Understanding Process Safety Challenges associated with Heater Operations in the Process Industry[1]

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The Abnormal Situation Management® Consortium (ASMC)[2] funded a study to investigate challenges associated with heater operations. At the 2009 symposium, an ASMC sponsored paper reported on an investigation on common failure modes and root causes associated with operations practices (Bullemer and Laberge, 2010). At the 2010 symposium, a follow-on ASMC paper was presented on the failure modes associated with procedure execution failures during abnormal situations (Bullemer, Kiff, and Tharanathan, 2011). This presentation provides an update to the previous findings with the additional analysis of incident reports specific to heater operations. The additional analysis emphasizes the specific challenges identified with the operator human-machine interface (HMI) and the use of Safety Instrumented System (SIS) platforms with an emphasis on the process safety management practice. The study team analyzed 16 incident reports using the TapRoot® methodology to identify root causes associated with heater operations failures. The main finding was the failure mode profile for heater operations was different from the profile found in the larger pool of 48 process industry incidents that did not specifically involve heater operations. Specifically, the investigation found a higher prevalence of operations failures due to: (1) Inadequate HMI to support situation awareness, (2) Inadequate operator training for abnormal situation management and team collaboration skills, (3) failure to insure automation applications are fit for purpose before commissioning, and (4) failure to establish maintenance program to ensure automation applications are performing as intended. This paper discusses the implications of these findings for a company's process safety management practice requirements such as HMI design for SIS platforms, operator abnormal situation management training, and automation deployment and maintenance.

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). 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.

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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 conducted a root cause analysis of existing major incident reports (Bullemer and Laberge, 2010). A main result of the 2010 study was the development of an incident analysis methodology that provided a better understanding of the impact of the operations practices on human reliability. A follow-on study used the same methodology to examine the impact of procedure execution failures during abnormal situations (Bullemer, Kiff and Tharanathan, 2011).

Based on experiences within ASM Consortium member companies, and also on anecdotal sharing within the ASM Consortium member discussions, safe and efficient heater operations was identified as a recurring challenge in the process industry. Consequently, the ASM Consortium sponsored a research project to identify operational challenges associated with heater operations and associated contributing factors, such as operator competency, Human Machine Interface (HMI) design, and Safety Instrumented System (SIS) complexity.

Using the incident analysis methodology developed in the earlier ASM Consortium studies, the project team conducted a root cause analysis of sixteen incident reports involving heater operations to understand the nature of the operations practice failures and associated common root cause manifestations.

Analysis Methodology

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.

The project team selected sixteen incident reports made available from ASM Consortium members. The selection criteria included recent occurrence (within last 15 years) and event details sufficient to apply the TapRoot methodology.

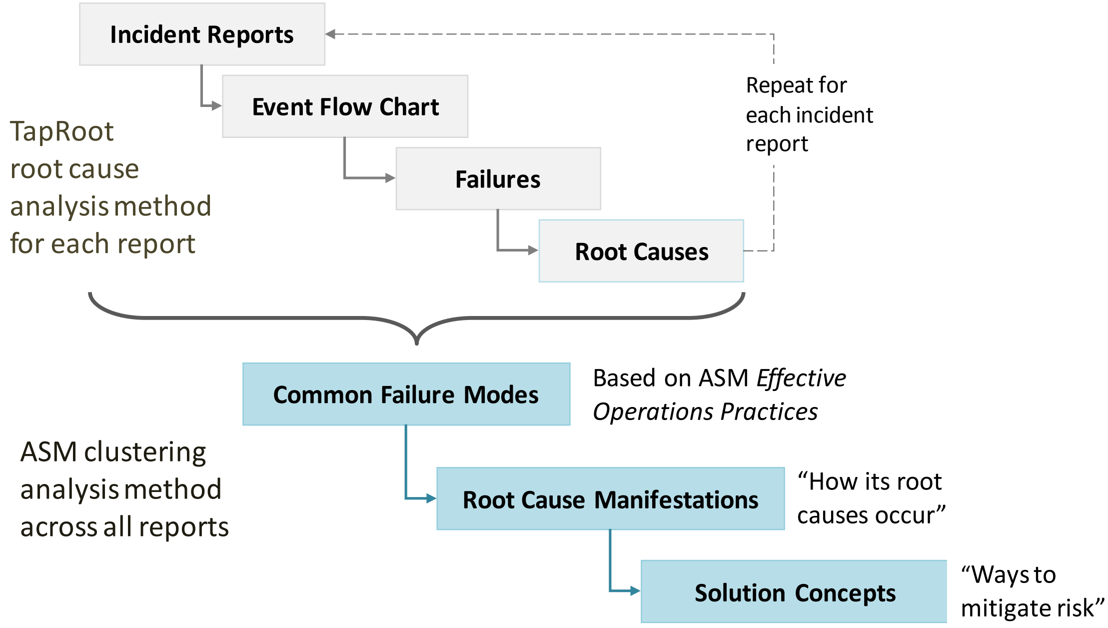

Figure 1 Work flow for the failure analysis methodology.

The methodology used to analyze the incident reports was developed as part of a project to investigate the impact of operations practice failures in major process safety incidents (see Bullemer and Laberge, 2010 for detailed description of the methodology). Figure 1 illustrates the seven steps in the work process used to analyze the heater incident reports.

The project's analysis methodology was based solely on the content of what was provided to the team in the way of documentation, such as the formal report and supporting analysis documentation, when available. The project team did not conduct any interviews or additional incident investigation as part of the project's analysis.

The first four steps correspond to the TapRoot® methodology (Paradies and Unger, 2000). The output of these initial steps is a list of operations practice failures in the language of the incident investigation team and the associated root causes per the TapRoot classification scheme:

- **Operations practice failure** is any failure 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*.
- **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.

In the previous ASM research study of 32 major process safety incidents (Bullemer and Laberge, 2010), the project team found that additional analysis was valuable to identify the systemic failures across incidents, so as to better understand how to address the operational risk indicated by the operations failures and root causes with ASM solutions that would have the broadest impact. The second half of the methodology clusters the initial findings into common operations practice failures and common root cause manifestations to indicate where ASM solutions may reduce the apparent operational risks identified in the incident analysis:

- **Common operations practice failure** 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, 2014). 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*.
- **Common 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.

Analysis Results

This section presents the results of the analysis of the sixteen process industry incident in terms of top common operations practice failures as well as the root cause manifestations associated with the common failure modes specific to heater operations.

Common Operations Practice Failures

Table 1below shows the number of operations practice failures identified as a function of the seven ASM Operations Practice categories. The top 4 categories in Table 1 account for 88% of all of the identified operations failures: Process Monitoring, Control and Support Applications (33%); Organizational Roles, Responsibilities, and Work Processes (29%); Knowledge and Skill Development (13% and Procedures (13%).

Table 1 Summary of operations practice failures as a function of the seven categories of ASM operations practices as defined in the *Effective Operations Practices* guideline document.

#	Operations Practice Category	Total Failures	% of Failures
1	Understanding Abnormal Situations	4	4%
2	**Organizational Roles, Responsibilities, and Work Processes**	**35**	**29%**
3	**Knowledge and Skill Development**	**16**	**13%**
4	Communications	4	4%
5	**Procedures**	**15**	**13%**
6	Work Environment	0	0%
7	**Process Monitoring, Control, and Support Applications**	**39**	**33%**
	Other	6	5%
	Total	**119**	**100%**

Table 2 presents a characterization of the scenario context in which the incident occurred. The examination of the mode of operations associated with the incidents found that 69% of the incidents were associated with Startup operations (11 of 16). Moreover, the majority of the incidents involved heaters with SIS implementations (69%; 11 of 16). The other major finding was that in 38% of the incidents, the controls were in manual or SIS instrumentation was bypassed.

Table 2 Characterization of heater incident scenario contexts.

Context of Incidents	# Incidents	% of Incidents
Associated with startup operations	11	69%
Involved heaters with SIS implementations	11	69%
Involved controls in manual or SIS instrumentation bypasses	6	38%

The incident reports did not contain a consistent description of impacts and most were incomplete. For example, only four incident reports provided a cost of the incident. The reported cost of equipment and/or production losses ranged from $1MM to $100MM. All incident reports did indicate whether there were safety impacts. Five of the sixteen incidents resulted in injury and/or fatalities.

Table 3 Top Common Operations Practice Failures shown in rank order of most frequent to least frequent.

Rank	GL #	Top Failure Common Failure Modes	Total Failures	% of Failures
1	2.5	Failure to implement a comprehensive hazard analysis and communication program.	11	9%
1	7.4	Failure to ensure adequate support for operator situation awareness through the integrated use of overview, detail, and trend monitoring displays.	11	9%
3	2.3	Failure to establish effective first line leadership roles to direct personnel, enforce organizational policies, and achieve business objectives.	9	8%
3	7.1	Failure to use design guidelines and standards for consistent, appropriate implementation of process monitoring, control, and support applications.	9	8%
3	7.3	Failure to establish a maintenance program to ensure that all applications are performing as intended.	9	8%
6	2.6	Failure to implement a comprehensive Management of Change (MOC) program that specifically includes changes in staffing levels, organizational structures, and job roles and responsibilities.	8	7%
6	3.1	Failure to establish initial and refresher training based on competency models that address roles and responsibilities for normal, abnormal, and emergency situations.	8	7%
8	7.2	Failure to ensure that all applications are fit for purpose before commissioning.	6	5%
9	3.3	Failure to conduct training on situation management and team collaboration skills for abnormal situations.	5	4%
9	5.3	Failure to ensure compliance with an explicit policy on the use of procedures in plant operations.	5	4%
10	1.3	Failure to establish a formal work process for the periodic analysis of abnormal situation event data to determine systemic root causes of abnormal situations and their relative impact on plant performance.	4	3%
10	5.6	Failure to use formal methods to validate content of procedural operation instructions.	4	3%
10	7.5	Failure to address an application's response during abnormal operations in the design of process monitoring, control, and support applications.	4	3%
		Total	93	78%

Table 3 shows the top common operations practice failures in rank order. The top ten operations practice failures account for 78% of the operations practice failures. An earlier ASM Consortium research project investigated operations practice failures in 32 major process safety incidents (Bullemer and Laberge, 2010). A comparison to the top ten operations practice failures in the previous study found four failure modes that were unique to the heater-related incidents:

- Failure to ensure adequate support for operator situation awareness through the integrated use of overview, detail, and trend monitoring displays. (Rank #2)
- Failure to establish a maintenance program to ensure all applications are performing as intended (Rank #5)
- Failure to ensure all applications fit for purpose before commissioning (Rank #8)
- Failure to conduct training on situation management and team collaboration skills for abnormal situations (Rank #9)

Common Basic and Root Causes

To better understand the nature of the operations practice failures, the common basic and root causes were analyzed for each of the operations practice failures. Table 4 shows the common basic and root causes associated with the operations practice failures. The table shows all of the basic causes and root causes that occurred more than two times.

Table 4 Common basic and root causes associated with the operations practice failures.

Basic Causes	%	Top Root Causes	Rank	%	#
Human Engineering	**20%**	**Displays NI***	**1**	**11%**	**17**
		Controls NI	**9**	**3%**	**5**
		Knowledge-based decision required	16	2%	3
Management System	**22%**	**No SPAC***	**7**	**4%**	**6**
		SPAC not followed	**9**	**3%**	**5**
		Not strict enough	**9**	**3%**	**5**
		Corrective action NI	14	3%	4
		Enforcement NI	16	2%	3
		Trending NI	16	2%	3
Design	**17%**	**Management of change (MOC) NI**	**3**	**5%**	**8**
		Hazard analysis NI	**7**	**4%**	**6**
		Specification NI	**9**	**3%**	**5**
		Problem not anticipated	16	2%	3
Procedures	**12%**	**Situation not covered**	**5**	**5%**	**7**
		Procedure not used	14	3%	4
Work Direction	**12%**	**Crew teamwork NI**	**3**	**5%**	**8**
		No supervision	**9**	**3%**	**5**
Quality Control	**7%**	**No inspection**	**5**	**5%**	**7**
		Inspection techniques NI	16	2%	3
Training	**7%**	**Learning objective NI**	**2**	**6%**	**9**
Communications	1%				
Preventive/Predictive (PM)	2%				
	100%			**76%**	**116**

*NI = Needs Improvement; SPAC = Standards, Policies, Administrative Controls]

Human Engineering, Management Systems and Design accounted for 59% of the basic causes. The Display Need Improvement (NI) root cause stands out relative to all other root causes with 17 occurrences across the 16 incident report (11% of all root causes).

Common Root Cause Manifestations

To better understand the nature of the top operations practice failures that were unique to heater operations, the common manifestations were analyzed for each of the root causes associated with the failure.

Failure to ensure adequate support for operator situation awareness (Rank #1)

A significant challenge to the designer of the operating displays lies in providing appropriate information support to keep operators aware of the overall plant situation and at the same time provide adequate detail to make appropriate compensatory or corrective actions. Failure to ensure support for operator situation awareness was identified as an operation practice failure in 7 of the 16 incident reports (44%). A 2010 ASM Research project investigation of 32 major process safety incidents found 50% of the operations practice failures involved poor individual and team situation awareness. In this investigation of 16 heater-related incidents, there were 17 instances where the operations practice failures were associated with ineffective use of the display types in the console operator interface to their process control system.

The following common manifestations were identified with this Process Monitoring, Control & Support Application practice failure:

- Key indicators and alarms to indicate the health of the heater were not available to the console operator such as loss of feed, fuel rich or flameout conditions. (10 root causes)
- Appropriate response required operator to integrate status across multiple parameters simultaneously. (2 root causes)
- Site did not have formal practice to communicate SOL and excursions to operators. (1 root cause)
- Key indicator for health of the furnace was not conveniently located near the local panel where field operators made field adjustments. (1 root cause)

Failure to establish maintenance to ensure applications work as intended (Rank #3)

An effective maintenance program ensures that applications perform as intended throughout their life cycles. All process monitoring, control, and support applications need to be evaluated and updated to ensure functionality performs as intended including the control instrumentation and control devices. This particular failure mode was not a significant factor in the analysis of the 32 major process safety incidents but did surface as a significant factor in the analysis of the 16 heater-related incidents occurring in 7 of the incidents (44%).

The following common manifestations were identified with this Process Monitoring, Control & Support Application practice failure:

- Controllers did not adequately control process in auto mode (2 root causes)
- No formal practice to assess need and adequacy of preventative maintenance based on equipment reliability or criticality of equipment for operations (2 root causes)
- Industry substandard inspection methods fail to detect critical conditions (2 root causes)

- Operability verification checks not performed following installation (1 root cause)
- Lack of effective maintenance on field labeling to ensure accurate information is available to field operations (1 root cause)
- Maintenance program did not prevent recurring equipment problems (1 root cause)
- Maintenance program did not result in timely replacement of important instrumentation (1 root cause)

Failure to ensure applications are fit before commissioning (Rank #8)

A formal validation process reduces the risk of deploying faulty applications. A formal validation process is used to test all applications and application modifications before putting the application into unattended service. Failing to ensure applications were working properly was a frequent failure mode in the analysis of the 16 heater-related incidents occurring in six of incidents (38%).

The following common manifestations were identified with this Process Monitoring, Control & Support Application practice failure:

- Operability verification checks not performed following installation (6 root causes)
- Industry substandard inspection methods fail to detect critical conditions (1 root cause)
- Insufficient review of electrical and instrumentation package from vendor (1 root cause)

Failure to conduct training on situation awareness and team collaboration skills (Rank #9)

Training specifically for abnormal situation management to develop situation awareness and team collaboration skills increases the likelihood of individuals performing appropriately under the potentially stressful conditions. The analysis of the 16 heater-related incident reports found ineffective training for shift team competencies for abnormal situation management to be a significant factor occurring in 4 incidents (25%).

The following common manifestations were identified with this Knowledge and Skill Development practice failure:

- Members of the shift team lacked effective troubleshooting skills (2 root causes)
- The shift team did not establish effective team situation awareness on all of their upset response activities. (2 root causes)
- The shift team failed to maintain overall situation awareness focusing on single problem. (2 root causes)

Implications for Operations Practices

The analysis of sixteen industry heater incidents produced some indication of significant challenges unique to heater operations. Based on these heater specific findings, the project team identified some key areas for solution development to improve the process industries to meet these challenges.

Need to Improve Situation Awareness during Startup

Failure to ensure adequate support for operator situation awareness through the integrated use of overview, detail and trend monitoring displays (#1 operations failure) and failure to conduct training on situation management and team collaboration skills for abnormal situations (#9 operations failure) coupled with the fact that 68% of the heater incidents were in the context of startup operations provide strong motivation to develop solutions to improve challenges associated with heater startup.

Solution concept research and development to address this challenge area might include the following:

- **Improve the quality and content of the Operating Displays.** The industry needs to better understand the operator interface requirements to support situation awareness across modes of operations including startup. In many of the incidents, operators were not fully aware of the actual conditions of the heater during startup due to ineffective information presentation to support their decision making. There appears to be opportunity to improve the HMI design through the integrated use of different display types to show high level qualitative status simultaneously along with detailed data and controls to execute startup actions. In the case of complex equipment start-up sequences, the ASM Consortium guidelines on *Effective Console Operator HMI Design* (Bullemer and Reising, 2013) promote the practice of task-specific displays to support such infrequent, non-routine activities.
- **Identify and develop effective training methods for individual and team competencies for abnormal situation management during heater startup activities including the role of first-line leadership**. There appears to be a need to formally define and develop individual and team competencies necessary to manage the abnormal functioning of heater startup such that operators understand how to detect abnormal situations, assess the associated risks for the current abnormal situation, and take the appropriate actions to mitigate potential undesirable consequences. There is a need for effective team training that ensures that all team members understand the situation awareness requirements of their team members and have the skills to communicate and collaborate effectively as the situation demands.

Need to improve Quality of SIS Deployment and Maintenance

Failure to establish maintenance to ensure applications worked as intended (#3) and failure to ensure applications are fit before commissioning (#8) coupled with the fact that 38% of the incidents were in the context of non-normal operations due to controls in manual or SIS functions in bypass indicate need to better understand effective deployment and maintenance practices for SIS systems and associated controls and instrumentation.

Solution concept research and development to address this challenge area might include the following:

- **Improve the quality of inspection and operability checks for SIS instrumentation and controls.** In several of the incident reports, the instrumentation and/or control devices associated with the SIS platform were not inspected sufficiently, nor tested properly, to verify proper functioning per design. In some cases, critical instrumentation or controls were not adequately maintained to ensure availability during startup activities. Hence, the SIS function was bypassed or control loop was operated in manual during startup.

- **Establish effective practices for mitigating hazards for 'non-normal' start-up conditions.** Despite future efforts to improve SIS instrumentation and control device deployment and maintenance, it is likely that 'non-normal' start-up conditions will continue to occur (at least at a reduced frequency), resulting in the potential need to bypass SIS safeguards. There is a need to improve the quality of operations practices for assessing and mitigating risks during these 'non-normal' startup conditions. This may require a first-line leadership role to monitor the overall potential for hazards, given current conditions, as well as more effective training for field and console personnel to continually assess and challenge the process safety status for the current startup conditions.

Conclusions

This study was funded by the ASM® Consortium, motivated by the ASM User Members challenges with safe heater operations, despite the increased prevalence of SIS applied to heaters. The analysis of 16 incident reports summarizing heater operations incidents indicated that there were four unique operations practice failures when compared to previous ASM studies summarizing operations practices failures for 32 incidents not specific to heater operations. This paper summarized the common root causes across the 16 incidents that contributed to the four unique operations practice failures. In addition, the current study identified two critical areas for improved operations practices, namely the need to improve (i) situation awareness during startup and (ii) the quality of SIS deployment and maintenance.

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