EVALUATION OF ACCIDENT INVESTIGATIONS CONDUCTED BY REGULATORY AUTHORITIES AND ADVISORY AGENCIES

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ABSTRACT

Due to the large quantities of hazardous chemicals, an accident at a chemical facility can have serious consequences. The owner/operator of a chemical facility has a great interest in investigating the cause of any accident as a basis for corrective action. The lessons learned from an accident investigation can be instrumental in preventing a recurrence. However, there can be many other stakeholders in a chemical accident, including regulatory authorities (e.g., the Occupational Safety and Health Administration (OSHA) and the United States Environmental Protection Agency (USEPA)) and advisory agencies (e.g., the Chemical Safety and Hazard Investigation Board (CSB) and the National Transportation Safety Board (NTSB)). How well do these organizations investigate chemical accidents? What can we learn from their recent investigations?

This paper critically examines investigations conducted by OSHA, USEPA, CSB and NTSB. The scope of this investigation is restricted to a sample of published reports available during the five-year period 1995-1999. The survey of reports includes an analysis of the chemicals involved in the accidents as well as the types of equipment and work activities. Consideration is given to the identification of causal factors and the proposed corrective actions. The analytical tools used in the investigations are compared and the overall methodology is assessed. Finally, the lessons learned from these investigations are reviewed and compared with case studies drawn from the chemical process safety literature.

INTRODUCTION

Safety management is a process of continuous improvement. Various forms of feedback can be used to identify imperfections in the safety management system. One of these feedback mechanisms is accident investigation. Properly identified root causes for an accident provide a sound basis for corrective action recommendations. The lessons learned from an accident may not only be instrumental in preventing its recurrence, but may suggest ways to improve the overall effectiveness of the safety management system.

An accident at a chemical facility can have serious consequences for both onsite workers as well as the surrounding population due to the large quantities of hazardous chemicals handled at the facility. This was demonstrated on a horrific scale in December 1984 at the Union Carbide plant in Bhopal, India. A release of methyl isocyanate killed at least 2,000 people and injured another 200,000. The Bhopal accident served as a stimulus for the federal government to establish regulations that govern the design, operation and maintenance of certain kinds of chemical facilities.

There are two regulatory authorities involved in the regulation of chemical facilities. The first is OSHA, which is concerned with the safety and health of onsite workers. The applicable OSHA regulations are codified in 29 CFR 1910.119, “Process Safety Management for Highly Hazardous Chemicals”. The second is the USEPA, which is concerned with the safety and health of offsite populations and protection of the environment. The applicable USEPA regulations are codified in 40 CFR 68, “Accidental Release Prevention Requirements Risk Management Programs Under Clean Air Act Section 112(r)(7)”. Both sets of regulations require the investigation of accidents as one component of the safety management system. The regulations also require that the results of the accident be documented in a report and that corrective actions be implemented to prevent a recurrence of a similar accident. Furthermore, both sets of regulations require that process hazard analyses be conducted using any one of a number of system safety techniques. This implies that both OSHA and USEPA recognize the value of system safety.

The federal government has established advisory organizations to conduct accident investigation and communicate the lessons learned to the general technical community. There are two such organizations interested in chemical safety. The first is the NTSB, founded in 1967, which investigates transportation accidents of all kinds, including those involving chemicals. The second is the CSB, founded in 1990, which investigates chemical accidents at chemical facilities.

The primary focus of this paper is on CSB investigations. Due to funding restraints, the CSB was not able to begin investigating accidents immediately upon its formation. During the interim, OSHA and USEPA conducted joint investigations and published their findings in an attempt to fulfill the role of CSB. CSB was eventually able to begin conducting its own investigations in November of 1997.

This paper critically examines investigations conducted by OSHA, USEPA, NTSB and CSB. The scope of the examination is restricted to a sample of published reports available during the five-year period 1995-1999. The survey of reports includes an analysis of the chemicals involved in the accidents, as well as the types of equipment and work activities. Consideration is given to the identification of causal factors and the proposed corrective actions. The analytical tools used in the investigations are compared and the overall methodology is assessed. Finally, the lessons learned from these investigations are reviewed and compared with case studies drawn from the chemical process safety literature.

BACKGROUND

Over the last forty years, there has been a growing sophistication and effectiveness in the accident investigation process. The discipline of system safety has contributed significantly to this growth. System safety is concerned with the systematic identification, evaluation and control of hazards. One contribution of system safety has been the clarification of two key concepts: accident and root cause. Traditionally, an accident is defined as an unplanned event that results in property damage, human injury or death. System safety expands on this definition: an accident is an unintended release of energy or substance which, due to less than adequate barriers or controls, results in harm to persons or objects in the path of the release. This expanded definition emphasizes the role of barriers (physical safeguards) and controls (procedural safeguards) in controlling hazardous energies or substances [compare with Adams, 1995].

The second key concept clarified by system safety is root cause. A root cause can be defined as the most basic cause that can be reasonably identified and that management has control to fix [Paradies, et al., 1996]. From the perspective of system safety, an accident investigation is a feedback mechanism for corrective action to improve barriers or controls.

The system safety perspective is grounded in the scientific method. The basic approach is to use the evidence gathered during the investigation (physical artifacts, physical layout of the accident scene, witness interviews, process data, documentation, laboratory test results) to reconstruct the sequence of events of the accident and to identify its causal factors. A number of structured analytical techniques have been developed to assist the investigator in organizing the evidence, testing hypotheses and identifying causal factors. William Johnson, a former general manager of the National Safety Council, was instrumental in developing many of these tools into a coherent framework for the Department of Energy (formerly the Atomic Energy Commission) in the 1970s. His book, MORT Safety Assurance Systems [Johnson, 1980], has become a classic in the field of system safety.

Several guidance documents are available which address the system safety perspective of accident investigation. The reference most relevant to this study is Guidelines for Investigating Chemical Process Incidents, published by the Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (AIChE), [CCPS, 1992]. This reference relies heavily on system safety methods and cites numerous references to the system safety literature. Although the CCPS [1992] reference is not the only applicable guidance document on the subject of accident investigation at chemical facilities, it is certainly a good representation of the state of the art. Therefore, the system safety approach to accident investigation, as described in CCPS [1992], was selected as the reference point against which to compare the government investigations considered in our study.

METHODOLOGY

This study spans the time frame from 1995 to 1999. This corresponds to the period during which the government began supporting independent investigations of chemical facility accidents. All chemical facility accidents that had been investigated by OSHA, USEPA and CSB were considered. In the early portion of this five-year period, instead of the CSB, chemical accidents were investigated by a joint OSHA-USEPA committee. During that time period, CSB was not funded for operation. In the latter portion of this period, CSB conducted its own investigations. The CSB has 12 incidents from 1999 under investigation and 10 incidents from 1998. The CSB has published only 3 reports to date. This study only considered investigations that were complete and for which written reports had been issued. Of the NTSB reports written during this period, only those accidents involving storage of chemicals (in rail tank cars) were considered. Chemical accidents due to train derailments or pipeline ruptures were excluded from this study as not relevant to chemical facility operation.

Table 1 summarizes the accident investigations selected for this study. The organization responsible for the investigation is identified, as well as the date, location and type of accident. In this time period, thirteen investigations were conducted by OSHA, USEPA or the CSB. Five were conducted by the NTSB. These 18 accidents form the set of investigations evaluated in this study.

FREQUENCY ANALYSIS OF ACCIDENTS

The results of the 18 accident investigation reports were examined to determine the types of chemicals involved in the accidents, the types of facilities or operations, the work activities and equipment, the causal factors, the corrective actions and the lessons learned. The accident reports were not assumed to offer a representative subset of the overall set of accidents investigated by these agencies during that time period. This set of accidents reflect only those accidents which were suitable for formal reporting, i.e., these accidents revealed enough risk to the specific industry or the general public that a formal report was necessary to provide corrective actions and lessons learned.

CHEMICALS

The list of chemicals and their hazards involved in this set of investigations was varied. The accidents dealt with the following types of commodity and specialty chemicals:

- Petrochemicals (6 out of 18)
- Specialty Chemicals (7 out of 18)
- Agricultural Chemicals (2 out of 18)
- Bulk Inert Gases (1 out of 18)
- Explosives (1 out of 18)
- Hazardous Waste (1 out of 18)

These chemicals represented all types of hazards: flammability, reactivity, corrosivity and toxicity. The 600K report [CSB, 1999] revealed that fuel products (petrochemicals) accounted for the vast majority of chemical accidents during the period from 1987 to 1996. Similarly, petrochemical incidents were the subject of six of the eighteen investigations. This number was eclipsed only by specialty chemicals, with seven out of eighteen. Significantly, the two largest classes of chemicals were petrochemicals and specialty chemicals. Also, little overlap was observed in the classes of chemicals that were the subject of each investigation. Eleven of the eighteen accidents involved an explosion.

FACILITIES AND OPERATIONS

The chemical incidents can be grouped according to type as either transportation or facility accidents. Incidents involving transportation of chemicals account for approximately one-third of the reviewed reports and suitably were investigated by the NTSB. However, the majority of the reviewed incidents could best be described as facility-based or facility incidents. These involve accidents at fixed locations that either produce, handle or store chemicals on a large scale. USEPA/OSHA and the CSB investigated all the facility accidents. Transportation and facility accidents shared an equal distribution of chemical incidents (43% to 42% respectively) in the CSB 600K report [CSB, 1999].

Generally, as the size (production or capacity) of the facility increases, the facility's capital and experience base should become more conducive toward developing and implementing sophisticated safety programs. In fact, some of the facilities were subject to OSHA's process safety management or USEPA's risk management regulations. The majority of the facilities, however, did not fall within these requirements. Thus, serious chemical hazards may be found lurking at smaller facilities engaged in operations as simple as bulk packaging.

EQUIPMENT AND WORK ACTIVITIES

The equipment and work activities at the time of the accident played direct roles in the root causes of the accidents. The types of equipment can be generalized as:

- Storage/Storage Tanks (10 of 18)
- Reactors and Mixers (7 of 18)
- Piping Systems (1 of 18)

The type of work activities which caused the accident are revealing to the nature of the accidents:

- Maintenance/Hot Work (4 of 18)
- Normal Operation (8 of 18)
- Abnormal Operation (5 of 18)
- Public Interference (1 out of 18)

The largest number of accidents that proved reasonable to offer corrective actions and lessons learned (fixable) happened during normal operation.

CAUSAL FACTORS

The determination of causal factors is concerned with identifying opportunities for improvement in the safety management system. This is not to say that management is responsible for the occurrence of all accidents. Safety is everyone's responsibility. Typically, chemical process accidents are the result of multiple causal factors, some of which may not be within the control of management. The implementation of the safety management program is, however, a management function. It is management's responsibility to investigate accidents with the ultimate goal of gleaning the fundamental lessons learned so that the safety management system can be improved.

System safety classifies causal factors into three broad categories: equipment, human factors and environmental factors. Equipment factors include design errors, defective manufacturing, incomplete instructions and warnings, and errors in installation, operation or maintenance. Human factors include procedures, training, communications, human factors engineering, immediate supervision and the management system. Environmental factors include time of day or season of the year, weather conditions, natural disasters and deliberate, harmful actions.

Of the 13 investigations conducted by USEPA-OSHA or CSB, six concluded that poor design (typically failure to understand or anticipate chemical hazards) was a significant causal factor in the accident. Incomplete or defective procedures were found in 11 of the 13 accidents. Only one of the 13 was initiated by an equipment failure. Environmental factors were cited in two of the 13 accidents (ambient temperature in one case, public access followed by an accidental harmful act in the other).

In the case of the NTSB investigations, four of the five accidents were the result of improper modifications to rail tank cars. In each case, these were procedural errors in maintenance. The fifth accident was the result of a design error.

CORRECTIVE ACTIONS

The corrective actions contained in the reports typically corresponded to the elements of OSHA's process safety management program. The most frequent recommended corrective actions were improvements in the following:

- Process safety information (5 out of 13)
- Hazard analysis (10 out of 13)
- Standard operating procedures (10 out of 13)
- Training (7 out of 13)

The recommendations in the NTSB investigations related to mechanical integrity in four of the five accidents and a design change in the fifth accident.

LESSONS LEARNED

The lessons learned from these accidents underscore two important points:

- Perform effective hazard analyses for both operational and maintenance activities.
- Develop standard operating procedures for hazardous activities.

These observations are easier to state than they are to implement. It is especially difficult to determine what constitutes a reasonable level of effort for these tasks. An unreasonably thorough effort may not only be too time-consuming and costly, it may also lose its effectiveness by burying the user under a pile of superfluous detail. A superficial effort may overlook significant hazards. One criterion that can help determine a reasonable level of effort is to consider the quantity of hazardous chemical (and, therefore, the potential consequence of an accident) involved in the process or facility under study.

A final observation can be drawn from these investigations. Serious chemical accidents can happen at smaller, less sophisticated facilities engaged in work outside of chemical manufacturing. The accident settings from this data set included an agricultural chemical packaging facility (BPS), a bulk chemical storage facility (Powell Duffryn), a swimming pool chemicals packaging facility (Surpass) and a turkey farm (Feather Creek Farm).

SURVEY OF INVESTIGATION TECHNIQUES

Three categories of investigation techniques were considered: evidence collection, accident analysis and engineering analysis. Evidence collection refers to the task of gathering facts. Evidence from a chemical accident can be classified into four categories: physical artifacts (including samples for chemical analysis), witness statements, process data and documentation. Most of the reports reviewed relied on all four types of evidence. The type and quantity of evidence varied with the type of accident and (presumably) the availability of the evidence.

Accident analysis refers to the development of the sequence of accident events and the identification of causal factors. The accident sequence can be summarized using a simple chronology or an events and causal factors chart. If uncertainties exist as to which of several possible cause-and-effect sequences occurred, the analyst may choose to apply the scientific method in a straightforward way (testing hypotheses with evidence) or to use any number of system safety techniques for a more structured approach. System safety techniques like failure mode and effects analysis (FMEA) work well for single-event failures and fault tree analysis (FTA) for multiple-event failures.

Of the 13 non-transportation accident investigations, three provided no information on the accident sequence of events, two used chronologies and eight used events and causal factors (E&CF) charts. Four of the 13 investigations used system safety techniques for the analysis of causal factors: two investigations used both barrier analysis and change analysis, one used FMEA and one used FTA. Seven of the 13 investigations explicitly detailed root causes for the accidents but only one report specifically identified a structured root cause analysis methodology (the Management Oversight and Risk Tree, or MORT, was used in the Tosco Avon Refinery investigation). In four of the investigations, the root cause analysis was based on professional judgment and experience while the remaining two did not specify the method used.

In all five of the NTSB investigations, a chronology was used to describe the accident sequence of events. Each of these investigations used the scientific method rather than system safety techniques to identify causal factors or root causes.

In the context of accident investigation, engineering analysis is defined as a form of deductive reasoning in which scientific principles are used in conjunction with the empirical data from the accident scene to test hypotheses of accident causation. All 13 of the non-transportation accident investigations relied on knowledge or application of chemistry. Other bodies of scientific or engineering knowledge were employed as well but, due to the unique character of each accident, they are difficult to generalize. Examples of other types of knowledge used include the fluid dynamics of vent systems (Surpass), explosion dynamics (Shell), mechanical system failure analysis (Shell) and unit operations (Powell Duffryn). The NTSB investigations relied primarily on metallurgy for their engineering analysis.

DISCUSSION AND RECOMMENDATIONS

Due to the biased sampling of NTSB accident investigations (i.e., exclusion of transportation accidents), the NTSB reports selected were more focused on failure analysis than accident investigation. Therefore, the NTSB reports are not discussed in this section. The primary goal of this study was to compare the chemical accident reports published from 1995-1999 with the system safety approach as typified in [CCPS, 1992]. With the exception of the first report issued (Terra Industries), the investigations have been consistent with the CCPS guidance document. These investigations have demonstrated the effectiveness of system safety techniques when the level of effort is tailored to the complexity of the accident. The most important benefit of the system safety approach is that root causes are derived from a rational, evidence-based framework. There will always be room for disagreement amongst experts, but the system safety approach should result in a reasonable set of corrective actions targeted at improving the safety management system. Even more importantly, these reports communicate lessons learned that can benefit the entire chemical industry.

The reports issued during 1995-1999 are somewhat inconsistent in quality. Not all are adequate in describing the sequence of events. Accident investigation reports should describe the sequence of events with either a chronology or an E&CF chart. The choice of technique and the format of its presentation depends on the complexity of the accident. Without an adequate description of the sequence of events, it is not possible to accurately identify causal factors and infer root causes.

Root cause analysis should not rely on experience or judgment alone (as was the case for the Pennzoil, Powell Duffryn, Shell and Surpass investigations). The danger of relying on experience and judgment only is the potential for a loss of objectivity. Root cause analysis should be a rational, evidence-based process. MORT [Johnson, 1980] and TapRooT® [Paradies, et al., 1996] are two examples of objective root cause analysis processes. There are many advantages of objective root cause analysis: it is more accurate, complete and, to a large degree, reproducible. An objective root cause analysis has greater credibility than a subjective one. Thus, it is recommended that future CSB reports describe the root cause analysis more completely.

A brief comparison of the investigation reports with the process safety literature (see e.g., Kletz [1994, 1998], Sanders [1999] and Lees [1996]) reveals a certain degree of repetition in the lessons learned. This is not to say that the chemical industry is ignoring these lessons. All of these lessons represent best practices in safety management and, therefore, bear repetition. Furthermore, the structure of the chemical industry continues to evolve. The number of firms handling chemicals and the sophistication of their technical staff is in a constant state of flux. While some manufacturing facilities may use the latest technologies and brand-new equipment, others are quite successful using pre-WWI technologies with some pieces of equipment older than the plant manager. With the ever-changing ownership and management of companies due to mergers and acquisitions, the need for continually refreshing the corporate memory becomes all the more urgent. The CSB can play a critically important role in maintaining the institutional memory for the chemical industry.

Finally, the most important lesson from these accident investigations is this: chemical accidents happen to people who handle chemicals. Serious chemical accidents occur at relatively unsophisticated industrial facilities that are not typically considered to be part of the chemical industries. These are the people who could benefit the most from the lessons learned from CSB investigations. CSB, USEPA and OSHA need to continue in their role of communicating the lessons learned from chemical accidents. They also need to find ways to broaden the distribution of this information to as wide of an audience as possible.

CONCLUSIONS

This study critically examined 18 chemical accident investigations conducted by the federal government during the period 1995-1999. Thirteen of these were facility accidents investigated by CSB (3) or a joint USEPA-OSHA team (10). The remaining five were transportation accidents investigated by the NTSB. The survey of reports revealed the following conclusions:

- Chemicals: The chemicals included both specialty and commodity types. The most common hazard event (11 out of 18) was an explosion.
- Facilities and Operations: No specific trend.
- Equipment and Work Activities: There was no specific trend for equipment but the most common work activity (8 out of 18) was normal operation.
- Causal Factors: Poor design of operating processes was cited in 6 of the 13 facility accidents. In the vast majority of the facility accidents (11 out of 13), operating procedures were found to be inadequate.
- Corrective Actions: The need for better process hazard analyses and operating procedures were the most frequently cited items.
- Lessons Learned: Serious chemical accidents can occur at virtually any type of facility where chemicals are handled or stored.

The facility accident investigations emphasized the use of system safety techniques. This is consistent with the CCPS/AIChE guidelines on chemical process accident investigation. It is strongly recommended that CSB maintain its system safety perspective in all future investigations. It is further recommended that they explicitly document their root cause analysis using a proven method, such as MORT or TapRooT®.

Finally, the most important lesson learned from these investigations is that chemical accidents happen to people who handle chemicals. Large chemical facilities can experience a chemical accident despite a knowledgeable and sophisticated safety management system. It should not be surprising then, that serious chemical accidents can happen at smaller, less sophisticated operations involved in handling or storing hazardous chemicals. CSB can play a vital role in preserving the institutional memory of the chemical industry and communicating the lessons learned from their accident investigations. CSB, USEPA and OSHA need to find ways to broaden the distribution of chemical safety information to as wide an audience as possible.

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TABLE 1 SAMPLE OF ACCIDENT INVESTIGATIONS (CHRONOLOGICAL ORDER)

COMPANY NAME	LOCATION	ACCIDENT DATE	ACCIDENT TYPE	INVESTIGATING ORGANIZATION	REPORT DATE
BPS, Inc.	West Helena, AR	1997 May	Explosion, Fire, Toxic Release	USEPA, OSHA	April 1999
Tosco Avon Refinery	Martinez, CA	1997 January	Explosion, Fire	USEPA,OSHA	1998 November
Georgia Pacific Resins	Columbus, OH	1997 September	Explosion	USEPA, OSHA	1999 August
Terra Industries	Port Neal, IA	1994 December	Explosion	USEPA, OSHA	1996 August
Napp Technologies	Lodi, NJ	1995 April	Explosion, Fire	USEPA, OSHA	1997 October
Pennzoil Product Refinery	Rouseville, PA	1995 October	Explosion, Fire	USEPA, OSHA	1998 March
Powell Duffryn Terminals	Savannah, GA	1995 April	Fire, Toxic Release	USEPA, OSHA	1998 May
Shell Chemical Company	Deer Park, TX	1997 June	Explosion, Fire	USEPA, OSHA	1998 June
Surpass Chemical	Albany, NY	1997 April	Explosion, Toxic Release	USEPA, OSHA	1998 September
Chief Supply Corporation	Haskell, OK	1997 March	Fire, Explosion	USEPA, OSHA	2000 April
Sierra Chemical Company	Mustang, NV	1998 January	Explosion	CSHIB	1998 September
Union Carbide	Hahnville, LA	1998 March	Confined Space	CSHIB	1999 February
Herrig Bros. Feather Creak Farm	Albert City, IA	1998 April	Fire, Explosion	CSHIB	1999 June
Georgia Gulf Corporation	Pasadena, TX	1997 November	Flammable Gas Release	NTSB	1998 December
Illinois Central Railroad	Memphis, TN	1997 April	Toxic Release	NTSB	1998 December
Consolidated Rail Corporation	Selkirk, NY	1996 March	Fire	NTSB	1998 April
Norfolk Southern Railway Co.	Sweetwater, TN	1996 February	Toxic Release	NTSB	1998 April
Gaylord Chemical Co.	Bogalusa, LA	1995 October	Toxic Release	NTSB	1998 January