AN EXPLOSION ACCIDENT – CAUSES AND SAFETY INFORMATION MANAGEMENT LESSONS TO BE LEARNED

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A terrible accident occurred at a process plant in Taiwan on May 18, 2001. The plant was destroyed by a series of explosions that resulted in the death of one man, 112 injuries and extensive damage. The accident was caused by the ignition of a leak of mixed flammable vapours from an out-of-control exothermic batch reactor, which produced water-born acrylic resin. Most of the victims, who were employees of nearby factories, were cut by glass splinters and other debris that rained down over an area of radius 200 metres around the plant.

This accident reveals that both the process plant and the neighbouring factories did not handle safety information properly. This paper describes the accident, the discussions and the conclusions from the viewpoint of safety information management. The lessons learned from this accident include the importance of information management and the need for using a safety information management system throughout the plant life cycle. A research project at Loughborough University is investigating safety information management and its measurement and is developing a prototype tool for use in this area. This project is also described briefly in the paper.

KEYWORDS: accident, explosion, safety information management

INTRODUCTION

There is no doubt that batch polymerization reactors for the manufacture of polymers and resins should be considered inherently risky systems. Their main purpose is to react acrylic monomers to form high molecular weight acrylic resins via free radical exothermic polymerization. An analysis of industrial incidents in the UK involving thermal chemical reactions in batch or semi-batch reactors has shown that 47.8 percent of these 134 incidents were related to polymerization reactions[1]. Because acrylic monomers are highly reactive and are capable of undergoing fast polymerization that can generate substantial heat and pressure if not controlled suitably and correctly [2,3,4], most companies making these polymers are aware of the importance of safe handling of chemical material to avoid runaway reactions. However, do they have enough information to do so, particularly when the reaction equipment has been successfully operated over a long period of time, say twenty years or more?

During the afternoon of May 18, 2001, a 6-ton reactor at the Fu-Kao Chemical Plant ruptured during a runaway polymerization reaction, leading to a terrible accident. The plant was destroyed and nearby factories were seriously damaged by a series of explosions and fires that resulted in the death of one man, 112 injuries and extensive damage. The accident was caused by the ignition of a leak of mixed flammable vapours from an out-of-control exothermic batch reactor. Most of the victims were cut by glass splinters and other debris that rained down over an area of radius 200 metres around the plant.

This paper presents the initiating and root causes of the accident. In particular, it focuses on those things that were wrong or deficient with respect to managing safety information. This accident demonstrates that both the plant and the neighboring factories did not manage safety information properly. The plant did have some information about the hazard held somewhere within its organization. However, this knowledge was 'inactive' because it was simply filed and no one knew about it. Most of the neighboring factories had no knowledge of the hazards existing in the facilities close to them. This accident provides a typical case history of how safety information management could have prevented the occurrence of such an accident or, at least, have reduced its effect. This case is also interesting because it illustrates the importance of information exchange in an industrial park.

Safety information is the basis of safety management for the entire plant life cycle, from design, through fabrication, construction, operation, and maintenance to decommissioning of the process plant. There should be systems in place to accumulate safety information and communicate it to employees and to the public who need to use this information. Many organizations and software houses have created commercial products to support safety information management for clients. However, there is not enough guidance on how to improve safety information management for the process industry. The industry needs a new paradigm for measuring the performance of safety information management. Therefore, a safety information management audit tool (SIMAT) for the process industry is being developed at Loughborough University.

THE PROCESS INSTALLATION

The accident happened at the Fu-Kao Chemical Plant which is located in an industrial park in northern Taiwan. The plant is a medium-sized manufacturer of polymers and resins used in the composites and coatings industry. The plant was situated in a three-floor building, divided into three areas: raw materials with 7 storage tanks, production with 7 reaction units and product storage area.

A unit, called Reactor A, was in the production area. The reactor produced water-born acrylic resins through the reaction of acrylic monomers in solvent and using organic peroxide initiators. Because of the highly exothermic polymerisation reaction, the solvents, methyl alcohol and isopropyl alcohol (IPA), were used in the reaction to remove heat through a condenser. The initiator, Dibenzoyl peroxideb (BPO), which could then thermally decomposed to form primary free radicals that reacted with monomers grow into long polymer chains.

The Reactor A system was composed of an agitated 6-ton capacity vessel, an overhead condenser, a pure water feed tank and pump and emergency cooling water tank. Heating and cooling of the reactor was achieved using the same external dimpled jacket with manually operated valves. The operators determined the degree to which these valves were opened based on their experience of running the process. The timing of switches from heating to cooling or vice versa was also based on operator experience. The overhead condenser provided additional cooling capacity during reactions operating under reflux. The pressurized (3.5 kg/cm^2) pure water tank which supplied water as a reactant in normal operation as well as acting as a killing system when a runaway reaction happened, was connected to the reactor via a manually operated valve. Further cooling was achieved by spraying water on to the outer wall of the reactor. However, since Reactor A was designed and installed in the plant about twenty years ago, it did not have an emergency relief disposal system attached. Figure 1 shows the Reactor A system.

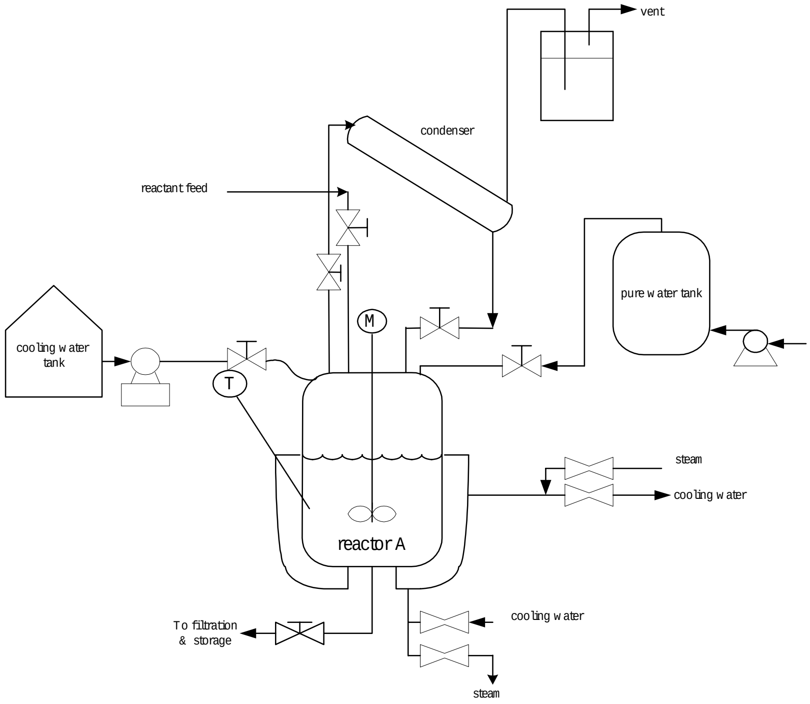

Figure 1. Simplified process flow diagram of Reactor A system

The operating procedure for making a batch in Reactor A was:

1. Add 1293.2 kg of methyl alcohol and 373.3 kg of IPA to the reactor.
2. Start the agitator.
3. The desired amount of several kinds of acrylic monomers, including 172.8 kg of acrylic acid (AA), 1500 kg of methyl acrylate (MA), 32.6 kg of methacrylic acid (MAA) and 20 kg of acrylonitrile (AN), are added to the reactor in sequence.
4. Pump 2130 kg of pure water and add 5.6 kg of BPO into the reactor.
5. Supply steam to heat the reactor between 60–65°C using the reactor jacket, and continue mixing until the exothermic polymerisation is initiated while the reactants in the reactor are boiling.
6. Stop the steam flow, vent the jacket and coils, and circulate cooling water under manual control and allow the temperature to gradually rise to 70°C within 70 minutes.
7. Stop circulating the cooling water, stop the agitator and maintain the polymerisation reaction for about 4 hours.
8. When the batch is completed, the acrylic resin is transferred to a product adjustment tank. If necessary the reactor is cleaned, then the next batch is started.

The Reactor A process had been in use for over twenty years. The Reactor A system was staffed with only one experienced operator. The plant manager did not order anyone to assist the operator in normal circumstances but the operator could ask for assistance when needed.

ACCIDENT DESCRIPTION

On May 18, 2001 at approximately 8:00 A.M., the operator of Reactor A began a batch of acrylic resin just like every other normal day. He stated in interviews that he fed the required amount of solvents, acrylic monomers and initiators in the morning. The steam valve to the reactor jacket and coil was opened to begin heating the reactant at 10:00 A.M. while the agitator continued to operate. The operator left to have lunch at 0:10 P.M. and came back at 0:40 P.M. During lunchtime there was no one monitoring the reactor. Soon after the operator came back from lunch the reaction temperature reached 65°C. So, the operator stopped the steam and started the cooling water at 0:50 P.M. He stated in interviews that he had heard the sound of the cooling water flowing through the piping, an indicator he used to check cooling water flow. Approximately 5 minutes later, the operator reported that the reaction temperature had extraordinarily increased to 80°C and it was out-of-control. The operator tried to add extra cooling water from the valve on the pipe that connects the reactor to the condenser but he failed. At 1:10 P.M. the flashing reactor contents were ejected upward from the reactor. Meanwhile the emergency alarm was started and the plant manager instructed all the plant employees to evacuate immediately. At 1:20 P.M. the first explosion happened and set fire to the plant. Moments later there were several further explosions with accompanying fires. The fire was extinguished by the Fire Bridge in two hours.

During the accident, the ambient temperature was about 23°C. It was a clear day, with light winds mostly from the northwest. These winds blew plumes of reactant, products, and smoke off the plant site. The fallout was mainly to the south of the plant. The vapours spurted out and spread as far as 1 kilometre downwind from the plant.

After the explosions the resulting pressure wave and fire completely destroyed the plant (see Figure 2) and extensively damaged the surrounding structures of neighbouring factories (see Figure 3), resulting in the death of one man and 112 injuries. The man who died was an employee of a factory next to the plant. He was killed by the flame/blast while he was working outside the factory building very close to the Fu-Kao plant. Most of the injuries were to employees of nearby factories or residents around the industrial park. They were cut by glass splinters and other debris that rained down over an area of radius 200 metres around the plant, or/and felt dizziness and nausea after smelling the odours. Whereas, responding to an emergency alarm, most of the plant workers were evacuated about 5 minutes before the first explosion occurred and most escaped serious injury.

Many odour complaints were received from community members, during and following the accident. Air monitoring was performed by the Environmental Protection Agency and Industrial Technology Research Institute. Tests were negative for acrylonitrile, methanol, methyl acrylate and acrylic acid.

Figure 2. Explosion at Fu-Kao chemical plant

The accident totally destroyed the plant and seriously damaged 46 nearby factories including 16 high-tech companies that produced IT-related products. These factories had to stop their production for at least 5 days and some of them took more than 30 days to recover. The total property loss was estimated to be US $12m and the total loss due to business suspension was estimated to be US $50m.

INITIATING CAUSE OF THE ACCIDENT

An official committee of technical experts was formed whose members came from the Institute of Occupational Safety and Health and the local HSE authority in Taiwan. The committee concluded that the initiating cause of the accident was that the operator failed to recognize and act promptly when the reaction temperature was too high, leading to an uncontrollable runaway reaction. The committee briefly explained the accident thus:

1. The first explosion was a small vapour cloud explosion (VCE), which was caused by the ignition of a leak of mixed flammable vapours from the out-of-control exothermic 6-ton batch reactor, while the reaction temperature was extraordinarily increased to 80°C and the cooling water system failed.
2. According to evidence gathered on-site, such as the agitator pump was blown far away and the condenser and decanter had unfolded outwards but the vessel was not blown away (see Figure 4), the explosion location was assessed to be 1–2 metres above the reactor.
3. The second and main explosion was due to the combustion of 100 kilograms of BPO stored on a shelf 10 meters away from Reactor A. The first explosion heated the stored BPO over its unreturned temperature of 65°C. Then the BPO was decomposed at 104°C and exploded after 0.1–0.3 second. Even with a small amount of BPO the peroxide explosion has a huge effect, because its maximum explosion pressure rise $(dP/dt)_{max}$), 900-1100 bar/sec, is similar to explosive combustion and it is 2 to 3 times greater than either an organic vapour or gas explosion.
4. Several of the explosions that followed were believed to be BLEVEs, since most storage tanks in the plant had exploded upwards and the contents of these tanks were completely burnt.

(3a)

(3b)

(3c)

Figure 3. Explosion effects on neighbouring factories

Figure 4. Post-accident photo of the 6-ton reactor

The Ministry of Economic Affairs of Taiwan also funded a research institute to analyse the causes of the accident. The research carried out a consequence analysis and calorimetric tests, and concluded the causes of the accident were briefly[5]:

1. The initiating cause was a vapour cloud explosion due to a runaway reaction in the 6-ton reactor. The blast mass was estimated to be equivalent to 1000 kg of TNT.
2. During the runaway the temperature had risen rapidly from 60°C to about 170–210°C and the maximum temperature rise rate might have reached 192 K/min.
3. The three most probable failure scenarios (with cooling failure) were identified as follows:
   - Normal recipe;
   - Normal recipe with 50% methyl alcohol added (solvent undercharged);
   - Normal recipe with double charge of BPO (initiator overcharged).

The two investigations have different views as to the cause of the most significant explosion, there are BPO explosion or VCE. These differences have not yet been reconciled at the time of writing. However, both investigations agreed that the main initiating causes of the accident were:

1. The reactor cooling system was insufficient to safely control the exothermic polymerisation reaction. The operator controlled a process temperature manually only by opening and closing steam and cooling water valves. The runaway happened because the operator delayed operating the valves.
2. Inadequate process design led to operating procedures requiring that the process run in the temperature range (65–70°C), which is too near the temperature at which the reaction could become uncontrollable (80°C). Thus, unusual variations in the operator's responses to the batch temperature or delays in adjusting the valves could result in overheating or undercooling, with the result that the heat generated by the reaction would exceed the cooling capacity of the reactor.
3. The reactor was not equipped with safety equipment, such as a quench system or a reactor dump system, to stop the process and avoid a runaway reaction.

ANALYSIS OF THE CAUSE FROM THE VIEWPOINT OF SAFETY INFORMATION MANAGEMENT

Kletz[6] describes accident investigation as being like peeling an onion. The outer layers deal with ways of avoiding the hazards, while the inner layers are concerned with the underlying causes, such as weakness in the management. Many accident investigation tools and guides also emphasize the need to 'drill down' the causal factors into Process Safety Management (PSM) programme. For instance, The Center for Chemical Process Safety of the AIChE suggests a 'multiple-cause' systems-oriented investigation that focuses on root cause determination, integrated with an overall PSM[7]. Therefore, when we examine the performance of the plant with respect to the twelve elements of the CCPS's PSM model, as reproduced in the Table 1, we find all 12 to be weakly and insufficiently represented. This is a sure sign that integral safety was not in the minds of top management and it explains the root cause of this accident.

Table 1. Assessment of the PSM performance at the Fu-Kao Chemical Plant

PSM element	Performance
1. Accountability: objectives and goals	No overall safety goal and objective for the plant
2. Process knowledge and documentation	Limited in operating procedures and maintenance records
3. Capital project review and design procedures	No critical reviews
4. Process risk assessment	No activity
5. Management of change	No activity
6. Process and equipment integrity	Very limited on equipment fabrication, initial inspection and testing
7. Incident investigation	No near-miss reporting and investigating
8. Training and performance	Insufficient
9. Human factors (error assessment, task design, ergonomics)	None
10. Standards, codes, and laws	Partly covered
11. Audit and corrective actions	No activity
12. Enhancement of process safety knowledge	Poor activity

Examination of the PSM performance of the plant revealed the poor documentation and safety information management (SIM) of the plant, which should be analysed in greater depth. Reviewing data, information and the investigation papers related to the accident, and interviewing with the operator and manager of the plant, led to the following main findings and discussion points with respect to SIM:

1. For the Fu-Kao Chemical Plant
    - The plant maintained information on the manufacturing process, such as process and instrument diagrams, design codes and standards, a simplified process-flow diagram and Material Safety Data Sheets (MSDS) for most of the explosives it used. Workers at the plant did not use and were not aware of most of the written safety programmes and documentation. They were aware of the MSDSs and of the information they contain; however, they were not aware of any specific hazards associated with the explosive materials.
    - In several previous instances, the operator had reported to the manager that the process temperature rose at a faster-than-expected rate and exceeded the upper limit specified in the operating procedures, in spite of the operator's efforts. The temperature of these batches eventually returned to within the operating limits. These operator reports of significant deviations in controlling batch temperature were vital safety information but the management did not investigate the causes of these events. This shows that the plant simply put safety information away and waited for another deviation to happen. Unfortunately, this time there was not only a deviation but also a catastrophe.
    - The Safety Information File and MSDS, which the plant used as the basis for a Process Hazard Analysis (PHA) conducted in 1995, noted the desired exothermic synthesis reaction, but did not include information on the exothermic runaway reaction. The inadequate PHA did not provide sufficient safety information to help revise the weakness of the safety equipment and management of the plant.
    - Similar accidents had happened in 1997 in the USA[8] and in 2000 in Taiwan. The local HSE authority sent a leaflet to inform the plant to learn from these accidents. This kind of information can be an ideal training material and should be used for PHA. However, the manager ignored the information and put it in an archive cabinet only.
    - In this accident although a manually operated emergency shutdown system was available, the operator did not know what was the 'exact time' to activate it, since there was no emergency operating instruction.
    - The plant also did not effectively implement the requirements of its internal PSM programme. The PHA conducted for the process and the operating procedures (batch sheet) did not address the consequences of potential deviations such as excessive heating and the runaway operating range. The batch sheet did not list the actions operators should take to correct or avoid deviations.
    - During the first interview of the investigation, the Fu-Kao manager said that the reactor was equipped with safety equipment in the form of a dump system to shut down the process in case of a runaway reaction emergency. However, according to the accident site and the blueprint of the reactor, there is no dump or quench system in the equipment. This revealed that the manager already had information and knowledge that the plant should add desired safety devices to the reactor but he did not act.

- The last inspection by the local HSE authority was on February 2001. The result of the inspection was sent to inform the plant to carry out a prompt review of its operating procedures and training on hazardous material handling. The authority also suggested the plant reviewed its PHA to assess the safety equipment of the process reactor. The plant manager did not act or respond to this information. After a couple of months the accident happened.

2. For the neighbouring factories
   - The Fu-Kao Chemical plant was built earlier than most of the other factories in the industrial park. Some of the new 'high-tech' facilities were only built a few years ago. Most of these factories did not know what was happening in neighbouring sites and had no information about the hazards existing in the facilities close to them. So most of the buildings in these factories were constructed using a lot of glass, which acted as flying knifes injuring victims in the accident. Furthermore, these factories had no efficient emergency response plans for evacuation, rescuing victims nor did they have personal protection equipment. Fortunately, the accident did not spread toxic materials to hurt people in these factories.
   - If materials that are not there cannot leak, people who are not there cannot be killed[9]. This accident would have had a much smaller impact if the neighboring factories had not been allowed so near the plant. It is, of course, much more difficult to forego high-profit 'high-tech' industries than chemical industries. Nevertheless this must not stop collection of information and risk assessments to prevent accidents or, at least, reduce their effects.
   - In this 300-factory industrial park there is no information exchange system nor emergency plan for the whole park. This accident also showed the need for companies to collaborate with local authorities and emergency services in drawing up plans for handling emergencies to reduce consequences and to prevent a 'domino effect'.

SAFETY INFORMATION MANAGEMENT (SIM) RESEARCH AT LOUGHBOROUGH

According to the findings and discussion above, inadequate SIM was a critical factor contributing to the accident. Tuner[10] writes "Disasters equal energy plus misinformation" and King & Hirst[11] modify the equation to "Disasters equal energy and/or toxic substances plus misinformation or rejection of information" to emphasize the importance of handling information in preventing disaster. Kletz[12] also states that industrial accidents occur because organisations have no memory and do not use the knowledge that is available. There have been too many experiences in which even simple data were not noted because they were relatively hard to find[13]. Furthermore, 'safety information' has been treated as one of major components not only in PPCS's PSM programme but also in other PSM models published by U.S. Chemical Manufactures Association, the American Petroleum Institute, the U.S. Environmental Protection agency and the Occupation Safety and Health Administration. Thus, every company should ask itself not only if it has enough safety devices, alarm systems and so on, but also if its organizations have an adequate SIM system to improve understanding and communication, which will enhance awareness of hazards in the workplace and result in a better, safer working environment.

Safety information flow in a process plant should link all elements together. The SIM system should ensure that safety information is kept current throughout process changes, equipment maintenance, and other normal activities. Maintaining information requires appropriate linkages between the process safety information management system and the four other elements of the PSM system: capital project review, management of change, process equipment integrity, and process risk management[14]. These linkages are depicted in Figure 5. As changes to the facility or process are reviewed and implemented, these changes should be reflected in the process safety information. Specific responsibility should be assigned and resources allocated for ensuring that this occurs.

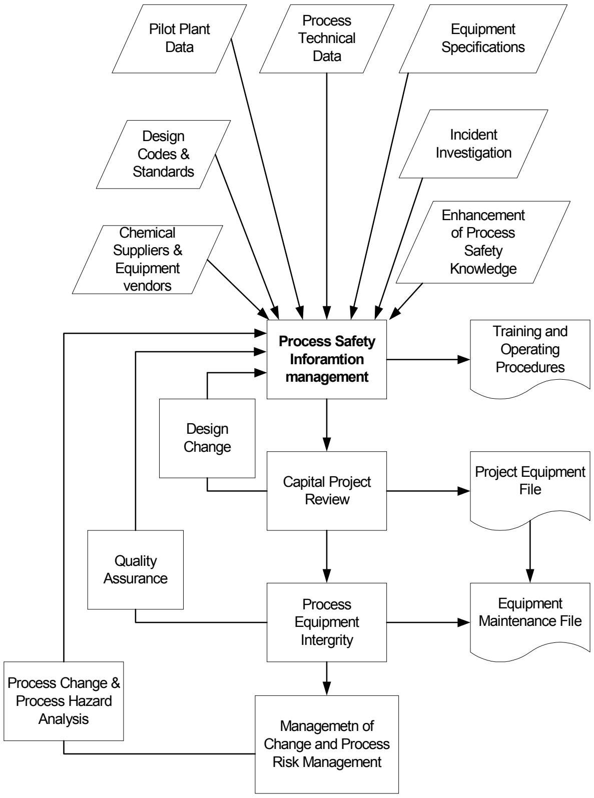

Figure 5. Process safety information management linkage

Furthermore, during the last 10 years, there has been a revolution in information handing technology. For example, many types of documents are now created, revised and stored using computers and the Internet[15,16]. The opportunity and challenge today is to make the best use of new technology to more effectively manage the increased volume of information. Many process plants might want to developed SIM systems that specifically addressed their requirements; it can still be a frustrating and bewildering task. Learning how to properly acquire, utilize and apply safety information can be considered the very core to successful safety programmes. The main problem is how can we ensure that a SIM system in current use or a newly developed one is suitable for the plant. Therefore, an information audit, which is an established management methodology, must be used to evaluate the current information environment[17].

Nevertheless, evaluating a practical process industry SIM system poses a number of questions, including:

1. Why and how does a SIM system fail?
2. What are the scope, function and model of a good SIM?
3. How to make SIM available proactively during all interactions with the plant?
4. How to audit SIM?

These questions are still not answered. Therefore, Loughborough University is doing a SIM research project to explore these issues. The principal aim of this research is to investigate and analyse major process industry accidents in relation to inappropriate SIM and to provide a tool to audit not only the integrity of a SIM but to evaluate the effectiveness of SIM performance. This will be realised through the following three objectives:

1. identify and classify inadequate safety information by conducting causal analysis of past incident reports;
2. identify the important proactive indicators of SIM performance;
3. develop a SIM audit tool (SIMAT) and implement it on site to demonstrate its ease of use and its accuracy and usefulness.

CONCLUSIONS

The initiating cause of the Fu-Kao accident was that the operator failed to recognize and act promptly when the reaction temperature was too high, leading to an uncontrollable runaway reaction. The reactor was not equipped with adequate safety equipment to stop the process and avoid such a runaway reaction. However, inadequate SIM was one of the root causes of the accident. Learning from accidents dictates that every process plant should establish a programme that ensures that reactive chemical process safety information and operating experience are collected and shared with all relevant internal unit and external organizations. Unfortunately, past research and investigation of accidents did not focus on this issue.

Successful SIM will help reduce operational risk, avert litigation and regulatory fines, cut management costs, and ensure reputation. A computer-aided SIM may reduce accidents by 60% in one year[18]. However, good performance in this field requires a consistent prevention programme built upon shared experience. Lack of a common approach to SIM often makes this difficult. Moreover, industrial facilities today are faced with the challenge of collecting, storing, managing and evaluating an immense amount of safety information. There are potentially many information management problems: not getting the right information; spending more time organizing and finding information than analysing it; the length of time it takes to reinterpret an information set after new information is collected; no 'big picture' of site conditions. It can be simply summarised that one has too much information but not enough useful information.

SIM is a primary element in a Process Safety Management programme. Many organizations and software houses have created commercial products to support safety information management for clients. However, how to measure SIM performance is still unclear, and there is not enough guidance on how to improve SIM for the process industry. Therefore, the ongoing research project at Loughborough University, to develop a SIM audit tool (SIMAT), will focus on examining SIM performance in order to establishing and maintaining good SIM practices.

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