Safety management systems from Three Mile Island to Piper Alpha: a review in English and Dutch literature for the period 1979 to 1988

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ABSTRACT

Objective: Which general management and safety models and theories trends influenced safety management in the period between Three Mile Island in 1979 and Piper Alpha in 1988? In which context did these developments took place and how did this influence Dutch safety domain?

Method: The literature study was limited to original English and Dutch documents and articles in scientific and professional literature during the period studied.

Results and conclusions: Models and theories of human errors, explaining occupational accidents were still popular in the professional literature. A system approach was introduced into mainstream safety science, starting in process safety, and subsequently moving into occupational safety. Accidents were thought to be the result of disturbances in a dynamic system, a socio-technical system, rather than just human error. Human errors were also perceived differently: they were no longer faults of people, but consequences of suboptimal interactions during process disturbances. In this period quality of safety research increased substantially, also in the Netherlands.

Major disasters in the 1980s generated knowledge on process safety, and soon process safety outplaced developments in occupational safety, which had been leading before. Theories and models in this period had advanced sufficiently to explain disasters, but were still unable to predict probabilities and scenarios of future disasters. In the 1980s ‘latent errors’ appeared in safety literature, and in The Netherlands the concept of ‘impossible accidents' appeared. Safety management was strongly influenced by developments in quality management.

INTRODUCTION

This article is one in a series on knowledge development of both safety domain, and safety management. Previous publications examined periods extending from the late 19th century until 1979 (Gulijk et al., 2009; Oostendorp et al., 2016; Swuste et al., 2010, 2014, 2016). These reviews provide insight into developments of the international scientific safety domain and in The Netherlands. The current article describes developments in process safety, starting in 1979, till the Piper Alpha disaster in 1988.

The present paper follows the same structure as previous papers. It focuses on knowledge development in the designated period but, for completeness, sometimes referrers to earlier papers of this series. In conjunction with earlier papers, this work focuses on the following questions:

1. Which general management schools, and theories, models for accident causation have been developed?
2. What was the influence of such developments on safety management in companies?
3. What was the context within which this development took place?
4. What were the consequences for professional safety in The Netherlands?

MATERIALS AND METHODS

The answers to these questions were based on an extensive literature research. The literature research was limited to English and Dutch literature, meaning that the developments of safety in the United States, the United Kingdom, Scandinavia, and The Netherlands tend to be emphasized. Original references and scientific articles were accessed via the Delft University of Technology Library and through the internet. The following journals were consulted for the period discussed: Accident Analysis and Prevention, Journal of Hazardous Materials, Journal of Loss Prevention, Journal of Occupational Accidents, Journal of Safety Research and Safety Science. References were followed from: Academy of Management Journal, Administrative Science Quarterly, American Sociological Review, Ergonomics, California Management Review, Hazard Prevention, IEEE Transactions on reliability, IEEE Transactions on Systems, Man, & Cybernetics, International Journal of Man-Machine Studies, Journal of Applied Behaviour Analysis, Journal of Business & Psychology, Journal of Management, Journal of Management Studies, Naval War College Review, Organisation Science, Policy Sciences, Plant/Operation Progress, Public Health Reports, Reliability Engineering & System Safety, Risk Analysis, Social Science Information Studies, The Academy of Management Review and Reliability Engineering & System Safety (from 1988 onward). De Veiligheid (Safety Journal), Maandblad voor Arbeidsomstandigheden or MAO (monthly journal concerning working conditions), and Risicobulletin (Risk Journal) were used to study developments in The Netherlands.

Annex 1 will provide an overview of serious incidents, and major accidents occurring in oil and process industries. For this Annex only publicly available information was consulted (Lees, 1996, Mannan, 2005; March 2012; Wikipedia, 2014). This table only gives an impression. There is an unknown level of underreporting. This bias will vary by country, time and sector. The level of underreporting is difficult to estimate. Apart from uncertainties of the numerator, the denominator is a big obstacle. There was no information on exposure, or an estimation of the number of active installations, or activities, therefore no rates, or time trends could be calculated

The period concerned saw quite a few disasters in various domains: the process industries, nuclear power plants, chemicals storage, space endeavours, maritime transport and railways. The disasters generated significant media attention which spurred the professionalization of safety management systems that, in retrospect, were relatively simple systems from World War II onwards. The introduction of ISO-9000, as a vehicle for improving quality management showed this professionalization and was also the model for professionalization of safety management systems (ISO, 1987).

Two disasters are described with some degree of depth in this article. The article starts with Three Miles Island (1979), which was not actually a disaster but painfully exposed a lack of safety management.

The paper ends with Piper Alpha, in which shortcomings in safety management, one decade later, caused the death of 167 people. The paragraphs between these disasters will discuss five subjects:

1. The approaches of general management schools with a focal point on Total Quality Management;
2. Occupational safety, the state of the art and its knowledge development on accident causality in areas of: human factors, sequence of events, energy transport, information exchange, system approach, safety climate, epidemiology of accidents, and the OARU model, which was based on process disturbances. This era produced just one accident-theory: risk homeostasis;
3. Process safety, the knowledge development in loss prevention and reliability engineering as well as changing views on human factors;
4. Safety management and safety management systems, their developments, audit systems, high reliability and the reaction of corporations to safety issues;
5. The last part describes developments in The Netherlands. This part features a case study in which Shell plays a central role.

This paper, as with previous papers in this series, focuses on the analysis of scientific progress. Changes in safety legislation are not included, while for companies legislation is often leading. Our assumption is that legal developments, to some degree, will follow scientific developments.

THREE MILE ISLAND

On the 28th of March 1979, a defect in the secondary cooling system almost caused a meltdown of a nuclear power reactor at Three Miles Island near Harrisburg in Pennsylvania (US). Radioactive gasses were vented into the atmosphere, but a nuclear meltdown was prevented. The Report of the President's commission on this accident stated the accident was due to technical failures and to human error. Also, the management procedures and emergency response were found to be deficient, and the organisation's safety management system was inadequate (Kemeny, 1979; Lees, 1980). Operators were not trained well, procedures were contradicting and safety management only focused on a few major risk scenarios. A comprehensive overview of possible major accident scenarios was lacking. A failure in a water pump started the process. It led to an increased pressure in the primary cooing circuit, and radioactive gasses could escape through a pressure safety valve was inadvertently left open. This particular combination of conditions had not been identified in a safety analyses. Also, the control room (Figure 1) was not adequately designed to react to a crisis. After the initial fault over 100 audio-alarms were continuously ringing in the control room. Operators struggled to identify which alarms were the most important ones. Responsible management managed a number of sites from a central office. Managers were several hundreds of kilometres distant from the actual site, making communication laborious. Safety was perceived as just another bureaucratic task and, lacking priority, had not received sufficient attention.

Figure 1: Control room TMI-2 during the accident (Kemeny, 1979)

Tragically, the accident report for the Piper Alpha found similar shortcomings one decade later (Cullen, 1990). Cullen found that the oil- and gas processing techniques had become exceedingly complex, and safety management systems were too fragmented and too inconsistently administered to cope with the complexity of the process installations. Before discussing the knowledge development in the fields of occupational safety and process safety, we present a brief overview of general management approaches is presented.

GENERAL MANAGEMENT APPROACHES

The management school of 'modern management', discussed in a previous article, was the general management approach during the period discussed. Modern management was based on the open-systems approach, with a focus on the environment within which a company or organisation had to operate, with attention to in- and external stakeholders. Management was a decision-making and information-processing activity in which managers had to plan, organise, manage and supervise. At this time, quality of processes and products became an important element of general management. In 1982, Deming's work on quality control would prove to be an important driver in this school of thought. Deming, as well as his countryman, Juran, had revolutionized quality management of production processes in Japan after World War II (Deming 1982, Juran 1951, Juran and Barish, 1955). Deming's work was based on earlier collaborations with Walter Shewhart at Bell Laboratories in New York. As early as 1939, Shewhart and Deming published their Statistical Process Control or SPC, an approach to understand and reduce production process variations (Shewhart and Deming, 1939; Greisler, 1999). Process variations came in two kinds, those that were relatively small, and occurred regularly as a consequence of naturally variations in the production process, like variations in temperature. There were also large process variations, pushing a process to or beyond its tolerances. These large process variations rarely followed a normal distribution. Large variations occurred less frequently, but were potentially disrupting to the process. Examples include faulty machine-settings or extremely low qualities of raw materials. With statistical process control, the process variations could be detected and corrected before the actual product was produced. This constituted a major step forward of quality control of products. SPC first took off in manufacturing, but the approach proved to be useful in any process with a quantifiable output.

Total Quality Management

Deming left for American-occupied Japan in 1947. America supported Japanese industry, preventing the economically weakened country would become vulnerable to communism. The Marshall Plan for Europe had a similar goal. (Leitner, 1999; Judt, 2012). Deming found that weak management was the pivotal problem in the low quality of Japanese produced products. He used a simple but effective mantra for Japanese managers: 'if management focuses on quality, costs will drop; but if the focus is on cost, quality drops'. Other important features were continuous customer analysis and staff empowerment in management decisions. Management's role was to support staff to work more efficiently and to work towards leaner production processes reducing process, stock, and storage cost. Quality control thus became part of the relationship between staff and management where all organisational levels were subject to statistical control processes (Vinzant and Vinzant, 1999). Such principles made Deming one of

the founding fathers of Total Quality Management (TQM). It would take almost thirty years before these ideas took root in the west (Pindur et al., 1995; Nye, 2013). Leading western publications of TQM were ‘The change masters’ (Kanter, 1984), ‘In search of excellence’ (Peters & Waterman, 1982) and ‘Images of organisations’ (Morgan, 1986). These ideas would slowly trickle down into process and occupational safety.

OCCUPATIONAL SAFETY

Occupational safety state-of-the-art

The 1980s showed a notable increase of scientific publications on safety. Safety research centres were situated in Scandinavia (Stockholm, Tampere and Trondheim), the United Kingdom (Loughborough, Manchester, Surrey, Imperial College and Birmingham-Ashton), the United States (Boston, Chicago, Morgantown, Texas Tech and San Diego), The Netherlands (Leiden and Delft), Germany, (Wuppertal and Cologne) and France (Paris).

The United States kept close to its traditional domains, such as cost of safety (Miller et al., 1987) and technical safety measures, such as safety on stairs (Templer et al., 1985) and accidents with presses (Collins et al., 1986). Comprehensive works for manufacturing safety were published: the Accident Prevention Manual of the National Safety Council (McElroy, 1980) and the last edition of Heinrich's accident prevention book (Heinrich et al., 1980).

With the increased focus on research, safety and accidents were taken equally seriously as occupational diseases (Haddon, 1980). In the 1980s more articles appeared on the quality of safety research, like the beginning of the 1960s. Slowly safety knowledge evolved to a domain with a dominant engineering approach (Fellner and Sulzer, 1984). Some authors found that advancements on accident classification and causality fell behind (Singleton, 1984). On the topic of prevention there was a lot of good will, with little theoretical background (Kjellén and Larsson, 1981; Saari, 1982). This was particularly a problem for safety training and education. Cohen and Jensen (1984) stated that training was not very effective since it did not focus on the practicalities of job performances. The relation between results of accident analyses, and prevention was rather obscure. Often, safety training was based on Haddon's ten strategies for injury control, these being preventive strategies discussed in a previous article. These strategies were more like rules of thumb and were not based on scientific research (Compes, 1982). Also, the ten strategies were not suited for complex industrial processes, as in process industries (Barnett, and Brickman, 1986).

Often, safety prevention evaluation studies were based on statistics of sick leave after accidents, or on sick leave trends before and after implementation of an intervention. This was a troublesome approach. Firstly, only averages were used, and hazards were not the only factor affecting sick leave. These comparisons were prone to regression to the mean, meaning that differences were wrongly attributed to the effects of interventions or measures, leading to faulty conclusions on effects of interventions (Hauer, 1980, 1983). Secondly, sick leave was a poor indicator for accident prevention since it focused on consequences and suffered from registration biases (Menckel and Carter, 1985; Purswell and Rumar, 1984). Thirdly, there was little information available on exposure to hazards, and

accident inducing conditions. The concept of exposure was (and still is) poorly developed within safety science. Often, the closest organisations approached these pre-existing conditions, like exposure, was to stress implementation of a list of safe practice and safe conditions. But this approach did not really catch on in organisations (Saari, 1984; Hubbard and Niel, 1985). These safety practices and conditions could be scored, providing a numerical ranking of a safety level of different factory departments and workplaces. These scores had much in common with the later developed safety indices (Fellner and Sulzer, 1984; Frijters, et al., 2008).

Occupational safety: theory, and models

From the 1970s onwards the accident process of occupational accidents and scenarios were seen as a complex phenomenon (Swuste et al., 2016). The insight that occupational accidents were complex processes that could not be predicted easily, was still present in the 1980s (e.g. Shannon, 1980). Before, occupational accidents were seen as a relative simple phenomenon, the consequence of only one cause. More factors played a dominant role, which were labelled with colourful names as ‘unsafe acts’ or ‘unsafe conditions’. The relatively straight-forward guidance rules for safe and effective production set out by earlier authors (Heinrich et al., 1980), was questioned. Preventive measures and interventions costing time and money were doomed to fail. This was also true for measures introducing devious working methods, and slowing down production speed (Sulzer and Santamaria, 1980; Monteau, 1983). In this period models for causes of accidents were often combinations of pre-existing accident models:

1. The human error model: This model started from the concept that sources of human error should be controlled and its frequency should be lowered. The human error model dated back to Heinrich’s metaphor of falling dominoes of the early 1940s;
2. The sequential accident model: where a sequence of events resulted in an accident. This model was also based on the domino-metaphor;
3. The energy model: where the interaction between hazardous energy, the victim and their environment determined the accident process. The interplay of technological, human and organisational factors determined this interaction. This model originated from Haddon’s work in 1968;
4. The information model: where an accident was caused by a disruption in communications. This model was produced in the 1970s and further developed in Scandinavia. It assumes that workers’ access to information and cognitive processes involved played a central role (see Figure 2). Workers at risk combined information received with earlier experiences, which influenced how they worked. Various internal factors had an influence, like physical condition, motivation, intelligence, and sensory limitations. This made this model rather complicated (Saari, 1984);

5. The system model: accidents were outcomes of abnormal system conditions. The model focused on subsystems, components and their interactions to explain accidents. An accident was an outcome of a process disruption of a dynamic system. Injuries occurred when risk factors came into contact with individuals. (Tuominen and Saari, 1982; Leplat, 1984).

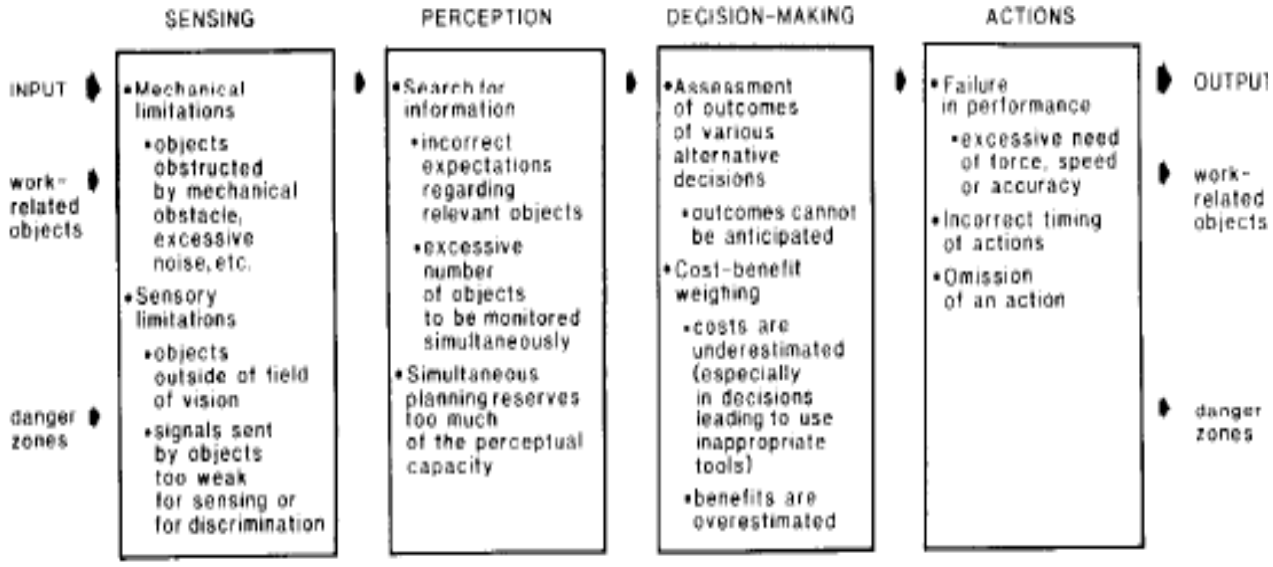

Figure 2. Mechanisms leading to errors in human information processing (Saari, 1984)

The International Labour Office (ILO) adopted the system approach in their encyclopaedia and focused on improving occupational systems that were improperly designed or otherwise inherently unsafe (Monteau, 1983). The link between design and accidents was, again, a Scandinavian viewpoint (Harms-Ringdahl, 1987a). The United Kingdom contributed to this model with their results of fieldwork at the Liverpool Ford manufacturing plants (Shannon, 1980; Shannon and Manning, 1980). Process disturbances were unforeseen events, like being hit, or wricked, or cut by objects like machines, particles, oil, tools and moving objects;

6. The safety climate model: This model was developed in Israel (Zohar, 1980a-b). It was assumed that behaviour of workers was influenced by organisational climate which was determined by management engagement, the status of safety experts and the importance of safety at work;
7. The deviation model: a special type of system model. Human errors were seen as consequences of poor interactions with the production process, in particular inadequate responses to changes in production processes (Kjellén, 1984a, Häkkinen, 1982). This view was immediately attacked by authors who emphasized that humans are excellent problem solvers (Hovden and Sten, 1984);

8. The accident epidemiology model: This model was used to study accidents with forklifts in the United States. An investigation studied and classified 88,000 fork-lift accidents from 1983 – 1985 in terms of gender, age, months in a year, type of injury and job description (Stout, 1987). The statistical approach raised some eyebrows in the scientific domain; especially the lack of scenario-descriptions was seen as a severe shortcoming as causal factors could not be established (Purswell, 1984).

Models were often combined to new models. The time-sequence approach from the deviation model was often combined with other models, such as the energy model (Figure 3).

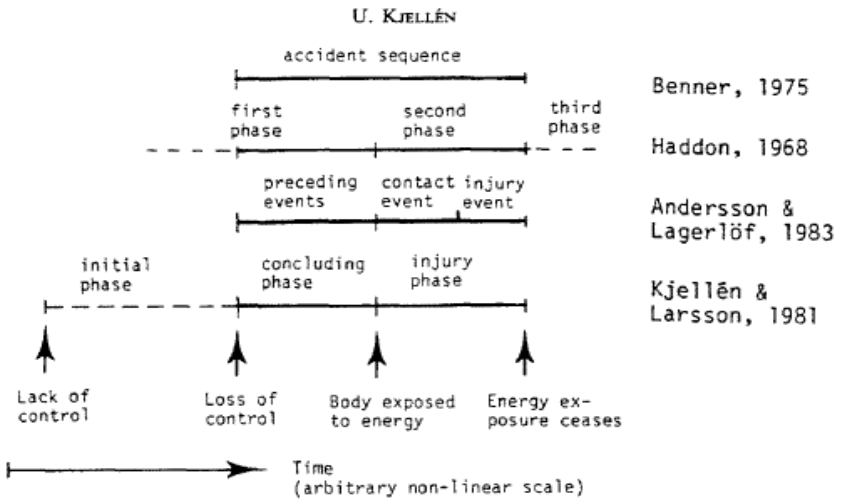

Figure 3: The relation between accident process models (Kjellén, 1984a)

An example is the IJEM factors by the ILO (1988). IJEM combined Individual, Job, Environment and Materials (Faverge, 1983). The OARU model (Occupational Accident Research Unit, Sweden) was a system model that treated deviations and process disturbances as causes of accidents (Figure 4) (Kjellén and Larsson, 1981; Kjellén, 1984a-c). The model was based on accident research in mining, construction, steel production and railways. Disturbances were leading to injuries, and system factors determined accident sequences. The system factors were events, or conditions of a production process, deviating from normal process conditions in the material flow, information, simultaneous activities, environmental factors or personal protection equipment. Such factors were seen as relative stable conditions, present during accident processes, and referring to physical and technical conditions of the design of a work process, workplace and work environment. Additional factors were organisational, like decision making, maintenance, planning, and training etc., and social-individual, like management instructions, communication, and competency.

In the United States, the focus on workers' responsibility for their own safety was more prevalent. US literature demonstrates a distinct focus on the human error model. Prevention of accidents could be achieved by positive feedback and rewarding safe behaviour. The psychological insights of the time dictated that positive sanctions worked better than negative ones (Sulzer and Santamaria, 1980; Heinrich et al., 1980; Fellner and Sulzer, 1984; Chhokar and Wallin, 1984; Cohen and Jensen, 1985). This view was supported by Scandinavian researchers (Grondstrom et al., 1980; Vuorio 1982). A key element of this approach was to observe human behaviour. Sulzer (1987) suggested training some staff to be observers. These proposals paved the way toward behaviour-based-safety programs.

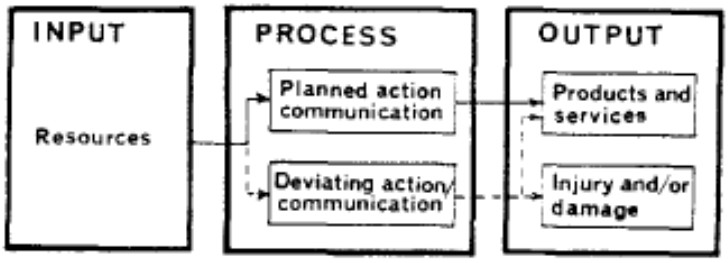

Figure 4: The deviation model (Kjellén, 1984a)

One new theory was developed in the time-span of this paper: the homeostasis theory. The term was derived from the natural sciences and described an organism's capacity to maintain stable internal conditions despite changing environments. This dynamic equilibrium in an open system was known as 'steady-state', and differed from a physical-chemical equilibrium, which is static and, according to thermodynamics, only applicable to a closed system. The theory originated from traffic safety research explaining why drivers seemed to adapt their behaviour according an accepted risk level (Wilde, 1982). When drivers felt they drove exceedingly safely, they started driving more aggressively and vice versa. Also, owners of very safe cars drove more aggressively than their peers. The debate about this compensation behaviour was extensively discussed in the traffic safety literature. This theory had some practical problems; how to define a safety level and to combat unsafe adaptations (McKenna, 1985 a-b)? The concept was also introduced in occupational safety, extreme safe working environments would stimulate unsafe behaviour (Wilde, 1986). However, the homeostasis theory was never accepted in occupational safety.

PROCESS SAFETY

In process safety, two distinct research schools developed: technical process safety and man-machine interactions in a complex technical environment.

Technical process safety

The explosion at Flixborough in 1974 stimulated British safety researchers to focus on technical causes of vapour cloud explosions (Roberts and Pritchard, 1982; Baker, 1982). This research took a turn to a more generic interest in safety of complex technical installations. Frank Lees (1931-1999) and Trevor Kletz (1922-2013) were important protagonists of this technical approach to safety. In 1980, Lees produced a comprehensive compendium 'Loss prevention in the process industry' which saw reprints in 1996, 2005 and 2012 (the last two editions under editorship of Sam Mannan). Lees and Kletz limited their field of interest to chemical and petrochemical processing, and their approach provided useful guidance in an industry with their increased volumes, dimensions and complexity of chemical process plants (Kletz, 1999).

Loss prevention was based on a system model. It mapped risks through system analysis and quantifies risks with probabilistic techniques and physical-chemical-reliability models. Kletz argued that process plants could be made safer by considering three E's: Equipment, which focused on creating safer process equipment; Equations, to calculate risk and; Experiments, to investigate whether controls worked adequately and to explore unknown risks (Kletz, 1988c). Loss of containment, or LoC, was considered to be the most important process disturbance of chemical processes. In order to carry out comprehensive and reliable quantitative risk analysis (QRA), extensive inter-corporate and international databases were established listing risk data in the chemical processing industries (Lees, 1980, 1996; Mannan, 2005; Kletz, 1988d). Annex 1 lists major incidents in the era this paper is covering. The United States, Japan and Europe seem to have many more accidents than the rest of the world, but this is partly due to the focus of this paper on English-language reports. In fact, except Africa, all corners of the world are represented in the list, which shows that chemical safety is a worldwide problem. The level of underreporting is discussed in the materials and methods paragraph, and shown by the overrepresentation of the United States, and the underrepresentation of Japan, and Europe. The large portion of accidents with storage and transport in the list is striking (Lees, 1983; Kletz, 1984b-c, 1985a, 1986). Table 1 shows some of Lees' process deviation parameters. Four factors were important in LoC events: the quantity of materials, the energy they carried, time frame, and dispersion. Quantity was the mass and volume of the release. The energy factor was related to the energy needed to transform hazardous substances to a toxic, flammable or explosive mixture. The energy content of compressed

flammable gasses is high since a LoC could create a huge energy release in a very short time (e.g. via explosion). With cryogenic liquids, the energy was lower since energy must be extracted from the environment, which would occur relatively slowly. Time was related to the speed in which a material was released and the length of time during which the release occurred. Dispersion related to the type and rate of release (e.g. sudden or continuous) and the relation between the damage and distance from the point of release. Risk analyses used these indicators for their estimations of risk and were considered to be key parameters in understanding accident scenarios.

Some deviations of operating parameters from design conditions	
Process variables	Pressure, temperature, flow, level, concentration
Pressure system	Mechanical stress, loading, expansion, contraction, cycling effects, vibration, cavitation, resonance, hammer; corrosion, erosion, fouling
Chemical reactions	Reactions in reactors: nature, rate of main/side reactions; amount and rate of energy production (fire, explosion), catalyst behaviour: reaction, regeneration, poisoning, fouling, disintegration, and unintended reactions such as: heating, polymerization, corrosion
Material characteristics	Vapour density; liquid density, viscosity; melting point, boiling point; latent heat; phase change; critical point effects; physical state of solids, such as particle size, water content
Impurities	Contaminants; corrosion products; air; water
Localized effects	Mixing effects, mal-distribution; adhesion, separation, vapour lock, surging, siphoning, vortex generation, sedimentation, fouling, blockage, hot spots
Time aspects	Contact time, control lags, sequential order
Process disturbances	Operating point changes, changes in linked plants, start-up, shutdown, utilities failure, equip-ment failure, control disturbance, operator disturbance, blockage, leakage, climatic effect, fire
Constructional defects	Plant not complete, not aligned, not level, not supported, not clean, not leak-tight; materials of construction incorrect or defective
Loss of containment	Sudden and rapid Loss of Containment (e.g. pressure vessel failure); slower Loss of Containment, e.g. via leakage, spillage

Table 1: Some deviations of operating parameters from design conditions (after Lees, 1980).

Scandinavian researchers wrote extensive reviews about risk-based safety analyses and methods. They tended to focus on the reliability of data, for instance for failure frequencies for components (Suokas, 1985; Harms-Ringdahl, 1987b). An engineering approach was prevalent in these publications; they emphasized design and re-design of technical installations as the dominant solution for safer industry.

What you don't have can't leak' was one of Kletz' mantras (Kletz, 1978). 'The mantra was repeatedly used to explain inherently safe design: keep the design simple, ensure the designer familiarizes himself with tasks of the operators, and verify the design with post-hoc risk analysis such as HAZOP (Kletz, 1982, 1984a; Clarke, 2008). Scandinavians adopted a similar approach for nuclear power

plants and process industries (Rasmussen, 1980, 1985; Hollnagel, 1983; Suokas, 1985, 1988). The prevention measures focused on relatively small accidents and were not easily transferrable to large catastrophes (Kletz, 1988a). Kletz's inherent safe design illustration (Figure 5) tended to be most useful for individual processes and sub-processes rather than for entire sites. For reasons of confidentiality, litigations and the fear of negative publicity, the findings of safety research in the process industries were generally not publicly available. Kletz proposed that transparency would be preferable for several reasons. Firstly, because morally it is preferably to inform society 'if we know, we must tell'. Secondly, and more pragmatically, organisations would be better off from learning from each other's mistakes.

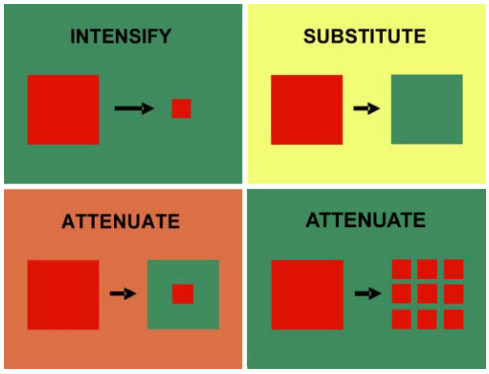

Figure 5: Principles of inherently safe design (Kletz, 1985c).

Intensify:	use smaller amounts of dangerous goods, which limit the effects of unintended release;
Substitute/Replace:	use safer alternatives, e.g. less toxic or less flammable;
Attentuate:	if a dangerous substance is essential, dilute it, try to operate with less severe conditions or use it in a more stable form;
Attenuate:	reduce effects, change the design to limit the effects of individual releases.

Thirdly, more sharing would be economically beneficial since good practice could be shared. And finally, if any one organisation had an accident that could have been prevented by knowledge in another organisation, the entire sector would suffer unnecessarily (Kletz, 1988c).

The United States developed a slightly different approach. They introduced a risk triplet that included information about the scenario to the risk calculation. This approach clarified what could go wrong and how bad the consequences could be. (Kaplan and Garrick, 1981). After introducing this formal method, the question of acceptability of such risks becomes relevant. Acceptability of risk is not a forthright proposition. First, comparing alternatives is not always straightforward.

$$R = \{\langle s_i, p_i, x_i \rangle\}$$

s_i: scenario i, which accident scenarios i are relevant?

p_i: what is the probability of occurrence of the scenario i?

x_i: what is the damage that can be expected from the scenario i?

Consider alternative A and B in Figure 6. A has a higher probability for low consequence consequences and B vice-versa, but which is better? To discuss acceptability, the context in which risks take place is relevant too: who benefits, who suffers, who pays for it, what if a completely different industry could also provide societal benefits? Few people are willing to bear risks if benefits are unclear, so the societal context is pivotal (Conrad, 1980; Fischhoff et al., 1981; Short, 1984; Covello et al., 1987). A detailed description on the acceptability of risk was discussed in one of our earlier publications (Oostendorp et al., 2016).

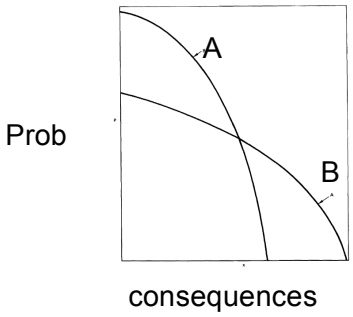

Figure 6: comparing alternative risks (Kaplan and Garrick, 1981)

In the nuclear industry probabilistic risk analysis was an accepted safety technique. Also the process industries adopted the approach, entailing functional analyses, fault trees, event trees and risk profiles. However, there were major concerns about uncertainties. Model uncertainties in the form of unknown risks and uncertainties concerning the quality of data, e.g. component failure rates being one of them. But there was also a lack of data concerning human effects of exposure to toxic substances. Thus the quantitative approach to risk, suggesting an absolute level of safety, slowly changed status to a best practice method in cost-benefit analyses. (Oostendorp et al., 2016, Paté-Cornell, 1987).

Extensive research efforts in the United Stated led to the development of new safety theories. Charles Perrow was spurred by the nuclear incident at Three Mile Island to search for indicators that would predict catastrophes. Like Barry Turner (1978), also Perrow was a sociologist, and interested in

indicators of major accidents. He systematically investigated process industries, maritime transport, and air transport, space travel, dams, mining and DNA-techniques and nuclear power plants. Similar to Kletz, he concluded that catastrophic events may have small beginnings, and, additionally, high-risk industries share special characteristics explaining the occurrence of catastrophes: coupling and interactions. If coupling is tight, and buffers are absent, a fault in one sub-system propagates into other sub-systems, and system collapse is more likely. If the system is also complex in the sense that there are strong relationships between the sub-systems, system collapse is highly probable. Thus Perrow concluded that if processes (with or without dangerous goods) are tightly coupled and the interactions between the processes are complex, catastrophe is inevitable, leading to the seminal concept of 'Normal Accidents' (Perrow, 1984).

Table 2 shows some of the parameters relating to coupling that Perrow considered relevant. Loose systems have slack and allow for delays. They offer flexibility and time for recuperation and restoration.

Tight and Loose Coupling Tendencies

Tight Coupling	*Loose Coupling*
Delays in processing not possible	Processing delays possible
Invariant sequences	Order of sequences can be changed
Only one method to achieve goal	Alternative methods available
Little slack possible in supplies, equipment, 'personnel	Slack in resources possible
Buffers and redundancies are designed-in, deliberate	Buffers and redundancies fortuitously available
Substitutions of supplies, equipment, personnel limited anq designed-in	Substitutions fortuitously available

Table 2: Tight and loose coupling (Perrow, 1984).

Manual processes tend to be loosely coupled and delays can be dealt with. Production pressure or any other form of pressure that infringes on time increase the level of coupling. Table 3 shows some parameters relating to interactions. In Perrow's view there were two extremes: linear and complex interactions. Complex interaction could be defined in terms of common mode functions. When a process controlled several functions, failure effects multiply to affect multiple sub-systems. When many such control functions exist, the system became complex. Complexity could also be defined when transformation processes were not fully understood, such as certain chemical or nuclear reactions or flying in the stratosphere. Complex reactions, multiple product pathways, feedback loops, unexpected changes, this complexity became visible in control rooms, in the many parameters necessary for process

control, like in Three Mile Island (Figure 1). The assessment of sectors based on the concepts represented in Tables 2 and 3 yielded Figure 7 which became famous amongst safety researchers.

Reason would add a new metaphor in 1987. Following Perrow's example he analysed the nuclear incident at Chernobyl. He introduced 'resident pathogen' as a medical metaphor. Similar to the human body, technological systems could carry pathogens with the potential to destroy them. Unfortunate events can trigger such pathogens, and several of these pathways, scenarios, can combine into catastrophes, even if the individual events did not pose a direct threat. This also explained why accidents rarely have a single cause. Perrow and Reason paved the way for a new understanding of accidents and catastrophes.

Complex vs. Linear Systems

Complex Systems	*Linear Systems*
Tight spacing of equipment	Equipment spread out
Proximate production steps	Segregated production steps
Many common-mode connections of components not in produi;tion sequence	Common-mode connections limited to power supply and environment
Limited isolation of failetl components	Easy isolation of failed components
Personnel specialization limits awareness of interdependendes	Less personnel specialization
Limited substitution of supplies and materials	Extensive substitution of supplies and materials
Unfamiliar or unintended feedback loops	Few unfamiliar or unintended feedback loops
Many control parameters with potential interactions	Control parameters few, direct, and segregated
Indirect or inferential information sources	Direct, on-line information sources
Limited understanding of some processes (associated with transformation processes)	Extensive understanding of all processes (typically fabrication or assembly processes)

Summary Terms

Complex Systems	*Linear Systems*
Proximity	Spacial segregation
Common-mode connections	Dedicated connections
Interconnected subsystems	Segregated subsystems
Limited substitutions	Easy substitutions
Feedback loops	Few feedback loops
Multiple and interacting controls	Single purpose, segregated controls
Indirect information	Direct information
Limited understanding	Extensive understanding

Table 3: Complex and linear interactions in systems (Perrow, 1984).

Disasters originate from non-observable and usually unforeseeable deviations that cause complex chains of events. With the installation of the Chernobyl nuclear plant, society opted for cheap, tightly coupled production systems of (nuclear) power, which yielded complex nuclear plants. During an experiment, tunnel vision was preventing to understand the reactor was close to its design limits. Management was

monolithic, distant, and slow and operators only had a limited understanding of the process they had to control. It was recognized that the same conditions were present outside Russia.

Just two years after Chernobyl, two catastrophes would shake the world again. The two most lethal catastrophes to date occurred in quick succession: Mexico City, San Juan Ixhuatepec and Bhopal, India (Lees, 1996; Pietersen, 2009; Shrivastava et al., 1988; Shrivastava, 1992). The staggering loss of life ensured worldwide media coverage and process safety, once again, took centre stage. In Mexico-City, an LPG storage facility leaked large amounts of flammable vapour into a densely populated area through a flange-leak. The gas cloud ignited, damaging supply lines to the storage tanks, and the subsequent fires cause multiple Boiling Liquid Expanding Vapour Explosions (BLEVEs).

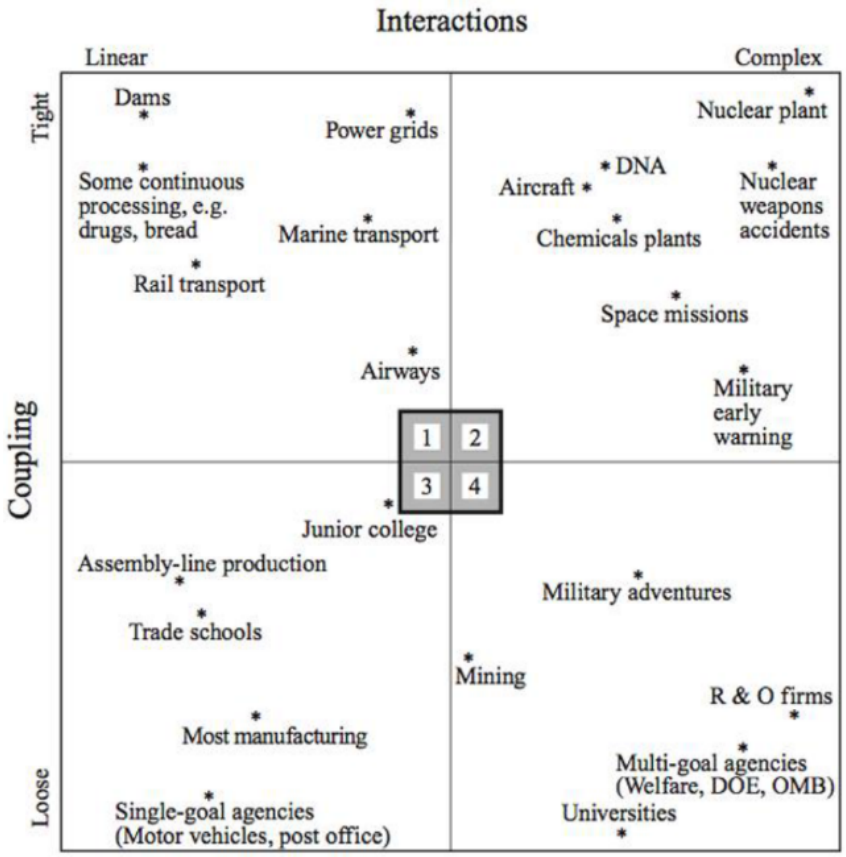

Figure 7: Industry sectors scaled along coupling and interaction (Perrow, 1984).

The explosions wrecked the storage facility, turning storage tanks into missiles that flew into nearby residential areas. An estimated 500 people died with an unknown number of people injured.

In Bhopal a vapour cloud of the highly toxic substance, methyl-isocyanate (MIC), spread over the city from a leaking pipe at the nearby Union Carbide factory. MIC had come in contact with rinsing water,

leading to an exothermic reaction, increasing pressure and forced MIC through the stack of the factory. It took hours before the leak was detected. As MIC spread over the city, more than 2000 people died within hours and tens of thousands of people were injured. A decade after the catastrophe, the number of direct fatalities had tripled, and an official 30,000 were listed as permanently injured. Union Carbide consistently claimed that sabotage, not poor engineering design, was the cause.

These catastrophes and the high frequency of accidents made the 'defence in depth' approach popular, first in the nuclear industry and later steadily propagating into the chemical process industries. The concept consist of multiple layers of safety barriers, each capable of stopping the accident. This would create a more successful accident prevention strategy. Rasmussen (1988a,b) warned the approach was not without its shortcomings. Referring to Reason (1987) he argued that multiple barriers might not necessarily be visible to operators, meaning failure scenarios were partly activated and could lead to consequences if other barriers would fail simultaneously, or later on, without operators ever knowing it. In literature, this became known as the 'fallacy of defence in depth'.

Man-Machine interaction in complex technological systems

Disasters in this period led to increased attention to human performance. The United States and Western Europe developed different views. Human Factors (HF) dominated in the United States. This branch of research dealt with quantification of human errors. The United Kingdom and Scandinavia focused on human performance in complex technological systems (Swuste et al., 2016). These topics were discussed extensively during so-called NetWork (New Technologies and Work) sessions, a multi-disciplinary workgroup of experts and scientists with different backgrounds, and supported by the Werner-Reimers-Foundation (Bad Homburg) and Maison des Sciences de l'Homme (Paris). This group published two books during the period covered by this paper: 'New technologies and human error' (Rasmussen et al., 1987) and 'The meaning of work and technological options' (Keyser et al., 1988).

The engineering approach entailed a separation between workers and hazards as much as possible. Automation and remote controlled operations were key to this strategy. In some industries, like car manufacturing, energy production and hazardous processes, this trend was already prevalent. In the eighties, even more processes were automated, and computers controlled machines in the production processes. The distance between the worker and the production process increased and detailed knowledge of the production process, and craftsmanship diminished (Singleton, 1984; Rasmussen, 1980; Hollnagel et al., 1981). Automation reduced workers' activities to trouble shooting in case of process disturbances (Figure 8). Human performance in technologically complex environments was not well understood in the 1980s (Eberts and Salvendy, 1986). Human errors were still viewed as results of incompetent operators, and the psychology of fault-generation was underdeveloped. Rasmussen

proposed that errors were actually normal variations of human behaviour: variability was a mechanism explaining how operators learned to operate the system and deal with unexpected circumstances (Rasmussen, 1982; Rasmussen and Lind, 1982). Human errors were viewed as unsuccessful experimentations that produced unacceptable consequences. Rasmussen thought an unsupportive workplace caused errors because for workers the process was hard to analyse and understand. The traditional single-indicator single-response was found to be ineffective, where an action was required from an operator, and he, or she, had to discover the state of the system on the basis of the indicator and training received. Too little attention went into ergonomic principles whilst designing process control systems. An operator required sufficient time and information to correctly react to process deviations. The Three Mile Island control room was an example of such an inadequate design.

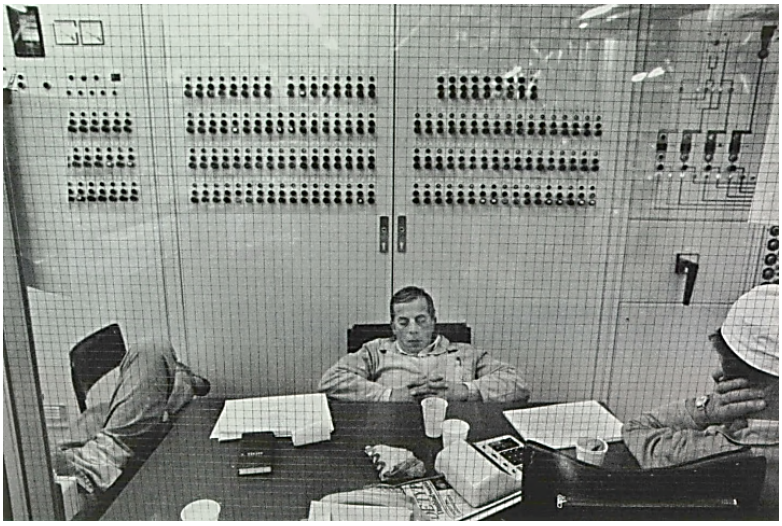

Figure 8: Control room of potato-mill (© Michel Pellanders 1980).

Information needed to be presented in terms of human mental functions that operator easily comprehended and enabling them to perform control functions, and not only in terms of system requirements. Humans respond to a total situation: operators have a holistic approach to a state of a process. Humans could integrate technically incompatible sources of information and recognizing patterns, but were less good at responding adequately to incidental events and deviations arising from a one sensor, one indicator technology (Rasmussen, 1983; Rochlin, 1986).

Rasmussen developed a taxonomy for operator behaviour which he based on empirical evidence gathered in the 1970s while analysing problem solution strategies of maintenance operators. He published his well-known skill-rule-knowledge model for human behaviour in his 1982 and 1983 papers (see Figure 9). The individual levels are not alternatives but interact (Rasmussen 1983). Some years

later, this theory would be referred to as the Rasmussen-Reason model (Rasmussen and Reason, 1987). An operator's behaviour in a high-risk, complex technological work environment was captured in three different categories:

1. Skill-based: automated and subconscious processes which were prevalent in skills internalized by operators' experiences;
2. Rule-based: this behaviour was prevalent when the operators used explicit rules to execute a specific task;
3. Knowledge-based: operators used their intelligence to judge situations and find solutions for problems that were new or not within the explicit remit of their task; this behaviour required knowledge, attention and concentration.

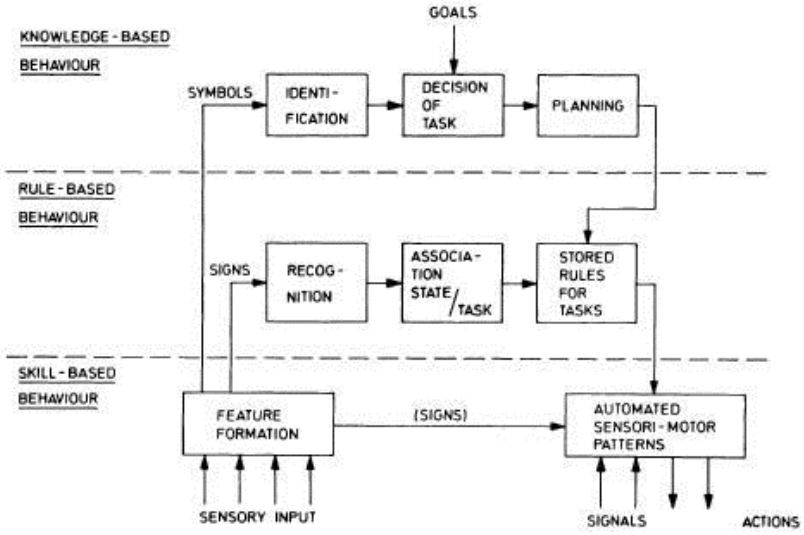

Figure 9: Simplified representation of Rasmussen's mental model for operator performance.

Le Coze's (2014) paper discussed the origin of this model, and pointed to the concept of cognitive engineering and its relationship with process design. In cognitive engineering the man-machine interface is designed to support operators in their complex task of dealing with unexpected process disruptions and deviations. This taxonomy of behaviour was the first initiative to make human performance part of the design of controls and so initiated cognitive engineering.

The Rasmussen-Reason approach was fundamentally different from the contemporary American approach to human error, 'Technique for Human Error Rate Prediction or THERP. This techniques originated from the 1960s and based on a probabilistic approach to human errors, the Human Reliability

Assessment (HRA) calculations. HRA estimating probabilities of human errors combined with a fault-tree approach, similar to a fault-tree for technical systems. A large database was developed to quantify the fault trees by the Sandia Laboratories for the US Nuclear Regulatory Commission (Swain and Guttmann, 1983). Quantification of errors was not restricted to the US alone (Rafaat and Abdouni, 1987). Also in the UK it was ascertained that many human errors occurred in so-called 'human-factor-poor' working environments (Hawkins, 1987). Many authors expressed concerns against quantification. The reliability of information was questioned, and therefore its predictive power. A reliable database containing observable and reversible errors was nigh impossible, which was also the case for fault-predictions. A more fundamental concern was the reduction of human behaviour to a technical system component. It did not represent the way how people in technologically complex environments were dealing with process deviations. (Singleton, 1984; Rasmussen 1982).

Organisation psychologists also doubted the quantitative approach, amongst others the American Karl Weick (1974, 1979) and the Dutchman Geert Hofstede (1978). Hofstede doubted the quality and effectiveness of system feedback loops in organisations. He stated that managing a company, or an organisation were fundamentally social processes and not technical ones. Weicks (1974, 1979) comments were similar: in his view people in an organisation had to deal with practical organisational puzzles and trying to make sense of their predicament. Control, system and feedback were terms that carried no value in their decision-making processes; their actions and decisions were rational only in retrospect. It would be more sensible to focus on organisational processes (Daft and Weick, 1984; Rochlin, 1986; Weick, 1987). Balance, control, feedback, terms from a system approach would not explain organisational dynamics.

By the end of the 1980s a new research direction took off: 'high reliability organisation (HRO)'. HROs were defined as organisations that dealt with very complex processes that were tightly coupled, and in contrast to Perrow's normal accidents, experienced a very low number of accidents. Flight operations on aircraft carriers and air traffic control were examples. HROs were organisations that performed very reliably despite operating dangerous processes. Reliability, in this context, was characterized by learning, understanding and correcting complex processes to prevent accidents. This approach was diametrically opposed to the traditional, on mechanistic efficiency focused management approach. Weick found that the supposedly efficient HRA method yielded situations in which operators would simply not have enough time to respond to complex deviations (Weick, 1987; Roberts, 1988). It was actually claimed that: 'We have third generation machines and first generation minds' (Westrum, 1988). Additionally, accident reports of that time emphasized that accidents did not have purely separate technical or human causes, but tended to combine these into interactive or synergetic errors. Time pressure alone was not the problem; humans could simply no longer understand the complexity of the

systems they were operating, and traditional feedback learning was no longer sufficient to achieve optimal process control. The breakdown of traditional feedback leaning was part of the HRO philosophy; optimal process conditions were a utopian condition. That left two basic options: either the system had to simplify, which Kletz proposed; or the operators had to become smarter. When the complexity outgrew the capacity of a single human, teams or networks had to do the job. These teams had to be composed of people from diverse backgrounds to enhance reliability. An example was the Diablo Canyon reactor in California, which was built near four tectonic faults (including the San Andreas Fault and the Hosgri Fault) and had to be able to withstand earth quakes with a strength of up to 7.5 on the Richter scale. An elaborate seismic detection system was used that could shut down the reactor automatically. At shift change process control was handed over as a group process in which a supervisor, an engineer and some hand-on operators informed the next shift about the previous shift. To Weick this represented an efficient delegation of responsibility and expertise with a minimum of hierarchical structure. (Weick, 1987).

Another example central to HRO reasoning was aircraft carriers. Operating these carriers defied standard ways of working safely in complex organisations. Organisationally, there was a horizontal structure of squadrons, a vertical structure of maintenance and operations, and a crosscutting command structure to deal with military units at sea and in the air. On top of that, 100% of all staff was replaced every 40 months. And hazards were huge. An aircraft carrier stored vast amounts of high explosives and aircraft fuel; it controlled complex air manoeuvres; was propelled by a nuclear reactor, and it often operated in hostile waters. The only way to achieve reliability was to build in redundancy in several ways. Some responsibilities were delegated to the expert in the front line, meaning someone lowest in hierarchical rank could have the authority to cancel flights on the flight deck, or landing of planes. Officers had learned to trust the authority of these front-line men, on whom their safety depended. Young officers were trainers and learners at the same time; as if the ship was one big school. Fail-safe redundant systems were introduced: operations were supported by several teams that could take on each other's responsibilities, and double-checking was operational in nearly all safety-critical decisions and actions. The organisation was competent in dealing with process deviations, and all staff could be used multi-disciplinarily. (Rochlin et al., 1987; Roberts, 1988). Organisational culture was a dominant feature of such highly complex high-risk operations. People accepted the way it functioned, shared preconceptions and assumptions, identified with personal fulfilment of the activities and tasks, and respected the way decisions were made. Quite contrary to organisations in which traditional feedback learning was prevalent, HRO organisations hardly required any oversight (Weick, 1987). These specific high-reliability organisations did not appear to require a separate safety management system. Only examples of HRO

organisations were limited in the period discussed. The majority of organisations that dealt with less extreme safety concerns trusted and used safety management systems.

SAFETY MANAGEMENT AND SAFETY MANAGEMENT SYSTEMS

The time period before 1979 saw the development of basic principles for safety management and quality management (Swuste et al., 2016). By 1987 such principles were adopted in international standards for quality management, such as ISO 9000 (ISO, 1987). Though ISO 9000 was primarily designed for controlling quality, it was adopted for safety as well. Accident reports, time and again, demonstrated that management failure was the fundamental cause of accidents, especially by major accidents, and thus adequate safety management systems were desperately required. Similarly, the scientific literature concluded that management decisions were often haphazard, leading to unsafe situations. This was found both for high-risk organisations and occupational safety. Safety simply did not get the attention it deserved from contemporary managers. The only safety indicators used were sick leaves after accidents, but these provided no insight into the basic causes of accidents (Grondstrom et al., 1980; Kjellén, 1982, 1984a, 1987; Robinson, 1982; Kletz, 1985b; HSE, 1985; Fischhoff et al., 1987; Harms-Ringdahl 1987a). In this approach, managers were assumed not to make errors, whilst front line workers were consistently at fault. The Accident-Proneness theory was extremely popular, and it was the preferred theory to design accident prevention methods (Tombs, 1988). The disparity between science and practice became almost impossible to reconcile (Purswell, 1984; Kjellén 1984a). Another problem was litigation; after major accidents new laws were adopted which made safety laws very detailed and almost impenetrably complex. This led to an unclear relations between the law and safety performance (Kletz, 1984b, 1986; Benner, 1975, 1985). Kletz (1984a) went as far as to claim that criminal prosecution was contra productive for safety; prevention was much better.

After Petersons' audit system in the previous period, the International Safety Rating System (ISRS) was developed by Bird and Germain (1985). ISRS was based on a system of the Chamber of Mines of South Africa, the International Mining Safety Rating System measuring safety improvements in mining. The audit consisted of 20 elements, each with a dozen of questions (Figure 10). Answers to these questions produced a score allowing benchmarking, and guiding management to actions in case of negatively answered questions. Unfortunately, a clear relationship between accidents and the audit questions was never found (Eisner and Leger, 1988; Guastello, 1991).

Wildavsky (1988), a political scientist, introduced a completely different approach for safety management, in line with HRO. Wildavsky postulated that for well-known hazards in a stable environment, anticipation 'a trial without error' approach prevailed. In these situations hazards were predictable, and controlled with safety barriers, protocols, and simulations. This approach is risk avoiding aimed to guard the stability of a system. Risk avoidance was dominant amongst companies. Inevitably this stimulated an unbridled growth of legislations, protocols and rules amongst organisations and governments. Wildavsky

postulated that stable situations were practically non-existent, and a different strategy was required in a dynamic environment: resilience. Resilience was an organisation's capacity to adapt to, and react to dynamic conditions and hazards, before causing serious problems. These two fundamentally differing approaches concerning hazards and risks illustrated how little was known about functioning of complex organisations. And most high-hazard industries should be classified as such (Daft and Weick, 1984). Westrum (1988), in his contribution to the 'Safety Control and Risk Management' conference of the World Bank, presented a classification of organisational reactions towards safety, and saw huge differences between organisations and their responses to safety issues. His classification was similar to the one suggested by Petersen thirteen years earlier (see Swuste et. al., 2016):

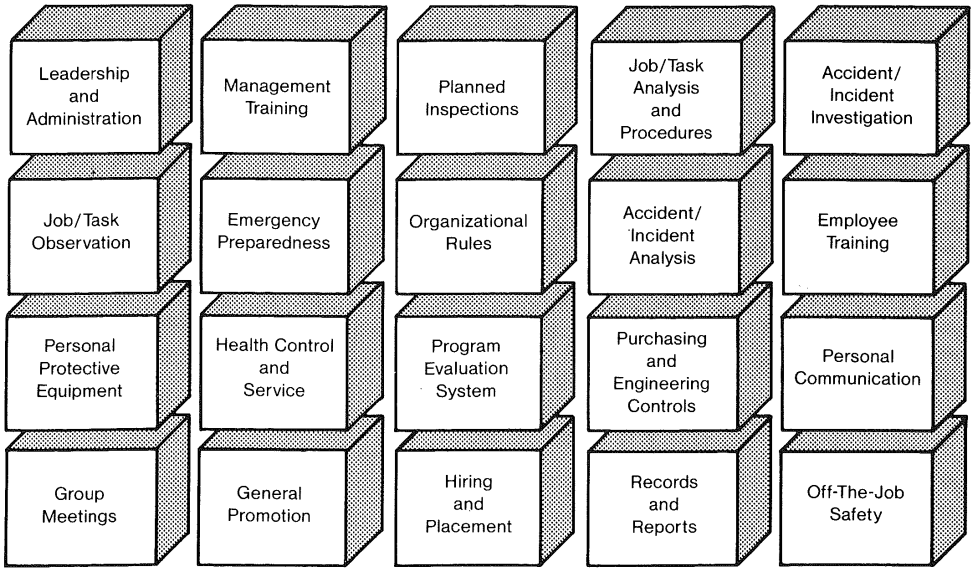

Figure 10: 20 elements of Loss Control Management (Bird and Germain, 1985).

1. Pathological organisations

   Even under normal operation circumstances, pathological organisations cannot deal with hazards effectively. Significant economic pressures forced these organisations to wilfully bypass safety regulations. Safety protagonists were ignored, suppressed or punished in such organisations. An example was Union Carbide in their bullying tactics in the Bhopal investigation (Shrivastava et al., 1988; Shrivastava, 1992);

2. Calculative organisations

   Such organisations work 'by the book' when it came to safety management. They were better than pathological organisations and could survive during relatively placid time periods. However,

this approach was no longer functional in times of change; when unforeseen events occurred; the organisation was not able to respond adequately. The incident at Three Mile Island fit that management category (Kenemy, 1979). During periods of calm, safety management functions reasonably well, but during the four-day crisis, operators could not comprehend the seriousness and magnitude of the disturbances occurring inside the reactor;

3. Generative organisations
   Generative organisations are resilient. They are characterized by strong leadership and creativity, which is stimulated throughout the organisation. High Reliability Organisations were examples of such an organisation.

Such knowledge, however, was not applied to industry, as the Piper Alpha catastrophe would illustrate: an organisation with a pathological management style failed abysmally in the North Sea.

PIPER ALPHA

An explosion in the gas-compression section on the 6th of July 1988 initiated the catastrophe on the North Sea oil-drilling rig Piper Alpha. The rig connected to three other rigs in the North Sea (see Figure 11). The explosion occurred with a pump that was taken out of operation due to a leak but was inadvertently switched on.

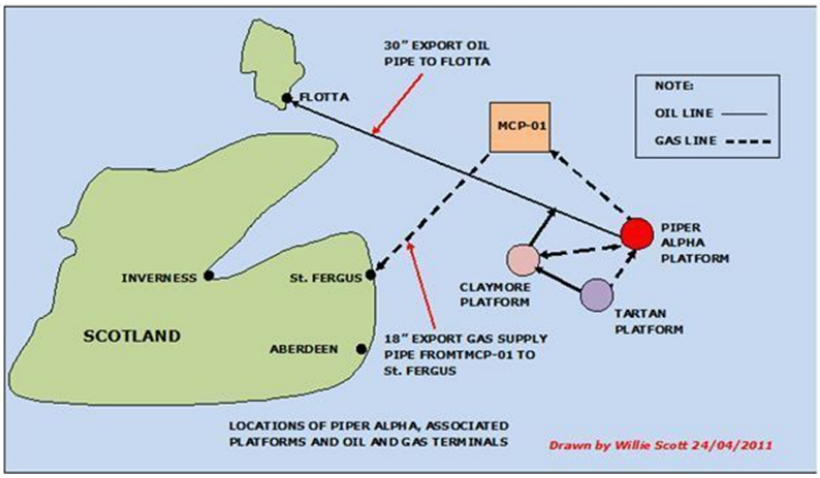

Figure 11: connections between Occidental rigs.

It was a consequence of a faltering 'permit to work' system. The first explosion destroyed fire-resistant walls; the control room; the communication system and the energy supply system. The fire extinguisher was out of operation because divers were working near the water inlet which, and a series of explosions followed, which razed the rig. It also took a long time to stop the flow of oil and gas kept flowing to the platform from Tartan and Claymore, which fed a fire that created a lethal black smoke in the living areas where most workers had fled. The catastrophe was the most lethal in offshore history: 167 people died, and over 60 survived by jumping off the platform, sometimes from a height of 30 meters.

Lord Cullen (1990) was asked to lead the investigation. His report contained, the most comprehensive accident investigation that had ever been performed in the UK. The report contained extensive technical information about the accident and how it had occurred, but it also contained an extensive critique of the safety management system operated by Occidental, the operator of the rig, and the Department of Energy, the regulator. Occidental managers lacked adequate safety training and knowledge, such as basic knowledge of fire control. The 'permit to work' system was fatally flawed, and, additionally, there was only rudimentary feedback from audits and findings from earlier safety issues. The

regulator had failed to detect such shortcomings in their inspections, which was attributed to the lack of knowledge on the part of the regulator. The catastrophe laid bare that, despite years of research, safety systems were still too underdeveloped to prevent such catastrophes.

DEVELOPMENT OF SAFETY SCIENCE IN THE NETHERLANDS

In The Netherlands occupational safety remained important. This period in time saw changes in the Dutch professional safety journals and magazines. The name of the magazine 'De Veiligheid' (Safety) was changed into 'Maandblad voor Arbeidsomstandigheden, or MAO' (Monthly magazine for Occupational Safety) and the 'Tijdschrift voor toegepaste Arbeidswetenschap, or TtA' (Journal for Applied Occupational Sciences) was born. TtA published scientific articles on occupational safety, hygiene, medicine, and organisational sciences (Korstjens, 1988; Vernooy, 1988). The protection of workers was often discussed in this national magazine and journal. Ergonomics and the design of inherently safe workstations and equipment were frequently reported (Stassen, 1981; Poll, 1983, 1984; Jong and Poll, 1984). A popular slogan was 'you should expect trouble if you allow safe people to work in an unhealthy environment' (Boudri, 1979). Also the attention shifted from the victim of an accident to its context (Keyser, 1979; Redactie, 1986). Task dynamics became an important factor (Kraan, 1981; Zuuren, 1983a) as did ergonomics and safety at the design phase (Comeche, 1979; Zwam, 1979b).

The second major point of attention focused on safety departments and safety management systems. There was focus on the so-called 'soft' side of safety: organisational factors (in particular, management), perception, and responsibility. This refocusing stared in the 1970s and manifested itself in studies in which risk perception, safety climate and safety culture were measured (e.g. Zohar, 1980). Zohar's work was translated into Dutch in the magazine 'Safety' (De Veiligheid). The importance of safety meetings, training, audits and regulation was also stressed (Zwam, 1979a; Putman, 1986). An early type of 'safety ladder' was presented which showed quantitatively the different maturity levels of safety for organisations. The method proposed safety indicators, like the number of safety audits, frequency of safety meetings, number of training courses and the number of task analysis featured (Leij, 1979).

Concerning the question of responsibility for safety, two schools of thought existed in The Netherlands. The first school adhered to the American style Human Factors approach; i.e. primarily, workers were responsible for their own safety and the safety of their less senior colleagues. Training and exchange of experiences in management teams could facilitate this approach. The Swain project report disseminated this approach in The Netherlands (Anonymous, 1982; Blijswijk and Mutgeert, 1987). The second school of thought adhered to the British approach in which the responsibility for worker safety was primarily that of the organisations and its managers. This approach followed the Robens' report of

1972, blamed failing management and management systems as the primary cause of inadequate safety (Oirbons, 1981).

Amidst discussions about occupational hazards, organisation and responsibility, the new law in The Netherlands for occupational hazards was created: the Working Conditions Law (Arbowet). Its philosophy was based upon harmonious collaboration and discussion between labour and management about safety issues. 'Humanisering van de arbeid' (humanization of labour) was the word. The endeavour to change labour, and labour conditions where the chances of injury to body and mind were minimized (Roos, 1979). The Arbowet also introduced "wellbeing" as a central concept. Additionally, the Minister of Labour at the time, Alberda, specifically stated that women and foreigners should not carry an uneven burden. Discussion and personal development were to be nurtured, monotonous work to be avoided and craftsmanship to be stimulated. (Anonymous, 1979, 1980a; Sluis, 1984). Perhaps not surprisingly, in practice these ideals were hard to achieve. Publications in occupational safety journals, such as the 'Risicobulletin' ('Risk Bulletin') showed that many corporations often failed in their obligations. Labour unions like the industry-union IBFNV supported these findings. Many publications criticized corporations that failed to meet the requirements of the new law. Often such publications were based on cooperation between unions, universities, and semi-governmental bodies concerning workers' safety and wellbeing, like the Advisory Group on Work and Health (Adviesgroep Stichting Arbeid and Gezondheid). An example of such cooperation was research conducted by the University of Leyden Science Shop, scrutinizing the American corporation Cyanamid for exposing workers to unacceptably high levels of toxic chemicals (Beek et al., 1982).

Unions played a central part in the critique of corporations. A long list of reports was written about poor working conditions in corporations and factories in manufacturing, chemical process industries, rubber factories, transport corporations, food processing, construction, electrical engineering and printing presses (Vreeman, 1982; Buitelaar and Vreeman, 1985). The reports described unsafe installations and unacceptable levels of exposure to chemicals, vibrations, noise, shocks and toxic dusts. Additionally, many problems about pay, leave, product quality and low frequency of work meetings were identified (Hattem, 1980). For the unions at that time, occupational safety was an important point of critique in the Netherlands.

Alternatively, DuPont Company was criticized because the company stressed safety too much, arguing that corporate safety management could even extend into the private lives of it workers (Duyvis, 1979). This generated quite some resistance amongst Dutch workers. DuPonts' justification was based on the high frequency of domestic accident, influencing labour performance. Workers were encouraged to follow corporate safety standards during their holidays (Sluis, 1983). There were safety procedures at DuPont for pretty much everything: generic ones, department-specific ones, section-specific ones, and

procedures right down to individual tasks. Weekly inspections were turned into ‘unsafe act index scores’. So many procedures were put in place that if an incident occurred, there was bound to be a broken procedure, creating an atmosphere of a negative competition with consequences for pay-rise and advancement. DuPont focused on occupational safety and stressed personal protection equipment. Staff complained about this approach; a lot was invested in state of the art of personnel protective equipment but redesign of machinery to more fundamentally increase safety was out of the question (Boonstra, 1983, 1983/4). On the whole, this type of behavioural focus on safety, popular in the US, was not welcome in the Netherlands (Anonymous, 1980b, 1983b).

Safety research in the Netherlands also led to a comprehensive compendium for quantitative risk analysis (QRA) for process safety. The increased interest in reliability engineering, operations research and risk analysis for external risks was treated in the CPR committee, the committee for prevention of disasters. CPR published their so-called ‘coloured books’ to support QRA (see Oostendorp et al., 2016). These publications became important sources for the initial Seveso Directive of 1982 and contained a long list of dangerous goods and activities with threshold values for safe operations. The Dutch Labour Inspectorate was also very productive in this period. With their V- and R-series, guidelines for HAZOP, process safety analyses, and risk detection systems were published (DGA 1979, 1981, 1984a, b). Also the professional press, like ‘De Veiligheid’ (Safety) kept treating process safety and probabilistic risk analysis as it had done earlier (Hanken and Andreas, 1980; Leeuwen, 1982; Dop, 1981; 1984, 1985). It continued the tradition of publishing about the quality, consequences and results of risk analyses. But only a handful of experts seemed to understand the numbers of QRA (Bjordal, 1980) and it was feared QRA would be labelled as a scientific approach to the fear of citizens (Irwin, 1984; Eindhoven, 1984). Risk perception was inexorably connected to these discussions and extensive studies were performed and published into ‘De Veiligheid’ (Stallen, 1980; Stallen and Vlek, 1980; Andreas, 1981). In 1983 the magazine featured a paper about the Management Oversight Risk Tree (MORT) an American analysis technique targeted at system failures, at that time a decade-old (Zuuren, 1983b). This was in stark contrast to the absence of publications on other theories and metaphors, like Perrows’ normal accidents, Weicks’ high reliability organisations and Reasons’ resident pathogens. More popular were studies of human behaviour in automated process plants. The taxonomy of behaviours and the skill-rule-knowledge model by Rasmussen and Reason were discussed in the magazine (Kolkman, 1980, 1981; Stassen, 1981). This was also the topic of the professorship on Safety Science at the Delft University of Technology (Hale 1985). The chair was taken by Andrew Hale, who with co-author Ian Glendon published a textbook on ‘Individual behaviour in the control of danger’ (Hale and Glendon, 1987). They argued that generally mental information processing of operators and maintenance staff were excellent. Only occasionally errors were made, leading to system deviations. However, operator possessed good

skills to correct, and therefore could put a process back into its intended operation mode. But systems could also move too far out of control. According to the authors, and in line with Rasmussen, this was, however, not usually caused by human error, but a consequence of insufficient system knowledge, information overload, or management decisions that had insufficiently considered potential risks, and disaster scenarios. In reality process safety in industrial plants had become so complicated that academic training in chemistry and chemical engineering was required for adequate safety analyses (Lemkowitz and Zwaard, 1988; Kletz, 1988b). The Delft University of Technology and the University of Amsterdam followed up on these developments by adding chemical process safety as a required course in their chemical engineering curriculum (Sectie Veiligheidskunde, 1983; Hale 1987; Bibo, 1987).

The Shell Case

Another important contributor in the Netherlands was the psychologist Wagenaar (1941-2011). In the 1970s he worked at the section Human Sensory Studies, an institute of TNO. His work focused on decision-making and factors that influenced decision-making. In 1982 he accepted a professorship at the University of Leiden, where he studied the origin of human errors. His inaugural speech analysed a historic Dutch disaster, namely the huge explosion in Leyden in 1807 of a ship filled with gun powder-that destroyed much of the city and killed hundreds. Wagenaar's concluded it was probably erroneous to completely blame the captain who lit a cooking fire on the gun powder loaded ship. More correctly would be to consider the wider web of decision makers and decision making that had occurred (Wagenaar, 1983). The Maritime Research institute granted TNO and Leiden projects to investigate maritime safety. A checklist for air transport safety by Feggetter (1982) was used to re-analyse 100 maritime accidents. The accidents were classified into three factors of sub-systems: cognitive, social, and situational. In 28% of cases, human errors were the main contributing factor, but even with technical factors there was always a human element present (Wagenaar and Groeneweg, 1987). This finding justified further scrutiny of the human contribution. The conclusion of the subsequent research was that most accidents were too complex to blame on humans because it was often too hard for humans to completely understand the consequences of their actions. The concept of 'impossible accident' was introduced to reflect the fact that occurrence and results of accidents were too unpredictable for humans to assess the consequences of their actions; their mistakes could only be explained after the accident. It was found much more prudent to find the factors that caused people to make mistakes; the diversity of those causes was much more manageable than consequences of accidents. By elimination of disturbances to humans, entire accident classes could be prevented. Also, the cause of such disturbances was found to be due to poor decision making by management. Analysis of accidents at NAM, the Dutch Natural Gas

Corporation, and misuse of force cases of the Dutch Police supported these findings time and again (Groeneweg, 2002).

The maritime safety investigation drew attention of Royal Dutch Shell. According to Van Engelshove, a top manager of the Exploration and Production division of Shell, the number of people killed in Shell's industrial activities were completely unacceptable, and he challenged local manager Koos Visser to come up with solutions to lower the number of casualties. Visser, inspired by Wagenaars work, assigned a research grant to Wagenaar (Leyden University) and to Reason (Victoria University at Manchester) to investigate industrial safety in Shell's process plants. The project, 'From Jungle to Board Room,' had to develop a sensible model on accident causation and tools for 'local triggers' and 'resident pathogens'. Additionally, better safety management techniques had to be developed. The whole project was called 'Tripod', after a three-legged dog in Gabon that had been put down for rabies that he turned out not to have. The concept of the safety management system was developed and based upon accident research at NAM (Groeneweg and Wagenaar, 1989).

According to the model accidents were consequences of unsafe acts in combination with specific local conditions or precursors. Though such conditions were almost impossible to predict, there was only a handful of root causes responsible for accidents: the so-called General Failure Types or GFTs. The GFT's were extracted from the literature to create a list of factors that an organisation ought to control. Failure to manage these factors increased the chances of humans of making errors in situations where accident precursors were present. The list included: poor ergonomics, inadequate procedures, insufficient training and insufficiently clear communication. Ten out of eleven GFT's were related to ordinary business processes which, at first glance, had little bearing on safety. Safety became a product of good management and well-managed business processes. The model was quite generic in its design so that virtually any organisation could use it by identifying local aspects of GFT's in their organisations. The mantra was relatively straightforward: whether you are dealing with an oil-rig or a lemonade factory bad design gets you in trouble. The eleventh GFT was a special one: safety defences. It dealt with mapping safety controls. This design triggered a search for indicators that would identify erroneous GFTs before accidents had happened. This led to the development of Tripod Delta in the first part of the research project. Later on, a tool was developed to try to identify GFT failures after an accident had occurred (Tripod Beta). At that time, 1987/1988 Reason had already started writing his seminal work, 'Human Error', which appeared in 1990 (Reason, 1990). It is a tragedy for modern safety scientists that Chapter 7 of the original manuscript, which dealt with a history of safety science from the ancient Greeks to modern times, was discarded because peer reviewer Brehmer thought it was too dull. Reason decided to write an alternative chapter, 'Latent errors and system disasters' (Reason, 2013) in which he illustrated the new human error concept by applying it to modern incidents, such as the sinking of the Herald of

Free Enterprise and the nuclear melt down at Chernobyl. In the Netherlands, Wagenaar became a local celebrity and the first media star in the field of human error and safety. What this mostly demonstrates is that modern thinking about organisational factors in accidents, which is quite popular today, was quite well developed before Piper Alpha blew up in the North Sea.

DISCUSSION AND CONCLUSIONS

This literature review describes the development of safety management and accident theories between 1979 and 1988 in occupational safety, and in process safety, or more generally in high-hazard-high-risk industries. It does not mean this knowledge and concepts were popular, or even used by practitioners of that time. Sometimes it took years for the knowledge to be taken up by practitioners and sometimes such knowledge just disappeared. The uptake was slow for key concepts, such as safety climate, the deviation model, and the IJEM risk factors. Tables 4 and 5 present the theories developed in this period of time. These Tables answer the first research question of this paper but they also show that occupational safety developed less powerful theories than process safety. The rapid knowledge development in process safety was probably stimulated by a great number of major accidents in this period, of which many received none of only minimal media attention (see Annex 1).

Human error models prevailed in occupational safety. This was not just the case in the Netherlands. But also Scandinavian and American sources, and from publications of the British Society for Social Responsibility in Sciences (BSSRS) confirmed a similar trend in many more countries (Kjellén, 1984c; Purswell and Rumar, 1984). The complexity of accidents was discovered. Additionally, Frank Lees created Loss Prevention as a scientific discipline, and Trevor Kletz supplied hands-on practical solutions supplemented with his appealing safety one-liners. Furthermore, the systems approach developed in process safety found its way into occupational safety: human errors were no longer causes of accidents but consequences of complicated process deviations. These findings reiterated findings by Winsemius in the 1950s, and an ergonomic approach to safety which started around that time. Tragically, literature seldom referred to Winsemius. The term ‘socio-technical systems’ which became a commonplace in a previous period, became a popular expression to indicate that relationship. And terms like ‘latent conditions’. ‘resident pathogens’, and ‘impossible accidents’ were introduced, the faults of organisations came to light, and the concept of human error was redefined.

Purwell and Rumar (1984) tried to capture the changing relationship between employees and their work to explain how safety had changed beyond recognition during the second half of the 20st century. They started their narrative before the industrial revolution (Figure 12). The evolution of industry, they proposed, caused significant changes in safety. From an original direct coupling between employees and their tasks by manual labour before 1800, when employees determined their own safety and production speed, the early 1800s saw the introduction of powered manufacturing. This increased production speed immensely and changed the relation between the employee and his work fundamentally. The employee was now the controller of machinery and was expected to solve problems, which increased the pressures on concentration and mental processing. The distance between the

employee and powered machine was short, which caused many accidents in factories. Also, managers started to depend on employees' knowledge and experience, which distanced managers from production processes. While mechanization of processes made tremendous progress; employees remained fundamentally unchanged. The responsibility for safety, however, was now shared between designers and managers, who determined the interaction between machines and employees. This relation changed again during the second half of the 20th century, when automation and remote control were introduced. This new technology changed work and safety another time. The direct control of production processes was now in the hands of computers, and productivity and complexity increased immensely. Employees' tasks were reduced to monitoring processes and, if necessary (which occurred rarely), to intervene during process disturbances. Both literally and figuratively, the distance to hazards increased. As did the need for greater cognitive capabilities of the controller, even if this cognitive power was required only infrequently. Thus while employees experienced long periods of boredom, they also experienced infrequent, short periods of frantic situations, during which their mental models of the complexity of the process they were monitoring proved inadequate.

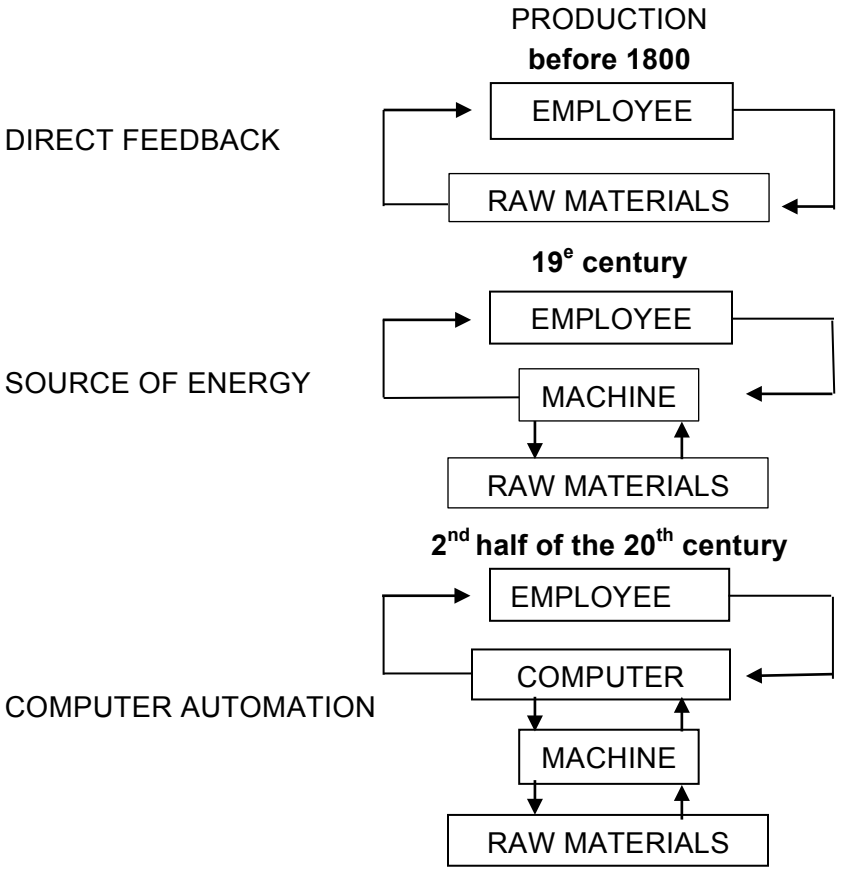

Figure: 12 Evolution of industry, after Purwell and Rumar (1984).

The responsibility for safety was still the responsibility of designers and managers, but the interactions between employees' actions and accidents were not so clear. Situational factors and various human shortcomings played a role in safety, but how these interacted was not well understood. At the same time, the large accidents increased, both in number and in extent, often extending into public spaces, making safety a political issue.

The prevalent approach in the United States was technocratic in origin and fundamentally different, although it had some influence in Europe. It involved databases containing failure frequencies of components and humans. The technocratic approach drew varied reaction. In high-density residential areas in the Netherlands the technocratic approach was used in urban planning processes (Oostendorp. 2016), but it was not without critique, related to risk acceptance and consequences of quantification. It was thought that the number of high-risk accidents would decrease because they would draw so much public attention, while, the risk of low-frequency accidents would actually increase.

Though much progress was made between 1979 and 1988 there still no clear relation was found between general management approaches and safety models and theories and safety management. General management approaches were mainly based upon market developments and production efficiency. Safety theory and models were fuelled by major accidents, while safety management was usually a subsidiary of quality management and became an independent area of attention only after Piper Alpha. This disaster served as a wake-up call, but was only partially successful. Accident and disaster scenarios did not become prevalent in management decision making. Quality circles from TQM did not develop in similar circles for safety to reduce, for incidence, frequencies of process disturbances. What did change was the status of safety, which had grown into an academic research discipline. In the Netherlands not one but two safety professors were inaugurated: Willem Wagenaar in 1982 at the University of Leyden and Andrew Hale in 1984 at the Delft University of Technology. This was not without its problems; both professors experienced serious resistance from colleagues in other faculties. Nevertheless, the appointment of Wagenaar and Hale was a leap forward for safety sciences.

year	theories	models	safety management	management approaches
1979				
1980		Positive feedback Sulzer-US System model Shannon-UK Safety climate Zohar-Israel		
1981		Deviation model Kjellén-Sweden		
1982	Risk homeostasis Wilde-Canada			Total Quality Management Deming-US
1983		IJEM risk factors Faverge-ILO		In search for excellence Peters-US
1984		Information model Saari-Finland		The change masters Kanter-US
1985			ISRS Bird & Germain-US	
1986				Images of organisations Morgan-US
1987		Accident epidemiology Stout-US Human behaviour Hale, Glendon-Netherlands Behaviour classification Rasmussen-Bad Homburg		
1988				

Table 4, Occupational safety, theories, models, and management approaches during 1979-1988

year	major accidents-disasters	theories, models, metaphors	safety management	management approaches
1979	3 Mile Island Harrisburg PA			
1980		System Safety Lees-UK		
1981		Risk triplet R = {<s_i, p_i, x_i>} Kaplan-US		
1982		Skill-rule-knowledge Rasmussen-Denmark		Total Quality Management Deming-US
1983				In search for excellence Peters-US
1984	Bhopal, Mexico City	Normal Accidents Perrow-US		The change masters Kanter-US
1985		Inherent safe design Kletz-UK	Loss Control Management Bird-US	
1986	Challenger, Tjernobyl			Images of organisations, Morgan-US
1987	Zeebrugge	Resistant pathogen Reason-UK High reliability organisations Weick-US Impossible accidents Wagenaar-NI		
1988	Piper Alpha, Clapham Junction	3E's (equipment-equations-experiments) Kletz-UK Fallacy of defence in depth Rasmussen-Den	Resilience Wildavsky-US Classification corporate response	

NI-Netherlands, Den-Denmark

Table 5, Process safety, theories, models, metaphors, and management approaches during 1979-1988

REFERENTIES

Andreas H (1979). Safety as a system approach (in Dutch). De Veiligheid 55(11):605-609

Anonymous (1979). Democratisation and humanisation of labour. Policy on working conditions of Minister Albeda as laid down in the Explanatory Notes on the Budget of the Ministry of Social Affairs, 1980 (in Dutch). De Veiligheid 55(10):505-508

Anonymous (1980a). Provide decent work, Policy of working conditions of Minister Alberda (in Dutch: Zorg voor menswaardige arbeid. Arbeidsomstandighedenbeleid van Minister Albeda zoals neergelegd in de Memorie van Toelichting op de Begroting van het ministerie van Sociale Zaken voor 1981). De Veiligheid 56(10):495-499

Anonymous (1980b). You are playing too wild with your children and are straining your muscles - go back three places (in Dutch). Mare, weekblad Rijksuniversiteit Leiden 18 september p. 9-11

Anonymous (1982). The Swain safety project (in Dutch). De Veiligheid 58(11):21-24

Anonymous (1983). Safety, at what costs (In Dutch). De Veiligheid 59(4):189-191, 199

Baker A (1982). The role of physical simulation experiments in the investigation of accidents. Journal of Occupational Accidents 4:33-45

Barnett R Brickman D (1986). Safety hierarchy. Journal of Safety Research 17:49-55

Beek F ter Fransen R Kerklaan P Swuste P (1982) Cyanamid. Risicobulletin 4(1):5-8

Benner L (1975). Accident investigation. Multilinear events sequencing methods. Journal of Safety Research 7(2):67-73

Benner L (1985). Rating accident models and investigation methodologies. Journal of Safety Research 16:105-126

Bibo, B.H., Carcinogen, and then? (in Dutch) Inaugurational Lecture on assuming professorship in Process Safety at Delft University, 1987l

Bird F Germain G (1985). Practical loss control leadership. International Loss Control Institute, Loganville, Georgia

Bjordal E (1980). Are risk analyses outdated (in Dutch)? De Veiligheid 56(12):627-629

Blijswijk M van Mutgeert B (1987). Thinking ad talking makes people more safety minded (in Dutch). Swain project DSM. Maandblad voor Arbeidsomstandigheden 63(4):232-237

Boonstra J (1983). A paradox in safety and health care (in Dutch). Tijdschrift voor Sociale Gezondheidszorg 61(13):450-457

Boonstra J (1983/4). Safety at what cost (in Dutch)? Risicobulletin 5(5-6):15-18; 6(1):12-16; 6(3):8-13; 6(5):12-15

Boudri H (1979). Ergonomics ad safety, a multifaceted approach (in Dutch). De Veiligheid 55(4):183-184

Buitelaar W Vreeman R (1985). Union work and quality of labour, examples of workers research in the Dutch industry (in Dutch). PhD thesis, TH Delft

Chhokar J Wallin J (1984). Improving safety through applied behaviour analysis. Journal of Safety Research 15:141-151

Clarke D (2008). A Tribute to Trevor Kletz. Journal of System Safety 44(6), http://www.system-safety.org/ejss/past/novdec2008ejss/spotlight1_p1.php

Cohen H Jensen R (1985). Measuring the effectiveness of an industrial lift truck safety training program. Journal of Safety Research 15:125-135

Collins J Pizatella T Etherton J Trump T (1986). The use of simulation for developing safe workstation design for mechanical power presses. Journal of Safety Research 17:73-79

Comeche S (1979). Safety problems during machine design (in Dutch Veiligheidsproblemen bij het ontwerpen van machines). De Veiligheid 55(3):109-113

Compes P (1982). Perspectives of accident research by safety science. Journal of Occupational Accidents 4:105-119

Conrad J (1980) (Ed). Society Technology and risk assessment. Academic Press London

Covello V Lave L Moghissi A Uppuluri V (1987). Uncertainty in risk assessment, risk management and decision making. Advances in risk analysis, Plenum Press, New York

Cullen W (1990). The Public Inquiry into the Piper Alpha Disaster. Department of Energy, Her Majesty's Stationary Office, London

Daft R Weick K (1984). Model of organisations as interpretation systems. Academy of Man Review 9(2):284-295

Deming W (1982). Out of crisis, quality, productivity and competitive position. Cambridge University Press, Cambridge

DGA Directoraat generaal van de Arbeid – Arbeidsinspectie (1979). Hazard and operability study, why? when? how? Report R nr 3E of the Directorate General of Labour of the Ministry of Social Affairs, Voorburg

DGA Directoraat Generaal van de Arbeid – Arbeidsinspectie (1981). Hazard and operability study, why? when? How (in Dutch). Directoraat generaal van de Arbeid. Voorlichtingsblad V2

DGA Directoraat Generaal van de Arbeid – Arbeidsinspectie (1984a). Instrumental security and hazard detection systems in the process industry (in Dutch). Voorlichtingsblad V6. Directoraat –Generaal van de Arbeid, Voorburg
DGA Directoraat Generaal van de Arbeid – Arbeidsinspectie (1984b).Process safety analyse. Towards the detection of process inherent dangers. Information Sheet V7 (in Dutch). Directoraat –Generaal van de Arbeid, Voorburg
Dop G (1981). Catastrofe theory (in Dutch) (1-3). De Veiligheid 57(4):165-168, 57(5):217-220, 57(6):273-276
Dop H (1984). Operational and technical security. Living with Murphy's Law. (in Dutch). De Veiligheid 60(9):433-437
Dop H (1985). Probability calculations in technology and safety (in Dutch). De Veiligheid 61(4):179-180; Toeval en kansberekening. De Veiligheid 61(6):299-301
Duyvis J (1979). Interfaces of occupational safety ad private safety (in Dutch). De Veiligheid 55(6):309-310
Eberts R Salvendy G (1986). The contribution of cognitive engineering to safe design of CAM. Journal of Occupational Accidents 8:49-67
Eindhoven J (1984). Scientific approach to risk, a meta controversy (in Dutch). Wetenschap en Samenleving (3):17-22
Eisner H Leger J (1988). The International Safety Rating System in South African Mining. Journal of Occupational Accidents 10:141-160
Faverge, F (1983). Accidents, human factor. In: Parmeggiani L (Ed) Encyclopaedia of Occupational Health and Safety, 3rd revised edition. International labour Office, Geneva
Feggetter A (1982). A method for investigating human factor aspects of aircraft accidents and incidents. Ergonomics 25:1065-1075
Fellner D Sulzer B (1984). Increasing industrial safety practices and conditions through posted feedback. Journal of Safety Research 15:7-21
Fischhoff B Lichtenstein S Slovic P Derby S Keeney R (1981). Acceptable risk. Cambridge University Press, Cambridge
Fischhoff B Furby L Gregory R (1987). Evaluating voluntary risk of injury. Accident Analysis & Prevention 19(1):51-62
Frijters A Swuste P Yperen (2008). Ca none quantify safety in the construction domain (in Dutch). Tijdschrift voor toegepaste Arbowetenschap 21(2):39-46
Greisler D (1999). William Edward Deming: the man. Journal of Management History 5(8):434-453
Groeneweg J (2002). Controlling the Controllable, preventing business upsets 5th revised edition, Leiden: Global Safety Group
Groeneweg J Wagenaar W (1989). Accident prevention at NAM, an integrated approach (in Dutch). Leiden: Werkgroep Veiligheid, Rijksuniversiteit te Leiden, R-89/30
Grondstrom R Jarl T Thorson J (1980). Serious occupational accidents – an investigation of causes. Journal of Occupational Accidents 2:283-289
Guastello S (1991). Some further evaluations if the International Safety Rating System. Safety Science 14:253-259
Gulijk C van Swuste P Zwaard W (2009). Development of safety science during the interbellum, the contribution of Heinrich (in Dutch). Tijdschrift voor toegepaste Arbowetenschap 22(3):80-95
Haddon W (1968). The changing approach to the epidemiology, prevention, and amelioration of trauma: the transition to approaches etiologically rather than descriptive based. American Journal of Public Health 58(8):1431-1438
Haddon W (1980). Advances in the epidemiology of injuries as a basis for public policy. Public Health Reports 95(5):411-421
Häkkinen K (1982). The progress of technology and safety in materials handling. Journal of Occupational Accidents 4:157-163
Hale A (1985). The human paradox in technology and safety (in Dutch). inaugural speech THDelft
Hale A (1987). Education in safety (in Dutch). Risicobulletin 9(4):11-12
Hale A Glendon A (1987). Individual behaviour in the control of danger. Industrial safety Series Volume 2, Elsevier, Amsterdam
Hanken A Andreas H (1980). System approach and safety (in Dutch). De Veiligheid 56(12):603-609
Harms-Ringdahl L (1987a). Safety analysis in design. Evaluation of a case study. Accident Analysis & Prevention 19(4):305-317
Harms-Ringdahl L (1987b). Safety Analysis. Elsevier Applied Science, London
Hattem B van (1980). Safety and health in the industrial union FNV (in Dutch). De Veiligheid 56(11):583-587
Hauer E (1980). Bias by selection Overestimation of the effectiveness of countermeasures. Accident Analysis & Prevention 12:113-117
Hauer E (1983). Reflection on methods of statistical inference in research on the effect of countermeasures. Accident Analysis & Prevention 15(4):275-285

Hawkins F (1987). Human Factors in flight. Gover Technical Press, Aldershot, Hant, UK
Heinrich W Petersen D Roos N (1980). Industrial Accident Prevention, a safety management approach. McGraw-Hill Books, New York
Hofstede G (1978). The poverty of management control philosophy. Academy of Management Review 3(3):450-461
Hollnagel E Pedersen O Rasmussen J (1981). Notes on human performance analysis. Risø-M-2285, Risø National Laboratory, Roskilde, Denmark
Hollnagel E (1983). Human error. Position paper NATO conference on human error, Bellagio Italy
Hovden J Sten T (1984). The workers as a safety resource in modern production systems. Journal of Occupational Accidents 6(1-3):213-214
HSE (1985). Health and Safety Executive. Monitoring safety. Occasional Paper Series OP9. HMSO London
Hubbard R Neil J (1985). Major and minor accidents at the Thames barrier construction site. Journal of Occupational Accidents 7:147-164
ILO (1988). International Labour Office, Major Hazard Control, a practical manual. ILO, Geneva
Irwin A (1984). Risk analysis. Who chooses in science and technology? (in Dutch). Wetenschap en Samenleving (3):7-9
ISO 9000 (1987) International Organisation for standardisation, Quality Management and Quality Assurance Standards, Geneva
Jong M de Poll K (1984). Ergonomic norms ad guidelines for enforced hand tools (in Dutch). De Veiligheid 60(12):609-612
Judt T (2012). Thinking the twentieth century. Penguin books, London
Juran J (1951). Quality control handbook. McGraw-Hill Book Company New York
Juran J Barish N (1955). Case studies in industrial management. McGraw Hill Book Company New York
Kanter R (1984). The change masters, corporate entrepreneurs at work. George Allen & Unwin, London
Kaplan S Garrick J (1981). On the quantitative definition of risk. Risk Analysis 1(1):11-27
Kemeny J (1979). Report of the Presidential Commission on the accident at Three Mile Island, the need for change: the legacy of TMI, Washington DC
Keyser V de (1979). The human factor and accidents (in Dutch). De Veiligheid 55(12):633-637
Keyser V de Qvale T Wilpert B Ruiz Quintanilla S (1988). The meaning of work and technological options. John Wiley & Sons Ltd, Chichester
Kjellén U Larsson T (1981). Investigating accidents and reducing risk. Safety Science 3(2):129-140
Kjellén U (1982). An evaluation of safety information systems at 6 firms. Journal of Occupational Accidents 3:273-288
Kjellén U (1984a). The deviation concept in occupational accident control I definition and classification. Accident Analysis & Prevention 16(4):289-307
Kjellén U (1984b). The role of deviations in accident causation. Journal of Occupational Accidents 6:117-126
Kjellén U (1984c). The deviation concept in occupational accident control II data collection and assessment of significance. Accident Analysis & Prevention 16(4):307-323
Kjellen U (1987). Simulating the use of computerised injury near miss information. An evaluation of safety information systems. Journal of Occupational Accidents 9:87-105
Kletz T (1978). ‘What You Don't Have Can't Leak’. Chemistry and Industry, 6:287-292
Kletz T (1982). Human problems with computer control. Plant/Operation Progress 1(4);209-211
Kletz T (1984a). Accident investigation How far should we go. Plant/Operation Progress 3(1):1-2
Kletz T (1984b). The Flixborough explosion 10 years later. Plant/Operation Progress 3(3):133-135
Kletz T (1984c). Cheaper, safer plants. Institute of Chemical Engineers, Rugby
Kletz T (1985a). What went wrong? Gulf Publishing Company, Houston
Kletz T (1985b). An engineer's view of human error. Institute Chemical Engineers, Rugby, Warwickshire, UK 1st edition 1985, 2nd edition 1991
Kletz T (1985c). Inherently safer plants. Plant/Operation Progress 4(3):164-167
Kletz T (1986). Transportation of hazardous substances. Plant Operation/Progress 5(3):160-164
Kletz T (1988a). Learning from accidents in industry. Butterworths, London
Kletz T (1988b). Should undergraduates be instructed in loss prevention? Plant/Operation Progress 7(2):95-98
Kletz T (1988c). On the need to publish more case histories. Plant/Operation Progress 7(3):145-147
Kletz T (1988d). Fires and explosions of hydrocarbon oxidation plants. Plant/Operation Progress 7(4):226-230
Kletz T (1999). The origins and history of Loss Prevention. Process Safety 77(3):109-116
Kolkman H (1980). The human error in safety systems (in Dutch). De Veiligheid 56(12):621-622
Kolkman H (1981). Again, the human error in safety systems (in Dutch). De Veiligheid 57(4):177-178
Kortjens, G (1988). Journal of applied occupational sciences, a fait accompli (in Dutch). Maandblad voor Arbeidsomstandigheden 64(3):73
Kraan (1981). Human factor (in Dutch). De Veiligheid 57(7/8):329-330

Le Coze J (2014) Reflecting on Jens Rasmussen's legacy. Safety Science, special issue WOS 2012 (in press)
Leeuwen C van (1982). The safety officer from phenomenon combatting to systemic approach (in Dutch). De Veiligheid 58(6):33-34
Lees F (1980). Loss prevention in the process industry. Butterworth Heinemann, Oxford
Lees F (1983). The relative risk from materials in storage and in production. Journal of Hazardous Materials 8(2):185-190
Lees F (1996). Loss prevention in the process industry. Hazard Identification, assessment and control. Butterworth Heinemann, Oxford
Leij van der (1979). Safety surveillance, useful and feasible (in Dutch)? De Veiligheid 55(5):269-272
Leitner P (1999). Japans post-war economic success: Deming, quality and contextual realities. Journal of Management History 5(8):489-505
Lemkowitz A Zwaard A (1988). Safety and environmental education should be part of an educational package (in Dutch). Chemisch Magazine (11):708-712
Leplat J (1984). Occupational accidents research and system approach. Journal of Occupational Accidents 6:77-89
Mannan S (2005) (Ed). Lees' Loss prevention in the process industry. Hazard Identification, assessment and control. 3rd edition. Butterworth Heinemann, Oxford
Mannan S (2012) (Ed). Lees' Loss prevention in the process industry. Hazard Identification, assessment and control. 4th edition. Butterworth Heinemann, Oxford
Marsh (2012). The 100 Largest Losses 1972-2011 22nd edition Marsh & McLennan Co
McElroy F (1980). Accident Prevention Manual of Industrial Operations. Engineering and technology. National safety Council, Chicago, Ill
McKenna F (1985a). Do safety measures really work? Ergonomics 28(2):489-498
McKenna F (1985b). Evidence and assumptions relevant to risk homeostasis. Ergonomics 28(11):1539-1542
Menckel E Carter N (1985). The development and evaluation of accident prevention routines, a case study. Journal of Safety Research 16:73-82
Miller T Hoskin A Yalung D (1987). A procedure for annually estimating wage losses due to accidents in the US. Journal of Safety Research 18:101-119
Monteau M (1983). In: Parmeggiani L (Ed) Encyclopaedia of Occupational Health and Safety, 3rd revised edition. International labour Office, Geneva
Morgan G (1986). Images of organisations. Sage Publications, London
Nye D (2013). America's assembly line. The MIT Press, Cambridge MA
Oirbons J (1981). Labour committee for safety, health, and well being (in Dutch: Arbeidscommissies voor veiligheid, gezondheid en welzijn). De Veiligheid 57(11):483-486
Oostendorp Y Lemkowitz S Zwaard W Gulijk C van Swuste P (2016). The introduction of the concept of risk within safety science in the Netherlands focusing on the years 1970-1990. Safety Science 85:205-219
Paté-Cornell E Boykin R (1987). Probabilistic risk analysis and safety regulation in the chemical industry. Journal of Hazardous materials 15(1-2):97-122
Perrow C (1984). Normal accidents. Living with high-risk technologies. BasicBooks, US
Peters T Waterman R (1982). In search for excellence, lessons from America's best-run companies. Harper & Row Publisher, New York
Petersen D (1971). Techniques of safety management. McGraw-Hill Book Company, New York
Pietersen C (2009). 25 years later, two biggest industrial disasters with dangerous chemicals. Research on facts, lessons for safety is these lessons learned (in Dutch)? Gelling Publishing, Niewerkerk aan den IJsel
Pindur W Rogers S Kim P (1995). The history of management: a global perspective. Journal of Management History 1(1):59-77
Poll K (1984). Norms for lifting (in Dutch). De Veiligheid 60(5):281-285
Poll K (1983). Ergonomics ad workplace improvement (in Dutch). De Veiligheid 59(12):615-618
Purswell J Rumar K (1984). Occupational accident research: where have we been and where are we going? Safety Science 6:219-228
Putman J (1986). Onvoldoende kennis en vaardigheden oorzaak van groot aantal ongevallen. Maandblad voor Arbeidsomstandigheden 62(12):746-751
Rafaat H Abdouni A (1987). Development of an expert system for human reliability analysis. Journal of Occupational Accidents 9:137-152
Rasmussen J (1980). What can be learned from human error reports? In: Changes in working life. Duncan K (Ed) John Wiley & Sons Ltd, London
Rasmussen J Lind M (1982). A model for human decision making. MP3 2:30 IEE Transactions on systems 270-276
Rasmussen J (1982). Human errors. A taxonomy for describing human malfunctioning. Journal of Occupational Accidents 4(2-4):311-333

Rasmussen J (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. IEEE Transactions on systems man and cybernetics SMC 13(3):257-266
Rasmussen J (1985). The role of hierarchical representation in decision making and system management. IEE Transactions on systems, man, and cybernetics SMC-15(2)234-243
Rasmussen J Duncan K Leplat J (1987). New Technology and human error. John Wiley & Sons Ltd, Chichester
Rasmussen J Reason J (1987) Causes, and human error, in New Technology and Human Error, Wiley, London, 1987
Rasmussen J (1988a). Human error mechanisms in complex working environments. Reliability Engineering and System Safety 22:155-167
Rasmussen J (1988b). Human factor in high risk systems. IEEE Transactions on systems man and cybernetics SMC 18:43-48
Redactie (1986). The real danger of human error (in Dutch). Maandblad voor Arbeidsomstandigheden 62(7/8):445
Reason J (1987). The Chernobyl errors. Bulletin of the British Psychological Society 40:201-206
Reason J (1990). Human error Cambridge University Press.
Reason J (2013). A life in error. From little slips to big disasters, Asgate
Roberts A Pritchard D (1982). Blast effect of unconfined vapour cloud explosions. Journal of Occupational Accidents 3:231-247
Roberts K (1988). Some characteristics of one type of high reliability organisation. Organisation Science 1(2):160-176
Robinson G (1982). Accidents and sociotechnical systems principles for design. Accident Analysis & Prevention 14(2):121-130
Rochlin G (1986). High reliability organisations and technical change. Some ethical problems and dilemma. IEEE Technology and Society Magazine, September 3-9
Rochlin G La Porte T Roberts K (1987). The self-designing high reliability organisation: aircraft carrier flight operation at sea. Naval War College Review 40:76-90
Roos A (1979). Humanisation of labour, what does it mean? (in Dutch). De Veiligheid 55(7/8):384-387
Saari J (1982). Summary theme accidents and progress in technology. Journal of Occupational Accidents 4:373-378
Saari (1984). Accidents and disturbances in the flow of information. Journal of Occupational Accidents 6(1-3):91-105
Sectie Veiligheidskunde (1983). Report on symposium ‘Safety education in The Netherlands (in Dutch: Verslag symposium veiligheidskundige opleiding in Nederland). THDelft, 26 jan
Shannon H (1980). The use of a model to record and store data on accidents. Journal of Occupational Accidents 3:57-65
Shannon H Manning D (1980). Differences between lost time and non-lost-time accidents. Safety Science 2:265-272
Shewhart W Deming W (1939). Statistical methods quality control. The Graduate School. The Department of Agriculture. Washington
Short J (1984). The social fabric at risk: towards the social transformation of risk analysis. American Sociological Review 49(6):711-725
Shrivastava P Mitroff I Miller D Miglani A (1988). Understanding industrial crises. Journal of Management Studies 25(4):285-303
Shrivastava P (1992). Bhopal anatomy of a crisis. Paul Chapman Publishing Ltd London
Singleton W (1984). Future trends in accident research in European countries. Journal of Occupational Accidents 6:3-12
Sluis W (1983). Safety at what price (in Dutch). De Veiligheid 59(10):519-521; Own initiative should get more room. De Veiligheid 59(11):581-582; How changes influence safety (in Dutch). De Veiligheid 59(12):606-607
Sluis W (1984). Humanisation of labour stimulates a social policy and effectiveness in organisations (in Dutch). De Veiligheid 60(5):267-269
Stallen P (1980). The individual judgement of risk (in Dutch). De Veiligheid 56(1):3-7
Stallen P Vlek C (1980). The individual judgement of risk (in Dutch). De Veiligheid 56(2):67-73
Stassen H (1981). Mens-machine systemen. De Veiligheid 57(9):391-396
Suokas J (1985). On the reliability and validity of safety analysis. Thesis Tampere University
Suokas J (1988). The role of safety analysis in accident prevention. Accident Analysis & Prevention 20(1):67-85
Stout N (1987). Characteristics of work related injuries involving forklift trucks. Journal of Safety Research 18:179-190
Sulzer-Azaroff B Santamaria C de (1980). Industrial safety hazard reduction. Journal of Applied Behavioural Analysis 13:287-295

Sulzer-Azaroff B (1987). The modification of occupational safety behaviour. Journal of Occupational Accidents 9:177-197
Swain A Guttmann H (1983).Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications. NUREG/CR-1278, USNRC
Swuste P Gulijk C van Zwaard W (2010). Safety metaphors and theories a review of the occupational safety literature of the US UK and The Netherlands. Safety Science 48:1000-1018
Swuste P Gulijk C van Zwaard W Oostendorp Y (2014). Safety theories 3 decades after WO II. Safety Science 62:16-27
Swuste P Gulijk C van Zwaard W Lemkowitz S Oostendorp Y Groeneweg J (2016). Developments in the safety science domain 1970-1979. Safety Science 86:10-26
Templer J Archea J Cohen H (1985). Study of factors associated with risk of work related stairway falls. Journal of Safety Research 16:183-196
Tuominen R Saari J (1982). A model for analysis of accidents and its application. Journal of Occupational Accidents 4(2-4):263-273
Tombs S (1988). The management of safety in the process industry: a redefinition. Journal of Loss Prevention in the process industry 1:179-181
Turner B (1978). Man-made disasters. Butterworth-Heinemann Oxford
Vernooy A (1988). To a journal of occupational sciences (in Dutch). Tijdschrift voor Arbowetenschap 1(1):1-2 scientific section of Maandblad voor Arbeidsomstandigheden 1988;64(5)
Vinzant J Vinzant D (1999). Strategic management spin-offs of the Deming approach. Journal of Management History 5(8):516-531
Vreeman R (1982). The quality of labour in Dutch industry (in Dutch), workers' research to the quality of labour. SUN Nijmegen
Vuorio S (1982). Investigation of serious accidents. Journal of Occupational Accidents 4:281-290
Wagenaar W (1983). Human failure (in Dutch: Menselijk falen). Nederlands Tijdschrift voor de Psychologie, 38:209 – 222
Wagenaar W Groeneweg J (1987). Accidents at sea Multiple causes and impossible consequences International. Journal of man-machine studies 27:587-598
Weick K (1974). Middle range theories of social systems. Behavioural Science 19(6):357-367
Weick K (1979). The social psychology of organising. Addison-Wesley Publishing Company Readings, Massachusetts
Weick K (1987). Organisational culture as a source of high reliability. California. Man Review 29(2):112-127
Westrum R (1988). Organisational and inter-organisational thought. Contribution to the World Bank Conference Safety control and risk management, October
Wikipedia (2014). Beacon (in Dutch: Zwaailichten.org) consulted Juni 2014
Wildavsky A (1988). Searching for Safety. Social Philosophy and Policy Centre, Transaction Publishers, Rutgers The State University, Piscataway NJ
Wilde G (1982). The Theory of Risk Homeostasis: Implications for Safety and Health. Risk analysis 2(4):209-225
Wilde G (1986). Beyond the concept of risk homeostasis: suggestions for research and application towards the prevention of accidents and lifestyle-related disease. Accident Analysis & Prevention 18(5):377-401
Zohar D (1980a). Safety climate in industrial organisations. Journal of Applied Psychology 65(1):96-102
Zohar D (1980b). Safety climate in industrial organisations (in Dutch). De Veiligheid 56(11): 551-555
Zuuren P van (1983a). Safety psychology (in Dutch). De Veiligheid 59(5):265-266
Zuuren P van (1983b). MORT a new approach of safety of industrial organisations (in Dutch). De Veiligheid 59(1):27-30
Zwam H van (1979a). Influencing safety: the worker ad his motives (in Dutch). De Veiligheid 55(1):11-16
Zwam H van (1979b). The regulation of safe behaviour (in Dutch). De Veiligheid 55(5):215-221

Appendix 1 Major accidents in the oil and process industries 1979-1988. Empty cells, no information available

Date	location	plant/transport	chemical(s)	event(s)	wounded-wou; death-†	costs 10^6 $
1979,Dec 11th	Australia – Geelong	storage	Oil	fire		17.4
Nov 10th	Canada - Mississauga, Ont	rail tanker	Cl_2	emission		
Jan 6th	Germany – Burghausen	process industry	H_2S	emission		
Feb 6th	Germany – Bremen	flour factory	flour dust	explosion	14†, 17 wou	
?	Germany – Hamburg	grain silo	grain dust	dust explosion	2 wou	
Jan 8th	Ireland - Bantry Bay	oil tanker	crude oil	explosion	50†	31.9
Jan 11th	Norway - Rafnes	process industry	Cl_2	emission		
Feb 15th	Poland Rotunda Bank			gas cloud explosion	36†	
Dec 11th	Puerto Rico - Ponce	tank	HC's	explosion		23.3
Oct 17th	Spain - Lerida	grain silo	grain dust	dust explosion	7†	
Nov 24th	Turkey - Danaciobasi			gas cloud explosion	105†	
Mar 20th	US - Linden, NJ	catalytic cracker	LPG	gas cloud fire		27.1
Apr 8th	US - Crestview, FL	rail tanker	hazardous chemicals	emission	14 wou	
Apr 9th	US - Port Neches, TX	oil tanker	crude oil	explosion		49.6
Jun 26th	US - Ypsilanti, MI	storage	C_3H_8	gas cloud explosion		
Jul 21st	US - Texas City, TX	alkylation unit	C_3H_8	gas cloud explosion		37.2
Jul 18th	US - Bayonne NJ	tanker	Cl_2	emission	10†	
Jul 28th	US - Sauget, IL	reactor	mixture	explosion		11.9
Aug 30st	US - Good Hope, LA	tanker	C_4H_{10}	fire ball	12†, 25 wou	16.4
Aug	US - Orange, TX	pipeline	LPG	explosion	1†, 1 wou	
Sep 1st	US - Deer Park, TX	tanker - Chevron	distillate	explosion		105.4
Sep 4th	US - Pierre Port, LA	pipeline	LNG	gas cloud fire		
Sep 8th	US - Paxton, TX	tanker	chemicals	bleve	8 wou	
Sep 18th	US - Torrance, CA	catalytic cracker	C_3C_4 HC's	gas cloud explosion		
Oct 6th	US - Cove Point, MD	pipeline	LNG	explosion	1†, 1 wou	
Nov 1st	US - Galveston Bay, TX	oil tanker	crude oil	explosion	32	
1980, Jun 26th	Australia - Sydney	oven, refinery	oil	explosion		25.0
Feb 26th	Canada - Brooks, AB	compression station	natural gas	explosion		55,6
Aug 18th	Iran - Gach Saran	storage	$C_3H_5(NO_3)_3$	major explosion	80†, 45 wou	
Aug 16th	Japan - Shizuoka			gas cloud explosion	15†	
?	Italy - Naples	grain silo	grain dust	dust explosion	8 wou	
Oct 8th	Mexico - Mexico City	filling station	NH_4OH	emission	9†, 28 wou	
Mar 26th	Netherlands - Enschede		C_3H_8	gas cloud explosion		
Jul 24th	Netherlands - Rotterdam	oil tanker	crude oil			
Jan 30st	Porto Rica - Bayamon	pipeline	oil products	explosion	1†	
Nov 29th	Spain - Ortuella	storage	C_3H_8	explosion	51†	
Jan 21st	UK - Barking	storage	$NaClO_3$	fire		
Feb 11th	UK - Longport	storage	LPG	fire, explosion		
Nov 20st	UK - Wealdstone	storage	C_3H_8	emission	0†, 1 wou	
Jan 3rd	US - Acobn, CA	refinery		sabotage		20.9
Jan 20st	US - Borger, TX	alkylation unit	light CH's	gas cloud explosion	0†, 41 wou	48.5
Mar 3rd	US - Los Angeles. CA	tanker	gasoline	bleve	2†, 2 wou	
May 17th	US - Deer Park, TX	phenolaceton plant		fire		28.8
Jul 15th	US - New Orleans, LA	pipeline	natural gas	fire		
Jul 23rd	US - Seadrift, TX	C_2H_4O reactor	reaction mixture	detonation		16.4
Jul 26th	US - Muldraugh, KY	tanker	H_2C=CHCl	fire	0†, 4 wou	

Date	location	plant/transport	chemical(s)	event(s)	wounded-wou; death-†	costs 10^6 $
Oct 26th	US - New Castle, DE	polypropylene plant	C_6H_{14}, C_3H_6	gas cloud explosion	5†, 25 wou	
Oct 29th	US – New Castle, DE	platform		gas cloud explosion		
Nov 25th	US - Kenner, LA	tanker	gasoline	fire	7†, 6 wou	
Dec 31st	US - Corpus Christi, TX	H_2 creaker	HC's	fire		23.6
1981,Aug 30st	Kuwait - Shuaiba	storage	oil	fire	1†, 1 wou	
Aug 1st	Mexico - Montana	tanker	Cl_2	emission	17†, 280 wou	
Jun 24th	Netherlands - Rotterdam	ore-bulk-oil ship	oil	explosion	6†, 3 wou	
Oct 1st	Czechoslovakia	NH_3 plant	syngas	gas cloud explosion		
Sep 6th	UK - Stalybridge	solvent unit	C_6H_{14}	explosion		
Feb 11th	US - Chicago Heights, IL	tank	tank content	explosion		17.4
Jul 19th	US - Greens Bay, TX	reactor	herbicides	explosion		13
May 15th	Venezuela - San Rafael	pipeline	LPG	explosion	18†, 35 wou	
May 8th	Sweden - Gotenburg	pipeline	C_3H_8	gas cloud explosion	1†, 2 wou	
1982, Jan 20th	Canada - McMurray, AB	compressor	H_2	fire		24.6
Apr 18th	Canada - Edmonton, AB	compressor	C_2H_4	explosion		24.6
Jan 17th	France - Moselle river	pipeline	CO	emission	5†	
Dec 29th	Italy - Florence	tanker	C_3H_8	explosion	5†, 30 wou	
Mar 31st	Japan - Kashima	de-sulferasation unit	HC's	fire		16.3
Feb 13th	UK - Morley	storage	herbicides	fire, emission		
Sep 25th	UK - Salford	storage	$NaClO_3$	explosion	0†, 60 wou	
Mar 9th	US - Philadelphia, PA	phenol plant	$C_6H_5C_3H_6$	gas cloud explosion		29.3
May 3rd	US - Caldecott tunnel, CA	rail tanker	Gasoline	fire	7†	
Jun 28th	US - Portales, NM	pipeline	natural gas	explosion	6†	
Sep 28th	US - Livingston, LA	tanker	mixture	detonation, bleve		
Oct 1st	US - Pine Bluff, AR	pipeline	natural gas	gas cloud explosion		
Oct 4th	US - Freeport, TX	transformator	oil	fire		17.2
Nov 4th	US - Hudson, IA	pipeline	natural gas	explosion	5†	
Dec19th	Venezuela - Caracas	Tank	oil foam	fire	150†, >500 wou	58.9
1983, Apr 14th	India - Bontang	LNG plant	LNG	explosion		
Nov 2nd	India - Dhurabar	rail tanker	kerosene	explosion	47†	
Dec 7th	Poland - Lódz			gas cloud explosion	8†	
Aug 31st	UK - Milford Haven	tank	crude oil	fire	20 wou	
Sep 25th	UK - Salford	storage	$NaClO_3$	explosion	60 wou	
Jan 7th	US - Port Newark, NJ	tank	gasoline	gas cloud explosion	0 wou	40.3
Mar 15th	US - West Odessa, TX	pipeline	LPG	fire, explosion	6 †	
Apr 3rd	US - Denver, CO	rail tanker	HNO_3	emission		
Apr 7th	US - Avon, CA	catalytic cracker	slurry	fire		56.3
May 26th	US - Bloomfield, NM	compressor station	natural gas	explosion	2 wou	
May 26th	US - Produoe Bay, AK	drums	liquid natural gas	fire		40.3
Jul 1st	US - Port Arthur, TX	polyethylene plant		fire		17.8
Jul 30st	US - Baton Rouge, LA	rail tanker	H_2C=CHCl	fire		
30-sep	US - Basile, LA	gas plant	HC's	gas cloud fire		33.9
1984,Feb 24th	Brazil - Cubatao	pipeline	gasoline	fire	>100†, 150 wou	
Aug 16th	Brazil - Petrobas Campos			explosion	49†	
Apr 20st	Canada - Sarnia, Ont	benzene plant	H_2	gas cloud explosion	2†	
Aug 15th	Canada - McMurray, AB	heating unit	HC's	gas cloud fire		85.9
Mar 8th	India - Kerala	heating unit	HC's	explosion		13.6
Dec 3rd	India - Bhopal	tanker	CH_3NCO	emission	>4000†, ? wou	

Date	location	plant/transport	chemical(s)	event(s)	wounded-wou; death-†	costs 10^6 $
Nov 19th	Mexico - Mexico City	terminal	LPG	gas cloud fire	650†, ? wou	22.5
May 23rd	UK - Abbeystead	valve	CH_4	explosion	16†, 28 wou	
Sep 15th	UK - Cheshire	process industry		fire		
Jul 23rd	US - Romeoville, IL	absorption column	C_3H_8	gas cloud explosion	15†, 22 wou	
Sep 25th	US - Phoenix, AZ	pipeline	natural gas	explosion		
Dec 2nd	USSR - Tiblisi			gas cloud explosion	200†	
Dec 13th	Venezuela - Las Piedras	de-sulpherisation	oil	fire		70.1
1985,Feb 19th	Canada - Edmonton, AB	pipeline	liquid natural gas	gas cloud explosion		
Jan 18th	Germany - Keulen	ethylene plant	C_2H_4	gas cloud explosion		
May 19th	Italy - Priola	ethylene plant	HC's	fire		72.8
Dec 21st	Italy - Napels	terminal		fire		
Jan 10th	Netherlands - Den Helder	fish factory	Cl_2	emission	31 wou	
Jan 23rd	US - Wood River, IL	asphalt unit	C_3H_8	gas cloud fire		25.2
Feb 23rd	US - Jackson, SC	tanker		emission		
Feb 23rd	US - Sharpville, PA	pipeline	natural gas	explosion		
Mar 9th	US - Lake Charles, LA	reforming unit	C_3H_8	gas cloud explosion		
Apr 27th	US - Beaumont, KY	pipeline	natural gas	fire	5†, 3 wou	
Jun 9th	US - Pine Bluff, AR	rail tanker	hazardous chemicals	emission		
Jun 25th	US – Hallet, OK	fireworks		explosion	21†	
Jul 6th	US - Clinton, IA	ammonia plant	syngas	explosion		14.7
Jul 23rd	US - Kaycee, WY	pipeline	jet fuel	explosion	1†, 6 wou	
Nov 5th	US - Mont Belvieu, TX	salt storage	C_2H_6, C_3H_8	gas cloud explosion		44.8
Nov 21st	US - Tioga, ND	gas production	HC's	gas cloud explosion		11.3
1986,Feb 24th	Greece - Thessaloniki	oil terminal	oil	fire		
Feb 21st	US - Lancaster, KY	pipeline	natural gas	fire	3†	
Jun 15th	US - Pascagoula, MS	distillation column	$C_6H_5NH_2$	explosion		
Oct 30st	Swiss - Basel	storage	pesticides	emission		
1987, Jul 3rd	Belgium - Antwerp	distillation column	C_2H_4O	explosion		
Jun 23rd	Can. - Mississauga, Ont	H_2 unit	H_2, HC's	fire		22.4
Oct 11th	Canada - McMurray, AB	Oil sand extraction	oil sand	fire		39.7
Dec 17th	Canada – Rowan Gorilla	platform		gas cloud explosion	0†	
Aug 23rd	China - Lanzhou	rail tanker	gasoline	fire	5†	
Jun 2nd	France - Port Herriot	storage	oil	fire	2†, 8 wou	
Feb 24th	Greece. - Thessaloníki	oil terminal	oil	fire		
Feb 24th	Nederl. - Alphen a/d Rijn		Cl_2	emission	30 wou	
Jun 19th	Netherlands - Zeewolde	swimming pool	Cl_2	emission	94 wou	
Aug 15th	Saoudi A. - Ras Tanura	gas plant	C_3H_8	gas cloud explosion		67.2
Mar 22nd	UK - Grangemouth	ship	H_2	fire		87.9
Nov 4th	US – Golf van Mexico	platform		explosion		
Nov 14th	US - Pampa, TX	acetic acid plant	C_4H_{10}, CH_3COOH	gas cloud explosion	3†	24.1
Nov 24th	US - Torrance, CA	alkylation unit	HC's	fire		16.4
Dec 20st	US – Cook Inlet, AK	platform		fire		
1988, Apr 24th	Brazil - Enchchova	platform	oil	fire		690
Apr 7th	Netherlands - Beek	polyethylene plant	C_2H_4	gas cloud explosion		
Sep 8th	Norway - Rafnes	vinyl chloride plant	C_2H_3Cl, C_2H_4	gas cloud explosion		12.0
Oct 25th	Singap. - Pulau Merlimau	tanks	nafta	fire		13.1
July 7th	UK – Piper Alpha	oil-gas platform	oil-gas	explosion	167†, 61 wou	1800
Jan 2nd	US - Floreffe, PA	tank	diesel	emission		14.5

Date	location	plant/transport	chemical(s)	event(s)	wounded-wou; death-†	costs 10^6 $
May 4th	US – Hendersen, NV	CH_4ClO_4 production	CH_4ClO_4	explosion	2†, 372 wou	630
May 5th	US - Norco, IA	catalytic cracker	HC's	gas cloud explosion	7†, 28 wou	327
May 5th	US – Norco, LA	refinery	HC's	gas cloud explosion	7†, 48 wou	600
Jun 8th	US - Port Arthur, IX	storage	C_3H_8	fire		17.4
Jul 30st	US - Altoona, IA	rail tanker	hazardous chemicals	emission		
Jun 4th	USSR - Arzamas	station	explosives	explosion	73†, 230 wou	