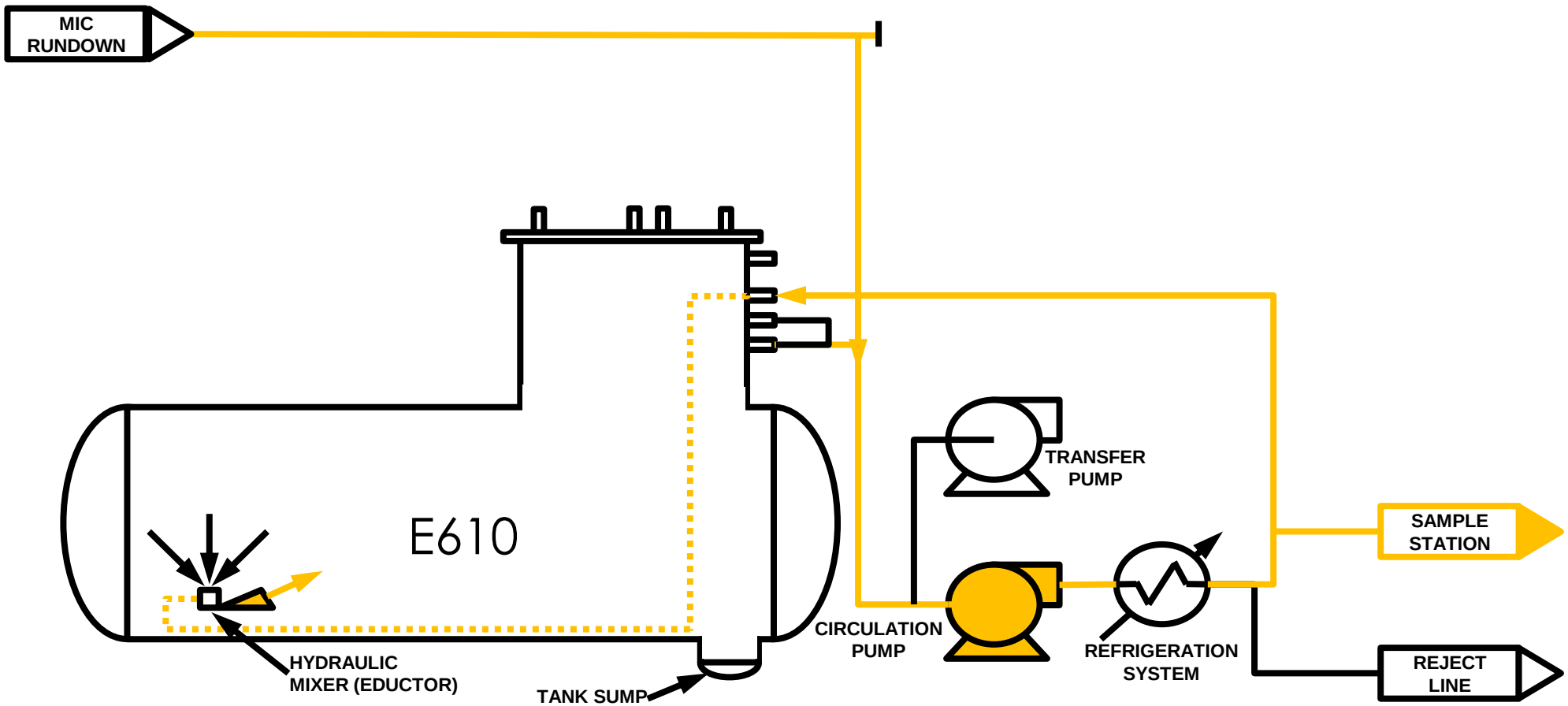


E610 – Pressure Control



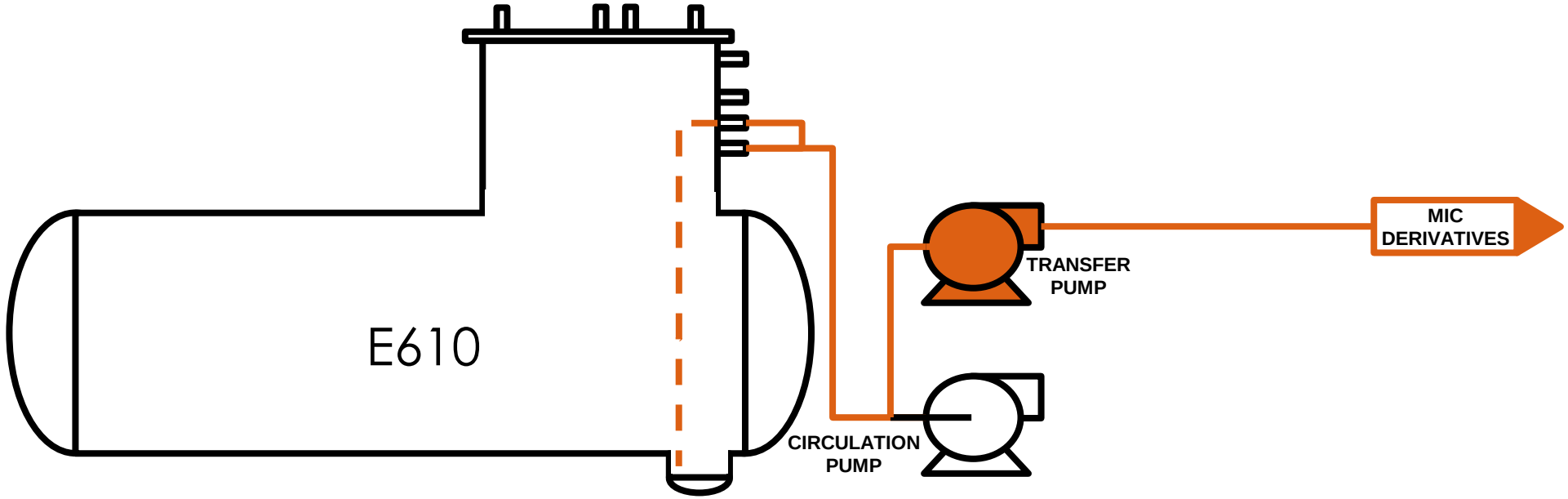
P = 2 psig Design Storage P
P >10 psig Max P (USA)
P = 40 psig Relief BD+PRV

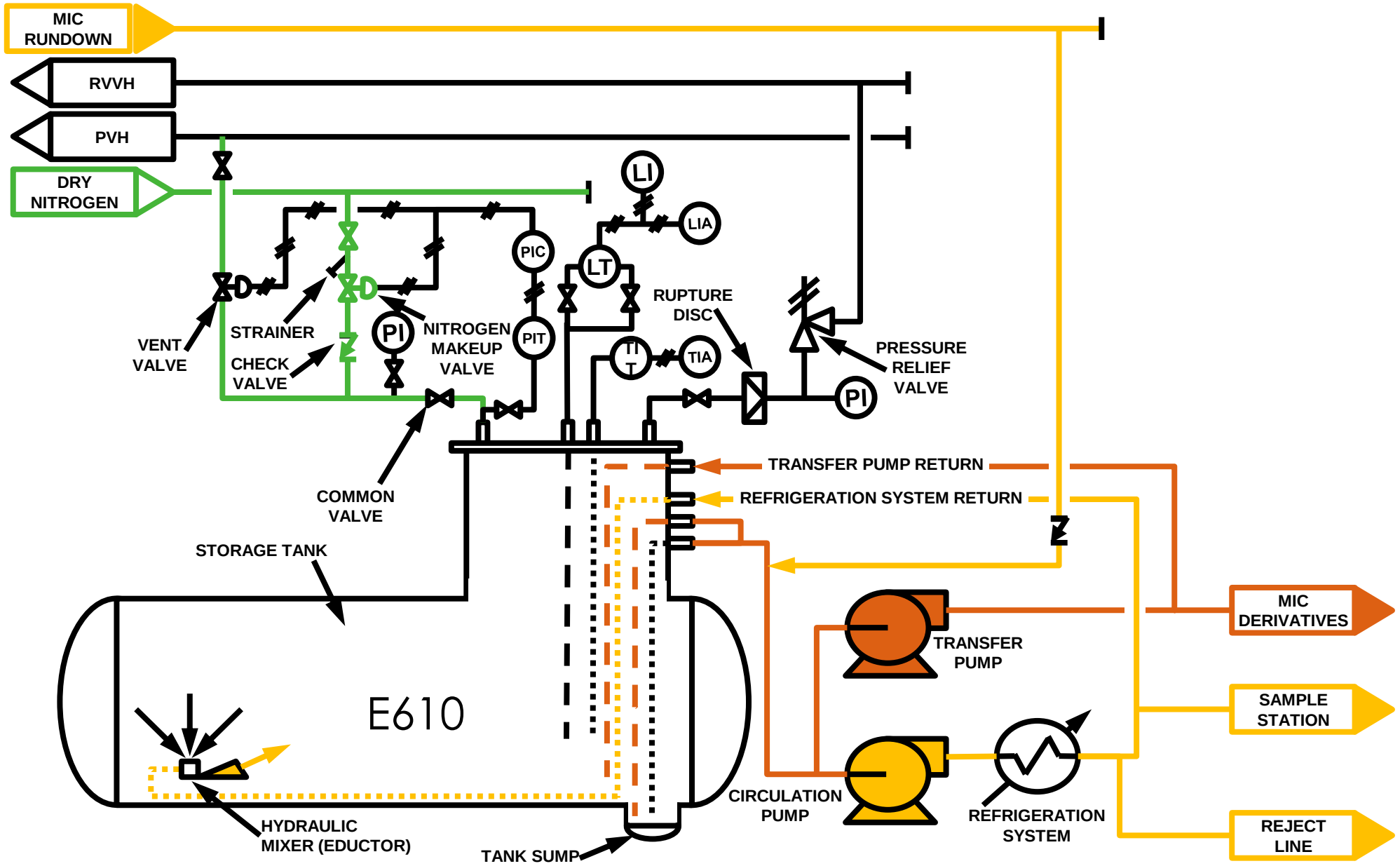
E610 – Quality Control



Kenneth Bloch – Rethinking Bhopal

E610 – Transfer

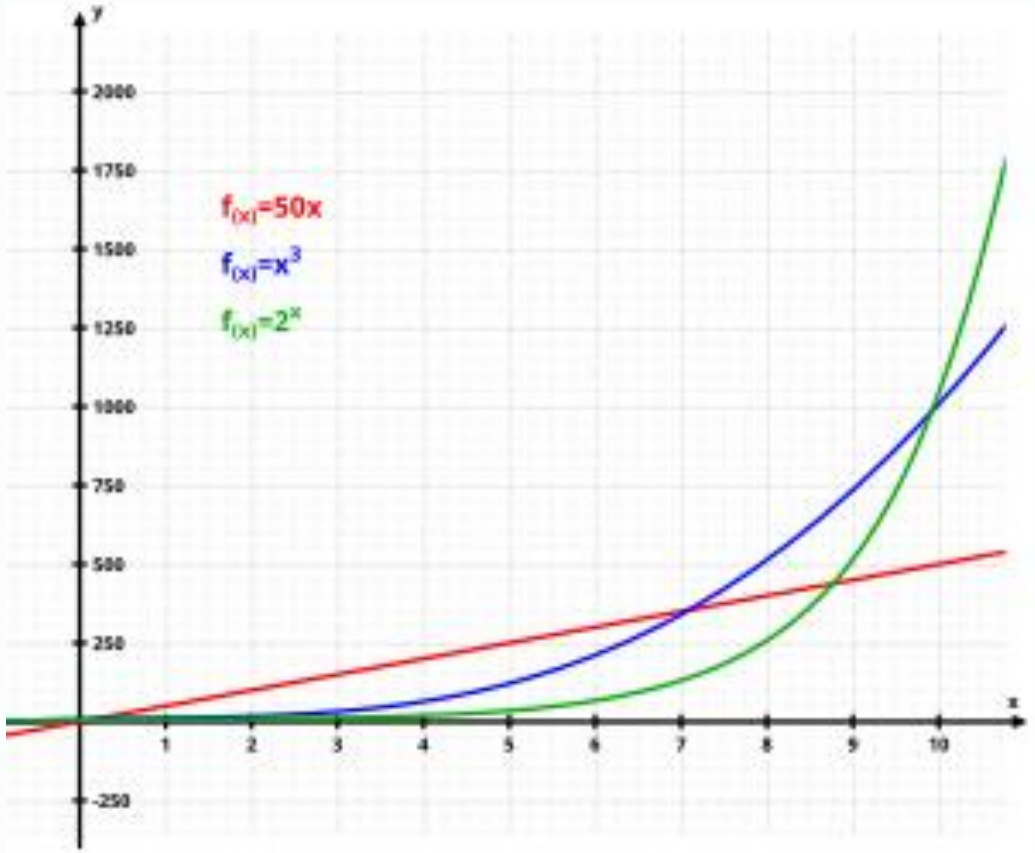


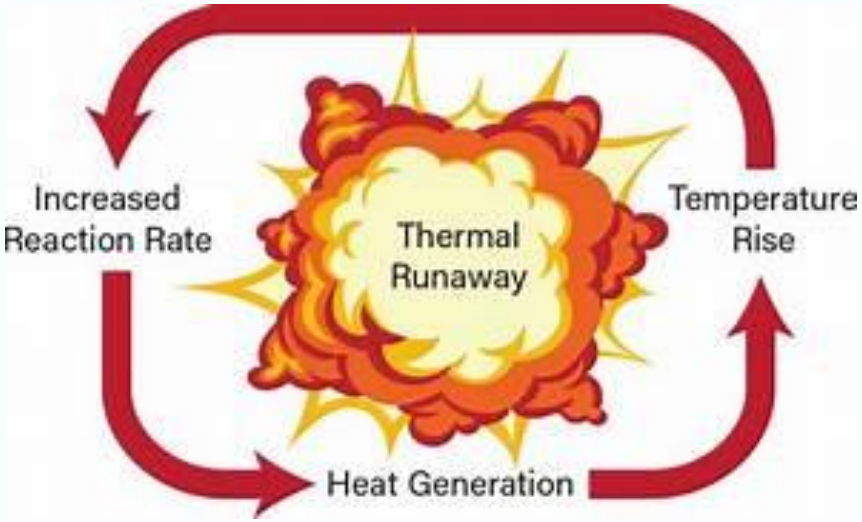


Kenneth Bloch – Rethinking Bhopal

How did water enter the MIC tank?

1. The MIC slow degradation theory



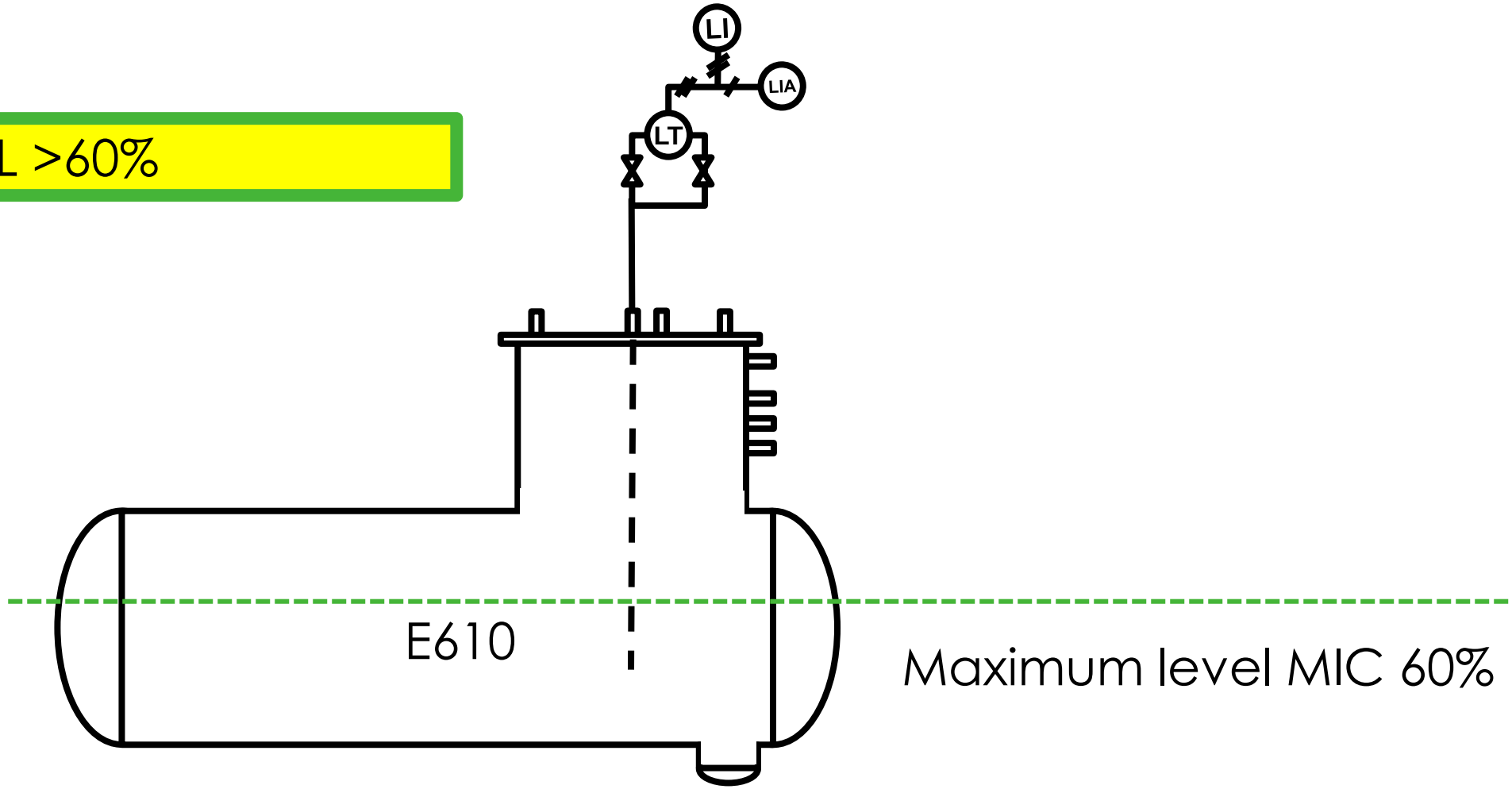


Operations

- 27 Day to Permanent Closure
- Loss of experienced staff
- Operational workarounds
- Reduced maintenance
- Compromised safety systems
- Increased inventory

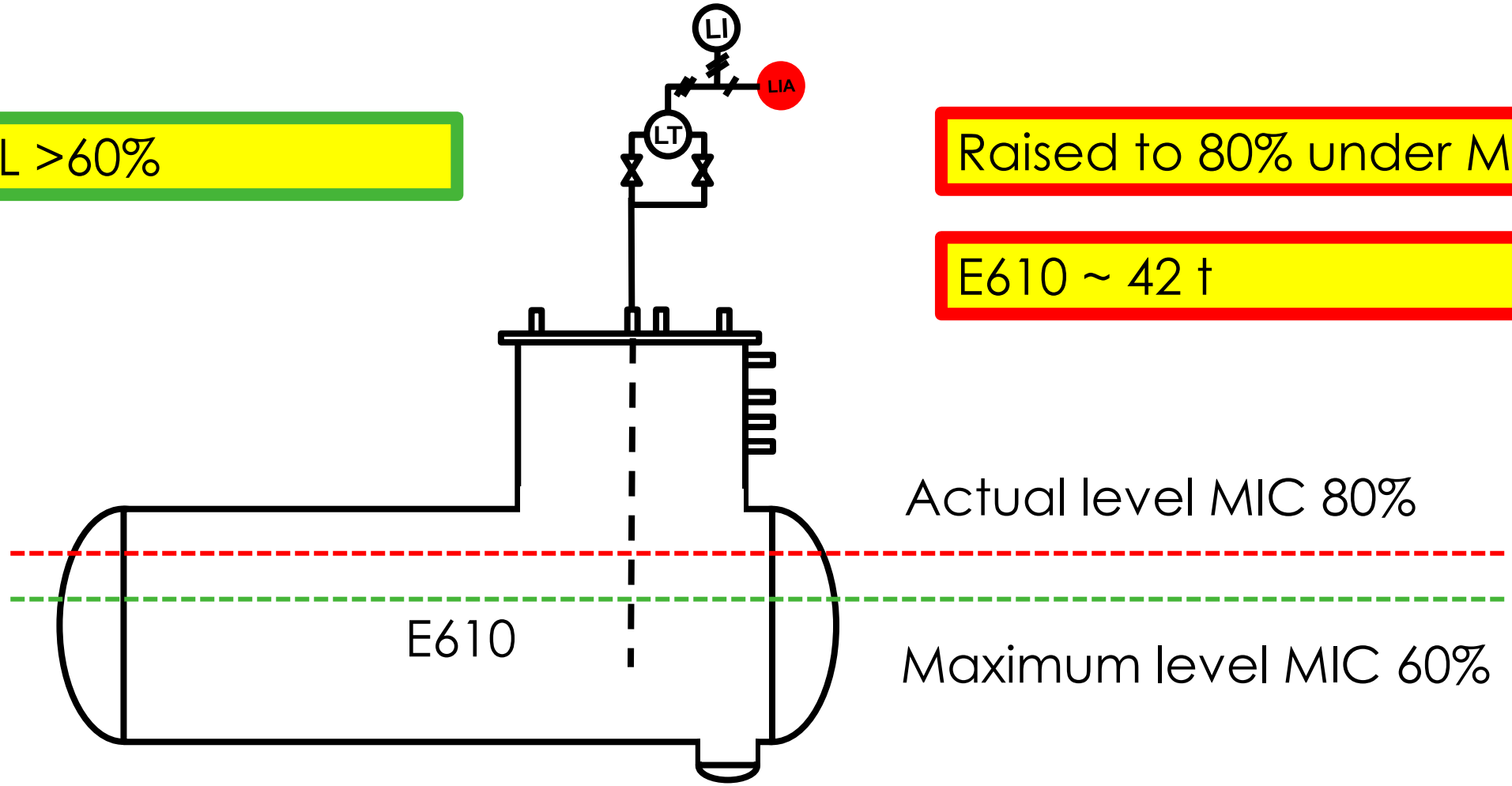
E610 – Level September to December 1984

20% < L >60%



E610 – Level September to December 1984

20% < L >60%



Raised to 80% under MOC

E610 ~ 42 t

31st October 1984

INDIAN EXPRESS

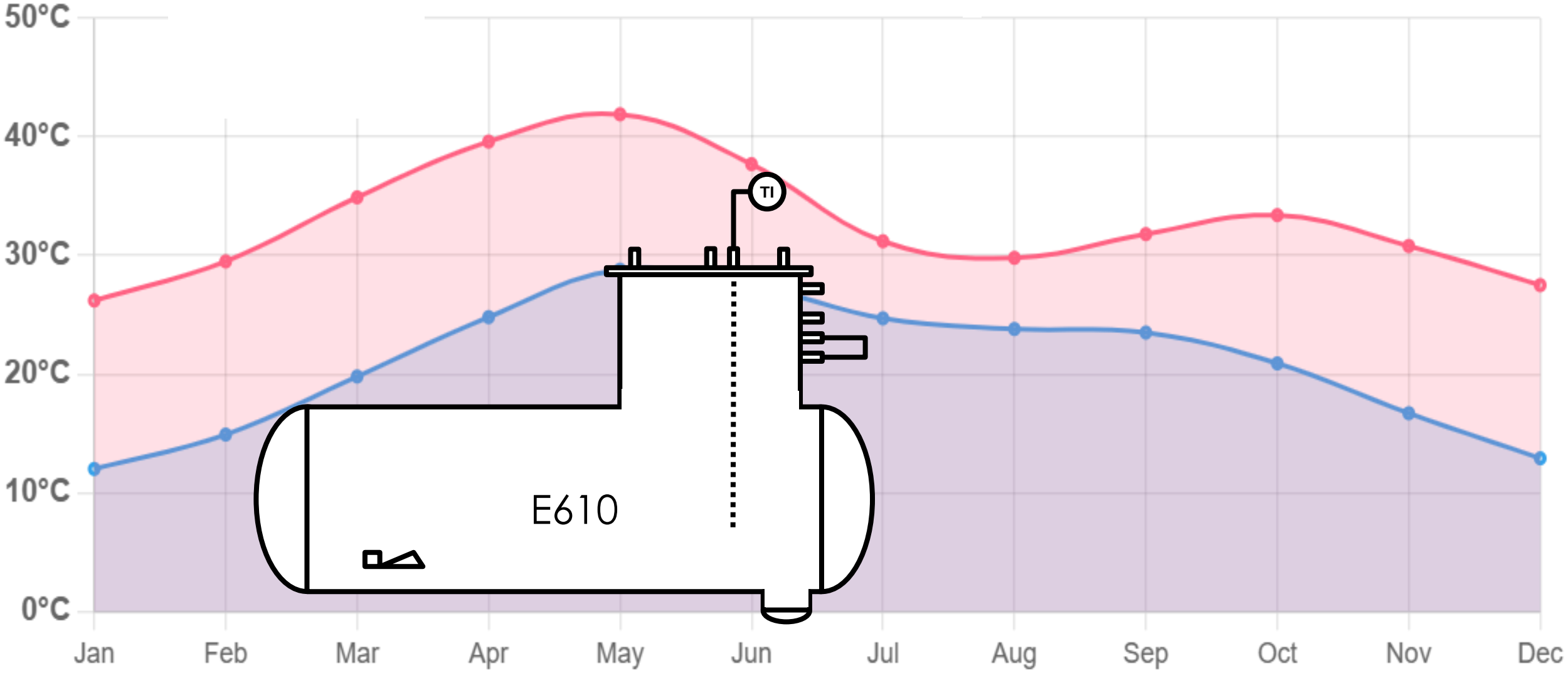
INDIRA GANDHI SHOT DEAD

Attack by security men at 1, Safdarjang Road

One assailant killed, another held

University of Sheffield

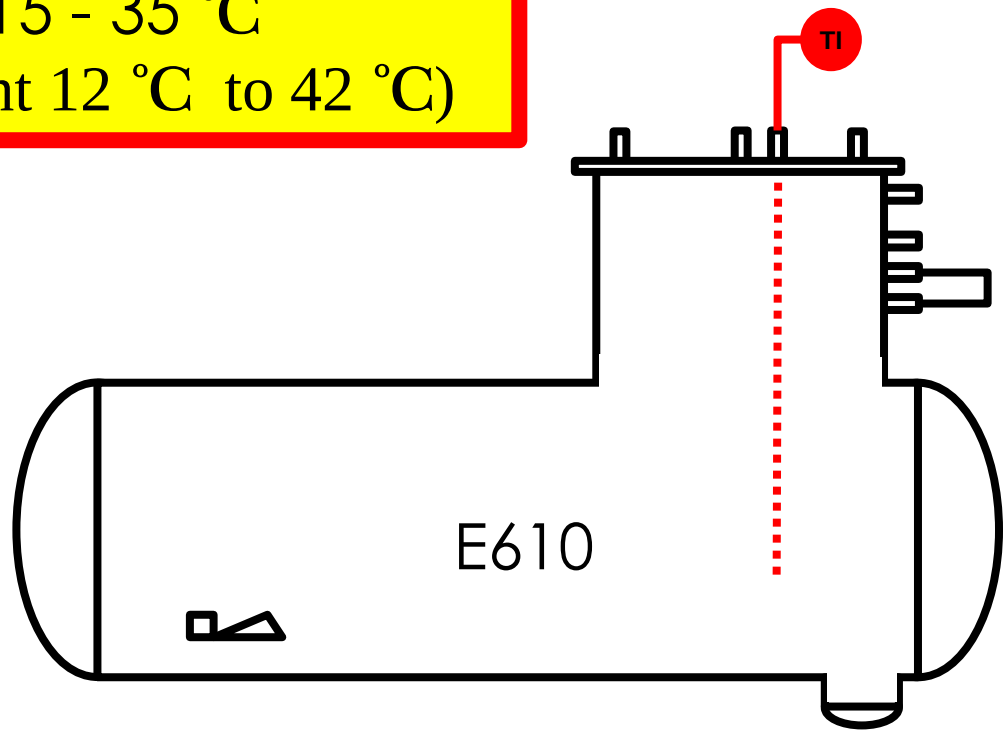
E610 – Temperature 1984



https://weather-and-climate.com/average-monthly-min-max-Temperature,bhopal-madhya-pradesh-in,India

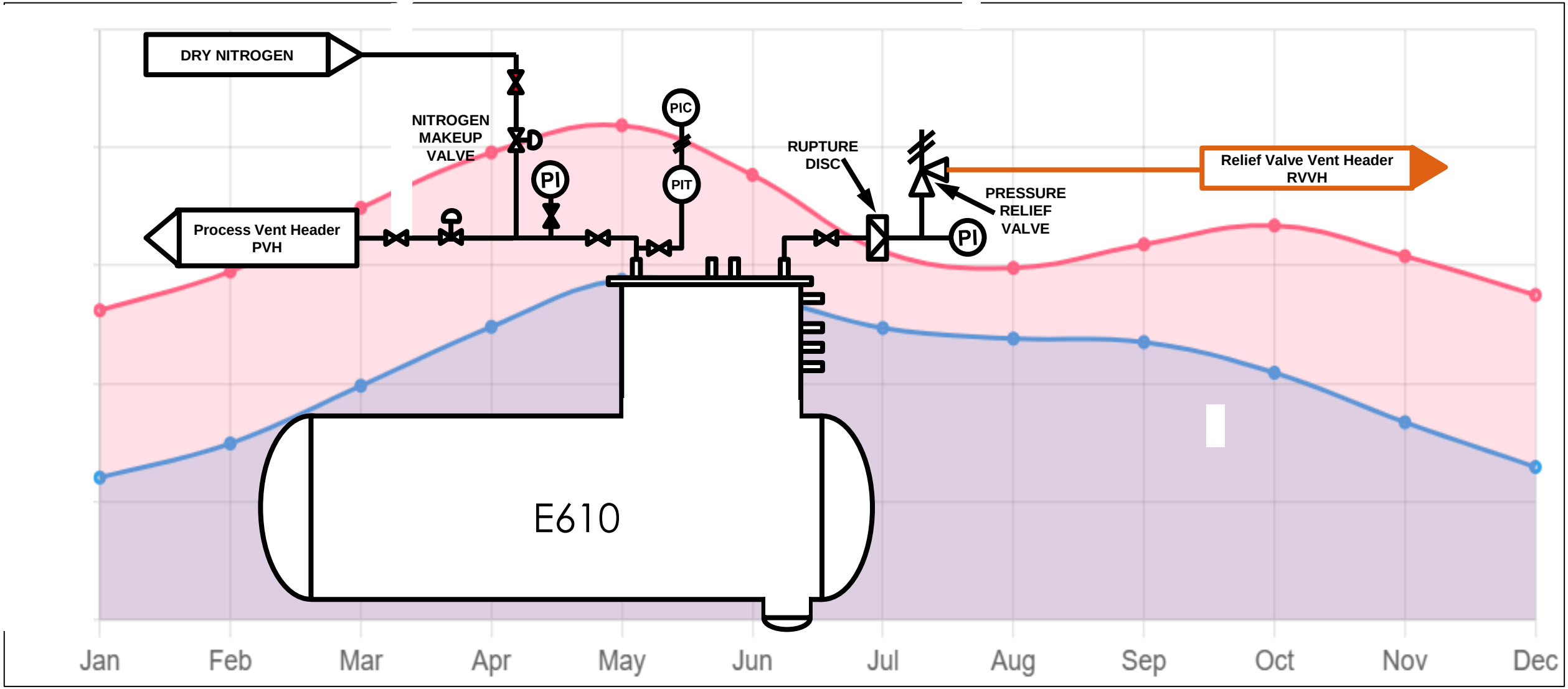
E610 – Temperature 1984

Actual temperature
15 - 35 ℃
(Ambient 12 ℃ to 42 ℃)

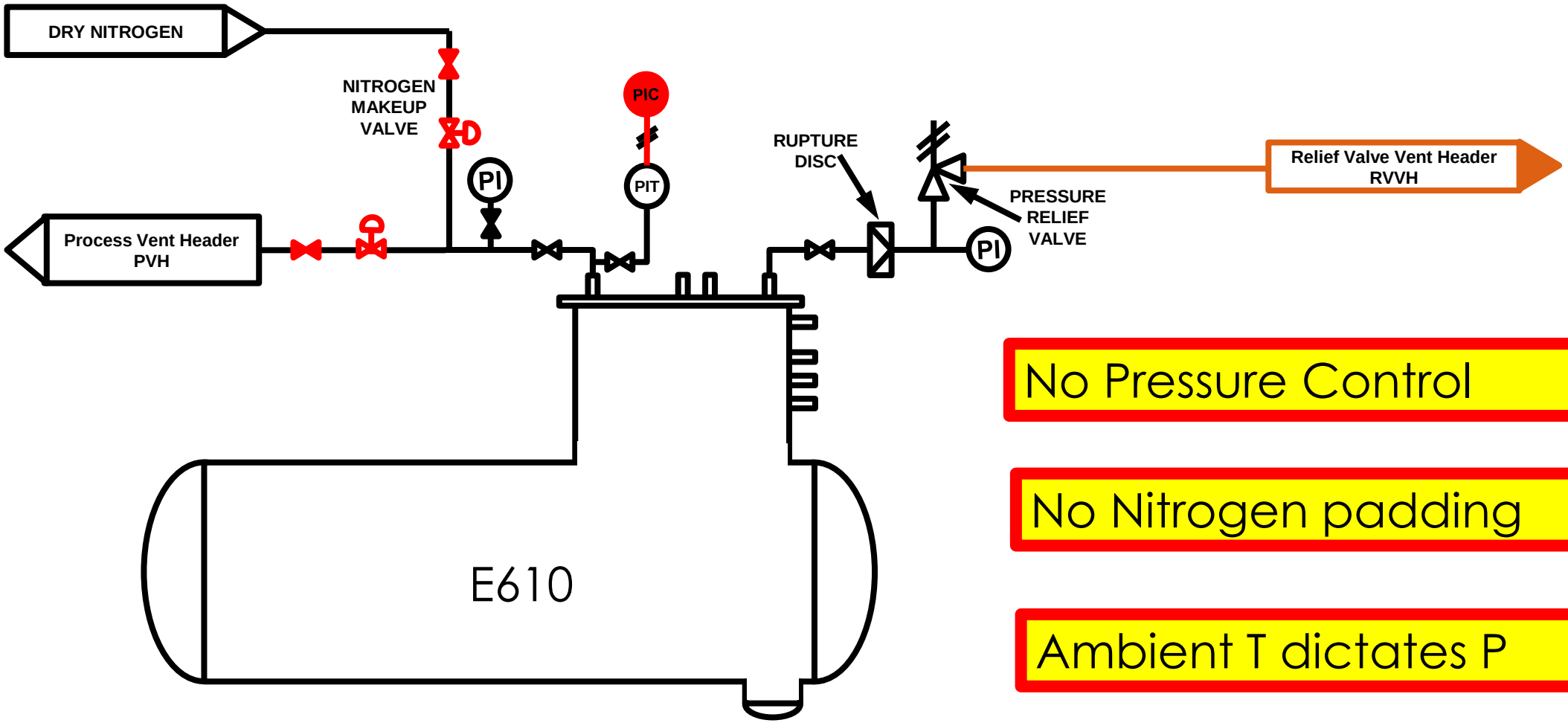


- No refrigeration
- Permanent T alarm
- No Circulation
- No Sampling
- No Reject route

E610 – Pressure 1984



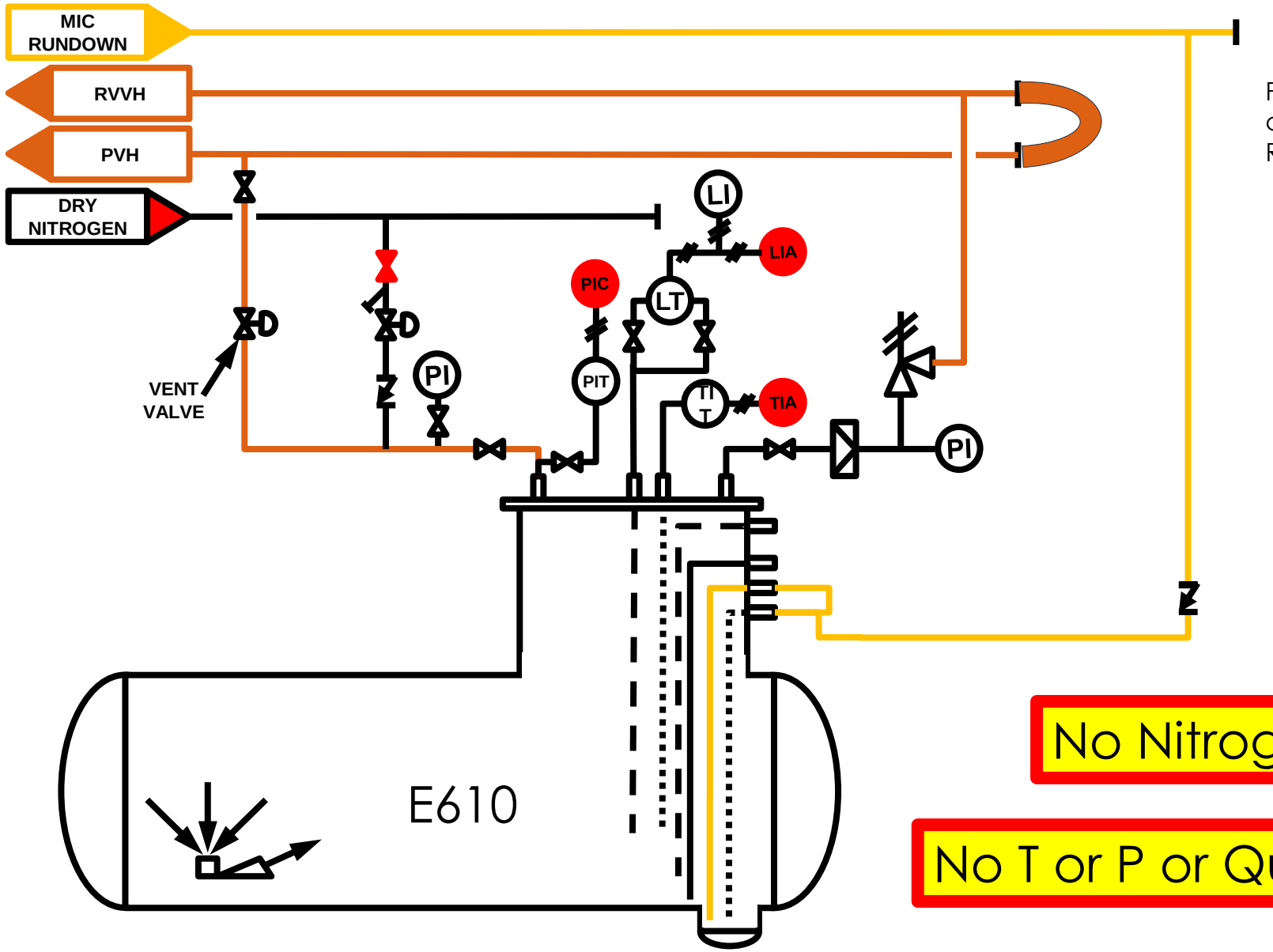
E610 – Pressure 1984



No Pressure Control

No Nitrogen padding

Ambient T dictates P



Process Vent Header
connected to
Relief Valve Vent Header

High Level

High CHCl3

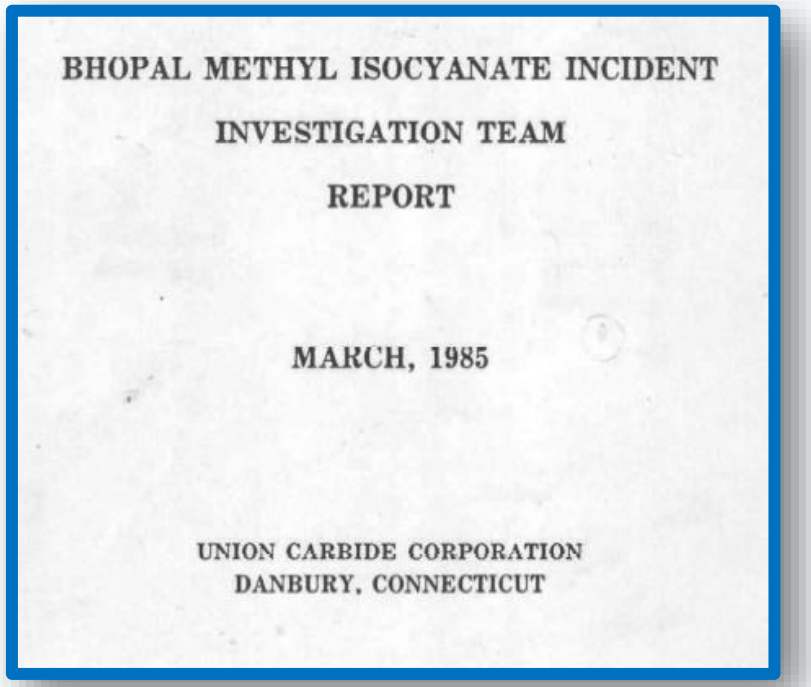
No Mixing

No Cooling

No Nitrogen padding

No T or P or Quality Control

UCC Investigation (March 1985)



BHOPAL METHYL ISOCYANATE INCIDENT

INVESTIGATION TEAM

REPORT

MARCH, 1985

UNION CARBIDE CORPORATION
DANBURY, CONNECTICUT

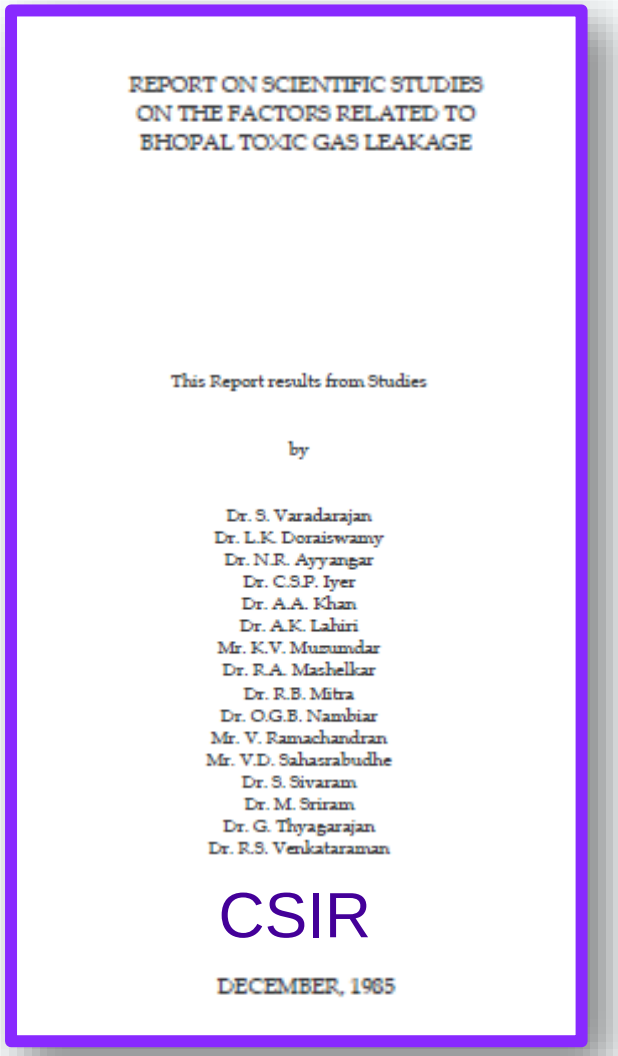
‘Tank 610 residue (was most likely) produced by the reaction of MIC with (450 – 900 kg) water, higher than normal amounts of chloroform and an iron catalyst’

‘Water could have been introduced inadvertently or deliberately’

How did water enter the MIC tank?

1. The MIC slow degradation theory
2. The filter washing theory

CSIR Investigation (December 1985)



REPORT ON SCIENTIFIC STUDIES
ON THE FACTORS RELATED TO
BHOPAL TOXIC GAS LEAKAGE

This Report results from Studies

by

Dr. S. Varadarajan
Dr. L.K. Doraiswamy
Dr. N.R. Ayyangar
Dr. C.S.P. Iyer
Dr. A.A. Khan
Dr. A.K. Lahiri
Mr. K.V. Muzumdar
Dr. R.A. Mashelkar
Dr. R.B. Mitra
Dr. O.G.B. Nambiar
Mr. V. Ramachandran
Mr. V.D. Sahasrabudhe
Dr. S. Sivaram
Dr. M. Sriram
Dr. G. Thyagarajan
Dr. R.S. Venkataraman

CSIR

DECEMBER, 1985

- Accident conditions inherent and extant
  Bulk storage of a very high hazard intermediate
- Inadequate
  - Design
  - Materials
  - Instrumentation
  - Control
  - Disposal routes
- Tank pressure atmospheric
  Entry contaminants (alkali, metal) from 22nd October 1984
- Water washing MIC pipelines common practice
  500kg water to E610 from filter washing on 2nd December 1984

Theory 2 - Filter washing theory

Indian Council of Scientific and Industrial Research (CSIR)

During the cleaning of choked filters with water in the Relief Valve Vent Header, such water could have entered the non-pressurised tank and may have carried some metallic contaminants from the carbon steel portions of the header pipelines

Water used to wash filter No

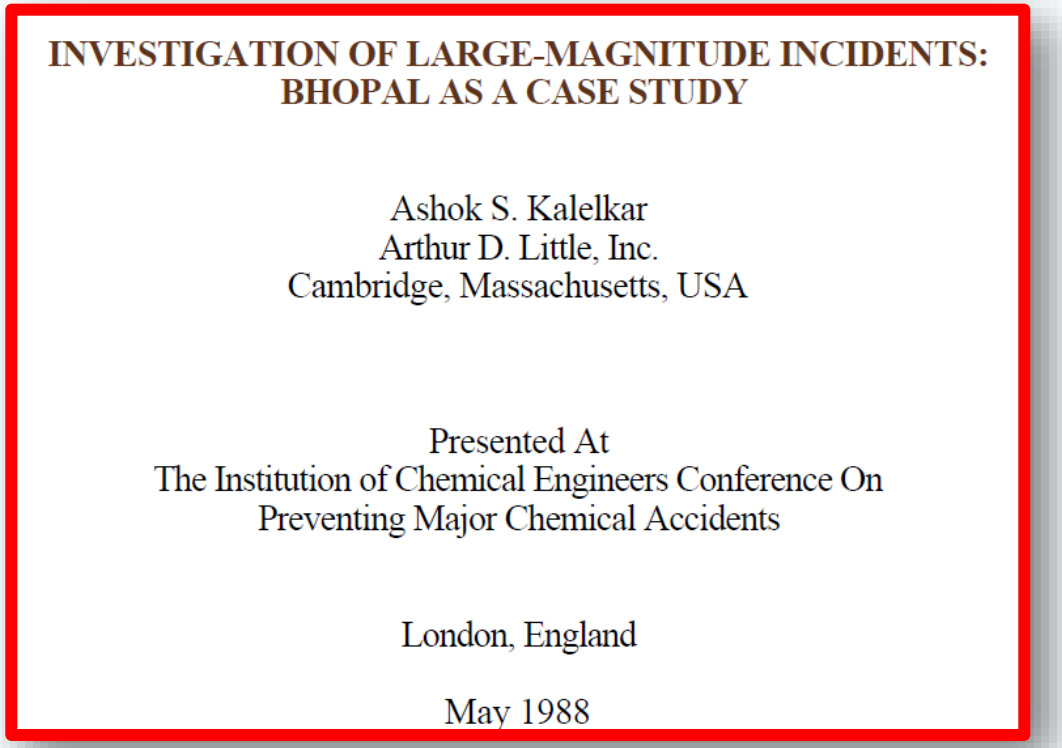
Isolating blank installed

Ramin Abhari – Butterflies of Bhopal

AD Little (UCC) 1988

Water-washing of lines in the filter area could not possibly have been the cause of water entry into Tank 610

UCC commissioned report



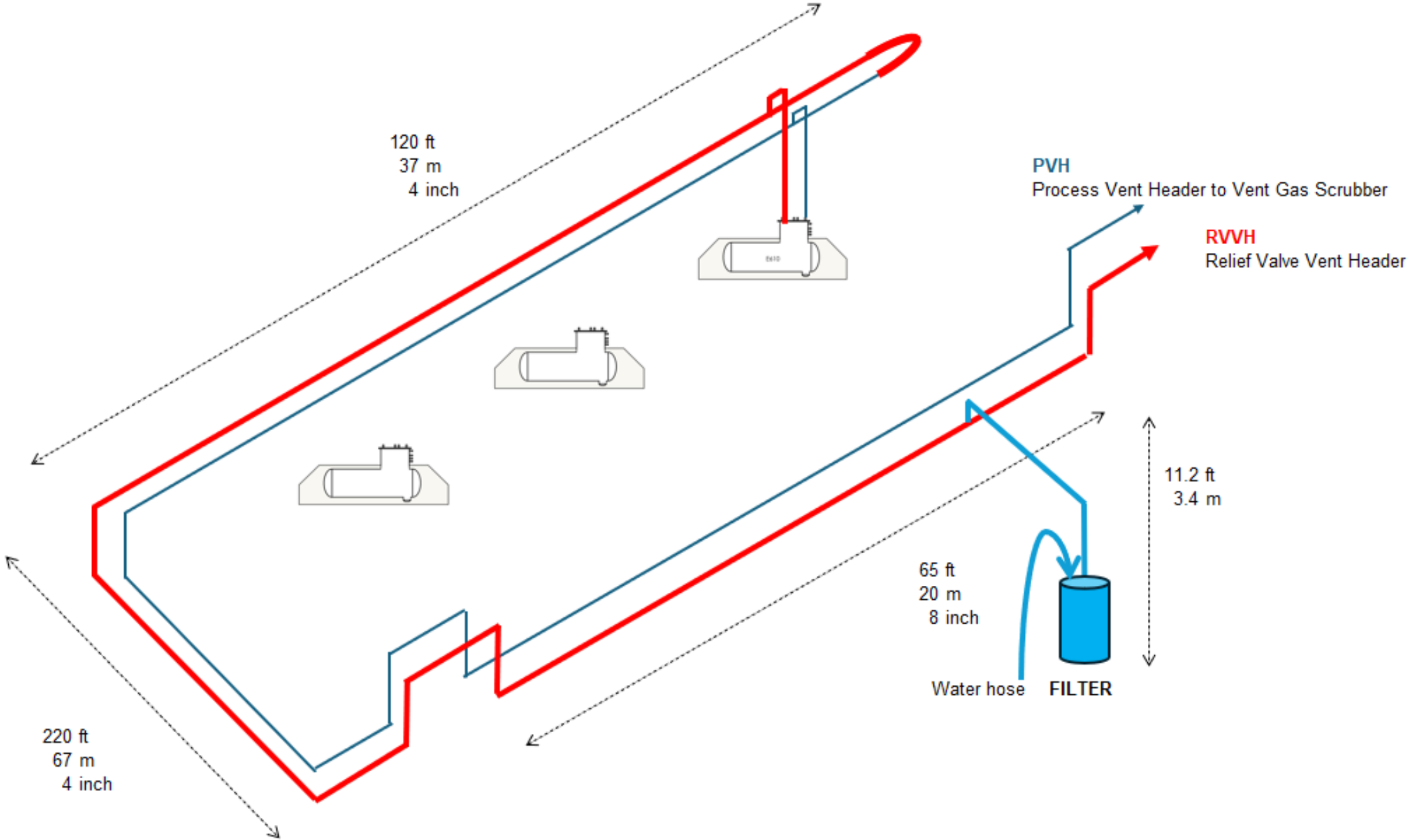
INVESTIGATION OF LARGE-MAGNITUDE INCIDENTS: BHOPAL AS A CASE STUDY

Ashok S. Kalelkar
Arthur D. Little, Inc.
Cambridge, Massachusetts, USA

Presented At
The Institution of Chemical Engineers Conference On
Preventing Major Chemical Accidents

London, England

May 1988


120 ft
37 m
4 inch
PVH
Process Vent Header to Vent Gas Scrubber
RVVH
Relief Valve Vent Header
11.2 ft
3.4 m
65 ft
20 m
8 inch
Water hose
FILTER
220 ft
67 m
4 inch

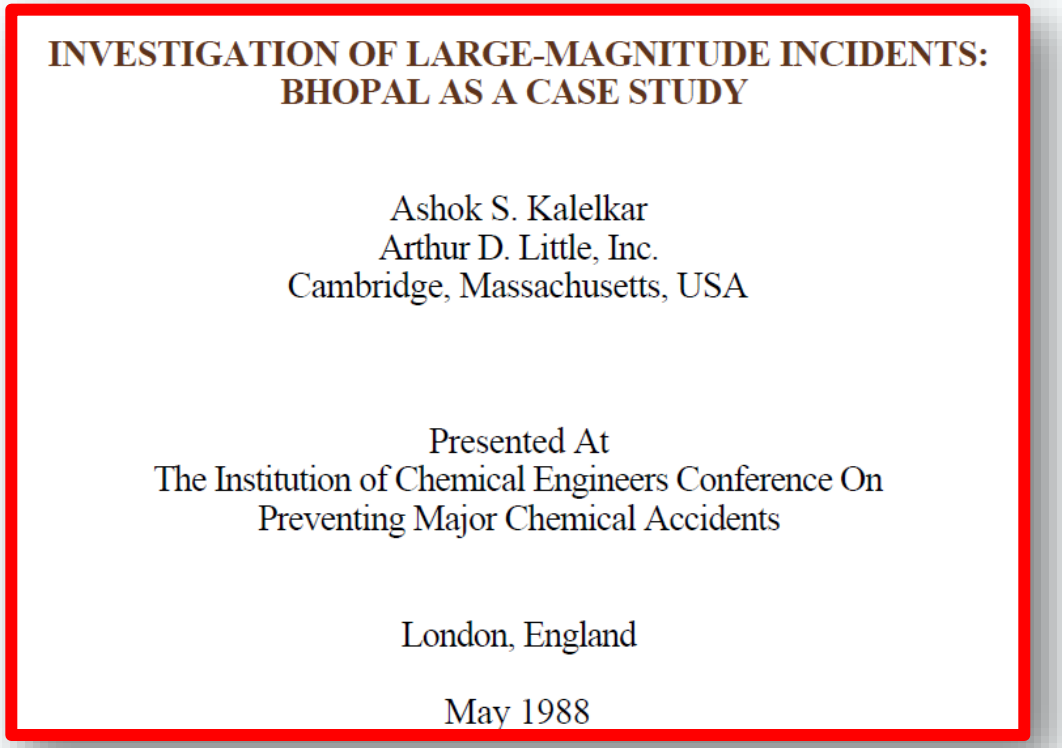
How did water enter the MIC tank?

1. The MIC slow degradation theory
2. The filter washing theory
3. The sabotage theory

3. Sabotage theory

A disgruntled operator entered the storage area and hooked up one of the readily available rubber hoses to Tank E610 with the intention of contaminating and spoiling the tank's contents

UCC commissioned report



INVESTIGATION OF LARGE-MAGNITUDE INCIDENTS:
BHOPAL AS A CASE STUDY

Ashok S. Kalelkar
Arthur D. Little, Inc.
Cambridge, Massachusetts, USA

Presented At
The Institution of Chemical Engineers Conference On
Preventing Major Chemical Accidents

London, England

May 1988

Prior accidents

Year	Accidents and Incidents Involving MIC unit	Management Response
1981	One fatality and two serious injuries during removal slip blind	The worker died from his own mistake
1982	25 employees injured due to pump seal leak	3 union leaders, protesting about safety concerns were sacked
1982	18 employees injured due to a piping leak	UCC safety audit found multiple safety deficiencies including ‘potential for release of toxic materials
1983 &1984	Leaks of MIC, Chlorine, Monomethylamine, Phosgene and Carbon Tetrachloride	UCIL action plan claimed that the issues were ‘either corrected or in the process of being corrected.’

Death of Ashraf Khan

- Maintenance worker
- Asked to assist with removal isolation in MIC plant
- Loosened pipe – liquid spurted out
- In panic removed air mask
- Taken to hospital
- Died Christmas Eve 1981
- Investigation - The worker died from his own mistake

3. Sabotage theory

Why sabotage?	No independent investigation Inconsistencies in evidence Industrial Relations (IR) poor Failure to appreciate operational reality
Why were Industrial Relations (IR) poor?	Long history of safety issues Dispute over training
Why stop training?	27 days to factory closure
Why close factory?	Unreliable and uneconomic

University of Sheffield

Never ascribe to malice what can be explained by genuine intent – Hanlon's

3. Sabotage

Why claim sabotage?

Strict Liability Doctrine (Indian Penal Code 1860)

Sabotage is one of the few exceptions that overrides legal responsibility for restitution.

Why push for out of court settlement?

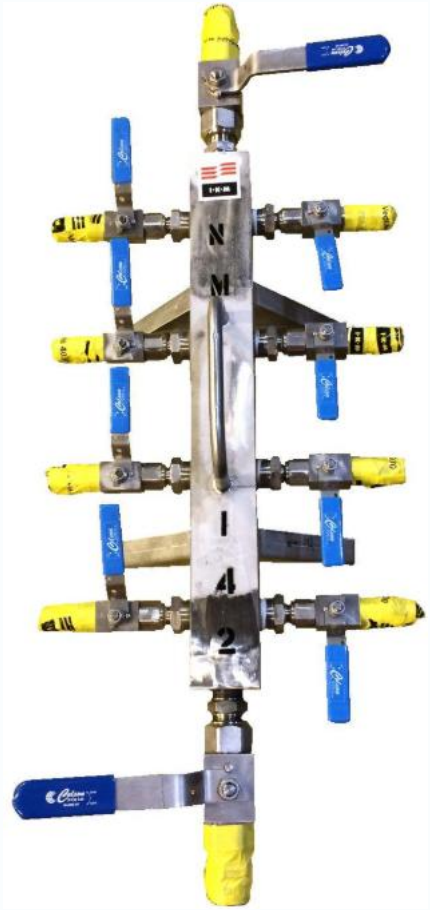
Avoid investigation and sharing facts publicly

https://www.ihrb.org/latest/40-years-later-what-are-the-lessons-from-the-lessons-from-the-bhopal-gas-disaster

How did water enter the MIC tank?

1. The MIC slow degradation theory
2. The filter washing theory
3. The sabotage theory
4. The nitrogen mix up theory
5. Rethinking Bhopal

4. Nitrogen and water mix up during cleaning

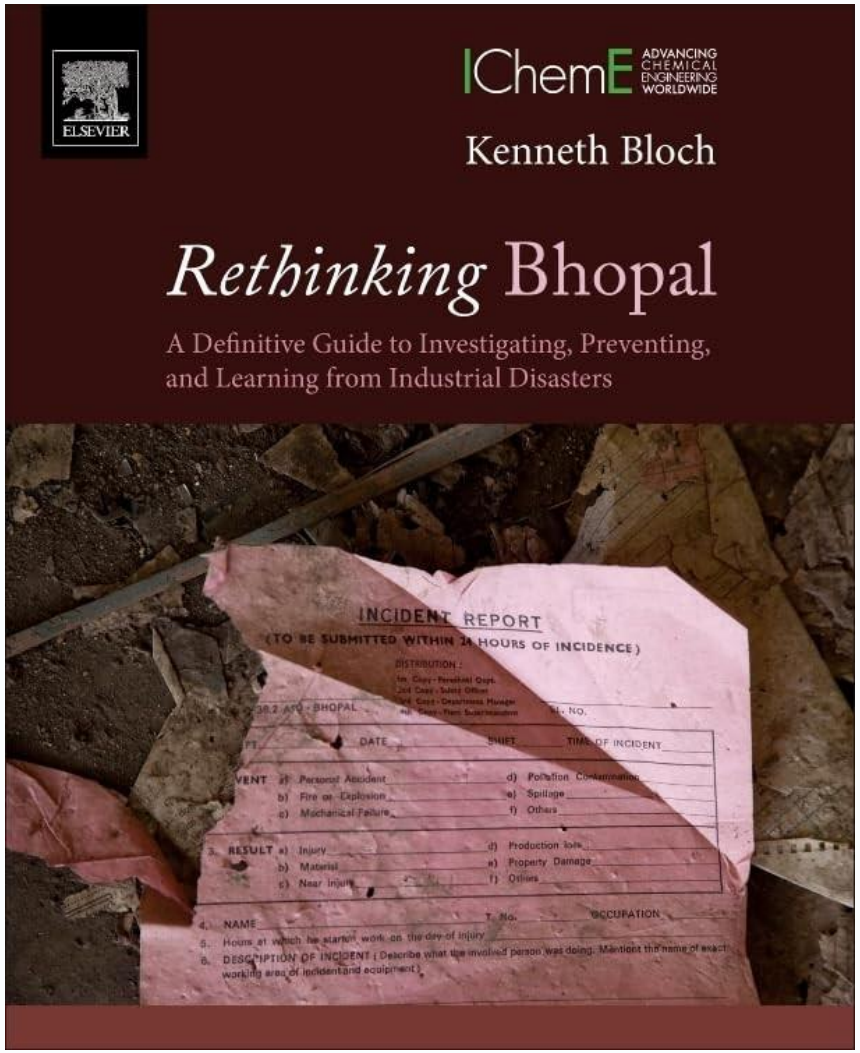


Ramin Abhari – Butterflies of Bhopal

How did water enter the MIC tank?

1. The MIC slow degradation theory
2. The filter washing theory
3. The sabotage theory
4. The nitrogen mix up theory
5. Rethinking Bhopal

5. Rethinking Bhopal



University of Sheffield

27 days to closure

- Loss of experienced staff
- Operational workarounds
- Reduced maintenance
- Compromised safety systems
- Increased inventory

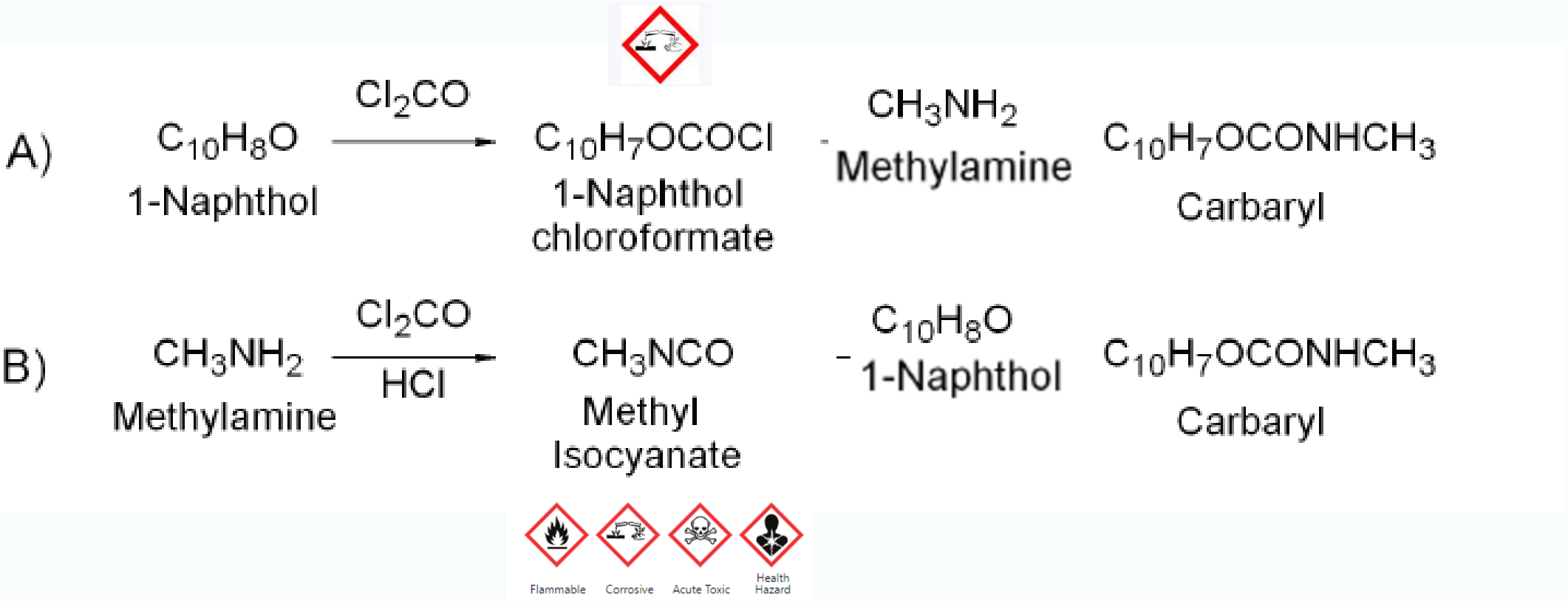
Design decisions

A. Process Hazard Analysis

B. Equipment Selection

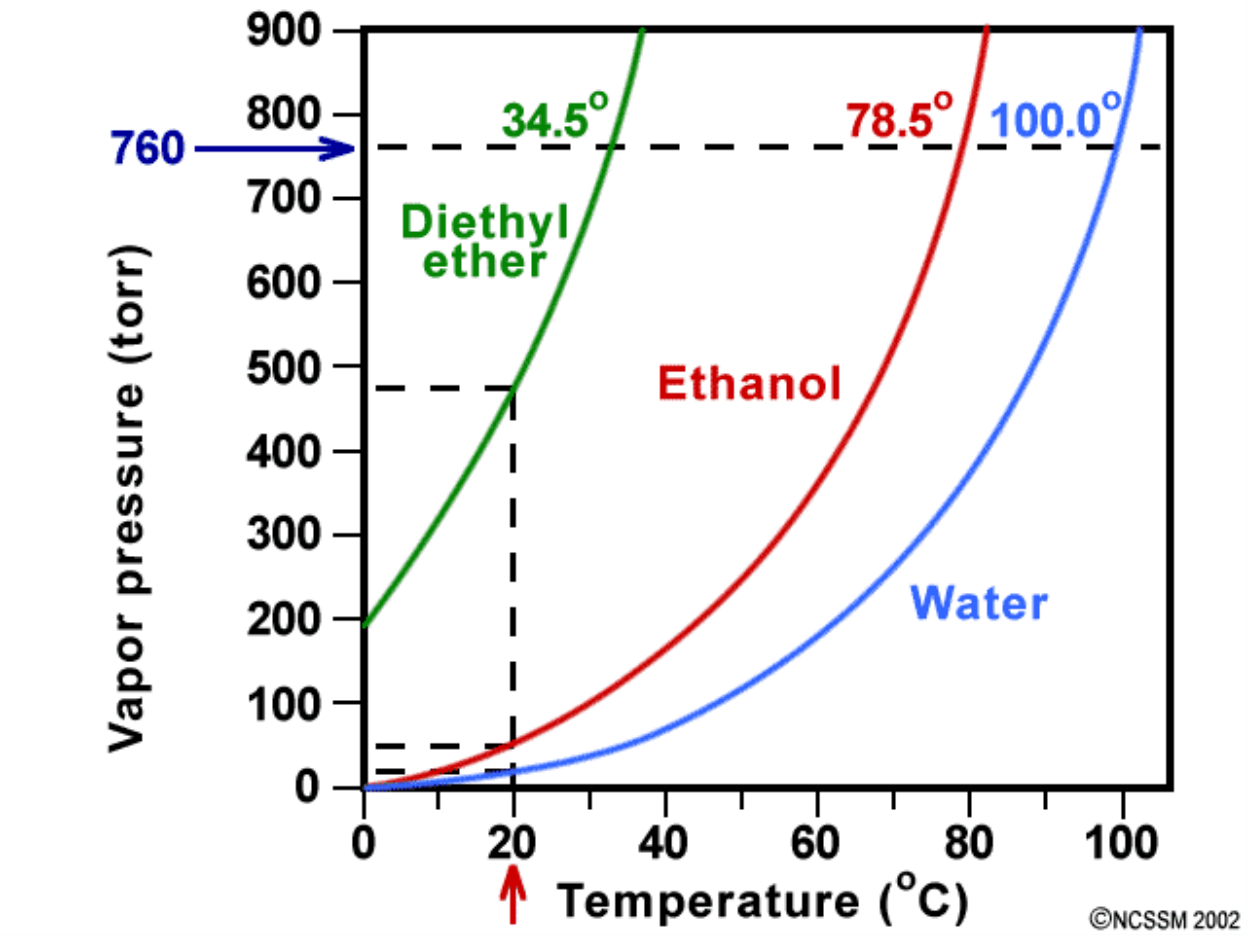
C. Materials of Construction

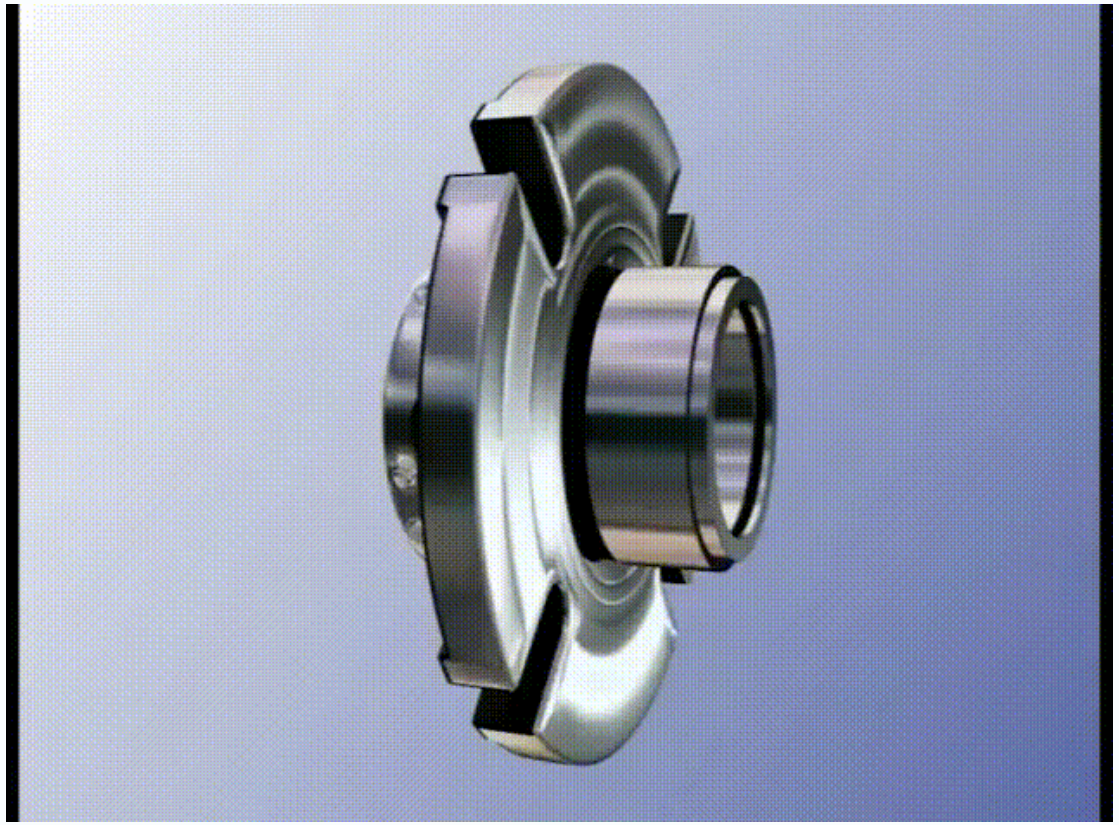
A. Process Hazard Analysis - Change



MIC boiling point 35°C, High Volatility, Extremely Flammable, Acutely Toxic

B. Equipment selection – MIC pumps





RODELTA/ AESSEAL®

C. Design Decisions – Materials

Vent header constructed in carbon steel - Dry Nitrogen essential

Transfer pumps unreliable - Nitrogen diverted for MIC pressure transfer

Vent header corrodes - MIC forms solid trimers with iron

Water used to wash away MIC trimers – corrosion gets worse

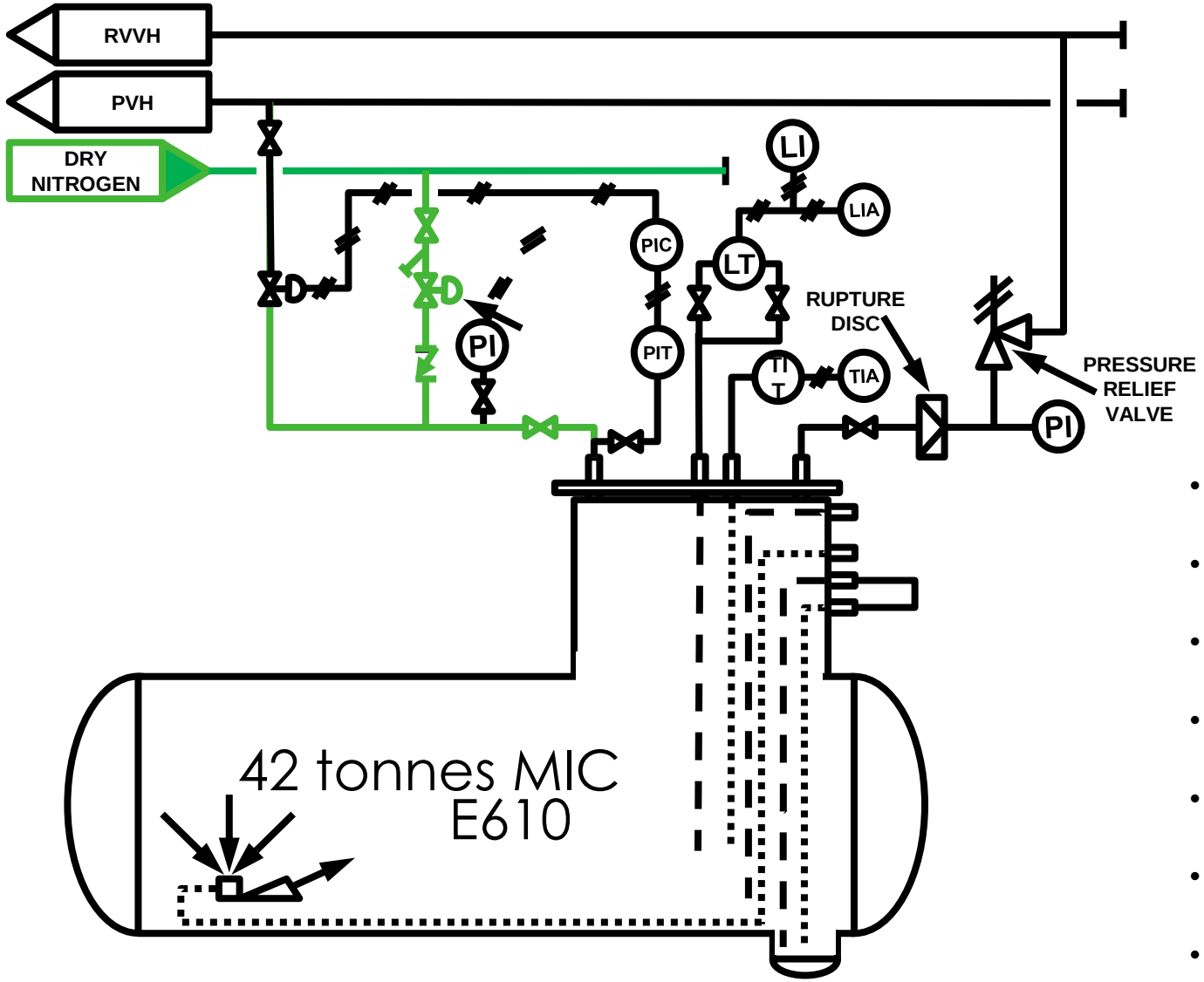
Design decisions

A. Hazards of bulk methyl isocyanate (MIC) underestimated

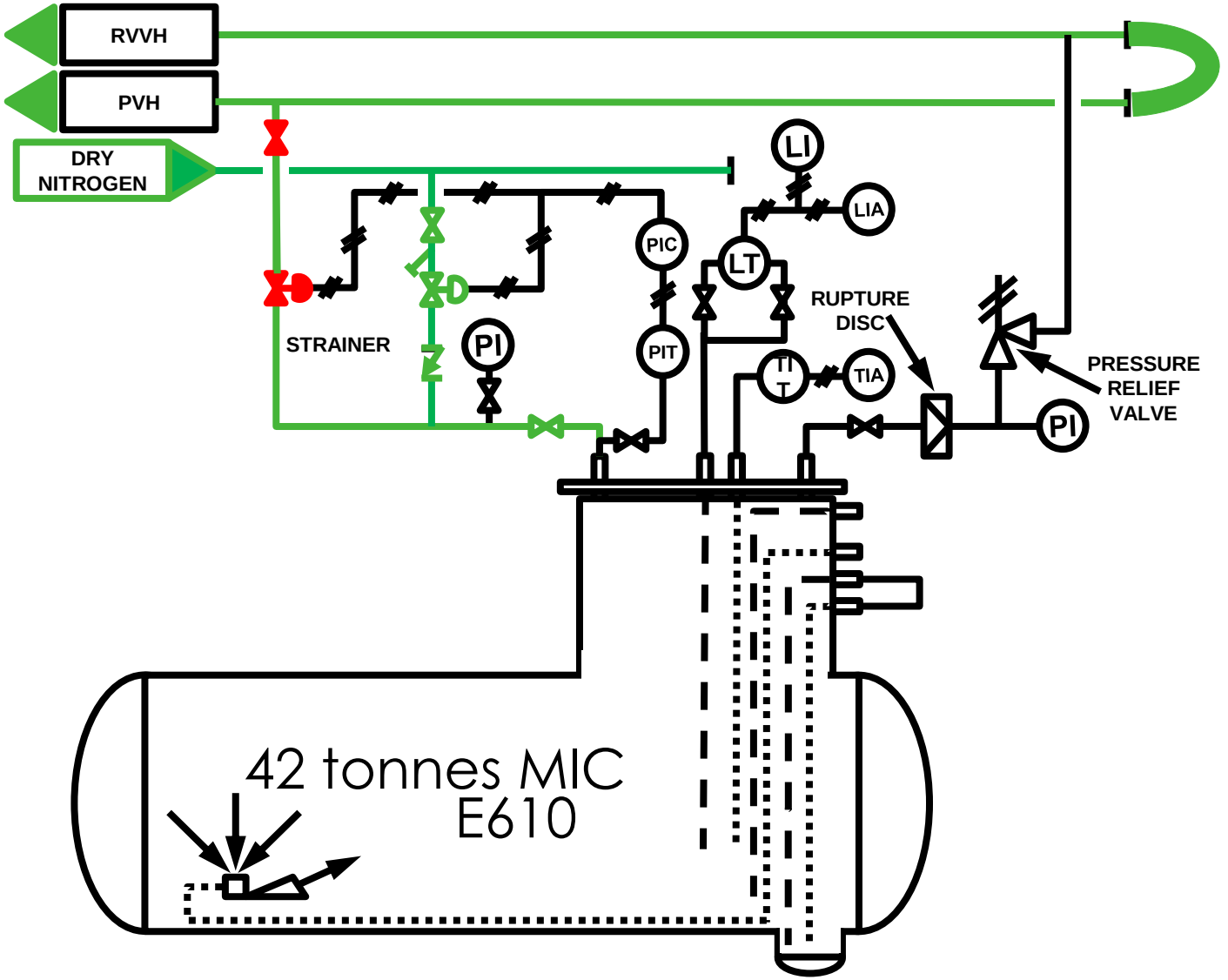
B. Pumps unreliable - Nitrogen diverted to provide MIC pressure transfer

C. Carbon steel rusts and catalyses solid trimer from MIC

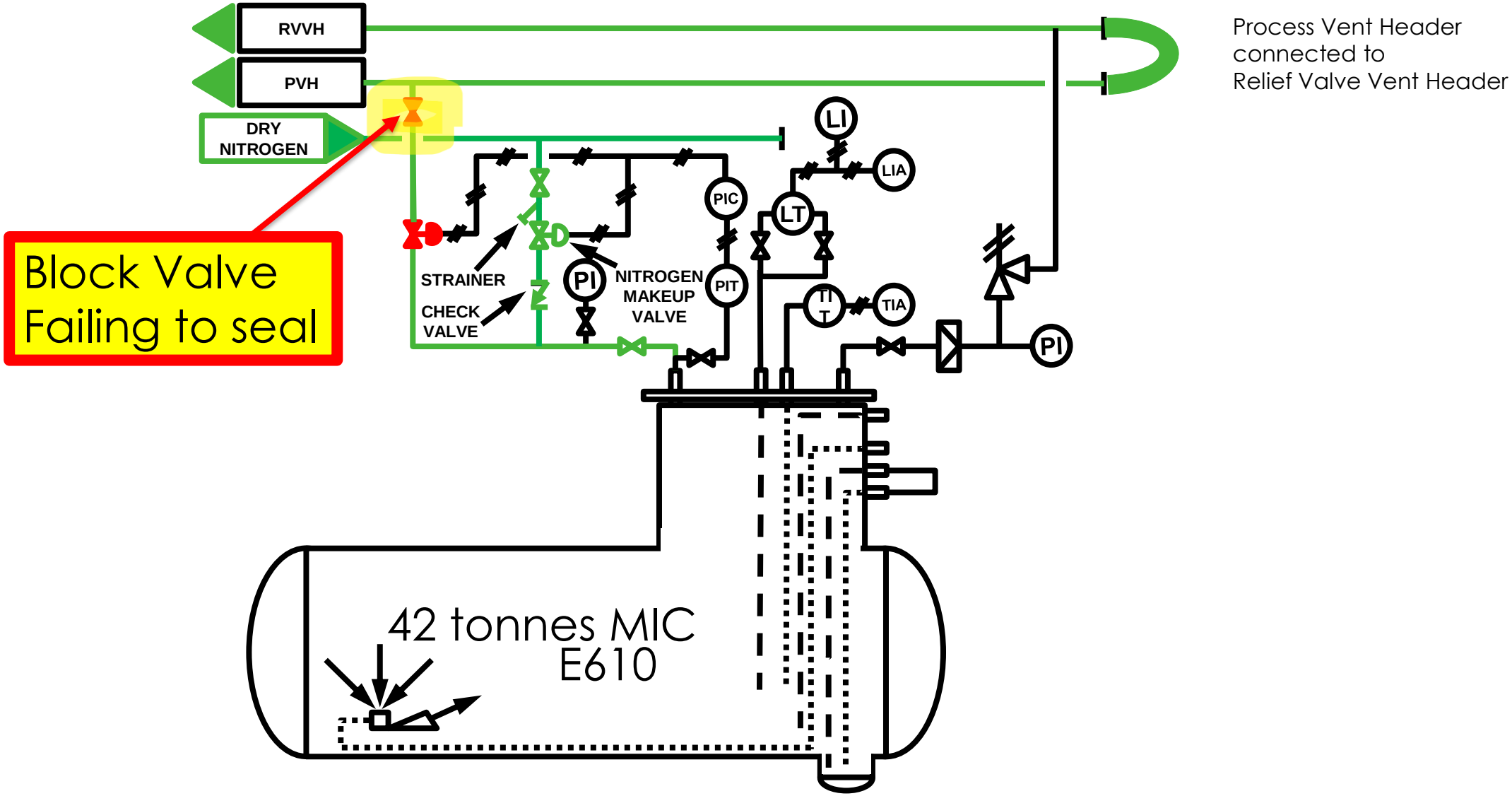
Water used to wash away solid trimer – Water + MIC + rust



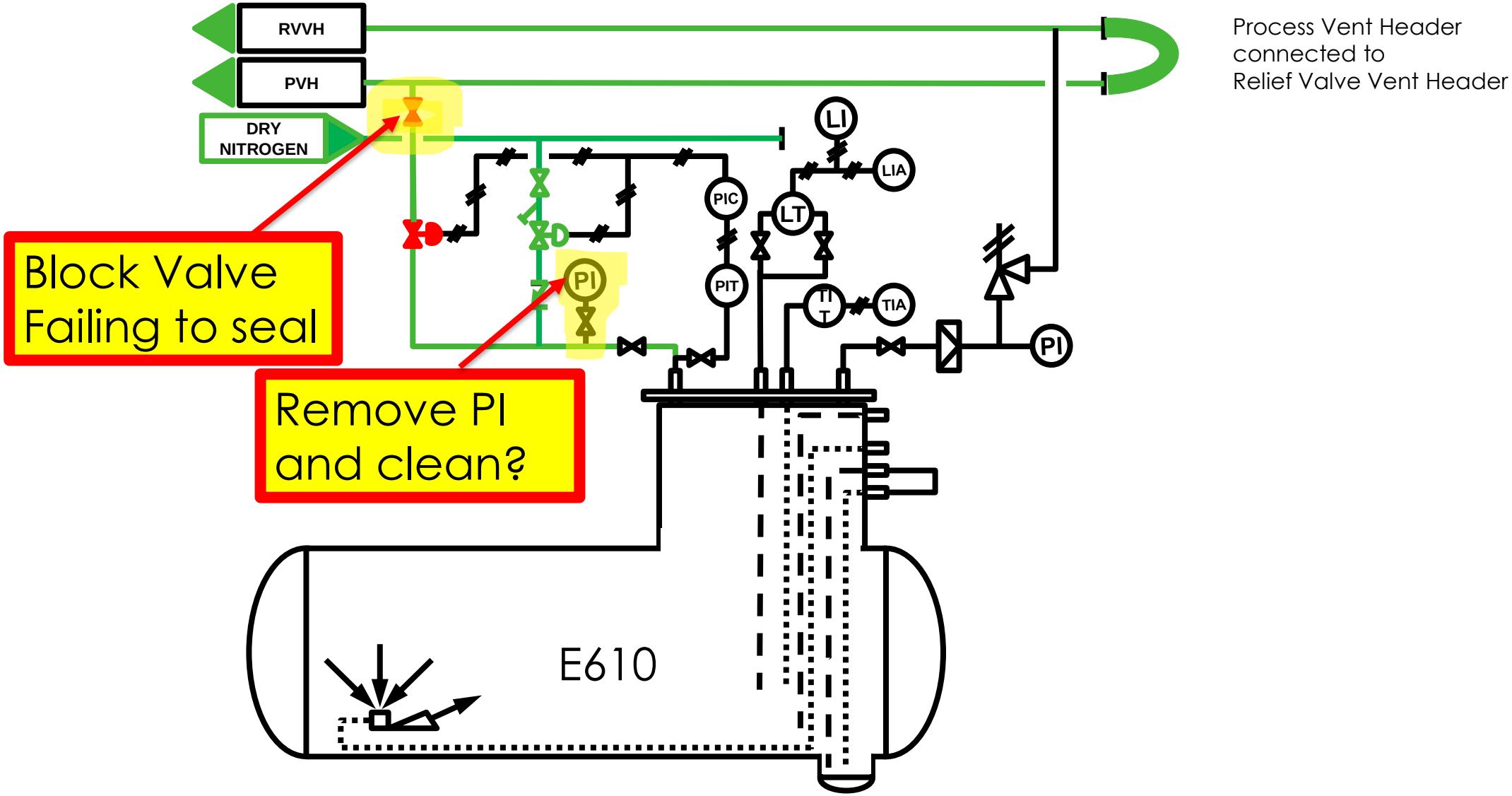
- NO TRANSFER PUMP
- NO CIRCULATION PUMP
- NO INTERNAL TANK MIXING
- NO SAMPLING SYSTEM
- NO REJECT ROUTE
- NO REFRIGERATION SYSTEM
- NO MAINTENANCE SUPPORT
- 27 DAYS TO CLOSURE



Process Vent Header
connected to
Relief Valve Vent Header

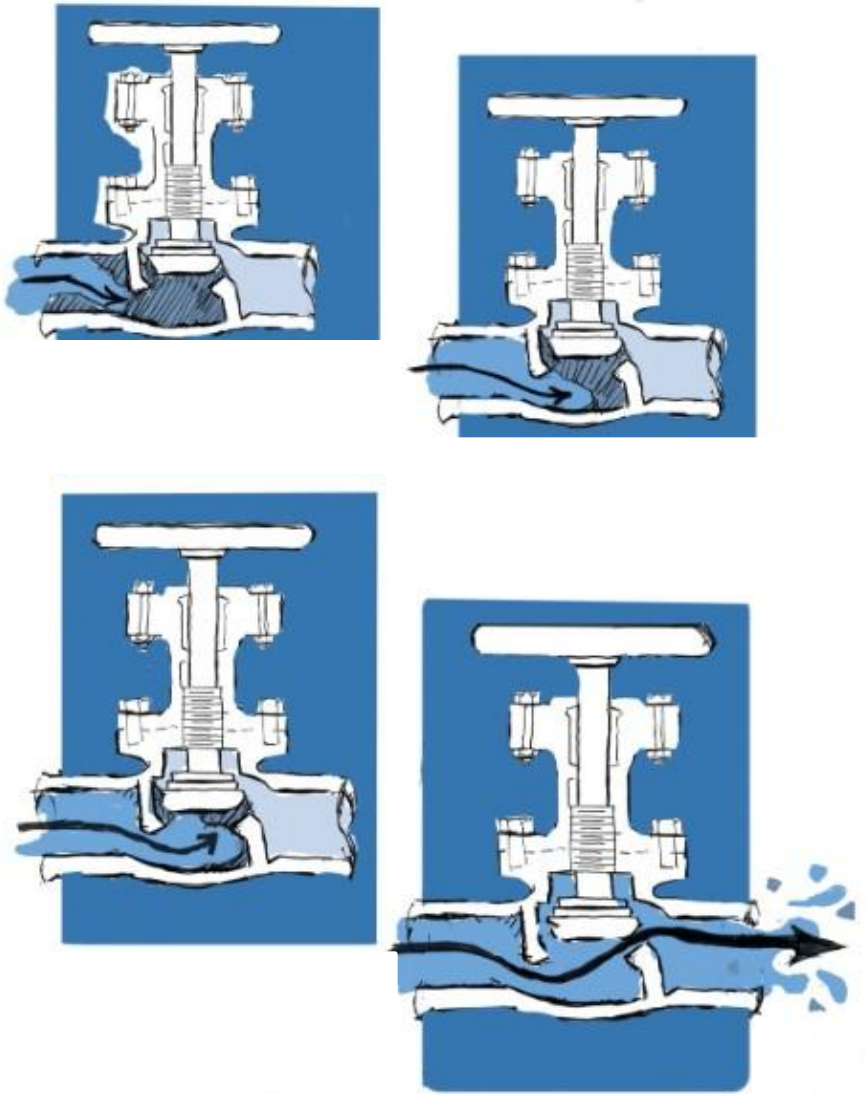


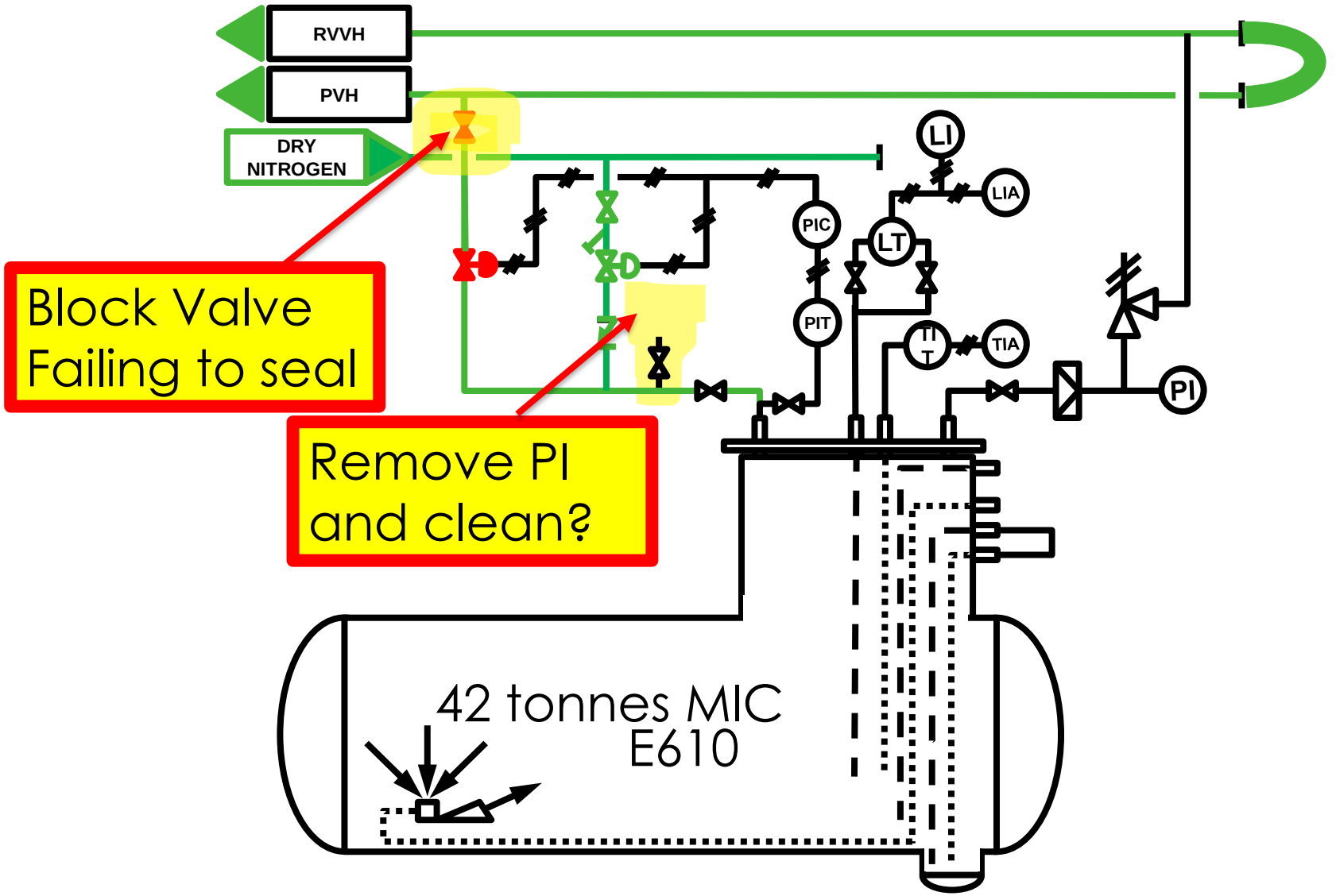
Process Vent Header
connected to
Relief Valve Vent Header



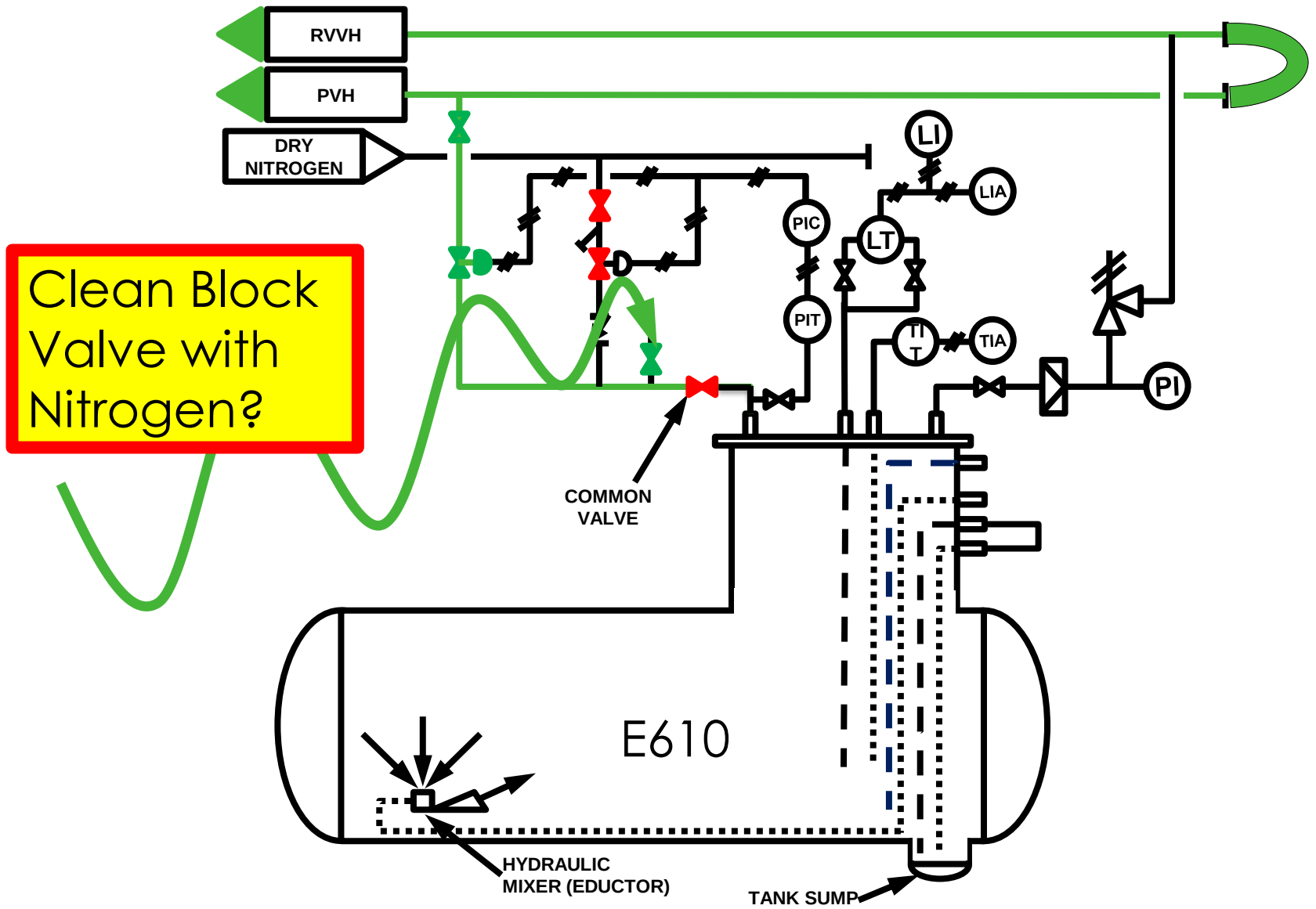
Process Vent Header
connected to
Relief Valve Vent Header


THE MIC TRIMER DEPOSIT IS OBVIOUSLY WORSE THAN USUAL...
UNION CARBIDE
E ENGINEER CHA
...AND IS KEEPING THIS VENT VALVE FROM CLOSING FOR PRESSURE-TRANSFER. SO WE NEED TO FLUSH IT CLEAR!
WHERE DO YOU SUGGEST CONNECTING THE WATER HOSE FOR THAT?
ISN'T THERE A RISK OF WATER GETTING INSIDE?
PI
WE'LL HAVE TO REPLACE THE PRESSURE GAUGE WITH A WATER HOSE QUICK CONNECT FITTING.
THE ISOLATION VALVE IS CLOSED. WATER'S NOT GONNA GET IN.
E-610
23



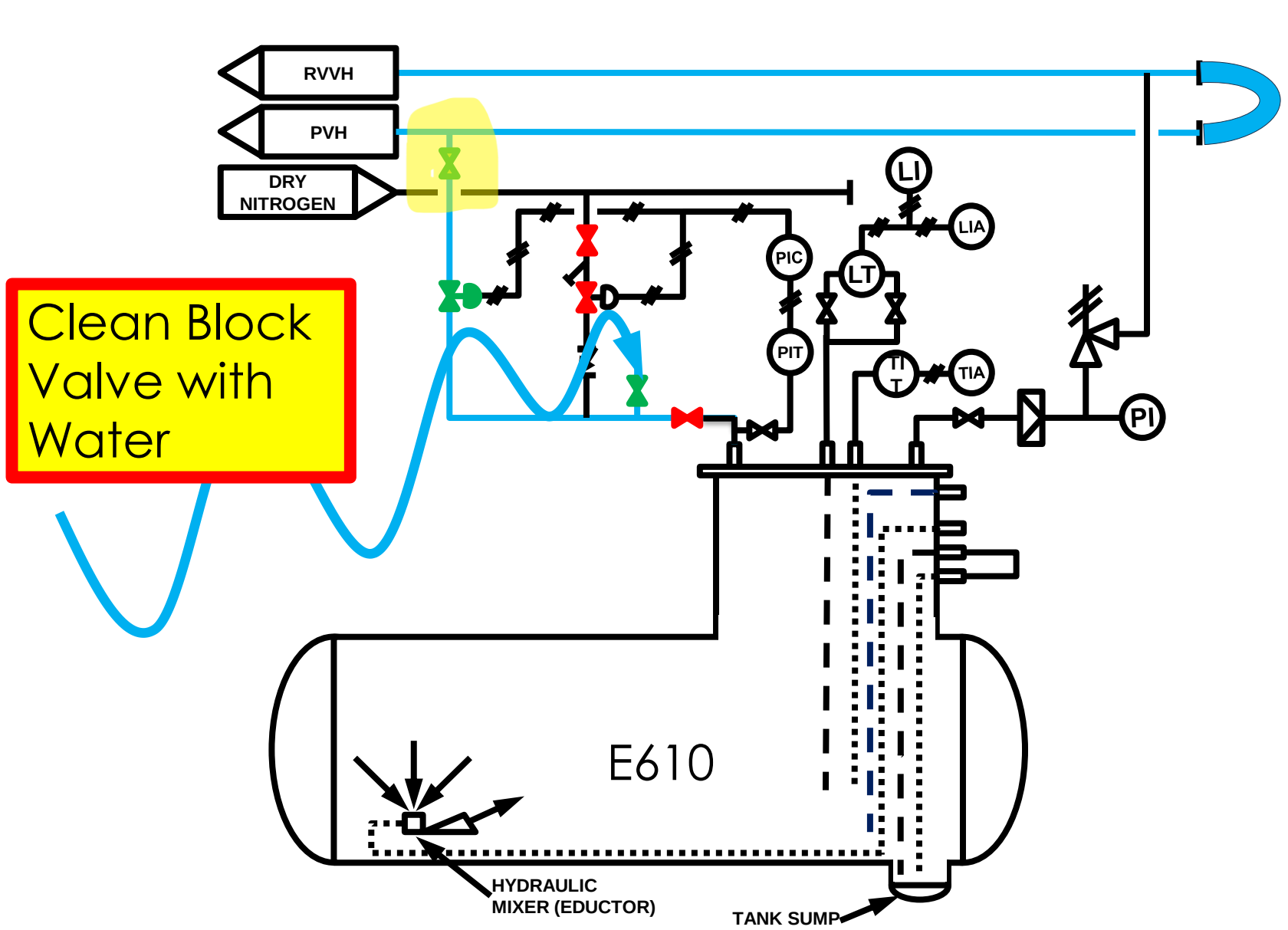


Process Vent Header
connected to
Relief Valve Vent Header

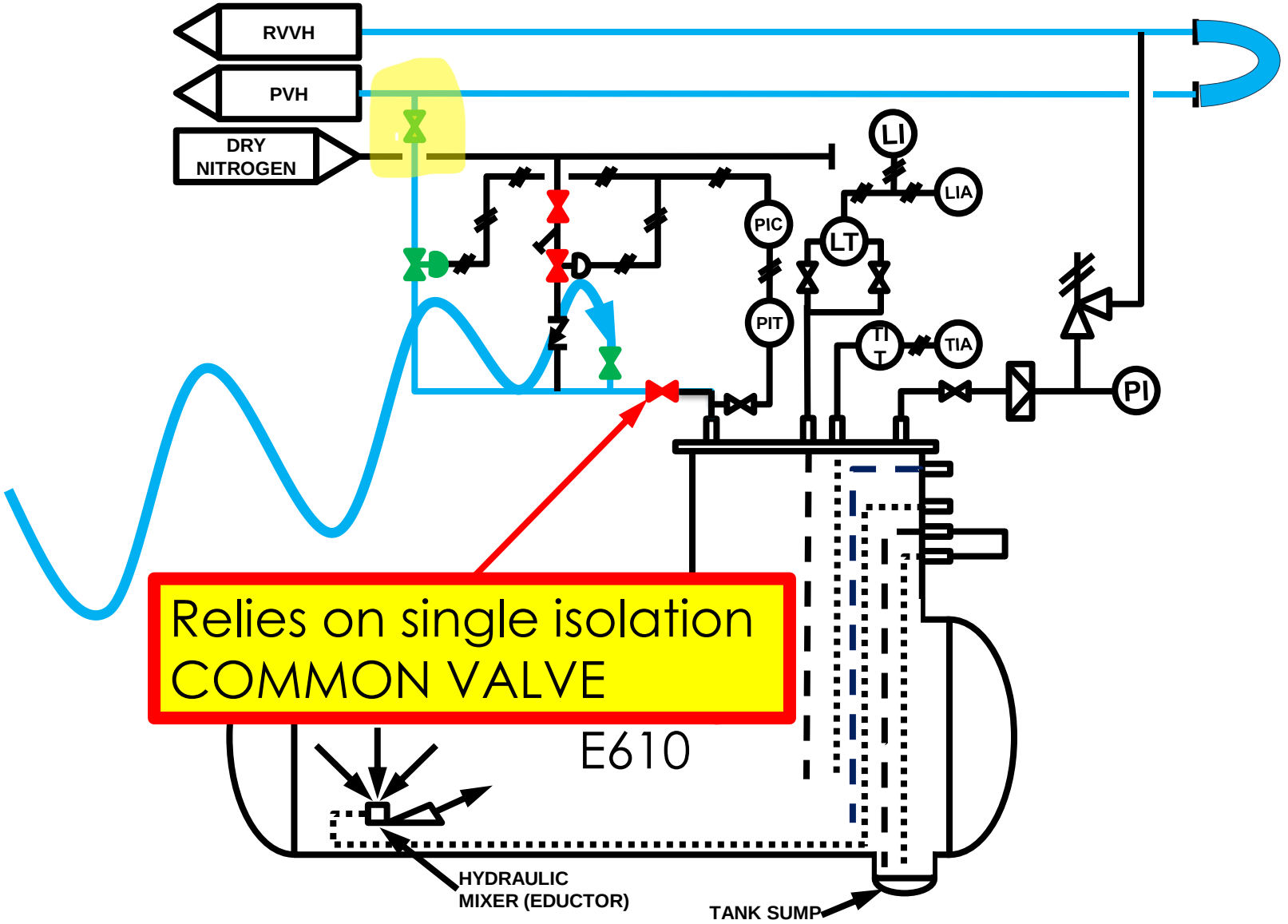


Clean Block Valve with Nitrogen?

Process Vent Header connected to Relief Valve Vent Header

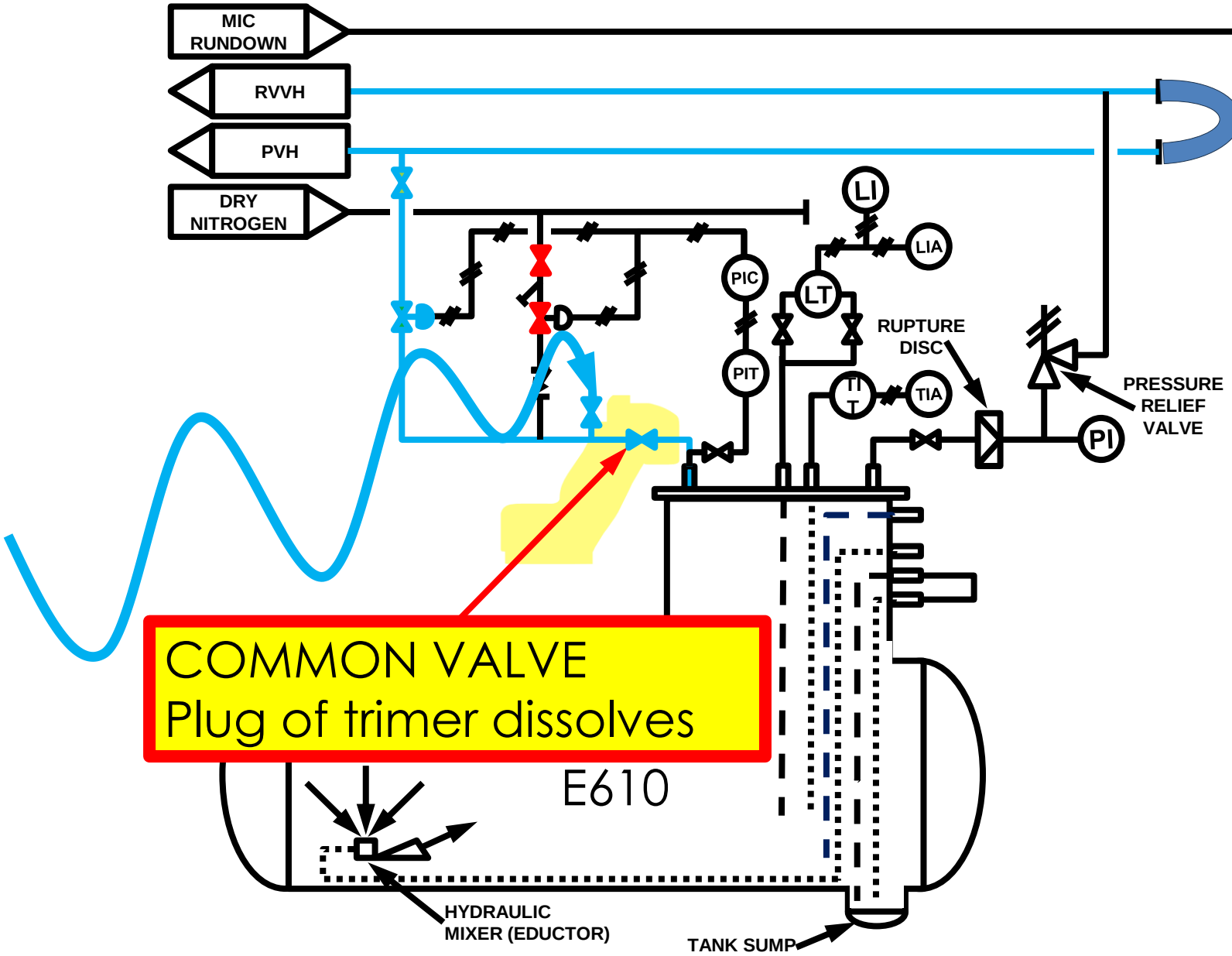


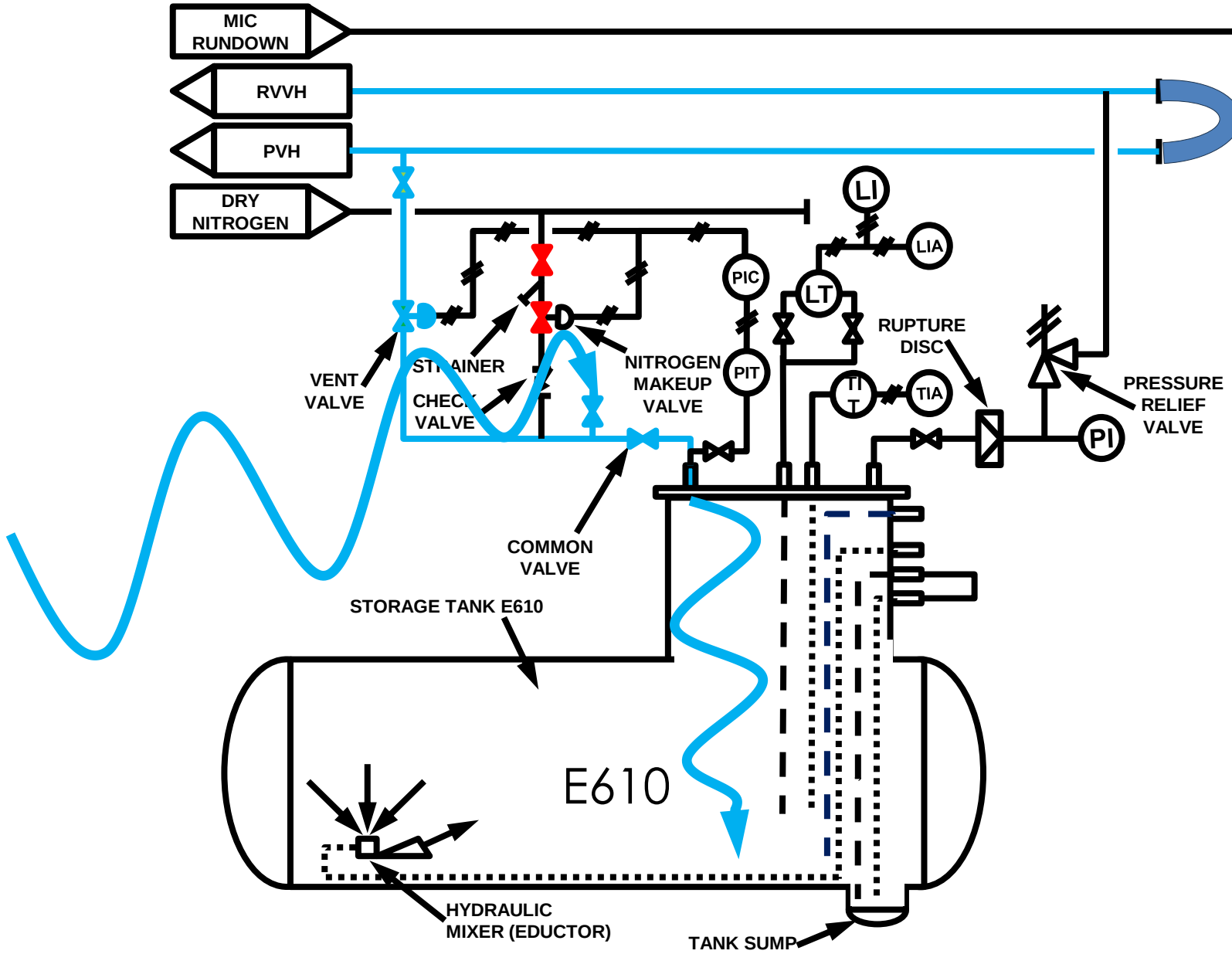
Process Vent Header
connected to
Relief Valve Vent Header



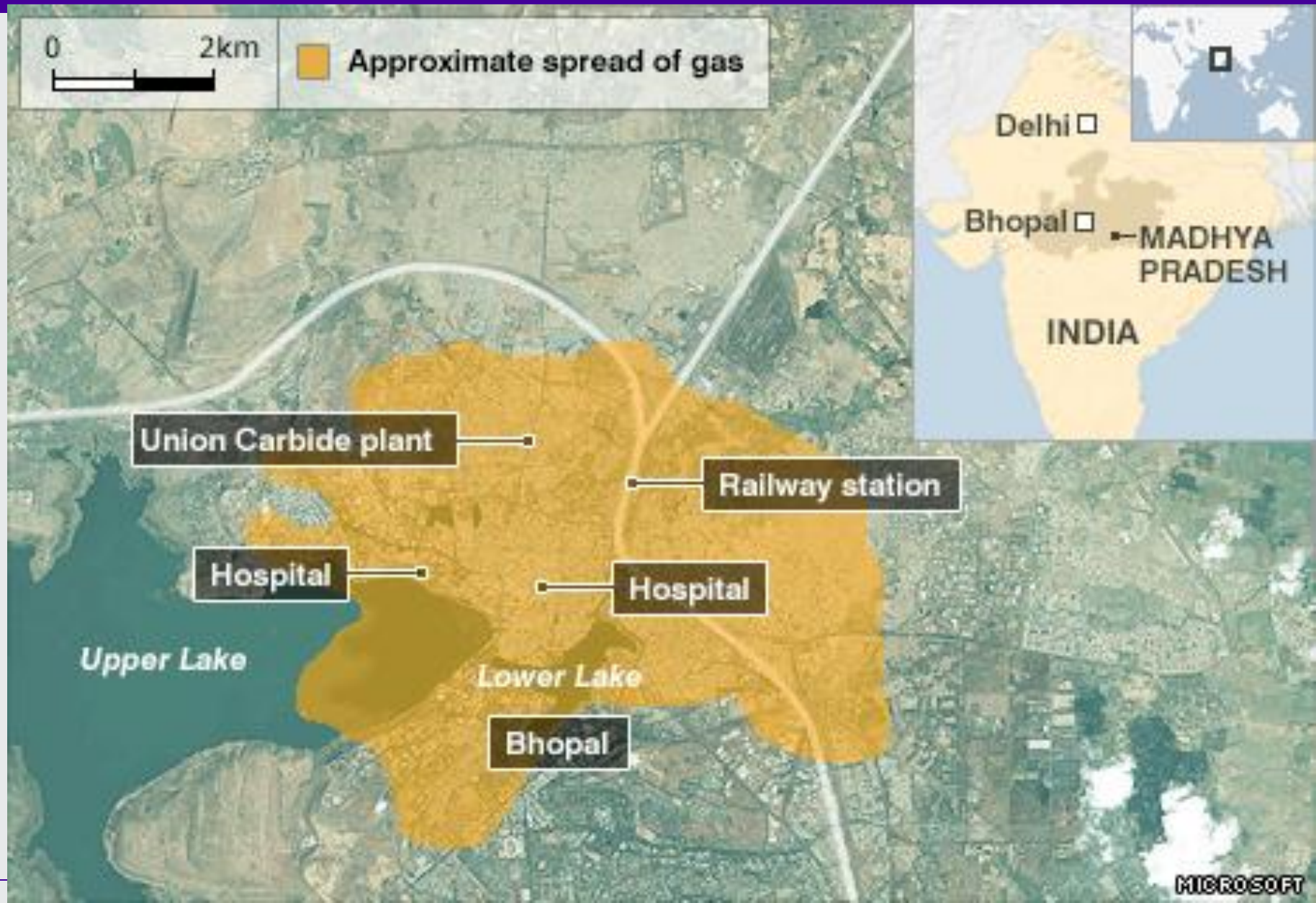
I

Process Vent Header
connected to
Relief Valve Vent Header


MIC
RUNDOWN
RVVH
PVH
DRY
NITROGEN
LI
LIA
PIC
LT
RUPTURE
DISC
PIT
TI
T
TIA
PRESSURE
RELIEF
VALVE
PI
COMMON VALVE
Plug of trimer dissolves
E610
HYDRAULIC
MIXER (EDUCTOR)
TANK SUMP

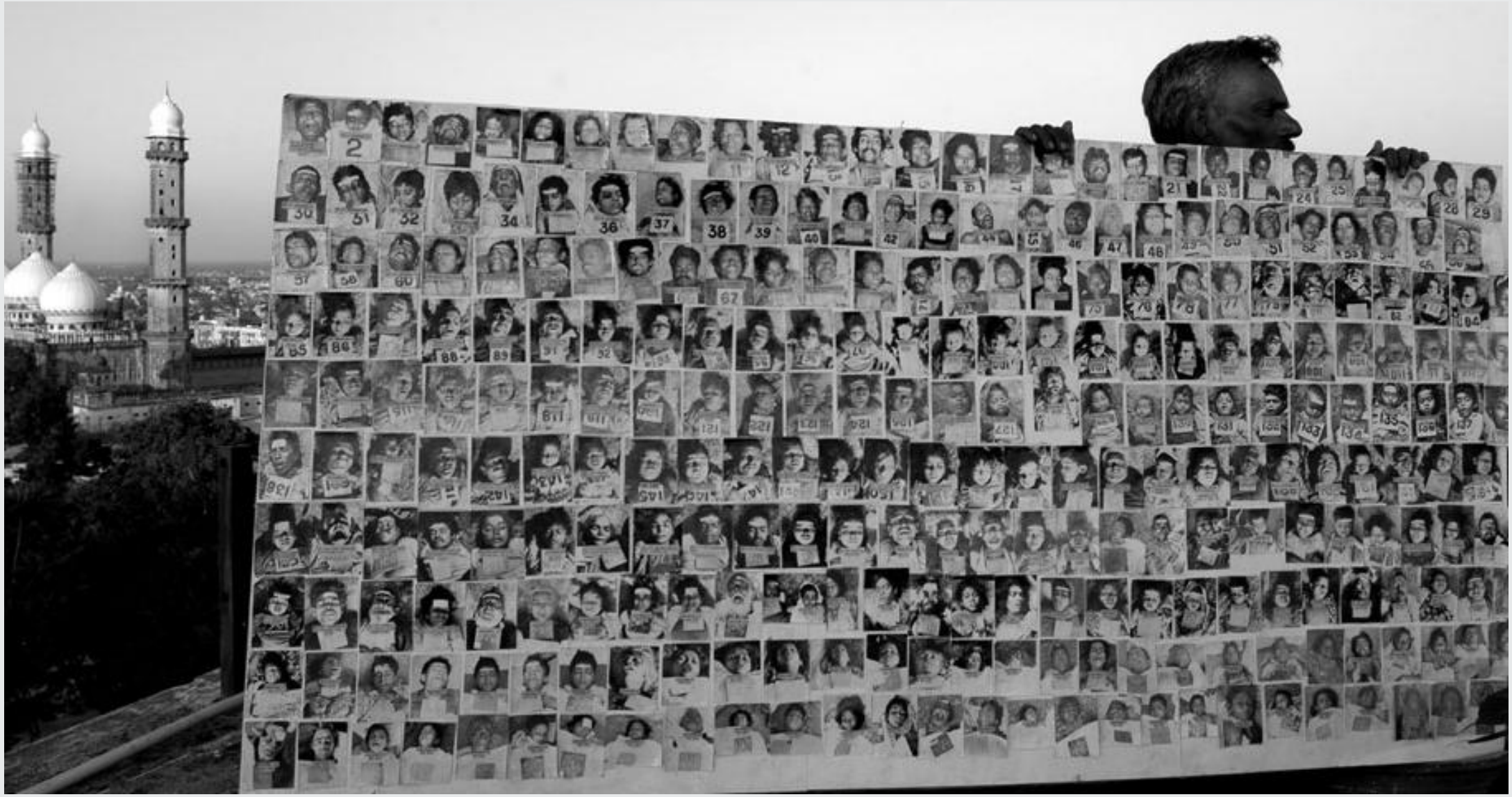

MIC
RUNDOWN
RVVH
PVH
DRY
NITROGEN
LI
LIA
PIC
LT
PIT
TI
T
TIA
PI
RUPTURE
DISC
PRESSURE
RELIEF
VALVE
VENT
VALVE
STRAINER
CHECK
VALVE
NITROGEN
MAKEUP
VALVE
COMMON
VALVE
STORAGE TANK E610
E610
HYDRAULIC
MIXER (EDUCTOR)
TANK SUMP

The Consequence

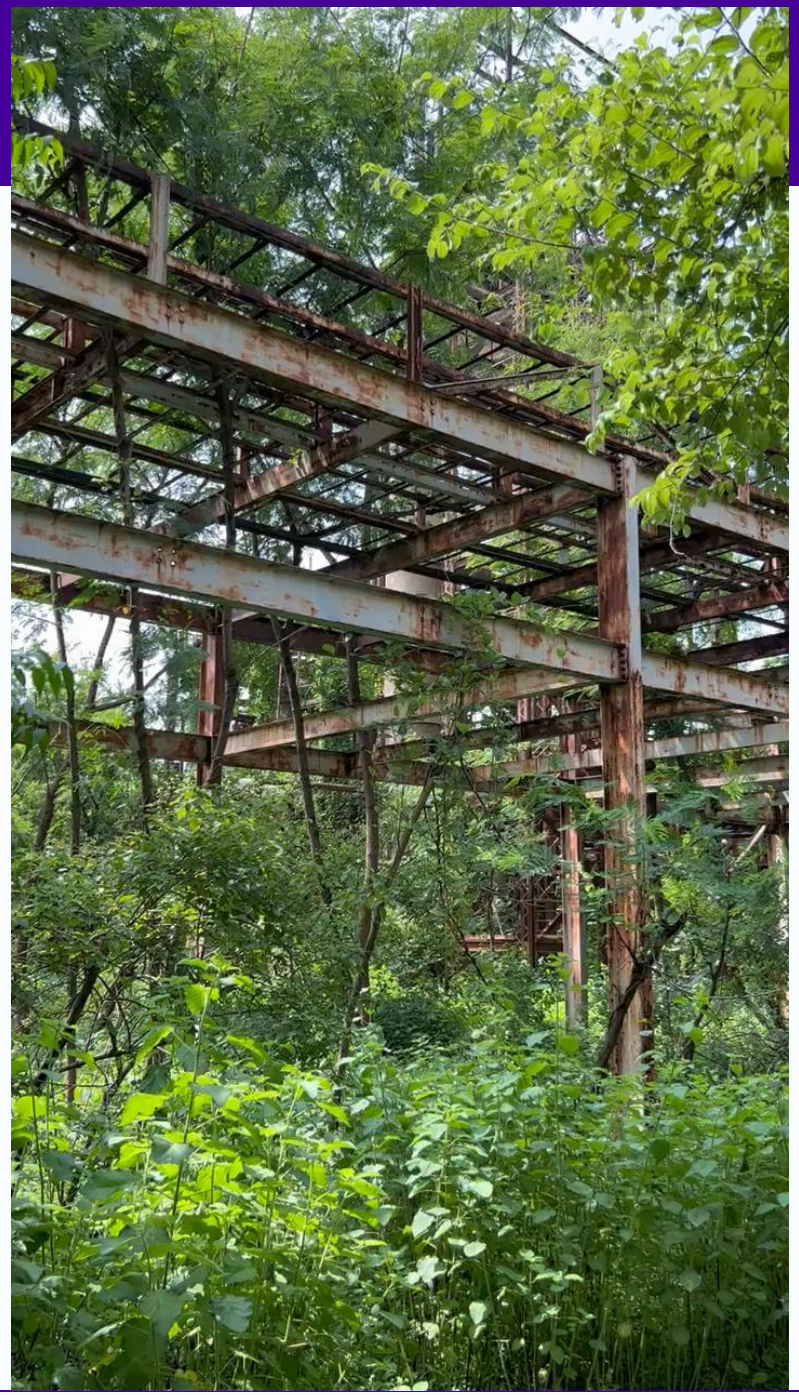


University of Sheffield

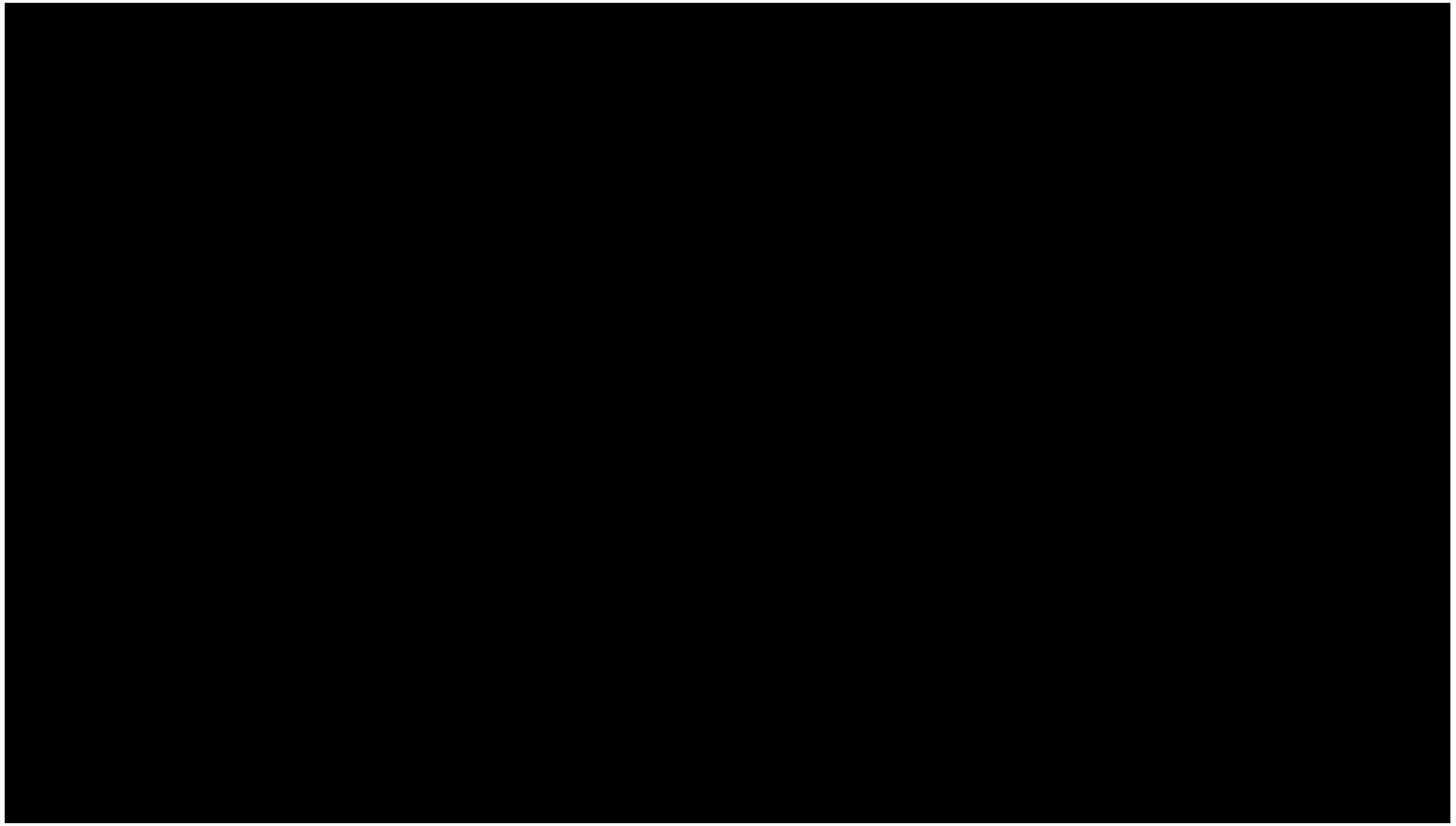
The Consequence



University of Sheffield



Solar Evaporation Ponds

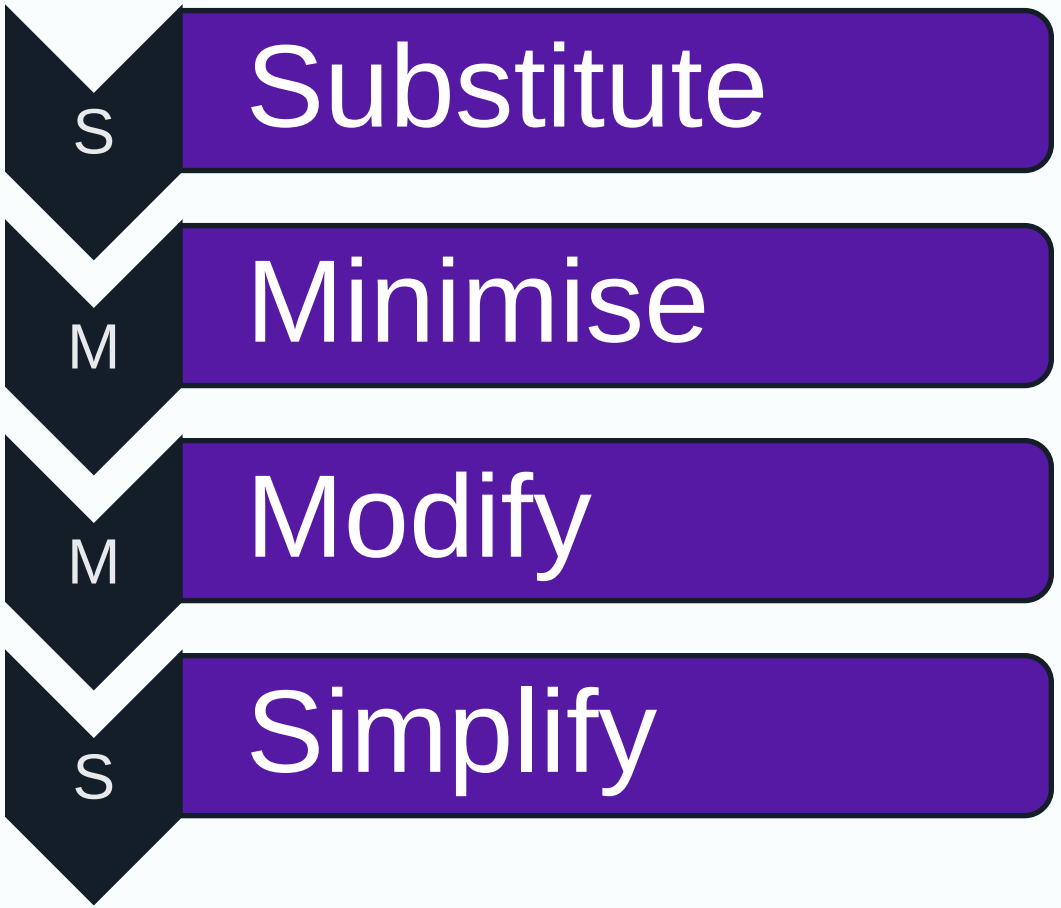


OECD Guiding Principles for Chemical Accident Prevention, Preparedness and Response

Prevent	Prepare	Respond	Follow-up
avoid loss of containment	plan for emergency	respond to emergency	investigate & clean up

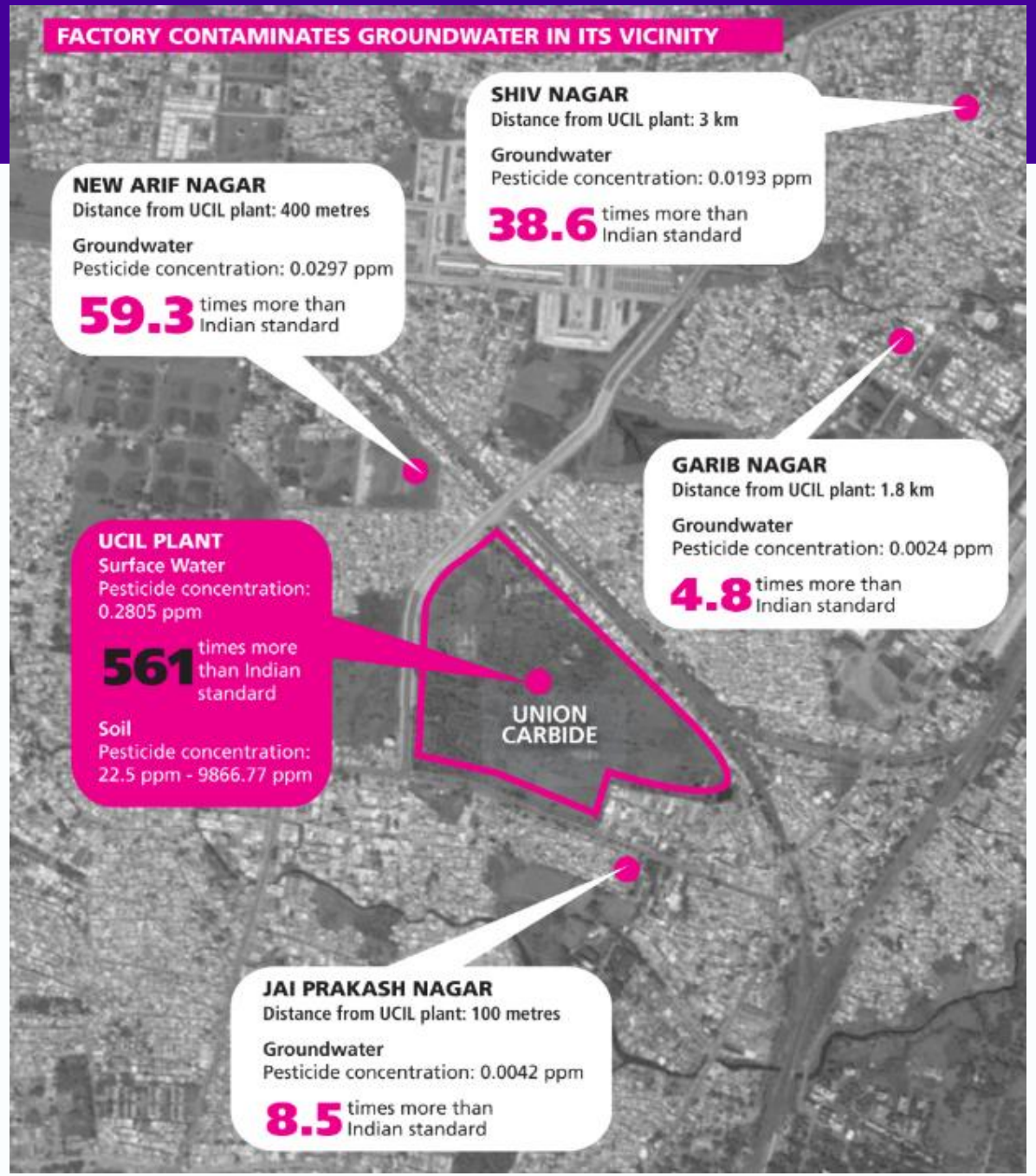
Design for Inherent Safety

- What you don't have
  can't leak
- People who aren't there
  can't be hurt
- Better to remove a hazard
  than keep it under control



Ongoing Tragedy

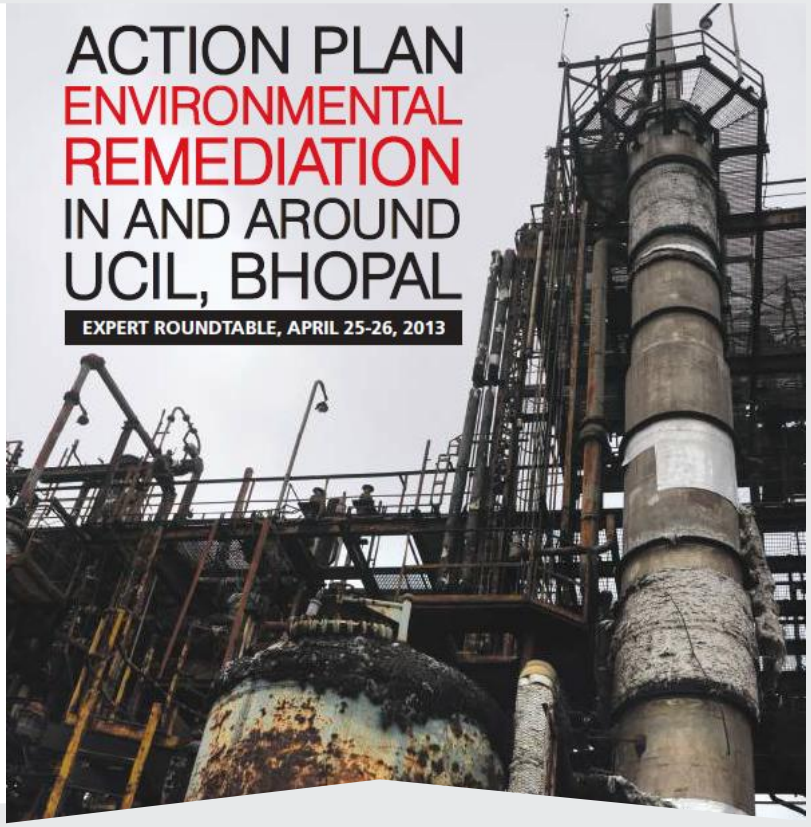
Maximum concentration of key contaminants found in soil	(ppm)
Organic	
Hexachlorocyclohexane (HCH)	99,700
Carbaryl (naphthyl methylcarbamate)	51,003
Alpha napthol	9,914
Aldicarb (carbamate pesticide)	7,876
Chlorinated benzenes	2,049
Heavy metals	
Mercury	128,000
Chromium	1,065
Lead	408

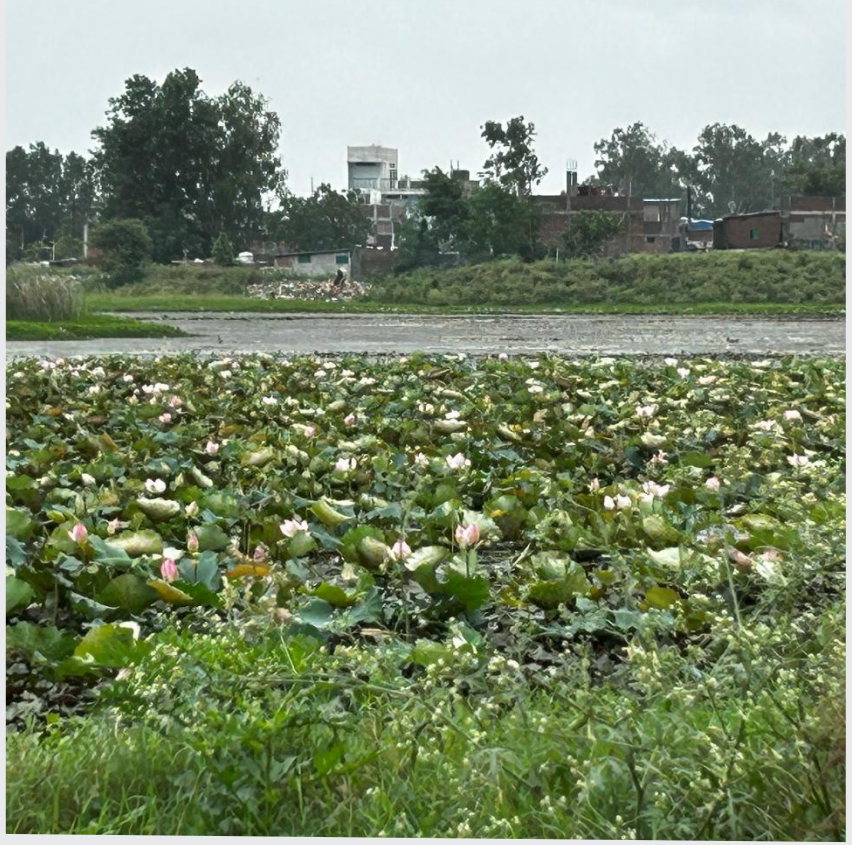


Progress on 2013 plan

Summary of Action Plan

IMMEDIATE MEASURES	
SECURING THE SITE AND PREVENTING ANNUAL SURFACE WATER RUNOFF	**THREE MONTHS**
Fencing and guarding of the UCIL site and landfill area within the SEP	Immediate
Stopping construction at the SEP area	Immediate
Measures to be taken to protect annual surface water runoff from the site during monsoon	Three months
EXCAVATION, RECOVERY AND CHARACTERISATION OF WASTE DUMPED AT THE UCIL SITE	**SIX MONTHS**
Clearing vegetation and dewatering the site	One month
Identification and refurbishment of a temporary storage area for excavated waste	Three months
Excavation and recovery of dump materials from already identified and new sites	Three months
Recovery of mercury present in drains, pan filters and soil with the help of local community	Three months
Characterisation and inventorisation of the collected waste for proper treatment and/or disposal	Six months
CHARACTERISATION AND INCINERATION OF THE STORED WASTE AT THE UCIL SITE	**SIX MONTHS**
Trial at the Pithampur incinerator with ten tonnes of similar waste from HIL, Kerala	Three months
Characterisation results of the stored UCIL waste to be made public; if required, further characterisation and inventorisation to be done in parallel with the trials	Three months
Waste with high calorific value and hazardous in nature to be incinerated with continuous stack monitoring; remaining waste to be dealt with suitable decontamination/remediation measures	Six months
MEDIUM- AND LONG-TERM MEASURES	
GROUNDWATER CONTAMINATION ASSESSMENT AND REMEDIATION OUTSIDE THE UCIL SITE	**TWO TO THREE YEARS**
Field investigation and lab analysis of the groundwater	One year
Possibility of hydraulic containment to be explored as an interim measure	Six months to one year
Remediation/containment plan to be developed and implemented	Two to three years
CHARACTERISATION AND REMEDIATION OF WASTE DUMPED IN LANDFILL IN THE SEP AREA	**ONE TO TWO YEARS**
Characterisation of waste and development of a basket of disposal/decontamination/remediation options	One year
Disposal/remediation of the waste and decontamination of the landfill area	One to two years
REMEDIATION OF ENTIRE SEP AREA	**THREE TO FIVE YEARS**
Assessment of the need of geohydrological and contamination analysis based on previous reports	Three months
If required, SEP to be studied for waste characterisation and source of groundwater contamination	One year





University of Sheffield

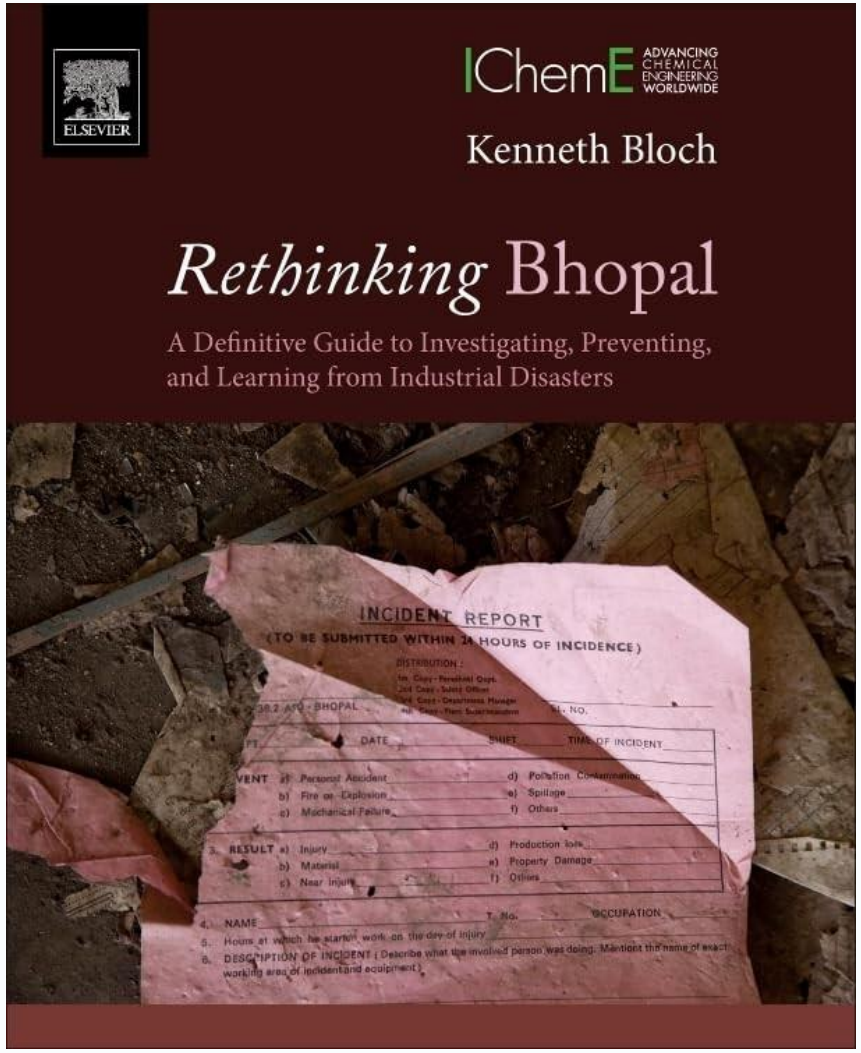
What have we learned ?

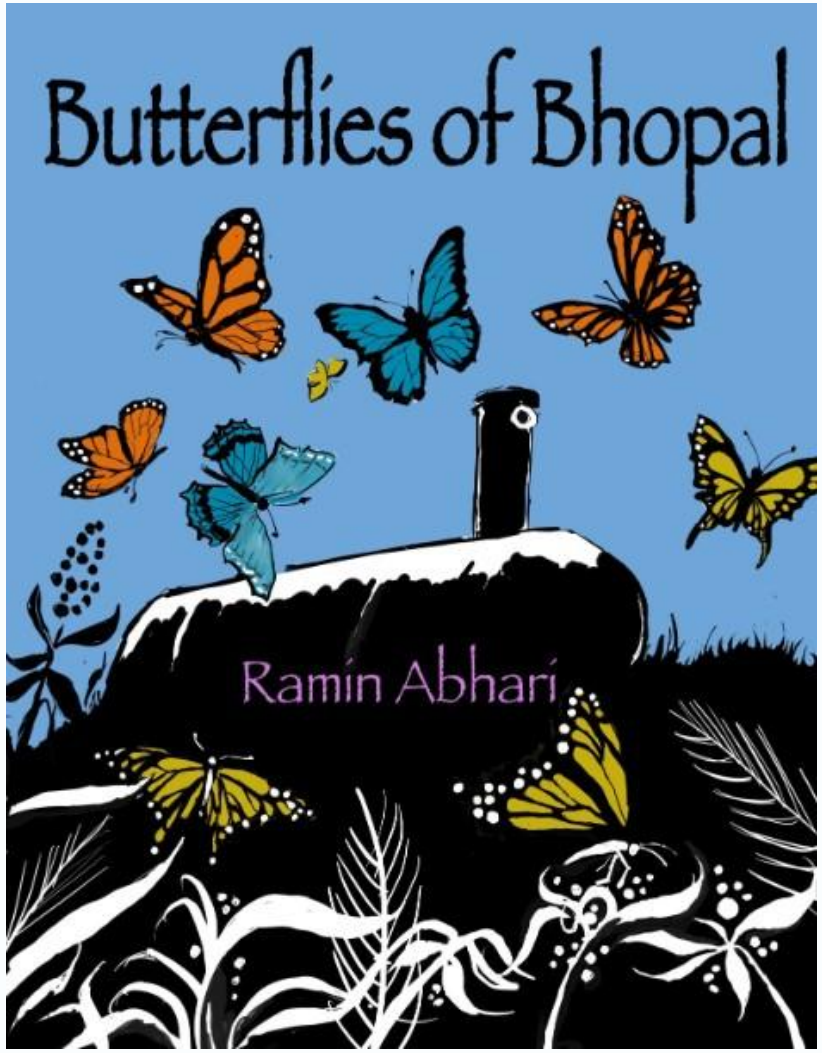
- Understand your Hazards
- Design for Inherent Safety
- Investigate when things go wrong
- Listen to what your people say
- Closure is complex
- Identify and retain key people
- Safety Critical Equipment MUST remain operational

Trevor Kletz

- Every accident is due to human error:
- someone, usually a manager, has to decide what to do;
- someone, usually a designer, has to decide how to do it;
- someone, usually an operator, has to do it.
- All of them can make errors but the operator is at the end of the chain and often gets all the blame.
- We should consider the people who have opportunities to prevent accidents by changing **objectives** and **methods** as well as those who actually carry out operations

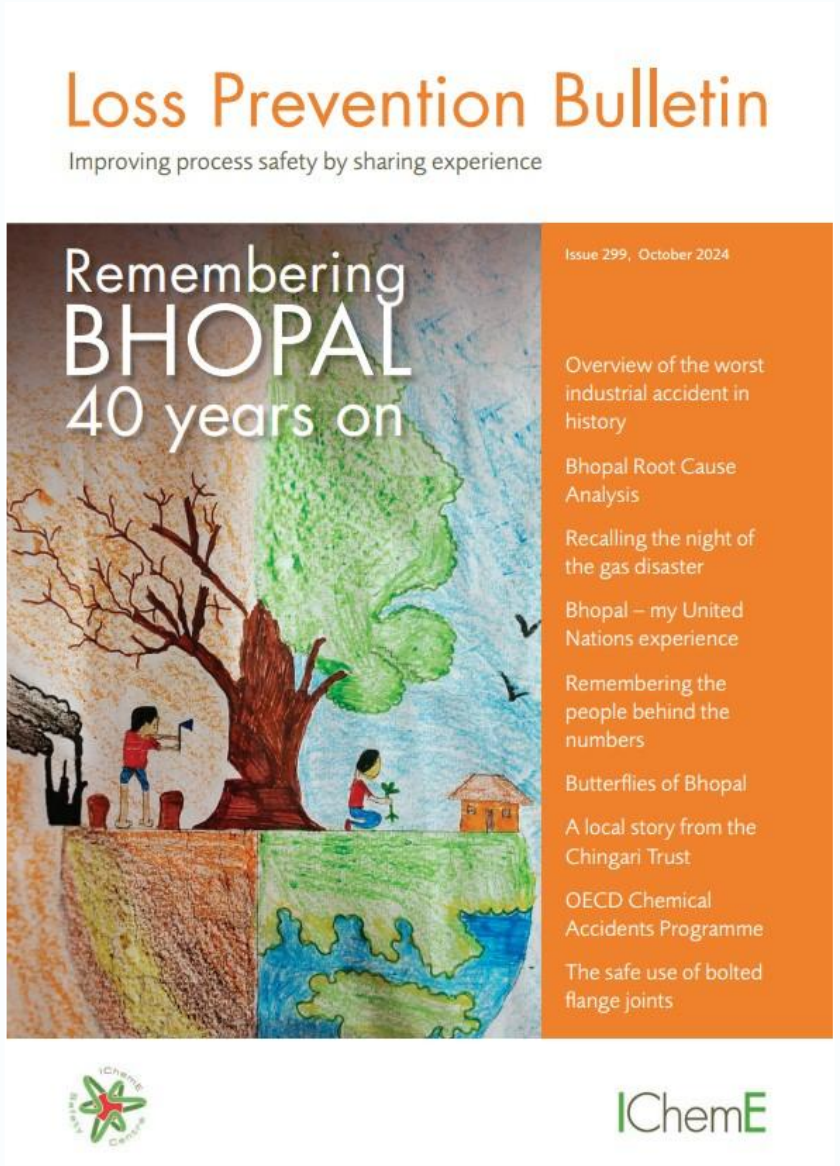
With thanks to Kenneth Bloch and Ramin Abhari





University of Sheffield

Loss Prevention Bulletin free downloads



University of Sheffield