An era of unprecedented industrialization and catastrophic industrial disasters

Emergence of loss prevention, inherently safe design, reliability engineering, fundamental safety models, and the rise of the risk concept

LEGEND
- Safety scientist/activist
- Safety problem
- Safety metaphor
- Safety legislation/milestone
- Safety concept

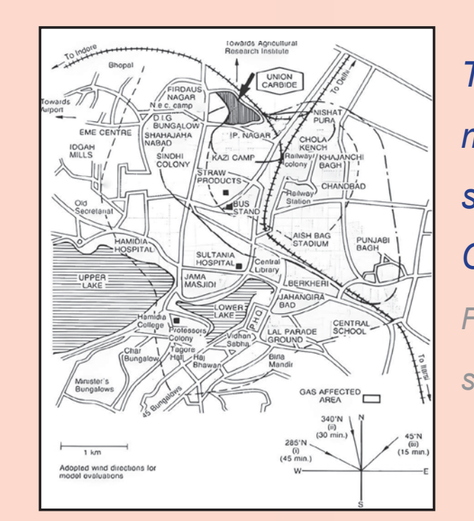
In this period, The world experienced unprecedented catastrophic human, environmental, and property losses, especially in nuclear, oil, gas, and petrochemical sectors. The 1988-1989 period still holds the record for highest capital losses in the (petro)chemical process industries.

Asia, the Soviet Union, and The Developing Countries became increasingly industrialized and experienced catastrophic accidents, highlighting the safety concerns surrounding industrial development.

The Bhopal disaster (1984, Madhya Pradesh, India) *at Union Carbide Corporation's (UCC) plant methyl isocyanate (MIC) leak remains the worst industrial disaster in history, with fatalities between 15000 and 20000, while more than 500,000 people suffered respiratory problems and environmental damages persisting to date.*

Photo of the Bhopal plant site by Julian Nyča, Wikimedia Commons, CC BY-SA 3.0.

Demonstrations on the 32nd anniversary of the disaster in Bhopal on December 3, 2016. "Bhopal Mecial Appeal" by Colin Toogood, via Flickr, CC BY-NC 2.0.



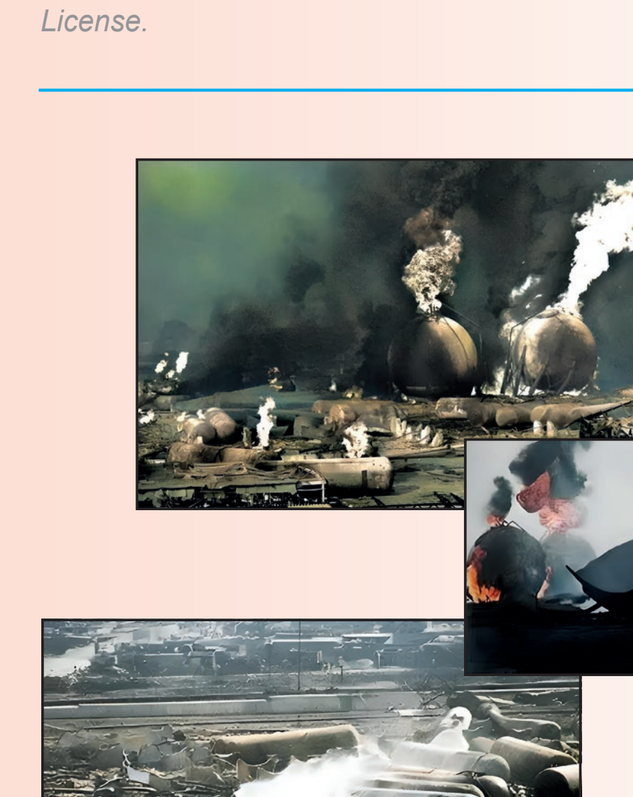
The geographical map of the area surrounding the Union Carbide plant. From safety to safety science, after Lees 1996

The Chernobyl disaster (1986, Ukraine, USSR) *ranks among the most devastating nuclear incidents, resulting in the evacuation of around 49,000 people, with estimated fatalities ranging from 4,000 to 16,000, and long-lasting ecological and health consequences.*

Chernobyl reactor post-explosion view from a helicopter, April 27, 1986, by USFCRFC, hosted by IAEA Imagebank on Flickr, CC BY-SA 2.0. License.

View of Chernobyl reactor 4 from 2012. by Michael Kötter, via Flickr, CC BY-NC-SA 2.0

San Juanico disaster (1984, Mexico), *where an LPG terminal leakage resulted in multiple explosions, causing widespread destruction and over 650 casualties.*



Photos from the San Juanico Disaster, taken from: AIChE. (2014, November). Thirty Years Ago – An LPG Tragedy. The Beacon.

The United States witnessed unprecedented industrial development, especially in the nuclear field, and had to struggle with the ensuing complexities.

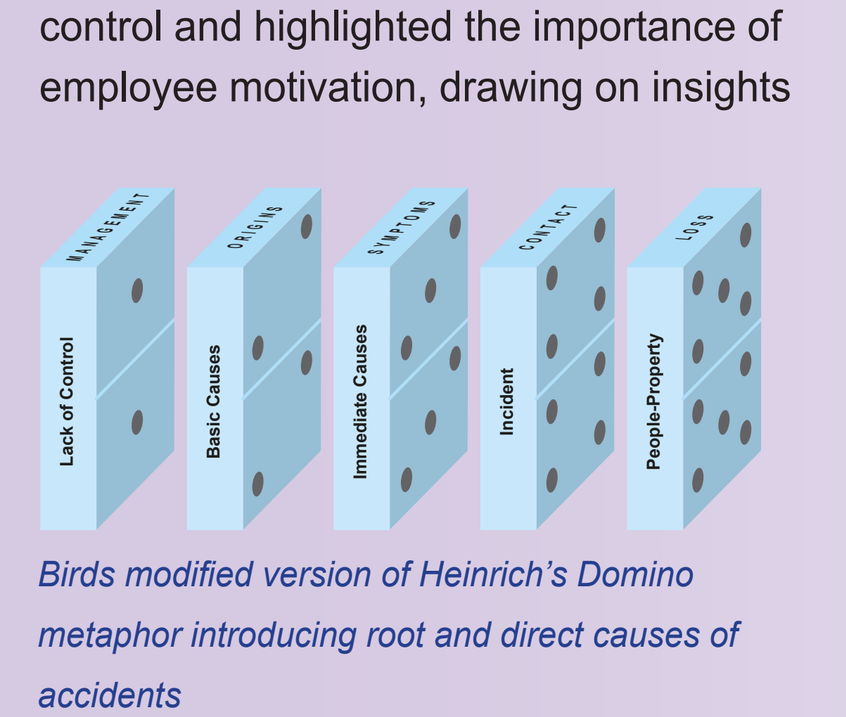
The Three Mile Island accident (1979, Pennsylvania) *was the nuclear meltdown resulting in the release of radioactive gases and iodine into the environment, marking the worst accident in US commercial nuclear power plant history, reaching level 5 of the International Nuclear Event Scale.*

Photo of the Three Mile Island Unit 2 Control Room during the crisis in 1979, "TMI-2 Control Room in 1979" by Nuclear Regulatory Commission, via Flickr

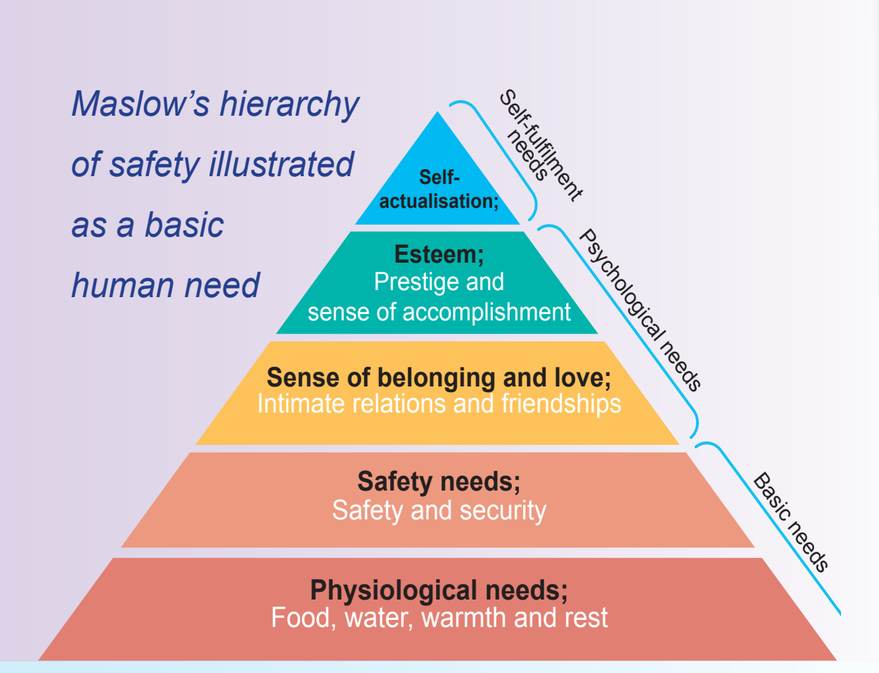
President Carter's motorcade following his visit. President Carter leaves Three Mile Island - April 1, 1979 by the Nuclear Regulatory Commission, courtesy of the National Archives at College Park, via Flickr.

Occupational research in the 1980s is associated with safety research centers emphasizing cost and technical measures, producing key publications like the Accident Prevention Manual.

Bird modified Heinrich's domino metaphor to represent a lack of management control and highlighted the importance of employee motivation, drawing on insights from Maslow's pyramid of needs. The pyramid illustrates safety as an essential human need.



Birds modified version of Heinrich's Domino metaphor introducing root and direct causes of accidents



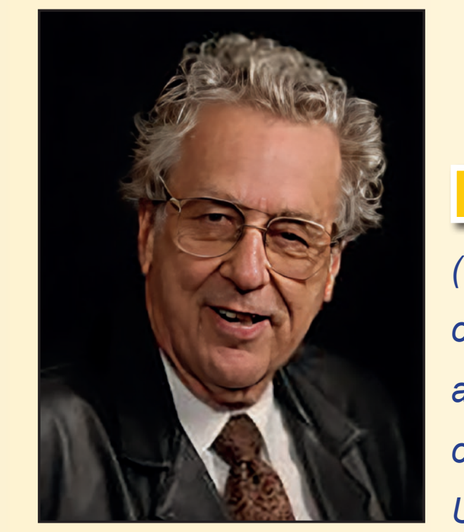
Self-actualisation;
Esteem; Prestige and sense of accomplishment
Sense of belonging and love; Intimate relations and friendships
Safety needs; Safety and security
Physiological needs; Food, water, warmth and rest
Self-fulfilment needs
Psychological needs
Basic needs

Maslow's hierarchy of safety illustrated as a basic human need

Technology and automation since the late 20th century altered the worker-task dynamic, making industrial safety complex. Pre-1800s manual work allowed personal control over safety, but post-1800s mechanization raised accident risks. Automation later changed roles to cognitive monitoring, blurring the cause of accidents and making safety a political issue due to major public impacts.

Reliability Engineering and Loss Prevention emerge as two key approaches to process safety. Reliability engineering from the military and aerospace sectors and loss prevention from the processing industry, which utilized probabilistic risk assessment (PRA) methodologies but encountered challenges due to uncertainties and data limitations, leading to a focus on best-practice methods in cost-benefit analyses.

Normal accident theory resulted from Perrow's research (1984), emphasizing that high-risk industries with tightly coupled and complex processes are prone to major unavoidable accidents due to unobservable and unforeseeable deviations. In contrast, Turner believed batch processes were safer as they are too complex to control, and their decoupling effect could mitigate some safety concerns.



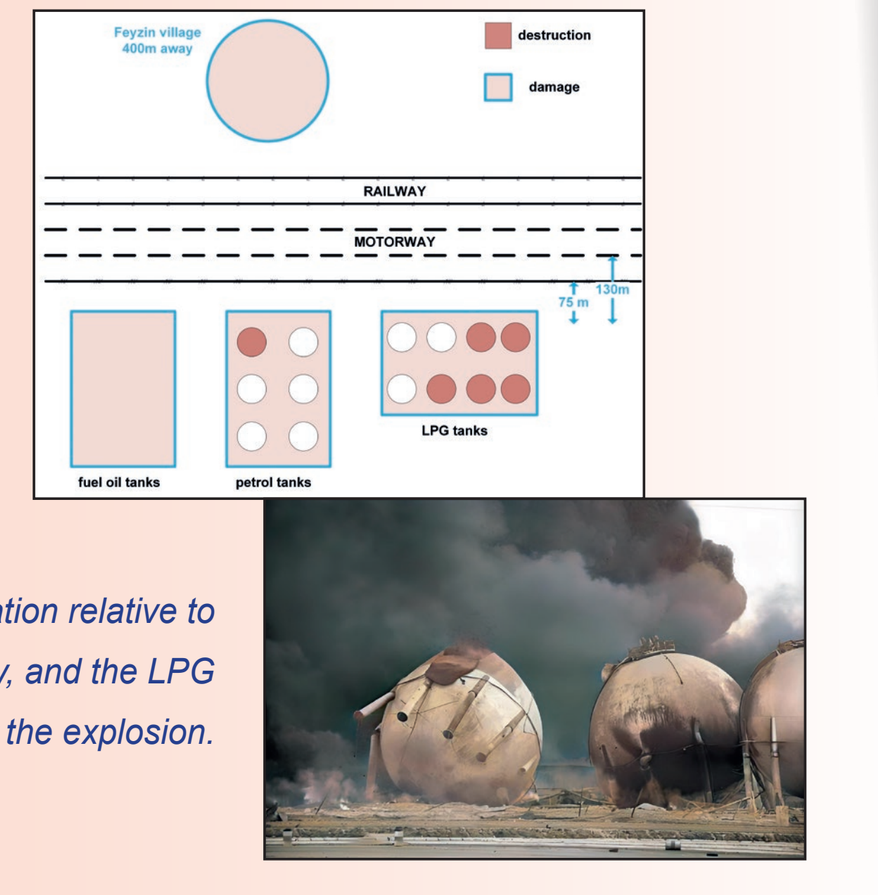
Charles B Perrow (1925-2019) was an organizational theorist, author, and professor of sociology at Yale University. Yale Sociology

High-reliability organizations (HROs) emerged by the late 1980s. HROs like aircraft carriers and air traffic control achieved safety in complex environments through learning, understanding, and corrective actions rather than separate safety management systems.

A congested runway and the deck of an aircraft carrier are examples of high-reliability organizations. "Changi Airport traffic jam" by Simon_sees, via Wikimedia Commons, CC BY 2.0. (left), flight deck of the aircraft carrier USS MIDWAY (CV-41) from the US National Archives via picryl (right)

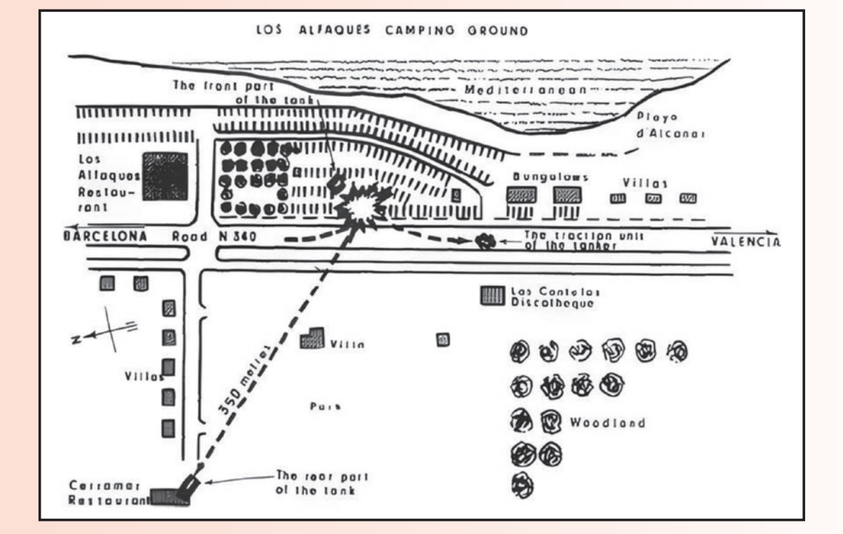
Europe and Nordic countries experienced numerous catastrophic accidents that had profound effects on their legislation and safety science.

The Feyzin Disaster (1966, Feyzin, France) *resulted in 18 deaths, 81 injuries, and extensive damage following a series of critical safety failures during the handling of liquefied petroleum gas (LPG) – leading to massive Boiling Liquid Expanding Vapour Explosions (BLEVE) highlighting inadequate safety protocols and a lack of understanding of LPG's properties*



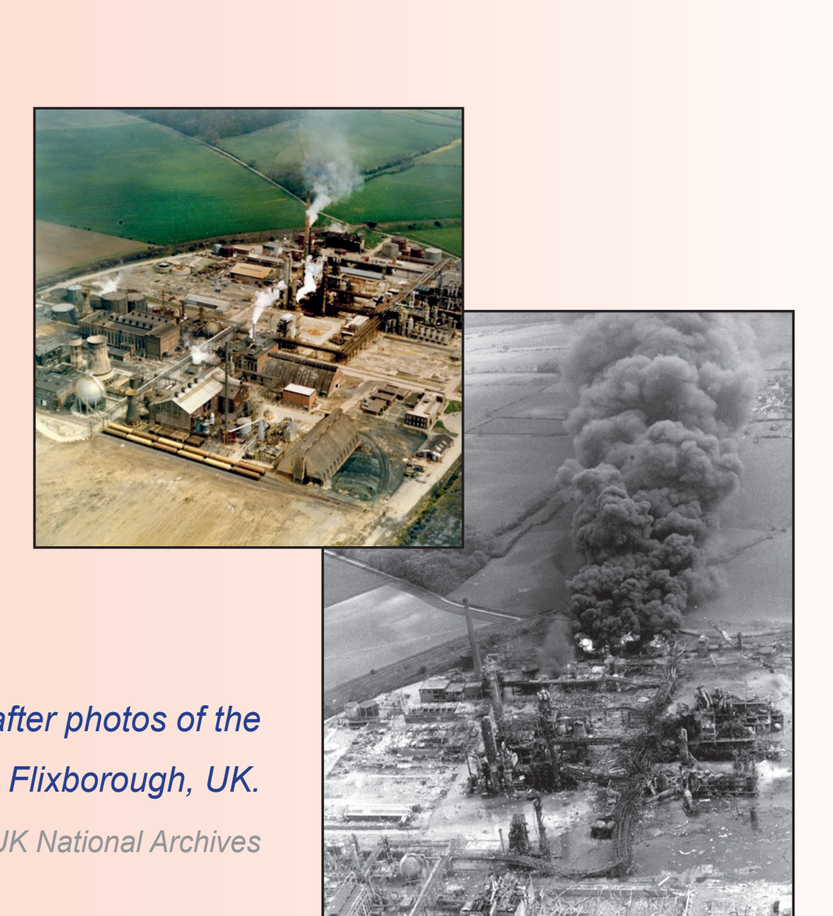
LPG facility, Feyzin France, location relative to Feyzin village, motorway, and railway, and the LPG tanks after the explosion.

Los Alfaques disaster (1978, Tarragona, Catalonia, Spain) *A road tanker carrying 23 tons of liquefied propene (propylene) – exceeding its load limit by almost 4 tons – swerved offroad, leading to a Boiling Liquid Expanding Vapor Explosion (BLEVE), killed 217, and left 200 with severe burns at a campsite. This event resulted in the prohibition of the transport of dangerous goods through populated areas.*

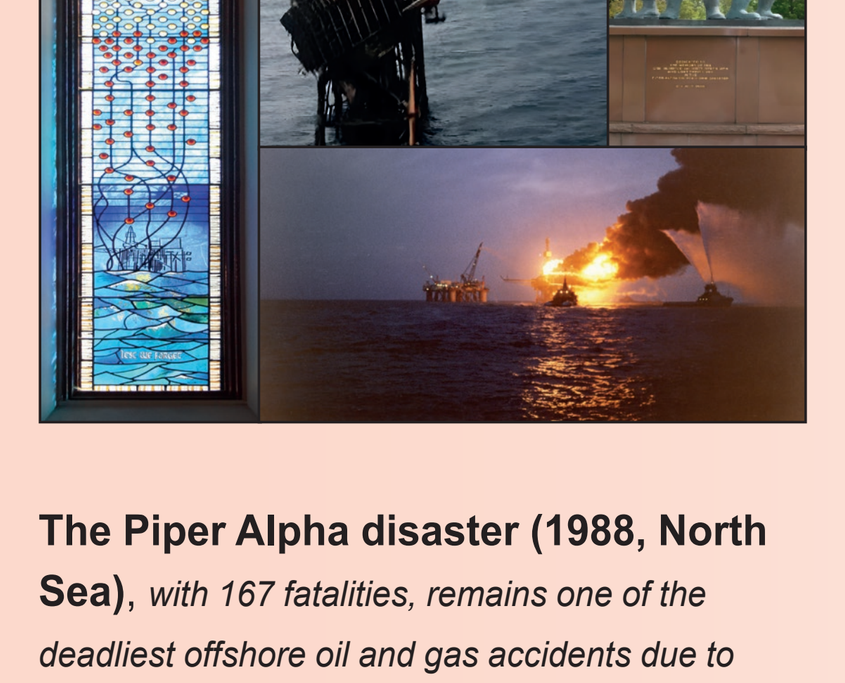


Los Alfaques site map From Safety to Safety Science (2021). the dotted line illustrates the trajectory of the tanker and its parts to the impact zone, the camping grounds. After safety and safety science taken from Arthurson 1981

The Flixborough disaster (1974, UK) *resulted in 28 fatalities, and significant injuries were caused by an explosion at a chemical plant due to a bypass assembly failure. This incident led to widespread changes in industrial safety regulations and practices in the design and modification of chemical plants focused on rigorous safety reviews and the implementation of more stringent control measures across the chemical industry. Photo credit: The National Archives*



The before and after photos of the chemical plant in Flixborough, UK. UK National Archives



Left: The Piper Alpha Window, Ferryhill Church, Aberdeen. Each disc represents a life lost. Bob Embleton / CC BY-SA 2.0, via Wikimedia Commons. *Top middle: remains of the platform. Top right: Piper Alpha victim's memorial in Hazlehead Park, Aberdeen.* Lizzie/ CC BY-SA 2.0, via Wikimedia Commons. *Bottom: Emergency responders fighting the fire.* UK National Archives

The Piper Alpha disaster (1988, North Sea), *with 167 fatalities, remains one of the deadliest offshore oil and gas accidents due to a gas condensate leak and ensuing explosions. Fires prompted significant changes to oil and gas safety protocols following the Cullen Inquiry, leading to improvements in safety management and emergency response in offshore operations.*

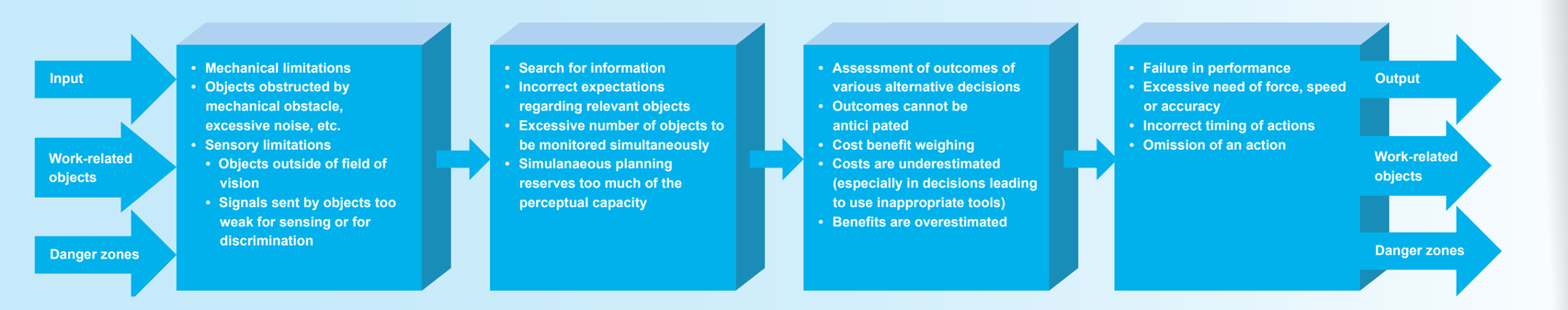
The Windscale accident (1975, United Kingdom), *where a reactor fire resulted in a radioactive cloud spreading over the UK and Europe, solidifying opposition to nuclear energy. The accident was classified as level 5 on a severity scale by the Nuclear Energy Agency, which was the worst in UK history.*

The Windscale Piles. Storm Clouds over Sellafield/ Chris Eaton/ CC BY-SA 2.0, via Wikimedia Commons

The United Kingdom's government commissions the 1972 Robens Report due to poor occupational safety, revealing high rates of disease and accidents. The complex legal system was found to be ineffective and slow to change. The Robens Committee proposed shifting hazard control to the industry, leading to the 1974 Health and Safety Act that favored goal-based regulations. It also established the Health and Safety Commission (HSC) in 1974 and the Health and Safety Executive (HSE) in 1975 for enforcement and research. The 1976 HSE report stressed the need for humanitarian working conditions and noted insufficient safety training for managers.

Perception about occupational accidents shifted from being viewed as simple phenomena with singular causes to complex interactions involving multiple factors from the 1970s. Researchers recognized that accidents were the result of various human, technological, and organizational elements. Several models were developed to understand the causes of accidents, including:

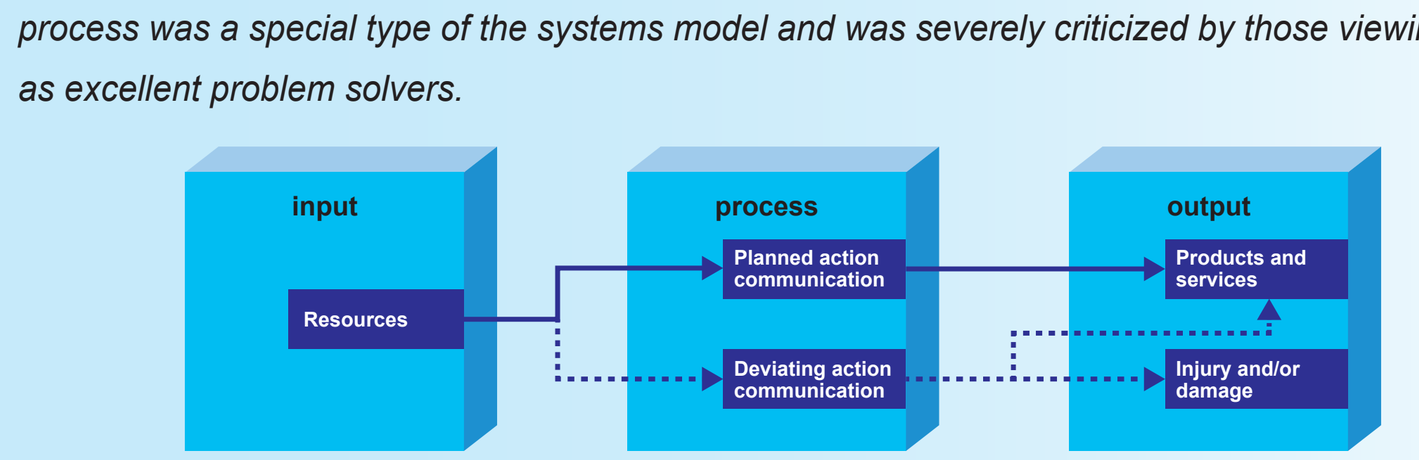
Information Model: Introduced in the 1970s by Hale and Hale and further developed in Nordic countries, accidents are posited to occur due to communication disruptions.



Input
Work-related objects
Danger zones
• Mechanical limitations
• Objects obstructed by mechanical obstacle, excessive noise, etc.
• Sensory limitations
• Objects outside of field of vision
• Signals sent by objects too weak for sensing or for discrimination
• Search for information
• Incorrect expectations regarding relevant objects
• Excessive number of objects to be monitored simultaneously
• Simulanaeous planning reserves too much of the perceptual capacity
• Assessment of outcomes of various alternative decisions
• Outcomes cannot be antici pated
• Cost benefit weighing
• Costs are underestimated (especially in decisions leading to use inappropriate tools)
• Benefits are overestimated
• Failure in performance
• Excessive need of force, speed or accuracy
• Incorrect timing of actions
• Omission of an action
Output
Work-related objects
Danger zones

The overview of the information model assumes that access to information and cognitive processes are central to accident occurrence.

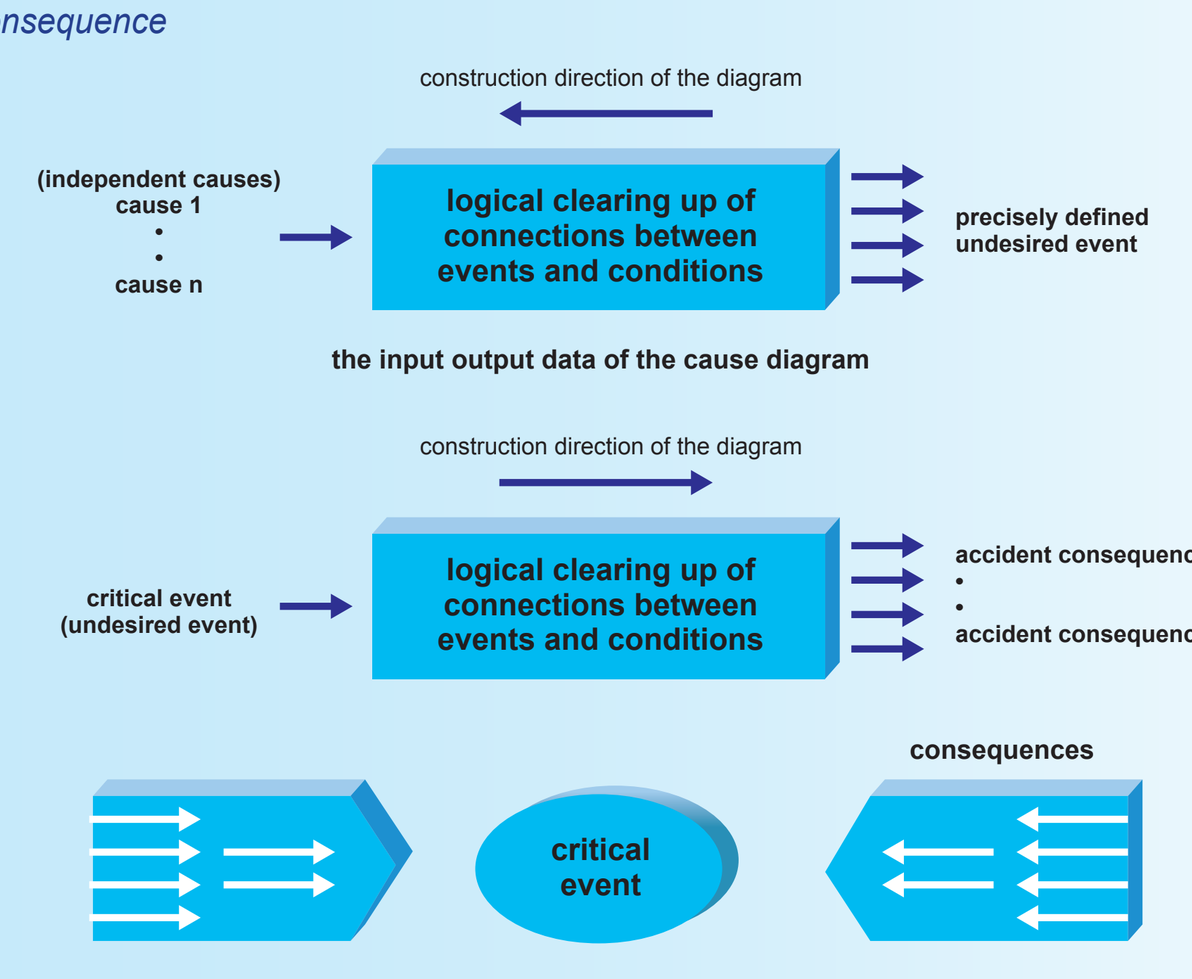
Deviation Model: Viewing human errors as consequences of poor interactions with the production process was a special type of the systems model and was severely criticized by those viewing humans as excellent problem solvers.



The deviation model

Ergonomics, particularly Dutch researcher Winsemius' task dynamics theory emphasized skilled control and ergonomic design for safety. By the 1970s, the UK and Nordic countries became safety research hubs. Developments included the multi-causality concept, focusing on accident-prone conditions, not workers. Information ergonomics identified four accident causes information gaps, overload, incorrect strategies, and physical limitations.

The input and output data of the consequence diagram:

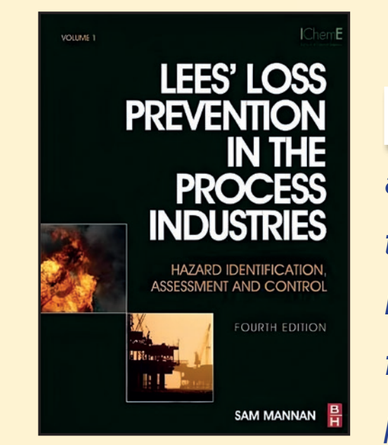


construction direction of the diagram
(independent causes)
cause 1
cause n
logical clearing up of connections between events and conditions
precisely defined undesired event
the input output data of the cause diagram
construction direction of the diagram
critical event (undesired event)
logical clearing up of connections between events and conditions
accident consequence 1
accident consequence n
consequences
critical event

The nuclear accidents and fear of future accidents paved the way for advancements in nuclear safety and revolutionizing safety in industrial environments through loss prevention.

The consequence diagram developed by Jens Rasmusen for the Danish Atomic Energy Commission In 1971 was a model focused on "critical events" in nuclear safety, aiming to visualize the moments a reactor crosses safety limits. This has influenced future safety approaches, including the "bowtie metaphor."

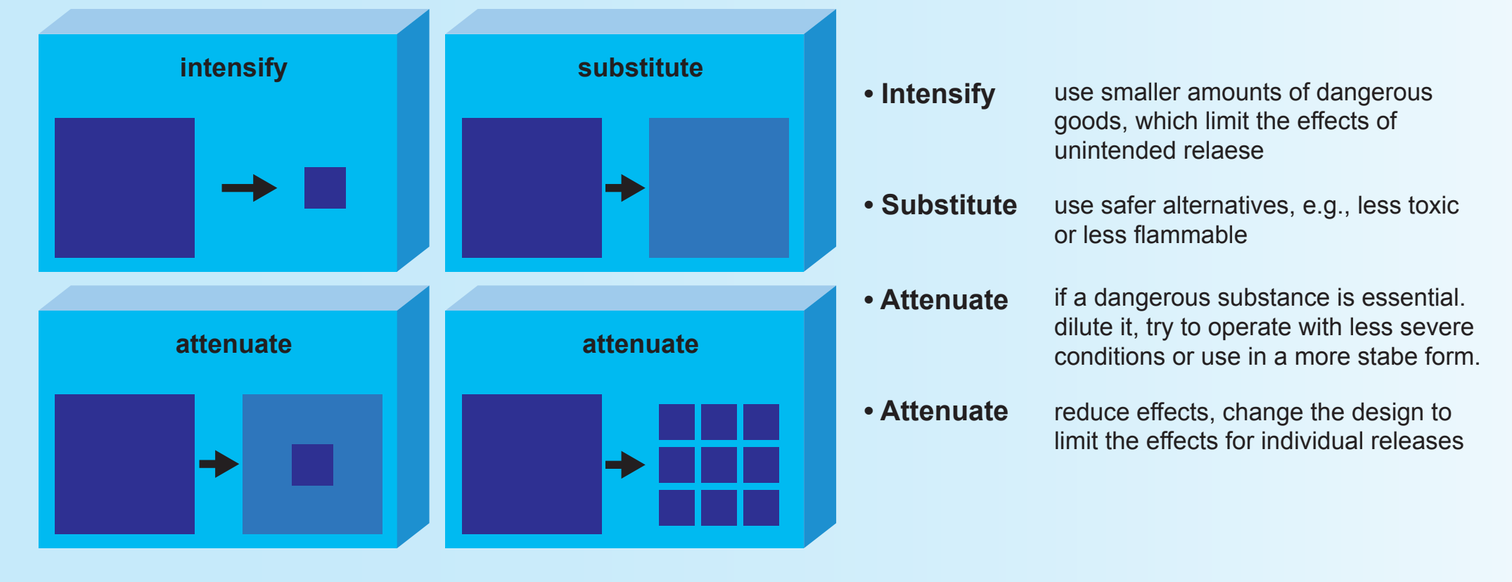
Loss prevention, which focuses on Industrial risk identification and quantification, was shaped by Frank Lees and Trevor Kletz. Events like the 1960 Hazards Conference and the 1974 Flixborough explosion led to new safety standards. They influenced legislation, including the Health and Safety Commission's "major hazards" work. The Canvey Island study, which followed the approval of two oil refineries, spurred public protests and safety improvements.



Francis Pearson Lees (1931-1999) – usually recognized as Frank Lees was a chemical engineer and prolific scholar. He is widely recognized for his contribution to the field of loss prevention through risk identification and reduction. He is mostly recognized through his book, Loss Prevention In the Process Industries, first published in 1980, with its fifth edition in the works almost 25 years after his passing.

Inherently safe design

Inherently safe design, promoted by Kletz with "What you don't have can't leak," advocates simplicity. While effective for individual processes, whole-site application faces secrecy issues. Kletz supported transparency to inform society, learn from errors, share best-practices, and prevent broad harm.



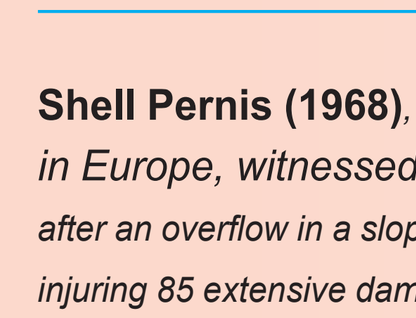
intensify
substitute
attenuate
attenuate
• Intensify use smaller amounts of dangerous goods, which limit the effects of unintended relaese
• Substitute use safer alternatives, e.g., less toxic or less flammable
• Attenuate if a dangerous substance is essential. dilute it, try to operate with less severe conditions or use in a more stabe form.
• Attenuate reduce effects, change the design to limit the effects for individual releases

Trevor Kletz (1922-2013), an engineer, a prolific scholar, and a professor, played a pivotal role in establishing the field of process safety in the (chemical) process industries. He introduced the concept of inherent safety and was a major promoter of HAZOP studies.

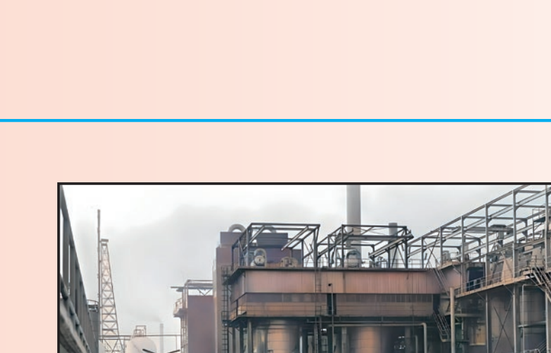
The Netherlands

Witnessed several major accidents, prompting research and discussions on risk in this period.

Shell Pernis (1968), *the largest refinery in Europe, witnessed fire and explosions after an overflow in a slop tank, killing two and injuring 85 extensive damage and a large fire.*



Firefighters responding to the Shell refinery fire in Pernis (colorized). Nationaal Archief / CC0



The scene of the fire at the Shell refinery in Pernis (colorized). Nationaal Archief / CC0

Photos showing devastation after the explosion (colorized). Nationaal Archief / CC0

DSM Beek (1975, The Netherlands), *A vapor cloud explosion following a leak during startup operations of the ethylene plant at the Dutch State Mines (DSM) works killed 14 and injured 104 people inside and three outside the mine.*

NAM Schoonebeek (1976, The Netherlands) *A valve breakdown of an oil well resulted in the blowout, spewing oil-bearing sand for two days, covering a large part of Schoonebeek, taking three months to clean the area.*

NAM technicians working on the valve (colorized). Nationaal Archief / CC0

In the 1930s, the Dutch journal "De Veiligheid" covered accident proneness and Heinrich's safety concepts. By the 1970s, it included international safety science like Winsemius's theories and Bird's loss control management. Petersen introduced 'safety management' to the Netherlands, and Zwam authored the first book on it. Issues discussed ranged from labor humanization to professional ethics. Working Group 13 of the Dutch Society for Safety Science (NVVK) examined conflicts between the company and employee safety interests and the challenge of aligning safety roles with worker well-being.

In 1983, the Working Conditions Act shifted the focus from 'occupational safety' to 'working conditions.' "De Veiligheid" was succeeded in 1986 by the Monthly Journal on Working Conditions. The 1988 Journal of Applied Occupational Sciences (TtA) aimed to bridge research and practice. In 1987, the Safety Institute merged with Coördinatie Communicatie Onderzoek Ziekteverzuim (Coordination of Communication Research on Absenteeism) CCOZ to form the Nederlands Instituut voor Arbeidsomstandigheden (NIA; Dutch Institute for Working Conditions). Within years, the Dutch safety field underwent significant changes, including the loss of a law, a journal, and an institution.

Ergonomics and safe design became crucial in the late 20th-century Netherlands as the focus on worker protection shifted from individuals to work environments, epitomized by the slogan: 'Expect trouble if you allow safe people to work in an unhealthy environment.' The 1970s saw the rise of the 'soft side' of safety, including organizational factors like management.

Humanization of labor and "well-being" became the center of focus in The Dutch Arbowet in 1979 (Working Conditions Law). The law aimed to minimize injuries and improve working conditions for all, including women and immigrants. However, companies like DuPont faced criticism for neglecting these aims and even negatively affecting employees' personal lives by overlooking basic safety measures like machinery redesign.

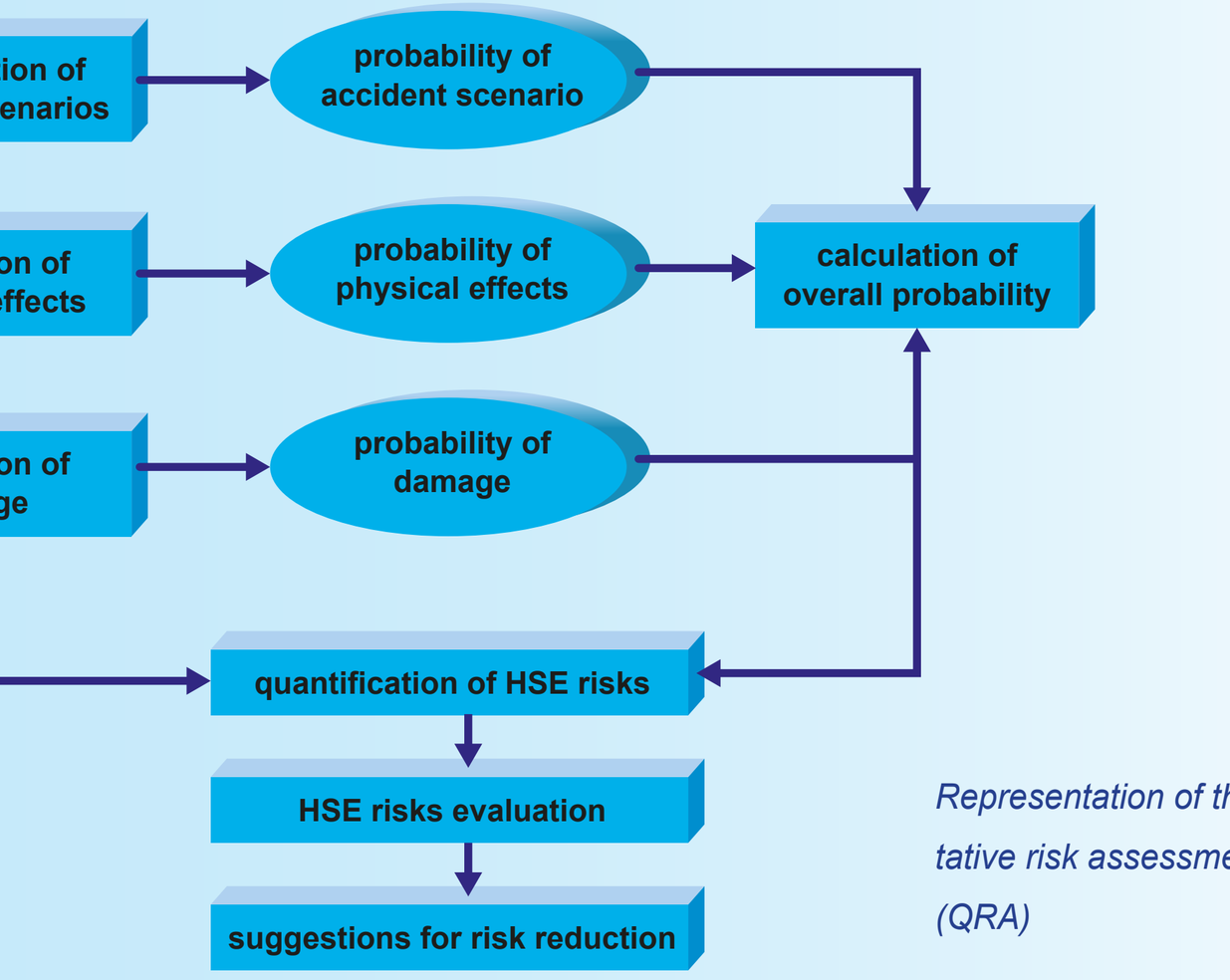
Origins of risk in the Netherlands date back to Van Veen and Wemelsfelder's modernization of flood control with statistical analyses, moving away from traditional dam raising. Ignored warnings culminated in the 1953 Great Flood, leading to the risk-centric Delta Works. In 1975, the Commissie voor Preventie van Rampen (Commission for Disaster Prevention) CPR began a 'risk thinking' era with hazardous substance storage standards. Risk became a political focus in the 1970s, supported by Dutch Labour Inspectorate guidelines and De Veiligheid reports. However, the understanding of quantitative risk assessment was criticized as limited by experts like Hofstede.

The colored books

The colored books guided the Dutch government's risk strategy and became international landmarks in risk management. The Yellow Book was used for the consequence assessment of hazardous substances; the Green Book was concerned with the models of property and people damage. The red book addressed failure probabilities in technical systems, and the purple book, which was published in the '90s, was a guideline for conducting QRAs.

The acceptability of risks associated with safe levels of workplace exposure to carcinogens is debated by Dutch experts, including Zielhuis. The Dutch Health Council and WGD classified substances as initiators, causing irreversible DNA changes and promoters with less severe effects. Initiators had no safe level, while promoters did. WGD proposed a 1 in 10,000 cancer rate over 35 years as an acceptable risk for initiators. The US Food Safety Council's "near zero" risk standard of 10^-6 led to differing views, from symbolic to comparable to natural risks.

Loss prevention became key in the Netherlands' safety approach, influenced by the Flixborough and Beek accidents in the 1970s. Organizations like KNCV and KIVI led safety initiatives through conferences. Dutch Minister Boersma introduced quantitative risk assessment, leading to CPR "colored books." Delft University focused on human safety factors through a professorship. Hale and Glendon promoted system approaches to risk control, and debates on risk quantification and acceptance became political in scientific communities.

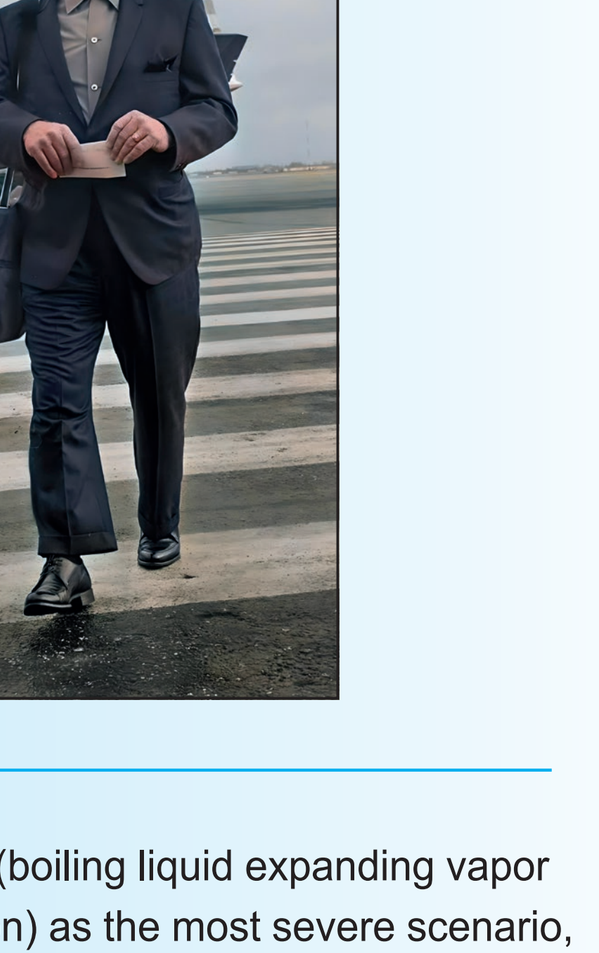


identification of accident scenarios
probability of accident scenario
calculation of physical effects
probability of physical effects
calculation of overall probability
calculation of damage
probability of damage
quantification of HSE risks
HSE risks evaluation
suggestions for risk reduction
Health, Safety and Environment (HSE)

Representation of the quantitative risk assessment process (QRA)

Vapor gas explosions such as the 1974 Flixborough and 1975 Beek accidents, linked to the Dutch company DSM, led to heightened research on vapor cloud explosions. These incidents surprised experts due to their unanticipated extensive damage. Studies in the 1970s found that mild explosions could escalate significantly, especially when obstacles like piping were present.

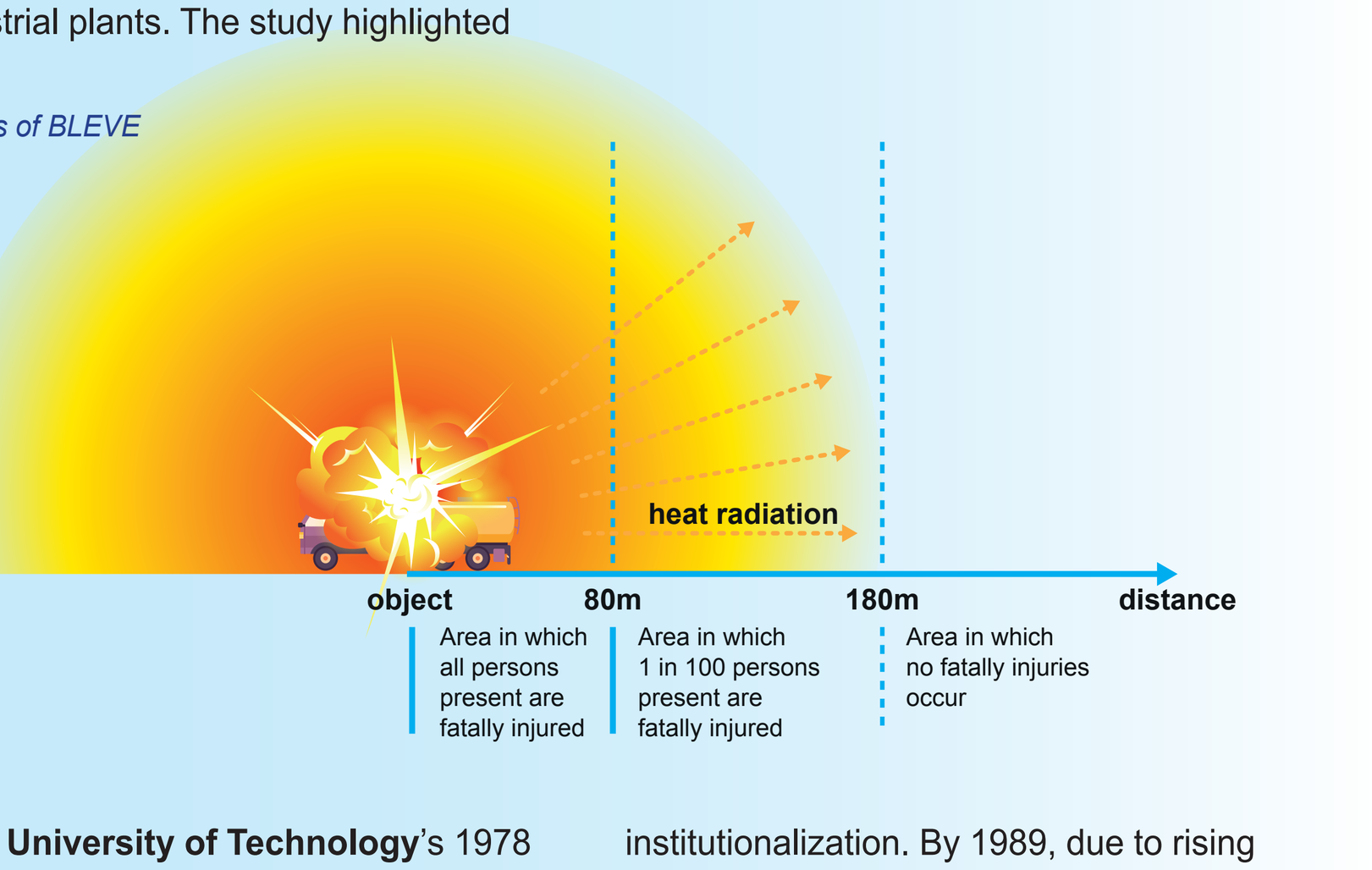
Fighting blowouts were effectively addressed after the NAM Schoonebeek blowout by inviting the renowned blowout fighter Red Adair to the Netherlands by NAM (Dutch Petroleum Company), owned by Shell and ExxonMobil. His expertise led to updated emergency plans, organizational schemes, and special equipment purchases to prevent major disasters like blowouts. Adair's impact extended globally, including his work in Kuwait.



Red Adair's arrival to the Netherlands at Schiphol (1964) (colorized). Nationaal Archief / CC0

TNO's LPG integral study in 1978 introduced risk measures that later shaped Dutch safety criteria (PR and GR) for industrial plants. The study highlighted BLEVE (boiling liquid expanding vapor explosion) as the most severe scenario, influencing societal discussions.

Effects of BLEVE



Delft University of Technology's 1978 symposium expanded the safety discussion beyond industry to include home and road safety, leading to the Safety Science Group's formation and academic institutionalization. By 1989, due to rising complexities in industrial safety, Delft and Amsterdam universities launched postgraduate safety courses incorporating chemical process safety at Delft.

1970-1990

TU Delft

1800-1910 | 1910-1930 | 1930-1950 | 1950-1970 | 1970-1990 | 1990-2010 | 2010→

Based on the book From Safety to Safety Science (Swuste et al. 2022)