IChemE

Safety & Loss Prevention
Special Interest Group

Learning lessons from major incidents

Improving process safety by sharing experience

Centenary edition

IChemE Lessons Learned Database (LLD)

I had the privilege of meeting the late, great Professor Trevor Kletz several times while I was an undergraduate chemical engineer at Loughborough University (1977 to 1981). For me, he was the person who really brought to life the concept of process safety. The seeds of my interest in the subject had been sown and cultivated by two other greats of the Loughborough Chemical Engineering department: Professors Don Freshwater and Frank Lees in their lectures on plant reliability and hazard analysis. But it was Professor Kletz who most helped me understand the practical application of that knowledge and opened my eyes to the potential consequences of poor design. He was a great communicator: "If you think safety is expensive, try an accident. Accidents cost a lot of money .... not only in damage to plant and in claims for injury, but also in the loss of the company's reputation." He famously observed that "Organisations have no memory. Only people have memory, and they move on." Organisations should therefore have systematic processes and procedures in place for recording and retrieving lessons of the past, lessons for which in many cases a high price has been paid in fatalities and injuries as well as money. Professor Kletz also reminded us that "Accidents are not due to lack of knowledge, but failure to use the knowledge we have."

The IChemE Safety & Loss Prevention Special Interest Group (S&LP SIG) has developed a Lessons Learned Database (LLD) to raise awareness of some high-profile major incidents in the process industries by providing a peer-reviewed 1-page summary report for each incident. The incident reports contain a brief description of the event, basic cause, critical factors, root causes, lessons learned and reference documentation. I hope these incident reports serve to aid communication of the key issues as they can be shared across all levels of an organisation unlike detailed investigation reports which are only likely to be reviewed by senior leaders and engineering specialists within their discipline. Clearly, it is impossible for a 1-page summary to capture anything more than a few key points and learnings pertaining to an incident, but it will signpost readers to the detailed investigation report and selected other pertinent reference materials. I hope the consistent format used for the incident reports will help to reinforce the importance of root cause analysis and to catalyse cross-sector sharing of lessons learned and good practices.

The incident reports can be used as posters in the workplace to help raise awareness or as handouts to promote discussion at University lectures, IChemE Member Group technical events or manufacturing site safety stand-downs. This booklet contains 52 such incident reports; one for each week of the year!

Peter Marsh CEng MIChemE
Director - XBP Refining Consultants Ltd.
IChemE S&LP SIG Committee Member

Learning Lessons from Major Incidents
First (IChemE Centenary) Edition
ISBN: 978-1-911446-77-4
2nd May 2022

Incident	Page

Foreword

Over many decades, the world has tragically continued to see process safety incidents occur, resulting in the loss of many lives and impacts on the environment. Chemical Engineers have a vital role in working with others to take up the challenge to learn from past events and continually improve process safety. Indeed, the late Trevor Kletz reminded us that we need to influence key stakeholders and decision-makers "by showing them the consequences of bad practices and design, sharing the lessons of accidents and near misses."

The Safety and Loss Prevention Special Interest Group of the Institution of Chemical Engineers (IChemE) has overseen this project to condense the lessons learned from key incidents into a consistent and readable format, making them accessible for people at any stage of their career. We would like to acknowledge the many volunteers whose commitment and dedication has enabled this invaluable compendium to be made available for members and for the benefit of society.

The sharing of lessons learned is a key step to helping us all to learn and advance process safety. We encourage all organisations to share their lessons learned material with industry bodies and the like for broad dissemination, helping others to learn without having to suffer the tragic consequences.

Process safety has always been at the heart of the professional requirements for Chemical Engineers throughout the 100 years that this institution has existed. As we move forward, we must use the lessons from major incidents to help us continue to drive improvements in process safety management. We must all learn from the past, to do better at preventing incidents in the future – this is too important an issue not to solve, because people's lives depend on it.

Margaret Donnan AFIChemE
Chair of IChemE Major Hazards Committee
Chair of IChemE Safety Centre

Dr Steven Flynn CEng FIChemE
Deputy Chair of IChemE Major Hazards Committee
Learned Society Committee Member

Acknowledgements

The author gratefully acknowledges the support and wise counsel provided by the following people who kindly volunteered their time to peer-review the incident summaries:

Page	Incident	Peer Reviewers
10	Piper Alpha	Prof. Stephen Richardson CBE FREng CEng CSci FIChemE
11	Mumbai High North	John Munnings-Tomes CEng FIChemE
12	Macondo	Prof. Geoff Maitland CBE FREng
13	Camarupim	John Munnings-Tomes CEng FIChemE
14	Skikda	Eur Ing R. T. Canaway FIChemE MIMarE
15	Longford	Eur Ing R. T. Canaway FIChemE MIMarE
16	Valdez	John Munnings-Tomes CEng FIChemE
17	Lac Mégantic	John Munnings-Tomes CEng FIChemE
18	Feyzin	Eur Ing R. T. Canaway FIChemE MIMarE
19	Romeoville	Eur Ing R. T. Canaway FIChemE MIMarE and David Moore P.E.
20	Grangemouth	Eur Ing R. T. Canaway FIChemE MIMarE
21	Milford Haven	Dr. Geoff Stevens AMIChemE
22	Avon	Eur Ing R. T. Canaway FIChemE MIMarE
23	Izmit	Eur Ing R. T. Canaway FIChemE MIMarE
24	Humber	Dr. Geoff Stevens AMIChemE
25	Texas City	Dr. Geoff Stevens AMIChemE
26	Delaware City	Richard Mundy MEng CEng MIChemE
27	McKee	Eur Ing R. T. Canaway FIChemE MIMarE
28	Anacortes	Eur Ing R. T. Canaway FIChemE MIMarE
29	Chiba	Eur Ing R. T. Canaway FIChemE MIMarE
30	Richmond	Dr. Geoff Stevens AMIChemE
31	Torrance	Dr. Geoff Stevens AMIChemE
32	San Juan Ixhuatepec	John Munnings-Tomes CEng FIChemE
33	Buncefield	Ken Rivers CEng FIChemE
34	Bayamón	John Munnings-Tomes CEng FIChemE
36	Three Mile Island	Bill Harper CEng FIChemE
37	Chernobyl	Bill Harper CEng FIChemE
38	Fukushima Daiichi	Bill Harper CEng FIChemE
39	Gannon	Mark Shipley CEng PEng
40	Dallman	Andrew Lowry PEng CIP CRM
41	Flixborough	Eur Ing Andy Mackiewicz CEng CSci CEnv FIChemE CMIOSH
42	Pasadena	Eur Ing Andy Mackiewicz CEng CSci CEnv FIChemE CMIOSH
43	Castleford	Eur Ing Andy Mackiewicz CEng CSci CEnv FIChemE CMIOSH
44	Ellesmere Port	Eur Ing Andy Mackiewicz CEng CSci CEnv FIChemE CMIOSH
45	Hahnville	Richard Mundy MEng CEng MIChemE
46	Geismar	Eur Ing Andy Mackiewicz CEng CSci CEnv FIChemE CMIOSH
47	Moerdijk	Richard Mundy MEng CEng MIChemE
48	Crosby	Richard Mundy MEng CEng MIChemE and Dr. Andrew Nixon CEng MIChemE
49	Seveso	Dr. Andrew Rushton MSaRS FIChemE
50	Bhopal	Dr. Jim Carrick CEng FIChemE and Keith Miller CEng MIMechE
51	Toulouse	Dr. Andrew Rushton MSaRS FIChemE
52	La Porte	Eur Ing Andy Mackiewicz CEng CSci CEnv FIChemE CMIOSH
53	West	Dr. Andrew Rushton MSaRS FIChemE
55	Grimsby	Mike Rantell CEng MIChemE PPSE CCPSC FSP
56	Kinston	Eur Ing Keith Plumb CEng CSci FIChemE

57	Cork	Eur Ing Keith Plumb CEng CSci FIChemE
59	Abbeystead	Alun Rees CEng FIChemE FCIWEM and Eur Geol Eur Ing Prof. Rick Brassington CGeol FGS CEng MICE FCIWEM
60	Lowermoor (Camelford)	Alun Rees CEng FIChemE FCIWEM and Eur Geol Eur Ing Prof. Rick Brassington CGeol FGS CEng MICE FCIWEM
61	Milwaukee	Alun Rees CEng FIChemE FCIWEM, Dr Martin Currie MEng CEng FIChemE FIWater, Eur Geol Eur Ing Prof. Rick Brassington CGeol FGS CEng MICE FCIWEM
63	Hamlet	Richard Mundy MEng CEng MIChemE and Helen Wade AMIChemE RIMCert
64	Louisville	Richard Mundy MEng CEng MIChemE and Helen Wade AMIChemE RIMCert
65	Port Wentworth	Eur Ing Keith Plumb CEng CSci FIChemE

The author also acknowledges the following organisations (alphabetical order) which made available most of the incident reports used in development of the incident summaries:

- Dutch Safety Board (DSB):
  https://www.onderzoeksraad.nl/en/
- EC Joint Research Council (JRC) Major Accident Hazards Bureau:
  https://minerva.jrc.ec.europa.eu/
- FR Bureau for Analysis of Industrial Risks and Pollution (BARPI):
  https://www.aria.developpement-durable.gouv.fr/
- UK Health and Safety Executive (HSE):
  https://www.hse.gov.uk/
- UK Institution of Chemical Engineers (IChemE):
  https://www.icheme.org/
- US Chemical Safety and Hazard Investigation Board (CSB):
  https://www.csb.gov/
- World Nuclear Association (WNA):
  https://www.world-nuclear.org/

Finally, the author would like to acknowledge IChemE staff members Tracey Donaldson and Alex Revell for their assistance in designing the cover of the booklet and obtaining the necessary permissions to use the images included with each incident summary report.

Disclaimer

The incident summaries contained in this publication are based on information available in the public domain. They are published only to raise awareness of the incident and some of the key learnings. IChemE and the author expressly disclaim any and all liability and responsibility for undesirable consequences resulting from any act or omission taken as a result of reading the contents of these summaries.

IChemE
Safety & Loss Prevention
Special Interest Group

The Process Safety Challenge

“A central challenge in chemical engineering is to do safely at industrial scale things that may have only trivial potential for harm at bench scale. The goal-setting Health and Safety at Work Act, and similar acts in other jurisdictions, acknowledged that prescription could not keep pace with an increasingly diverse, novel, complex and large-scale industrial scope. Rapid technological advances will continue, for example relating to steps towards zero carbon processes and digitalisation, in tandem with external challenges to plant integrity such as impacts of climate change. All changes represent threats to hard-won process safety performance improvements. Facing a continually changing context for our work, we have to decide what to do, not merely do as we are told.

Chemical engineers bear a particular responsibility when fixing on the process to be managed – then choosing the cage to contain the lion, in Kletz's analogy. We are uniquely well-placed to help identify, communicate and control process safety risks to minimise environmental and societal impacts. We play a pivotal role in creating the engagement needed across disciplines to ensure the security of the "cage".

It is not enough for there to be adequate technology and standards at our disposal. Without management systems that drive their application and a culture that implements those management systems, in spirit as well as in letter, all can be lost in a relatively short time - even when starting from a good foundation.

Root cause analysis is a key to success, feeding back into improved design and management. Particularly instructive, therefore, is the root cause matrix following this page. Root causes serve as the features in an *identikit* of incidents. Some incidents have new features, but most – when the dust has settled – are recognisable near relations of those that went before. Across all the case histories there is clearly strong overlap between underlying causes and lessons that can be learned. Our ability or willingness to learn from accidents has been deficient and so incidents continue. Systematic and conscientious attention to root causes can help to educate decision makers and to inform prioritisation of improvement projects, and so can help in reducing the frequency and consequence of incidents. Everyone shares an interest in ensuring that good practice becomes common practice and a responsibility for pursuing that goal.

“No plant is an Island, entire of itself; every plant is a piece of the Continent, a part of the main. Any plant's loss diminishes us, because we are involved in the Industry: and therefore never send to know for whom the Inquiry sitteth; it sitteth for thee.” [Kletz, paraphrasing Donne]

Adaptation of training and career paths to modern realities such as mergers, restructuring and staff churn is leading, more than ever, to potential for loss of knowledge and experience in our design houses and operating companies. Relying on your organisation’s memory is becoming more precarious (and was never sound). We need to find better ways to share knowledge widely throughout organisations.

It is inescapably difficult to maintain focus and resources when the epitome of success in process safety is to be able to report "Nothing happened today". I commend to you this database, to provide compelling examples and as a door through which journeys of more intense study can begin. I hope and expect that you will reap rewards for your attention to these pages.”

Dr Andy Rushton MSaRS FIChemE
Chair of IChemE Safety & Loss Prevention Special Interest Group

Major Process Safety Incident vs Root Cause Map
(Quick Reference Guide)

IChemE
Safety & Loss Prevention
Special Interest Group

Sector		Date	Event	Country	Type	Fatalities	Injuries	Context		Natural Hazards ("Natech" Triggers)					Design Factors (Root Causes)									Operations Factors							Maintenance Factors								Personal			Competency					Culture							Regulator			Links
								Abnormal Operations	Escalation Potential	Earthquake	Tsunami	Flood	Cyclone/Hurricane	Extreme Cold/Ice	Hazard Identification	Process Design	Equipment/Piping Design	Materials of Construction	Instrumentation	Safety Instrumented Systems	Protective Systems	Plant Layout	Occupied Buildings	Process Monitoring	Process Control	Cyber Security Breach	Alarm Management	Creeping Change	Hazard Awareness	Operations Risk Assessment	Preventative Maintenance	Inspection	Material Degradation	Work Planning	Maintenance Risk Assessment	Energy Isolation	Control of Work	Housekeeping	Human Factors	Role Clarity	Personal Protective Equipment	Communication	Procedures	Training	Supervision/Leadership	Contractor Selection	Production over Safety	Normalisation of Deviance	Quality Assurance/Control	Management of Change	Failure to Learn	Emergency Preparedness	Process Safety Management	Design Standards	Land Use Planning	Regulatory Compliance Audits	Investigation Reports
Oil & Gas	Upstream	06-Jul-88	Piper Alpha	UK	Explosion	167	?										X				X	X													X	X	X		X			X	X	X	X					X		X	X				Click
		27-Jul-05	Mumbai High North	India	Explosion	22	?									X						X							X	X									X	X		X	X	X												X	
		20-Apr-10	Macondo	USA	Explosion	11	17	X							X	X	X		X	X				X						X	X								X	X		X	X	X	X								X	X	X		X	Click
		11-Feb-15	Camarupim	Brazil	Explosion	9	26	X							X	X			X			X							X	X							X		X	X		X	X	X	X		X			X		X	X			X	Click
	LNG	19-Jan-04	Skikda	Algeria	Explosion	27	74		X							X		?	X	?		X	X								X	X	X						X					X								X	X	X	X		
	GPP	25-Sep-98	Longford	Australia	Fire	2	8	X							X					X				X			X		X				X						X			X	X	X	X			X				X	X			X	Click
	Ship	24-Mar-89	Valdez	USA	Pollution	0	0		X					X			X		X					X															X			X	X	X	X							X	X			X	
	Rail	06-Jul-13	Lac Mégantic	Canada	Fire	47	?								X		X				X							X		X			X						X				X	X	X		X			X		X	X			X	
	Downstream	04-Jan-66	Feyzin	France	BLEVE	18	84									X	X				X								X														X	X								X		X			Click
		23-Jul-84	Romeoville	USA	Explosion	17	22								X			X											X			X	X										X											X			
		22-Mar-87	Grangemouth	UK	Explosion	1	0	X	X						X		X		X	X	X								X								X						X	X			X			X	X		X				Click
		24-Jul-94	Milford Haven	UK	Explosion	0	26	X	X								X		X					X			X			X	X	X	X				X		X			X		X						X		X	X				Click
		23-Feb-99	Avon	USA	Fire	4	1	X							X													X		X	X	X	X	X		X	X						X	X	X		X			X			X				Click
		17-Aug-99	Izmit	Turkey	Fire	0	0		X	X						X	X	X			X	X								X			X						X			X		X								X	X			X	Click
		16-Apr-01	Humber	UK	Explosion	0	5		X						X		X														X	X	X									X								X			X				Click
		23-Mar-05	Texas City	USA	Explosion	15	180	X							X	X			X				X	X				X		X	X		X				X		X	X		X	X	X			X	X		X	X		X			X	Click
		05-Nov-05	Delaware City	USA	Asphyxiation	2	0																						X						X		X		X				X	X													Click
		16-Feb-07	McKee	USA	Fire	0	4		X					X	X	X				X	X	X										X			X															X				X			Click
		02-Apr-10	Anacortes	USA	Explosion	7	0	X							X		X	X	X					X				X		X			X										X					X					X	X		X	Click
		11-Mar-11	Chiba	Japan	BLEVE	0	6		X	X							X				X	X						X		X		X		X										X								X	X		X		Click
		06-Aug-12	Richmond	USA	Fire	0	26											X												X		X	X												X					X	X	X	X		Click
		18-Feb-15	Torrance	USA	Explosion	0	4	X	X						X				X	X				X							X	X	X			X	X						X		X					X	X		X				Click
	Terminal	19-Nov-84	San Juan Ixhuatepec	Mexico	BLEVE	542	4,248										X		X	X	X	X						X		X	X													X			X			X		X	X	X	X		
		11-Dec-05	Buncefield	UK	Explosion	0	43		X						X	X			X	X		X		X	X			X			X				X				X			X	X	X			X			X		X	X		X		Click
		23-Oct-09	Bayamón	Puerto Rico	Explosion	0	3		X						X	X			X	X		X		X	X				X	X	X								X				X	X			X				X	X	X	X			Click
Power Gen	Nuclear	28-Mar-79	Three Mile Island	USA	Near Miss	0	0		X						X	X			X			X					X			X									X			X	X	X								X				X	
		26-Apr-86	Chernobyl	Russia	Explosion	> 30	~ 7,000	X	X						X	X	X			X									X	X									X			X	X	X			X			X	X	X	X			X	
		11-Mar-11	Fukushima Daiichi	Japan	Explosion	0	13		X	X	X				X				X			X								X													X	X								X	X			X	
	Coal	08-Apr-99	Gannon	USA	Explosion	3	48																							X					X	X	X		X			X	X		X								X			X	
		10-Nov-07	Dallman	USA	Explosion	0	0	X	X								X	X	X	X	X		X							X	X		X										X	X				X									
Petrochemical	Manufacture	01-Jun-74	Flixborough	UK	Explosion	28	104	X	X													X	X						X	X		X	X		X				X			X	X	X	X		X		X	X		X	X		X		Click
		23-Oct-89	Pasadena	USA	Explosion	23	314	X									X		X		X	X									X				X	X	X					X	X	X				X		X	X	X	X				
		21-Sep-92	Castleford	UK	Fire	5	201	X														X	X						X						X		X		X					X	X					X	X	X	X				Click
		01-Feb-94	Ellesmere Port	UK	Fire	0	18		X						X		X		X										X		X	X	X									X	X	X								X	X	X			Click
		27-Mar-98	Hahnville	USA	Asphyxiation	1	1								X														X	X							X						X														Click
		13-Jun-13	Geismar	USA	BLEVE	2	167	X							X														X	X												X	X							X	X		X				Click
		03-Jun-14	Moerdijk	Netherlands	Explosion	0	2	X							X				X	X					X				X										X			X	X	X						X	X	X	X			X	Click
		31-Aug-17	Crosby	USA	Decomposition	0	21					X	X		X						X	X						X	X	X									X			X										X	X	X	X		Click
Agrochemical	Manuf.	10-Jul-76	Seveso	Italy	Toxic Release	0	~ 500	X	X						X	X			X	X					X				X	X									X			X	X					X				X	X	X			
		03-Dec-84	Bhopal	India	Toxic Release	2153	>200,000	X							X	X		X											X	X	X								X				X	X	X		X			X		X	X		X		
		21-Sep-01	Toulouse	France	Explosion	31	2442		X						X			X				X							X	X					X			X					X	X							X	X	X		X	X	Click
		15-Nov-14	La Porte	USA	Toxic Release	4	0	X							X		X				X		X				X		X	X	X						X		X		X	X	X	X				X		X	X	X	X	X		X	Click
	Store	17-Apr-13	West	USA	Explosion	15	> 160		X						X			X				X							X						X									X							X	X			X	X	Click
Pharma	Manuf.	04-Jan-92	Grimsby	UK	Runaway	0	0	X	X						X	X			X						X			X		X													X					X		X							
		29-Jan-03	Kinston	USA	Explosion	6	38								X		X				X		X						X	X								X				X	X	X									X	X			Click
		28-Apr-08	Cork	Ireland	Runaway	1	1								X	X	X													X									X				X	X								X		X			Click
Water	Dist	23-May-84	Abbeystead	UK	Explosion	16	28	X							X	X			X										X														X	X					X				X			Click
	Treat	06-Jul-88	Camelford	UK	Pollution	1	~ 400								X							X								X									X			X	X	X								X	X				
		05-Apr-93	Milwaukee	USA	Disease	69	>403,000								X	X								X	X																			X			X					X					
Food		03-Sep-91	Hamlet	USA	Fire	25	54								X			X	X	X	X	X	X									X			X				X			X		X			X	X		X	X	X	X	X		X	Click
		11-Apr-03	Louisville	USA	Explosion	1	0		X						X		X		X		X			X	X				X		X	X										X	X	X							X					X	Click
		07-Feb-08	Port Wentworth	USA	Explosion	14	36								X	X					X								X	X								X	X			X	X	X	X			X		X	X	X	X			X	Click

Process Safety in the Oil and Gas Industry

Unfortunately, industrial accidents have occurred throughout history. Many have resulted in a tragic loss of life and significant financial consequences. The magnitude and cost of major incidents in the oil and gas sector is often very high due to the large inventories, energy intensity and flammable/explosive/toxic nature of the raw materials and products, the complex process technologies involved, and the diverse and extensive types of transportation, storage and distribution systems required for these hazardous materials.

This booklet provides a portfolio of accident case studies, including many from the oil and gas industry. The case studies can be used for training exercises and refresher courses for staff and contractors at any site to help raise awareness of hazards and may even reduce the likelihood of an accident. They can also be studied to improve emergency response plans, thereby avoiding escalation and limiting the scale of the consequences of an accident. For example, fire pre-plans, firefighting measures (including adequacy of hardware), evacuation routes, public protection measures and so on can all be checked against these scenarios. Ultimately, it is hoped the case studies will help us avoid repeat accidents and address the weaknesses which led to them become major incidents.

Over the years, the oil and gas industry generally has delivered an improved process safety performance through better hazard analysis and risk assessment techniques, advanced monitoring systems (including alarm rationalisation and safety instrumented systems), and more substantial training and emergency planning to provide competency assurance. Root cause failure analysis and accident investigations have become recognised as an essential part of process safety risk management, but accidents do still occur because lessons learned and good practice in mitigating the risks are not always being applied correctly.

There is no doubt that the introduction of risk assessment methodology has contributed to a better understanding of hazard exposure in industrial facilities. However, more work is needed to ensure the encapsulation of all possible risks, not only to the owners but also to the public and the environment. The oil and gas sector has learned lessons the hard way, but in response has created some best practices for risk mitigation which are applicable to other process industry sectors. In some cases, it has been necessary to change legislation in the form of code and standard revisions to drive improvements in process safety.

Regulatory authorities and production/manufacturing plant owner/operators are encouraged to make loss information, ‘near-miss’ data and corrective actions publicly available so that, collectively, we can all make every effort to prevent accidents. There is no shame in providing knowledge/guidance to others to help save lives/prevent injury and to help eliminate incidents such as fire/explosion and/or pollution.

Eur Ing R. T. Canaway BSc (Hons) FIChemE MIMarE
IChemE Oil & Natural Gas Special Interest Group

Incident Title	**Gas Condensate Reinjection Pump Leak**
Incident Type	Explosion and Fire
Date	6th July 1988
Country	UK (offshore Scotland)
Location	Piper Oil Field (North Sea)

Fatalities	Injuries	Cost
167	?	US$ 2.4 bn (2021) – Ref. 3

Incident Description

Credit: PA/PA Archive/PA Images

A standby condensate pump for reinjecting gas condensate into an oil export line on the Piper (Alpha) platform had been de-energised for maintenance. Its discharge pressure safety valve (PSV) was also removed and blind flange assemblies were fitted to the open PSV pipe connections. Meanwhile, the running condensate pump failed and would not restart. Liquid levels in the gas/liquid separation system were rising and would eventually trigger a total shutdown of the platform if not reversed. Night shift operators were aware the standby pump had been taken out of service for maintenance by the day shift but believed the work had not yet begun, so they decided to re-energise and start the standby pump. Gas condensate leaked from a PSV blind flange assembly; it found an ignition source and exploded. The explosion was soon followed by an oil pipe rupture and pool fire. The incident escalated rapidly as 3 high pressure gas lines ruptured after 20, 50 and 80 mins, respectively, creating a towering inferno. Smoke and flames outside the accommodation module made evacuation by helicopter or lifeboat impossible.

Incident Analysis

Basic cause (most probable) was a loss of primary containment (LOPC) of hydrocarbon condensate due to overpressure of a temporary blind flange assembly after a pump undergoing maintenance was started in error.

Critical factors included: 1) The platform was originally designed to produce and export oil only but was extensively modified to also enable export of gas, 2) Gas compression and condensate reinjection facilities were retrofitted beneath the control room, electrical utility and accommodation modules, 3) Absence of fire protection for structural steel and gas risers, 4) Continued operation of inter-connected oil production platforms after the first explosion.

Root causes included: 1) Inadequate control of work (work permit systems), 2) Poor communication (shift handover and inter-platform), 3) Inadequate management of change (retrofitting a gas treatment system on a congested platform), 4) Inadequate protection (absence of automatic shutoff valves and dedicated deluge systems for gas risers), 5) Poor emergency preparedness (failure to conduct evacuation drills and to depressure the subsea pipelines), 6) Inadequate leadership (personal safety prioritised over process safety).

Lessons Learned

1) Offshore safety legislation should be goal-setting rather than rule-based to foster innovation and continuous improvement in installation integrity,
2) Owner/operators of fixed and mobile offshore installations should submit a Safety Case document to the regulator detailing how major accident risks and safe evacuation, escape and rescue of personnel are managed,
3) Production platforms should be provided with fire and gas detection systems, explosion protection and active (water deluge) and passive (insulation) fire protection systems, 4) Production platforms should have temporary safe refuges (TSRs) which protect personnel from external fire and smoke while an emergency is assessed and/or preparations are made for evacuation, 5) Evacuation drills should be routinely practised.

More Information

1) "Public Inquiry into the Piper Alpha Disaster, Volumes 1 and 2", Her Majesty's Stationery Office (HMSO), ISBN 0-10-113102-X (1990).
2) "Piper Alpha - What Have We Learned?", F. Macleod and S.M. Richardson, IChemE Loss Prevention Bulletin 261 (2018).
3) "100 Largest Losses in the Hydrocarbon Industry", Marsh Property Risk Consulting Practice, 27th Edition (2022).

Industry Sector	Process Type	Incident Type
Oil & Gas	Offshore Production Platform	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Piping	Blinds

Incident Title	**Support Vessel Collision With Platform**	
Incident Type	Explosion and Fire	
Date	27th July 2005	
Country	India (offshore)	
Location	Mumbai High North oilfield (Arabian Sea)	
Fatalities	**Injuries**	**Cost**
22	?	US$ 630 m (2021) – Ref. 3

Incident Description

Credit: Health & Safety Executive/ONGC

A multi-purpose support vessel (MSV) was carrying out a medical evacuation of an injured crewmember to the Mumbai High North production platform (helicopters had been grounded due to monsoon conditions). The platform Offshore Installation Manager (OIM) agreed the injured person could be transferred in a basket via a cargo loading crane. The MSV had problems with its computer-assisted dynamic positioning system, so it was brought in stern-first under manual control. During this operation, the MSV experienced a strong heave and its helideck struck one or more of the export gas-lift risers, causing a high-pressure release. An explosion and intense fire followed. The fire escalated rapidly, and the platform was abandoned. Within 2 hours, the production platform had collapsed into the sea. Adjacent platforms were severely damaged by heat radiation; the MSV also caught fire.

After fires on the MSV had been extinguished, it was towed offsite and abandoned. Six divers in saturation chambers on the MSV were left behind but were rescued 36 hrs later. The MSV sank soon afterwards.

Incident Analysis

Basic cause was collision of the MSV with the production platform, resulting in rupture of one or more export gas risers.

Critical factors included: 1) Risers and platform cargo loading zones were located on prevailing weather side of platform, 2) Risers were located outside the jacket, 3) Riser collision protection guards were only designed for smaller offshore supply vessels (not large MSVs), 4) Risers had no fire protection, 5) Alternative medical evacuation methods were not available (helicopters grounded, leeward cargo loading crane unavailable for basket transfer, etc.), 6) MSV's dynamic positioning system malfunctioned.

Root causes included: 1) Inadequate design (riser location on prevailing weather side of platform and close to cargo off/loading crane), 2) Failure to apply inherently safer design (ISD) principles (locate risers within jacket or J tube/caisson-type protective sleeves), 3) Inadequate procedures (ship/platform collision risk management), 4) Impaired judgement (MSV captain and platform OIM were under extreme pressure to undertake medical evacuation as all other options were exhausted).

Lessons Learned

1) India set up regulatory body to provide oversight of offshore oil and gas production, 2) Risers are safety-critical elements (due to high inventory) and should be subjected to independent risk assessment, 3) Risers may require subsea isolation valves (SSIVs) to limit the consequences any riser damage below topsides emergency shutdown valves (ESDVs), 4) Riser fire protection should include fire-resistant insulation and deluge systems, 5) Risers should be protected against collision, 6) Risers should be located away from platform cargo loading zones, 7) Minimum separation between production and accommodation platforms should be determined by fire and explosion modelling, 8) Hyperbaric evacuation points should be provided for divers.

More Information

1) "Mumbai High North Platform Disaster", J. Daley (2013).
2) "Guidelines for Ship/Installation Collision Avoidance", United Kingdom Offshore Operators Association (2010).
3) "100 Largest Losses in the Hydrocarbon Industry", Marsh Property Risk Consulting Practice, 27th Edition (2022).

Industry Sector	**Process Type**	**Incident Type**
Oil & Gas	Offshore Production Platform	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Pipe	Gas-lift Riser

Incident Title	**Oil Well Blowout During Temporary Abandonment Operation**	
Incident Type	Explosion and Fire	
Date	20th April 2010	
Country	USA (offshore)	
Location	Gulf of Mexico, LA	
Fatalities	**Injuries**	**Cost**
11	17	US$ 782 m (2021) – Ref. 5

Incident Description

Credit: US Chemical Safety Board

An uncontrolled release of oil and gas ("blowout") occurred at the Macondo oil well during a temporary well abandonment procedure which involved plugging the well with specially formulated cement so it could be left in a safe condition until a production facility arrived at a later date to extract the oil and gas. The escaping hydrocarbons found an ignition source on the Deepwater Horizon drilling rig and caused an explosion. Eleven people died, 17 were injured and 115 people were evacuated. The drilling rig sank within 36 hours of the initial explosion. It took 87 days to arrest the oil spill. Nearly 5 million barrels of oil were released, causing massive marine and coastal damage.

Incident Analysis

Basic cause was failure of the cement plug installed during the temporary well abandonment procedure to contain oil and gas within the well bore.

Critical factors included: 1) The cement formulation used was inadequate for the intended service, 2) The operating crew misinterpreted the results of pressure tests carried out to verify the well was sealed, 3) The blowout preventer (BOP) failed to close, 4) The diverter system was designed to route overflowing hydrocarbons to the mud gas separator (MGS) located on the rig rather than overboard, 5) The gas-in-riser event rapidly progressed to an uncontrolled blowout, 6) The onboard gas detection system failed to operate.

Root causes included: 1) Failure to verify availability of the two redundant automated mode function (AMF)/deadman systems which initiate closure of the blind shear ram in the blowout preventer (BOP) to shear the drillpipe and seal the well, 2) Inadequate design (the MGS was not rated for the pressure and flow of a gas-in-riser event or a blowout), 3) Inadequate crew training (data interpretation), 4) Inadequate leadership (too much focus on personal rather than process safety metrics), 5) Poor communication (between the rig operator and sub-contractors), 6) Inadequate regulation of offshore activity (eg. US Minerals Management Service rules-based regulatory system).

Lessons Learned

1) Large pressure differences between the inside and outside of a drillpipe can cause effective compression and bending or buckling of the drillpipe in a blowout preventer (BOP) even after the well has been sealed (potentially incapacitating the BOP), 2) The complexities of multi-part risk management between an operator and a drilling contractor need better role clarity and more oversight, 3) Risk analysis and mitigation studies should consider worst case scenarios (eg. uncontrolled subsea release), 4) The International Association of Oil and Gas Producers (IOGP) established a multi-year programme to capture learnings from these and similar incidents, and to enhance future prevention and preparedness.

More Information

1) "Drilling Rig Explosion and Fire at The Macondo Well" Executive Summary Report of the US Chemical Safety and Hazard Investigation Board, Report No. 2010-10-I-OS (2016).
2) "Response Strategy Development Using Net Environmental Benefit Analysis (NEBA)", IOGP-IPIECA (2016). [NEBA now called SIMA]
3) "Guidelines on Implementing Spill Impact Mitigation Assessment (SIMA)", IPIECA (2018).
4) "Offshore Oil and Gas in the UK – an independent review of the regulatory regime", Professor G. Maitland et al (December 2011).
5) "100 Largest Losses in the Hydrocarbon Industry", Marsh Property Risk Consulting Practice, 27th Edition (2022).

Industry Sector	Process Type	Incident Type
Oil & Gas	Offshore Drilling Platform	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Pipe	Casing Seal

Incident Title	**Condensate Stripping Pump Leak**	
Incident Type	Explosion	
Date	11th February 2015	
Country	Brazil (offshore)	
Location	Camarupim gas field	
Fatalities	**Injuries**	**Cost**
9	26	US$ 316 m (2021) – Ref. 2

Incident Description

Credit: Brazilian Navy/Reuters

A natural gas condensate leak occurred in the aft pump room of the Cidade de São Mateus (CDSM) Floating Production, Storage and Offloading (FPSO) vessel while a cargo tank was being pumped out to the aft slop tank via a temporary line-up and stripping pump. The CDSM was originally a very large crude oil carrier (VLCC) which had been converted to an FPSO in 2008 and was moored in 790 m of water at the Camarupim gas field. Several gas detectors in the pump room alarmed, confirming presence and movement of an explosive atmosphere. However, emergency responders entered the area multiple times to locate, assess and repair the leak. Attempts to clean-up the leaked material with adsorbent mats were unsuccessful, so a fire hose was deployed to perform a "water sweep" while the repair was ongoing. A major explosion occurred, destroying the bulkhead between the engine room and the adjacent pump room, breaching the main deck and wrecking the single access route to the pump room. The hull remained intact, but the vessel developed a severe list to the stern because the pump room flooded (due to fire water and sea water main ruptures and damage to the sea chest valves).

Incident Analysis

Basic cause was overpressure of an isolation blind on the discharge side of a reciprocating-type stripping pump resulting in loss of primary containment (LOPC) of natural gas condensates and creation of an explosive atmosphere in a confined space.

Critical factors included: 1) Natural gas condensate was stored in the crude oil cargo tanks contrary to the conversion project specification (condensate should be reinjected into gas export line when no oil production), 2) Isolation blind did not meet the pipe spec for the service, 3) Stripping pump was operated with discharge valve closed, 4) Use of fire hose for "water sweeping" leaked hydrocarbon condensate (static generation), 5) The single access/egress route to the pump room was destroyed by the explosion.

Root causes included: 1) Failure to follow proper pumping procedures (discharge valve closed), 2) Inadequate risk assessment (entry into confined space with explosive atmosphere present), 3) Failure to complete VLCC to FPSO conversion project before FPSO commissioning (eg. stripping pump stroke counter and high discharge pressure alarm not installed), 4) Inadequate management of change (storage of condensate in crude cargo tank and installation of blind restricting pump transfer line-up options), 5) Inadequate supervision (poor decisions to send multiple crew members into high hazard area in violation of installation safety procedure and prematurely de-mustering the crew while incident was ongoing).

Lessons Learned

1) Never enter a confined space containing an explosive atmosphere, 2) All projects involving a change of service and/or process fluids should undergo a rigorous management of change (MoC) review and a pre-startup safety (PSSR) review, 3) Individual (deep well) submerged pumps in each tank are an inherently safer design which avoids the need for a pump room.

More Information

1) "Investigation Report of Explosion Incident Occurred on 11/02/2015 in the FPSO Cidade de São Mateus", National Agency for Petroleum, Natural Gas and Biofuels (ANP), August 2015.
2) "100 Largest Losses in the Hydrocarbon Industry", Marsh Property Risk Consulting Practice, 27th Edition (2022).

Industry Sector	Process Type	Incident Type
Oil & Gas	Offshore FPSO	Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Piping	Blinds

Incident Title	**LNG Production Plant Partially Destroyed**
Incident Type	Explosion
Date	19th January 2004
Country	Algeria
Location	Skikda

Fatalities	**Injuries**	**Cost**
27	74	US$ 841 m (2021) – Ref. 3

Incident Description

Credit: H. Zaourar/AFP via Getty Images

The Skikda Liquified Natural Gas (LNG) complex comprises 6 LNG liquefaction trains (Units 5, 6, 10, 20, 30 and 40). Units 10, 20, 30 and 40 are located parallel to each other on the west side of the LNG storage tank area. Units 5 and 6 are located remotely on the east side of the LNG storage tanks. The administration, maintenance and security buildings are located adjacent to the most westerly unit (Unit 40). Units 10, 20 and 30 (utilising double mixed refrigerant technology) were brought on-line in 1971 – 1973. Units 40, 5 and 6 (utilising single mixed refrigerant technology) were brought on-line in 1981.

On 19-Jan-04 with Unit 40 operating normally, a steam boiler providing high pressure motive steam for the Unit 40 refrigeration compressor turbine driver exploded. The boiler firebox casing was breached, triggering a fireball and a second, much larger, vapour cloud explosion (VCE) which spread outward, completely destroying Units 40, 30 and 20 (43% of the site's production capacity). It also destroyed the administration, maintenance and security buildings, trapping workers under the debris. Damage to Units 10, 5 and 6 and the LNG storage tanks was minimal. However, surrounding facilities and structures including a nearby power plant, an LNG loading berth at Skikda harbour and numerous homes and other buildings in the community were also damaged. The neighbouring refinery was shut down as a precaution. Unit 6 of the LNG Complex was restarted in May 2004. Units 5 and 10 were restarted in September 2004. Units 20, 30 and 40 were eventually rebuilt.

Incident Analysis

Basic cause is believed to be release of mixed refrigerant vapours and/or LNG (probably from a cold box heat exchanger leak – Ref. 3) which were ingested by the air intake of the forced draft combustion air fan at the Unit 40 steam boiler, creating an explosive mixture in the boiler firebox.

Critical factors included: 1) The Unit 40 steam boiler was located very close to the LNG liquefaction and separation sections of the Unit 40 process plant (newer LNG plant designs use gas turbines to drive the refrigerant compressor – these are more efficient, more robust and eliminate the need for a steam boiler), 2) The loss of primary containment (LOPC) at the cold box released hydrocarbon vapour into a congested space between Unit 40, the control room and the boiler (exacerbating the impact of the VCE), 3) Still ambient conditions (no wind to disperse leaking vapours).

Root causes are believed to include: 1) Poor plant layout (proximity of neighbouring LNG liquefaction trains and occupied buildings), 2) Inadequate inspection and maintenance (cold box heat exchanger).

Lessons Learned

1) Escalation impact studies should be carried out to determine the best plant layout and equipment spacing to minimise the risk of a major accident.
2) Land use planning regulations specifying minimum separation distances between high hazard facilities and residential buildings should be enforced.

More Information

1) "The Incident at the Skikda Plant: Description and Preliminary Conclusions", LNG14 Conference Session 1, Doha (Qatar), 21st March 2004.
2) "Deadly LNG Incident Holds Key Lessons For Developers, Regulators", J. Dweck and S. Boutillon, Pipeline and Gas Journal, May 2004.
3) "100 Largest Losses in the Hydrocarbon Industry", Marsh Property Risk Consulting Practice, 27th Edition (2022).

Industry Sector	**Process Type**	**Incident Type**
Oil & Gas	LNG Production	Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Heat Exchanger	Cold Box

Incident Title	**Deethaniser Reboiler Catastrophic Failure**
Incident Type	Fire
Date	25th September 1998
Country	Australia
Location	Longford, VIC

Fatalities	**Injuries**	**Cost**
2	8	US$ 987 m (2021) – Ref. 4

Incident Description  Credit: Fairfaxmedia/The Age	A gas processing plant was taken off-line following a major upset. A few hours later, the rich oil deethaniser reboiler had become intensely cold and failed catastrophically when warm lean oil was re-introduced during restart. The failure released more than 10 tonnes (22,000 lb) of hydrocarbon vapour to atmosphere. The vapour cloud drifted 170 m (560 ft) to a set of fired heaters and ignited. The flame front from the resulting deflagration burned through the vapour cloud without causing an explosion. When it reached the ruptured exchanger, a fierce jet fire developed beneath an elevated piperack junction and flame impingement caused 3 more leaks. The resulting fire burned for more than 2 days. Two employees were killed and eight more were injured. Supplies of natural gas to domestic and industrial users throughout the State of Victoria were halted for more than 2 weeks, causing substantial losses to industry and massive inconvenience to people in their homes.
Incident Analysis	**Basic cause** was brittle fracture of the deethaniser reboiler channel end due to intense low temperature (-42 °C vs 100 °C in normal operation). **Critical factors** included: 1) Loss of warm lean oil flow for an extended duration. 2) Absence of remote-operated emergency block valves (EBVs) to isolate interconnecting plant, 3) Senior engineering staff had been relocated to the head office in Melbourne several years earlier. **Root causes** included: 1) Inadequate hazard identification (low temperature hazard due to loss of lean oil), 2) Incomplete operating procedures (due to inadequate hazard identification), 3) Inadequate operator training (abnormal operations and upsets), 4) Inadequate alarm management (too many alarms, poorly prioritised), 5) Failure to conduct a management of change (MoC) review (organisational change relocating senior staff to head office), 6) Safety management system not fully implemented (inadequate supervision of operations and personal safety prioritised over process safety).
Lessons Learned	1) Cold metal embrittlement of carbon/low alloy steels is a low probability, high consequence hazard that is sometimes overlooked, 2) Risk assessment can only be conducted against known hazards, so it is imperative that comprehensive process hazard analysis (PHA) studies (including Hazop) are conducted on hazardous plant, 3) Organisations should ensure their workforces always remain mindful of the possibility of disaster ("chronic unease") and report all incidents and their root causes, 4) Remote-operated emergency block valves (EBVs) can be deployed to control large accidental releases of flammable materials, 5) The State of Victoria introduced the Occupational Health and Safety (Major Hazard Facilities) Regulations 2000 which legislated a requirement for a Safety Case at all major hazard facilities.
More Information	1) "Report of the Royal Commission into the Accident at Esso Longford", June 1999. 2) "Lessons from Longford", Andrew Hopkins, CCH Australia Ltd., 2000, ISBN 1-86468-422-4. 3) "Have Australia's Major Hazard Facilities learnt from the Longford Disaster?" James Nicol, Institution of Engineers Australia (IEAust), 2001, ISBN 0-85825-738-6. 4) "100 Largest Losses in the Hydrocarbon Industry", Marsh Property Risk Consulting Practice, 27th Edition (2022).

Industry Sector	**Process Type**	**Incident Type**
Oil & Gas	Gas Processing Plant	Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Heat Exchanger	Shell & Tube

Incident Title	**Very Large Crude Carrier Grounding**	
Incident Type	Water Pollution	
Date	24th March 1989	
Country	USA	
Location	Prince William Sound, AL	
Fatalities	**Injuries**	**Cost**
0	0	US$ 3.2 bn (1996) – Ref. 2

Incident Description


Credit: RGB Ventures/SuperStock

A single-hull very large crude carrier (VLCC) which had been loaded with approximately 1,263,000 barrels of Prudhoe Bay crude oil at the Valdez Marine Terminal (AL, USA) ran aground on Bligh Reef, a well-known navigational hazard in Prince William Sound, while bound for Long Beach (CA, USA). The vessel was under the navigational control of the Third Mate at the time of the incident. The grounding ruptured 8 cargo tanks, spilling around 258,000 barrels of oil into the sea. At the time, this was the largest single oil spill in US waters. There were no injuries but there was catastrophic damage to the environment. The oil spill killed an estimated 250,000 sea birds, 3,000 otters, 300 seals, 250 bald eagles and 22 killer whales. Fishing in oil-polluted waters was prohibited so many villages in the area, which were heavily dependent on salmon and herring fishing, faced financial ruin.

Incident Analysis

Basic cause was rupture of cargo tanks due to damage sustained by the ship's hull when it ran aground on a reef.

Critical factors included: 1) The ship deviated from the vessel traffic separation scheme (TSS) to avoid an ice float field, 2) The Master's judgement was impaired (due to alcohol), 3) The Third Mate was suffering from fatigue (due to work overload), 4) The remote location of Prince William Sound impeded emergency response efforts (accessible only by helicopter, plane or boat) and resulted in late deployment of oil spill cleanup barge(s).

Root causes included: 1) Inadequate vessel tracking system (eg. outdated radar, inadequate communication system), 2) Inadequate piloting services, 3) Inadequate staffing (fit Master and rested crew), 4) Violation of procedures (Master placing unqualified Third Mate in charge of navigation at a critical time), 5) Inadequate training (alcohol/drug rehabilitation supervision), 6) Inadequate corporate management oversight, 7) Insufficient oil spill response equipment inventory (eg. booms, oil-skimmers), 8) Inadequate contingency plans and communication strategy for dealing with major spills.

Lessons Learned

1) Fatigue can severely impair crew members' judgement and performance, 2) Organisational change impacting crew levels require careful consideration of human factors, particularly at times of abnormally high workload (e.g. tank cleaning, cargo handling, navigating in narrow shipping lanes), 3) Double-skin hulls may help reduce water pollution in the event of a (low intensity) grounding or collision, 4) Any crew member suspected of consuming alcohol or drugs (including the Master) should be subjected to testing before sailing, 5) Twin tug escorts should be provided for oil-laden ships in narrow shipping lanes, 6) Booms to cordon off long stretches of shoreline become ineffective in stormy seas, 7) Dispersants, detergents, and hot water cleaning of shoreline can cause substantially more wildlife mortality than the oil itself, 8) Oil spill response procedures should be routinely practised, 9) The US federal Oil Pollution Act (OPA) of 1990 created procedures for responding to future oil spills and established the legal liabilities of responsible parties.

More Information

1) "Marine Accident Report - Grounding of the US Tankship Exxon Valdez on Bligh Reef, Prince William Sound, Near Valdez, Alaska, March 24, 1989", National Transport Safety Board Report No. NTSB/MAR-90/04.
2) "Trouble on Oiled Waters: Lessons from the Exxon Valdez Oil Spill", R. T. Paine et al, Annu. Rev. Ecol. Syst. 1996. 27:197–235.

Industry Sector	Process Type	Incident Type
Oil & Gas	Transportation	Water Pollution
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment-related	Not applicable	Not applicable

Incident Title	**Crude Oil Freight Train Runaway and Derailment**
Incident Type	Fire
Date	6th July 2013
Country	Canada
Location	Lac Mégantic, QC

Fatalities	Injuries	Cost
47	Unknown	Unknown

Incident Description

Credit: The Canadian Press/Alamy

A freight train with 5 locomotives, a control car, a buffer car and 72 Class 111 tank cars containing 7.7 million litres (48,400 barrels) of Bakken crude oil had been parked on the main line at a dedicated crew change point. The track at this point had a downward slope of 1.2%. The solitary locomotive "engineer" applied hand brakes on all 5 locomotives and 2 other cars and shut down all but the front locomotive. The engineer tested the hand brakes as required by railway regulations, but the air brakes had been left on during this test. Soon after the engineer left, a fire was reported in the front locomotive. Firefighters turned off electrical breakers in the locomotive to stop fuel circulation feeding the fire. 2 hours after the firefighters and track foreman departed the scene, the train began to roll downhill, reaching a speed of 101 km/h (63 mph) over a distance of 11 km (7 miles). 63 of the 72 tank cars derailed in downtown Lac Mégantic and many of them ruptured releasing ~ 6 million litres (37,700 barrels) of crude oil. A huge fire and several explosions followed, killing 47 people. The lake and river were polluted with crude oil.

Incident Analysis

Basic cause was rupture of dozens of tank cars due to damaged sustained when the runaway train derailed at high speed in the downtown area.

Critical factors included: 1) Bakken crude is more volatile than conventional crudes, 2) The train had been parked on the main line (siding occupied by empty boxcars; not prohibited by regulations), 3) Air brakes had been left on during hand brake test (giving false impression hand brakes alone could hold the train), 4) The front locomotive engine caught fire (defective repair leaked oil into hot turbocharge unit), 5) The train had been left unattended overnight (to avoid exceeding engineer's hours worked limit), 6) Firefighters shut down the front locomotive per regulations (inadvertently disabling the air brakes), 7) Absence of track signals (to alert rail traffic controller of runaway train).

Root causes included:1) Inadequate (non-standard) engine repair using inappropriate epoxy-like material, 2) Violation of procedures (hand brakes tested with air brakes still applied), 3) Inadequate training (hand brake operation, securement of trains), 4) Inadequate safety management system (poor supervision and testing of employees), 5) Inadequate risk assessment (inappropriate test method used for determining crude volatility and shipping risk classification, single crew train operation), 6) Inadequate emergency response plan and communication strategy (for dealing with major spills), 7) Inadequate regulatory oversight (failure to audit train operator's activities).

Lessons Learned

1) Tank cars used for transporting highly volatile and flammable goods should have safety features such as head shields (reinforcement), tank jacket (leak protection), top fitting housing (impact protection), insulation (to maintain contents at appropriate temperature), thermal blanket (fire protection) and fail-safe braking systems or wheel chocks (runaway prevention), 2) Trains carrying dangerous goods should not be left unattended, 3) Mutual aid firefighting teams should use standardised fire hose sizes and connections and compatible frequencies for radio communication, 4) Single crew trains are now prohibited for use in transporting hazardous goods in Canada.

More Information

1) Transportation Safety Board of Canada (TSB) Railway Investigation Report No. R13D0054 (2014).
2) "The Lac Mégantic Railway Disaster – A Closer Look At The Cargo", R. Abhari, IChemE Loss Prevention Bulletin 274 (2020).

Industry Sector	Process Type	Incident Type
Oil & Gas	Transportation	Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessel	Tank Car

IChemE Safety & Loss Prevention Special Interest Group

Incident Title	**Propane Storage Sphere Rupture**
Incident Type	Fire and BLEVE
Date	4th January 1966
Country	France
Location	Feyzin

Fatalities	**Injuries**	**Cost**
18	84	Unknown

Incident Description  Credit: J. Garofalo/Paris Match via Getty	An operator was draining water from a propane storage sphere via a DN 50 (2" NS) vertical drain leg below the sphere. The drain had 2 manual isolation valves in series. Both were opened but, contrary to operating procedure, the lower valve was half-opened first, then the upper valve was opened further. When draining was almost complete, the upper valve was closed, then cracked open again. No flow was observed so the upper valve was opened fully. A blockage (probably ice or hydrate) suddenly cleared, and propane gushed out. The handle fell off the upper valve and could not be reinstated. Attempts to close the lower valve failed as it had frozen in the half-open position. A large vapour cloud formed and drifted to a nearby road where it ignited and flashed back to the sphere causing a fierce fire. Around 1 hour later, a boiling liquid expanding vapour explosion (BLEVE) occurred as the sphere ruptured. Some shrapnel struck the support legs of an adjacent sphere which then collapsed and toppled over. Damaged pipe fittings on the toppled sphere began discharging liquid which further fed the fire and, 45 minutes later, this second sphere ruptured in another BLEVE. Three more spheres collapsed and ruptured but did not explode.
Incident Analysis	**Basic cause** of first fire was ignition of a vapour cloud formed by accidental release of a large quantity of propane from an open drain. Basic cause of first BLEVE was fire engulfment and overheating of the sphere. **Critical factors** included: 1) The lower drain valve was erroneously opened before the upper drain valve (causing Joule-Thomson chilling and ice or hydrate formation), 2) The ground under the sphere was level (allowing pooling of leaked propane in the bund), 3) The firewater pump capacity was insufficient to protect all the spheres, 4) The local fire brigade did not try to cool the burning sphere, mistakenly believing it would be protected by its PSV (they directed their hoses to cool 4 adjacent spheres instead). **Root causes** included: 1) Failure to follow operating procedure (drain valve operating sequence), 2) Inadequate storage sphere design (support legs not reinforced), 3) Inadequate drain system design (removable valve handles, open discharge in close proximity to valves), 4) Inadequate overpressure protection (absence of remote depressuring valve), 5) Insufficient active (water spray) and passive (insulation) fire protection, 6) Failure to train local fire brigade on how to deal with this type of incident.
Lessons Learned	1) Sphere support legs should be reinforced (for shrapnel impact protection), 2) Storage spheres and support legs should be insulated (for fire protection), 3) The ground below spheres should slope towards a collection pit outside the sphere shadow (to avoid pooling under the sphere), 4) A deluge system capable of flooding the outer surface of the sphere should be provided (and regularly tested), 5) The drain system should include a remote-operated, accessible, fire-safe, quick shut-off valve (min. distance from the sphere), a throttle valve at least 1 m (3 ft) further downstream and a drain pot connected to a closed drain. The line should have welded joints (where practicable) and should be self-draining (no pockets) and well-braced (to minimise vibration). Screwed fittings should be prohibited (except for instruments), 6) Flammable gas detectors alarming to DCS should be provided (for early leak detection).
More Information	1) ARIA No. 1 https://www.aria.developpement-durable.gouv.fr/wp-content/files_mf/A1_ips00001_003.pdf

Industry Sector	**Process Type**	**Incident Type**
Oil & Gas	Liquified Gas Storage	Fire & BLEVE
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessel	Storage Sphere

Incident Title	**Amine Absorber Catastrophic Failure**
Incident Type	Explosion and Fire
Date	23rd July 1984
Country	USA
Location	Romeoville, IL

Fatalities	Injuries	Cost
17	22	US$ 603 m (2021) – Ref. 3

Incident Description  Credit: American Petroleum Institute	An operator working near an LPG amine absorber tower at the Unsaturated Gas Plant (USGP) of a Fluid Catalytic Cracking Unit (FCCU) noticed gas escaping from a horizontal crack about 150 mm (6") long at a circumferential weld near the bottom of the vessel and tried to close the main inlet valve. While closing the valve, he noticed the leak rate increasing and immediately initiated evacuation of the area. As the firefighters arrived, the crack propagated rapidly and a large amount of propane/butane was released which ignited and resulted in a massive explosion. The upper 14 m (46 ft) section of the vessel was propelled 1 km (0.6 miles) away where it struck and toppled a 138 kV power transmission tower. The loss of electrical power rendered an electric motor-driven firewater pump inoperable. A fire hydrant barrel was sheared off, causing a further reduction in firewater pressure from the 2 diesel engine-driven firewater pumps that were still operating. The role of the absorber was to remove hydrogen sulphide (H_2S) from a mixed LPG stream by counter-current contacting with a monoethanol amine (MEA) solution at approximately 38 °C (100 °F) and 13.8 barg (200 psig). The vessel was fabricated from killed carbon steel plate (ASTM A516 Gr.70) to the relevant design codes and had been in service since 1970. It was inspected at 2 year intervals. The second course (ring section) of the vessel (above the feed inlet nozzle) had been replaced in 1974 due to hydrogen blistering and an internal monel liner had been added to the bottom head and first course (below the feed inlet nozzle) in 1976 to reduce corrosion.
Incident Analysis	**Basic cause** was rupture of the absorber vessel due to cracks initiated by sulphide stress corrosion cracking (SSCC) and propagated by stress-oriented hydrogen induced cracking (SOHIC) in the heat affected zone (HAZ) of a repair weld joining a replacement course to the original vessel. **Critical factors** included: 1) Hydrogen embrittlement significantly reduced the fracture resistance (toughness) of the original steel, 2) A hard micro-structure formed in the HAZ of the circumferential weld when the replacement course was installed (no post-weld heat treatment applied), 3) The firewater supply pressure was reduced by explosion damage (escalated severity). **Root causes** included: 1) Inadequate corrosion control (hydrogen embrittlement), 2) Inadequate hazard awareness (SOHIC), 3) Inadequate weld procedure (absence of bakeout and post-weld heat treatment).
Lessons Learned	1) Weld procedures should be designed to avoid formation of high hardness microstructures in steels for service in hydrogen-containing environments. 2) PWHT is recommended for all equipment and piping in MEA service regardless of service temperature,
More Information	1) “Examination of a Pressure Vessel that Ruptured at the Chicago Refinery of the Union Oil Company on July 23, 1984”, H. McHenry, T.R. Shives, D.T. Read, J.D. McColskey, C.H. Brady, and P.T. Purtscher, NBSIR 86-3049, National Bureau of Standards, Boulder, CO (1986). 2) “Analysis of the Catastrophic Rupture of a Pressure Vessel”, T. Siewert, NIST Publications. 3) “100 Largest Losses in the Hydrocarbon Industry”, Marsh Property Risk Consulting Practice, 27th Edition (2022).

Industry Sector	Process Type	Incident Type
Oil & Gas	Fluid Catalytic Cracking	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessel	Absorber

Incident Title	**Low Pressure Separator Catastrophic Failure**
Incident Type	Explosion and Fire
Date	22nd March 1987
Country	UK (Scotland)
Location	Grangemouth (Stirlingshire)

Fatalities	Injuries	Cost
1	0	US$ 107 m (2003) – Ref. 2

Incident Description  Credit: UK Health & Safety Executive	A hydrocracker unit (HCU) was being restarted after a spurious high reactor temperature trip. Hydrogen was circulating through the reaction section with hydrogen leak-off from the high pressure (HP) separator liquid outlet to the low pressure (LP) separator being regulated by 2 control valves. When the control valves were placed in manual mode, they opened fully and over-pressured the LP separator. The vessel suffered an explosive failure, releasing its contents to atmosphere as a cloud or mist which subsequently ignited. The force generated by the explosion was equivalent to 90 kg (198 lb) of TNT and large fragments from the disintegrated vessel were projected over 1 km (0.6 miles) away. A contract crane driver in the vicinity was killed. Fortunately, the incident occurred on a Sunday morning when there were far fewer personnel on site than a normal weekday and none of the fragments hit any personnel or vulnerable plant. Surface water drains partially blocked with waxy material were overwhelmed by the volume of firewater used to tackle the blaze, resulting in flooding of the area. Leaking petroleum spirit spread over a large area of the pooled water and several flash fires erupted in locations where the foam blanket was not complete or had separated.
Incident Analysis	**Basic cause** was overpressure and catastrophic failure of the LP separator vessel due to gas breakthrough from the upstream HP separator. **Critical factors** included: 1) The alarms on the HP separator extra-low level detection system failed (operators not alerted to imminent danger), 2) The low level trip system on the HP separator had been deliberately taken out of service (no automatic shutoff capability on liquid outlet), 3) The gas outlet line on the HP separator was isolated (valved closed) while the HCU was on standby with no feed to unit (PSV was only available route for gas disposal). **Root causes** included: 1) Inadequate design of HP separator liquid shutoff system (independent extra-low level detection and secondary shutoff valve) and LP separator PSV (not sized for gas breakthrough), 2) Inadequate heat tracing and insulation (extra-low level switches), 3) Failure to conduct a Management of Change (MoC) review (removal of HP separator low level trip), 4) Inadequate startup procedures and training (warmup and blow-through of inter-connecting pipework between HP and LP separators), 5) Inadequate safety management system (failure to ensure protective systems are maintained and tested), 6) Failure to learn (previous near miss incident).
Lessons Learned	1) The company urgently reviewed all HP/LP interfaces on worldwide assets and rectified deficiencies in overpressure protection, 2) Trip systems should only be disconnected after careful risk assessment and an MOC review have been completed to verify that alternative means are in place to adequately control the associated hazards. Also, the basis for the risk assessment should be properly documented and should highlight any conditions affecting validity of the change (eg. maximum duration).
More Information	1) "The Fires and Explosion at BP Oil (Grangemouth) Refinery Ltd.", Report of the Investigations by the Health & Safety Executive into the fire and explosion at Grangemouth and Dalmeny, Scotland, HSE Books (1989), ISBN 0 1188 5493 3. 2) "The 100 Largest Losses 1972 – 2001", Marsh Property Risk Consulting Practice, 20th Edition (2003).

Industry Sector	Process Type	Incident Type
Oil & Gas	Hydrocracker	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessel	Drum

Incident Title	**Flare Knockout Drum Outlet Line Rupture**
Incident Type	Explosion and Fire
Date	24th July 1994
Country	UK (Wales)
Location	Milford Haven (Pembrokeshire)

Fatalities	**Injuries**	**Cost**
0	26	US$ 154 m (2018) – Ref. 2

Incident Description  Credit: UK Health & Safety Executive	A lightning strike on the crude distillation unit (CDU) caused a fire, so the CDU and all other process units except the fluid catalytic cracker (FCC) were shut down. Approximately 5 hours later, amid the confusion of a cascade of alarms and attempts to restart the FCC wet gas compressor, the FCC flare knockout (KO) drum outlet line ruptured, releasing 20 tonnes (44,000 lbs) of flammable hydrocarbons which found an ignition source 110 m (360 ft) away and exploded. A major fire erupted at the FCC flare KO drum and several secondary fires ensued in adjacent units. The flare system was incapacitated by the explosion, so fires were allowed to burn themselves out over 2½ days. Fortunately, there were no fatalities (the explosion took place on a Sunday afternoon when very few people were on site). The site suffered severe damage to process plant, storage tanks and buildings. Properties in the nearest town 3 km (2 miles) away were also damaged. The refinery remained shut down for 9 weeks and took a further 9 weeks to restore full capacity.
Incident Analysis	**Basic cause** was rupture of a corroded DN 750 (30" NS) elbow on the FCC flare KO drum vapour outlet line due to liquid carryover and two-phase flow. **Critical factors** included: 1) The FCC debutaniser level control valve failed closed but the distributed control system (DCS) indicated it was open, 2) Control board operator was overwhelmed by alarm flood in an emergency situation, 3) The FCC flare KO drum automatic high-rate pumpout system to slops tankage had been modified years earlier to a low-rate recycle system to the FCC vapour recovery section to minimise hydrocarbon loss and reprocessing costs, 4) The FCC flare KO drum vapour outlet line was not designed for two-phase flow and had been weakened by internal corrosion. **Root causes** included: 1) Overpressure of the FCC debutaniser (blocked in due to level control valve failure), 2) Inadequate monitoring (DCS graphics did not provide the process overviews required to facilitate troubleshooting), 3) Inadequate warning systems (too many alarms, poorly prioritised), 4) Inadequate risk assessment (continuing operation of the FCC under extreme upset conditions), 5) Inadequate maintenance (defective control valve function and corroded flare header), 6) Inadequate Management of Change (FCC flare KO drum automatic pumpout system modification).
Lessons Learned	1) Control panel graphics should provide a process overview including mass and heat balance data, 2) Safety-critical alarms requiring immediate operator intervention should be prioritised and the necessary operator responses documented for each, 3) The total number of alarms should be limited to a quantity that the control board operator can effectively monitor, 4) All plant modifications (including emergency modifications) should undergo a formal hazard analysis, 5) Flare KO drums should be designed with critical high level alarms (LAHH) to promptly initiate removal of liquid slops at a high enough rate to prevent overfill of the drum and carryover to the flare header.
More Information	1) "The Explosion And Fires At The Texaco Milford Haven Refinery, 24th July 1994", Report of the Investigations by the Health & Safety Executive into the Explosion and Fires at the Pembroke Cracking Company Plant at the Texaco Refinery, Milford Haven", HSE Books, ISBN 0-7176-1413-1, (1997). 2) "The 100 Largest Losses 1978 – 2017", Marsh Property Risk Consulting Practice, 25th Edition (2018).

Industry Sector	**Process Type**	**Incident Type**
Oil & Gas	Fluid Catalytic Cracking	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Piping	Fittings (Elbow)

Safety & Loss Prevention Special Interest Group

Incident Title	**Naphtha Spill During Maintenance**
Incident Type	Fire
Date	23rd February 1999
Country	USA
Location	Avon (Martinez), CA

Fatalities	Injuries	Cost
4	1	Unknown

Incident Description

Credit: US Chemical Safety Board

A pinhole leak was discovered on a DN 150 (6" NS) pipe elbow in the naphtha sidedraw line of a crude distillation unit (CDU). The elbow was on the pipe (downstream) side of the CDU tower isolation valve 34.2 m (112' 3") above grade. Operators immediately attempted to isolate the leak while the CDU remained on stream by closing 4 valves. Subsequent inspection of the piping revealed significant thinning of the line, requiring a large section of pipe between the CDU naphtha sidedraw and its associated sidestripper to be replaced. Numerous unsuccessful attempts were made over the next 13 days to isolate and drain the corroded section of pipe. Low point drains at the sidestripper level control valve were found to be plugged.

On the day of the accident, more unsuccessful attempts were made to drain the line. A work permit was issued authorising workers to drain and remove the corroded section of pipe even though draining of the line could not be verified and the CDU was on stream. The maintenance supervisor directed workers to make 2 cuts in the pipe with a pneumatic saw. The first cut was 31.9 m (104' 6") above grade and was successful. The second cut 24.0 m (78' 7") above grade was stopped when naphtha started weeping out. The supervisor directed workers to open a flange in a vertical section of the pipe 11.6 m (38' 1") above grade. Naphtha leaking from the parted flange was collected in a plastic pan and removed via hose connection to a vacuum truck parked below. About 33 minutes later, naphtha started to blow through the open end at the top of the pipe and ignited (probably on hot equipment or piping). The resulting fire quickly engulfed 5 workers on the CDU tower and temporary scaffold structure, killing 4 workers and seriously injuring another.

Incident Analysis

Basic cause was ignition of naphtha released from process piping onto nearby hot surfaces while breaking containment during on-line maintenance.

Critical factors included: 1) The desalter was operating beyond its design limits (increasing water and corrosive salt carryover to the CDU tower), 2) The naphtha sidedraw line was extensively plugged and isolation valves passed, 3) The sidestripper level control bypass valve was routinely operated partially open, damaging its internals (allowing stripper to pressure up sidedraw line).

Root causes included: 1) Inadequate hazard identification (ignition source created by hot surfaces), 2) Inadequate preventative maintenance (corrosion management), 3) Inadequate risk assessment (valve leakage, line pluggage, inability to drain line), 4) Inadequate work planning (no escape routes from elevated workfaces), 5) Inadequate control of work (inappropriate permitry), 6) Poor judgement (allowing CDU to remain on stream), 7) Inadequate supervision (non-routine maintenance), 8) Inadequate management of change (desalter and sidestripper level control bypass valve operation), 9) Inadequate process safety management (failure to audit isolation procedure).

Lessons Learned

1) Management of change (MoC) reviews should be conducted when conditions change (crude composition, throughput etc), 2) Isolation, blinding and Lock out/Tag out (LOTO) procedures should be regularly audited, 3) Permit issuing authorities should be regularly re/trained and re/certified.

More Information

1) “Refinery Fire Incident”, US Chemical Safety and Hazard Investigation Board, Report No. 99-014-I-CA (2001).

Industry Sector	Process Type	Incident Type
Oil & Gas	Atmospheric Crude Distillation	Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment related	Not applicable	Not applicable

Incident Title	**Furnace Stack Collapse During Earthquake**	
Incident Type	Fire	
Date	17th August 1999	
Country	Turkey	
Location	Izmit (Kocaeli Province)	
Fatalities	**Injuries**	**Cost**
0	0	US$ 439 m (2021) – Ref. 3

Incident Description

Credit: Enric Marti/AP/Shutterstock

Following a magnitude 7.4 earthquake on the Richter scale, a 115 m (377 ft) high reinforced concrete crude distillation unit (CDU) charge furnace flue stack catastrophically failed and collapsed onto the furnace and a pipe rack, rupturing 63 product and utility lines and triggering a major fire. Concurrently, 4 floating roof naphtha storage tanks caught fire (which subsequently spread to 2 more tanks). Meanwhile, a smaller fire developed in a chemical storage warehouse when glass containers fell to the floor and smashed. The refinery's firefighting capability was lost because of electrical power failure and rupture of the water pipeline supplying all the refinery's water from a lake 45 km (28 miles) away. Fire tugs were sent to feed the fire main but it had been breached by earth movement and could not supply the tank farm area. Some fires burned for 5 days and had to be contained by aerial bombardment with foam. International support was needed to finally extinguish the fires.

Fortunately, there were no fatalities at the site. All process units were safely shut down and were undamaged (except the CDU) but 30 out of 45 floating roof tanks were damaged. During firefighting operations, large quantities of oily water leaked from tank bunds, spilled into the water drainage system, flooded the wastewater treatment plant (WWTP) and overflowed into the sea resulting in significant oil pollution. Lost production was ~ 6 months operation.

Incident Analysis

Basic cause was an earthquake which caused collapse of a CDU furnace stack (pipe ruptures), liquid sloshing and bouncing of floating roofs against walls of the naphtha tanks (sparking ignition) and breakage of glass chemical storage containers (spillage, mixing and exothermic chemical reaction).

Critical factors included: 1) Proximity to the epicentre of the earthquake, 2) Loss of electrical power (national grid infrastructure damage), 3) Loss of all telephonic communication systems (power failure), 4) Loss of water supply (pipeline ruptures), 5) Failure of CDU stack internal lining and concrete reinforcing bar splices (collapsing brick mass increased stress on stack shell).

Root causes included: 1) Inadequate design (backup fire water system), 2) Inadequate emergency planning (for "Natech" events), 3) Inadequate first response (insufficient personnel and equipment, road access compromised), 4) Inadequate disaster management (co-ordination of aid agencies).

Lessons Learned

1) Earthquakes can cause underground piping to become displaced and fail, 2) Portable diesel pumps with large bore hose connections and enough fire hose to reach the most remote process plant/storage tanks should be held on site to ensure adequate backup fire water supply from the sea, 3) All tanks containing flammable fluids in earthquake zones should have full coverage water sprinkler and foam systems with in-situ foam stocks, 4) Emergency response plans for sites in earthquake zones should consider total and immediate loss of all utilities with compromised telecommunications and road access, 5) Regular emergency response exercises ("gun drills") should be conducted covering "Natech" events and involving all refinery personnel.

More Information

1) www.nat-hazards-earth-syst-sci.net/11/1129/2011/
2) https://enatech.jrc.ec.europa.eu/view/natech/2
3) "100 Largest Losses in the Hydrocarbon Industry", Marsh Property Risk Consulting Practice, 27th Edition (2022).

Industry Sector	**Process Type**	**Incident Type**
Oil & Gas	Atmospheric Crude Distillation	Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Heaters & Boilers	Stack

Incident Title	**Deethaniser Overhead Line Rupture**
Incident Type	Explosion and Fire
Date	16th April 2001
Country	UK (England)
Location	South Killingholme (Lincolnshire)

Fatalities	Injuries	Cost
0	5	US$ 136 m (2018) – Ref. 3

Incident Description

Credit: UK Health & Safety Executive

The Deethaniser overhead line of a Saturated Gas Plant (SGP) suffered a catastrophic failure at an elbow immediately downstream of a washwater injection point. The release caused a huge vapour cloud which ignited after 20 – 30 seconds, resulting in a massive explosion and fire. The pressure wave from the blast caused widespread damage to houses and businesses within a 1 km radius of the site. Debris from the explosion was spread over a wide area including on an adjacent public highway. Some 10 – 15 minutes later, a second release occurred which also ignited and caused the fire to increase in size and intensity. Several other pressurised piping systems in the fire zone overheated and ruptured. The fire was brought under control within 70 minutes and was extinguished 5 hours and 40 minutes later. The damage to the SGP caused the refinery to be shut down for several weeks, followed by a phased startup.

Fortunately, the incident occurred on a public holiday when there were only 185 people on site rather than the normal weekday workforce of around 800 staff and contractors. Only a few people were outside when the explosion occurred because most were inside preparing for shift handover.

Incident Analysis

Basic cause was erosion-corrosion of an elbow at a point downstream and close to a water injection point that was not part of the original design.

Critical factors included: 1) Continuous rather than intermittent injection of washwater, 2) Absence of an injection quill or other atomising device and poor injection point pipe geometry (leading to erosion of the protective iron sulphide scale layer), 3) Absence of an in-service pipework inspection plan.

Root causes included: 1) Failure to conduct a Management of Change (MoC) review (continuous vs occasional washwater injection), 2) Inadequate design (injection point pipe geometry and absence of atomising device), 3) Inadequate communication (Operations failed to alert other groups when the washwater injection strategy was switched), 4) Inadequate corrosion management system (insufficient resources and failure to meet industry best practices for inspection and maintenance of piping at injection points).

Lessons Learned

1) Erosion-corrosion of carbon steel piping in sour service tends to be most pronounced high turbulence areas such as elbows and tees because erosion damages the protective internal iron sulphide scale layer, 2) Washwater injected into process piping should be via a quill or other atomising device in order to minimise erosion of the sulphide scale layer an atomising device or quill in order to minimise erosion of the sulphide scale layer, 3) API 570 ("In-service Inspection, Repair, and Alteration of Piping Systems") and NACE Publication 34101 ("Refinery Injection and Process Mixing Points") describe good practice for in-service inspection of injection points.

More Information

1) "Public Report of The Fire and Explosion at the ConocoPhillips Humber Refinery On 26th April 2001", Health & Safety Executive (2005): https://www.hse.gov.uk/comah/conocophillips.pdf
2) "Explosion at the Conoco Humber Refinery - 16th April 2001", J. Carter, P. Dawson and R. Nixon, IChemE Loss Prevention Bulletin 151 (2006).
3) "The 100 Largest Losses 1978 – 2017", Marsh Property Risk Consulting Practice, 25th Edition (2018).

Industry Sector	Process Type	Incident Type
Oil & Gas	Saturated Gas Plant	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Piping	Fittings (Elbow)

Incident Title	**Raffinate Splitter Liquid Overfill**	
Incident Type	Explosion	
Date	23rd March 2005	
Country	USA	
Location	Texas City (now Galveston Bay), TX	
Fatalities	**Injuries**	**Cost**
15	180	US$ 1.5 bn (2007) – Ref. 2

Incident Description

Credit: US Chemical Safety Board

A Raffinate Splitter was inadvertently overfilled with liquid during startup. As the splitter warmed up, the pressure rose and liquid puked into the overhead line. The pressure safety valves (PSVs) were located in the overhead line approximately 45 m (148 ft) below the top of the tower. The overfill created enough static head to cause the PSVs to lift, discharging a large quantity of light hydrocarbons to the unit blowdown drum which was connected to an atmospheric vent stack (not equipped with a flare). Most of the liquid released flowed to a closed sewer but some puked like a geyser from the top of the stack. The resulting vapour cloud found an ignition source and exploded. Fifteen people in or near temporary turnaround office trailers located close to the blowdown stack were killed and a further 180 were injured. A shelter-in-place order was issued requiring some 43,000 people to remain indoors.

Incident Analysis

Basic cause was light naphtha puking from an atmospheric blowdown stack, forming a vapour cloud which found an ignition source (probably idling diesel vehicle engine) and exploded.

Critical factors included: 1) Displacer-type level indicator (level appeared to drop as base temperature rose), 2) Faulty level alarms, 3) Failure to institute rundown before heatup, 4) Tower de-rated due to corrosion under insulation (lower PSV set pressure), 5) Poor trailer (temporary turnaround office) siting.

Root causes included: 1) Inadequate design (blowdown stack not connected to flare), 2) Inadequate hazard identification (reducing the PSV set pressure shrinks the safe operating envelope and increases the risk of liquid discharge to the blowdown vent stack), 3) Inadequate maintenance (level alarms), 4) Failure to follow and enforce pre-startup safety review (PSSR) procedure, 5) Failure to follow unit startup procedure (establish rundown before commencing heatup), 6) Poor communication (shift handover), 7) Inadequate operator training (troubleshooting), 8) Inadequate control of work (trailer siting), 9) Failure to learn (previous incidents).

Lessons Learned

1) Light hydrocarbons heavier than air should not be routed to atmospheric blowdown stacks, 2) Instruments and alarms should be tested and verified before startup, 3) Operating procedures should be kept up to date and strictly enforced (all deviations requiring MoC review), 4) Occupied portable buildings should be sited outside well-defined exclusion zones, 5) Vehicles should not enter potentially hazardous areas and should not be left running unattended, 6) Non-essential personnel should not be permitted on or near operating plant (especially during startup), 7) Leading and lagging process safety indicators should be used to drive performance improvement.

More Information

1) “The Report of the BP US Refineries Independent Safety Review Panel”, J.A. Baker, January 2007.
2) “Investigation Report - Refinery Explosion and Fire”, US Chemical Safety and Hazard Investigation Board, Report No. 2005-04-I-TX (2007).
3) “Failure to Learn - the BP Texas City Refinery Disaster”, Andrew Hopkins, CCH Australia Ltd., ISBN 978 1 921322 44 0 (2012).
4) “Management of Hazards Associated with Location of Process Plant Portable Buildings”, API RP-753, American Petroleum Institute (2007).
5) “Process Safety Indicators for the Refining and Petrochemical Industries”, API RP-754, American Petroleum Institute (2016).

Industry Sector	**Process Type**	**Incident Type**
Oil & Gas	Naphtha Splitter	Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Safety & Control	Instruments	Level

Incident Title	**Hydrocracker Reactor Nitrogen Asphyxiation**
Incident Type	Asphyxiation
Date	5th November 2005
Country	USA
Location	Delaware City, DE

Fatalities	Injuries	Cost
2	0	Unknown

Incident Description  Credit: US Chemical Safety Board	Two contract workers were preparing to "box up" a hydrocracker reactor by reinstating the piping inlet elbow at the top manway. The reactor was being purged with nitrogen (N_2) from a temporary supply and vented to atmosphere through the open manway. A roll of duct tape had inadvertently been dropped into the reactor, landing on a vapour/liquid distribution tray about 1.5 m (5 ft) below the manway opening. One of the workers tried recovering the duct tape from outside the reactor with a long wire hook but either fell in or climbed in to the reactor and passed out. A second worker hurriedly inserted a ladder and climbed into the reactor to attempt a rescue. A third worker approached the manway, observed the 2 workers lying motionless on the distribution tray, and radioed for emergency assistance. The stricken workers were recovered from the reactor, but both were unresponsive and could not be revived.
Incident Analysis	**Basic cause** of fatalities was deprivation of oxygen initially resulting in loss of co-ordination followed by loss of strength, and ultimately respiratory failure. **Critical factors** included: 1) Work permit did not mention nitrogen hazard and did not specify use of special breathing apparatus, 2) Warning sign did not mention nitrogen hazard, 3) Second worker attempted rescue of first worker without "fresh air" breathing equipment. **Root causes** included: 1) Inadequate hazard awareness (oxygen-deficient atmosphere also present above reactor manway opening), 2) Inadequate control of work (jobsite inspection and permitry), 3) Failure to follow safe rescue procedure (stay safe distance away and call for qualified rescue crew), 4) Inadequate company training programmes and industry good practices on hazards of oxygen-deficient atmospheres in and around confined spaces.
Lessons Learned	1) Nitrogen (N_2) is a colourless, odourless, tasteless, non-irritant gas at ambient conditions and can displace oxygen (O_2) in air. 2) Deprivation of oxygen can cause impaired perception and judgement, dizziness, nausea, loss of consciousness, coma, respiratory failure or death, depending on the extent of oxygen deficiency and duration of exposure. 3) Permit signatories should visit the job site to discuss hazards and controls. 4) Warning signs should be posted on any process equipment or piping being purged with nitrogen to alert personnel to the potential presence of a life-threatening oxygen-deficient atmosphere. 5) All access and egress points around vessels being purged with nitrogen should be barricaded and an access control system should be set up to log all personnel entering/leaving the barricaded area. 6) All personnel entering the barricaded area should wear a personal gas monitor with an audible and visible alarm set at 19% O_2 concentration. 7) Never enter a confined space alone to attempt rescue (misguided bravery resulted in death of would-be rescuers in 34 of 88 cases studied – Ref. 1). 8) Only properly trained personnel with all appropriate safety equipment and protection should attempt a rescue in oxygen-deficient atmospheres (refinery standard respiratory equipment is only suitable for use in unconfined spaces).
More Information	1) "Case Study: Confined Space Entry - Worker and Would-be Rescuer Asphyxiated", US Chemical Safety and Hazard Investigation Board (CSB), Report No. 2006-02-I-DE. 2) "Hazards of Nitrogen and Catalyst Handling", BP Process Safety Series, 6th Edition, IChemE (2006), ISBN: 978-0-85295-540-6.

Industry Sector	Process Type	Incident Type
Oil & Gas	Hydrocracker	Asphyxiation
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment-related	Not applicable	Not applicable

Incident Title	**Extractor Mixed Feed Line Rupture**	
Incident Type	Fire	
Date	16th February 2007	
Country	USA	
Location	Sunray, TX	
Fatalities	**Injuries**	**Cost**
0	4	Direct > US$ 50 m (2007) – Ref .1

Incident Description

Credit: US Chemical Safety Board

A leak of high pressure propane on a Propane Deasphalting (PDA) unit formed a large flammable vapour cloud which found an ignition source causing a series of jet fires and collapse of an elevated pipe rack which further fuelled the fire. Three employees and one contractor suffered serious burns and several others suffered minor injuries. The resulting damage forced the refinery to remain shutdown for just under 2 months. It then operated at reduced capacity for nearly 1 year.

The intensity of the fire resulted in blistering of the paint on the surface of a neighbouring butane storage sphere and prevented emergency responders reaching the fire water deluge valves provided to protect the sphere from overheating due to fire exposure. If the wind direction had been different and flames had impinged directly on the sphere or if the sphere had been exposed to significant overheating for an extended duration, there could easily have been a catastrophic rupture of the sphere and a major explosion. Furthermore, one of the jet fires caused a large release of highly toxic chlorine gas stored in pressurised cylinders near the PDA unit (used as biocide in cooling water). Fortunately, first responders and all other refinery personnel had already been evacuated from the refinery by then.

Incident Analysis

Basic cause was a freeze-related rupture of an elbow below an isolation valve at a control valve station on 1 of 2 propane feed lines to the Extractor Tower which had been taken out of service some 15 years earlier.

Critical factors included: 1) An isolation valve at the redundant control valve station was passing due to a piece of metal debris trapped between its gate and seat, 2) Absence of positive isolation of the dead-leg from the propane supply system, 3) Absence of fireproofing on steel support columns of the elevated pipe rack some 23 m (77 ft) away, 4) Absence of remote-operated emergency block valves (EBVs).

Root causes included: 1) Failure to conduct a management of change review (removing control valve station from active service), 2) Inadequate process hazard analysis (failure to adequately engage operating staff), 3) Inadequate risk assessment (fire exposure from neighbouring process plant), 4) Inadequate design (absence of remote-operated EBVs and structural steel fireproofing), 5) Inadequate freeze protection practices (including periodic inspection of dead-legs and infrequently-used piping and equipment).

Lessons Learned

1) Process units and piping systems should be systematically reviewed and field-checked to identify presence of dead-legs, 2) Dead-legs should be eliminated (by design) or removed (by positive isolation with blinds); if this is impractical, freeze protection should be provided or (as a last resort) regular monitoring and draining of low points should be implemented, 3) Remote-operated emergency block valves (EBVs) can help control large accidental releases of flammable materials, 4) Pressurised storage vessel water deluge valves should be located where they are accessible in an emergency, 5) Inherently safer biocide chemicals should be used instead of pressurised chlorine gas to prevent microbial fouling in refinery cooling water systems.

More Information

1) "LPG Fire at Valero McKee Refinery", US Chemical Safety and Hazard Investigation Board, Report No. 2007-05-I-TX (2008).

Industry Sector	**Process Type**	**Incident Type**
Oil & Gas	Propane Deasphalting	Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Piping	Pipe

Incident Title	**Catastrophic Heat Exchanger Shell Rupture**
Incident Type	Explosion and Fire
Date	2nd April 2010
Country	USA
Location	Anacortes, WA

Fatalities	Injuries	Cost
7	0	Unknown

Incident Description

Credit: US Chemical Safety Board

A Naphtha Hydrotreater (NHT) Feed/Effluent Exchanger train comprised 2 parallel banks of 3 stacked shells in series. One of the two banks was being placed back in service after off-line cleaning and inspection. The procedure for this "restreaming" operation includes gradual and concurrent operation of several large isolation valves, requiring the help of several Operations personnel. While the restreaming operation was taking place, the carbon steel (CS) shell of the middle exchanger of the adjacent "in-service" bank of 3 exchangers ruptured catastrophically along the seam welds of the shell. The rupture caused a massive release of hot hydrogen and naphtha which auto-ignited and exploded. Seven employees working in the immediate vicinity of the exchangers were fatally injured.

Incident Analysis

Basic cause was a loss of primary containment due to rupture of the carbon steel shell caused by high temperature hydrogen attack (HTHA) at a point just downstream of the internal 316 SS partial lining.

Critical factors included: 1) Inaccurate Nelson curve for carbon steel (this curve predicts susceptibility to HTHA as a function of process temperature and hydrogen partial pressure based on observed industry experience), 2) The shell had been in service for a cumulative total of 38 years when it failed, 3) High residual stresses were present in the seam welds of the shell due to lack of post-weld heat treatment (PWHT), 4) The reactor feed side (tubeside) of the exchanger had a history of significant fouling (resulting in higher shell temperatures), 5) There was no instrumentation on either the inlet or outlet stream of the intermediate shells, 6) Additional Operations personnel were present to assist in restreaming (multiple large isolation valves).

Root causes included: 1) Inadequate process safety management system (required proof of danger rather than proof of effective risk mitigation), 2) Inadequate process monitoring (inadequate thermometry), 3) Inadequate process hazard analysis (design parameters used for assessing HTHA susceptibility rather than actual operating conditions), 4) Failure to apply inherently safer design principles (Cr-Mo alloy steels have greater resistance to HTHA), 5) Inadequate regulatory oversight (no requirement for adopting Safety Case methodology or applying inherently safer design principles).

Lessons Learned

1) The Nelson curve for carbon steel has been revised.
2) HTHA is most likely in heat affected zones (HAZs) around welds.
3) Gradual changes to operating conditions (e.g. heat exchanger fouling or catalyst deactivation) may lead to an accidental breach of operating limits.
4) Abnormal (transient) operating conditions (e.g. startup, fouling, shutdown, etc) can create major process safety hazards.
5) For CS and C-0.5 Mo steel in hydrogen service, the safe operating limit should be > 28 °C (50 °F) and > 3.5 bar (50 psi) below the new Nelson curve.
6) Refinery equipment and piping susceptible to HTHA should be replaced with inherently safer materials (e.g. low Cr-Mo alloys) to mitigate the risk.

More Information

1) "Catastrophic Rupture of Heat Exchanger", US Chemical Safety and Hazard Investigation Board (CSB), Report No. 2010-08-I-WA (2014).
2) "Rupture of a Heat Exchanger at a Refinery Causes Fatalities", T. Fishwick, IChemE Loss Prevention Bulletin 228 (December 2012).
3) "API RP 941 Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants" (2016).

Industry Sector	Process Type	Incident Type
Oil & Gas	Naphtha Hydrotreating	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Heat Exchanger	Shell & Tube

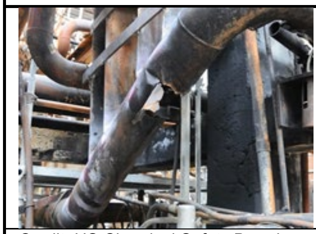
Incident Title	**Multiple LPG Storage Tanks Rupture After Earthquake**	
Incident Type	Fire and Explosion	
Date	11th March 2011	
Country	Japan	
Location	Chiba	
Fatalities	**Injuries**	**Cost**
0	6	Unknown

Incident Description  Credit: Newscom/Alamy Stock Photo	On 11-Mar-11, a massive earthquake measuring magnitude 9.0 on the Richter scale occurred off the east coast of Japan, triggering a huge tsunami. Both the earthquake (known as the Tohoku earthquake) and the tsunami were of unexpected severity, leaving a trail of destruction affecting multiple high hazard installations (including the Fukushima Daiichi nuclear power plant). Ground motion from the earthquake damaged support braces on a Liquified Petroleum Gas (LPG) storage sphere (Tk 364). The tank was undergoing regulatory inspection at the time and had been filled with water to exclude air and check for leakage. An aftershock 29 minutes later caused its support legs to buckle, and the tank collapsed onto a neighbouring pipe track. An uncontrolled LPG release followed which found an unknown ignition source, initiating a major fire. The fire quickly spread to neighbouring LPG tanks causing several consecutive boiling liquid expanding vapour explosions (BLEVEs), eventually destroying all 17 tanks in the LPG tank farm. Burning missiles from the explosions also damaged nearby asphalt tanks, causing a loss of containment and spillage into the sea. The sea wall prevented the tsunami inundating the site, but the flammable LPG vapour release started fires in 2 neighbouring chemical plants (domino escalation). It took 10 days to extinguish the fires and 2 years to restore the refinery to full production.
Incident Analysis	**Basic cause** was failure of the support legs of LPG storage sphere (Tk 364) to withstand the ground acceleration forces of a severe earthquake. **Critical factors** included: 1) Sometime before the earthquake struck, an automatic emergency block valve (EBV) on an LPG pipe had been locked open pending repair to an air supply line to its actuator, 2) Tk 364 had been full of water for 12 days when the earthquake struck (increased vulnerability due to 1.8 times higher density of water versus LPG), 3) Tk 364 collapsed onto an adjacent pipe rack (causing a release of LPG and fire), 4) The locked open EBV was not manually closed in the 29 minutes between the earthquake and aftershock (allowed leaking LPG to continuously fuel the fire), 5) Initial firefighter response was delayed (poor communication and traffic chaos). **Root causes** included: 1) Violation of regulations (EBV locked open), 2) Inadequate seismic design (failure to account for higher vulnerability to seismic damage when tank is filled with water), 3) Inadequate maintenance planning (tank water-full for 12 days versus expected 2 to 3 days), 4) Inadequate inspection, 5) Tight equipment spacing (LPG tank farm), 6) Poor land use planning (neighbouring chemical plants too close to refinery), 7) Creeping change (ageing plant, structural decay due to earlier seismic activity)
Lessons Learned	1) Support legs and braces on pressurised gas storage tanks in earthquake zones should be reinforced to enable them to cope with seismic effects. 2) Safety Management Systems should include emergency response plans to deal with natural hazard ("Natech") triggers (eg. earthquake and tsunami). 3) Regular exercises ("gun drills") should be carried out practising quickly extinguishing fires with telecommunications and access routes compromised.
More Information	1) https://enatech.jrc.ec.europa.eu/download/attachment/24 2) https://enatech.jrc.ec.europa.eu/view/natech/14 3) "Impact of 11 March 2011, Great East Japan Earthquake and Tsunami on the Chemical Industry", E. Krausmann & A-M. Cruz, Nat Hazards 67, (2013).

Industry Sector	**Process Type**	**Incident Type**
Oil & Gas	Liquified Gas Storage	Fire & Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessel	Storage Sphere

Incident Title	**Light Gas Oil Sidedraw Line Rupture**
Incident Type	Explosion
Date	6th August 2012
Country	USA
Location	Richmond, CA

Fatalities	Injuries	Cost
0	26	Unknown

Incident Description  Credit: US Chemical Safety Board	The light gas oil (LGO) sidedraw from a crude distillation unit (CDU) experienced a catastrophic pipe rupture, releasing a large volume of hot LGO to grade. The hot LGO partially vapourised and formed a large vapour cloud which engulfed 19 company employees. Approximately 2 minutes after the rupture occurred, the fluid ignited. Eighteen employees managed to escape from the vapour cloud before it ignited; the other was engulfed in the fireball but was wearing full-body firefighting protective equipment and managed to make his way to safety. Six employees suffered minor injuries during the incident and subsequent emergency response activity. A large plume of vapour, particulates and black smoke travelled across the surrounding area and approximately 15,000 people from neighbouring communities sought medical treatment over the next few weeks for a range of ailments such as breathing problems, chest pains, sore throats and headaches. Twenty of these were admitted to local hospitals for treatment as inpatients.
Incident Analysis	**Basic cause** was rupture of the LGO sidedraw piping caused by wall thinning due to high temperature sulphidation corrosion (HTSC). **Critical factors** included: 1) Firefighters removed insulation from the leaking pipe to enable Operations and Maintenance specialists to determine if an on-line repair using a pipe clamp was feasible or if a unit shutdown would be required (the leak could not be isolated), 2) Failure to identify high corrosion rates in unmonitored low silicon (Si) carbon steel straight-run piping (due to corrosion measurement locations being located in high-Si fittings), 3) The relatively close proximity of local housing to the refinery perimeter fence. **Root causes** included: 1) Inadequate design standards (ASTM A53B and other design codes used before 1985 did not specify a minimum Si content for carbon steel pipe), 2) Inadequate material selection (low Si carbon steel), 3) Failure to implement industry-recognised HTSC risk mitigation measures (conducting 100% component inspection on all high temperature carbon steel piping susceptible to sulphidic corrosion or upgrading to inherently safer materials of construction such as 5 Cr/0.5 Mo steel), 4) Inadequate risk assessment (allowing continued operation despite inability to isolate leaking pipe and failing to restrict the number of personnel entering a hazardous area), 5) Inadequate land use planning (close proximity of local housing).
Lessons Learned	1) In the absence of hydrogen, the rate of sulphidation corrosion depends on many factors such as concentration and type of sulphur compounds, fluid temperature and fluid flow rate, 2) Hydrogen sulphide (H_2S) is the most active sulphur species from corrosion perspective and sulphidic corrosion rates increase rapidly above 260 °C (500 °F), especially for carbon steel, 3) Carbon steels with silicon content of < 0.10 wt% are especially susceptible and can corrode at accelerated rates up to 16 times faster than carbon steel with a high Si content, 4) High chrome alloys offer excellent resistance to HTSC and are inherently safer than carbon steels when operating at temperatures above 260 °C (500 °F).
More Information	1) "Chevron Richmond Refinery Pipe Rupture and Fire", US Chemical Safety and Hazard Investigation Board, Report No. 2012-03-I-CA (2015). 2) API RP 939-C: Guidelines for Avoiding Sulfidation (Sulfidic) Corrosion Failures in Oil Refineries, 1st edition, Section 3.1.6, May 2009.

Industry Sector	Process Type	Incident Type
Oil & Gas	Atmospheric Crude Distillation	Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Piping	Pipe

Incident Title	**Electrostatic Precipitator Explosion**
Incident Type	Explosion
Date	18th February 2015
Country	USA
Location	Torrance, CA

Fatalities	Injuries	Cost
0	4	Unknown

Incident Description  Credit: US Chemical Safety Board	On 16-Feb-15, the Fluid Catalytic Cracker (FCC) unit's regenerator flue gas expander tripped, initiating the automatic safeguarding system which placed the FCC unit in "safe park" (standby) mode. This automatically stops feed and starts steam injection to the FCC reactor riser, closes the safety-critical spent and regenerated catalyst slide valves (RCSV and SCSV, respectively) and trips the main air blower. The FCC main fractionator pumparound (heat removal) circuits continue circulating oil. Reverse flow of hydrocarbon vapour from the FCC main fractionator to the air-containing atmosphere of the FCC regenerator in safe park mode is prevented by injecting sufficient riser and stripping steam to maintain FCC reactor pressure > FCC main fractionator pressure and by maintaining catalyst seals above the RCSV and SCSV. On 18-Feb-15, the FCC unit was in "safe park" mode pending cleaning of the expander (which was not positively isolated). Steam was escaping from the open outlet flange, so FCC reactor steam flow was reduced to stop it. Around 2 hrs later, an explosion occurred in the FCC electrostatic precipitator (ESP), severely damaging it and nearby equipment. Shrapnel projectiles came close to puncturing 2 vessels on the adjacent Modified Hydrofluoric Acid Alkylation (MHFA) unit which contained a large inventory of extremely toxic hydrofluoric (HF) acid. Fortunately, there were no fatalities, but 4 contractors suffered minor injuries while fleeing the explosion area and required first aid treatment.
Incident Analysis	**Basic cause** was ignition of a flammable mixture of hydrocarbon vapours (backflowing from the FCC fractionator and reactor) and combustion air (from the CO Boiler auxiliary air blowers) due to presence of sparks within the ESP. **Critical factors** included: 1) The ESP remained energised in safe park mode (potential ignition source), 2) Significant erosion of SCSV internals (loss of catalyst seal), 3) FCC riser steam flow reduced to manage steam release at expander (FCC reactor pressure < FCC main fractionator pressure), 4) Slurry pumparound exchanger tube failure (light hydrocarbon leakage caused abnormally high FCC main fractionator pressure in safe park mode), 5) Low FCC regenerator temperature in safe park mode (hydrocarbons not burned). **Root causes** included: 1) Inadequate process hazard analysis (possibility of hydrocarbons entering ESP was not considered when designing safe park safeguard system), 2) Inadequate inspection frequency (excessive RCSV and SCSV internal erosion), 3) Inadequate process monitoring (RCSV and SCSV differential pressures), 4) Inadequate risk assessment (re-validation of 2012 variance of expander isolation procedure), 5) Inadequate leadership (failure to enforce refinery isolation standards).
Lessons Learned	1) Safety-critical equipment must be properly maintained, 2) All modes of operation (including "safe park") should be considered during process hazard analysis studies, 3) Electrical power to FCC electrostatic precipitators should be isolated if there is a risk of a combustible/explosive mixture entering.
More Information	1) "Electrostatic Precipitator Explosion; Torrance, California", US Chemical Safety and Hazard Investigation Board, Report No. 2015-02-I-CA (2017). 2) "Managing Risk in Major Maintenance – A Case Study on Fire and Explosion Incidents in the Process Industry", A. Musthafa, IChemE Loss Prevention Bulletin 268 (August 2019).

Industry Sector	Process Type	Incident Type
Oil & Gas	Fluid Catalytic Cracking	Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessel	Electrostatic Precipitator

Incident Title	**Multiple LPG Storage Tank Ruptures**	
Incident Type	BLEVE	
Date	19th November 1984	
Country	Mexico	
Location	San Juan Ixhuatepec, HG	
Fatalities	**Injuries**	**Cost**
542	4,248 (Kletz)	US$ 29 m* (2001) – Ref. 3

Incident Description

Credit: Sipa/Shutterstock

A DN 200 (8" NS) liquified petroleum gas (LPG) transfer line ruptured at a state owned and operated storage/distribution terminal while being filled from a refinery 400 km (250 miles) away. The leaking LPG formed a vapour cloud which spilled over the bund walls which surrounded the pressurised storage vessels (spheres and bullets) and migrated towards a ground flare. The flame front accelerated back towards the leak source. Several pool fires erupted, causing a series of catastrophic boiling liquid expanding vapour explosions (BLEVEs) which blew many of the vessels off their supports. The first BLEVE occurred 15 minutes after the initial release. Burning LPG liquid rained down on the neighbouring shanty town which had expanded to 130 m (427 ft) from the terminal fence. The official death toll was 542 with 4,248 injured but unofficial estimates were higher (shanty town population unknown). Around 200,000 people had to be evacuated and ~ 10,000 people became homeless.

Incident Analysis

Basic cause was a loss of primary containment (LOPC) due to overpressure of an LPG transfer pipe or overfilling of a pressurised storage vessel (exact cause unknown as much of the physical evidence was destroyed by fire).

Critical factors included: 1) Defective level instrumentation, 2) Inadequate spacing between LPG storage vessels, 3) Storage vessels were surrounded by 1 m high concrete walls (allowing LPG to accumulate where most harmful), 4) Absence of passive fire protection (eg. gas detectors, storage vessel and support fireproofing), 5) The firewater system was disabled in the initial blast, 6) Proximity of housing to the terminal perimeter, 7) Arrival of the emergency services was delayed by traffic chaos as panicked residents tried to flee.

Root causes included: 1) Inappropriate design (no gradient in bunded area below storage vessels to prevent pooling, inadequate vessel spacing and vulnerable above-ground firewater system), 2) Inadequate safeguards (absence of overfill protection, gas detectors and fireproofing of vessels and supports), 3) Inadequate management of change (relief capacity not raised when LPG fill rate increased), 4) Inadequate maintenance (instrumentation), 5) Inadequate operator training (ESD system initiated too late), 6) Inadequate emergency response planning (emergency vehicle access and evacuation routes), 7) Inadequate land use planning (shanty town too close to terminal).

Lessons Learned

1) Escalation impact studies should be carried out to inform plant design (eg. plant layout, equipment spacing, active/passive fire protection, etc).
2) LPG bulk storage vessels should be equipped with remote-operated emergency isolation valves (EIVs) to minimise inventory loss in case of pipe rupture. EIV actuators should be designed so that the valves cannot close too quickly and create a pressure surge through hydraulic hammer.
3) High hazard installations should have designated emergency access and egress routes available which should be regularly inspected and tested.
4) Land use planning regulations specifying minimum separation distances between high hazard facilities and residential buildings should be enforced.

More Information

1) "Analysis of the LPG Disaster in Mexico City", C.M. Pietersen, TNO, Apeldoorn, Netherlands.
2) API Standard 2510: "Design and Construction of LPG Installations", 9th Edition, American Petroleum Institute (2020).
3) "The 100 Largest Losses 1972 – 2001", Marsh Property Risk Consulting Practice, 20th Edition (2003). [* First party property damage cost only]

Industry Sector	Process Type	Incident Type
Oil & Gas	Pressurised Gas Storage	BLEVE
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Piping	Pipe

Incident Title	**Gasoline Storage Tank Overfilled**
Incident Type	Explosion and Fire
Date	11th December 2005
Country	UK (England)
Location	Buncefield (Hertfordshire)

Fatalities	**Injuries**	**Cost**
0	43	£ 894 m (2008) – Ref. 1

Incident Description

Credit: UK Health & Safety Executive

A gasoline (petrol) tank at an oil storage and distribution terminal was overfilled with gasoline (petrol) which subsequently overflowed into a bund. A large vapour cloud formed and eventually flowed over the bund wall. Multiple explosions occurred and the resulting major fire engulfed 20 large storage tanks. Large clouds of black smoke from the burning fuel spread over southern England and beyond. The fire burned for 5 days, destroying most of the terminal and damaging surrounding homes and business premises. Fortunately, there were no fatalities (probably because the explosion took place in the early hours of a Sunday morning when very few people were on site). However, 43 people suffered minor injuries and approximately 2000 people had to be evacuated from the area. Firewater, foam and fuel product runoff from the site caused pollution of an underlying potable water aquifer.

Incident Analysis

Basic cause was a loss of primary containment (LOPC) due to failure of the servo-type level sensor used by the automatic tank gauging system and the digital high level switch used by the automatic high level shutdown system.

Critical factors included: 1) The automatic tank gauging (ATG) system operator interface only had a single display screen, 2) The independent high level switch (IHLS) failed to operate (test arm had not been locked in "operate" position), 3) The incident occurred in cold, still conditions (low-lying vapour cloud, not well-dispersed), 4) Flexible sealant joints between sections of concrete tank bund failed on fire exposure, 5) The site drain and catchment system was only designed for containment of rainwater and minor spills.

Root causes included: 1) Inadequate operating procedures (tank filling), 2) Inadequate monitoring of tank inventories (ATG control system graphics), 3) Inadequate management of change (IHLS replacement and changes to tank bund design during construction), 4) Inadequate maintenance (ATG servo level sensor sticking and IHLS test arm lock criticality not understood), 5) Inadequate maintenance management system (defect logging), 6) Human factors (staff under pressure due to terminal throughput creep reducing ullage and inability to control flow/timing of pipeline receipts), 7) Inadequate design of secondary (bunds) and tertiary (drain/catchment) containment systems, 9) Inadequate emergency planning (major spill and multi-tank fire response).

Lessons Learned

1) Severe vapour cloud explosions can occur in open areas in still (nil-wind) conditions; this may be the dominant risk for liquid fuel storage terminals.
2) Risk assessments should consider potential worst-case scenarios involving multiple tank/bund fires and large volumes of firewater run-off.
3) Bunds should be treated as safety-critical equipment and regularly inspected (and repaired if necessary) to assure their integrity,
4) Tertiary containment (eg. drainage) should be designed to cope with a large-scale spill so runoff is contained on site and pollution is prevented.

More Information

1) "The Buncefield Incident 11 December 2005: Report of the Major Incident Investigation Board Volume 1", HSE Books, 2008, ISBN 978-0-7176-6270-8.
2) "Safety and Environmental Standards for Fuel Storage Sites", Process Safety Leadership Group, HSE Books, 2009, ISBN 978-0-7176-6386-6.
3) "Buncefield: Why Did It Happen", COMAH Competent Authority, 2011, https://www.hse.gov.uk/comah/buncefield/buncefield-report.pdf.
4) "Managing Risk: The Hazards That Can Destroy Your Business", COMAH Strategic Forum, 2017.

Industry Sector	**Process Type**	**Incident Type**
Oil & Gas	Oil Storage	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Safety & Control	Instruments	Level

Incident Title	**Gasoline Storage Tank Overfilled**
Incident Type	Explosion and Fire
Date	23rd October 2009
Country	Puerto Rico
Location	Bayamón

Fatalities	Injuries	Cost
0	3 (offsite)	Unknown

Incident Description

Credit: US Chemical Safety Board

An above-ground storage tank overfilled with gasoline (petrol) during a night-time unloading operation from a ship berthed 3 km (2 miles) away. Nearly 790 m^3 (5,000 bbl) of gasoline overflowed into a secondary containment bund. The resulting large vapour-mist cloud found an ignition source in the nearby wastewater treatment plant, leading to a vapour cloud explosion (deflagration). The resulting fire caused multiple secondary explosions, destroying 17 of the 48 tanks on site and damaging neighbouring businesses and homes. The fire burned for ~ 66 hours and significant environmental damage was inflicted by petroleum product and firewater/foam runoff. The operating company filed for bankruptcy in August 2010.

Incident Analysis

Basic cause was incorrect estimation of tank fill-time due to failure of the automatic tank gauging system.

Critical factors included: 1) The volume of the ship's gasoline cargo exceeded the capacity of any single available tank (requiring filling of multiple tanks), 2) Tank farm operators had to estimate tank fill times based on hourly level checks (using unreliable float and tape gauges) and adjust flow rate by manually adjusting tank fill valves, 3) The tanks had no independent high level alarm instrumentation, 4) The tank bund drain valves had inadvertently been left open (reported closed in valve inspection log), 5) The site topography allowed gasoline leaking from the bund drain to flow to the wastewater treatment plant area (which contained electrical equipment not rated for flammable atmospheres), 6) The tank farm lighting was inadequate (operators were unable to see the liquid overflow and resulting vapour cloud).

Root causes included: 1) Inadequate design (absence of independent high level alarms and automatic overfill protection system to stop product transfer) and use of inconsistent bund drain valve types (fixed stem and rising stem) making visual determination of valve position difficult, 2) Inadequate tank monitoring and control (manual operation), 3) Inadequate preventative maintenance (level sensors, transmitters and automatic tank gauging system), 4) Inadequate tank fill procedure, 5) Inadequate hazard awareness (failure to learn from similar incidents), 6) Inadequate emergency response planning (training, resources, mutual aid cover), 7) Inadequate emergency response capability (insufficient equipment to deal with multi-tank fire).

Lessons Learned

1) Safety integrity level (SIL) reviews should be conducted on all gasoline tanks in liquid fuel storage terminals to check if automatic overfill protection systems (fully independent of their tank gauging systems) are required.
2) Risk assessments should consider potential worst-case scenarios involving multiple tank/bund fires with large volumes of firewater run-off and review lessons learned from other liquid fuel storage terminal major incidents.
3) Severe vapour cloud explosions can occur in open areas in calm wind conditions; this may be the dominant risk for liquid fuel storage terminals.

More Information

1) "Caribbean Petroleum Tank Terminal Explosion and Multiple Tank Fires", US Chemical Safety and Hazard Investigation Board, Report No. 2010.02.I.PR (2015).
2) "Safety and Environmental Standards for Fuel Storage Sites", Process Safety Leadership Group, HSE Books, 2009, ISBN 978-0-7176-6386-6.
3) "Managing Risk: The Hazards That Can Destroy Your Business", COMAH Strategic Forum, 2017.

Industry Sector	Process Type	Incident Type
Oil & Gas	Oil Storage	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Safety & Control	Instruments	Level

IChemE
Nuclear Technology
Special Interest Group

Process Safety in the Nuclear Energy Sector

"The history of commercial nuclear energy production is intrinsically linked to the desire to harness atomic science in the pursuit of atomic weapons production which began during World War Two. From the first self-sustaining fission reactor built in a squash court led by Enrico Fermi in 1942 to the use of nuclear weapons only three years later, the speed of development and understanding of fundamental nuclear principles was greatly accelerated by military requirements.

Post-war efforts focused on peaceful use for atomic energy with the 'Atoms for Peace' programme being enacted by President Eisenhower in 1953, which reoriented significant research effort towards electricity generation and set the course for civil nuclear energy development in the USA. Other countries continued to develop nuclear technologies for energy generation with nuclear power reactors being brought on-line by many nations, fuelled and funded primarily by government mandates.

The case studies presented in this document outline the potential dangers associated with nuclear energy with consequences which are apparent from the initial uses of the technology. After Three Mile Island (1979) and Chernobyl (1986), public support for nuclear energy fell, bringing sharp focus to the risks associated with incorrectly operating in a nuclear environment. The incident at Fukushima (2011) further engrained public distrust in the technology with political support following suit.

In reaction to the growth of nuclear energy, as well as nuclear incidents, organisations such as the International Atomic Energy Agency (IAEA), World Association of Nuclear Operators (WANO) and the Nuclear Energy Agency (NEA) have since been set up around core principles of supporting safe nuclear operations and co-operation between member states.

The role of Chemical Engineers in the safe design, construction, operation and decommissioning of nuclear power stations (both current and future), as well as the associated fuel cycle and final disposition of radioactive material cannot be understated. As such, it is incumbent on us to ensure that lessons learned help us to shape and guide the nuclear industry.

There are more than 400 operable nuclear power reactors in over 30 countries as of 2021, with the number due to increase over the coming decades. As governments look to de-carbonise their economies, use of nuclear energy will only become more important in the years to come, with emerging nuclear technologies such as Small Modular Reactors (SMRs) and Molten Salt-cooled Reactors (MSRs) supporting the drive to Net Zero by 2030 or sooner."

Felipe Basaglia CEng MIChemE MNucl
Chair of IChemE Nuclear Technology Special Interest Group

Incident Title	**Nuclear Reactor Partial Meltdown**
Incident Type	Near Miss
Date	28th March 1979
Country	USA
Location	Three Mile Island, PA

Fatalities	Injuries	Cost
0	0	US$ 973 m (2012) – Ref. 2

Incident Description

Credit: Wikimedia Commons

The main feedwater pump on the secondary (non-nuclear side) cooling system supplying the steam turbine-generator failed. As no heat was being removed from the circuit, the reactor pressure began to rise until a pilot-operated pressure relief valve (PRV) on the primary (nuclear side) reactor cooling system lifted. This initiated an automatic shutdown of the pressurised water reactor (PWR) and steam turbine-generator 8 seconds later. However, the PRV failed to reseat and continued to discharge water to a relief tank for more than 2 hours. Instrumentation in the control room implied that the PRV was closed and appeared to indicate that too much water was being injected into the reactor vessel. Consequently, operators did not replace the water that was lost as a result of the PRV opening. The loss of coolant caused the upper portion of the reactor core to become uncovered and overheat. Attempts to restart the reactor cooling system were hindered by the large quantity of steam and non-condensable hydrogen present in the reactor. This was vented into the containment building via the relief tank overflow. Officials only publicly declared an emergency 2 hours 50 minutes into the accident.

Incident Analysis

Basic cause was overheating of the pressurised water reactor (PWR) core due to failure of feedwater pump and consequent loss of coolant.

Critical factors included: 1) The pilot-operated PRV on the PWR cooling system failed to close, 2) The backup emergency cooling water system was not in service due to maintenance activity and the secondary backup system was not available due to failure to correctly reset an isolation valve after regulatory testing of the system a few days earlier, 3) Inability of the control room operators to identify the loss of coolant level surrounding the reactor core, 4) The primary cooling water circuit piping arrangement created siphon loops which became vapour locked and prevented convection cooling.

Root causes included: 1) Inadequate design (relatively small elevation difference between reactor and steam generator created siphon loops in the cooling water circulation line), 2) Inadequate instrumentation (relief tank water level indicator and absence of reactor cooling system PRV position indicator – a "command to close" signal is not an adequate proxy), 3) Too many alarms (poorly prioritised), 4) Inadequate emergency response training, 5) Inadequate communication (late alerting of local and state authorities).

Lessons Learned

1) The industry recognised that core melt, previously considered utterly improbable, was possible, 2) The critical role of human performance in plant safety was also recognised, 3) High temperature oxidation of the zirconium alloy cladding on fuel rods can generate hydrogen, 4) The US Nuclear Regulatory Commission (NRC) upgraded rules on operator training, plant design and emergency response planning, 5) The NRC requires regular external audits and has robust enforcement practices, 6) The industry established the Institute of Nuclear Power Operations (INPO) to promote excellence in training, plant management and operations.

More Information

1) "President's Commission on the Accident at Three Mile Island. 1979: The Need for Change", Washington, D.C., U.S. Gov Printing Office.
2) WNA Fact Sheet (https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/three-mile-island-accident.aspx).
3) "Lessons From the 1979 Accident at Three Mile Island", Nuclear Energy Institute (NEI), October 2019.

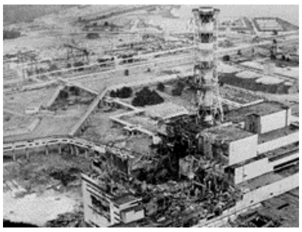
Industry Sector	Process Type	Incident Type
Power Generation	Nuclear	Near Miss
Equipment Category	**Equipment Class**	**Equipment Type**
Safety & Control	Valves – Safety	PSV – Pilot Operated

IChemE Safety & Loss Prevention Special Interest Group

Incident Title	**Nuclear Reactor Temperature Runaway**
Incident Type	Explosion
Date	26th April 1986
Country	Ukraine (formerly part of Soviet Union)
Location	Chernobyl

Fatalities	Injuries	Cost
31	~ 7000	Unknown

Incident Description



Credit: Wikimedia Commons

The Chernobyl nuclear power plant had 4 operating thermal neutron RBMK ("Reactor Bolshoy Moshchnosty Kanalny") reactors moderated by a graphite stack. The core was cooled by water circulating through zirconium-niobium pressure tubes (the water also acted as a neutron absorber). The power level in the core was controlled by boron carbide absorber rods with graphite tips. At the time of the accident, a test was being conducted on an off-line reactor to determine whether the power generated during spindown of the turbo-generator by its own inertia would be sufficient to power the reactor coolant pumps in the event of a loss of external electrical power, thereby providing more time for the backup diesel generators to be run up and brought on-line. A "prompt criticality" temperature runaway developed and high pressure (HP) steam leaked into the reactor, blowing off the top cover. The reaction of water and steam with the zirconium fuel rod cladding and graphite moderator core generated a mixture of hydrogen (H_2) and carbon monoxide (CO) which caused an explosion large enough to blow the concrete roof off the reactor building and disperse radioactive particles across much of Western Europe.

Incident Analysis

Basic cause was failure of the fuel rod cladding and rupture of the moderator core coolant pressure tubes due to extreme over-temperature and core melt.

Critical factors included: 1) The test was conducted at lower power (less stable conditions) and later (soon after shift change) than planned, 2) The automatic shutdown systems were disabled during the test, 3) Insertion of control rods displaced water (graphite absorbs fewer neutrons than water so insertion caused transient power level increase at already unstable operating conditions), 4) Absence of a nuclear (secondary) containment building capable of withstanding significant overpressure around the reactor core.

Root causes included: 1) Inadequate design (RBMK reactor positive void coefficient and graphite tips on control rod assemblies), 2) Violation of operating procedures (too many control rods withdrawn and safety systems overridden), 3) Inadequate training, 4) Inadequate emergency response planning (evacuation delayed), 5) Absence of independent safety regulator.

Lessons Learned

1) A concrete "sarcophagus" containment structure was built around the damaged reactor in the 6 month period after the explosion to try to limit the ongoing release of radioactive materials to atmosphere, 2) Control rods in all operating RBMK reactors were retrofitted with neutron absorbers and graphite displacers to prevent cooling water backfilling the voids created by the control rods being withdrawn (improving stability at low power), 3) Automatic shutdown systems were modified in all RBMK reactors to increase their speed of response, 4) This disaster prompted increased transparency and collaboration between the East and West, 5) The International Nuclear and Radiological Event Scale (INES) was developed to facilitate sharing of incident severity data on a consistent basis.

More Information

1) "The Accident at Chernobyl Nuclear Power Plant and Its Consequences", Lewis H.W., Environment (November 1986).
2) World Nuclear Association website (accessed 20-Nov-19): https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/chernobyl-accident.aspx.
3) "Chernobyl Lessons In Process Safety", K. Kolmetz, Engineering Practice Volume 6, Number 20 (January 2020).

Industry Sector	Process Type	Incident Type
Power Generation	Nuclear	Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessels	Reactor

Incident Title	**Multiple Nuclear Reactor Partial Meltdowns**	
Incident Type	Explosion	
Date	11th March 2011	
Country	Japan	
Location	Fukushima Daiichi	
Fatalities	**Injuries**	**Cost**
2259 (indirectly) – Ref .2	13	US$ 188 bn (2016) – Ref. 3

Incident Description  Credit: Keystone/Zuma/Shutterstock	Following a magnitude 9.0 earthquake on the Richter scale, 3 of 6 boiling water reactors (BWRs) operating at the time automatically shut down, as designed. However, all 6 external electrical power supplies failed due to earthquake damage. Emergency diesel generators started up as designed. However, approximately 41 minutes later, the plant was hit by a 15 m tsunami which damaged the sea cooling water pumps for the main condensers and auxiliary cooling circuits (including the residual heat removal system). It also drowned the diesel generators and inundated the electrical switchgear and battery systems. All 3 reactor cores melted within 3 days. Fortunately, there were no in-core steam explosions, but 13 people were injured by hydrogen explosions which breached their respective nuclear containment buildings, releasing radioactive material to the environment. More than 100,000 people within 20 km of the site had to be evacuated and 2259 (mainly elderly) people died during the evacuation process. This accident was eventually declared a Level 7 ("severe accident") on the International Nuclear Event Scale (INES).
Incident Analysis	**Basic cause** of the hydrogen explosions and release of radiation was overheating and extreme over-pressure of the reactor cores due to the total loss of offsite (earthquake) and onsite (tsunami) electrical power. **Critical factors** included: 1) Coastal location (exposure to tsunami), 2) Magnitude of earthquake (tsunami wave height), 3) Loss of offsite and onsite electrical power (cooling systems disabled), 4) Loss of instrument power (reactor monitoring and control impeded), 5) Delayed injection of alternative water supply by fire crews (reactors under pressure due to core overheating), 6) Hydrogen was generated by fuel rod zirconium cladding reaction with water in the reactor core and/or radiolysis of hot water in the spent fuel ponds. **Root causes** included: 1) Inadequate risk assessment (design basis used historical rather than recent seismic and weather data), 2) Failure to promptly implement tsunami countermeasures after maximum expected tsunami flood levels were reassessed in 2002 and found to exceed design basis levels for the plant (Japan believed its nuclear power plants were so safe that an accident of this magnitude was not credible), 3) Inappropriate plant layout (safety-critical electrical equipment located in turbine hall basements), 4) Inadequate operating procedures, 5) Inadequate emergency preparedness, 6) Inadequate crisis management, 7) Inadequate regulatory system (conflict of interest between government, safety regulator and operating company).
Lessons Learned	1) Distribution of potassium iodide to residents near the plant helped limit adverse health effects by preventing their thyroid glands absorbing radiation. 2) Nuclear power plants should be prepared to handle catastrophic natural disasters simultaneously at multiple reactors regardless of the cause. 3) Portable equipment to provide backup power and rapid injection of cooling water into the reactor core(s) and spent fuel pond(s) should be stored on site and designed for easy deployment in any area of the plant.
More Information	1) "The Fukushima Daiichi Accident – Report by the Director General", International Atomic Energy Agency (IAEA), Vienna, 2015, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1710-ReportByTheDG-Web.pdf. 2) "Fukushima Daiichi Accident", World Nuclear Association, April 2020. 3) "An update from Fukushima, and the challenges that remain there", Tatsujiro Suzuki, Bulletin of the Atomic Scientists, 11th November 2019.

Industry Sector	**Process Type**	**Incident Type**
Power Generation	Nuclear	Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessels	Reactor

Incident Title	**Confined Space Hydrogen Explosion**
Incident Type	Explosion and Fire
Date	8th April 1999
Country	USA
Location	Gannon, FL

Fatalities	Injuries	Cost
3	48	Unknown

Incident Description

Credit: PE Vol 3 ıssue 5/Tampa Tribune

A routine maintenance outage was in progress on a 375 MW turbine and generator set (Unit 6) at a coal-fired power station. Some 13 days into the shutdown, with the turbine and generator already partially dis-assembled, mechanics removed an access cover from the Unit 6 generator's gaseous hydrogen cooling system. A release of pressurised hydrogen occurred and resulted in multiple explosions and fires. Three workers were killed by injuries sustained in the blast. Two were employees working near the generator (one died at the scene, the other died in hospital a few hours later). The third was a contractor working outside the turbine hall who was killed by a Transite siding panel blown off the turbine hall enclosure by the explosion.

The fires were brought under control after 15 minutes. Only 1 of the 6 turbo-generator sets in the turbine hall was damaged, but the remaining 5 were taken off-line for precautionary safety inspections. The cost of replacement fuel and purchased power associated with this accident was US$ 5 m.

Gaseous hydrogen is used as a coolant in large electric power generators because it has high heat capacity (14 times higher than air which is typically used for smaller generators), high thermal conductivity, high specific heat, low viscosity and low(est) molecular weight (minimises windage losses).

Incident Analysis

Basic cause was a confined space hydrogen explosion due to ignition of gaseous hydrogen accidentally released from the closed-circuit generator cooling system.

Critical factors included: 1) Purging (displacing with carbon dioxide then air) and depressuring of the gaseous hydrogen cooling system had not been carried out before disassembly of the turbine and generator set commenced, 2) The experienced mechanics working on the machine assumed hydrogen had already been purged from the system (common practice was for this to be done before disassembly begins, usually by day 2 or 3 of the shutdown).

Root causes are believed to include: 1) Inadequate control of work (violation of lock out-tag out procedures, failure to use lock out devices and tags), 2) Inadequate communication between maintenance and operations personnel (work scope and equipment preparation status), 3) Failure to comply with energy isolation procedures (purging and depressuring hydrogen cooling system), 4) Inadequate process safety management (failure to enforce procedures), 5) Inadequate regulatory oversight (failure to visit the plant to audit control of work despite several leaks, fires and explosions since 1992).

Lessons Learned

1) Shutdown and lock out/tag out (LOTO) procedures for maintenance of machinery should specify all measures required to verify a safe energy state for all its associated process, hydraulic, pneumatic, mechanical, electrical and other utilities before maintenance is permitted to begin.
2) Shutdown/LOTO procedures should be rigorously enforced and energy isolation status should be clearly communicated to maintenance crews.

More Information

1) US Dept. of Labour Occupational Safety and Health Administration (OSHA) Region 4 News Release USDOL 99-197 (7th October 1999).
2) US Dept. of Labour Occupational Safety and Health Administration (OSHA) Inspection Report Nr. 109212571 (13th February 2001).

Industry Sector	Process Type	Incident Type
Power Generation	Coal-Fired	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment related	Not applicable	Not applicable

Incident Title	**Turbo-generator Disintegration**
Incident Type	Overspeed
Date	10th November 2007
Country	USA
Location	Springfield, IL

Fatalities	Injuries	Cost
0	0	US$ 45 m (2012) – Ref. 2

Incident Description

Credit: CWLP/Texas A&M University

A 1968 vintage 100 MW_e steam turbine/generator tripped due to an unknown hydraulic control oil system failure. Within 30 seconds of the generator circuit breaker opening, the turbine accelerated from 3600 rpm to an estimated 6000 rpm (overspeed condition), resulting in catastrophic failure of multiple components of the turbine. Seal and bearing lube oil were released under pressure as the emergency battery-powered lube-oil pumps continued operating. The leaking lube-oil ignited, causing an intense fire around and below the stricken machine. The exciter and bearings were ripped from their mountings, causing total destruction of the generator. The generator shell was punctured, releasing hydrogen coolant which accumulated in the roof space of the turbine hall before exploding a few seconds later. The blast blew out ~ 30% of the turbine hall exterior block wall. Falling masonry damaged 3 outdoor transformers, rupturing associated oil coolers and initiating an oil fire. Repair and re-commissioning of the damaged machine took ~ 17 months.

Fortunately, the incident occurred on a Saturday evening with few employees on site. On a weekday, 14 people would have been in imminent danger as they normally work in a nearby electrical workshop where a wall collapsed.

Incident Analysis

Basic cause of turbo-generator set disintegration was turbine overspeed (this also initiated an accumulated hydrogen explosion and lubricating oil fire in the turbine hall, and an outdoor transformer insulating oil fire).

Critical factors included: 1) The steam turbine trip and throttle (T&T) and governor valves failed to close fully when the generator breaker opened (caused the turbine to accelerate), 2) Gaseous hydrogen accumulated in the turbine hall roof space (increased explosion severity), 3) Falling masonry damaged external transformers (initiating a transformer insulating oil fire).

Root causes included: 1) Inadequate preventative maintenance (T&T valves had a history of binding due to excessive stem oxidation ["blue blush"] and governor valves had a history of jamming due to excessive stem wear ["stepping"]), 2) Normalisation of deviance (operators used hydraulic jacks to dislodge sticking valves during startup), 3) Inadequate testing of safety-critical equipment (overspeed protection system, T&T and governor valves).

Lessons Learned

1) Trip and throttle (T&T) valve stems should be exercised regularly in accordance with original manufacturer guidelines (e.g. weekly).
2) Steam turbine overspeed protection systems should be tested regularly in accordance with original manufacturer guidelines (e.g. annually).
3) T&T valves and governor valves should be dismantled, inspected and leak tested regularly (e.g. 3 – 5 year intervals).
4) T&T valve and governor valve trims should be designed with appropriate metallurgy/coating to mitigate the risk of "blue blush" and "stepping" and with appropriate geometry and clearances to minimise buildup of fouling deposits.
5) Deviations from proper operation of safety-critical equipment should not be tolerated (e.g. eliminate use of hydraulic jacks to free sticking valves).
6) Steam turbine/generators should have automatic fire suppression systems.

More Information

1) "Unit 31 Generator Failure Report", CWLP Generation Division (2008).
2) "The Impact of Large Losses in the Global Power Industry", Marsh Risk Management Research (2012).

Industry Sector	Process Type	Incident Type
Power Generation	Coal-Fired	Overspeed
Equipment Category	**Equipment Class**	**Equipment Type**
Rotating	Steam Turbine	Condensing

Incident Title	**Temporary Reactor Bypass Line Rupture**
Incident Type	Explosion and Fire
Date	1st Jun 1974
Country	UK (England)
Location	Flixborough (Lincolnshire)

Fatalities	Injuries	Cost
28	53	US$ 359 m (2021) – Ref. 3

Incident Description  Credit: The National Archives	Caprolactam (an intermediate product in the production of nylon) was being manufactured by oxidation of cyclohexane with air in a series of 6 mild steel, inter-connected reactors. A temporary 20" NS (DN 500) bypass pipe assembly incorporating expansion joints (bellows units) had been installed around one of the reactors to enable it to be taken off-line to repair a large crack. On the day of the incident (Saturday), while the plant was on hot circulation pending restart, the bypass line ruptured releasing 30 tonnes of hot cyclohexane that formed a flammable cloud and subsequently found an ignition source. A huge unconfined vapour cloud explosion (UVCE) occurred and 28 employees were killed instantly (18 of them in the control room). The entire plant was destroyed and 1821 homes and 167 business premises suffered significant damage. The resulting fire burned for 3 days. The loss of life would have been greater if the explosion had occurred on a weekday.
Incident Analysis	**Basic cause** was a hot cyclohexane release to atmosphere due to squirm and rupture of a bellows unit in the temporary reactor bypass pipe assembly. **Critical factors** included: 1) The process was inefficient and required a large amount of recycle (hence large inventory), 2) One of the six reactors had developed a crack (hence taken out of service), 3) The Works Engineer post at the plant was vacant (consequently the temporary bypass pipe assembly was designed by unqualified staff without reference to design standards or bellows unit manufacturer), 4) The bypass pipe assembly was not properly supported (rested on scaffold), 5) Bellows unit was exposed to transverse loads (due to inadequate support), 6) Proximity of control room to the plant. **Root causes** included: 1) Lack of hazard awareness (limited data available on potential consequences of UVCEs at the time), 2) Inadequate design (bypass piping assembly including re-use of existing bellows units), 3) Inadequate risk assessment (absence of bellows unit failure modes and effects analysis), 4) Inadequate quality assurance (no inspection and testing of bypass piping assembly), 5) Inappropriate plant layout (control room too close to plant), 6) Inadequate management of change (to plant and organisation), 7) Inadequate leadership (failure to investigate cause of cracking in bypassed reactor - later found to be external nitrate stress corrosion cracking - and to inspect remaining reactors for similar cracks), 8) Inadequate emergency response planning (major loss of plant inventory), 9) Inadequate land use planning (close proximity of local housing).
Lessons Learned	1) All plant modifications should undergo a rigorous safety, engineering and technical (management of change) review, 2) The positioning and structural design of occupied buildings and control rooms close to process plant require careful consideration, 3) Management should provide role clarity and training for staff to avoid unconscious incompetence (staff unaware of their own limitations), 4) New legislation was developed (UK Health & Safety At Work Act, UK Pressure Systems Regulations, EU Seveso Directive, etc).
More Information	1) "The Flixborough Disaster: Report of the Court of Inquiry", Her Majesty's Stationery Office, London (1975), ISBN 011-361075-0. 2) "Flixborough: Lessons Which Are Still Relevant Today", R. Turney, IChemE Loss Prevention Bulletin 237 (2014). 3) "100 Largest Losses in the Hydrocarbon Industry", Marsh Property Risk Consulting Practice, 27th Edition (2022).

Industry Sector	Process Type	Incident Type
Petrochemicals	Caprolactam	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Piping	Expansion Joint

Incident Title	**Reactor Inventory Release Via Settling Leg**
Incident Type	Explosion and Fire
Date	23rd October 1989
Country	USA
Location	Pasadena, TX

Fatalities	**Injuries**	**Cost**
23	314	US$ 1.8 bn (2021) – Ref. 3

Incident Description  Credit: AP/Shutterstock/E. Kolenovsky	A reactor in a slurry phase catalytic loop process for manufacturing high density polyethylene (HDPE) had been taken off-line to enable removal of blockages from 3 of 6 product settling legs at the bottom of the reactor by specialist maintenance contractors. (As the polymerisation-condensation reactions proceed, HDPE particles drop out of the circulating reaction mixture and flow through the settling legs to a product flash tank.) Each settling leg had an 8" NS (DN 200) air-actuated ball valve at the top of the leg to isolate it from the loop reactor. The settling leg isolation procedure required the valve to be closed and its actuator air hoses to be disconnected. The day before the incident, the first leg was cleared without problems but the following day, a blockage in the partially-dismantled second leg cleared suddenly and dumped almost the entire 40 tonne (88,000 lb) reactor inventory to atmosphere in seconds. A huge vapour cloud formed which was ignited by an unidentified source and exploded. More explosions followed later when a polyethylene reactor and 2 isobutane storage spheres failed catastrophically.
Incident Analysis	**Basic cause** was loss of containment of highly flammable reactor inventory via an open ball valve in a partially-dismantled reactor settling leg. **Critical factors** included: 1) Air hoses had not been removed from the ball valve actuator (contrary to maintenance procedure) and had been incorrectly fitted (cross-connected in the reverse position), 2) Absence of fixed gas detection equipment (early warning of emergency situation), 3) Damage to firewater supply system (impeded emergency response), 4) Close proximity of process equipment and control room (exacerbated severity). **Root causes** included: 1) Inadequate isolation (no lockout device in place on ball valve actuator), 2) Inadequate design (actuator had interchangeable air hose connections and firewater system was part of process water system rather than a dedicated system), 3) Inappropriate plant layout (control room too close to plant), 4) Inadequate risk assessment (potential for reverse operation of ball valve not recognised), 5) Inadequate control of work (permit to work system not enforced), 6) Inadequate process safety management system (local maintenance procedures deviated from corporate procedures and standard industry practice which required double valve isolation or a blind flange insert for breaking containment), 7) Normalisation of deviance (failure to enforce procedures), 8) Inadequate training (maintenance contractors), 9) Inadequate inspection, maintenance and testing (standby firewater pumps), 10) Inadequate emergency response planning (escape routes too close to plant).
Lessons Learned	1) Worst case scenarios should be considered and escalation impact studies should be carried out to inform plant design (e.g. plant layout, equipment spacing) and emergency response planning strategies, 2) Safeguards on live plant should not be removed for any reason except for maintenance and testing, regardless of how inconvenient this might be.
More Information	1) "Phillips Petroleum Chemical Plant and Fire", US Fire Administration, Report No. USFA-TR-035 (1989). 2) "Explosion at the Phillips' Houston Chemical Complex, Pasadena, 23 October 1989", Dr. J. Bond, IChemE Loss Prevention Bulletin 097 (1991). 3) "100 Largest Losses in the Hydrocarbon Industry", Marsh Property Risk Consulting Practice, 27th Edition (2022).

Industry Sector	**Process Type**	**Incident Type**
Petrochemicals	Polyethylene (HDPE)	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Valves - Actuated	Ball Valve

Incident Title	**Nitration Plant Residue Exothermic Runaway**
Incident Type	Jet Fire
Date	21st September 1992
Country	UK (England)
Location	Castleford (W. Yorkshire)

Fatalities	**Injuries**	**Cost**
5	201	Unknown

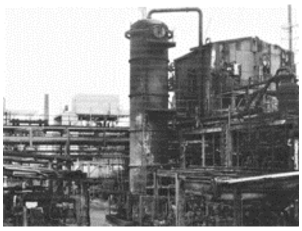
Incident Description  Credit: UK Health & Safety Executive	Mononitrotoluene (MNT) was being manufactured by continuous reaction of toluene with a sulphuric/nitric acid mixture under controlled conditions. The nitration reaction produced 3 types (isomers) of MNT which were separated from each other by distillation and crystallisation. The residual by-product contained dinitrotoluenes (DNTs) and nitrocresols, both of which were known to be unstable and to decompose violently. The by-product was routed to intermediate storage for subsequent batchwise processing in a vacuum still to recover good quality nitrobenzene. In the period immediately before the incident, heavy heel material that had accumulated at the bottom of an intermediate (vacuum still feed) storage tank over many years was being removed to enable re-purposing of the tank. The heel material was charged to the vacuum still where it was distilled satisfactorily. However, the residue did not drain from the stillbase vessel and became more viscous and harder as it cooled. The vessel was opened for cleaning for the first time in 30 years. A decision was taken to warm the residue using the stillbase internal steam batteries. A few hours later, while the warmed residue was being manually raked out, a 60 m (197 ft) long jet fire emerged from the open manway. Five people were killed (4 in the control room, 1 in the main office block).
Incident Analysis	**Basic cause** was exothermic decomposition and auto-ignition of nitration residues during stillbase vessel internal cleaning activities. **Critical factors** included: 1) The atmosphere and sludge in the stillbase had not been analysed, 2) The residue in the stillbase was heated and manually raked (high risk as unstable), 3) The steam pressure regulator was faulty (steam supply hotter than intended), 4) The temperature sensor was located above the sludge level (did not indicate sludge temperature), 5) The control room was located close to the plant, 6) The control room had a timber frame construction and inward opening doors (impeded escape), 7) The integrity of the office fire walls had been breached during earlier internal modifications. **Root causes** included: 1) Inadequate control of work (sludge and stillbase atmosphere not sampled), 2) Inadequate management of change to organisation and plant operations (inexperienced team leaders, overworked area manager and abnormal stillbase operation), 3) Inadequate training, 4) Inappropriate plant layout (occupied buildings too close to plant).
Lessons Learned	1) People transition through organisational change cycles at different speeds and have different training and support needs, 2) Organisational change and the process of transition to the new organisation require careful assessment and should take into account human factors (e.g. workload, stress, fatigue, etc), 3) The positioning and structural design of control rooms and occupied buildings close to process plant require careful consideration, 4) Doors to occupied buildings on process plant should open outwards, 5) Muster/roll call procedures should be routinely practised.
More Information	1) "The Fire at Hickson & Welch: A report of the investigation by the Health and Safety Executive into the Fatal Fire at Hicks & Welch Ltd, Castleford", HSE Books (1994), ISBN 0 7176 0702 X. 2) "The Fire at Hickson & Welch", T. Kletz, IChemE Loss Prevention Bulletin 227 (October 2012). 3) "Failure to Manage Organisational Change - a Personal Perspective", M. Lynch, IChemE Loss Prevention Bulletin 267 (June 2019).

Industry Sector	**Process Type**	**Incident Type**
Fine Chemicals	Meissner Nitration	Jet Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment-related	Not applicable	Not applicable

Incident Title	**Ethyl Chloride Recirculation Line Failure**
Incident Type	Fire
Date	1st February 1994
Country	UK (England)
Location	Ellesmere Port (Cheshire)

Fatalities	**Injuries**	**Cost**
0	18	£ 6.1 m (2010) – Ref. 2

Incident Description


Credit: UK Health & Safety Executive

Ethyl chloride (EC) was being manufactured by a liquid phase reaction between ethylene (C_2H_4) and hydrogen chloride (HCl) with an aluminium chloride ($AlCl_3$) catalyst at around 3.1 barg (45 psig) and 50 °C (122 °F). EC was drawn off the top of the reactor and polymer (waste) oil was drawn off the bottom. Both were fed to a slops drum where liquids were separated and pumped back to the reactor. The slops recirculation pump stopped running. Around 20 minutes after the standby pump (a common spare for polymer oil and slop recirculation) was started, the discharge pipe of the standby pump failed causing a release of reactants and formation of large flammable and toxic vapour cloud. The vapour cloud eventually found an ignition source (believed to be an electrical control panel for a nearby compressor). An intense pool fire ensued directly below the reactor.

Incident Analysis

Basic cause was release and ignition of a flammable vapour cloud due to mechanical failure of a pump discharge pipe spool either at a corroded flange or at a PTFE bellows connection in a flexible pipe spool.

Critical factors included: 1) The common spare standby pump discharge flange had a history of severe corrosion, 2) The associated motor driver was not adequately anchored to the baseplate and the shaft coupling was misaligned (causing pipe vibration), 3) Visual alarms indicating a slop recirculation pump fault and a high liquid level in the slop drum were missed by control board operators on successive shifts for 11 hours (increased inventory of flammable slops), 4) Isolation valves required manual operation with poor access due to a complex piping arrangement in a congested space, 5) Fire fighters were initially unaware that the leaking fluids were flammable, 6) The off-site alarm indicating toxic gas release was only sounded ~ 30 minutes after the on-site fire alarm was initiated.

Root causes included: 1) Inadequate design (manual isolation valves, poor access), 2) Inadequate alarms (visual not audible), 3) Inadequate hazard awareness (EC flammability), 4) Inadequate preventative maintenance (reactive rather than proactive work orders and inadequate documentation of maintenance activity), 5) Inadequate inspection (corrosion monitoring), 6) Inadequate emergency response planning (toxic risk prioritised over fire risk), 7) Inadequate training (absence of emergency response drills), 8) Inadequate communication (informing the public).

Lessons Learned

1) Process hazard analysis (PHA) studies should consider public health and environmental impacts of all types of loss of primary containment events.
2) Remote-operated emergency block valves (EBVs) can be deployed to control large accidental releases of flammable materials.
3) The toxicity of products of combustion from plant fires should be assessed in advance to facilitate appropriate response by emergency responders and appropriate communications with public health officials and nearby residents.
4) Maintenance and inspection activity should be supervised by a competent, professionally qualified engineer to ensure plant integrity.

More Information

1) "A Report of the Investigation by the Health and Safety Executive into the Chemical Release and Fire at the Associated Octel Company, Ellesmere Port on 1 and 2 February 1994", HSE Books (1996), ISBN 0 7176 0830 1.
2) "A Release of Chemicals followed by a Major Fire"; T. Fishwick, IChemE Loss Prevention Bulletins 214 & 215 [Parts 1 & 2 respectively] (2010).

Industry Sector	**Process Type**	**Incident Type**
Petrochemicals	Ethyl Chloride	Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Piping	Flanged Joint

Incident Title	**Nitrogen Asphyxiation During Maintenance**
Incident Type	Asphyxiation
Date	27th March 1998
Country	USA
Location	Hahnville, LA

Fatalities	Injuries	Cost
1	1	Unknown

Incident Description  Credit: US Chemical Safety Board	A manufacturing plant producing ethylene oxide (EO) by direct reaction of ethylene with oxygen (O_2) over a catalyst was undergoing a maintenance turnaround. A 1.2 m (48") diameter flanged O_2-feed mixer had been removed for thorough cleaning (grease or oil residues are incompatible with O_2). The open ends of the pipe formerly connected to the mixer had been covered with a clear plastic sheet to keep the pipe free of debris until the mixer was reinstated. Fresh catalyst had been loaded in the reactors and nitrogen (N_2) hoses had been connected to maintain them under an inert atmosphere to protect the moisture-sensitive catalyst and retard rust formation. The N_2 was being vented from the reactor-side of the opening where the mixer had been. Two workers were conducting ultra-violet (UV or “black light”) inspection of the 1.2 m (48") diameter flanges at the two openings (UV makes organic materials glow). They successfully completed inspection of the first (recycle gas-side) flange and then placed a black plastic sheet over the second (reactor-side) opening to provide shade to aid conducting UV inspection of the flange in bright daylight. While working just outside the pipe opening and inside the black plastic sheet, the 2 workers were overcome by N_2. One worker died from asphyxiation. The other survived but was severely injured.
Incident Analysis	**Basic cause** of both casualties was deprivation of oxygen (O_2). **Critical factors** included: 1) N_2 hoses had been connected to reactor inlet piping the previous night at a remote location not visible from the workface, 2) The black plastic sheet placed over the open-ended pipe inadvertently created a confined space, 3) N_2 gas is invisible, odourless and tasteless, 4) Absence of confined space entry permit and O_2 monitoring at workface. **Root causes** included: 1) Inadequate management of change (N_2 blanketing of reactors is abnormal operation), 2) Inadequate process isolation (reactor inlet valves were bypassed allowing N_2 to vent via process piping instead of reactor vents), 3) Inadequate control of work (absence of procedures for use of temporary enclosures and confined space entry permit), 4) Inadequate hazard awareness (no warning signs identifying pipe as confined space and alerting workers to presence of N_2 and potentially O_2-deficient atmosphere).
Lessons Learned	1) Nitrogen (N_2) is a colourless, odourless, tasteless, non-irritant gas at ambient conditions and can displace oxygen (O_2) in air. 2) Deprivation of oxygen can cause impaired perception and judgement, dizziness, nausea, loss of consciousness, coma, respiratory failure or death, depending on the extent of oxygen deficiency and duration of exposure. 3) Warning signs should be posted on any process equipment or piping being purged with nitrogen to alert personnel to the potential presence of a life-threatening O_2-deficient atmosphere (especially in confined spaces). 4) All access and egress points around process equipment or piping being purged with nitrogen should be barricaded and an access control system should be set up to log all personnel entering/leaving the barricaded area. 5) All personnel entering the barricaded area should wear a personal gas monitor with an audible and visible alarm set at 19% O_2 concentration.
More Information	1) “Nitrogen Asphyxiation”, Summary Report of the US Chemical Safety and Hazard Investigation Board (CSB), Report No. 98-05-I-LA. 2) “Hazards of Nitrogen and Catalyst Handling”, BP Process Safety Series, 6th Edition, IChemE (2006), ISBN: 978-0-85295-540-6.

Industry Sector	Process Type	Incident Type
Petrochemicals	Ethylene Oxide	Asphyxiation
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment-related	Not applicable	Not applicable

Incident Title	**Propylene Fractionator Reboiler Shell Rupture**
Incident Type	Explosion and Fire
Date	13th June 2013
Country	USA
Location	Geismar, LA

Fatalities	Injuries	Cost
2	167	US$ 510 m (2014) – Ref. 2

Incident Description

Credit: US Chemical Safety Board

A Propylene Fractionator was equipped with 2 shell and tube-type reboilers (one in service, one on standby). The standby reboiler was being brought on stream to allow the operating reboiler to be taken off-line for cleaning. The Operations Supervisor opened the manual tubeside isolation valves to establish a flow of hot quench water to the standby reboiler in preparation for the reboiler switchover. Three minutes later the standby reboiler shell failed catastrophically. The escaping propane/propylene mixture caused a boiling liquid expanding vapour explosion (BLEVE) and fire, releasing approximately 13.6 tonnes (30,000 lb) of flammable hydrocarbons to atmosphere. The fire burned for 3.5 hrs and the plant remained shut down for 18 months.

Incident Analysis

Basic cause was overpressure of the reboiler shell during warmup due to thermal expansion of trapped (blocked in) propane/propylene liquid.

Critical factors included: 1) The original Propylene Fractionator design had both reboilers operating continuously (so no shellside isolation valves) with over-pressure protection for both reboilers provided by a pressure safety valve (PSV) on top of the Propylene Fractionator, 2) Isolation valves were added to both reboilers in 2001 to enable the Propylene Fractionator to remain on-line while one of its reboilers was taken out of service for cleaning (the operating philosophy was changed to one reboiler in service, one on standby under a nitrogen blanket), 3) The standby reboiler shell was isolated from the PSV by its closed shellside isolation block valves, 4) The shellside isolation valve(s) leaked, allowing process fluid into the reboiler shell.

Root causes included: 1) Inadequate management of change (MoC) review (for installation of reboiler isolation valves), 2) Inadequate documentation (P&IDs not updated to show isolation valves), 3) Inadequate process hazard analysis (PHA) study (both reboilers assumed to be in operation as P&IDs did not show isolation valves), 4) Inadequate hazard identification (potential for overpressure not recognised), 5) Inadequate procedures (absence of equipment-specific operating procedure for reboiler switching), 6) Inadequate pre-startup safety review (PSSR), 7) Failure to properly implement recommendations from 2006 PHA (car seal open shellside isolation valves), 8) Inadequate process safety management (PHA, MoC, PSSR and related action-tracking processes; failure to confirm existence of safety-critical car seals on shellside isolation valves).

Lessons Learned

1) Single block (gate) valve is not an adequate method of isolation as valves can leak and are susceptible to inadvertent opening.
2) A rigorous management of change (MoC) review should be carried out before any changes are implemented on process plant.
3) Overpressure protection must be provided if the maximum allowable working pressure (MAWP) can exceed design code limits.
4) PSVs (passive safeguards) installed directly on the equipment to be protected are higher in the hierarchy of controls and provide more robust protection than car seals and operating procedures (administrative controls).

More Information

1) "Williams Geismar Olefins Plant Reboiler Rupture and Fire", US Chemical Safety and Hazard Investigation Board, Report No. 2013-03-I-LA (2016).
2) "The 100 Largest Losses 1974 – 2013", Marsh Property Risk Consulting Practice, 23rd Edition (2014).

Industry Sector	Process Type	Incident Type
Petrochemicals	Olefins	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Heat Exchanger	Shell & Tube

Incident Title	**Hydrogenation Reactor Catastrophic Failure**	
Incident Type	Explosion and Fire	
Date	3rd June 2014	
Country	Netherlands	
Location	Moerdijk, NB	
Fatalities	**Injuries**	**Cost**
0	2	Unknown

Incident Description

Credit: Dutch Safety Board

A styrene monomer and propylene oxide (MSPO) chemical intermediate manufacturing plant was being restarted after a routine catalyst changeout. The hydrogenation reaction section of the plant had been successfully air-freed, leak-tested, flushed with ethyl benzene (EB), placed on circulation with a fresh charge of EB, and allowed to "line out" to ensure the catalyst bed was wetted and heated homogeneously. The next step of the startup procedure was heat up ("reheat") of the trickle-bed reactors in preparation for reduction of the active metals on the catalyst. The Control Board Operator decided the reheat step was proceeding too slowly and manually increased the heat up rate. An unexpected exothermic (heat-liberating) runaway chemical reaction occurred which generated gases and rapidly increased the reactor pressure. This was not recognised as flows and levels were fluctuating widely and alarms were sounding regularly (as expected from previous restarts). Two explosions occurred in rapid succession and a major fire followed.

Incident Analysis

Basic cause was overpressure of the reactor due to presence of hot spots created by an exothermic EB dehydrogenation reaction catalysed by the fresh (un-reduced) catalyst during the reheat step of the startup procedure.

Critical factors included: 1) The new catalyst contained more active metals in oxidised form than the original catalyst (tests on the original catalyst in 1977 showed it to be inert to EB), 2) Inadequate wetting of the catalyst pellets during the reheat step (due to EB flow instability), 3) The product separator gas vent to flare system tripped closed on high level (to prevent liquid discharge to flare) but was not reset by the Control Board Operator when the level returned to normal (this had the unintended consequence of preventing venting of gases generated by the runaway reaction), 4) The remote-operated emergency block valves (EBVs) were disabled by the explosion.

Root causes included: 1) Inadequate communication between catalyst supplier and operator (new formulation not explicitly reported), 2) Inadequate management of change (new catalyst formulation not re-tested and changes to startup procedure not reviewed), 3) Inadequate instrumentation (reactor thermometry), 4) Inadequate design (absence of automatic controls for heat up during reheat step, product separator high level trip closing gas vent to flare, pressure relief system undersized for the unexpected chemical reaction), 5) Failure to adequately investigate similar incident at sister plant.

Lessons Learned

1) Quantitative reaction hazard assessment data (thermal stability tests, calorimetry, etc) should be used to inform design of appropriate safeguards,
2) A rigorous management of change (MoC) review should be carried out before any changes are made to process plant or operating procedures,
3) Operating procedures should clearly identify safety-critical steps and any relevant limits on key operating variables.
4) Control systems should be designed to provide stable process control under transient (e.g. startup) as well as steady-state conditions.

More Information

1) "Explosions MSPO2 Shell Moerdijk", Dutch Safety Board, The Hague, July 2015.
2) "CAST Analysis of the Shell Moerdijk Accident", N.G. Leveson, Massachusetts Institute of Technology (MIT) for the E.U. Major Accident Hazards Bureau (2016): http://sunnyday.mit.edu/shell-moerdijk-cast.pdf

Industry Sector	Process Type	Incident Type
Petrochemicals	Styrene Monomer	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessel	Reactor

Incident Title	**Organic Peroxide Thermal Decomposition**	
Incident Type	Fire	
Date	31st August 2017	
Country	USA	
Location	Crosby, TX	
Fatalities	**Injuries**	**Cost**
0	21	Unknown

Incident Description

Credit: US Chemical Safety Board

The Crosby plant manufactures and stores a range of organic peroxides. These are powerful oxidising agents used to initiate polymerisation reactions in the manufacture of materials such as polyvinyl chloride and polystyrene. On 25-Aug-17, the manufacturing plant was proactively shut down to prepare for arrival of a Category 4 hurricane ("Harvey"). However, by 27-Aug-17, unexpectedly high and rising water levels threatened the electrical power, backup power and refrigeration systems in the low temperature warehouses where thermally unstable organic peroxides were stored. So the electrical equipment in the warehouses was turned off. On 28-Aug-17, the rising water level reached a transformer and all electrical power to the site was lost. The low temperature organic peroxide products were transferred to 9 standby refrigerated trailers, but flooding prevented 3 of the trailers being moved to high ground. On 29-Aug-17, all employees at the plant and neighbouring residents in a 2.5 km (1½ mile) exclusion zone had to be evacuated.

On 31-Aug-17, organic peroxide products in one of the refrigerated trailers decomposed, causing the peroxides and trailer to combust. On 01-Sep-17, 2 more trailers caught fire. On 03-Sep-17, a controlled burn was carried out by emergency responders on the remaining 6 trailers. Fumes generated by decomposing organic peroxides drifted across a public road, causing 21 people to seek medical attention. A total of ~ 159 tonnes of organic products were burned and ~ 200 evacuated residents could not return home for a week.

Incident Analysis

Basic cause was thermal decomposition of organic peroxide products due to refrigeration systems becoming inoperable because of rising floodwater.

Critical factors included: 1) Organic peroxides are reactive and inherently unstable, 2) Staff were not aware that a flood insurance map revision in 2007 designated part of the site a 500-year flood plain, 3) Hurricane Harvey flood levels greatly exceeded the 500-year flood level design basis, 4) A public highway passing through the exclusion zone was kept open for hurricane relief and rescue resource transportation (hazardous fumes exposure risk).

Root causes included: 1) Inadequate hazard identification (common mode failure of multiple layers of protection due to rising floodwater), 2) Inadequate process hazard analysis (risk of flood), 3) Creeping change (frequency and severity of extreme weather events appear to be increasing), 4) Inadequate federal process safety regulations (flood insurance maps not explicitly specified as required input for process safety hazard assessment).

Lessons Learned

1) The interaction of natural hazards and technological systems such as chemical manufacturing plant can lead to major accidents ("Natech events").
2) Worst case scenarios (e.g. extreme flooding) should be considered for land use planning, hazardous facility siting, hazard analysis and plant layout.
3) Multiple independent layers of protection may be needed to prevent common mode failure of safety-critical systems to maintain thermally unstable chemicals below their self-accelerating decomposition temperature (SADT).

More Information

1) "Organic Peroxide Decomposition, Release, and Fire at Arkema Crosby Following Hurricane Harvey Flooding", US Chemical Safety and Hazard Investigation Board, Report No. 2017-08-I-TX (2018).
2) "Rain Starts Fire", P. Carson & R. Abhari, IChemE Loss Prevention Bulletin 277 (Feb 2021) https://www.icheme.org/media/15306/lpb277_pg29.pdf.

Industry Sector	**Process Type**	**Incident Type**
Petrochemicals	Organic Peroxides	Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Electrical	Switchgear	Miscellaneous

Lessons Learned Database
Individual Incident Summary Report

IChemE Safety & Loss Prevention Special Interest Group

Incident Title	**Batch Reactor Toxic Material Release**
Incident Type	Runaway Reaction
Date	10th July 1976
Country	Italy
Location	Seveso (Lombardy)

Fatalities	Injuries	Cost
0	~ 500	Unknown

Incident Description  Credit: Wikimedia Commons	An exothermic reaction occurred in a trichlorophenol (TCP) reactor after a batch process for production of chemical intermediates used in herbicide and disinfectant manufacture was halted for the weekend. The process involved reacting tetrachlorobenzene with sodium hydroxide in an ethylene-glycol solvent followed by distillation to remove the solvent. The reactor overheated and the pressure rose until a bursting disc ruptured discharging its contents to atmosphere. A thick white cloud containing a small but significant quantity of the ultra-toxic compound 2,3,7,8-tetrachlorodibenzo-para-dioxin (TCDD) drifted slowly over neighbouring communities. The response to the incident was chaotic due to ignorance of the scale of potential hazards and poor information exchange/communication between local and regulatory authorities. Around 200 people developed skin lesions (chloracne), many more suffered other effects and around 80,000 animals were slaughtered to stop dioxin compounds entering the food chain.
Incident Analysis	**Basic cause** of the release was an unexpected exothermic reaction which overheated the reactor contents until a bursting disc (BD) ruptured and vented the contents of the reactor to atmosphere. **Critical factors** included: 1) Turbine exhaust steam used for reactor heating was unnecessarily hot, 2) The reactor's stirrer and the steam supply to its external dual-purpose heating/cooling coil had been switched off before completion of the distillation step (prolonging reaction mixture retention time), 3) The cooling water supply to the external coil had not been turned on (operators thought the reactor would cool by itself), 4) The company did not inform the authorities about the presence of ultra-toxic TCDD in the release until 10 days after the event. **Root causes** included: 1) Inadequate hazard identification (exothermic side reactions producing dioxins, turbine exhaust steam temperature rises as load reduces), 2) Inadequate process control (absence of automatic temperature and pressure control), 3) Violation of operating procedure (shutdown after only partial solvent removal was prohibited), 4) Inadequate communication (between company, local authorities and national regulatory authority), 5) Inadequate emergency response planning (company and external emergency responders).
Lessons Learned	1) Quantitative reaction hazard assessment data (thermal stability tests, calorimetry, etc) must be used to inform design of appropriate safeguards. 2) Production planning for batch operations should be designed so that all operations can be safely concluded within the time available. 3) Pressure relief systems for batch reactors used for hazardous chemical manufacture should discharge to appropriate containment systems. 4) The Seveso Directives, first adopted by the European Commission in 1982 (Directive 82/501/EEC) require operators of industrial plants to make information on major hazard identification, control and mitigation available to the regulator and are implemented in the UK by the Control of Major Accident Hazards (COMAH) Regulations.
More Information	1) "Lessons from Seveso", D. C. Wilson, Chemistry in Britain (1982). 2) "Seveso – 40 Years On", M. Hailwood, IChemE Loss Prevention Bulletin 251 (2016): https://www.icheme.org/media/2078/lpb251_pg14.pdf.

Industry Sector	Process Type	Incident Type
Agrochemicals (Manufacture)	Herbicide	Runaway Reaction
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment related	Not applicable	Not applicable

Incident Title	**Methyl Isocyanate Storage Tank Temperature Runaway**		
Incident Type	Toxic Gas Release		
Date	3rd December 1984		
Country	India		
Location	Bhopal, MP		
Fatalities	**Injuries**	**Cost**	
2153 (minimum)	> 200,000	Unknown	

Incident Description

Credit: D. Hendershot/CCPS Staff Cons

Carbaryl (an insecticide) was being manufactured by reacting methylamine with phosgene to make a methyl isocyanate intermediate product which was then reacted with 1-naphthol. On the morning of the incident, an exothermic reaction occurred in the nitrogen-purged stainless steel methyl isocyanate intermediate storage tank. The temperature and pressure in the tank continued to rise until 40 tonnes of highly toxic vapours, including methyl isocyanate (MIC) and hydrogen cyanide (HCN) were released to atmosphere via the pressure relief system. The official death toll was 2153 but some unofficial estimates were > 16,000 (uncertain due to unknown population of shanty town adjacent to the plant). The plant never restarted.

Incident Analysis

Basic cause was a runaway chemical reaction caused by water ingress to the MIC intermediate storage tank (isolation error or sabotage?).

Critical factors included: 1) The refrigeration system, vent gas scrubber and flare stack were not in service, 2) MIC was routinely pressured out of the tank with nitrogen because the MIC transfer pump was unreliable (seal leaks), 3) The carbon steel vent headers were routinely water flushed to clear fouling deposits, 4) The tank high temperature alarm was disconnected when the refrigeration system was taken out of service, 5) The emergency water spray was only capable of knocking down vapour clouds at low elevation (e.g. MIC pump seal leak), 6) The presence of a shanty town near the plant boundary.

Root causes included: 1) Inadequate preventative maintenance (instruments and safety-critical equipment), 2) Inadequate risk assessment (MIC inventory during plant outages), 3) Inadequate management of change (refrigeration, vent gas and flare system outages), 4) Inadequate training (plant operators), 5) Inadequate leadership (operational oversight), 6) Inadequate emergency response planning (due to inadequate risk assessment), 7) Failure to apply inherently safer design principles (MIC intermediate storage), 8) Inadequate land use planning (close proximity of shanty town to high hazard plant).

Lessons Learned

1) Carbon steel process piping and equipment is incompatible with MIC in atmospheres containing oxygen because rust (Fe_2O_3) catalyses an MIC trimerisation (polymerisation) reaction which can cause heavy fouling.
2) An inherently safer process for carbaryl manufacture which avoids production of MIC intermediate (but has higher operating costs) uses the same reactants in a different sequence (phosgene reacts with 1-naphthol to produce 1-napthylchloroformate which is then reacted with methylamine).
3) Regulators should ensure that manufacturing companies are made fully accountable for contaminated land clean-up costs in the event of a spill or release and site remediation costs when production is finally terminated.
4) The Public Liability Insurance Act 1991 was introduced in India to provide for public liability insurance for providing immediate relief to anyone affected by an accident while handling any hazardous substance.

More Information

1) "Union Carbide: Disaster at Bhopal", P. Cullinan, S. Acquilla and V. Ramana Dhara (1993).
2) "Remembering Bhopal" IChemE Loss Prevention Bulletin 240 (2014): https://www.icheme.org/media/1277/lpb240_digimag.pdf
3) "What Went Wrong? Case Histories of Process Plant Disasters and How They Could Have Been Avoided", 4th Edition (1999), Trevor Kletz, Elsevier, ISBN-10: 0-88415-920-5, ISBN-13: 978-0-88415-920-9.

Industry Sector	**Process Type**	**Incident Type**
Agrochemicals (Manufacture)	Pesticide	Toxic Gas Release
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment-related	Not applicable	Not applicable

Incident Title	**Ammonium Nitrate Warehouse Explosion**
Incident Type	Explosion
Date	21^{st} September 2001
Country	France
Location	Toulouse

Fatalities	**Injuries**	**Cost**
31	2442	> € 2.0 bn (2013) – Ref. 1

Incident Description  Credit: Christophe Ena/AP/Shutterstock	A huge explosion occurred approximately 20 minutes after a small quantity of sodium dichloroisocyanurate ($C_3Cl_2N_3NaO_3$ or "SDIC") was spilled onto a pile of off-specification ammonium nitrate (NH_4NO_3 or "AN") which had been stored in Shed 221 for recycling. The blast was equivalent to a magnitude 3.4 earthquake on the Richter scale (20 - 120 tonnes of AN detonated). Much of the plant was destroyed and significant escalation occurred (including a secondary explosion) at a neighbouring hazardous process plant owned by others. More than 1000 homes were rendered uninhabitable and many more were damaged. More than 82 schools were also damaged. Atmospheric pollutants released after the detonation of the AN included nitric acid (HNO_3), ammonia (NH_3), nitrogen dioxide (NO_2) and nitrous oxide (N_2O). A nitric acid plant at the site was also damaged, causing pollution of the River Garonne.
Incident Analysis	**Basic cause** was probably either chemical incompatibility or major electrical failure in an adjacent storage area (exact cause not determined). [SDIC additive reacts with AN to form explosively unstable nitrogen trichloride. Shed 221 was lit by natural light only but an electrical failure at an adjacent plant could have produced a massive electrical arc in the AN storage area.] **Critical factors** included: 1) Shed 221 contained several different grades of AN which were off-spec. for chemical composition or grain size (adjacent sheds were used for packaging of various grades of AN products), 2) Shed 221 operations were managed by waste management subcontractors (potential for incomplete knowledge of hazards associated with AN handling and storage), 3) SDIC was accidentally spilled onto an off-spec. pile of AN during transfer to Shed 221, 4) Shed 221 floor was paved with bitumen (potential source of contamination which increases AN explosive sensitivity). **Root causes** included: 1) Inadequate risk assessment (detonation had not been included as a credible scenario by the operating company, third party technical experts, or the regulator), 2) Failure to learn (from previous incidents involving fertiliser and other grades of AN), 3) Inadequate land use planning regulations (urbanisation of land adjacent to existing plant), 4) Inadequate regulatory oversight (off-spec. AN storage not regulated).
Lessons Learned	1) The ammonium nitrate (AN) inventory reporting threshold was reduced to broaden the applicability of the Seveso II Directive to include smaller plant. 2) Escalation impact studies should be carried out to inform plant design (eg. inventory control, plant layout, equipment spacing) and emergency response planning strategies. 3) AN should be stored in single storey, well-ventilated buildings constructed from non-combustible materials (eg. concrete, bricks or steel) and located away from potential sources of heat, fire or explosion. 4) Different grades of AN should be stored separately and their inventories minimised. 5) Written procedures for handling and storage of bulk AN should be communicated to employees and subcontractors and regularly reviewed.
More Information	1) ARIA No. 21329 https://www.aria.developpement-durable.gouv.fr/wp-content/files_mf/A21329_ips21329_008.pdf. 2) "Incidents That Define Process Safety", J. Atherton & F. Gil, Center for Chemical Process Safety (CCPS), ISBN 978-0-470-12204-4 (2008). 3) INDG230: "Storing and Handling Ammonium Nitrate", UK Health & Safety Executive (2004) https://www.hse.gov.uk/pubns/indg230.pdf.

Industry Sector	**Process Type**	**Incident Type**
Agrochemicals (Manufacture)	Fertiliser (Storage)	Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment-related	Not applicable	Not applicable

Incident Title	**Toxic Chemical Release**
Incident Type	Toxic Gas Release
Date	15th November 2014
Country	USA
Location	La Porte, TX

Fatalities	Injuries	Cost
4	0	Unknown

Incident Description  Credit: US Chemical Safety Board	Operators of a Lannate® insecticide manufacturing process were attempting to clear a hydrate blockage in the methyl mercaptan feed line between the methyl mercaptan storage tank and the reaction section by pouring hot water on the outside of the pipe to melt it. In order to prevent over-pressure of the line as the hydrate plug melted, isolation valves between the methyl mercaptan feed line and the vent gas header were temporarily cracked open. The pressure in the vent gas header began to rise but this was incorrectly assumed to be a consequence of liquid accumulation in the vent gas header to the downstream incinerator/vent gas scrubber (a common occurrence), so the header was drained through a hose to an open floor drain. Almost 24,000 lb (10,900 kg) of highly toxic methyl mercaptan was released to atmosphere inside the enclosed, unventilated manufacturing building via the drain.
Incident Analysis	**Basic cause** of the fatalities was a combination of asphyxia and acute exposure (by inhalation) due to a toxic gas release in a confined space. **Critical factors** included: 1) The manufacturing building ventilation fans were not in service, 2) The manufacturing building gas detection system had alarms display automatically on the control board but relied on verbal communication by the control board operator to order evacuation of the building, 3) The control board operator was focussed on correcting a high pressure condition in the process and did not realise the gas detector alarms were indicating a major gas release in the building, 4) The control board operator failed to mention a toxic gas release when requesting assistance from emergency response team to rescue personnel, 5) Operators entered the building without respiratory protection in an attempt to rescue colleagues. **Root causes** included: 1) Inadequate process safety management system resulting in 2) Inadequate process hazard analysis (hydrate formation in methyl mercaptan feed line), 3) Inadequate engineering design (pockets in vent gas header pipe, ventilation system designed to prevent flammable gas concentration exceeding 25% of lower exposure limit rather than to avoid exceeding danger to life concentration threshold), 4) Inadequate toxic gas detection system (alarm set point too high, absence of visual/audible alarms in manufacturing building), 5) Inadequate operator training (troubleshooting, hazard awareness, ventilation fan criticality), 6) Inadequate maintenance of safety-critical equipment (ventilation fans), 7) Normalisation of deviance (operators frequently drained vent gas header and used methyl mercaptan odour to help locate leaks), 8) Inadequate personnel protective equipment (respiratory protection for vent gas header draining), 9) Inadequate control of work (absence of work permit for vent gas header draining), 10) Poor communication (failure to alert emergency response team to toxic gas release), 11) Failure to enforce procedures (emergency procedure required manufacturing building access to be restricted when ventilation fans not in service), 12) Failure to learn (past toxic gas release incidents - e.g. Bhopal).
Lessons Learned	1) Inherently safer design (ISD) reviews of the manufacturing building, dilution air ventilation systems and pressure relief systems should be conducted for any processes involving toxic process streams.
More Information	1) "Toxic Chemical Release at the DuPont La Porte Chemical Facility", US Chemical Safety and Hazard Investigation Board, Report No. 2015-01-I-TX (2019): https://www.csb.gov/dupont-la-porte-facility-toxic-chemical-release-/

Industry Sector	Process Type	Incident Type
Agrochemicals (Manufacture)	Insecticide	Toxic Gas Release
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment-related	Not applicable	Not applicable

Incident Title	**Ammonium Nitrate Storage Bin Explosion**
Incident Type	Explosion and Fire
Date	17^{th} April 2013
Country	USA
Location	West, TX

Fatalities	Injuries	Cost
15	> 260	US$ 230 m (2016) – Ref. 1

Incident Description  Credit: US Chemical Safety Board	A fire broke out at an agricultural chemical and grain storage/distribution site and was reported to the local fire brigade. Around 20 minutes later, while first responders were attempting to extinguish the blaze, a massive explosion occurred, registering as a magnitude 2.1 earthquake on the Richter scale. Approximately 27 of the 36 - 54 tonnes of fertiliser grade ammonium nitrate (FGAN) stored there detonated. Twelve first responders and three members of the public were fatally injured. The blast completely destroyed the facility, levelled dozens of homes and damaged other buildings including 2 schools and a nursing home. The company subsequently filed for bankruptcy.
Incident Analysis	**Basic cause** of the initiating fire was either an electrical fault or arson (exact cause was not determined). **Critical factors** included: 1) FGAN was stored in loose piles in plywood bins, 2) Absence of fire detection and mitigation systems, 3) Poor ventilation in the FGAN storage area (contributing to soot formation in the initial fire which caused contamination of the FGAN and increased its explosive sensitivity), 4) First responders were not aware of the potential for FGAN detonation on exposure to fire, 5) The city had expanded over several years and multiple occupied buildings had been erected close to the plant boundary. **Root causes** included: 1) Inappropriate plant layout (combustibles too close to FGAN storage), 2) Inappropriate materials of construction (plywood FGAN storage bins), 3) Inadequate emergency response planning (absence of pre-incident training), 4) Inadequate hazard awareness (training of volunteer firefighters), 5) Failure to learn (from previous incidents involving FGAN and other grades of AN), 6) Inadequate land use planning regulations (proximity of residential buildings and a school), 7) Inadequate regulatory oversight.
Lessons Learned	1) Pure solid ammonium nitrate (AN) is normally a stable compound and is not sensitive to most methods for initiating detonation (including mild shock, friction or sparks), 2) However, AN is a powerful oxidising agent which can behave unpredictably when contaminated or exposed to fire (may liberate toxic gases, "burn" uncontrollably even if air is excluded and/or explode), 3) AN should be stored in single storey, well-ventilated buildings constructed from non-combustible materials (e.g. concrete, bricks or steel) and located away from potential sources of heat, fire or explosion (e.g. timber yards, gas pipelines, oil storage tanks, etc), 4) AN storage bins should be constructed from non-combustible materials and should be located in areas of the AN storage building where electrical services are not required, 5) Direct electrical heaters should not be used in AN storage buildings, 6) Arson and faulty or damaged electrical equipment are major risk factors for warehouse fires, so unauthorised access should be prevented and electrical equipment and fittings should be regularly inspected and maintained (where used), 7) Care is required to avoid contaminating AN with foreign matter of any kind (e.g. grease, oil or fuel leaks from mechanical shovels used for un/loading).
More Information	1) "West Fertilizer Company Fire and Explosion", US Chemical Safety and Hazard Investigation Board, Report No. 2013-02-I-TX (2016). 2) INDG230: "Storing and Handling Ammonium Nitrate", UK Health & Safety Executive (2004) https://www.hse.gov.uk/pubns/indg230.pdf. 3) SI 2003/1082: "Ammonium Nitrate Materials (High Nitrogen Content) Safety Regulations", Her Majesty's Government (2003).

Industry Sector	Process Type	Incident Type
Agrochemicals (Distribution)	Fertiliser (Storage)	Explosion & Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Container	Storage Bin

Process Safety in the Pharmaceuticals Sector

"In common with other sectors in the chemical industry, pharmaceutical manufacturing involves processes that are inherently hazardous. A small molecule Pharma process (i.e. not biological) usually involves several stages of organic chemistry to make the active pharmaceutical ingredient, followed by formulation steps to produce the final dose form. Hazards such as handling toxic and/or flammable materials, controlling thermodynamically unstable chemical reactions, and transferring and drying powders are quite typical, plus there can be additional challenges with high potency materials and bio-safety.

The following three articles highlight the importance of understanding these hazards as a means to prevent incidences that cause harm to people and damage assets. They illustrate the potential consequences when risks that should have been foreseen and mitigated in the process engineering and facility design are overlooked and carried through to the plant's operation. Moreover, they show how human factors come into play when the plant is operational, and that changes to the plant, processes and personnel mean that risk profiles continue to evolve over time.

To counter this, the Pharma industry puts great emphasis and effort during the development lifecycle into understanding the fundamental safety hazards. There are several phases of scale-up between laboratory and commercial scale, and safety risk assessments are carried out at each stage. The initial phases of process development include testing and collating the material safety data, and characterising reaction calorimetry, which feed into the subsequent design reviews. A production scale plant's design will have been through a full suite of process and operational hazard assessments, e.g. HAZIDs, HAZOPs, SIL/LOPA reviews, pressure systems reports, COMAH reviews (as necessary). Also, and equally important, safe operation is maintained via rigorous change control procedures, safety audits and periodic re-evaluation HAZOPs.

Going forward, the sector will continue to progress safety by design wherever possible and practical – greener chemistry/biochemistry and a trend towards continuous instead of batch processes are just two examples where enhanced process safety, product quality and production efficiency go hand-in-hand. For the unavoidable process hazards, there are improving process technologies that provide better containment and more robust loss prevention through automation and control.

Aside from the production processes themselves, the Pharma sector has also made good progress in integrating a safety culture throughout the process design and operation of the plant. This must be a continuing theme in the education and training of the many disciplines involved in this sector."

Keith Taylor CEng MIChemE
Chair of IChemE Pharma SIG

ICHEME Safety & Loss Prevention Special Interest Group

Incident Title	**Synthesis Reaction Temperature Runaway (Near Miss)**
Incident Type	Runaway Reaction
Date	4th January 1992
Country	UK (England)
Location	Grimsby (Lincolnshire)

Fatalities	**Injuries**	**Cost**
0	0	Unknown

Incident Description


Credit: IChemE Loss Prev. Bulletin 273

A plant producing chemical intermediates for manufacture of active drug ingredients experienced a runaway chemical reaction. The process involved synthesis of 2-chloro-6-nitrodiphenylamine by reacting dichloronitrobenzene (DCNB) with aniline ($C_6H_5NH_2$) in the presence of sodium carbonate (Na_2CO_3 or "soda"). This synthesis reaction is mildly exothermic with an adiabatic temperature rise of 25 °C (45 °F). The decomposition reaction has an adiabatic temperature rise of 938 °C (1720 °F). Aniline provides a layer of protection against decomposition as evaporation of the aniline removes the heat of reaction (boiling point of aniline is 184 °C or 363 °F at NTP).

The process is operated batchwise in a jacketed continuously stirred tank reactor (CSTR). The jacket is used for both heating and cooling (pressurised water/steam for heating, water for cooling). The reactor had a vertical glass riser vent pipe with a tee section. The vertical branch of the tee incorporated 2 busting discs (BDs) and a vent pipe discharging to atmosphere. The other branch carried reactor vapour to a condenser and receiver. After charging soda to the reactor from bulk storage, molten DCNB at 70 – 80 °C (158 – 176 °F) is added from bulk storage while stirring. The batch is then heated to ~ 150 °C (302 °F) and a light vacuum is drawn to enable unreacted aniline to distil off. The jacket is then turned off and the heat of reaction increases the temperature to the target 160 °C (320 °F) where it is held until completion.

On the night of the incident, the reactor temperature was climbing slowly and reached the upper limit of the temperature sensor range while the reactor was still at atmospheric pressure. The aniline had started to distil off by itself and quickly began boiling vigorously. The jacket was found to be operating at a higher pressure than normal but an attempt to depressure the jacket by opening the drain valve was aborted due to the deafening noise generated by the venting steam. Soon afterwards, the reaction mix was seen rising up the glass riser and a decision was taken to evacuate the building. Two bursting discs ruptured, releasing fumes and black particulate matter to atmosphere for around 20 minutes. Several joints on the glass riser failed relieving black, tar-like decomposed material to the floor of the reactor hall.

Incident Analysis

Basic cause was abnormally high synthesis reaction end temperature.

Critical factors included: 1) A historical 10% batch size increase resulted in a small rise in synthesis reaction end temperature, 2) Reactor temperature exceeded measurable range (prevented early warning of runaway).

Root causes included: 1) Inadequate process design (inadequate boiling barrier; no distillate reflux or quench system), 2) Inadequate thermometry (insufficient range), 3) Inadequate process control (no auto temperature control), 4) Inadequate management of change (batch size increase).

Lessons Learned

1) A boiling barrier is only sufficient if it can remove all the decomposition reaction energy and if the process can cope with the rate of boiling from the energy released, 2) Decomposition reaction severity can be estimated from energy potential (eg. adiabatic temperature rise); probability can be estimated from maximum temperature of synthesis reaction (MTSR) and time required to reach maximum rate of decomposition at adiabatic conditions (TMR_{ad}).

More Information

1) "Historical Runaway Reaction Case Study (January 1992)", M. Rantell, IChemE Loss Prevention Bulletin 273 (2020).

Industry Sector	**Process Type**	**Incident Type**
Pharmaceutical	Active drug ingredients	Runaway Reaction
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment related	Not applicable	Not applicable

Incident Title	**Polyethylene Dust Explosion**
Incident Type	Dust Explosion
Date	29th January 2003
Country	USA
Location	Kinston, NC

Fatalities	Injuries	Cost
6	38	Unknown

Incident Description


Credit: US Chemical Safety Board

An explosion and fire occurred at a plant producing rubber drug-delivery components (e.g. syringe plungers, vial seals, septums etc). The semi-continuous manufacturing process involved compounding batches of rubber in mixers, rolling them into strips, and then either moulding them on site or shipping them off site. To reduce the stickiness ("tackiness") of the rubber, the rolled strips were first conveyed through a tank containing a slurry of very fine polyethylene powder in water ("anti-tack" agent). The coated rubber strips were then air dried with fans. The explosion occurred abruptly with while the plant was operating normally. Six workers were killed, 38 more (including 2 responding firefighters) were injured and much of the plant was destroyed.

Incident Analysis

Basic cause was accumulation of fine polyethylene dust above a suspended ceiling in the production area which somehow became dispersed creating an explosive mixture in a confined space which then exploded.

Critical factors included: 1) Polyethylene dust was not identified as a combustible material on the MSDS, 2) The room containing the rubber compounding process had a suspended tile ceiling and a comfort air (HVAC) system that drew air through the ceiling, 3) Small amounts of polyethylene dust will have become airborne as the rubber strips were blown dry, 4) Dust removal from hidden surfaces in the production area (e.g. above suspended ceiling) was not part of the permanent cleaning crew's housekeeping activity, 5) Electrical fixtures and wiring in the production area were not Ex rated, 6) The sprinkler system was rendered inoperable by the explosion.

Root causes included: 1) Inadequate hazard awareness (polyethylene dust not recognised as combustible material), 2) Inadequate risk assessment (ignition risk, hazardous area classification), 3) Inadequate process hazard analysis (consequences of combustible dust dispersion), 4) Inadequate building design (failure to comply with relevant design codes and fire safety standards), 5) Inadequate communication (combustible dust hazard not communicated to employees), 6) Inadequate training and procedures (control of combustible dust hazards).

Lessons Learned

1) A full combustibility assessment should be carried out on all fine powders even if the MSDS does not indicate a combustibility risk.
2) HVAC (comfort air) systems are capable of drawing fine dust through suspended ceilings and into air ducts operating at negative pressure.
3) Housekeeping (cleaning) activity should include all areas of a facility, not just the main manufacturing process area.
4) Dust accumulation significantly increases the risk of a larger secondary explosion with potential for major injuries, fatalities and facility destruction.

More Information

1) "Dust Explosion", US Chemical Safety and Hazard Investigation Board, Report No. 2003-07-I-NC (2004).
2) "Combustible Dust Explosion", US Chemical Safety and Hazard Investigation Board, Safety Digest, April 2018.
3) "Kinston Dust Explosion", Q. A. Baker & M. Kolbe, Proceedings of the 5th International Seminar on Fire and Explosion Hazards, April 2007.
4) HSG103: "Safe Handling of Combustible Dusts – Precautions against Explosions", UK Health & Safety Executive, ISBN 978 0 7176 2726 4 (2003).
5) BS EN 60079 Part 10-2: "Explosive Atmospheres – Classification of Areas – Combustible Dust Atmospheres", BSI (2015).

Industry Sector	Process Type	Incident Type
Pharmaceutical	Rubber compounding	Dust Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment related	Not applicable	Not applicable

Incident Title	**Batch Reactor Internal Overpressure**
Incident Type	Runaway Reaction
Date	28th April 2008
Country	Ireland
Location	Cork (Munster)

Fatalities	Injuries	Cost
1	1	Unknown

Incident Description

Credit: IChemE Loss Prev. Bulletin 237

The active drug intermediate compound 2-cyano-3-methylpyridine (CMP) was being manufactured by batch reaction of picoline-N-oxide (PNO) with diethylcarbamoyl chloride (DECC) in acetone (C_3H_6O). The resultant intermediate, an acyloxypyridinium salt, is then further reacted with an aqueous solution of sodium cyanide (NaCN) in another reactor to produce the CMP product. On the day of the day of the incident, a glass-lined, mechanically agitated carbon steel reactor suffered significant deformation and a blowout of the manway gasket and solids addition (charge) chute top cover, resulting in the release of reactants at high temperature and pressure. Two operators were present at the time. Both were severely injured (one later died from his injuries). The reactor and associated hardware suffered significant damage. The blast wave from the vessel failure also caused extensive damage to the 4-storey building.

Incident Analysis

Basic cause was failure of the reactor manway gasket and loss of primary containment (LOPC) due to an exothermic runaway chemical reaction and consequent two-stage thermal decomposition (acyloxypyridinium salt and then picoline-N-oxide) when the exothermic onset temperature was reached.

Critical factors included: 1) PNO and acyloxypyridinium salts are thermally unstable and decompose violently, 2) The acetone solvent charge step prior to DECC addition was omitted (reason unknown), 3) Omission of acetone solvent results in a lower acyloxypyridinium salt decomposition onset temperature and a more violent decomposition reaction, 4) Omission of acetone solvent also increases the reaction mix batch viscosity, adversely affecting mixing and heat transfer efficiency, 5) The consequences of omitting acetone solvent addition were underestimated in the HAZOP review, 6) The solids charge chute provided (unintended) additional emergency relief capacity which may have prevented catastrophic failure of the reactor vessel.

Root causes included: 1) Inadequate process hazard analysis (HAZOP) and risk assessment, 2) Inadequate operating procedures (addition of acetone not highlighted as safety-critical step), 3) Inadequate design (pressure safety valve (PSV) and bursting disc (BD) set pressures and relief line sizing), 4) Inadequate emergency procedures (operators required to approach unstable reactor to close valves to isolate reactor overheads glassware).

Lessons Learned

1) Process hazard analysis (HAZOP) and risk assessment reviews should be carried out by experienced and competent staff with the full breadth of chemistry, process, engineering and operating knowledge.
2) Quantitative reaction hazard assessment data (thermal stability tests, calorimetry, etc) must be used to inform design of appropriate safeguards.
3) Operating procedures should clearly identify safety-critical steps.
4) Reliance solely on plant operators to routinely carry out safety-critical tasks or to approach a reactor operating out of control is not acceptable.

More Information

1) “Runaway Chemical Reaction at Corden Pharmachem, Cork”, S. J. Gakhar, S. M. Rowe, M. Boylan and P. Conneely, IChemE Symposium Series No 159, Hazards 24 - Paper 59.
2) HSG143: “Designing and Operating Safe Chemical Reaction Processes”, UK Health & Safety Executive (2000), ISBN 0-7176-1051-8.
3) BS EN ISO 4126-3: “Safety Devices for Protection Against Excessive Pressure (Safety Valves and Bursting Disc Safety Devices in Combination)”.

Industry Sector	Process Type	Incident Type
Pharmaceutical	Active Drug Ingredients	Runaway Reaction
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessel	Reactor

IChemE
Water Special Interest Group

Process Safety in the Water Sector

“As the 'universal solvent', water is capable of dissolving a huge number of toxins and hazardous contaminants. Water is also home to myriad viruses, bacteria and parasites.

The water industry is unique in that one of its main products is supplied for human consumption on a continuous basis to almost the entire population of most high-income countries. Furthermore, the product is also expected to be supplied at such low cost that, as well as drinking it, people are able to afford to wash in it, wash their property with it and even flush it down the toilet.

It is therefore one of the greatest engineering achievements that, given these economies, our newspapers aren’t filled with water treatment incident reports. The elimination of waterborne disease, both through water and wastewater treatment, is the *raison d’être* of the water sector.

Water and wastewater are of course significant hazards in themselves (e.g. drowning), even more hazardous substances are used in their treatment. Pathogens are the greatest cause of waterborne disease, and the majority of chemicals and techniques used to kill these pathogens are similarly hazardous to treatment operators: chlorine, ozone, UV, etc. Where pathogens are removed rather than killed, their high concentration in waste streams also increases the exposure risks to treatment operators. Given the quantities of water and wastewater that require to be treated, water treatment projects can be huge in scale, coming with all the risks of any other large-scale civil construction and maintenance activity.

One might therefore consider the water sector is all about risks. As the risks of drinking untreated water and returning untreated wastewater to the environment are unacceptable, the water sector manages these risks for the greater good. It is a testimony to the work of process engineers and others in the sector that this risk is managed so well. However there remains a balance of risk and cost.

It is highly instructive and cost effective to study past incidents, like the brief but diverse set of three included in this document, to learn how to better manage risk and continue to improve the health and safety of both water sector customers and professionals. Rather than waiting for an incident to happen within your sector, it is even better to learn from the mistakes of others.

The most significant ongoing water treatment problems annually result in the deaths of ~829,000 people from diarrhoea as a result of unsafe drinking-water, poor sanitation and inadequate hand hygiene (https://www.who.int/news-room/fact-sheets/detail/drinking-water). The technology already exists to avoid the vast majority of these deaths and of future deaths resulting from climate change-induced drought and flooding. Again, it is a risk versus cost issue.”

Dr Martin Currie CEng FIChemE
Chair of IChemE Water SIG

Lessons Learned Database
Individual Incident Summary Report

IChemE Safety & Loss Prevention Special Interest Group

Incident Title	**Water Pumping Station Explosion**
Incident Type	Explosion
Date	23rd May 1984
Country	UK (England)
Location	Abbeystead (Lancashire)

Fatalities	**Injuries**	**Cost**
16	28	Unknown

Incident Description

Credit: ANL/Shutterstock

On the evening of the incident, a group of 44 visitors were attending a public consultation meeting which had been set up to allay local residents' concerns that water pumped into the River Wyre via the Lune/Wyre River Transfer Link Scheme may have aggravated winter flooding in the lower Wyre Valley. (The scheme was built to meet anticipated future increases in water demand in the region through the 1980s). The meeting was held in a Valve House set into a hillside at the Abbeystead Outfall Station located at the outfall end of the link. The meeting included a demonstration of the station's operation with water being pumped over the weir regulating the flow of water into the River Wyre. Shortly after pumping commenced, with the visitors congregated in the Valve House, there was an intense flash, followed immediately by an explosion which caused severe damage to the Valve House and fatally injured 16 people. Some were killed by the explosion, some by roof collapse and some by drowning (the steel mesh floor collapsed, throwing victims into the water chambers below which rapidly flooded with river water).

Incident Analysis

Basic cause was a confined space explosion caused by accidental ignition of methane (CH_4) gas from a coal seam 1200 m below which had been displaced from the Wyresdale Tunnel into the Valve House at the Abbeystead Outfall Station as the water level in the tunnel rose after pumps were started at the upstream Lune Pumping Station.

Critical factors included: 1) The Lune/Wyre transfer system had not been operational for 17 days before the explosion, 2) A washout valve had been left permanently open at a low point in the Abbeystead Outfall end of the Wyresdale Tunnel to avoid silt accumulation beyond the Valve House (the resulting water loss led to a void forming in the normally water-filled tunnel), 3) The Wyresdale Tunnel had been cut through a complex network of geological faults and had a concrete (porous) lining, 4) The tunnel high point vents were ducted to the underground Valve House at the Abbeystead Outfall Station, 5) Smoking was not prohibited in the Valve House.

Root causes included: 1) Inadequate hazard identification (CH_4 presence in Valve House not anticipated), 2) Inadequate design (water discharge system vented to underground room with limited natural ventilation), 3) Absence of gas detection equipment (due to inadequate hazard identification), 4) Violation of operating procedures (washout valve left open), 5) Inadequate management of change (flush procedure using washout valves).

Lessons Learned

1) Methane solubility in water increases with pressure, 2) Methane gas can be evolved from groundwater and in water boreholes, 3) Systems conveying water should be designed such that any gas evolved is vented to a safe location in the open air.

More Information

1) "The Abbeystead Explosion: a report of the investigation by the Health and Safety Executive into the explosion on 23 May 1984 at the valve house of the Lune/Wyre Water Transfer Scheme at Abbeystead", Her Majesty's Stationery Office, ISBN 0-11-883795-8.
2) "What Went Wrong? Case Histories of Process Plant Disasters and How They Could Have Been Avoided", 4th Edition (1999), Trevor Kletz, Elsevier, ISBN-10: 0 88415-920-5, ISBN-13: 978-0-88415-920-9.
3) Incident Overview: https://en.wikipedia.org/wiki/Abbeystead_disaster.

Industry Sector	**Process Type**	**Incident Type**
Water	Water Distribution	Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment-related	Not applicable	Not applicable

Incident Title	**Public Water Supply Contamination**	
Incident Type	Water Pollution	
Date	6th July 1988	
Country	UK (England)	
Location	Lowermoor (Cornwall)	
Fatalities	**Injuries**	**Cost**
1? – Ref. 2	~ 400	Unknown

Incident Description

Credit: British Broadcasting Corporation

The Lowermoor water treatment plant receives surface water run-off from Bodmin Moor and delivers treated water to the North Cornwall distribution network, including the nearby town of Camelford. The raw water is slightly acidic (low pH) and has a relatively intense brown colour caused by presence of suspended organic matter. Pre-treatment includes addition of aluminium sulphate ($Al_2(SO_4)_3$) flocculant to remove suspended solids and dissolved organic acids, and slaked lime ($Ca(OH)_2$) to adjust the pH. On the day of the incident, a temporary (relief) tanker driver inadvertently unloaded 20 tonnes of $Al_2(SO_4)_3$ flocculant into a chlorine contact tank instead of a storage tank at the unmanned Lowermoor plant. The contact tank is just upstream of the treated water reservoir, so water with a high concentration of $Al_2(SO_4)_3$ was able to enter the distribution system. Aluminium (Al) is a neurotoxin at high concentrations, but the increased acidity of the water caused by the $Al_2(SO_4)_3$ stripped lead (Pb) and copper (Cu) from piping in peoples' homes, increasing its toxicity. Camelford residents complained of sore throats, vomiting, bowel problems, joint pains and short-term memory loss. The water authority who operated the plant advised the public that the water was safe to drink.

Incident Analysis

Basic cause was accidental contamination of the treated water system by erroneous unloading of a batch of aluminium sulphate ($Al_2(SO_4)_3$) flocculant.

Critical factors included: 1) The treatment plant was unmanned, 2) The relief driver was unfamiliar with the plant layout and delivery procedures, 3) The contact tank and retaining tank were not labelled, 4) A common key was used for all locks including all gates, doors and tanks at the plant, 5) No landline telephone was available at the plant (mobile phones were not in common use at the time), 6) The lime dosing pump was unreliable (masked the problem), 7) The water authority failed to notify the public health authority of the severity of the incident until nearly 16 days after the incident.

Root causes included: 1) Inadequate monitoring (plant operation and treated water quality), 2) Inadequate training (chemical tanker drivers), 3) Inadequate risk assessment (potential for treatment chemical overdosing), 4) Inadequate emergency planning (absence of emergency procedures for chemical overdosing and emergency callout system for treatment plant staff), 5) Inadequate communication (with public health authorities).

Lessons Learned

1) Process hazard identification and mitigation studies should be carried out on the design and operation of water treatment plants and should include consideration of worst-case scenarios (e.g. bypassing of treatment steps leading to contamination of public water supply by treatment chemicals).
2) Chemical receipt facility designs and procedures should prevent deliveries to the wrong tank (e.g. labels, unique locks and keys, supervised deliveries).

More Information

1) "Water Pollution at Lowermoor, North Cornwall: 2nd Report", Lowermoor Incident Health Advisory Group, Nov 1991, Her Majesty's Stationery Office, ISBN: 978-0-11321-476-1.
2) "Subgroup Report on the Lowermoor Water Pollution Incident", Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment, Feb 2013: https://cot.food.gov.uk/sites/default/files/cot/lwpiapp811.pdf.
3) Coroner's Summing Up - Appendix 20 of the Subgroup Report (Ref. 2): https://cot.food.gov.uk/sites/default/files/cot/rlwpiapp20.pdf.

Industry Sector	Process Type	Incident Type
Water	Water Treatment	Water Pollution
Equipment Category	**Equipment Class**	**Equipment Type**
Not equipment-related	Not applicable	Not applicable

IChemE Safety & Loss Prevention Special Interest Group

Incident Title	**Public Water Supply Contamination**
Incident Type	Waterborne Disease
Date	5th April 1993
Country	USA
Location	Milwaukee, WI

Fatalities	**Injuries**	**Cost**
69 – Ref. 2	~ 403,000 – Ref. 1	US$ 96 m (2003) – Ref. 3

Incident Description

Credit: Kateryna Kon/Shutterstock

Milwaukee city water is sourced from Lake Michigan and supplied by 2 water treatment plants (WTPs); Linwood WTP on the north side and Howard Avenue WTP on the south side. The treatment process at both involved adding chlorine (disinfectant) and polyaluminium chloride (coagulant), rapid mixing, mechanical flocculation, sedimentation and rapid sand filtration. The treated water was stored in a large clearwell before entering the distribution network. The filters were backflushed with treated water which was then recycled through the WTP. On 5th April 1993, widespread gastrointestinal illness and significant school and workplace absenteeism was reported among Milwaukee residents. A survey of diarrhoea cases in local nursing homes (geographically fixed populations) and testing of infected resident's stools for cryptosporidium revealed that the outbreak was concentrated on the south side. These results coupled with discovery of treated water turbidity problems at the Howard Avenue WTP over the preceding 2 weeks suggested that drinking water supplied by the Howard Avenue WTP could be implicated. The plant was shut down and the city mayor issued a boil water advisory.

Incident Analysis

Basic cause was breakthrough of cryptosporidium oocysts to finished water due to inadequate filtration at the Howard Avenue WTP. (Cryptosporidium oocysts are tiny protozoan parasites which can cause severe or fatal gastrointestinal illness, especially in immunodeficient people.)

Critical factors included: 1) Cryptosporidium oocysts are 3 - 6 μm diameter and highly resistant to chlorine (coagulation and filtration control crucial), 2) Severe spring storms (high source water turbidity and microbial load), 3) Turbidity of finished water was only measured every 8 hours (the minimum allowed by authorities), 4) Rapidly changing source water quality, long sampling lag time and limited operating history with polyaluminium chloride (replaced aluminium sulphate in Sep-92) made dosage optimisation difficult.

Root causes included: 1) Inadequate monitoring (testing for turbidity and cryptosporidium oocysts ineffective), 2) Inadequate process design (recycling filter backwash effluent without extra treatment), 3) Inadequate training (WTP operators), 4) Inadequate/inconsistent state water quality standards.

Lessons Learned

1) Filter backflush effluent recycling was discontinued at both WTPs (to break the "concentration loop"), 2) Continuous turbidity monitoring with alarms and automatic shutdowns was installed at each filter in both WTPs, 3) Ozonation units were installed at both WTPs to improve disinfection, 4) Procedures for turbidity monitoring and cryptosporidium sampling/testing in both source and finished water were improved and standardised across the industry, 5) Filter backflush effluent requires additional treatment (e.g. lamella sedimentation) before recycling, 6) For WTPs where cryptosporidium breakthrough risk is high, additional disinfection (e.g. ozonation, ultra-violet irradiation) is required.

More Information

1) "Cryptosporidium and the Milwaukee Incident", K. Fox and D. Lytle, US Environmental Protection Agency, Report No. EPA/600/A-94/251 (1994).
2) "Lessons from Waterborne Disease Outbreaks", Institute of Medicine (US) Forum on Microbial Threats, Washington (DC), National Academies Press (2009): https://www.ncbi.nlm.nih.gov/books/NBK28459/#ch2.s10.
3) "Costs of Illness in the 1993 Waterborne Cryptosporidium Outbreak, Milwaukee, Wisconsin", P.S. Corso et al, Emerging Infectious Diseases Journal Volume 9 (2003): https://dx.doi.org/10.3201/eid0904.020417.

Industry Sector	**Process Type**	**Incident Type**
Water	Water Treatment	Waterborne Disease
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Filters and Strainers	Sand Filter

Process Safety in the Food and Drink Sector

“This document shines a light on some major process safety incidents from around the world and clearly shows that process safety is critical across all process industries as all are inherently hazardous. It also highlights that many of the hazards are similar despite the products or materials used being seemingly different. For example, petrochemical oils and vegetable oils can both be flammable and require thorough hazard and risk assessments within design, commissioning and operation to minimise fire risk.

The following three articles are good examples of where food processing, without the correct due diligence, has resulted in huge devastation and loss of lives. The industry is tightly regulated to prevent re-occurrences of fatal incidents with standards and guidance to help with the implementation of safety procedures. This spans from ‘the obvious’ Hazard and Operability studies (HAZOPs) through to strict change control procedures, safety audits and mandatory monitoring procedures. To complement this, where incidents or near misses occur, it is essential to follow up with a root cause analysis to identify what measures are required to minimise or eliminate the risk of future incidents occurring.

The food and drink sector continues to progress safety by design wherever possible and practical following regulatory guidance. For the unavoidable process hazards, there are improving process technologies that minimise risk through automation and control.

The focus of this document is process safety; this is one important aspect of health and safety within the food and drinks industry. Another key consideration is food safety, with serious incidents possible from physical, chemical or biological risks associated with the food itself; choking hazards, allergic reactions and food poisoning, respectively.

This document helps to highlight process safety challenges across the various chemical processing industries. Chemical and process engineers should take note of the hard-learned lessons of the past and influence a safer future for all.”

Dr Laura Malhi MEng CEng PhD MIChemE
Chair of IChemE Food and Drink SIG

Incident Title	**Chicken Processing Plant Fire**
Incident Type	Fire
Date	3rd September 1991
Country	USA
Location	Hamlet, NC

Fatalities	Injuries	Cost
25	54	Unknown

Incident Description


Credit: Wikimedia Commons

A major fire erupted at a gas-fired deep fat fryer in a chicken processing plant building. It spread rapidly, causing panic, and many workers were injured as they rushed to escape. Large quantities of dense smoke were produced by a combination of burning soybean oil and chicken, along with melting roof insulation. The smoke had the potential to disable a person after just a few breaths. Several gas pipes in the ceiling caught fire and exploded. 25 people died and a further 54 were injured, suffering after-effects including burns, blindness, respiratory diseases from smoke inhalation and post-traumatic stress disorder (PTSD). The plant owner received a prison sentence of almost 20 yrs, subsequently commuted to 4 yrs. The plant was never re-started.

Incident Analysis

Basic cause was failure of a pipe connector on a high pressure hydraulic oil feed line which powered a conveyor belt supplying a deep fat fryer (cooking vat). The pressurised oil release atomised and vapourised on hot surfaces, erupting into a fireball on contact with flames in the deep fat fryer.

Critical factors included: 1) Open layout of plant to allow easy movement of product by fork lift truck (no smoke/heat barriers), 2) Fire doors were kept locked to prevent theft, vandalism and incursion of flies (workers trapped), 3) Hamlet was not connected to the "911" emergency telephone service (workers unable to immediately call for help), 4) Worker who drove to nearby fire station to report the factory fire did not mention trapped workers, 5) No safety inspections were carried out by the state or local authorities (locked fire doors and inadequate emergency lighting not reported).

Root causes included: 1) Inadequate management of change (new hose trimmed), 2) Inadequate repair (old connector fitted to new hose and placed in service without pressure test), 3) Inadequate hazard analysis (atomisation and vapourisation of hydraulic oil), 4) Inadequate fire protection (automatic fire detection/suppression system), 5) Normalisation of deviance (failure to unlock fire doors after previous fires), 6) Inadequate safety management system (absence of evacuation plans, fire drills, fire training for workers), 7) Inadequate communication system ("911" emergency telephone), 8) Failure to enforce existing safety and fire protection regulations (inadequate funding for Occupational Health and Safety Administration [OSHA] safety inspectors yet US Department of Agriculture [USDA] poultry inspectors visited daily).

Lessons Learned

1) High pressure (HP) hydraulic oil system maintenance should only be carried out by specifically trained technicians, 2) HP hydraulic oil systems should incorporate automatic emergency shutdown systems (ESDs), 3) Cooking areas should be separated from other process areas, 4) Non-combustible materials should be used for construction of buildings (e.g. concrete, bricks or steel) and internal partitions should have time-rated fire resistance, 5) Federal and state inspectors from various departments should be cross-trained in hazard recognition.

More Information

1) "Chicken Processing Plant Fires; Hamlet, North Carolina and North Little Rock, Arkansas", US Fire Administration, Technical Report USFA-TR-057.
2) "The Hamlet Chicken Processing Plant Fire - Outcomes and Good Practices for Avoiding a Recurrence", T. Fishwick, IChemE Loss Prevention Bulletin 260 (2018). https://www.icheme.org/media/1991/lpb260_pg06.pdf.
3) "The Hamlet Fire; A Tragic Story of Cheap Food, Cheap Government and Cheap Lives", B. Simon, The New Press, ISBN 978-1-62097-238-0 (2017).

Industry Sector	Process Type	Incident Type
Food & Drink	Food Processing	Fire
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Piping	Hose Connection

Incident Title	**Spray Drier Feed Tank Catastrophic Failure**
Incident Type	Explosion
Date	11th April 2003
Country	USA
Location	Louisville, KY

Fatalities	**Injuries**	**Cost**
1	0	Unknown

Incident Description

Credit: US Chemical Safety Board

A spray drier feed mixing tank exploded on a plant manufacturing food-grade caramel colouring. The top head of the tank separated at the weld seam and was propelled approximately 91 m (100 yds) before landing on a railway line used by third parties for freight transportation. The explosion toppled the spray drier structure and pushed an aqueous ammonia (NH_3) storage tank off its foundation causing escalation of the incident due to release of 11.8 tonnes (26,000 lb) of the 29.4 vol% strength NH_3 solution. The resulting toxic NH_3 vapour cloud necessitated evacuation of 26 neighbouring residents and execution of a shelter-in-place order for a further 1500 residents.

The ruptured feed tank was the larger of two in the same service. Both tanks were fabricated from 316 stainless steel and contained an agitator and a dual-purpose internal stainless steel coil for heating with steam or cooling with water. Neither was rated for vacuum. Both could be pressurised with compressed air (when their respective vent valves were closed) to assist transfer of the highly viscous product to the spray drier feed pump. The air supply header operated at 8.6 barg (125 psig) and the tank pressures in each were modulated to approximately 1.5 barg (22 psig) by self-contained pressure regulators. The tanks were manually operated on an alternating basis to maintain a continuous feed flow to the drier (one tank in service while the second was prepared, then switched over when the first tank ran empty).

Incident Analysis

Basic cause was overpressure and rupture of the feed tank due to extended heating of the tank contents with the vent line plugged.

Critical factors included: 1) The feed tanks had not been designed to the relevant code (ASME VIII), 2) Both tanks had been relocated from plants in other States and installed without the pressure relief device provided in their previous service, 3) The ruptured tank had been weakened by misapplication of vacuum in service twice at another location, 4) The Louisville plant relied on operator vigilance for safe operation (the tanks had local temperature and pressure indication but no automatic process controls), 5) Operators were distracted by other duties (re-labelling mislabelled product boxes), 6) The vent pipe on the ruptured tank was subsequently found to be plugged.

Root causes included: 1) Inadequate design (not compliant with ASME VIII), 2) Inadequate communication (failure to register tanks with State authority), 3) Absence of fitness for service inspection, 4) Inadequate process hazard analysis, 5) Failure to learn (misapplication of vacuum), 6) Inadequate instrumentation (no alarms), 7) Inadequate operator training (response to abnormal operating conditions), 8) Inadequate operating procedures (failure to highlight importance of keeping vent valve open while heating and inherent risk of overpressure), 9) Inadequate maintenance (vent pipe plugged).

Lessons Learned

1) All pressure systems should be subjected to a process hazard analysis (PHA) to ensure appropriate control systems, alarms, trips and pressure relief systems are provided to prevent catastrophic failure due to overpressure.
2) Re-purposed equipment should always undergo a full fitness for service (FFS) inspection and pre-startup safety review (PSSR).
3) Relocated pressure vessels may need re-registration with a new authority.

More Information

1) "Catastrophic Vessel Failure", US Chemical Safety and Hazard Investigation Board, Report No. 2003-11-I-KY (2004).

Industry Sector	**Process Type**	**Incident Type**
Food & Drink	Food Processing	Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Mechanical	Vessel	Pressurised Mixing Tank

Incident Title	**Granulated Sugar Conveyer Belt Explosion**
Incident Type	Dust Explosion
Date	7th February 2008
Country	USA
Location	Port Wentworth, GA

Fatalities	Injuries	Cost
14	36	?

Incident Description  Credit: US Chemical Safety Board	An explosion occurred in the enclosed steel conveyer belt system under the granulated sugar storage silos. Seconds later, a series of massive secondary explosions propagated through the granulated and powdered sugar packing buildings, bulk sugar loading buildings and parts of the raw sugar refinery. Eight workers died at the scene and six more eventually succumbed to their injuries. Thirty six workers ultimately survived the accident, but had to be treated for serious burns and injuries; some had suffered permanent life-changing injuries. The major fires in the buildings were extinguished by the next day but some burned for up to 7 days after the initial blast. The sugar packing buildings, palletiser room and silos were destroyed, and the bulk train car loading area and parts of the sugar refining process areas were severely damaged.
Incident Analysis	**Basic cause** was sugar dust concentration in the conveyer belt enclosure exceeded the minimum explosive concentration and was ignited by an overheated bearing. **Critical factors** included: 1) Poor housekeeping (combustible sugar dust allowed to accumulate on floors and elevated surfaces throughout the packing buildings), 2) Fire suppression sprinkler system was rendered ineffective due to damage caused by the initial explosion. **Root causes** included: 1) Inadequate hazard awareness (combustible dust), 2) Inadequate risk assessment (installation of conveyer belt enclosure), 3) Inadequate design (absence of dust removal and over-pressure protection systems), 4) Inadequate housekeeping practices (failure to remove sugar dust accumulation and granulated sugar spillages), 5) Inadequate leadership (failure to correct non-compliance led to normalisation of poor housekeeping standards), 6) Inadequate emergency preparedness (absence of emergency intercom system in refining and packing areas where the explosions took place), 7) Inadequate training (absence of evacuation drills).
Lessons Learned	1) Provision of dust-handling equipment and good housekeeping to prevent dust accumulation are critically important risk mitigation measures against potential dust explosions, 2) Shockwaves from an initial explosion can dislodge accumulated dust, and the fireball can ignite it, triggering a chain reaction of secondary explosions, 3) Secondary explosions can be more powerful and destructive than primary explosions because of the increased concentration and quantity of airborne particles.
More Information	1) "Sugar Dust Explosion and Fire", US Chemical Safety and Hazard Investigation Board, Report No. 2008-05-I-GA (2009). 2) NFPA 61: "Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities", US National Fire Protection Association (2020). 3) HSG103: "Safe Handling of Combustible Dusts – Precautions against Explosions", UK Health & Safety Executive, ISBN 978 0 7176 2726 4. 4) INDG370: "Controlling Fire and Explosion Risks in the Workplace", UK Health & Safety Executive (2013). 5) BS EN 60079 Part 10-2: "Explosive Atmospheres – Classification of Areas – Combustible Dust Atmospheres", BSI (2015). 6) BS EN ISO 80079 Part 36: "Non-electrical Equipment for Explosive Atmospheres – Basic Method and Requirements", BSI (2016).

Industry Sector	Process Type	Incident Type
Food & Drink	Sugar Refining	Dust Explosion
Equipment Category	**Equipment Class**	**Equipment Type**
Rotating	Conveyer Belt	Bearing

IChemE
Education Special Interest Group

Safety in Chemical Engineering

"There is perhaps no aspect of chemical engineering with greater importance than that of safety because no matter how optimal it might be, any proposed technical solution or process would simply be of no value without consideration for safety. Consequently, process safety is a major component in the education of future chemical engineers and it features highly in accreditation requirements not only in reference to the content of a programme but also to the safety culture of the organisation where the programme is delivered.

In higher education programmes, process safety is covered in a variety of ways and through different means. Regardless of how it is delivered, learning from past incidents is widely used as a way of bringing safety concepts to life and highlighting the importance of safety and its impact on all aspects of what we do as engineers. Learning from previous failures, showing what can go wrong and why, helps to highlight not only the significant responsibility of practising engineers but also the constant strive to make things safer.

The Leasons Learned Database and this collection of one page summaries of major incidents is an excellent resource for those teaching process safety in higher education institutions. The Incident vs Root Cause mapping (pages 8 and 9) for the incidents reported in this booklet serves as a quick reference guide to pertinent information. The classification including industry sector, type of event, consequences and root causes for each incident is particularly useful. For instance, it could be used by lecturers when looking for real examples to demonstrate the importance of safe design, hazard identification and instrumentation and control and to show how things could go wrong. Equally, it will be an invaluable reference when exploring aspects ranging from regulatory frameworks to controls and operations in courses dealing with safety management systems. The summaries can also be used as the basis for student-centred activities where students might have to investigate and report their findings on specific topics related to process safety.

Beyond standard curricula and in the context of safety research, the one page summaries can also be used as a starting point for data collection that can be analysed and used to answer research questions on themes such as safety culture and how safety is managed within and outside an organisation.

Education is a continuous endeavour; we are constantly learning and progressing our knowledge, using the concepts and ideas learned to improve current systems. Practising engineers and those delivering Continuous Professional Development (CPD) courses will also find this a very valuable resource.

Hence, this resource is not only relevant in the context of university education but it is equally valuable to anyone within the chemical and process industries with an interest in avoiding past mistakes."

Dr Esther Ventura-Medina CEng MIChemE
Chair of IChemE Education SIG

Contact us for further information:

specialinterestgroups@icheme.org

UK
t: +44 (0)1788 578214
e: membersupport@icheme.org

Australia
t: +61 (0)3 9642 4494
e: austmembers@icheme.org

Malaysia
t: +603 2283 1381
e: malaysianmembers@icheme.org

New Zealand
t: +64 (0)4 473 4398
e: nzmembers@icheme.org

Singapore
e: singaporemembers@icheme.org

ChemEng Evolution

9 781911 446774

www.icheme.org

Front cover image credits (clockwise from top): Pasadena: Ed Kolenovsky/AP/Shutterstock; Macondo and Port Wentworth: US Chemical Safety Board; Valdez: RGB Ventures/SuperStock/Alamy Stock Photo; Buncefield: HSE

LC 0023_22