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Atypical Accident Scenarios: from Identification to Prevention of Underlying Causes

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The actual scenarios of several major accidents that took place in Europe in recent years were not considered by the site safety case because they deviated from normal expectations of unwanted events or worst case reference scenarios, despite several similar past events were present in literature. They witnessed that proper hazard identification has become progressively more difficult to achieve, in particular when routine activities such as safety reporting for well known technologies are carried out. Moreover, the identification of atypical accident scenarios is complicated by the rapid development in the industrial technology, which has brought about the need to upgrade the methodologies used. In fact, accident scenarios of new and emerging technologies, which are not still properly identified, may remain undetected until they take place for the first time. The consideration of atypical scenarios is an extremely challenging issue and non-identified scenarios constitute an unknown risk. This study outlines an innovative approach to tackle atypical accident scenarios on several levels in order to obtain structured and complete basis for accident prevention. A new and advanced HAZID technique for the identification of atypical accident scenarios has been developed with the purpose to obtain comprehensive but concise overviews of potential hazards related to the system. Moreover, a comparative assessment study has identified a complementary methodology aiming to address underlying causes of atypical scenarios. The synergy of the two methods constitutes an effective strategy against atypical accident scenarios in which human, organizational, cultural and technical factors are addressed in an integrated manner.

1. Introduction

Proper hazard identification has become progressively more difficult to achieve, in particular when routine activities such as safety reporting for well known technologies are carried out. This is witnessed by several major accidents that took place in Europe in recent years, such as the Ammonium Nitrate explosion at Toulouse in 2001 and the Vapour Cloud Explosion at Buncefield in 2005. The actual scenarios that took place were not considered by the site safety case because they deviated from normal expectations of unwanted events or worst case reference scenarios, despite several similar past events were present in literature. Furthermore, the identification of atypical accident scenarios is complicated by the rapid development in the industrial technology, which has brought about the need to upgrade hazard identification methodologies. In fact, accident scenarios of new and emerging technologies, which are not still properly identified, may remain undetected until they take place for the first time. The consideration of atypical scenarios is thus extremely challenging and non-identified scenarios constitute an unknown risk.
For these reasons, this contribution aims to provide an overview of the state of the art of research concerning atypical accident scenarios (Paltrinieri et al. 2012a, Paltrinieri 2012b, Wilday et al. 2011).
The present contribution focuses on this approach, analyzing the problem and proposing an integrated strategy to improve process hazard identification in order to capture early warnings and notions indicating the possibility of atypical scenarios. To this end, the synergy of the two techniques, the systematic HAZard Identification (HAZID) method named "Dynamic Procedure for Atypical Scenarios Identification" (DyPASI)

and a technique for the development of early warning indicators named Resilience based Early Warning Indicators (REWI) method, is suggested and tested on relevant case-studies.

2. Atypical accident scenarios

2.1 Definition and examples

Atypical accident scenarios are scenarios that deviate from normal expectations of unwanted events or worst case reference scenarios and, for this reason, are regularly not identified by common HAZID techniques and/or are deliberately omitted by HAZID analysts without adequate and transparent assessment of the related risk (Table 1) (Paltrinieri et al. 2012a). This definition of atypical accident scenarios stresses the importance of the hazard identification process and describes *atypicals* as a product of HAZID failure, as demonstrated by the analysis of the two significant examples of atypical major accidents performed in the framework of the EC project iNTeg-Risk (Jovanovic 2009, Jovanovic et al. 2010, Jovanovic et al. 2011, Paltrinieri et al. 2012a): the Ammonium Nitrate (AN) explosion at the Toulouse fertiliser factory in 2001 and the Vapour Cloud Explosion at the Buncefield oil depot in 2005. The explosion at the “off-specifications” AN warehouse of the AZF (AZote Fertilisant) factory in Toulouse caused 30 fatalities and €1.5 billion in damages, but the worst scenario considered by safety reports was an AN storage fire (Dechy and Mouilleau 2004). At the Buncefield oil depot a Vapour Cloud Explosion caused £1 billion of damage and fortunately no fatalities (MIIB 2008). In this case the worst-case scenario identified in the HAZID process was a less severe gasoline pool fire (MIIB 2008). Thus, in both cases, the accident scenarios that took place were not considered by the safety report of the site.

Table 1: Atypical accident scenarios: description and prevention

Main feature	Sub-components	Prevention strategy	Methodology proposed
Accident scenarios not captured by HAZID process because deviating from normal expectations.	Unknown Knowns we are not aware we (can) know	Reactive approach. Enhancement of knowledge management. Learning of past lessons and their translation in HAZID process.	Dynamic Procedure for Atypical Scenarios Identification – DyPASI.
	Unknown Unknowns we are not aware we don’t know	Proactive approach. Action on early deviation in the causal chain and on underlying social factors.	Resilience based Early Warning Indicators – REWI methodology.

Other similar past accidents represented available knowledge of the atypical events at Toulouse and Buncefield. In fact, many severe explosions occurred between 60 to 90 years ago, and VCEs involving gasoline and light hydrocarbon fuels occurred on average every 5 years since mid 1960 in oil depots (MIIB 2008). Furthermore, after 2005 other similar VCE explosions took place (CNN 2009, Indian Oil Corporation 2009). This highlights that all the lessons coming from existing knowledge (which in this case are major accidents, near misses, mishaps or specific studies) are not always effectively learned and put into practice. Thus, it should be remarked that “atypical” scenarios may be scenarios well known to specialists but not to the general safety community, that are likely to be overlooked even by expert safety professionals carrying out a HAZID if lacking the specific experience.

Another latent risk is represented by the accident scenarios related to new and emerging technologies, which are not still properly identified, and that may remain unidentified until they take place for the first time. Examples of new and emerging technologies can be found within the fields of Liquefied Natural Gas (LNG) regasification (Paltrinieri et al. 2011, Paltrinieri 2012) and Carbon Capture and Storage (CCS) (Paltrinieri 2012, Wilday et al. 2011), where new and alternative technologies are being defined and the scale and extent of substances (LNG and CO_2) handling is set to increase dramatically. A lack of substantial operational experience may lead to difficulties in identifying accurately the hazards associated with the process and HAZID analysts must rely on rare past events, experimental tests or theoretical studies. Hence, these new and emerging hazards may comply with the definition of “atypical” scenarios previously discussed.

2.2 Unknown Knowns
The study of past atypical major accident scenarios and new and emerging technologies in the framework of the EC project iNTeg-Risk (Jovanovic 2009, Jovanovic et al. 2010, Jovanovic et al. 2011, Paltrinieri 2012) confirmed the general need for a comprehensive and dynamic process of accident scenario identification and for a risk management framework that assesses likely hazards as soon as knowledge indicates their emergence. An adequate information management process proved to be essential in order to capture those aspects considered atypical in relation to the accidents. Thus, atypical events include those events which we are not aware we can know, because they have already occurred in the past and/or there are records, signals or studies about them. These events can be defined “Unknown Knowns” and need a process of elaboration of knowledge in order to metabolize them as “Known Knowns” (Table 1).

2.3 Unknown Unknowns
Unknown Unknowns are events we are not aware we don’t know, because they have never occurred in the past or there are no available records of their occurrence. The analysis of the causes of past atypical accidents brought to light the noticeable complexity of the phenomenon (Paltrinieri et al. 2012a, Paltrinieri et al. 2012b). An atypical scenario cannot be described by a linear chain of events, but is a result of a system deficiency, where various failures occur concurrently. However, underlying factors were found to be transversal to several atypical events and can turn into a fertile ground for the occurrence of atypical events. For instance, lack of communication, misleading control, poor knowledge management and, most of all, low risk awareness were identified as underlying organizational causes of the Buncefield accident (HSE 2011, Paltrinieri et al. 2012b). Reducing the possibility of these factors with an action on early deviations in the causal chain would help to prevent atypical events we are not aware we do not know (Table 1).

3. Methodology

3.1 General approach
Tackling the issue of atypical scenarios somehow means to address the habit of some companies dealing with dangerous products and processes to wait for an accident to take over risk management measures (NAE 2011). Organizations that are able to learn from others’ and their own experience, collecting and analyzing serious events and/or other knowledge (such as near misses) can improve their safety performance in the long run (Guldenmund 2010). There are examples of such organizations in the aviation, in the nuclear power and in the railway industry (Phimister et al. 2004). Moreover, several methodologies to establish early warning indicators are being developed and studied in international projects such as Building Safety (SINTEF 2012), that focuses on safety opportunities and challenges in petroleum exploration and production in the northern regions, and iNTeg-Risk (iNTeg-Risk 2012), that is aimed at improving the management of emerging risks related to "new technologies" in European industry.
A synergy between a HAZID technique for the systematic and dynamic screening of available knowledge (Dynamic Procedure for Atypical Scenarios Identification – DyPASI) and a method for the development of early warning indicators which are able to address atypical underlying factors (Resilience based Early Warning Indicator – REWI method) is proposed (Figure 1).

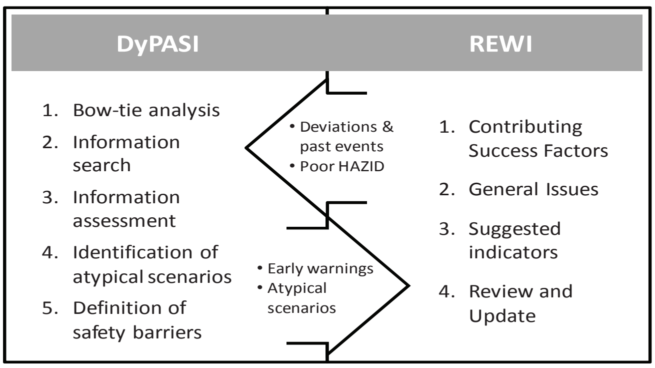

Figure 1: Synergy between DyPASI and REWI in the prevention of atypical scenarios

The two techniques were tested on several case studies within the iNTeg-Risk project (Jovanovic 2009, Jovanovic et al. 2010, Jovanovic et al. 2011, Paltrinieri et al. 2011, Paltrinieri et al. 2012a, Paltrinieri et al.

2012b, Paltrinieri 2012, Wilday 2011). For the sake of brevity, this contribution shows only the results from the application to CCS facilities (Wilday et al. 2011) and to a “Buncefield-like” oil depot (Paltrinieri 2012) in order to demonstrate the effectiveness of such a combined approach.

3.2 Dynamic Procedure for Atypical Scenarios Identification

DyPASI was built on the basis of the recommendations resulting from the in-depth analysis of atypical accidents performed by Paltrinieri et al. (2012a), which evidenced the need of a more effective and dynamic information management handling within the hazard identification process.

DyPASI is a HAZID technique derived from bow-tie analysis. Thus, the first step of DyPASI (Figure 1) corresponds to a standard hazard identification process. Then, the information search consists in the search of risk notions in past accident analysis or in literature studies. In the following phase, a determination is made as to whether the data are significant enough to trigger further action and proceed with the application of DyPASI. If indications of atypical scenarios are recognized, a reduction of the scenario to a consistent pattern and a gradual integration in the HAZID process is performed. Finally, appropriate safety measures are defined. A more detailed description of the method can be found in Paltrinieri (2012).

3.3 Resilience based Early Warning Indicators methodology

Several methods were coupled to DyPASI in order to test their ability in addressing underlying causes of atypicals and their complementarity with the HAZID technique. The REWI technique and the indicators it can develop were found to best fit to these requirements (Paltrinieri et al. 2012b, Paltrinieri et al. 2012c).

The REWI method aims to develop early warning indicators based on the concepts of resilience and Resilience Engineering, where resilience is defined as 'the capability of recognizing, adapting to, and coping with the unexpected' (Woods 2006). The first three elements of the REWI method highlighted in Figure 1 also represent the different tiers of the approach: i) Contributing Success Factors; ii) General Issues; iii) Indicators.

The REWI method consists of eight Contributing Success Factors (CSFs): Risk understanding, Anticipation, Attention, Response, Robustness, Resourcefulness/Rapidity, Decision support and Redundancy. These factors represent an operationalization of the concept of resilience. For each CSF there is a predefined set of general issues contributing to the fulfillment of the CSF goals, and attached to each general issue is a set of predefined candidate indicators. The predefined general issues and indicators represent a starting point on which the final establishment of indicators should be made. The selected indicators should be regularly reviewed and updated as a final step of the method.

A more detailed description of the method can be found in Øien et al. (2010).

4. Results and discussion

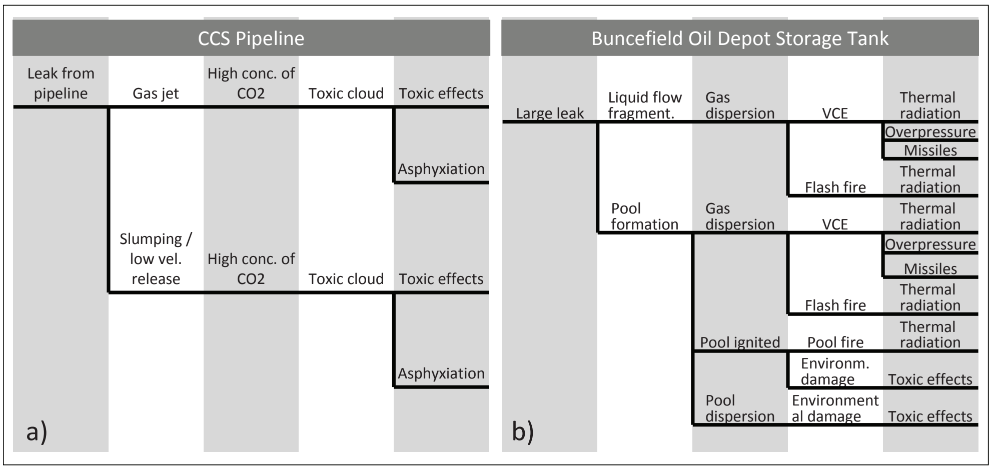

Figure 2: a) Event tree of a large leak from a CCS pipeline. b) Event tree of a large liquid leak from a “Buncefield-like” oil depot storage tank.

Figure 2a shows a representative example of the results obtained from the application of DyPASI to the emerging technology of Carbon Capture and Sequestration (Paltrinieri 2012, Wilday 2011). An event tree (which is the right-hand part of a bow-tie diagram) concerning a leak from a CO_2 transport pipeline is described/modelled. Some elements that can be disregarded by HAZID processes are slumping/low

velocity release of CO_2 and the toxic effects of such a release. This type of release was considered as a release alternative to a gas jet, because CO_2 is heavier than air and will tend to accumulate at ground level. An example of available knowledge considered is the detailed study performed by DNV on “potential HSE issues related to large-scale capture, transport and storage of CO_2” (DNV 2009).
An event concerning a large liquid leak from a Buncefield oil depot storage tank is described/modelled in Figure 2b. This diagram is an example of the set of results obtained by Paltrinieri (2012) demonstrating how DyPASI is able to identify and integrate atypical accident scenarios on the basis of past events, such as the one that occurred in Buncefield. In particular, the element concerning “liquid flow fragmentation” promoting gas dispersion was introduced in order to describe the droplets cascade from the tank top due to the overfilling.
The REWI technique was used to develop a set of early warning indicators for a “Buncefield-like” oil depot. Table 2 shows some examples of these indicators demonstrating how underlying causes of atypicals can be addressed and monitored with this technique. In particular, tackling the general issues of system knowledge and information about risk would increase risk awareness in the organization, which is essential for an effective prevention of atypicals, and monitoring the performance of hazard identification and the learning process from own and other’s experience would trigger and help the application of a HAZID model such as DyPASI.

Table 2: List of representative REWI indicators obtained for the Buncefield oil depot

General issues	System knowledge	Information about risk	Info. about quality of barriers	Risk/hazard identification	Learn from own & other’s experience	Activity level / simultaneous operations
Indicators	*Average no. of years of experience with this system*	*Portion of operating personnel taking risk courses last month*	*No. of internal audits / inspections covering technical safety last 6 months*	*No. of reviews of safety reports in the last 5 years*	*Fraction of internal and external past events considered in safety report review*	*Maximum no. of simultaneous operations last month*

4.1 Holistic approach

The coupling of the two techniques (DyPASI and REWI) showed clear benefits in the prevention of atypical accident scenarios. DyPASI is mainly a reactive technique, while REWI aims to be proactive. DyPASI can identify atypical scenarios, whose prevention and potential response performance can be monitored by REWI. Vice versa REWI can identify poor information and knowledge management in hazard identification and trigger DyPASI application. They can mutually help each other in the search and diffusion of information, as shown by Figure 1. The dissemination of this kind of information may encourage dialogues about safety in an organization, resulting in greater awareness of what can go wrong and greater willingness to discuss potential risks and safety hazards by analysts (Phimister et al. 2004). This can change risk perception in favour of a risk assessment more close to reality and may further improve the safety culture of an organization.

5. Conclusions

This study outlines an innovative approach to tackle atypical accident scenarios in order to obtain structured and complete actions of prevention. A new and advanced HAZID technique for the identification of atypical accident scenarios (DyPASI) has been developed in order to obtain a comprehensive but concise overview of potential hazards related to the system. The method allows a dynamic systematization of available knowledge and utilizes this knowledge, in order to prevent Unknown Known events. A complementary methodology has been developed in order to address underlying causes of atypical scenarios. The REWI technique addresses the resilience capacity of an organization through the development of specific early warning indicators. It allows keeping a high level of risk awareness and it positively affects the HAZID process by monitoring its reliability and updating its status. Thus, not only it lowers the occurrence probability of “Unknown Unknowns”, but it also triggers the use of DyPASI.
To conclude, the synergy of the REWI and DyPASI methods constitutes an effective strategy against atypical accident scenarios in which human, organizational, cultural and technical factors are addressed in an integrated manner.

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