Loss Prevention Bulletin

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SIF testing – it's more complicated than you think

Issue 289, February 2023

Obituary

Explosive failures of toughened glass

Ageing plants – corrosion is the real enemy

Tips for effective risk scenario identification

The 1957 Kyshtym disaster

West Valley nuclear legacy

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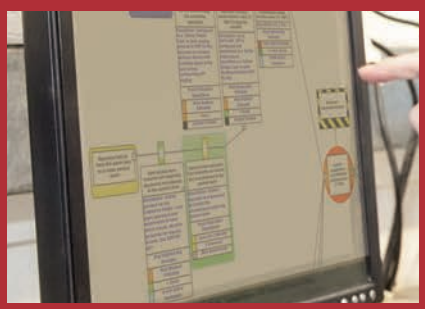
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Obituary

Dr Tony Fishwick 1942–2022

Tony served on the Loss Prevention Panel for 34 years. The Panel and its readership benefited enormously from Tony's unparalleled contributions to the *Loss Prevention Bulletin*, both in terms of volume and quality of content. Tony spent 27 years working in the nuclear industry, followed by a number of years as a consultant, and so many of his 165 articles were related to the nuclear field. However, the range of his subject matter went far beyond this. He covered subjects as diverse as waste recycling, railways, transport and the food industry. All of them written with an engaging style, and often peppered with humorous asides. Tony was never happier than when he was working and sharing his life with others, and this can be seen by the large number of articles he wrote in collaboration with fellow colleagues.

In recognition of his outstanding service in the fields of occupational health, safety, loss prevention and care for the environment, in 2004 Tony was awarded the Franklin medal. Then in 2022, he was presented with the Greene medal, awarded to a member volunteer who has made a most meritorious long-term contribution to the progress of IChemE.

Tony will be fondly remembered, not only for his contribution to the field of safety, but for the comradeship and support he gave to all those of us who were fortunate enough to benefit from his generosity of spirit, and quite simply, his zest for life.

He will be greatly missed.

Geoff Gill



Donations to Myeloma UK gratefully received via https://anthony-fishwick.muchloved.com

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Safety practice

SIF testing – it's more complicated than you think

Andy Brazier, AB Risk Limited, UK; Nick Wise, SSE Hornsea Limited, UK; Harvey Dearden, Time Domain Solutions Limited, UK

Summary

Safety Instrumented Systems (SIS) have rarely been identified as a cause of major accidents but IChemE's recently published *Learning from major incidents*[1] linked them to 13 of its 52 case studies. Installing SIS is often identified as a recommendation after an incident and is consistent with the hierarchy of risk controls that suggests that engineered controls can be relied on. On this basis it seems likely that they will feature in more accidents in the future, especially if people over-rely on them, which would be consistent with natural human behaviour. If this trend is going to be beneficial in terms of risk reduction it will be necessary to ensure that all Safety Instrumented Functions (SIF) are reliable when required.

Keywords: Safety instrumented functions

The development of SIF used in industry

Safety Instrumented Functions have been used in industry for many years. Previously known as an Emergency Shutdown (ESD) or 'trip,' publication of *IEC 61508 Functional safety of electrical/electronic/programmable electronic safety-related systems* standardised the term SIF and has been followed by sector specific standards including IEC 61511 for process plant[2,3].

Practical improvements arising from applying IEC 61508 have included avoidance of single point failures for subsea isolation valves, reduced use of relief valves, and reduced reliance on alarms and operators' response[4]. On the flip side it may have reduced the application of inherent safety and increased complexity; creating a false perception that technology increases safety because it eliminates the risks of human error.

Proof testing SIF

Periodic proof testing is carried out to confirm there are no dangerous, unrevealed faults with a SIF; confirming that all components and the system as a whole will operate with the required reliability so that risks posed by a hazardous system are As Low as Reasonably Practicable (ALARP).

Potential issues with proof testing methods that can create human error traps are discussed below and include:

- covering the 'obvious' failures and not considering the less common and potentially more obscure and potentially hidden failures;
- assuming successful operation during a test proves the system is reliable enough;
- fixing faults found without looking for systematic weaknesses;
- assuming it is a simple task that can be performed by a competent person without using a procedure.

What failures should we be looking for?

SIF can fail in lots of different ways. Some of these are likely to be noticed during normal operation. These types of failure are described as 'revealed.' Other 'unrevealed' failures are not so obvious because the components may not provide any evidence of degradation during normal operations, and these are the ones our proof testing should focus on.

Switch-type sensors (e.g. level, flow, pressure, temperature) can suffer unrevealed failures because most of the time they are in the same state. Analogue sensors will usually create fewer unrevealed failures because they are measuring a condition continuously. However, if the parameter is static (e.g. a flare knock-out drum that usually has no level) this is not the case because there will be no routine process changes that can confirm the sensor is working.

A valve used only as a final element for a SIF (i.e. not operated routinely) can have unrevealed failures because most of the time it is inactive (either open or closed). This is less likely to be the case for valves that have a dual role (SIF and routine operation). However, they may have two triggering solenoid valves (SOV) (one for the SIF and one for routine operation) so that operation under normal conditions does not mean the SIF SOV will work when required.

There is no technical reason why revealed failures cannot be included in proof testing. However, doing this can make the procedure unnecessarily long and mean people carrying out the test become less alert to the more obscure but critical failure modes.

What does a test tell us?

Testing can never cover every set of conditions under which the SIF may be required to operate. In many cases it is simply not possible or sensible to test the SIF with plant operational. A valve closing during a proof test with no flow in the pipe (with the plant shutdown) proves the valve has not seized open but does not prove that it will close with a high flow (and pressure drop) or that it will stop the flow successfully.

A SIF might pass a proof test and yet be showing signs of a developing failure. Inspection of the installation for signs of such deterioration are an important aspect of SIF management

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and usually conveniently carried out at the same time as a proof test. The challenge with inspection is that it is highly subjective. How does someone decide that the condition is good enough?

Other possible issues that can be very easily overlooked during a proof test include instrument tubing that may be blocked by ice or hydrates. In these cases, insulation or trace heating can be critical for the instrument and hence SIF reliability, but are easily overlooked because they are not part of the SIF loop. Trace heating is likely to be temperature controlled so very difficult to confirm it is working if tested on a warm day.

Faults can be introduced during or after testing. Potentially critical examples include failing to reconnect cables or pipework properly that had to be disturbed to allow testing to take place.

What does a failure under test tell us?

Technicians who carry out proof testing are likely to spend a lot of their time fixing problems reported by operators. For non-SIF items prompt repairs minimise disruption to operations and are encouraged. For SIF it is critical that all faults are reported so that a performance history can be acquired, and possible wider implications identified. The best way to achieve this is to raise a specific corrective maintenance for each fault. From testing we must distinguish between 'passed first time' and 'failed but now fixed'. A technician may not be very popular with the operations department if they do not repair a fault immediately, but they will be even less popular if a SIF fails to operate when there is a genuine demand.

How can we prevent human error during proof testing?

It is impossible to completely prevent human error during proof testing, but that applies to all human activities. However, there is plenty that we can do to reduce or manage the risks.

Competence is critical but even the most competent people need to be working with SIF test procedures that are perfectly explicit regarding the test method with pass/fail criteria specified[5]. This is not downgrading the role of competence but a recognition of the complexity and criticality of the task. It is not making the task 'idiot proof', it is making sure that the test is executed to provide the intended coverage, the test procedure cannot be left to the tester's discretion.

We should aim to make testing as simple as possible. Whilst the ideal may be to complete a full "end to end" test with 100% coverage under real operating conditions, this is rarely, if ever possible. Fixating on this ultimately impossible aim can add complexity with little benefit. Taking the risks introduced by testing itself into account highlights that a pragmatic approach with the aim of reducing risk to ALARP is required.

It is often more practical to test a SIF in separate sections rather than as a whole (e.g. individual channels with associated logic for the sensor subsystem, separately from the final element subsystem). Test coverage is not a question of what proportion of the SIF elements are exercised but rather the proportion of possible unrevealed failures that will be identified. Careful thought is required to enhance the test coverage as far as is practicable whilst minimising the disturbance to the installation. Testing that requires disturbance of the physical installation or process connections, modifications to set points or use of overrides raises the potential of introducing dangerous errors.

The most effective measure for reducing the risk of human error is to consider proof testing during design of the plant and SIF. This is not much help to you when developing procedures for existing SIF, but does emphasise why it is important to involve people with practical experience in design teams.

An overarching method of proof testing

Having carried out task and human error analysis for proof testing of a number of SIFs it has been possible to develop an overarching approach that allows some standardisation and structure to developing test methods, technician competence and supporting procedures.

Preconditions for the task will normally include:

- inhibits and overrides have been approved (if required);
- operations have made the plant available;
- access is in place (e.g. scaffold if required);
- permit to work has been issued;
- correct test equipment is available and calibration is in date;
- minimum two personnel will carry out the test if coordinated activity is required (e.g. one in field and one in control room);
- radio communication has been confirmed between field and control room.

The test itself can be broken down into seven subtasks, summarised in the table below.

Sub-task	Comments
1. Identify system components	Ensures the correct SIF is tested and all components are inspected.
2. Visually inspect the SIF components	Labelling, supports, cabling, process connections, electrical (Ex). Also, other items relevant to SIF reliability (e.g. insulation, trace heating). There is a high degree of subjectivity at this stage, which should be captured through competence management.
3. Prepare to activate the SIF/SIF section	The method for this subtask depends on the type of SIF (e.g. initiation by electronic simulation, pressure source, level bridle, exposing the sensor to a controlled condition).
4. Activate the SIF/SIF section	Adjust a simulated condition to activate the SIF or expose the sensor to a controlled condition that will activate the SIF. Monitor final elements to confirm operation. Record findings.
5. If test is successful, return SIF to operating status	The method for this subtask depends on the type of SIF (as above). An independent inspection of installation should be included after reinstatement wherever the physical arrangement was disturbed.
6. If test is unsuccessful, develop an appropriate plan	Deciding the operational strategy whilst waiting for repair. An Operational Risk Assessment (ORA) or similar may allow operations to continue but must be carried out by people with a thorough understanding of what the risks are and how the SIF (when operational) contributes.
7. Update and review SIF data file	Collecting data for future analysis and demonstration. Who looks at this data and how do they identify systemic issues?

A more complete analysis can be downloaded at https://www.abrisk.co.uk/sifprooftesting

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From the full analysis the following potential errors have been identified as being of particular concern:

- Activating the SIF too early when people are not in place to confirm correct operation of the final element (e.g. valve closure time) can be critical for some SIF. This is the case where the final element is not operated routinely and so delayed activation (e.g. sticking valve) is a concern.
- Failing to consider how SIF components may degrade before the next test or inspection.
- Not recognising the importance of items beyond the immediate loop to SIF reliability (e.g. connection between instrument and process, insulation, trace heating).
- Not confirming the final element was in its healthy state before the test and failing to observe it changing from healthy to tripped to confirm it did activate as required (if needed to achieve claimed test coverage).
- Using the wrong test fluid or failing to remove it from the sensor after the test (e.g. water remaining in a level instrument that can freeze).
- Collecting insufficient data to confirm the SIF is operating within its performance criteria.
- Failing to remove inhibits or overrides, or leaving sensors isolated after completing the test.
- Reconnecting cables to the wrong terminals.
- Failing to restore the in-service configuration of intelligent devices.
- Failing to cross check outputs from the SIF initiator with other process data to confirm it has been returned to service correctly.

The last error highlights issues raised above with using switch-type sensors as SIF initiators because they do not provide any output that can be used to confirm operation. If the sensor is disturbed for testing (e.g. high-level switch removed from a vessel and placed in a container of liquid) an independent check of physical status is probably the only risk control available and should certainly be included in the procedure.

Performance Influencing Factors (PIF)

Performance Influencing Factors are aspects of the job, person and organisation[6] that affect the likelihood of human error. An onsite assessment or walk-through talk-through is required to determine how they apply to specific SIF.

Job factor PIFs most relevant to SIF proof testing are illustrated in the table opposite.

PIF – Job Factors	Applicability to SIF proof testing
Labelling	Poor labelling may mean that SIF components are not inspected or the wrong ones (from another system) are inspected meaning that degradation that can affect SIF reliability is not detected.
Human Machine Interfaces	Poor interfaces can affect the ability to confirm the SIF is operating within its performance criteria. Data may be obtained from computer screen graphics, digital display, local gauges, and test equipment.
Routine or unusual	Whilst the general approach to all testing is similar and uses a lot of routinely used skills, individual SIFs are likely to be tested relatively infrequently and so specific requirements may not be remembered.
Procedures	High quality, detailed procedures are required to ensure tests are comprehensive and correct judgements are made about system reliability. Additional procedures may also apply (e.g. permit to work. inhibit/override management, operation of critical locked open/closed valves).
Preparation for task	Failing to prepare can lead to work-arounds to get the job done or time pressures. Items that require planning include plant status, authorisation from operations, availability of test equipment, and test fluid.
Time available/ required	Time pressure can encourage short cuts and may lead to obscure or infrequent failures being overlooked.
Tools	Correct test equipment with suitable accuracy and reliability. In date calibration.
Communication	Many tests require people at different locations to confirm correct operation. This is particularly relevant for time-critical actions (e.g. valve closure).
Working environment	Lighting inevitably affects the ability to identify the correct components, check and monitor operation of components. Noise and heat can cause distraction and increase the likelihood of error.
Visibility	Items may be hidden from view by insulation (lagging), structures or pipework. Issues may only be recognised when out on plant and may not be considered when reviewing a procedure from the office.

Avoiding analysis paralysis

Whilst having a suite of detailed and explicit proof test procedures is an expectation there is also a requirement to demonstrate that overall risks are tolerable or ALARP (depending on applicable regulations). Task and human error analysis is recognised as an effective method of supporting that demonstration but requires significant resource. Unless you have a very small number of SIFs, it will not be practical to complete a task and human error analysis for every proof test.

The development of the overarching assessment provides an opportunity to optimise the analytical effort and has some additional benefits. By using it as a generic benchmark each SIF can be evaluated to determine whether its proof test follows the generic method. This allows differences to be highlighted in procedures and training, reducing the likelihood that they are lost in the detail and overlooked when proof testing is being carried out.

By way of a sense check for anyone evaluating their SIF proof testing, the HSE has published a list of 'Common Failings,' highlighting failure modes that are commonly found to be missing from proof test procedures[7]. Examples include some general issues (e.g. failure to test redundant channels) and some item specific issues (e.g. level sensors with test buttons). It includes some very good reminders to be aware of 'strong but wrong' indications, such as valve linkage failures that can mean the valve position indicator does not match the actual valve status.

Conclusion

SIFs often act as a last line of defence to prevent major accidents. Testing is essential and is a critical human activity

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with potential for error.

Testing must be carried out by competent technicians, but they must also work to specific and detailed procedures. These need to present test methods that strike the right balance between coverage and practicality. Having applied task and human error analysis to a range of SIF tests it has been possible to generate an overarching approach.

Our overall aim has to be continual management of SIF reliability and not simply relying on proof testing. Proof testing is more complicated than you think and this needs to be taken into account when deciding if a SIF is an appropriate risk control measure. More thought about proof testing during early design could help to simplify it as much as possible, and may lead to other strategies being adopted, including inherent safety and passive engineered solutions.

An example of an overarching task and human error analysis for SIF proof testing can be downloaded from https://www.abrisk.co.uk/sifprooftesting

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Incident

Explosive failures of toughened glass in fume cupboard doors

Tom Craig

The safe use of toughened (tempered) glass sheet as a construction material relies on the way it fails on impact[1]. It is frequently used in fume cupboard doors. A sufficiently high impact force applied to the surface of a toughened glass sheet cracks the whole sheet into a substantially intact mosaic of fragments[2] though some fragments may fall out of the sheet.

There is however another sheet failure mode that can create flying glass fragments. That mode presents a risk of injury to users of fume cupboards because access to the workspace within a fume cupboard requires close and sometimes prolonged proximity to the glass.

This note describes examples of the latter type of failure in laboratory fume cupboards (hoods) having vertical sliding doors (sashes) made of toughened glass. In each case the glass door shattered completely into fragments that flew outward into the space in front of the fume cupboard where a person would stand while carrying out operations in the cupboard. In one incident about 22kg of glass shrapnel (essentially the whole door mass) were thrown up to 4 metres away from the front of the fume cupboard while it was in use.

In both failure modes the rapid creation of fragments is due to the sudden release of stresses embodied within the thickness of the toughened glass sheet. These stresses are created by softening ordinary float glass sheet[1] at about 600 degC and then rapidly cooling its surfaces. This tempering process brings the sheet's surfaces and edges into a permanent state of compression relative to the underlying interior of the sheet. That built-in stress condition makes the surface impact strength about four times higher than that of normal glass of the same thickness[1].

The failure mode that presents a hazard to users of fume cupboards is initiated by the growth of flaws present in the edges of the toughened glass sheet door. An edge flaw is subject to cyclic stresses created by the repeated raising and lowering of the fume cupboard door; the flaw eventually grows to a depth that penetrates the compressed surface layer on which toughness depends. The flaw then propagates spontaneously in all directions through the entire sheet, and some of the strain energy stored in the sheet becomes fragment kinetic energy[2].

Examples

One flying fragment incident[3] occurred in a large bench-top fume cupboard whose sliding door was a single sheet of 6mm thick toughened glass that opened vertically. The door was 1980 mm wide and 760 mm high. The cupboard was built and installed by a reputable laboratory furnisher and was then used 24/7 for about four months before the incident. The glass sheet was unframed[4] and its bare vertical edges ran smoothly in 20 mm deep vertical channels in each side panel of the fume cupboard. A UPVC coated L-section steel strip was bonded along the bottom edge of the glass as a handle to raise and lower the door. The glass sheet weighed about 22 kg and would have been raised and lowered 4-5 times in the course of a typical shift. A built-in counterbalance device enabled the door to be moved up and down with little effort.



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Fume hood in a laboratory

An experienced laboratory technician had lowered the door to an almost closed position and turned to walk away when the glass suddenly shattered completely, and he was hit by flying fragments. Some fragments landed 4 metres past him. He was uninjured, but shocked by the bang and the realisation that had the glass failed earlier his face would have been close by in the trajectory of the fragments. A new door was fitted, and self-adhesive clear polyester film was applied to its outer surface by a specialist contractor[5].

This unexpected hazardous behaviour of a fume cupboard door had not been reported in the literature. In the light of its potential to injure people, and the wide use of fume cupboards, the author described the incident in a letter to the wider chemical community[6].

After the letter appeared several organisations contacted us to share similar experiences with fume cupboards.

One respondent[7] described five explosive fragmentation incidents in their laboratory building containing 106 fume cupboards. These had been built and installed 4-5 years earlier

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by a specialist laboratory furnishing company. The incidents all occurred over a nine-month period. Some were in unoccupied laboratories. Eventually all work in the laboratories was suspended. Expert examination[8] of intact doors showed that in fourteen cases radial cracks were beginning to form in the edges of circular holes[9] carrying steel bolts that fixed a handle along the bottom of each door. Repeated stress transfer between the surface of the steel bolt shank and the glass edge was believed to have caused the cracks that initiated the failure process. New doors were installed using plastic bolts that did not touch the edges of the holes. The respondent noted that in the following four years there were no spontaneous shattering incidents.

Conclusions

Absence of other published reports (even today) suggests that the frequency of these incidents is very low and/or that they may have been regarded as trivial if nobody was injured when they occurred. But the potential consequences are not trivial and using fume cupboards is an essential element of work in many laboratories. The application of clear polyester film to their toughened glass doors merits consideration as a precautionary measure[5].

Notes and references.

1. *When tough is not enough: solving the mystery. (May 2020) https://www.pilkington.com/en/gr/news-insights/latest/when-tough-is-not-enough-solving-the-mystery*
2. *High speed photography showing the speed of propagating edge-initiated fractures in toughened glass is available at https://www.youtube.com/watch?v=GIMVge5TYz4*
3. *The author witnessed the immediate aftermath of this incident and interviewed the technician involved.*
4. *The relevant contemporaneous British Standard (BS 7258 Part 3: Laboratory Fume Cupboards: Recommendations for selection, use and maintenance) notes that "the edges of toughened glass are no less vulnerable than those of annealed glass" and that "edge protection by suitable framing is recommended". Arguably framing should be a requirement rather than a recommendation. The framing members and their assembly should be designed to carry the stresses of raising and lowering the door.*
5. *After edge-initiated failure a film-covered fragmented glass door can be regarded as a surface bonded mosaic sheet. Its rigidity may be low enough that it could buckle horizontally and fall. We decided that a falling sheet of surface-bonded fragment mosaic would be a lesser danger than flying fragments.*
6. *T.O. Craig, Toughened glass failure. Chemistry in Britain June 1991 506 (A Royal Society of Chemistry publication).*
7. *Dr J.F. Batchelor (Head of Preparations Unit, Department of Medicinal Chemistry, The Wellcome Foundation Ltd). Personal communication July 3 1991. Their first incident was regarded as a freak event (sic).*
8. *Expertise provided by British Glass Industries Research Association.*
9. *The holes were drilled before the sheets for the doors were toughened. Toughened glass cannot be drilled or cut without shattering.*

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Safety practice

Ageing plants – corrosion is the real enemy but there are other problems (Part 1)

Robert Canaway, Suregrove Limited, UK

Summary

Much has been written about the ageing of plants and concerns have been raised about the useful lifespan of industrial plants. This has arisen because most companies have had to prolong the deployment of their facilities beyond their intended life due to:

- worldwide growth increasing demand for products
- prohibitive costs for new replacement plants
- state employment requirements
- sales (often complete plants) to buyers

The main concerns are corrosion, erosion, wear and tear and obsoleteness.

Corrosion is the real enemy costing owners millions per annum in every country. It is one of the most potentially damaging losses to any commercial, private, or industrial property. An estimated one-sixth of all new worldwide steel production is used to replace corroded metal — corrosion problems are increasing in frequency and severity, not decreasing. The reasons for this are declining material quality (cheaper, less sustainable products are demanded for plants under design/construction) and inadequate corrosion control engineering combined.

Keywords: Corrosion, ageing plant

Background

The corrosion of steel piping/fittings/vessels/towers/drums/heat exchangers and so on is a continuous and virtually unstoppable process. The end-product is commonly the formation of rust (an electrochemical reaction through which the higher energy-processed metal slowly reverts to its naturally occurring form — metal ore). Many high-corrosion scenarios result from years of problematic conditions that have gone unaddressed, not only in process areas but also in secondary support systems such as utilities and offsites. They can be inherited from a previous owner or operator who was not effective at recognising/controlling corrosion problems. Apart from fire, corrosion represents the most serious threat and monetary loss to any facility, causing decline in heat transfer efficiency and plugged piping to pinhole leaks and temporary shutdown for repairs. If there is a loss of containment due to component failure, there could be a fire/explosion and also the potential for a Vapour Cloud Explosion (and catastrophic loss). Corrosion also causes flood damage, loss of production, and personal injury.

This paper describes 30 types of corrosion/erosion which can be found in ageing industrial plants and suggests the remedial actions that are usually required to correct the problem.

Key Identifiers (KIs) are presented which lead to plant failure such as changes in operating conditions, more aggressive feedstocks, Corrosion Under Insulation (CUI), inadequate inspection regimes, material mismatches, overdue retirements and obsoleteness.

A review of some of the other common problems found in many types of onshore/offshore ageing structures, process/energy plant equipment, utility systems, offsites, fire protections and pipelines are detailed in this two-part paper (Part 2 will follow in the next issue) along with the requirements for a rigorous inspection program to continuously assess their physical condition.

Some plants are 'mothballed', and this needs very careful steps to avoid corrosion occurring (use of oxygen free atmospheres such as nitrogen blanketing and desiccant to absorb free water) and the sealing of flanges and openings. Externally the corrosion could occur from rainwater or the local environment. Unused plant segments often become increasingly unreliable, can lead to serious incidents and should always be tested before re-commissioning.

Plant ageing[1,2] can also occur through thermal cycling caused by too many start-ups/shutdowns per annum, plant location (coastal plants tend to suffer higher corrosion rates than in-land facilities due to the saliferous environment and humidity) or the effects of nature such as microbiological attack, and events such as seismic damage caused by earthquake, flooding, windstorms and so on. However, there are also deteriorations caused by variance in soil conditions, stray electrical currents, biological effects (pipelines); stress (all plant), low point water accumulation and unstable flow regimes.

Lifespan Technical Examinations (LTEs) are becoming common place to establish the possibility of extending the operation of a plant. These often make recommendations to the plant to improve its integrity. Mature sites may have some key advantages such as generous equipment and pipework thicknesses (overdesign) and use of high-quality reliable materials although spares availability is obviously a concern.

This paper also considers retirement criteria such as inefficient production, high maintenance costs (corrosion and erosion) and safety issues. Downgrading of system pressures have to be made when pipework shows thinning, and this can also occur in pressure vessels with costly total replacement. The use of clamps is discussed which have either been used to seal leakage or are rated for full pressure.

Four case studies are provided (in Part 2) to demonstrate classic failures — the risk of mixing old obsolete equipment with newer plant leading to error in maintenance; gradual tank corrosion

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leading to major environmental pollution; operational limitations posed by retaining antiquated instrumentation and failure to modernise; particulate or dust explosions caused by erosion.

The COVID pandemic has created five problems:

1) Unavailability of international specialists to check site equipment for problems and a backlog of tasks to be completed.
2) Supply chain interruption for all types of equipment, components and materials, replacement parts and spares.
3) Maintenance/inspection deferrals or scope reductions.
4) Some owners have had to mobilise an extra contractor workforce to cater for teams required to isolate, illness and failure to attend their sites.
5) Delays in implementing modernisation programmes.

Ageing plants

Most high-corrosion scenarios result from years of problem conditions that have gone unaddressed. Often, it is inherited from a previous owner or operator who was not effective at controlling corrosion problems, and/or was obviously not concerned.

Inspection data is the key

All processing/utilities/energy/storage/pipelines/loading/unloading plants should always undergo a rigorous inspection program to continuously assess their physical condition. This will entail:

- Maintaining comprehensive inspection and maintenance records[3] which can be trended to illustrate changes in corrosion, erosion, wear, and tear. Typical areas for examination are tower trays and internals, lined or clad vessels, pump impellors, compressor and turbine rotors, seals and bearings, high-temperature services such as tubes in furnaces/boilers/exchangers, all types of pipework, pipelines and trunklines. Typical NDT techniques which are suitable are: visual inspection, ultrasonic thickness measurement, ultrasonic phase array, radiographic testing, measuring vibration, penetrant test.

Other criteria for investigation

- Noting the design basis of devices which generate heat (such as control systems, electrical equipment, instrumentation). Climatic changes may increase the temperature in enclosures/rooms and create a need to install more HVAC system capacity to prevent overheating.
- The adequacy of cooling systems (water, air etc.) can deteriorate overtime due to corrosion, fouling, wear and tear and this needs to be evaluated.
- Pump wear can reduce the performance (e.g., firepump wear means that the design flow cannot be achieved).
- Methods of pipeline inspection need to be considered where intelligent pig inspection cannot be used for buried locations such as through tunnels, submerged under water. Guided wave and ultrasonic testing systems can be deployed. RBI (Risk Based Inspection) cannot be used for reducing maintenance unless there is complete certainty that similar systems are in an identical condition.
- Subsidence and collapse can occur through drying out of foundations. Regular inspection using theodolite measurements are advised to discover movement.
- Damage will occur if the site is subject to earthquake, windstorm, cyclones, hurricanes, volcanic ash deposition, flooding or tsunami. Following any natural peril event, the plant should be checked for any form of damage.

Typical trend calculations

T_A-T_{Min} = Thickness remaining (mm) where T_A is the actual measured thickness and T_{Min} is the minimum required to meet the design conditions.

R_D = Rate of Wear = mm/year

So (T_A-T_{Min})/ R_D = Remaining life (years)

Many plants incorporate a corrosion/erosion allowance (usually 3-6mm in pipework or vessels) which supplements the design thickness. When this has been lost there is a no safety factor, and the plant will be able to meet the design conditions providing there is no further deterioration. Can the plant cope with the Maximum Operating Working Pressure (MOWP)? If not, then replacement is required.



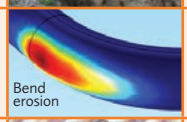
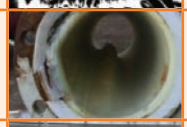
Figure 1– Old power plant showing corrosion

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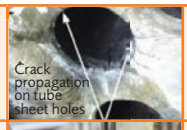
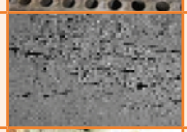
Corrosion/erosion types

The main problem is localised corrosion/erosion where this may be in a relatively small section/area. If this is the case, then inspection points have to be relied upon to identify them[3].

Guidance is given in the codes API 570 and 574 to select inspection points such as:

Inspection point suggestion	Most common failure cause	Example	Repair action
Injection or mixing point	Turbulence generated with change of fluid composition and/or temperature results in damage mechanisms to inside of pipe (e.g., corrosion).		Wear patch or thicker pipe specification before and after the injection/mixing point. Good nozzle design to avoid direct impingement.
Stagnant locations, dead legs	Water/chemical corrosion usually in acidic or alkaline conditions, light rust congregating in dead legs, low points.		Generate a register and then elimination of dead legs by reconfiguration of pipework. External sleeving, spot repairs, clamps. Sweeping of low points using pigging or flushing. Often complete section replacement is required.
Insulated surfaces *External corrosion* *Corrosion Under Insulation (CUI)* *Missing insulation*	Entrapped condensed water results in CUI and is often not detected. Inadequate moisture barrier allowing water to ingress to pipe surface creating a damp condition or pipe sweating.		Remove insulation and repair pit corrosion — use wire cage as personal protection insulation for hot/cold surfaces where heat loss/gain is not a significant concern. External sleeving, spot repairs, clamps & replacement insulation.
Soil-air interface. *Degraded external coatings* *External corrosion – surface pitting*	Breakdown of wrap at ground level and loss of integrity of insulation, PE/PP wrapping damage.		Re-instate wrap after inspection of pipework at the interface. Replace coatings New section in extreme cases.
Service specific and localised corrosion	Mould causes corrosion – deep localised pitting can occur. Microbiological Influenced Corrosion (MIC) – sulphuric acid formation attacks the pipework.		Upgrade materials for vessel cladding or piping for the process. Eliminate stagnant points. External sleeving, spot repairs, painting. New section in extreme cases.
Erosion/abrasive wear — check where fluids contain solids	Solids in fluids which have a higher hardness create wear or grooves. High velocities in condensing steam systems.		Wear plates. Thicker piping. Eliminate particles reaching lubricated surfaces.
Weathering – externally exposed to atmospheric conditions	Adverse weather (rain, humidity, snow). Nitrates or sulphates in air. In marine areas the environment will contain chlorides.		Paint protection including primer coat, shelter equipment from weather. In extreme conditions equipment may be enclosed in a building.
Corrosion beneath lining and deposits or plugging/ fouling	Cladding/lining failure. Inadequate cleaning/washing techniques allowing material to congregate and localised attack.		Metal spray can be used twice, after this replacement parts are needed.
Fatigue cracking – high stress points	Component beyond useful life, thermal cycling. Droplet impact on blades of turbines.		Nearly always requires replacement of parts.
Creep cracking	Concrete structures subject to freeze/thaw cycling. Piping distortion.		Repair structure with infill. Buckled piping will have to be replaced.
Brittle fracture	Crack growth from stress. In severe cases the item fails catastrophically.		Replacement of items/parts.
Hydrogen induced embrittlement	Diffusible hydrogen released by poor welding or incorrect welding materials. Increased H2 partial pressure or more severe conditions introduced.		Replacement of parts. Often difficult to detect.
Ductile fracture	Plastic deformation		Reduce stress loads and replace damaged areas.
Freeze damage	Unsuitable materials for climatic conditions or no winterisation installed.		Replacement of parts. Often the complete item.

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Sulphide stress corrosion	Inadequate materials or incorrect heat treatment – difficult to identify.		Replacement of parts. Often the complete item.
Temperature embrittlement	Long term exposure causes degrading of toughness of the material.		Replacement of parts.
Galvanic corrosion	Mismatch of materials causes electrical differential destroying one metal – notably at valve connections/fittings/ nozzles.		External sleeving, spot repairs, clamps, or metal change. Insulation joints, make sure bolts, nuts and washers are the same material.
Stray currents	Caused by electrical line in close proximity (eddy currents) setting up electrical cell effect		Removal of electrical source. External sleeving, spot repairs.
Steel to steel electrolysis	Pipe supports and hangars – direct pipe to support metal contact.		Install PTFE or equivalent as a barrier under pipe on support.
CO2 corrosion (sweet)	Formation of carbonic acid and then iron carbonate which thins the pipe wall.		Corrosion inhibitor. Upgrade of materials.
H2S corrosion (sour). With water present forms iron sulphide which initially protects the pipe inside surface.	But can break down causing severe pitting. Release of atomic H2 can then congregate into pockets and cause blistering and SSC.		Corrosion inhibitor Upgrade of materials.
Imperfections corrosion - surface pitting	Poorly welded or unprotected joints, grooved pipes.		External sleeving, spot repairs.
Chloride corrosion	Impurities in plant and external atmospheric conditions.		Often complete section replacements.
Cooling system/heat exchanger corrosion – internal corrosion	Internal corrosion can lead to tube failure and loss of performance.		Tube plugging, spot repairs, corrosion inhibitor, anti-fouling chemicals, improved cleaning.
Stress corrosion – weld or bend failure	Incorrect pipe stress at anchors or poor pipe configuration.		Remove stress points, usually requires line replacement.
Pipe thread failure – corrosion	Caused by weakness at joint corroding (less metal thickness in screw fitting up to 50% cut away).		Eliminate screw fittings.
Boiler/furnace tube failure due to corrosion at bends/ joints.	Fouled tubes, poor decoking, velocities too high after expansion of plant.		Replacement of tubes.
Cavitation corrosion	Bubbles of gas formed after pressure drop which then collapse on surface of pipework.		Correct pump NPSH to eliminate vaporisation. Increase downstream metal thickness after let-down valve or choke valve.
Crevice corrosion	Accumulation of corrosive material in imperfections, gaps around bolts holes, under washers.		Spot weld repairs. Check and replace corroded bolts, washers, nuts.
Mercury attack on aluminium	Mercury in feedstock can end up downstream and attack exchanger plates or nozzles.		Replacement parts.

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Critical aspects which can lead to failures and remedial measures

Vessels/pipework

Metallic equipment and its piping are subject to both external and internal corrosion[1, 4, 5]. Externally this is caused by acidic pollution carried in the atmosphere which condenses on the pipework or vessel (often under insulation). CUI (Corrosion Under Insulation) has received significant attention in the past 20 years but (Corrosion Under Supports) CUS is also a serious concern. Internal corrosion will occur whenever acidic or alkali conditions can occur with oxygen and/or water present.

Pipe repairs take on various forms, ranging from temporary clamps to the replacement of entire piping systems. The problem with allowing too many clamps on a plant is that they all require regular inspection and maintenance to ensure there are no leaks and they often cannot be removed until the next turnaround, which may be 3-6 years for some processes. Corrosion coupons have some benefit but are not totally reliable in reporting the complete picture[2]. Weld failures are usually associated with high pipe or nozzle stress.

There are two very positive aspects of mature plants:

- Vessels were often made with generous steel thicknesses and many therefore have long lifespans. Studies on lifetime extensions indicate that 10-15 years is often possible on some pressure vessels even after 40-years' service.
- Steel quality was often a high priority as opposed to cost thereby reducing the effect of corrosion.

Pipework remains the main concern as this was normally based on the design conditions plus corrosion allowance, however, increasing flowrates in expansions or revamps and more severe process conditions can lead to faster erosion and reduced design margins. Bolting also can deteriorate over time and also the use of incorrect bolts, nuts (size or material) is a concern. Old gaskets often leak and need to be replaced (tightening up may damage the fitting).

Valves

More mature plants tend to have a lower level of automation, in particular, fewer remotely operated shutdown valves to isolate major inventories. Also, some block or control valves can only be maintained by removing integral bolts (exposing the internal line conditions) and this has resulted in accidents (as will be described in case study no.1). Also, a number of stem failures have been noted, caused by acidic material leaking past seals.

Valves which are not regularly opened/closed such as ESD/relief valves/blowdown will 'stick' in some services and fail to perform. Except for full bore valve types, the valve internals will provide a restriction around which contaminants, solid particles can accumulate.

Power systems' substations switching valves (particularly oil-filled mechanical devices) can fail without regular testing and maintenance.

Reliable valve suppliers are important to avoid early change-out or repairs. Selection of an appropriate valve trim material for a specific due is essential particularly if the service can experience erosion. Valves which cannot be locked in position (such as flare lines to PSVs) should be replaced so that a LOTO system can be enforced (Lock Out Tag Out).

Rotating machinery[6]

Erosion is caused by high velocities/and or solid materials (particularly with a change of direction such as at vessel entry or bends). This will cause localised metal thinning. It can be resolved by installing wear plates (sacrificial material or an extra thickness).

Steam turbines are particularly susceptible to blade damage from steam containing water droplets and contaminants such as chlorides.

Sour gas compressor internals should be high grade steel suitable for the duty.

Blenders for hard metallic particles can be subject to erosion which produces fine metallic airborne dusts which will burn and/or explode if the dust removal system is not fully operational or absent (refer to case study no.4 in Part 2)

Pump seals — many older facilities relied on single mechanical seals for all duties including light hydrocarbons. Modern facilities are now constructed using double seals to reduce the likelihood of accidental release (note that a major source of fire and explosion in hydrocarbon-based plants is pump seal failure).

Compressors seals — dry gas seals have become the normal. Double dry gas seal is a preferred system when operational safety is crucial; the secondary seal is a back-up seal (normally running at a lower pressure) that can handle the full pressure in the event of a primary seal failure. Double seal arrangements are utilised when product leakage to the atmosphere is unacceptable or for low pressure applications.

With old pumps or compressors, the conversion to double seal is often impossible and new equipment has to be installed.

Supplier quality was often very high in the equipment purchased for mature plants; the only problem appears to be spares availability.

Vibration monitoring

Older plants may not have the most sophisticated vibrational monitoring equipment, relying on portable devices for checking pumps, compressors, turbines[6]. Vibration causes weld stress and can enhance corrosion activity. It is also more common than expected due to changing operational parameters and/or ageing of components.

The main problems are incorrect alignment of pump/compressor rotors, poor pipework design (inadequate stress analysis), slugging of gas lines, cavitation, restricted expansion/contraction which causes buckling and absence of dampeners.

Surge analysis is required for pipelines and good stress analyses. One solution for pipeline surge control is to break the flow into a surge vessel, if delaying the closure of line valves cannot solve this problem. Hammer (where the energy of the fluid moving in the pipeline is applied to the pipe wall and its valves) can cause major problems such as deformation and movement of supports.

Electrical systems[14, 15]

Mature plants and distribution systems often used paper/oil filled cabling which slowly decayed over time. This resulted in heat generation which accelerated shorting and ultimate failure. Most of these systems have been replaced by modern cabling such as XLPE. Also, older types of switch gear and relays have been phased out. Although the equipment has a long-life span the

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obtaining of spares is again an issue.

The need for a reliable power supply system is mandatory. A mature site should be checked for power supply to ensure it shuts-down safely avoiding any loss of containment and can then be re-started from a known status. The conversion of relay-based systems to electronic is a difficult piece of work and needs careful planning.

Instrumentation[12, 14]

Pneumatic/mechanical instrumentation has been phased out almost completely and replaced with electronic systems. However, some older sites may still operate with the following measurement systems:

- float gauges for storage tanks – which need to be adequately maintained (refer to case study no.3 in Part 2)
- weight balanced valves
- chart ink temperature and pressure recorders
- pneumatic valve actuators.

Although these systems are considered primitive, they have often worked for many decades and have only been replaced due to obsoleteness of spares. DCS[16] brings many advantages such as the design of ergonomically attractive control rooms, space saving and advances in instrumentation technology. Often no voting systems were installed which can lead to spurious trips[13, 14, 17].

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In Part 2, problems in other areas will be discussed:

- Firewater Systems, Passive Fireproofing
- Obsoleteness
- Poor Material Selection
- Difficult Plant Areas (access)
- Pipelines
- Control Rooms and Substations
- Boilers and Furnaces
- Heat Exchangers
- Flare/Vent/Blowdown
- Drains/Sewers
- Offshore Facilities/Jetties
- Water systems
- Leak Detection on Pipelines
- Fire/Gas Detectors
- Atmospheric Storage Tank Floor Plate Corrosion
- Pressurized Storage
- Steel Structures
- Cavern/Underground Storage
- Dust Accumulation
- Retirement Point
- Key Identifiers
- Case Study No.1 – mixing old and new valve designs
- Case Study No.2 – tankage leakage
- Case Study No.3 – Obsolete instrumentation
- Case Study No.4 – Dust Explosion

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Safety practice

Tips for effective risk scenario identification

Adam M Musthafa, Indonesia

Summary

A major hazard facility's capability to carry out its "risk treatment" (e.g., implementation of Process Hazard Analysis/PHA recommendation) is typically significantly lower than its capacity to conduct "risk discovery". This is the reason why the risk ranking of each identified scenario becomes an important step in Process Hazard Analysis (PHA - like HAZID, HAZOP, or LOPA). With the risk rank, an organisation can focus its resource on higher risk items before moving on to resolve lower risk ones. It is common for a major hazard facility to screen its PHA result for its top risks scenarios. Such practice allows the organisation to focus on the higher risks and bring them to the attention of senior management who are accountable to manage and reduce the risk to tolerable/acceptable risk. This paper outlines some tips for an organisation to identify its top risks from existing PHA.

Keywords: Risk scenario identification

Top risk vs major accident hazard (MAH)

A major accident hazard (MAH) is a hazard that causes a major accident event (MAE). A major accident event is a hazardous event that results in one or more fatalities or severe injuries or extensive damage to structure, installation or plant or large scale, severe and/or persistent impact on the environment[1-4]. In some operating companies, this is represented by a scenario that resulted in the highest consequence level in their risk matrix. Others have frequency-consequence pairing definitions on the risk matrix that are defined as "top risk" scenarios.

While major accident hazards are normally identified as part of compliance with a regulatory requirement, top risks are voluntarily identified as part of day-to-day operations. Typically, it has a wider definition than major accident hazard and the list has used a tool to prioritise focus and resources. The top risks should include scenarios identified as major accident hazard, but may not be limited to the MAH. Regardless of how the operating company defines their top risks, their understanding of what scenario falls into this category and what control and mitigation they currently have are critical. Thus, many companies screen their PHA and risk assessment reports to have a list of the top 10 or 20 risks. The intention is to make them "visible" and understood by all personnel within the organisation. Everyone then can play their role in ensuring that these major events are prevented from happening.

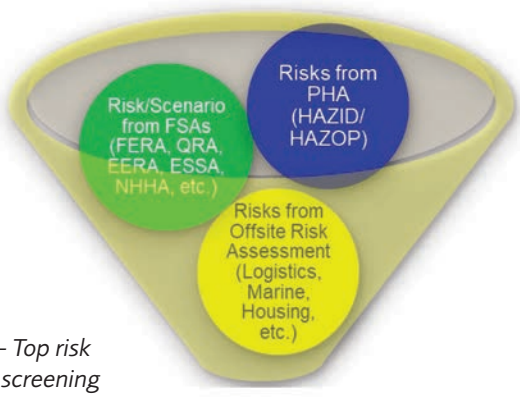


Figure 1– Top risk scenario screening

How are top risk scenarios identified?

In some organisations, risk assessments and PHA conducted on an integrated database screening for top risk scenarios is just a matter of filtering an array of scenario data according to the predefined criteria. In others, an engineer or task force of competent personnel will screen through PHA and risk assessment reports for these scenarios by looking at its risk level (or consequence level). After the potential risks are screened, the list is then discussed with the technical authority and appropriate management to be further refined and formally approved as the organisation's top risks. Figure 1 illustrates how this process is done. The scenario is to be screened from all types of Process Hazard Analysis and Risk Assessment.

Process Hazard Analysis (PHA) reports like HAZOP is the main source of the scenario. Some organisation's also screen their scenarios from safety studies and formal safety assessment (FSA), like Escape, Evacuation, and Rescue Analysis (EERA), Fire and Explosion Risk Assessment (FERA), Emergency System Survivability Analysis (ESSA), Non-Hydrocarbon Hazard Analysis (NHHA). Others include risk from offsite risk assessments including housing and logistic risk assessments.

While process and process safety studies will mainly identify major accident hazards (with high or very high severity levels), other risk assessments like task, logistic, marine, housing, and health risk assessment will help the organisation identify the top risks outside MAH. For example, occupational safety risks or non-process hazards such as the risk of falling during periodic rope access work to inspect and repair flare tip on a 60m flare stack or forest fire impacting on oil and gas plant operation (a not uncommon phenomenon in South East Asia) may not be identified as a MAH. However, for some operators in Indonesia, these are among their top risks.

While the task is not a complicated one, without proper planning and procedure this process may lead to either an unnecessarily high number of top risk scenarios or missing out on important scenarios in your top risks register. The following

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tips will help to systematically identify the top risks scenario in a worksite.

Tip #1 — Have a clear definition for screening

The most important reference in conducting top risk scenario identification is the criteria of top risks itself. In one top risk scenario identification workshop that we observed in Indonesia, the list was updated more than three times even before reaching technical authority and management desks. This was because the task force did not have clear and firm criteria on what constitutes a top risks scenario. The criteria were modified several times during and after the workshop, wasting valuable resources on reworks that should have been avoided by having clear and approved criteria for the top risk scenario from the start.

There are at least three approaches on how to define a top risk scenario. Figure 2 shows the difference between these approaches by using a 5 x 5 risk matrix. The first is consequence-based (normally used for major accident hazard identification). All scenarios with major or higher consequence levels (e.g. fatality and multiple fatality) are considered to be top risks. The advantage of this approach is that the definition is simple and mostly captures process safety risks. Occupational safety risk area usually falls on a lower consequence level and thus is automatically screened out (if they are to be managed separately from process safety risks).

The second approach is risk-based. All likelihood and consequence pairs that fall into "higher or extreme" risks are considered top risks. This approach requires more effort for screening as the screener needs to look into both likelihood and consequence when doing their job. The advantage of this approach is that it is consistent with the risk definition that considers both likelihood and consequence. The disadvantage is for most process safety risks that have multiple layers of protection, risks that are already controlled to the likelihood level of "unlikely" or "rare" will be unintentionally screened out. These risks may be major accident hazard scenarios (as some high severity risks are excluded). This can be mitigated by requiring all previously identified major accident hazard scenarios to be included in the top risks register.

The last approach is a mix of both consequence-based and risk-based. This approach combines the first two approaches' strengths. However, we may end up with a higher number of top risk scenarios with this approach. In this method, higher probability events with lower severity are included in the top risks on top of the typical major accident hazard risks. Some may ask the question, why don't we just focus on the Major Accident Hazards?

The answer is management needs and discretion. Normally MAH is regulated and acute focus is automatically given to these scenarios. However, there are some other lower severity scenarios (outside the definition of MAH) that may have a significant impact on operations or historically have a higher probability of happening that management wants to include them as their top priority risk to mitigate. In one of the operations, forest fires occurred several times outside the fence of a gas treatment plant. While fire escalation to the plant area is prevented by a safe distance of process equipment from the plant, its impact on operations is significant. Lack of visibility and smoke inhalation may impair human performance and prevent crew changes.

On another plant, diesel transfer for power generation becomes a top risk as spills and leaks during transfer had occurred more than once in the last five years. The remote operations coupled with a lack of available competent contractors caused these normally lower risks to become top risk (considering diesel is combustible, and not flammable). While the risk of spilled diesel catching fire is remote, repeated diesel leaks and spills caught the management's attention and prompted them to monitor and control this operation more closely by including them in the top risk register.

Tips #2 — Start from existing but revalidated PHA studies

Top risk scenarios should be identified from existing risk assessment and PHA studies as methodology commonly used in PHA like HAZOP and HAZID allows structured identification of hazards/risks. However, one should ensure that the PHA being referred to when conducting top risk scenario identification is up to date. Any inaccuracies and mistakes

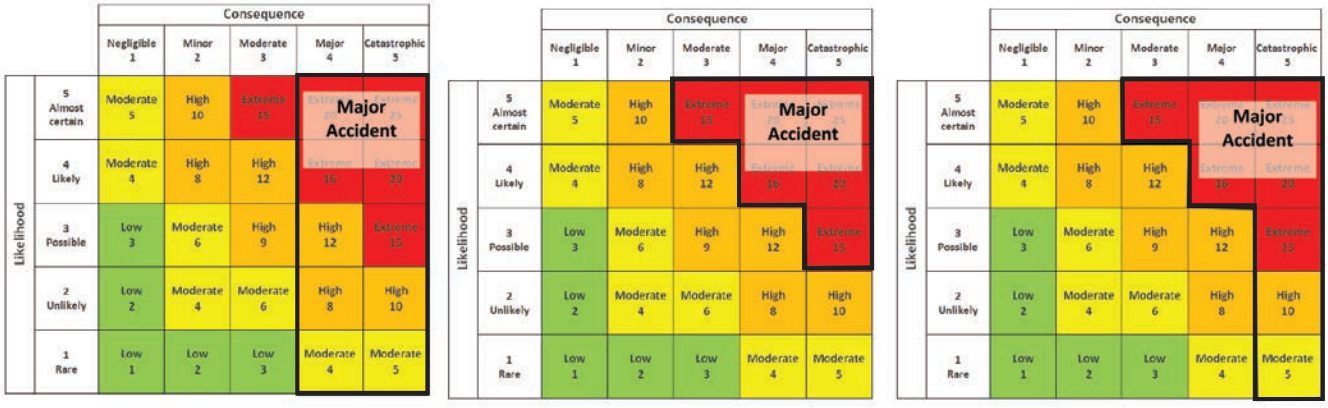


Figure 2 – Variations on top risk identification

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from the existing PHA will be carried over to the top risk scenario identification. Using obsolete PHA reports will lead to major integrity issues or defects in the scenario list.

Equipment may have been modified, operating conditions changed, or collective organisation competency on a task improved or reduced. This may render the identified top risks, including major accident hazard scenarios, invalid. Instead of jumping into top risk and major accident hazard scenario identification, it is more prudent to spend the resource to ensure all process safety information, risk assessments, and process hazard analysis are up-to-date first.

Tip #3 — Conduct quality control to ensure the list focuses only on top risks

Even when we have a clear and approved top risk criteria, we should still conduct quality control on the screened list. As we screen the top risk scenario from existing PHA and risk assessment reports, the quality of the list to a certain level depends on the quality of the report being screened.

In one experience, an engineer made a list of top risk scenarios where 90% of the top risk scenarios involved an operational error of valves that are not normally operated (e.g., locked closed drain valves to closed drain where liquid levels are normally controlled by a separate control valve). Not only were these scenarios not high-risk scenarios (competent operators will not operate something that is not needed to be operated), but they were also not valid PHA scenarios based on the company's PHA practices.

Not-normally operated and locked closed valves in a continuous plant (non-batch) are normally operated only in special operations (e.g start-up and shutdown) which are supported by a special permit and SOP. There is no need for the operator to even go near the valve in normal operation (no other valve is required to be operated). The risks thus should be managed not through PHA but rather through task or job risk assessment.

We still need to conduct "data/scenario cleaning" on the screened scenario. Not all PHA scenarios are valid, some may have errors. Some scenarios may be developed based on incorrect or obsolete information. Some PHA reports may have a gap in quality and integrity. Take a hard look at the initial screening result to ensure that only truly "top" risk scenarios are registered/screened.

Tip #4 — Follow up with risk communication and treatment

The last tip is arguably one of the most important steps of top risk scenario identification. It is to follow up the risk scenario identification with risk communication and risk treatment. Having a list of the top 10 or 20 risk scenarios will not help an organisation manage their risk better if the risks are not communicated to the workers and any recommendations are not appropriately followed up.

One method of top risk scenario communication that is now gaining a lot of interest is the use of bowtie diagrams. Bowtie helps communicate complex risk scenarios with a simple diagram. The bowtie should not be overly complicated if it is to be effective, and some training may need to be provided to the frontline team on how to read these diagrams before being rolled out and posted in a strategically located place.

Conclusion

Top risk scenario identification is now quite a common practice in major hazard facilities. Organisations screen their PHA results for major accident hazard scenarios and other higher risks scenarios to allow them to focus on these higher risks and bring them to the attention of senior management who are accountable to manage and reduce the risk to tolerable/acceptable risk. While it is not a complex task, the process requires proper procedure and planning.

Among many best practices, ensuring that the team has clear screening criteria, ensuring that only updated PHA and risk assessment reports are used, having a process to do a quality check of the initial screening product, and following up with risk communication and treatment is key to a successful top risk scenario identification.

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Incident

The 1957 Kyshtym disaster

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Summary

The Kyshtym disaster was a radioactive contamination accident that occurred on 29 September 1957 at Mayak, a plutonium production site for nuclear weapons and nuclear fuel reprocessing plant in the Soviet Union. Large quantities of radioactive material were released affecting an area of around 20,000 km², home to approximately 270,000 people. In terms of quantity of radioactivity released, only the Chernobyl and Fukushima disasters were greater in magnitude.

This paper describes the event itself, its causes and consequences, and also considers what knowledge, in particular with regard to emergency planning, has been gained from the accident.

Keywords: Kyshtym, nuclear, plutonium, release

Introduction

The Kyshtym disaster was a radioactive contamination accident that occurred on 29 September 1957 at Mayak, a plutonium production site for nuclear weapons and nuclear fuel reprocessing plant in the Soviet Union. It released large quantities of radioactive material affecting an area of around 20,000 km², home to approximately 270,000 people[1]. The event occurred in the town of Ozyorsk, Chelyabinsk Oblast (see Figure 1), a closed city built around the Mayak plant. Since Ozyorsk/Mayak (named Chelyabinsk-40, then Chelyabinsk-65, until 1994) was not marked on maps, the disaster was named after Kyshtym, the nearest known town. Viewed simply in terms of quantity of radioactivity released, only the Chernobyl and Fukushima disasters were greater in magnitude. On the International Nuclear Event Scale[a], it would be classed as level 6 – a serious accident (Chernobyl and Fukushima both being classed as 7 – the highest level on the scale). Despite this, for many years, details of the accident were, to say the least, very limited. Indeed, the Soviet authorities at the time did their utmost to hide the fact that an accident had happened at all. Vague reports of a catastrophic accident involving massive radioactive fallout began to appear in the western press in 1958, but it was not until Zhores Medvedev, a Soviet dissident, in his book *The Nuclear Disaster in the Urals* (1979)[2], provided the West with the first details of the disaster. It took until 1989 for the Soviet authorities to finally acknowledge that an accident had occurred.

Besides describing the event itself, its causes and consequences, this article examines the geo-politcal tensions which existed at the time, namely the rush by the world's superpowers to develop nuclear weapons. It also considers what knowledge has been gained from the accident.

Background

Twelve years prior to the Kyshtym disaster, during the conflict between the US and Japan, many people died as the US detonated atomic bombs in Nagasaki and Hiroshima. The USSR leader, Josef Stalin, realised that the USSR's nuclear program lagged significantly behind that of the US and needed to be accelerated. First, a secret location was needed. A mountainous region in the Urals around 1800 km from Moscow was chosen, and very soon the first-ever plutonium plant was created and named Mayak. Around 40,000 inmates from GULAG, or Axis prisoner of war camps were forced into carrying out its construction. Soon after, six reactors lined Lake Kyzaltash, and because cold war tensions were raised this was done in a hurry and in the utmost secrecy. Almost immediately the plant was producing plutonium, and the first nuclear weapon was detonated in 1949.

The situation which led up to the disaster

Research and information were gathered from Soviet spies working on the Manhattan project. However, despite this, the nuclear industry was in its infancy, and there were serious gaps in understanding of the nuclear safety risks involved. Little thought was given to the issue of nuclear waste, which rapidly caused massive environmental contamination.

Water from the Lake Kyzaltash and Techa River was used to cool the nuclear reactors. The reactors used an open cycle cooling system, where water circulated directly through the reactor core. The highly contaminated water was initially discharged without any treatment back into Lake Kyzaltash and the Techa river, in which children played and was also the main source of drinking water for about 20 villages. The practice of discharging the waste into the Techa river, and Lake Kyzaltash was eventually stopped, and instead dumped into Lake Karachay, soon making it 'the most contaminated spot on earth'.

The accident

By 1953, a storage facility for the highly active liquid nuclear waste was added. This consisted of stainless-steel tanks mounted on a concrete base, 8.2m underground. The accident involved waste which was from the sodium uranyl acetate process used by the early Soviet nuclear industry to recover plutonium from irradiated fuel. The acetate process was a special process which was never used in the West — the idea was to dissolve the fuel in nitric acid, alter the oxidation state of the plutonium, and then

[a] *The International Nuclear and Radiological Event Scale (INES) is a tool for communicating the safety significance of nuclear and radiological events to the public*

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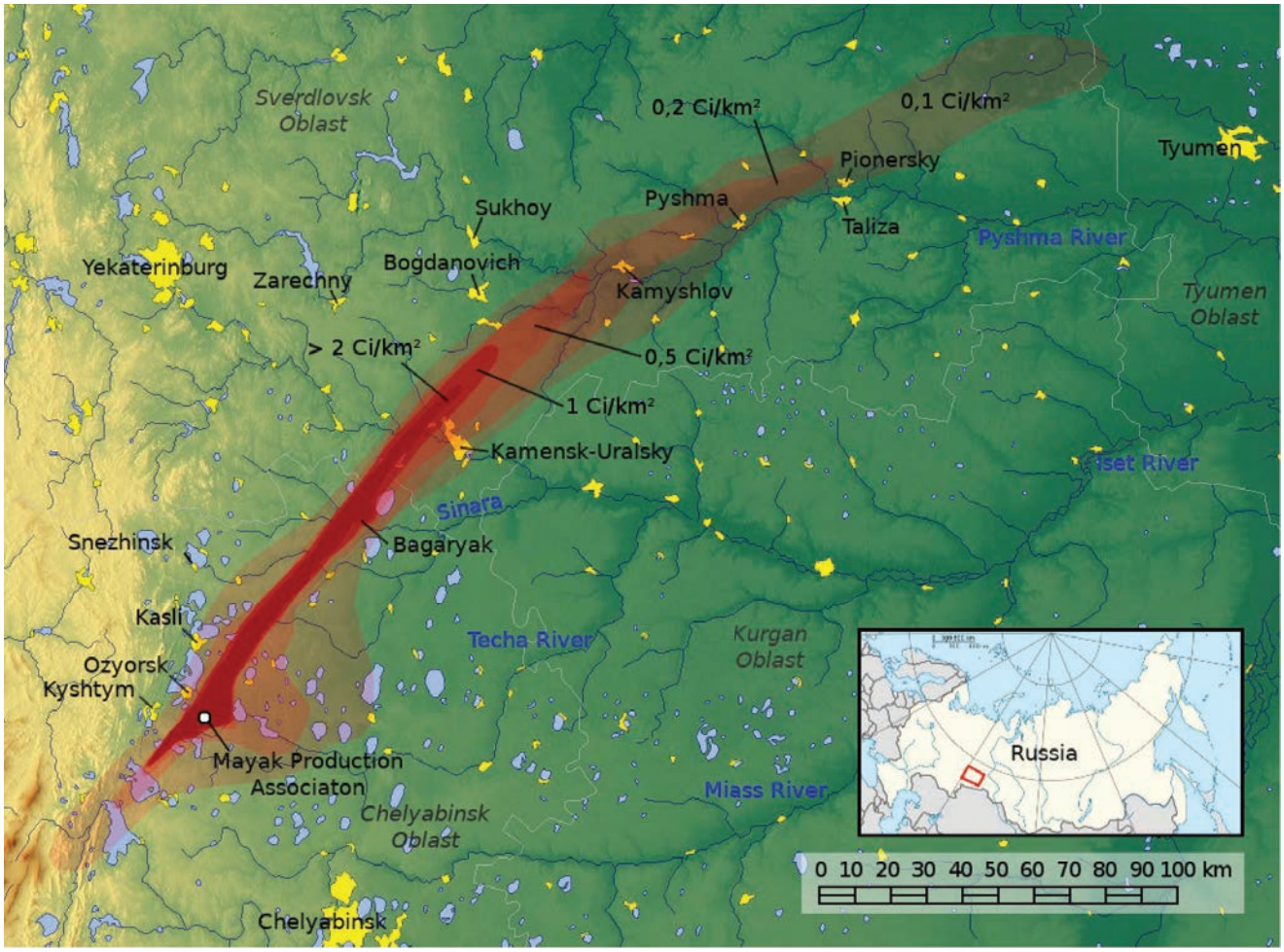


Figure 1 – Location of Mayak nuclear facility

add acetic acid and base. This would convert the uranium and plutonium into a solid acetate salt. The heat generated by the radioactive decay of the high-level nuclear waste stored in the tanks was removed by a water-cooling system. However, the cooling systems was inadequately maintained. A cooling system on one of the tanks, which contained 70-80 tonnes of highly radioactive waste had failed, and had been left unrepaired for a considerable period of time. During this period the temperature of the tank had risen to around 350ºC causing the water in the tank to evaporate, leaving behind a radioactive mix of ammonium nitrate and acetates. On 29 September 1957 the tank exploded with the force of approximately 70-100 tonnes of TNT[3]. The lid of the tank, approximately 160 tonnes of concrete, was blown free. A brick wall was destroyed in a building located 200m from the explosion site.

The workers at Ozyorsk and the Mayak plant did not immediately notice the polluted streets, canteens, shops, schools, and kindergartens. In the first hours after the explosion, radioactive substances were brought into the city on the wheels of cars and buses, as well as on the clothes and shoes of industrial workers. After the blast at the facilities of the chemical plant, dosimetrists noted a sharp increase in the background radiation.

It has been estimated that approximately 20 MCi (800 PBq) of radioactivity was released across the region. Most of this contamination (about 90%) settled out near the site of the accident and contributed to the pollution of the Techa River, but a plume containing 2 MCi (80 PBq) of radionuclides spread out over hundreds of kilometres.

Consequences

Over the next 10-11 hours the radioactive cloud drifted northeast to a distance of 300-350 km, causing widespread contamination. The contamination, consisting predominately of caesium 137 and strontium 90, was spread over an area of 800-20,000 km² depending on what contamination level is considered significant. A contamination density of Ci km^{-2} of ^{90}Sr was established as the intervention level for evacuation of the population. This delineated an area of approximately 1000 km² that became known as the East Urals Radioactive Trace (EURT). At the time of the accident, 63% of the area was used for agricultural purposes, 20% was forested and 23 rural communities existed in the area.

It was not until a week after the explosion that evacuation of 10,000 local people began. Even then, no reason for the evacuations was given. The evacuations were carried out over a period of nearly two years.

Effects on the population

An assessment of the consequences of the accident was carried out in 2017[3]. Of those people who were involved in the study, no case of acute radiation syndrome was found.[b]

The actual radiological consequences[4] for local inhabitants from

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the disaster is difficult to estimate. This is because their overall exposure is made up of that from the disaster itself, and that from the enormous quantities of radioactive material dumped into the Techa river and Lake Karachay. The populations living along the Techa River were chronically exposed to radiation, both externally and internally. Villagers were exposed via many different pathways, of which potable water from the Techa River was one of the most significant. External irradiation from the Techa River bottom sediments and shoreline was also an important factor. The radionuclides believed to contribute most to the dose commitment are ^{90}Sr and ^{137}Cs. Studies have been carried out in an attempt to determine the overall health effects of residents in the Techa river area and the EURT. It is worth noting, however, that for the first time in history, food intervention limits were introduced concerning the content of radionuclides (^{90}Sr) in foodstuffs to protect the public from radiation exposure at a dangerous level.

An epidemiological study in the 1990s showed an increase in the incidence of leukaemia and solid cancers in the exposed population[3]. The number of excess deaths is difficult to determine because the cancer caused by radiation is clinically indistinguishable from other causes, but this study estimated the number of excess deaths to be between 49 and 55.

Environmental effects

The intense radioactive contamination of the EURT territory resulted in a variety of environmental effects being observed, primarily in the first 12-18 months after the accident. The earliest impacts of radiation in pine forests of the area were being observed in 1958 with significant damage to the trees being evident including yellowing of pine needles, defects in tissue development and morphological changes in tissue structures. In areas with contamination greater than $5x10^2 Cikm^{-2}$, death of vegetation was evident and such effects were sustained for up to 3-4 years after the accident.

Radiation protection and monitoring

A program of emergency activities to mitigate the consequences of the explosion was approved on 2 October 1957. It included evacuation of the population from the nearest settlements, quality inspection of food products and fodder, and provision of 'clean' products, determination of the ^{90}Sr concentration per unit area and borders of the contaminated territory, and establishment of the Sanitary Protected Zone. Unfortunately, these measures were not taken in due time or to an adequate extent. The residents of three settlements located in closest proximity to the site of the explosion (1100 persons), were evacuated within 7–14 days after the accident, essentially because of high levels of external exposure. From autumn 1957, in the rest of the territory, quality inspection of food products and fodder with partial replacement of contaminated products was started to decrease the absorbed dose from internal exposure sources.

The first schematic map of contamination levels and borders of contaminated territory was obtained after three months (25 January 1958) based on the results of radiological analysis of the contaminated area. In early 1958, a sanitary protection zone (SPZ) was established with a restrictive regime (residence and economic activities were prohibited). The area of the SPZ was 700 km^2. Although the territory of the SPZ was taken under protection by the police, the population continued to use part of the SPZ area due to the lack of 'clean' pastures and hayfields, and lack of official information about radioactive contamination.

^{90}Sr soil deposition equal to 2 Ci km^{-2} was recognised as a maximum permissible level for safe living of the population and was used as the official boundary of the EURT (see Figure 1). Scheduled activities to reduce external radiation to residents included further relocation of the residents, decontamination of settlements and agricultural areas, development of a radiation monitoring system, including quality inspection of foodstuffs and fodder, as well as reorganisation and reorientation of commercial farms. In total, 22 settlements with a population over 10 000 people were relocated as a result of emergency and scheduled activities. Beyond this SPZ, it was established during the first year after the accident that the total contaminated area bounded by 0.1 Ci km^{-2} for ^{90}Sr (see Figure 1) (a reliably detectable level equal to double the value of global background contamination as of the date of the accident) comprised 23,000 km^2. 217 settlements with a population of about 270,000 people were located in this territory. Within the bounds of 2 Ci km^{-2} for ^{90}Sr, the contaminated area amounted to 1000 km^2. This territory acquired the official status of a Contaminated Area, and it is in this territory that the implementation of radiation protection measures for the population was considered indispensable. The territory of radioactive fallout also covered the facilities of the Mayak complex which had to continue its activities together with the implementation of countermeasures.

Whilst the Kyshtym accident was a tragic event on many levels with serious consequences for both the population and the environment, the accident, as can be seen from the above, served as an important impetus for a number of initiatives which form a significant part of emergency response planning today. An example of this is the use of dose or contamination intervention levels which are used to decide on actions such as sheltering or evacuation, and decontamination/remediation of affected areas following an accident.

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[b] *Acute radiation Syndrome is an illness caused by exposure to large dose of ionising radiation in a short duration of time. The severity of symptoms such as nausea, vomiting or diarrhoea, depends on the type and amount of radiation, and duration of exposure.*

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Incident

West Valley nuclear legacy

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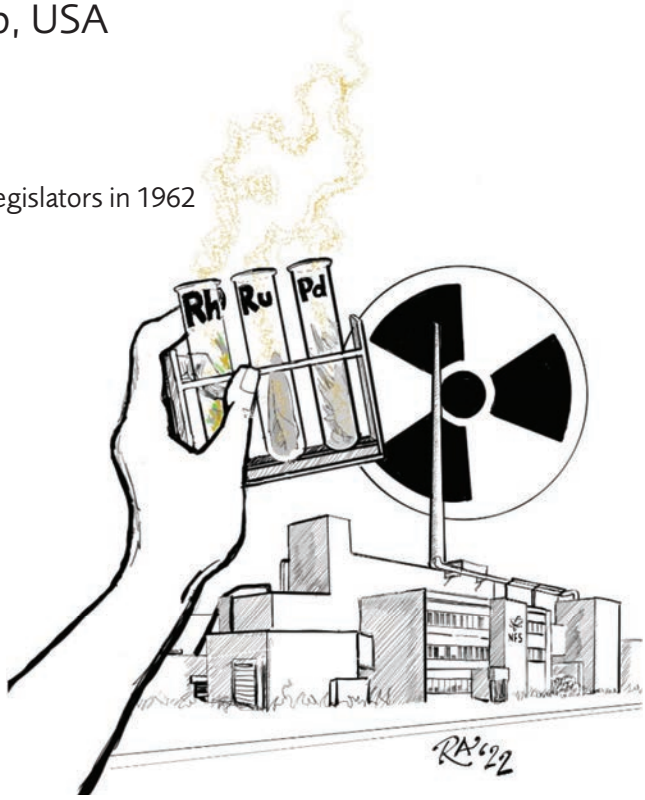
The atomic age,
Rich in challenge and opportunity,
Stretches limitlessly into our future
Gov. Nelson Rockefeller, addressing the New York State Legislators in 1962

Summary

The world's first privately owned nuclear fuel reprocessing plant was built in West Valley in 1966 by W.R. Grace, the fifth largest US chemical company at the time, on land leased from the state. The plant was designed to reprocess spent nuclear fuel from both civilian and defence reactors but the company was also looking at the potential of recovering high value metals for manufacture of catalysts and for other industrial uses.

This is the story of a highly promising industrial project going wrong, and it highlights a number of issues ranging from facility siting to waste disposal and occupational health/safety.

Keywords: Nuclear reprocessing, radioactive waste, waste disposal, facility siting, worker exposure



America's nuclear legacy

The Defense Nuclear Facilities Safety Board (DNFSB) is an independent organisation responsible for monitoring the nuclear weapons sites that are administered by the US Department of Energy (DOE). DNFSB lists 14 such locations on their website[1]. The list includes recognisable names such as Hanford and Rocky Flats, as well as lesser-known places. Reading through the descriptions provided for these sites, one emerges as different from the rest: West Valley. Unlike those other government facilities, West Valley began operations as a private enterprise.

West Valley, NY

West Valley is located in western New York State. During the early 1960s, a time when nuclear power had sparked the public's imagination as the "limitless" energy source of the future, the state picked West Valley as the site for a nuclear technology campus. The location was selected in part due to an understanding that the region's geology was suitable for nuclear waste storage. This would be found to be incorrect years later.

New York governor Nelson Rockefeller was an enthusiastic supporter of nuclear energy. Perhaps his desire to help shape the "energy business of the future" had something to do with Rockefeller being the grandson of the man most associated with creating the energy business of the present era.

Like much of western New York, West Valley was occupied by small farms. To develop the envisioned nuclear technology campus, 3,300 acres of land were taken from the farmers by compulsory acquisition.

Nuclear Fuel Services, Inc.

The world's first privately owned nuclear fuel reprocessing plant was built in West Valley on land leased from the state. The plant was designed to reprocess spent nuclear fuel from both civilian and defence reactors. The operating company, Nuclear Fuel Services (NFS), was a subsidiary of W.R. Grace, the fifth largest US chemical company when the plant came online in 1966.

A few of Grace's patents filed during this period suggests that the chemical company's interest in nuclear reprocessing went beyond the fuel cycle. They were also looking at the potential of recovering high value metals for manufacture of catalysts and for other industrial uses.

While generating the fabled amounts of heat, nuclear fission also creates new elements. Uranium or mixed-oxide nuclear fuels are converted to new isotopes of uranium and plutonium, as well as a series of other elements such as caesium, strontium, technetium, thorium, and in an alchemy of sorts, the precious metals palladium, rhodium, and ruthenium. Grace's patents[2] described methods for recovering the high-value trace metals from the spent nuclear fuel.

Despite these interesting ideas, the NFS reprocessing facility

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in West Valley only produced two saleable products — uranium nitrate and plutonium encased in plastic.

Reprocessing at West Valley

The fuel rods that are used in nuclear reactors are tube bundles of zirconia or stainless steel containing the uranium. Once spent and removed from the reactors, the tube bundles hold the unconverted uranium. The spent fuel also includes the main reaction product, plutonium, and the fission by-products listed earlier. The radioactive half-life of the fission by-products in the spent fuel ranges from several days to millions of years.

The spent nuclear fuel, shielded in heavy casks, would be brought to West Valley in rail cars. The first step in the process was removal of the spent fuel tube bundles from their casks. The long bundled tubes were then chopped into short pieces with a guillotine-like cutting device. These steps were performed with remotely operated mechanical arms under water and behind thick concrete walls to minimise operator exposure.

The chopped pieces of spent fuel were then transferred to a dissolver tank. That's where the uranium, plutonium, and fission by-products were dissolved in nitric acid, leaving behind the stainless steel/zirconia portion of the chopped-up fuel rods. The solution containing dissolved uranium, plutonium, and fission by-products was transferred to a chemical processing unit while the undissolved pieces were removed for burial as radioactive solid waste.

The chemical processing unit was designed based on a technology known as PUREX (Plutonium and URanium EXtraction)[3,4]. Here, tri-n-butyl phosphate organic solvent was used to selectively extract plutonium and uranium nitrates from the aqueous acid. The last step in the NFS process was treating the uranium nitrate with silica gel to remove any trace fission by-products before storage for customer shipments.

The plutonium solution was processed through beds of ion exchange resin. This plutonium product was encased in plastic as removed from the resin beds.

Worker exposure

Despite provisions for radiation shielding and handling of radioactive material with remotely operated mechanical arms, worker exposure at West Valley was among the highest in the industry. The sophisticated machinery was prone to breakdowns, and operators were routinely called upon to work in high radiation areas.

Unlike chronic chemical exposure, nuclear radiation can be measured in real time. The operators' daily exposure was tracked to ensure they did not receive a higher dose of radiation over a work year than specified in regulatory guidelines.

The average exposure level of the NFS operating staff increased with every year of operation, from 2.74 rem/person in 1968, to 7.15 rem/person in 1971[5]. (Federal guidelines limited worker exposure to 5 rem/year.) Instead of developing and implementing actual solutions to the exposure issue, workers who met their "exposure quota" were rotated and high-dose jobs assigned to others. "If a worker could draw five rems a year in his body bank," said a former NFS employee, "he got five rems... the company did not try to keep the dosages to a minimum."[6]

The economically depressed farming communities around West Valley provided a pool of temporary workers to draw from. Up to 1400 temporary workers were brought in every year to supplement the approximately 250 permanent workers at the plant.

High-level waste

This is the term used by the Nuclear Regulatory Commission to describe the solid and liquid wastes resulting from nuclear fuel handling and reprocessing. The acidic water from the dissolver tank was neutralised and placed in very large underground tanks, 70ft in diameter. Most of the fission by-products ended up in this tank. The solid waste, including the chopped pieces of fuel rod after treatment in the dissolver tank, was drummed and placed in unlined burial trenches next to the plant.

End of a dream

As a commercial enterprise, NFS was a failure. W.R. Grace sold NFS to Getty Oil in 1969. The former never deployed its technology for precious metals recovery at West Valley.

In 1972, NFS shut down for "upgrades and expansion." The plant site continued receiving and burying nuclear waste for three more years before it permanently shut down its activities.

In its six years of operation, NFS reprocessed 630 tons of fuel. This included spent nuclear fuels from both power plants and defence reactors.

Of particular concern when the plant shut down was the 600,000 gal of high-level liquid waste in the large underground storage tanks there. A similar carbon steel underground tank used for the same service at the Hanford nuclear facility had leaked some time earlier, and there was widespread concern about a repeat in West Valley.

The lease agreement signed between NFS and New York State assigned all long term waste storage responsibility to the state. Since NY lacked the technical expertise, the US DOE became involved through an Act of Congress.

West Valley Demonstration Project

A new chapter in the West Valley story began in 1980 as NFS logos and placards were replaced with DOE's, announcing the West Valley Demonstration Project. The main objective of the project was to scale up a vitrification technology for converting the high-level liquid waste into solid glass. The vitrification facility was built next to the old NFS reprocessing plant. It operated for 12 years.

In the new facility, radioactive liquid was enriched with silica and melted into glass. The project successfully converted the 600,000 gal of high-level waste into 275 "glass logs." These were then placed in 55 concrete casks. The radioactive sludge/sediment in the bottom of the tanks could not be removed during the DOE demonstration project.

The vitrification plant was decommissioned and demolished in 2018. It may seem ironic that treatment of just one waste stream from the NFS plant took longer than the length of time the company was in operation. Clearly, the original designers of the reprocessing plant never imagined that their "offsite" waste had to be reprocessed itself.

West Valley today

The site still contains the radioactive solid waste in the burial trenches, as well as the sludge in the large underground tanks and the radioactive material in the reprocessing building (Figure 1).

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Figure 1–The abandoned nuclear fuel reprocessing plant at West Valley (recent photo)

The land where the reprocessing building and the burial grounds were built on has been undergoing erosion. Concerns have emerged that the ongoing erosion may lead to radioactive material migrating from the trenches and reaching the nearby creek that feeds into Lake Erie. A "strontium plume" was observed via soil samples some years earlier; but this has not yet reached the creek.

The DOE seems to consider the risk of removing the buried high-level waste greater than the risk of leaving it in place. There are plans to demolish the reprocessing building, and with that, close the last chapter of the West Valley saga.

Final thoughts

West Valley is the story of a highly promising industrial project going wrong. From facility siting to waste disposal and occupational health/safety, the story offers a number of lessons.

The plant started with no viable route to treat the highly radioactive solution of fission by-products. Storing this as high-level waste in large underground carbon steel tanks was surely not a viable option for long term operation of the reprocessing plant.

Allowing workers to be exposed to maximum permissible levels was a questionable practice even during the plant's operation in the late 60s and early 70s. Nevertheless, this continued until the plant shut down. This highlights why safety needs to be part of the organisational culture.

The high-level waste was stored in land that is undergoing erosion, risking leakage into the creeks feeding the Great Lakes. Of course, the erosion issue was not known when the site was selected for the project. However, the nearby creeks and lakes should have been reasons to rank this site below many other places in the western deserts of the US which would have made much better burial sites. The project developers' New York State focus seems to have limited their options.

Small-scale Modular Reactors (SMRs) have attracted attention recently as an effective option for decarbonising baseload electricity. The smaller scale of SMRs (<300 MW) has enabled an inherently safer reactor design that can be deployed in many locations where larger nuclear power plants are not viable. However, the issues of spent fuel reprocessing and high-level waste remain and need to be fully considered. West Valley is a reminder of how important these considerations can be.

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SIESO Medal paper

Flixborough – looking forward

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Summary

On Saturday 01 June 1974 at 4:35 pm, the biggest explosion to occur in Britain during peacetime took place at the Nypro Chemicals' site at Flixborough. The consequences of the explosion were so severe that 28 workers were killed and 36 onsite and 53 offsite severe injuries occurred. While Flixborough was not the first major accident to occur during the 60s and 70s, an industry step change in the consideration of process safety followed, such that the changes it introduced are still relevant today. Looking forward, the chemical industry is expected to undergo drastic changes and face new challenges, and it is important that process safety is kept at the forefront.

Keywords: Flixborough, explosion

Introduction

Nearly 50 years on, Flixborough is still recognised as a wake-up call for process safety in the chemical industry. Until the Buncefield depot explosion in 2005, the Flixborough disaster was Britain's biggest peacetime explosion. The release of 10 to 15 tons of cyclohexane from the plant resulted in a vapour cloud explosion equivalent to 15 to 45 tons of TNT[1]. The consequences of the explosion resulted in 28 fatalities and complete destruction of the plant[2]. The Flixborough disaster served as an initiator of an investigation that led to guidelines for process safety in the chemical industry[2]. As a result, the outcomes of the disaster have been far reaching and the design philosophy of chemical plants has changed considerably since[3]. As chemical processes become more complex and the industry faces emerging challenges, it is vital that the process world continues to keep process safety and lessons learned at the forefront[4].

Background

The explosion occurred on a warm summers Saturday afternoon at the Nypro Chemicals plant in North Lincolnshire. The site was surrounded by fields and situated on low lying land on the east bank of the River Trent, a tributary of the Humber[1]. The Flixborough plant was operated by Nypro Chemicals, owned jointly by Dutch State Mines and the National Coal Board (NCB) at the time of the disaster[1].

The Flixborough plant produced caprolactam, a precursor for the production of Nylon 610. The process involved the partial oxidation of cyclohexane to produce a mixture of cyclohexanone and cyclohexanol by air injection in the presence of a catalyst[5]. This reaction was slow, and it was desirable to keep the conversion low to avoid the production of unwanted by-products[5]. This meant that the plant inventory was large relative to the production rate. The reaction took place in a train of six stirred reactor vessels at a pressure of 125 psi and a temperature of 155°C connected by 700 mm diameter metal bellows[1]. The reactors were made of 13 mm steel and a 3 mm thick stainless-steel liner, and each was of 5 m height and 3.5 m in diameter, built with an interior overflow weir, baffle plates, and an agitator[6].

In the subsequent stages, the reaction product was distilled to separate the unrecycled cyclohexane (which was fed back to the reactors with a mixture of fresh cyclohexane) and cyclohexanone and cyclohexanol, which are then converted to caprolactam[7]. At the time many similar processes were operated, with slight variations, in many plants around the world[6].

How the disaster occurred

Two months prior to the explosion on 27 March 1974, a 2 m long vertical crack leaking cyclohexane was discovered on Reactor 51. Subsequently, the plant was shut down and the reactor removed for repair[8]. In order to permit continued operation of the plant, the site management team decided to remove Reactor 5 and install a 0.5 m diameter bypass pipe between the bellows to take its place. Due to elevation changes, it was necessary to incorporate a 'dogleg' shape into this bypass as shown in Figure 1.

This modification was fabricated onsite without any engineering drawings, calculations or testing[1]. The team

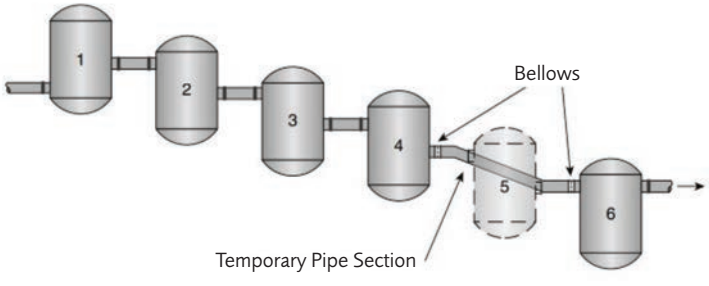


Figure 1 - Reactor vessels showing reactor bypass and bellow[9]

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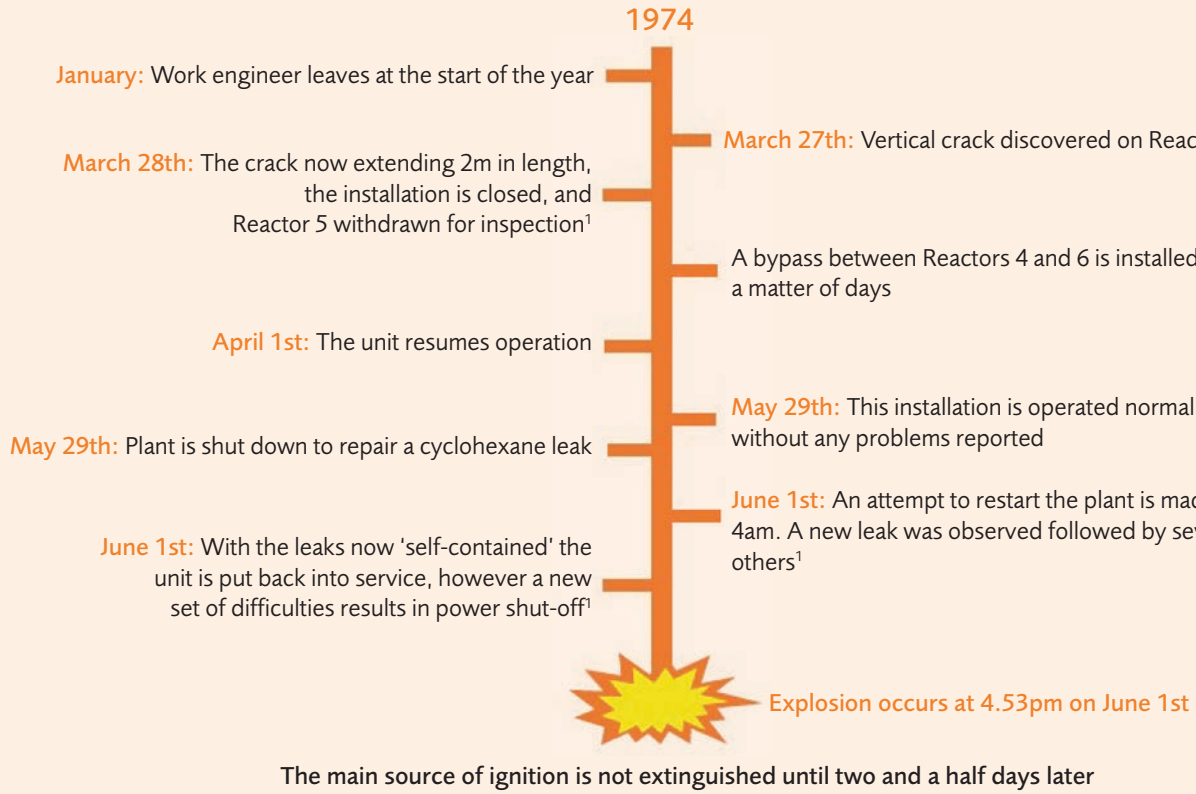


Figure 2 - Timeline of events of Flixborough

tasked with making and installing the temporary pipe were not professionally qualified to do so[5]. The pipe was constructed and supported by scaffolding; however, no account was taken for the turning moment that would act on the pipe due to fluid flow. Consequently, the scaffolding support was not adequate to resist the shear forces[1].

The temporary pipe performed satisfactorily for two months until, at the end of May, the plant was shut down to repair a leak. During the late afternoon on 01 June 1974, whilst the plant was being restarted, a slight rise in pressure occurred, well below the relief valve set point, causing the temporary pipe to twist[5]. The installed bypass ruptured, and tonnes of boiling cyclohexane were released. The cyclohexane formed a flammable vapour cloud and, at 4:53 pm, a massive vapour cloud explosion ignited. A brief outline of the timeline of events are presented in Figure 2.

Aftermath

In order to understand the causes of the disaster and the lessons learned an official Court of Inquiry was established. The investigation aimed to determine the causes of the disaster and find the lessons to be learned from them. The Court concluded the direct cause to be the release and explosion of cyclohexane caused by introducing a modification that destroyed the integrity of a well-constructed plant[6]. The plant modification occurred with only limited calculations on the integrity of the bypass line, and no analysis was conducted for the shape of the pipe and the bellows. At the time there were no specific UK regulations in place to control major industrial hazards. As a result of Flixborough, regulations regarding industrial processes were made considerably more rigorous[10].

Failings in technical measures and lessons learned

In the closing paragraphs of the report by the Court of Inquiry, various lessons are listed including issues that were referred to other bodies[11]. Reading through accident reports from recent incidents, the recommendations to prevent future accidents are often very similar to those contained in reports published several years previously. In the case of Flixborough, several major accidents could have been prevented if the lessons from this disaster had resulted in the adoption of the necessary measures discussed and recommended, such as the 2005 BP Texas City accident and the lessons in occupied buildings[11].

Management and control changes

The Court of Inquiry highlighted how deficiencies in management at the plant in Flixborough contributed to the incident[1]. After discovering the crack in Reactor 5, no action was taken at the plant to determine its cause. It was clear that the bypass between Reactors 4 and 6 was not considered a technical problem and no possible design alternatives were discussed[10]. Production was also favoured over safety in this critical moment as the main concern was to restart production with as little delay as possible due to market pressures from Nylon providers in Europe[10].

Nowadays no discussion on plant modifications occurs

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without mention of Flixborough as an example on the hazards of plant modifications[12]. No modification should be made until it has been authorised by a competent person and all the consequences of the change should be identified in detail[5]. Since Flixborough, there have been several tragic and catastrophic chemical plant accidents due to failures in managing changes in chemical plants, such as the tragedy at Pasadena, Texas in 1989[12].

Furthermore, the cause of the crack in Reactor 5 can also be linked back to a process modification. Prior to the crack there was a leak of cyclohexane from the stirrer gland and to condense the leaking vapour, water was poured on the top of the reactor[5]. Plant cooling water was used as this was conveniently available. However, the water contained nitrates which caused stress corrosion cracking of the mild steel pressure vessel. This was a common method of providing cooling, however, this was still a process change that should have undergone an appropriate modification procedure.

The article in issue 1 of the 1975 *Loss Prevention Bulletin (LPB)* Are your plant modifications safe? proposes a Management of Change procedure. The article explains that there should be a system in place for expenditure proposals to ensure that the right materials are selected, and to ensure that there are no unforeseen effects on any safety systems. Nowadays, the importance of a robust management of change procedure is well understood[13], and the application of such a procedure would have undoubtably prevented the disaster from happening.

Qualified staff

Prior to the incident, the works engineer had left at the start of the year, and by June 1974 the company had yet to find a replacement[1]. Instead, the services engineer had been given a coordination role managing day to day maintenance activities despite not receiving adequate training to equip him with assessing mechanical engineering issues[1]. To a suitably qualified engineer it would have been clear that the plant should be shut down until the other reactors were checked for defects. This was highlighted in the report that by the time of the accident 'there was no mechanical engineer on site of sufficient qualification, status, or authority to deal with complex or novel engineering problems and insist on necessary measures being taken.'[7]. This case emphasises the importance of a balanced team containing people of the necessary professional experience and expertise. On the other hand, it is equally important that engineers understand what they do not know. At the time of the incident, nitrate induced cracking was generally known to metallurgical specialists but was not very well known amongst engineers.

Occupied buildings

At the time of the disaster, large scale explosions were not considered in the design and location of occupied buildings. In Flixborough, the control room was located close to the plant for operational reasons[1]. Many features of the design of the control room offered little to no protection against relatively small overpressures and some features exacerbated the death toll — such as brick walls and its position on the ground floor underneath a concrete floor[1]. The Chemical Industries Association has since developed guidance on the location and design of occupied buildings which were published in the late 1970s and since Flixborough protection against overpressure was incorporated into new constructions[1].

Most of the fatalities were in the control room and the cause of which was the collapse of the building. Since Flixborough more attention has been paid to plant layout and location and the strengthening of control buildings, and many companies have built blast resistant control rooms. It is now clear that buildings within the blast zone must be blast resistant and only essential personnel are located within these, with others located away from units in appropriately designed buildings. It is now the industry standard that plants are laid out such that the impacts of an explosion are minimised. Despite this lesson, fatalities caused by an explosion in the case of the BP Texas city refinery highlights the importance that all buildings occupied for even limited time periods as well as temporary buildings need to be assessed for possible explosions, and their location and design needs to reflect this[1].

Inherently Safer Design (ISD)

As explained earlier, the plant site contained excessively large inventories of cyclohexane, naphtha, toluene, benzene, and gasoline[9]. These inventories likely contributed to the fire after the initial blast, which burned for ten days following the explosion. At the time, the high-inventory process used by Nypro was much the same as every other manufacture of nylon and considered the 'best current practice'[5].

Flixborough revealed issues in industry not previously considered, highlighting the idea of designing to minimise hazards rather than designing to control them. ISD should have been applied in order to mitigate the hazards at the source. It became clear that if the industry set out to reduce inventories in the early stages of the design the resulting plant is often cheaper e.g. less added-on protective equipment is needed, smaller cheaper equipment.

Since 1974 progress towards inherently safer plants, though significant, has been relatively slow. In part this has been due to recessions in the chemical industry but also due to the fact that ISD requires more time during the early stages of design for alternatives to be evaluated, which may not be desirable if the plant needs to meet a new market opportunity quickly[5].

Future outlook

Why is Flixborough still so relevant nearly 50 years on since the disaster? While Flixborough is very well reported and understood to experienced engineers, for students it serves as a fundamental basis for fostering an appreciation for safety. Using innovative methods such as virtual safety-based games, interactive models etc. can ensure this information is learned at an early stage in a student's professional career. Our triptych, shown in Figure 3, aims to provide an accessible and interactive method of sharing this information. As part of a multidisciplinary collaboration, utilising students in fields such as textiles and robotics it provides new and outside perspectives from different artistic fields on how lesson learning should and can be achieved.

Furthermore, Flixborough is also important as the chemical industry faces new challenges as it undergoes huge changes worldwide. Countries such as China, India, and Brazil have

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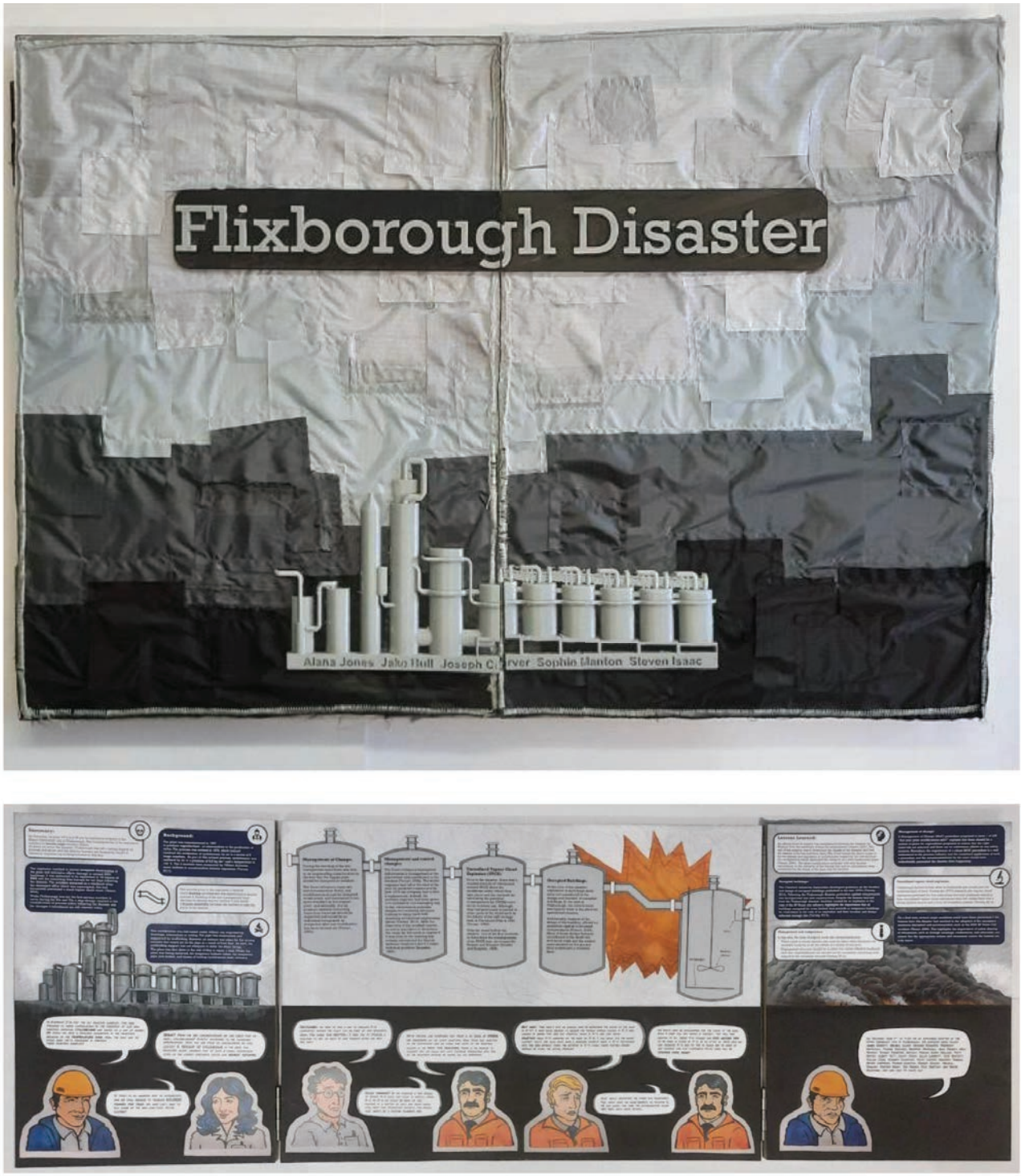


Figure 3 - Images of wooden triptych a) closed b) opened featuring artwork, 3D printing and textiles work

emerged as manufacturers of chemicals on a mammoth scale[14] with China alone between the years 2001 and 2014 increasing its percentage share from 8.1 to 30.4 of total worldwide chemical sales[14]. This presents a challenge for companies in the US and Europe to remain competitive among the growing international competition while ensuring they comply with regulations in safety and protecting the environment. On the other hand, the emerging countries face a number of challenges such as a lack of government supervision and weak safety management foundation of enterprises[15]. Flixborough showcased the role poor management and a lack of competency contributes to major disasters. It is therefore critical that there is awareness of events beyond national borders as the lessons of Flixborough become increasingly relevant[11].

Furthermore, as we strive to reduce our dependence on non-renewable resources to produce energy, chemical industries may be prevented from adopting effective safety management practices due to lack of time, lack of risk consciousness,

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and loss of process specific experience[14]. Similarities can be drawn between this and Flixborough. In the case of the latter, production was favoured over safety at critical moments in the face of market pressures. It is vital that this mistake is not repeated as oil and gas become scarcer and more expensive. Ensuring competency and proper training is also vital as the industry navigates these changes – another key lesson from Flixborough.

Conclusion

The Flixborough disaster helped to contribute and promote significant changes in the hazard processes. Key outcomes following the disaster include:

- Management of Change procedures that are now commonplace in the process industry.
- Guidance on the location and design of occupied buildings.
- Guidance on management structures and ensuring that qualified staff are employed.

As chemical process become more complex, and the chemical industry faces new challenges, industry needs to make sure that learning lessons is a fundamental aspect of process safety in the coming years.

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Editorial note

Ramin Abhari depicts the story of the Flixborough explosion in his graphic novel *Nylon Years*, which is available for free download from the LPB website.



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- Articles published in LPB are essentially practical relating to all aspects of safety and loss prevention. We particularly encourage case studies that describe incidents and the lessons that can be drawn from them.
- Articles are usually up to 2500 words in length. However we are also interested in accepting accident reports to be written up into articles by members of the Editorial Panel. Drawing and photographs are welcome. Drawings should be clear, but are usually re-drawn before printing. Any material provided can be returned if requested.
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