Common Operations Failure Modes in the Process Industries

Peter Bullemer
Human Centered Solutions
Independence, MN
pbullemer@applyhcs.com

Jason C. Laberge
Honeywell Advanced Technology
Minneapolis, MN
jason.laberge@honeywell.com

The Abnormal Situation Management® (ASM®) Consortium[1] funded a study to investigate common failure modes and root causes associated with operations practices. The study team analyzed 20 public and 12 private incident reports using the TapRoot® methodology to identify root causes. These root causes were mapped to operations practice failures. This paper describes the top ten operations failure modes identified in the analysis. Specific recommendations include how to analyze plant incident reports to better understand the sources of systemic failures and improve plant operating practices.

INTRODUCTION

Process industry plants involve operations of complex human-machine systems. The processes are large, complex, distributed, and dynamic. The sub-systems and equipment are often coupled, much is automated, data has varying levels of reliability, and a significant portion of the human-machine interaction is mediated by computers (Soken, Bullemer, Ramanthan, & Reinhart, 1995; Vicente, 1999). These systems are also social in that many plant operations function with a teamwork culture such that activities are managed by crews, shifts, and heterogeneous functional groups. Team members have to cope with multiple information sources, conflicting information, rapidly changing scenarios, performance pressure and high workload (Laberge & Goknur, 2005). Historically, the reporting of failures has tended to emphasize root causes associated with equipment reliability and less so on human reliability root causes (Bullemer, 2009). Consequently, there is limited information available on the frequency and nature of operations failures pertaining to human reliability. This tendency has limited the ability of process industry operations organizations to identify improvement opportunities associated with their management systems and operations practices.

A root cause is “the most basic cause (or causes) that can reasonably be identified that management has control to fix and, when fixed, will prevent (or significantly reduce the likelihood of) the [failure’s] recurrence” (Paradies & Unger, 2000, p. 52). Root causes may contribute to an incident in isolation or in combination with each other.

In an effort to improve on the understanding of the impact of ineffective operations practices and management systems on safe plant operations, the ASM Consortium decided to conduct root cause analysis of existing major incident reports. An initial study examined fourteen public and private incident reports to determine the impact of communication and coordination practice failures (Laberge, Bullemer & Whitlow, 2008). Based on the results of the initial study, this follow-on study was established to analyze an expanded set of incidents reports for failure modes of operations practices in general. This paper reports the main findings of this study with

---

[1] This research study was sponsored by the Abnormal Situation Management (ASM) Consortium.

emphasis on the project methodology to illustrate its potential value to process industry organizations as an aid to understanding the impact of the operations practices on human reliability. The project methodology illustrates an approach to identifying systemic operations practice failures that are not indicated when looking at root causes alone.

METHODOLOGY

This section describes the project's approach to the selection and analysis of incident reports.

Identify and Select Candidate Incidents

The project team conducted a search to identify potential public and private incident reports from sources world-wide sources. The details of the method for identifying and selecting incident reports are available in the initial study report (Laberge et al., 2008). To summarize, a total of 123 candidate incident reports were identified (99 public, 24 private) in the search. Of these 123, the project team selected 32 for analysis in this study.

In the selection process, priority was given to recent refining and chemical incident report with severe consequences (where recent is in the last 10 years) and the reports had sufficient detail to conduct a root cause analysis. In addition, the ASM Consortium wanted the analysis to represent operations practice failures from a global perspective so there was an attempt to get a global distribution. Table 1 shows the selection distribution results in terms USA versus non-USA incident reports.

Table 1 Distribution of USA and Non-USA sources of incident reports.

	Public	Private	Total
USA	14	7	21
Non USA	6	5	11
Total	20	12	32

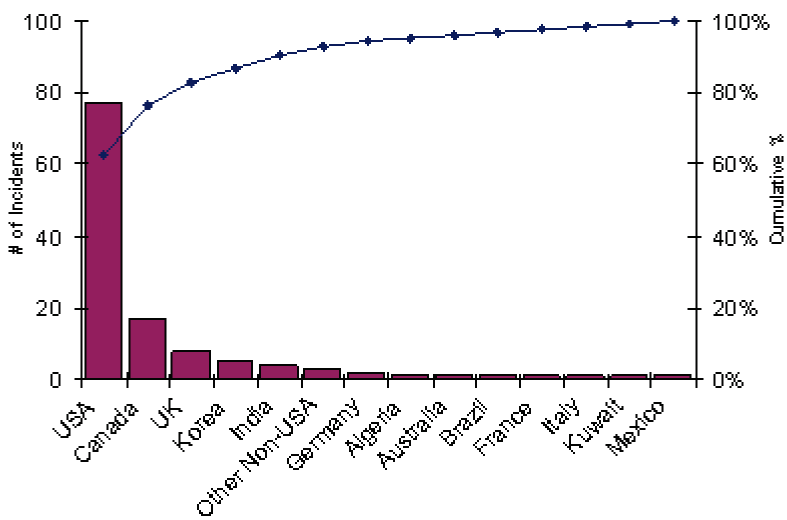


Figure 1 The distribution of incident reports by country of origin.

The distribution by country of origin (Figure 1) shows that approximately 66% of the incident reports were from North American Sources. The project team had hoped for more non-US reports but the availability of reports that met the selection criteria was quite limited.

Definitions

This section contains some basic definitions to help in understanding the analysis methodology.

- **Operational failure** is any operational practice flaw that, if corrected, could have prevented the incident from occurring or would have significantly mitigated its consequences. An operations failure describes 'What went wrong' in the specific incidents and is typically in the investigation team's own language/terms. An example of an operations failure is *Ineffective supervision of procedure execution.*
- **Common failure mode** is a description of multiple operational failures that appeared across incidents. A common failure mode represents a common problem across industry sites. The project team characterized these common failures using language from their *Effective Operations Practices* (Bullemer, Barreth, Laberge, & Nimmo, 2008). If a common failure mode did not map to one of the Effective Operations Practices, the project team created a new failure mode description. An example of a failure mode is *Ineffective first-line leadership roles*.
- **A root cause** is the most basic cause (or causes) that can reasonably be identified that management has control to fix and, when fixed, will prevent (or significantly reduce the likelihood of) the failure's (or factor's) recurrence (Paradies & Unger, 2000, p. 52). A root cause describes 'Why a failure occurred.' In the research project, the team used the root cause tree available in the TapRoot® methodology. Two root cause examples are *No Supervision* and *No communication* which can both result in the *Ineffective first line leadership* common failure mode.
- **Common root cause** is a description of a root cause that occurs across multiple incidents and is the frequency count of root causes for each common failure mode.
- **A root cause manifestation** is the specific expression or indication of a root cause in an incident. The root cause manifestations describe 'How' operational failure modes are expressed in real operations settings. The root cause manifestation characterizes the specific weakness of an operations practice failure mode. *Supervisor not in accessible to control room to discuss problems* is an example manifestation for the *No Supervision* common root cause and the *Ineffective First Line Leadership Role* common failure mode.
- **Common manifestations** are all the ways a common root cause was expressed across the incidents in a sample. A manifestation may appear in multiple incidents or be unique to a single incident in the sample.

Incident Analysis

The purpose of the incident analysis technique is to generate information to enable an understanding of why the incidents occurred and develop improvement programs and corrective actions to address weaknesses in operations practices or management systems. The focus is to eliminate common and systemic problems.

Several incident reports are analyzed to generate a list of common operations failures, common root causes and common manifestations. Together these information elements provide an understanding of causes of incidents in terms of what, why and how (See Figure 2).

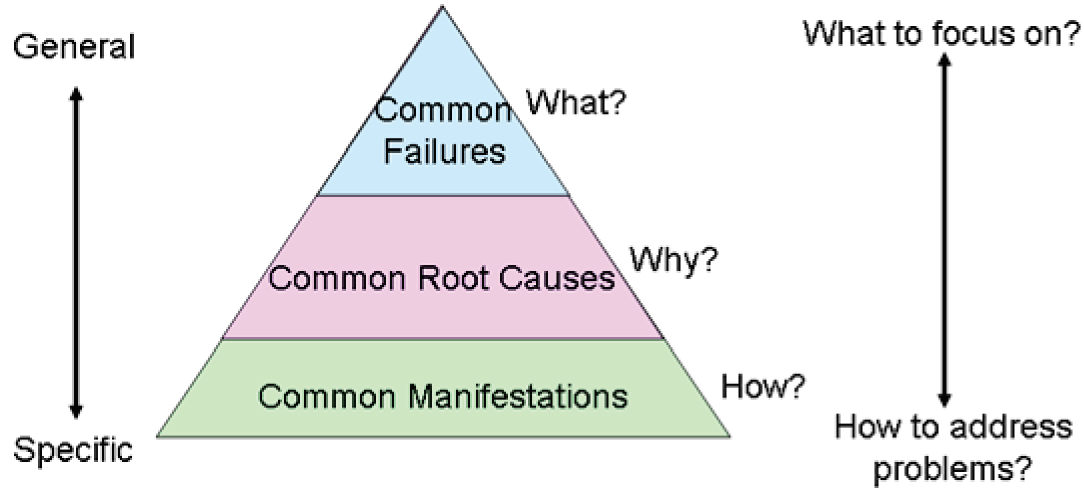


Figure 2 Three information elements generated by the incident analysis technique.

In the remainder of this section, the incident analysis technique description explains the steps used to identify the common failures, common root causes and common manifestations across several incident reports.

Step 1 Analyze Incident Reports

Step 1 in the incident analysis technique is to identify the operations failures, root causes and root cause manifestations in each incident report. In this study, the team used the TapRoot® (www.TapRoot.com) methodology and software to complete the root cause analysis (Paradies & Unger, 2000). TapRoot® is a structured approach to incident investigations that is based on sound process safety management principles and learning (CCPS, 2003).

The TapRoot® is one of several possible root cause analysis techniques that might have been used in the project. The project team selected this methodology because of its observed widespread use in the ASM Consortium member companies as well as in the industry in general. Moreover, the team's assessment of the comprehensiveness of the root cause categories is consistent with ASM Consortium's guidelines on incident reporting, in that, the root causes covers human, equipment and environmental sources and the associated management systems. Consequently, the methodology has been observed to have strong credibility in both research and industry settings. However, that being said, the methodology described herein is not limited to use with the TapRoot® methodology and may be implemented with other root cause methodologies.

The TapRoot® approach begins with the creation of a SnapChart®, which is a work process diagram, illustrating the sequence of events, the people involved, the related conditions, and the incident. The study team created a SnapChart® for each incident by reviewing incident reports (public or private) and determining what happened before, during, and after the incident.

Using the SnapChart event description, the team identified conditions that contributed to the incident that represented operations practice failures. Any operational practice flaw that, if corrected, could have prevented the incident from occurring or would have significantly mitigated its consequences was identified as an operational failure. After analyzing the event description for operations failures, the study team identified the root causes of each failure. There are many ways to identify root causes of a failure. TapRoot® uses a pre-defined tree where the investigation team applies the failures to each branch in the tree and discards those branches that are not relevant to the specific failure. This tree provides the team with structure, enabling a consistent investigation across incidents (CCPS, 2003). The operational definitions of each root cause and the specific questions used to navigate the root cause tree are in Paradies and Unger (2000).

In this study, at least two study team members reviewed all the incident reports, SnapCharts®, list of failures, and root cause analyses. This two-person team discussed differences of opinion and came to a consensus on the sequence of events, failures, and root causes before analyzing another incident. This difference resolution and consensus process provided a quality control mechanism to increase the consistency of the results and the reliability of the findings across incidents.

Figure 3 illustrates the relation between operation failures, root causes and root cause manifestations in a single incident report. A given failure can have one or more associated root causes. Each root cause has a manifestation.

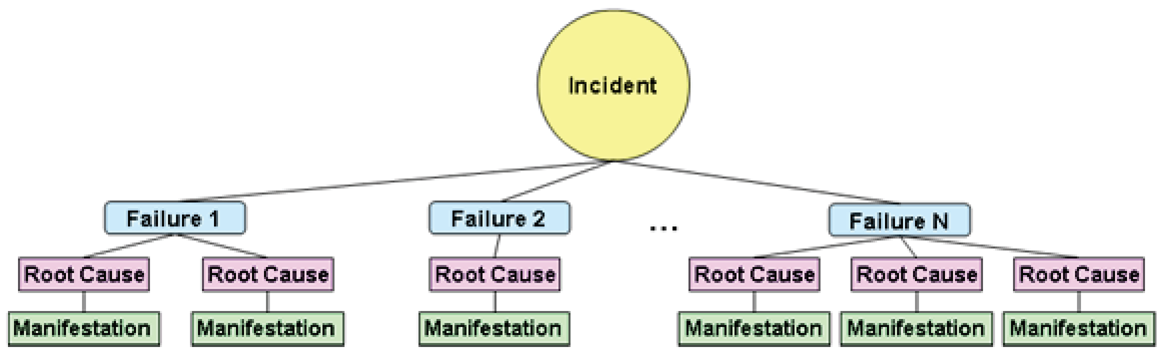


Figure 3 Relations between operations failures, root causes and root cause manifestations in a single incident report.

Step 2 Identify Common Operations Failures

In the second step, all of the failures from each incident were clustered into common failure modes. The clustering technique allowed a focus on common failures, rather than failures specific to each incident. This means the common failures highlighted aspects of the failures that were shared across incidents rather than the idiosyncratic aspects specific to each incident. Thus, the concept of common failures is more useful in establishing a general understanding for the process industries or for a specific site, because the concept represents the shared problem elements that can be used to develop solutions to prevent future incidents.

The two analysts independently clustered the individual failures from the incident analyses into common failures using the failure mode operational definitions from the ASM Consortium *Effective Operations Practices* guidelines document (Bullemer et al., 2008). While this document is not available to the general public, a process industry organization could develop a similar set of operational definitions based on their operations practice standards, policies and management systems.

Each failure could belong to only one common failure. Again, where there were disagreements between the two analysts on the common failure assignments, the differences were discussed and a consensus obtained on the appropriate common failure. Figure 4 illustrates the mapping relation between all identified failures to a set of common failure modes.

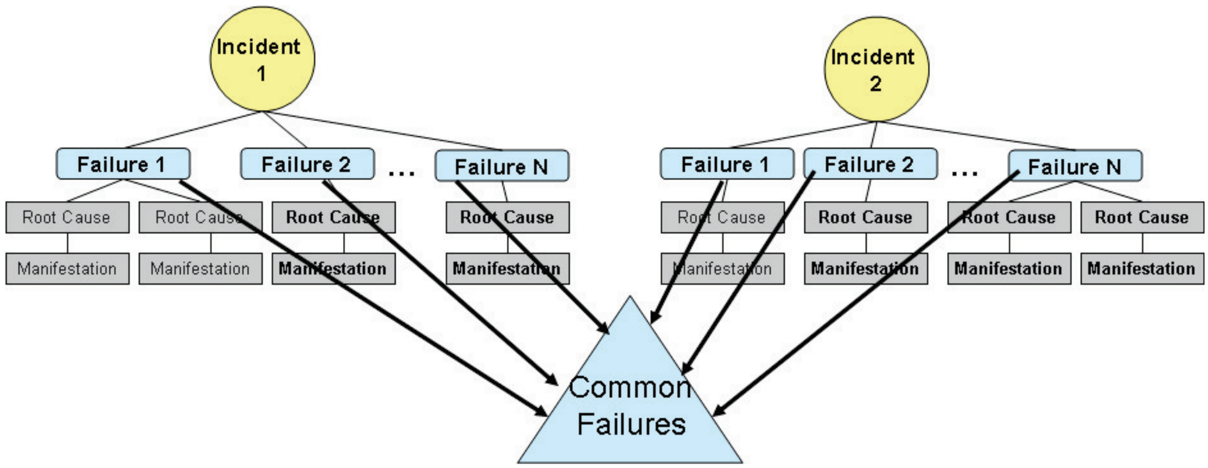


Figure 4 Illustration showing that all identified operations failures are mapped to a set of common failure modes.

In order to establish a focus for the following steps, the study team chose to focus on the top ten common failure modes. We found that the top 10 common failure modes accounted for approximately 70% of the incident failures.

Step 3 Identify Common Root Causes

The third step is identifying common root causes for each common failure across the incidents. For each the top 10 common failures, a root cause profile was generated as a frequency distribution of TapRoot root causes from the most frequent to the least frequent. The frequency distribution profiles enabled the team to identify why a particular common failure mode might occur across incidents. Organizations that have concerns with specific common failure modes can use the root cause profiles to determine the common reasons (i.e., root causes) why the failure might occur. Figure 5 illustrates the mapping relation between each root cause to a set of common root causes.

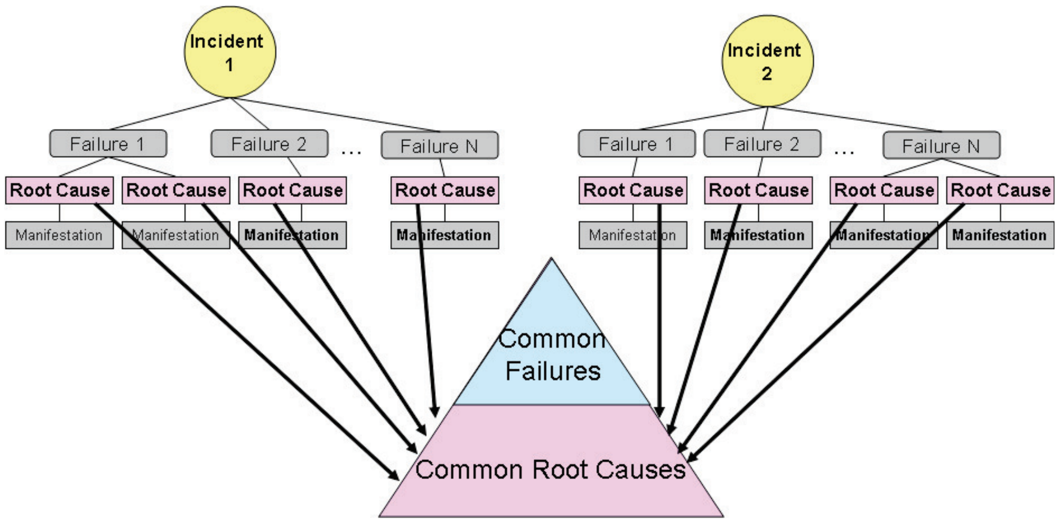


Figure 5 Illustration showing that all identified root causes are mapped to a set of common root causes.

Due to the large number of root causes associated with each common failure mode, the study team established a selection criteria that an individual root cause must represent at least 5% of the root causes associated with a given common failure mode to be shown in the root cause profile (see example in Table 4) and considered a common contributor to the failures occurrence. Generally, the use of the 5% threshold produced a list of 5-10 common root causes for each common failure.

Step 4 Identify Common Manifestations

After the common failures and common root causes were identified, the study team was asked to summarize the findings in terms of specific recommendations for improving operations practices. The team realized that while the failure modes and common root causes improved our understanding of what practices were failing and why they were failing, these elements did not indicated how they failed for each incident. Consequently, the team had to go back to the individual incident reports to identify manifestations of the root causes that were used to develop specific recommendations for how to improve elements of operations practices.

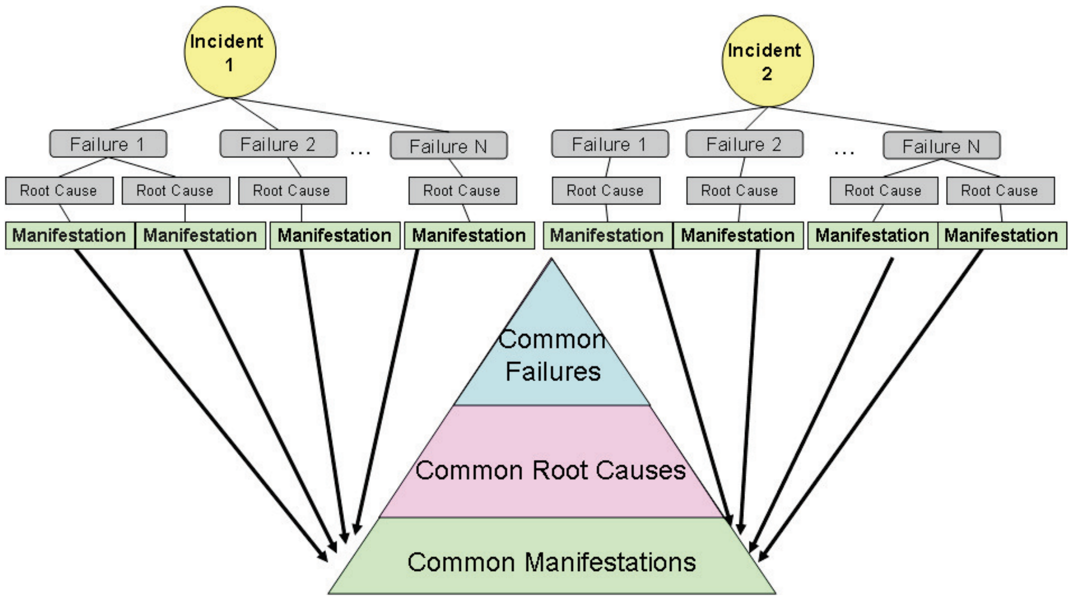


Figure 6 Illustration showing all identified manifestations are mapped to a set of common manifestations.

For each common root cause associated with each common failure mode, the team reviewed the associated root cause manifestations identified in the relevant incident reports. The cluster of manifestations was analyzed as a group. This cluster was re-described to characterize the common thread indicating how the operations practice failed. These common manifestations then provided the basis for specific recommendations for improving operations practices. Figure 6 shows the mapping relation between each manifestations and a set of common manifestations.

Table 2 provides some specific examples of the related information elements from two different incident reports.

Table 2 Examples of information elements from incident reports.

Incident Report	Operations Failure	Common Failure	Common Root Cause	Manifestation	Common Manifestation
Texas City	Shift Supervisor did not ensure procedures were being followed	Effective first line leadership	No Supervision	Supervisor did not check procedure progress before leaving site	Checking procedure progress for area of responsibility
Texas City	It was not clear who was in charge when supervisor was gone	Effective first line leadership	No Communication	Supervisor did not communicate with personnel that he was leaving the site	Bi-directional communication of status between supervisors and operators

			Accountability needs improvement	No policy that outlines responsibilities when supervisor leaves the site	Unclear policy for supervisor requirements and expectations
Esso Longford	No permit was issued or reviewed for the maintenance work	Effective first line leadership	Standards, Policies, Admin Controls (SPAC) not followed	Presence of field operator was assumed to remove need for permit	Enforcing practices/procedures across the site

Figure 7 summarizes the work process steps involving incident analysis as well as continuous improvement to achieve the overall goal of reducing future incidents and improving operations performance.

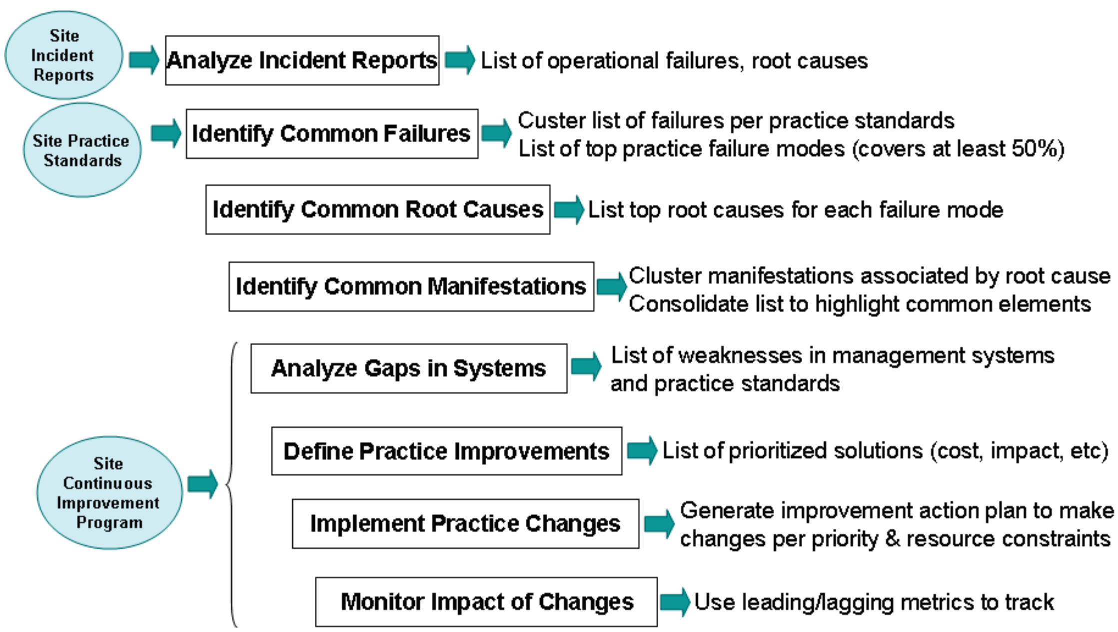


Figure 7 Summary of work process for incident analysis and continuous improvement.

Since the current study emphasis is on the nature of common operations failures associated with major process industry incidents, the details of performing the continuous improvement steps are not elaborated. These additional four steps, however, are essential for an organization or site striving to reduce the likelihood of future incidents.

RESULTS

Table 3 shows the top 10 common failure modes across all 32 incidents. The failure mode descriptions shown in the first column are rank ordered based on the frequency of occurrence across the 32 incident reports, that is, with the most frequent at the top and the least frequent at the bottom. The observed frequency of each of the failure modes shown in the table is listed in the second column. The last column of Table 3 shows the percent contribution of each failure mode relative to all observed failure modes across the sample of incident reports. The top ten failure modes accounted for 70% of the total number of failure modes across all 32 incident reports.

Table 3 Top 10 common failure modes across all the incidents.

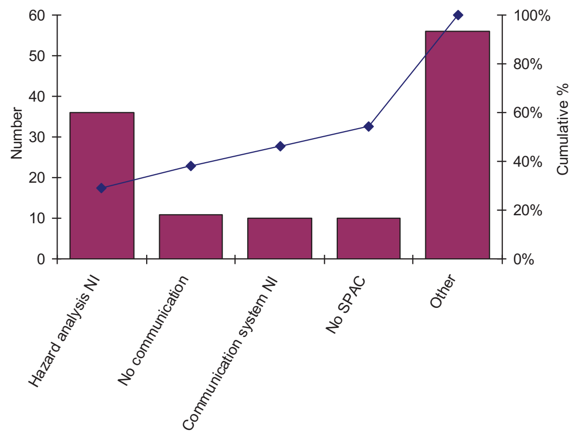
Common Failure Modes	Freq.	%
Implement a comprehensive hazard analysis and communication program	79	15%
Establish effective first line leadership roles to direct personnel, enforce organizational policies, and achieve business objectives	65	12%
Establish an effective and comprehensive program to continuously improve the impact of people, equipment, and materials on plant productivity and reliability	60	11%
Develop a strong safety culture	36	7%
Establish initial and refresher training based on competency models that address roles and responsibilities for normal, abnormal, and emergency situations	30	6%
Establish effective protocol for task-oriented collaborative communications within operations	29	5%
Implement a comprehensive Management of Change (MOC) program that specifically includes changes in staffing levels, organizational structures, and job roles and responsibilities	28	5%
Establish good, periodic communication across plant functional responsibilities	23	4%
Ensure compliance with an explicit policy on the use of procedures in plant operations	15	3%
Use design guidelines and standards for consistent, appropriate implementation of process monitoring, control, and support applications	14	3%
Other failure modes	160	30%
Total	539	100%

Note there is a clear drop in coverage between the top three failures and the rest (from 11% to 7%). The remaining seven failures each account for between 3%-7% of the total. Therefore, organizations that are looking for critical areas to focus on might consider the top three failures as most critical, which accounted for almost 40% of the total number of failures across incidents.

To illustrate the results of the common root cause analysis, Table 4 shows the common root cause profile for the most common failure mode. The most common failure across incidents related to poor hazard analysis and ineffective hazard communication (Table3). Using the 5% criterion for a common root cause, the common failure mode had four common root causes.

Table 4 Root cause profile for the most common failure.

Root Cause	#	%
Hazard analysis needs improvement (NI)	36	29%
No communication	11	9%
Communication system needs improvement (NI)	10	8%
No SPAC[2]	10	8%
Other	56	46%
Total	123	100%



DISCUSSION

The explicit focus on operating practice failures identified opportunities to reduce risk that may not be identified via traditional investigation approaches. To illustrate the difference, a specific example is shown below for the BP Texas City incident (March 23, 2005). The BP Texas City incident was one of the 32 incidents analyzed in this study. The team looked at the Baker panel report as well as the Chemical Safety Board and internal BP report. These three separate reports did not mention failures in the following three operations practice areas:

- **Task-oriented collaborative communication** (i.e., team coordination and real-time communication)
- **Training for situation management** and team collaboration (i.e., CRM-training)
- Need for a **common console operator interface framework** that supports all operator interaction requirements

Note also that the investigation of the BP Texas City incident was not typical in the level of detail and scope of coverage compared to many of the other 32 incidents. In fact, this study established a precedent in its emphasis on the need to address process safety as well as personal safety in its review. The Texas City incident typifies the analysis approach in the industry which focuses on root causes. In our experience, this approach is insufficient for identifying systemic improvement opportunities. While the root cause information is useful in explaining 'why' failures occur, it does not provide an explanation of 'what' occurred in terms of operations practice failures (Figure 8). When aggregating using the typical approach the common root causes are general and not specific enough to drive effective continuous improvement programs. Without the context of specific operating practice failures, the typical approach may aggregate root causes associated with different operations failures. However, the details for improvement (i.e., root cause manifestations) are buried in the incident report details. In the absence of documenting operations failures and root cause manifestations, incident analysis methods lack an effective way to aggregate root cause details across incidents for systemic analysis of problems and improvements.

2 Standards, policies, administrative controls—standardized work processes, rules, procedures.

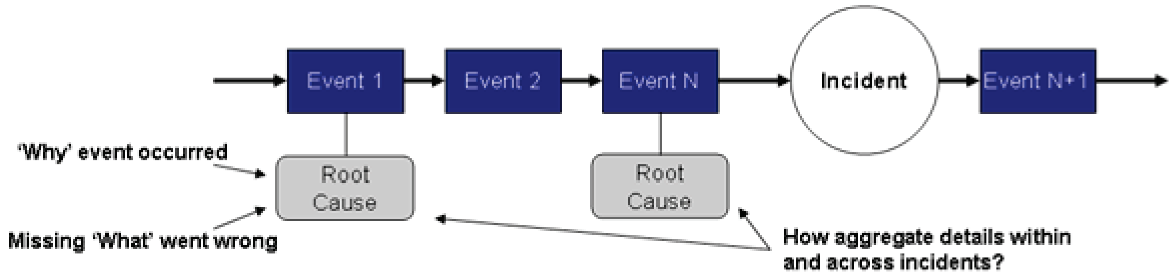


Figure 8 A typical approach to incident analysis with focus on root causes.

Table 5 shows the difference in overall findings when aggregating across all root causes versus aggregating across failure modes. *Ineffective first line leadership* is the second most common failure mode representing 12% of the identified failures in the ASM approach. In the typical approach, No Supervision as the fifth most common root cause representing only 4% of the identified root causes.

Table 5 Illustration of difference in summary findings for ASM approach in aggregating across common failures versus the typical approach of aggregating across root causes.

ASM Approach

Failure Modes	#	%
Hazard analysis/communication	79	15%
First line leadership	65	12%
Continuous improvement	60	11%
Safety culture	36	7%
Initial and refresher training	30	6%
Task communications	29	5%
Comprehensive MOC	28	5%
Cross functional communication	23	4%
Compliance with procedures	15	3%
Design guidelines and standards	14	3%
Other failure modes	160	30%
TOTAL	539	

Typical Approach

Root Causes	#	%
No communication	71	8%
Crew Teamwork Needs Improvement	58	7%
Hazard Analysis Needs Improvement	46	5%
Management of Change (MOC) Needs Improvement	40	5%
Displays Need Improvement	35	4%
No supervision	34	4%
Corrective Action Needs Improvement	33	5%
No Standards, Policy or Administrative Controls (SPAC)	32	4%
SPAC confusing or incomplete	32	4%
SPAC not followed	29	3%
Others	160	51%
TOTAL	432	

Consequently, the value of the analysis of operations practice failure modes is that it establishes the context for understanding the root cause information. Most importantly, understanding the causes of failures establishes the opportunity to make improvements to mitigate the risk of plant incidents. Neither the aggregation across operations failures or root causes on their own provides sufficient detail to identify the improvement opportunities. Consequently, the additional step to identify the root cause manifestations for each root cause profile (as shown in Table 6) is necessary. Improvement opportunities are identified by extracting the root cause manifestations for each root cause profile for the top common failure modes.

Table 6 Common root cause manifestations for two common root causes associated with the *Ineffective first-line leadership role*s operations failure mode.

Root Cause (from profile)	Manifestation
No supervision	Checking procedure progress for area of responsibility
	Being at job site and maintaining situation awareness
	Identifying and addressing risk to personnel
	Monitoring high risk activities for problems/issues
Crew teamwork needs improvement	Enforcing violations of practices/procedures (esp related to safety)
	Ensuring team members (eg ops, maint) stay coordinated
	Not correcting/communicating known problems
	Team members not questioning when evidence of problems
	Team not focusing on critical activities/indicators (tunnel vision)
	Supervisor not keeping track of big picture, losing sight of hazards

The detail in the common manifestations for each root cause profile provides:

- Specific reasons the failures occurred across incidents
- Manifestations are "indicators" of failures
- Potential candidates for leading indicators of incidents

After collecting this information, the continuous improvement program is in a better position to analyze gaps in their management systems and operations practices and identify specific solutions to reduce vulnerability to systemic and repeating root causes.

CONCLUSION

If analysis is limited to individual incident analysis, the tendency is to address root causes specific to the incident. A single incident focus may miss the larger management system contributions to safety risk. Hence, the improvement may not have the intended positive impact.

On the other hand, if the analysis is based on a sample of incidents (either common failures or root causes), analysts will make assumptions about how to address high-level root causes such as "No supervision." Going beyond root causes to identifying operations failures, enables the focus on common root causes associated with breakdowns in operations practices and management systems. Furthermore, the common manifestations of root causes provide specific details to identify the operational elements needed to direct improvement programs.

In the ASM analysis, common failure modes correspond to specific ASM *Effective Operations Practice* guidelines. For process industry organization, the operations failure modes should map to a site's operations practice standards, policy and guidelines. The organization that uses this approach to incident analysis and continuous improvement will have a better understanding where the vulnerabilities are in their operations practice or management systems. And ultimately, the organization will reduce the probability of occurrence of major plant incidents.

ACKNOWLEDGEMENTS

This study was funded by the ASM® Consortium, a Honeywell-led research and development consortium. TapRoot and SnapChart are registered trademarks of System Improvements, Inc. ASM is a registered trademark of Honeywell International, Inc. All other marks are trademarks of their respective owners.

The Abnormal Situation Management® (ASM®) Consortium (www.asmconsortium.com) is a long-running and active research and development consortium of 16 companies and universities concerned about the negative effects of industrial plant incidents. The consortium identifies problems facing plant operations during abnormal conditions, and develops solutions. Deliverables from the collaboration among member companies include products and services, guideline and other documents, and information-sharing workshops; all incorporating ASM knowledge.

REFERENCES

Bullemer, P. (2009). *Better metrics for improving human reliability in process safety*. Paper presented in the 11th Process Safety Symposium at the 5th Global Congress on Process Safety, Tampa, FL, USA.

Bullemer, P., Barreth, R., Laberge, J., and Nimmo, I. (2008). *Effective Operations Practices*. ASM Consortium Guideline Document. Minneapolis, MN: ASM Consortium.

Center for Chemical Process Safety (2003). *Guidelines for Investigating Chemical Process Incidents* (2nd Ed). New York: American Institute of Chemical Engineers.

Laberge, J.C., Bullemer, P., and Whitlow, (2008). Communication and coordination failures in the process industries. *Proceedings of the 52nd Annual Meeting of the Human Factors and Ergonomics Society*, New York, NY, USA.

Laberge, J.C., and Goknur, S.C. (2006). Communication and coordination problems in the hydrocarbon process industries. *Proceedings of the 50th Annual Meeting of the Human Factors and Ergonomics Society*, San Francisco, CA, USA.

Paradies, M. and Unger, L. (2000). *TapRoot®. The system for root cause analysis, problem investigation, and proactive improvement*. Knoxville, TN: System Improvement, Inc.

Soken, N., Bullemer, P.T., Ramanathan, P., and Reinhart, B. (1995). Human-Computer Interaction Requirements for Managing Abnormal Situations in Chemical Process Industries. *Proceedings of the ASME Symposium on Computers in Engineering*, Houston, TX.

Vicente, K. (1999). *Cognitive work analysis*. Mahwah, NJ: Lawrence Erlbaum Associates.