Human factors result in alarms and trips failing to achieve the expected risk reduction

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Rarely is an accident caused by a completely new failure of technology. Usually there is no failure of technology or the failure has occurred before. The issue is almost always what people have done or have not done. This paper addresses the human factors in the energy and process industries that result in alarms and trips failing to achieve the expected risk reduction and suggests what is being done and what more could be done to avoid these failures.

The need to focus on process and technical safety is now widely recognised as crucial to preventing major accidents. Hazards studies and risk assessment are part of the project, operational and maintenance planning of nearly all organisations. Very often the solution to risk reduction is to provide safety-related alarms and/or trips so that the resulting risk is ALARP.

Examples of accidents are analysed where defective alarms and/or trips contributed to poor prevention or reduced mitigation of the hazard. Human factors were a key issue in all the accidents analysed, not a new and unknown failure of technology. Although many older accident reports blame the operator, the paper shows that a lack of consideration of human factors contributed to increasing both the frequency and the consequences of human error. Many process designs and procedures do not assume that human error will happen, even though the different types of error are now well known. Similarly the suggestions for what is being done and what more could be done to avoid these failures is also widely known. Unfortunately what is known is not being implemented even though in many cases the cost is minimal at the design stage.

Legacy alarms and trips are more difficult to tackle, but some improvements are suggested than do not involve excessive cost and are easy to implement.

Keywords: Process safety, human factors, alarms, trips, incidents, accidents

Preface quoted from Bransby & Jenkins, 1997

I am pleased to acknowledge permission from the UK Health and Safety Executive (HSE) to reproduce the Preface to Bransby & Jenkins, 1997, from their Contract Research Report (CRR) 166/1998.

“Reg was reading the monthly production summary when the first alarm went off. He silenced the alarm, then brought up the alarm list on the VDU in front of him. By this time he saw that 5 new alarms had come in. He silenced the alarms again. The alarm at the top of the list showed that the reactor had tripped on low level. He knew that if he did not act quickly, the rest of the plant would be tripping shortly. Looking down the alarm list he noted that the first unacknowledged alarm was from low flow on the reactor inlet. He brought up the reactor overview on the VDU. This showed that the isolation valve was closed. New alarms were coming in so he silenced them. Then he phoned Mike to ask him to go and see what had happened to the isolation valve. The next 20 minutes were hectic as he tried to avoid the rest of the plant tripping. He was unlucky. After 10 minutes the feed pump tripped, and then there was really no chance of saving the unit, but he kept trying to stabilise the flows. He knew that if he could keep the regen unit on, then at least there should be enough feed for Brian to bring the distillation columns down to minimum load. If he could stop those from tripping it would save £20,000 an hour - and the boss was always going on about “avoidable losses”. He was pleased that he did manage to keep the regen unit on, and that Brian was able to get the columns down to minimum load. For the whole of this 20 minutes alarms were going off all the time. It was a horrible noise, and he kept silencing it. He said to himself “that noise doesn't make a chap's life any easier!” Later analysis showed that alarms were being annunciated at a rate in excess of 30 alarms per minute throughout this first 20 minute period. He didn't look at the alarm list at all as he was too busy with the reactor and the regen unit, and he had to keep switching between those two plant area formats on his VDU. There was also the safety systems formats to look at, and the trips to reset. After 30 minutes, when things had settled down a bit, he did bring up the alarm list for the first time. There were 8 pages of standing alarms to go through, and he didn't have time to acknowledge each one, so he quickly paged through them. Over half of the alarms were high priority. There were a few emergency alarms from the trips of the reactor and the trip approach on the regen unit. In scanning the list Reg didn't notice the high level alarm on the surge tank in the middle of the fifth page of alarms. Nor did he know that the instrument fitter had inadvertently left a temporary modification in the PLC logic for the vent system on the surge tank. He went back to trying to stabilise regen flows. One repeating alarm kept coming up every 15 seconds, and he kept silencing that.

A little later Mike phoned back to tell him that a scaffolder had slipped and accidentally closed the instrument air supply to the feed isolating valve. That was why the isolation valve had closed and tripped the reactor. Reg told Mike to “give the idiot a piece of my mind”. While he was doing this, the emergency gas release alarm went off. The HSE Inquiry into the accident never discovered where the ignition source was.....

The above tale is total fiction. The people in it do not represent any particular individuals living or dead, and the chemical plant described is a complete invention. On the other hand the way in which the alarm system was used during this imaginary incident is based on real events that have been reported during this project and on behaviour during one plant trip incident that was actually observed.”

Introduction to alarms and trips

Many processes are not inherently safe. Instead various layers of protection are provided to prevent hazards and/or mitigate their consequences. Two of the commonest layers of protection are alarms and trips.

"Alarms are signals which are annunciated to the operator {including the desk operator plus other primary users (e.g. supervisors) assisting in the control of the plant in the control room}, typically by an audible sound, some form of visual indication, usually flashing, and by the presentation of a message or some other identifier." [EEMUA 191, 2013]

A "trip" is shorthand for an emergency shutdown system. Such a safety-related system is defined as a "designated system that both

- implements the required safety functions necessary to achieve or maintain a safe state for the equipment under control; and
- is intended to achieve on its own, or with other safety-related systems and other risk reduction measures, the necessary safety integrity for the required safety functions." [IEC 61508, 2013]

A typical design assumption is that "pre-trip" alarms will alert the operator so that action can be taken to maintain production before trips shut down the process. If the operator fails to act, then the trip or trips will act to achieve or maintain a safe state for the equipment under control. EEMUA 191 also designates some alarms as "final warning" alarms, for example, alarms for fire, gas (implying loss of containment), or liquid effluent which is already breaching the required specification.

Sometimes this is expressed as the "Swiss cheese model" which originated from James Reason [Reason, 1990 & 2008] where alarms and trips are each described one of many independent layers of protection against incidents.

In reality the role of the operator in incidents is much more complex. Sydney Dekker states [Dekker, 2006] "James Reason has said it more colourfully: Rather than being the main instigators of an accident, operators tend to be the inheritors of system defects created by poor design, incorrect installation, faulty maintenance and bad management decisions. Their part is usually that of adding the final garnish to a lethal brew whose ingredients have already been long in the cooking [Reason, 1990]." Examples of such ingredients are given in Foord & Gulland, 2006.

When no reference is cited, the information came from a private communication or the personal experience of the author.

Why do alarms and trips so often fail to protect against hazards?

Alarms sounding too frequently

EEMUA 191 states very clearly that for multiple alarms the "long term average alarm rate of less than one every five minutes" and the "number of alarms displayed in 10 minutes following a major plant upset of under 10" per operator should be manageable. Higher frequencies of alarms are described as "likely to be over-demanding" or "hard to cope with". Despite the well known example of the explosion and fires at the Texaco Refinery, Milford Haven [HSE, 1997] in 1994, now nearly 20 years ago, many other process plants, offshore platforms and onshore terminals fail to achieve these targets.

After an investigation into several serious incidents, HSE & SEPA, 2000, states "BP recognised the problems caused by alarm flooding {at Grangemouth Refinery, Scotland} and work had been commenced at the site to address the problem."

Not surprisingly, with no time to read all the messages, the operators have little choice but to press the "acknowledge all" button, put a sock in the annunciator horn, or find some other means to suppress the alarms, for example, see "Manual reset for alarms " below.

Many organisations have been asked if they have high alarm frequencies; the answer is almost invariably "yes". When the same organisations are then asked if their operator training includes what to do if too many alarms are annunciated; the answer is almost invariably "no".

Poor choice of alarms priorities

EEMUA 191 states very clearly that the priority distribution benchmark values for alarms are "80% low, 15% medium, 5% high and about 20 altogether for critical alarms". Frequencies for each priority are stated as:

Priority band	**Target maximum occurrence rate**
Safety-related / Critical	Very infrequently
High	Less than 5 per shift
Medium	Less than 2 per hour
Low	Less than 10 per hour

Table 1 - Targets for alarm frequencies for different priorities

A Mediterranean gas platform had 6000 alarms, 3000 of which were designated as top priority alarms. The operators stated that multiple alarms annunciated too frequently and that the designated priorities gave them no guidance about which alarm to respond to first as half the alarms were top priority.

A North Sea oil platform had 2837 alarms (excluding 1941 Fire & Gas Alarms which were designated priority 2). The alarm frequency was much too high and even with two operators sharing the 189 Emergency Alarms, this significantly exceeded the benchmark target of "about 20 each."

No.	**Priority Band**	**Number of Alarms**	**Percentage of Total of 2837 Alarms**
1	Emergency Alarms	189	7

3	Process Alarms (High Priority)	542	19
4	Utility Alarms (High Priority)	445	16
5	Process Alarms (Low Priority)	765	27
6	Utility Alarms (Low Priority)	896	32

Table 2 - Number of alarms for each priority for a North Sea oil platform

Not surprisingly, the operators found the alarm system was a distraction rather than a help.

No response defined for alarms and trips

Bransby & Jenkins, 1997 stated "It was very rare for a site to have a response to every alarms defined in a written procedure. However, this was found at the nuclear power station that was visited."

Some alarms systems still annunciate an alarm when there is no action required from the operator; others assume the response is obvious. Again, EEMUA 191 states very clearly that every alarm should have a defined response. Unfortunately for the first Channel Tunnel fire [Channel Tunnel Safety Authority, 1997] there was a defined response, but the first step was for the operator to check that it was not a false alarm. This contributed to the significant delay before the train driver was informed of the fire. The subsequent report recommended both the removal of this step and that there should be a significant improvement to the alarm management system and to staffing.

Insufficient time to respond to an alarm or trips that take longer to operate than the process safety time

The time an operator needs to respond to an alarm depends on many things. Thus EEMUA 191, 2013 does not define a minimum time, though the nuclear power industry uses a minimum time of 30 minutes and different companies define different minimum times. Often the alarm setting is so close to the trip setting that the operator has very little chance to respond. As well as being another unnecessary alarm, it might have been claimed erroneously as an independent layer of protection reducing risk.

Again during the first Channel Tunnel fire [Channel Tunnel Safety Authority, 1997] there were too few operators to handle all the steps required in a timely manner. The staffing numbers had been defined for normal operation, not for emergencies.

Although at Texas City [US CSB, 2007] the problems were more about safety management, human factors and lack of layers of protection (including the lack of high level, pressure and temperature indication), by the time the drains alarm from the vent stack sounded, there was not time to respond.

There is a particular problem with low temperature alarms. If the hazard is brittle fracture leading to loss of containment then the process safety time may be very short. Turbulent flow will result in the pipewall temperature following the fluid temperature within a few seconds. A HAZOP at a power station identified this problem and raised a recommendation for action. The HAZOP Action Close-out Report stated that a low temperature trip had been connected to an isolation valve powered by an electric motor that took many minutes to close. The report also did not consider that the low temperature might be caused by power failure when the valve would not close at all.

Incorrect settings for alarms and trips

At Texas City [US CSB, 2007] a high level alarm in the column was set below the normal start-up level, so could not detect an abnormal level.

As mentioned above, the alarm setting is often so close to the trip setting that the operator has very little chance to respond.

Alarms and trips known to have failed

A power station tested every trip annually. One trip failed the test. A year later the same trip failed again because no repair action had been taken in the intervening year.

Long before the Buncefield Incident [MAIB, 2008] the tank level measurements were known to be faulty (tram-lining) and thus the high level alarms were unreliable. No significant remedial action was taken before the explosion. There does not seem to be an understanding that unless a faulty alarm or trip is repaired promptly it cannot achieve its designated SIL rating.

SIL	PFD_{avg}	Target risk reduction	Time the protective system is not available each year
SIL 1	0.1 - 0.01	10 - 100	876 to 87.6 hours
SIL 2	0.01 - 0.001	100 - 1000	87.6 to 8.76 hours
SIL 3	0.001 - 0.0001	1000 - 10000	8.76 hours to 53 minutes
SIL 4	0.0001 - 0.00001	10000 - 100000	53 to 5.3 minutes

Table 3 - Relationship between time off-line and SIL rating

Alarms and trips not known to be inoperable

A common reason for alarms and trips to fail to operate is that they have been left in the test position or have been bypassed or suppressed. The particular case of suppression caused by alarms not being reset is discussed separately below in Manual reset for alarms.

Before the Buncefield Incident [MAIB, 2008] the high high tank level trip was replaced with a new design. No-one the site recognised that unless correctly locked the trip would move to the test position. Thus with a known faulty high level alarm and a high high level trip in the test position there were no alarms or trips to warn the operator of impending tank overflow.

A plant processing liquid LNG discovered that liquid LNG at -160^{o}C had leaked into an ordinary mild steel pipe just in time before any loss of containment. An investigation revealed that the low low temperature trip had been tested recently and left in the test position.

Manual reset for alarms

Normally trips are reset manually and alarms are reset automatically. One exception to this was another plant processing LNG where the alarms were all reset manually. Thus if an operator forgot to rest an alarm it would not annunciate the next time the alarm setting was breached. If an alarm was irritating or repeating then the operator would deliberately not reset it without going through any formal alarm suppression procedure.

Missing layers of protection

Despite the well known advantages of inherent safety, it is often rejected on cost grounds, and replaced by layers of protection intended to achieve sufficient risk reduction. Identifying the capital saving is easy whereas calculating the additional lifetime costs of adequately maintaining the layers of protection is much more difficult. For example, it is often assumed that pressure relief valves are very reliable despite evidence that 4% will fail to operate as required [Flower & Jones, 2010]

The examples above from process and energy plants illustrate that all too often alarms and trips also fail to achieve the intended protection. Even worse in some cases the required layers of protection are non-existent, for example, Texas City, where human factors and lack of layers of protection including the lack of high level, pressure and temperature indication [US CSB, 2007], the Tosco Avon Accident where human factors were poorly considered in the design and operation of the temperature monitoring system including the lack of high temperature alarms [US EPA, 1998] and the runaway reaction and explosion at the First Chemical Corporation [US CSB, 2003].

Common causes of trip failures

Few project lifecycles include common cause analysis. The causes of the Russian 2009 Sayano–Shushenskaya hydroelectric power station accident [Rostechnadzor, 2010] were complex including that the trips to close the floodgates at the inlet to each of the 10 turbines required power to close the gates. During this major incident, the power failed, the floodgates stayed open on all the turbines, water levels rose very quickly and 75 people drowned.

Human factors, such as decisions by supervision and management staff, can be the common cause of removing more than one layer of protection.

Lack of learning from previous incidents

All too often the investigation after an accident reveals that similar incidents had occurred before with less serious consequences. The instability of the waste coal tips around Aberfan was well known in the decades before the disaster which killed over 100 children [Davies, 1967].

Sometime in mid 1980s there was a substantial tank overflow at Buncefield, but there were no serious safety or environmental consequences. The lessons from the incident do not seem to have been learned.

As well as databases of previous incidents held by companies, many of the major design contractors have their own databases. In addition there are publically accessible databases. The hyperlinks are given at the end of the Bibliography and References.

- APELL (United Nations Environment Programme Awareness and Preparedness for Emergencies at Local Level - Publications)
- CRED (online, through the "International Disaster Database")
- CSB (U.S. Chemical Safety Board - Completed Investigations and videos)
- eMARS (Major Accident Reporting System - Database of "major accidents" reported under Seveso, OECD and UN-ECE Managed by the- European Commission / Major Accident Hazards Bureau (MAHB))
- EPA-ERNS (Environmental Protection Agency - Emergency Response Notification System)
- FACTS (Failure and Accidents Technical information System)
- HSE ("HSE Public Register of Notice History" - information at UK Health and Safety Executive)
- NERC (North american electricity reliability corporation (NERC) eLibrary, a central listing of downloadable documents and reports)
- NTSB (U.S. National Transportation Safety Board – databases – includes pipelines)
- OECD (Programme on Chemical Accidents)
- OSHA (U.S. Occupational Safety & Health Administration - Accident Investigation Search)
- SINTEF (Offshore Blowout Database)

Discussion

Obviously alarm and trip hardware does sometimes fail because of random hardware failures. However it is well know that the dominant issues are systematic errors and human factors [HSE, 1995], [EEMUA, 2013], [HSG48, 1999] and [HSL, 2013]. Legacy alarms and trips are more difficult to tackle, but not all improvements involve excessive cost and some are straightforward to implement, for example, process safety metrics [ANSI/API, 2010] & [CCPS, 2011]. The solutions to these issues are also well known, for example,

- sufficient competent operational and maintenance staff [Stokes, Rich & Foord, 2006] and [HSE, 2007]
- a good safety culture [HSL, 2013]
- process safety metrics which include leading indicators [ANSI/API, 2010] & [CCPS, 2011]
- regular (say every 5 years) process safety reviews covering HAZOP, risk assessment and learning from previous incidents.

Unfortunately the process industry is being painfully slow to implement the known solutions and appears to be reluctant to learn from other industries. For example, nuclear submarines have only about 30 “alarms” which relate to deviations which could result in fatalities or cause the submarine to sink. All the other thousands of deviations arising from their nuclear power plant, air conditioning, munitions and the submarine itself are designated as “warnings”. These simple priority categories of alarm or warning are regarded as normal practice in naval engineering.

Another example is the aviation industry. Manufacturers of aeroplanes define a “minimum equipment list”. Before take off the pilots check every item on the list and do not take off if any item on the minimum equipment list is faulty. In addition there are defined responses for alarms from each item on the list such as “divert to the nearest airport” or “land as planned, but do not take off again until the item is fixed.” If such checks were done for all safety-related alarms and trips prior to every start-up in the process and energy industries, then many incidents could be prevented. In addition the procedure for doing such checks would reinforce the significance of all safety-related items for the operations and maintenance staff.

Many organisations have reduced their staffing for operation and maintenance to the number required to handle normal operation and routine maintenance with a small additional allowance for training, holidays and sickness. There seems to be little consideration of breakdown maintenance, emergencies, continuous improvement, modifications, regular process safety reviews covering HAZOP, risk assessment and learning from previous incidents, or the inevitable need to second staff to project teams. Even when these additional needs are recognised, recruiting competent staff is difficult. ‘A’ level entry requirements to study engineering in many universities are well below the requirements for other subjects such as veterinary medicine. As a result many engineering graduates struggle with the concepts of scenario and individual risk and manipulating very small numbers such as 10^{-6}.

One of the consequences of replacing inherent safety with multiple layers of protection is that people think that the failure of a single layer of protection is not significant. They know that there are other layers of protection but do not appreciate that with one failed layer of protection the resulting risk is no longer ALARP.

Top tier COMAH sites produce COMAH reports which aim to cover all possible hazard scenarios. They also have comprehensive alarm and trip schedules. However the schedule rarely indicates which alarms and trips are the layers of protection related to a specific hazard scenario. If such cross references were available it would reinforce the significance of all safety-related items for the operations and maintenance staff.

Conclusions

Unless the attitudes to process safety are changed in every organisation, then accidents of the type reported here will continue to happen.

Despite the claims of many organisations that inherent safety is their starting point, few projects achieve this. This is understandable for some items of equipment, such as storage tanks, but is much harder to justify for piping and many other items of process equipment. The lifecycle cost of properly maintaining the alternative layers of protection seems to be under-estimated or simply not a key performance indicator for the design contractor.

There needs to be a greater understanding of which layers of protection relate to which hazard scenarios and how human factors and other common causes can remove layers of protection and the resulting implications for residual risk.

Staffing for operations and maintenance staff should to consider all the many tasks required and sufficient competent operational and maintenance staff recruited.

Organisations should monitor process safety metrics, measure their safety culture and conduct regular (say every 5 years) process safety reviews covering HAZOP, risk assessment and learning from previous incidents.

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Databases of previous incidents

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- CRED (online, through the "International Disaster Database") http://www.emdat.be/Database
- CSB (U.S. Chemical Safety Board - Completed Investigations and videos) http://www.csb.gov/investigations/completed-investigations/
- http://www.csb.gov/videos/
- eMARS (Major Accident Reporting System - Database of "major accidents" reported under Seveso, OECD and UN-ECE Managed by the- European Commission / Major Accident Hazards Bureau (MAHB)) https://emars.jrc.ec.europa.eu/
- EPA-ERNS (Environmental Protection Agency - Emergency Response Notification System) http://www2.epa.gov/region8/emergency-response-notification-system-erns
- FACTS (Failure and Accidents Technical information System) http://www.factsonline.nl/
- HSE ("HSE Public Register of Notice History" - information at UK Health and Safety Executive) http://www.hse.gov.uk/noticeshistory/
- NERC (North american electricity reliability corporation (NERC) eLibrary, a central listing of downloadable documents and reports) http://www.nerc.com/Pages/default.aspx
- NTSB (U.S. National Transportation Safety Board – databases – includes pipelines) http://www.ntsb.gov/investigations/databases.html
- OECD (Programme on Chemical Accidents) http://www.oecd.org/fr/securitechimique/gestion-risques/publicationsintheseriesonchemicalaccidents.htm
- OSHA (U.S. Occupational Safety & Health Administration - Accident Investigation Search) https://www.osha.gov/oshstats/index.html

- SINTEF (Offshore Blowout Database) http://www.sintef.no/home/Technology-and-Society/Projects/Projects-SINTEF-TS-2001/SINTEF-Offshore-Blowout-Database/