Journal of Scientific Research and Reports

Volume 29, Issue 7, Page 57-70, 2023; Article no.JSRR.101097
ISSN: 2320-0227

Analysis of Critical Risk Factors in Five Iconic Major Accidents in Petroleum and Chemical Industries

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JSRR/2023/v29i71760

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/101097

Original Research Article

Received: 08/04/2023
Accepted: 11/06/2023
Published: 17/06/2023

ABSTRACT

This study determined the critical risk factors that influence the risk of major accidents in petroleum and chemical industries. The retrospective study assessed five iconic accidents using the tripod beta analysis methodology. Literatures on five iconic accidents were reviewed, and the immediate causes of the accidents, preconditions and latent failures were analysed using a focused group of process safety professionals. These failures were aggregated into critical risk factors for these major accidents. The findings of this study revealed empirically that there are broadly five critical risk factors that influence the risk of major accidents: (i) design flaws, (ii) site process safety management, (iii) barrier management / control, (iv) operating procedures, and (v) process safety culture. These findings highlight that major accident risks can accumulate "dangerous" from the impairment of safety-critical barriers and that the operators of petroleum and chemical facilities may be blind-sided to the cumulative risk of the impairments. The findings also highlight the need for a proactive risk assessment tool with the capability to check the health of safety-critical barriers on a real time basis, in an operating plant. The use of Tripod Beta as a tool in accident causation analysis is recommended.

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Keywords: Petroleum and chemical industries; critical risk factors; major accidents.

1. INTRODUCTION

Globally, major process safety accidents have increased in chemicals and petroleum facilities and operations [1]. Even though these major process safety accidents do not occur frequently, their consequences are high in terms of reputational damage, environmental degradation, multiple fatalities, total loss of asset [2,3] and license to operate. Causally, complex causal patterns usually characterize major accidents, and it is usually very difficult to attribute the causes to one factor [2,3]. According to Bubbico et al. [4], the causes of these incidents are usually traceable to many failures in technology, humans, management systems, external circumstances, and sometimes natural phenomena.

Understanding the causes of accidents plays a major role in learning from these accidents and helps in developing prevention and control strategies. In other words, the analysis of accidents is an essential stage in adopting adequate measures to prevent similar accidents. Therefore, it is important to gain a detailed understanding of all the causes contributing to the occurrence of major accidents, so that appropriate and adequate controls can be put in place. Usually, the analysis of major accidents focuses on investigating the causal factors and system failures, to prevent similar incidents in the future or mitigate their consequences [5]. A number of studies has considered different accident analysis methodologies. These studies revealed that the Tripod Beta methodology is more efficient for the analysis of accidents, compared with the other methods [5,6]. The methodology in a systematic way, deals with the analysis of the reasons for failure of the barriers and development of actions addressing the underlying causes

2. MATERIALS AND METHODS

This is a retrospective study that analysed five iconic major accidents in the petroleum and chemicals industry using the Tripod Beta Analysis methodology. Previously published articles and literatures on the five iconic accidents were reviewed, the immediate causes of the accidents, preconditions, latent failures were analysed and these failures were aggregated into critical risk factors for these accidents. A focused group of five process safety professionals and a “Tripodian” (a trained Tripod Beta practitioner) was used for the Tripod Beta analysis and input into the Tripod Beta software.

The following steps were used in the analysis:

a) Review of each of the five iconic accidents based on the published articles
b) Analysis of the immediate causes, pre-conditions and latent failures
c) Use of the Tripod Beta software to build the Tripod Beta Tree
d) Analysis of the risk factors by mapping the Tripod Basic Risk Factors to the accidents

The list of the five iconic major accidents analysed in this study, is shown in Table 1.

2.1 Tripod Beta Methodology Framework

This Tripod Beta theory is based on the premise that accidents happen because controls fail and the underlying causes of controls failing are latent failures. These latent failures are present long before an accident occurs and if these failures can be identified and corrective actions taken to remove them, the risk of accidents will be reduced. The immediate causes like unsafe acts considered in Tripod Beta do not occur separately, they are rather affected by a series of external factors or preconditions, originating themselves from a series of latent problems. These latent problems, in turn, originate from decisions or actions performed by designers or operators of the facilities, usually considered as human errors or error enforcing conditions. The immediate problems are those which are in close contact with the incident. The pre-conditions are the systemic, mental, psychological, positional, and/or environmental states which directly lead to superficial errors [7]. The latent problems are abnormal conditions creating the preconditions and leading to the immediate causes. The latent problems which have the potential for creating events may be hidden for long periods of time and display themselves only under the conditions of the creation of normal suitable conditions such as combination with some preventive factors, immediate causes, technical errors, or the unusual states of the system [7].

Table 1. List of 5 iconic major accidents

Year	Name	Product	Type of Incident
1984	Bhopal Methyl Isocyanate Release	Chemicals	Fire and explosion
1988	Piper-alpha Disaster	Oil and Gas	Fire and Explosion
2005	Buncefield incident	Petrol	Fire and Explosion
2005	BP Texas City Refinery Explosion	Gas	Fire and Explosion
2010	Macondo Deep Water Incident	Oil	Fire and Explosion

The Tripod Beta methodology is designed to help accident investigators to analyze the causes of an incident or accident in conjunction with conducting the investigation. This helps to direct the investigation, as the investigator will be able to see where more information is needed regarding what happened, or how or why the incident occurred [8]. The result from Tripod Beta analysis is a tripod tree that basically shows what happened, how did it happen and why did it happen.

2.2 Brief Description of the 5 Iconic Accidents

A brief description of the incidents is shown in Table 2.

Table 2. Brief description of 5 iconic major accidents

Incident	Bhopal	Piper-Alpha	BP Texas Refinery	Buncefiled	Macondo
Date of accident	3 December 1984	6 July 1988	23 March 2005	10 December 2005	20 April 2010
Product	Chemicals (Methyl Isocynate)	Oil and gas	Gas	Petrol	Oil and gas
Damages/consequences	2,000 fatalities; 100,000 injuries; significant damage to livestock	167 fatalities; total destruction of the platforms	15 fatalities; 180 injuries	Extensive damage of the tank farm	11 fatalities; 17 injuries, damage of drilling rig, extensive environmental pollution
Summary of the incident	40 metric tons of methyl isocyanate (MIC) accidentally released into the atmosphere from an exothermic reaction as a result of release of about 2,000 litres of water into the MIC tank. There were a lot of defects identified during the investigation. For example, the facility emergency response capability was poor, coupled with lack of awareness by local communities of the hazardous nature of the Bhopal plant product [9]	There was a release of a large quantity of condensate and gas from an incorrectly installed blind flange. The released condensate picked up ignition resulting into an initial fire and explosion. Other risers to the platform failed under the initial explosion and the resulting release of their inventories, increased the size of the inferno. The incident investigation also revealed the consideration for operation	During the start-up of an isomerization unit, the raffinate splitter tower overfilled and consequently caused the pressure relief devices on the tower to open. The opening of the safety valves resulted in overfilling of the blowdown stack and release of flammable liquid from a blowdown stack. The released flammable liquid found an ignition source from near office trailers located close to the blowdown drum and this led to	Oil storage tank overfilled with petrol, resulting into large quantities of petrol overflowing from the top of the tank. The overflowing petrol formed a vapour cloud, found an ignition source and this resulted in a massive explosion and a fire that lasted for days [13]	Due to a well "kick", during a well temporary abandonment operation, hydrocarbon flowed to the rig floor (called "blowout") when the drilling fluid column was removed. Even though a safety critical device located at the sea floor sealed the well temporarily, this could not stop the hydrocarbon from travelling up to the rig floor. Due to a number of safety-critical failures in the system, hydrocarbons rained down onto the rig floor, found an

Incident	Bhopal	Piper-Alpha	BP Texas Refinery	Buncefiled	Macondo
		output over safety, due to lack of stop work authority by the supervisor. Poor permit-to - work system was also implicated in the incident [9,10]	an explosion and fire [11] [12]		ignition source and fire /explosion [14]

3. FINDINGS

The Tripod-Beta Tree of the five iconic accidents are shown in Figs. 1-5. The analysis of the failures and the mapping of the failures to the relevant Tripod Beta “Basic Risk Factors” in each of the five major accidents is shown in Table 3.

For example, on the Bhopal incident, Barrier 1 preventing water breakthrough into the MIC tanks failed (source of the water is unknown). MIC tank as Barrier 2 failed due to the fact that it could not quench the exothermic reaction because it was containing some inventories. The pre-condition for this Barrier 2 failure is non-compliance with procedures on inventory management in MIC tanks and this is traceable to poor site safety management. Barrier 3 failure was the failure of the high temperature shutdown system. The high temperature alarm was known to be faulty but it was ignored, again traceable to poor site safety management. Barrier 4 failure was the refrigerant system installed to handle the heat from the exothermic reaction. It was shutdown for economic reasons as the company justified production over safety considerations, again traceable to poor site safety management. Pressure relief system failure as Barrier 5 failed because it was shutdown for maintenance and no proper risk assessment was carried out to mitigate the risk of the shutdown of the pressure relief system. This is again traceable to poor site safety management. On the consequence mitigation side, Barrier 6 is the fixed water curtains which were provided to absorb MIC vapour. However, it was insufficient to absorb the vapour due to inherent design flaws. Barrier 7 is the flare system provided to incinerate the MIC vapour but this barrier was shutdown for repairs and no proper risk assessment was carried out to mitigate the risk, again traceable to poor site safety management.

Further analysis of the Tripod Beta Basis Risk Factors by the Process Safety Focus Group re-classified the risk factors into the following categories. The mapping of the Tripod Beta BRFs to Critical Risk Factors is shown in Table 4.

a) Design flaws (design integrity)
b) Site process safety management (inadequate risk assessment including cumulative risk, poor permit to work management, management of changes, incompetence)
c) Barrier management/control (ineffective management of impaired and down-graded barriers, overrides /inhibits)
d) Plant operating procedures (no-compliance with procedures, obsolete procedures)
e) Process safety culture (Audits/reviews findings not implemented, poor risk appreciation)

4. DISCUSSION

From Table 3, five Tripod Beta Basic Risk Factors (BRFs) have the highest occurrence in the five iconic accident reports studied: Hardware (HW), Maintenance Management (MM), Procedures (PR), Organization (OR) and Defenses (DF). Further analysis of the dominating Tripod Beta BRFs re-classified the factors into five critical risk factors – design flaws, site process safety management, barrier management / control, operating procedures and process safety culture. Design flaws are to do with poor/improper design and integrity of the facility and this aligns with the opinion of

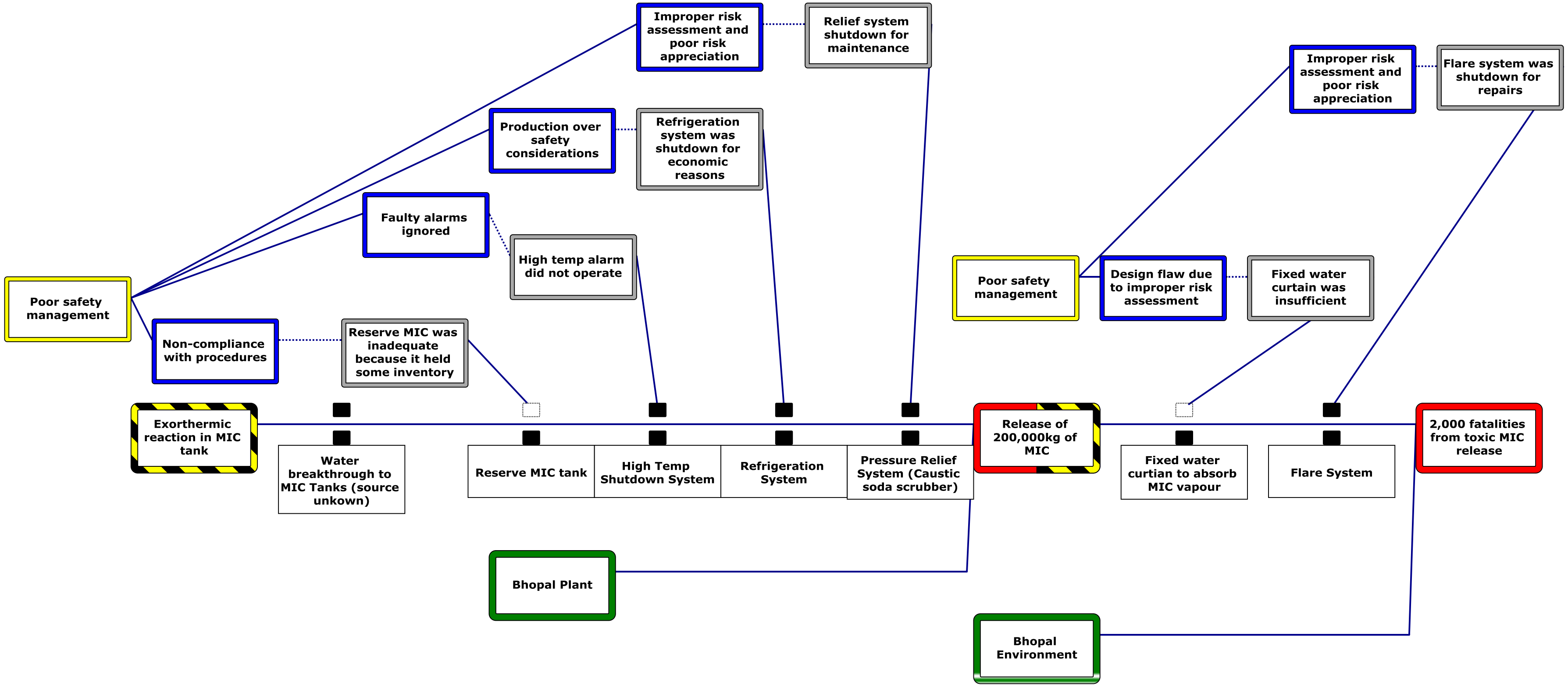


Fig. 1. Tripod beta tree for Bhopal incident

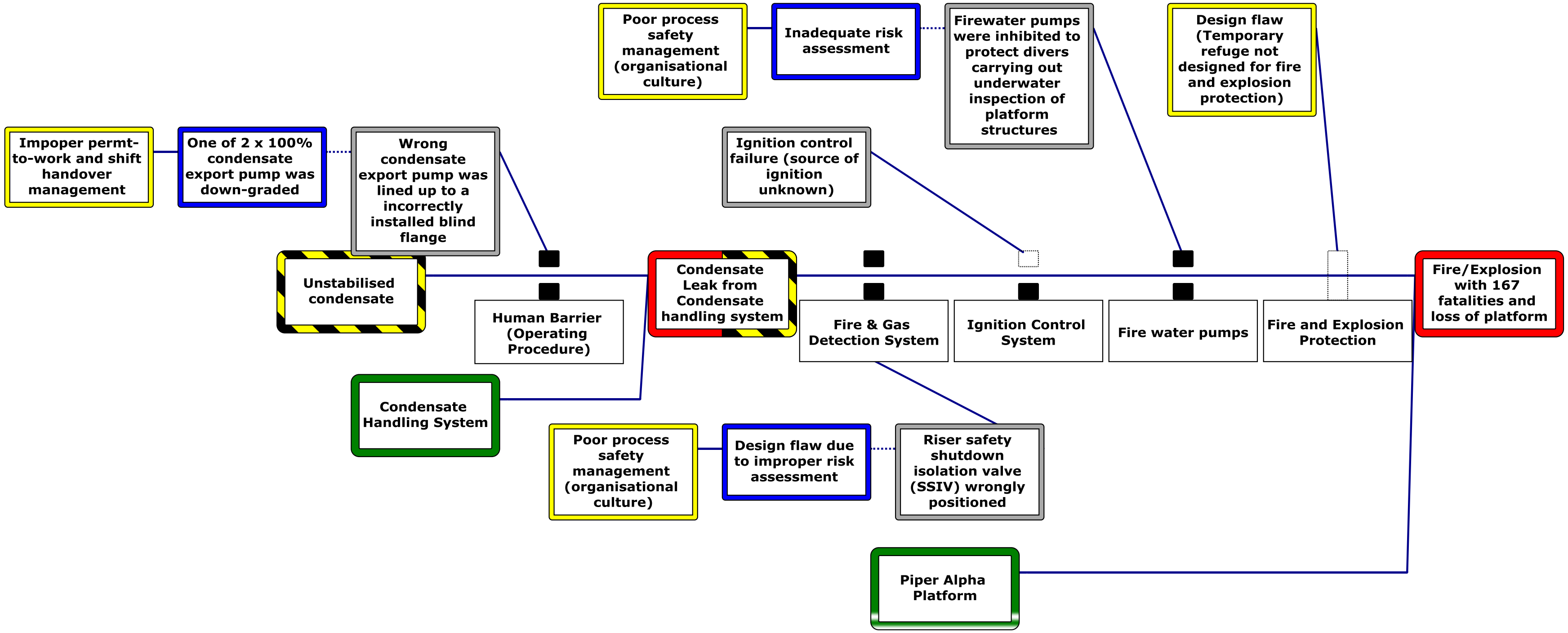


Fig. 2. Tripod beta tree for piper-alpha incident

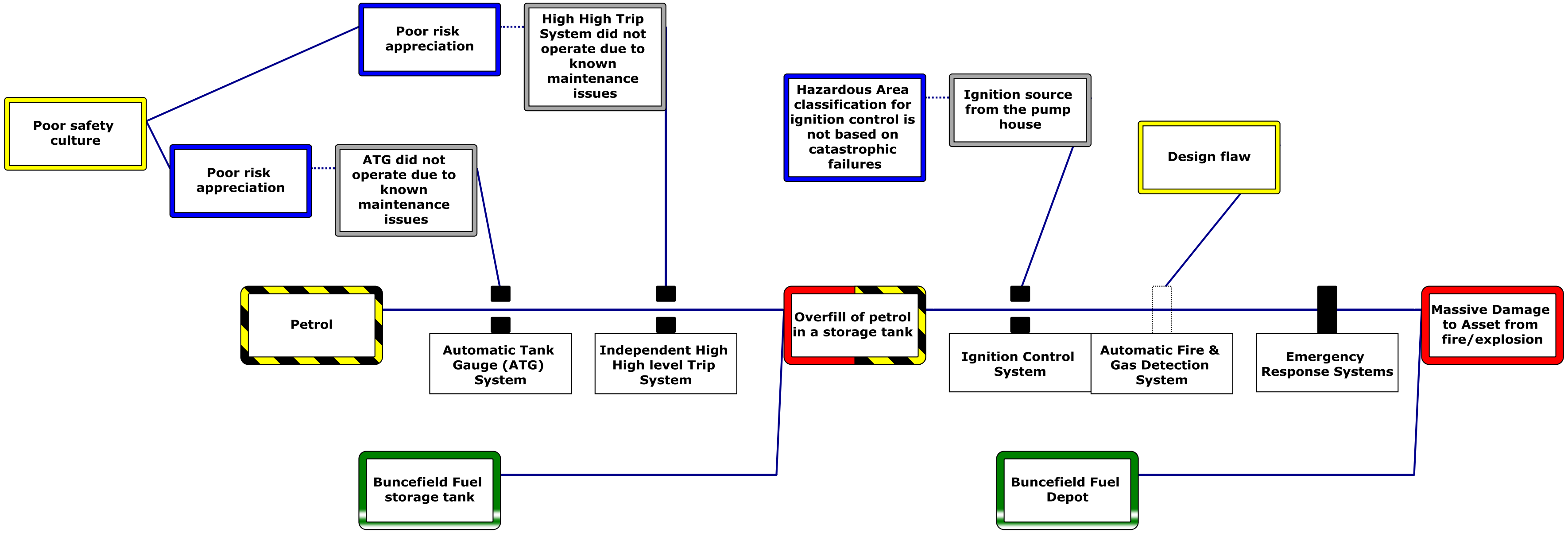


Fig. 3. Tripod beta tree for Buncefield incident

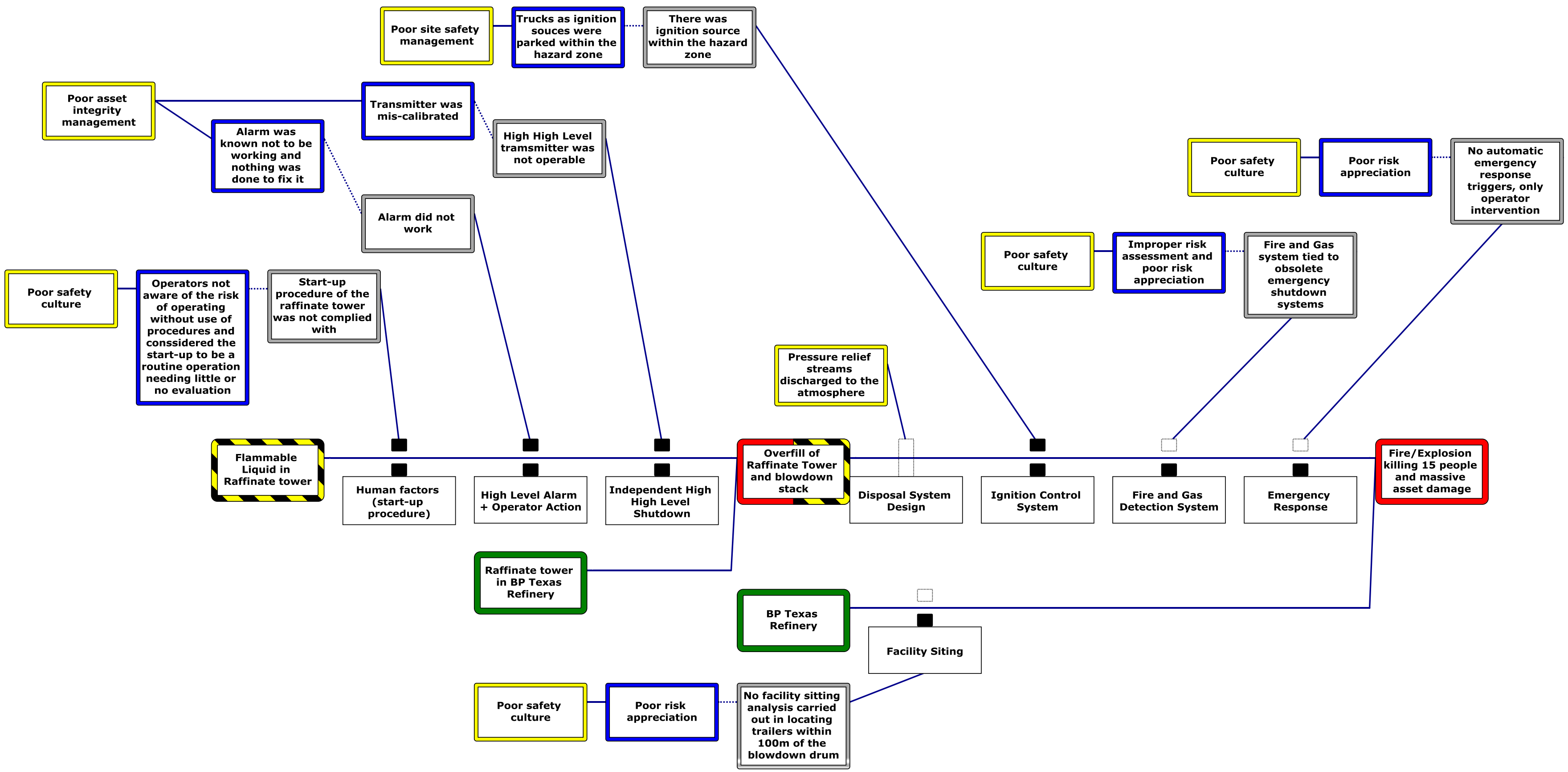


Fig. 4. Tripod beta tree for BP Texas refinery incident

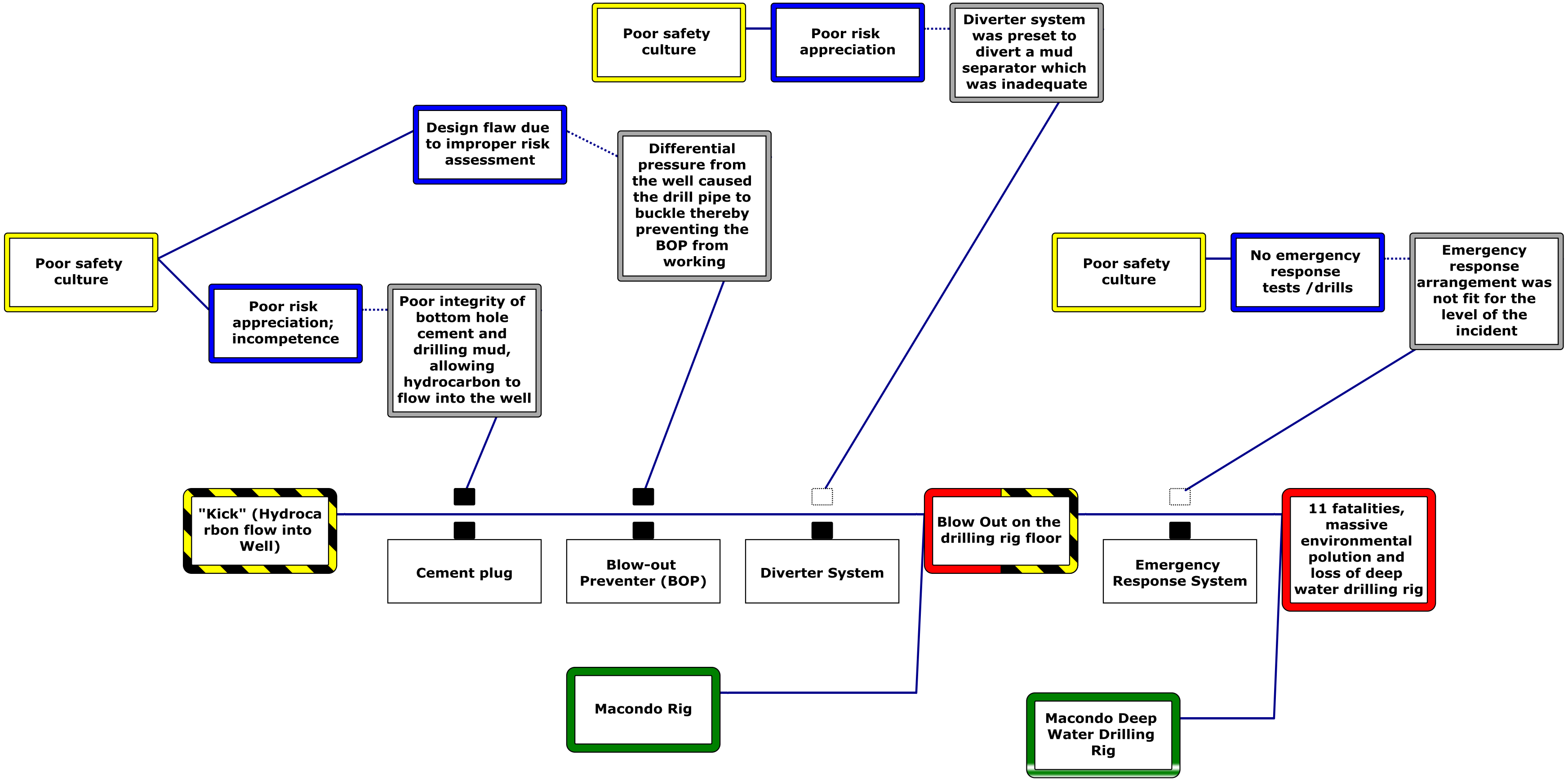


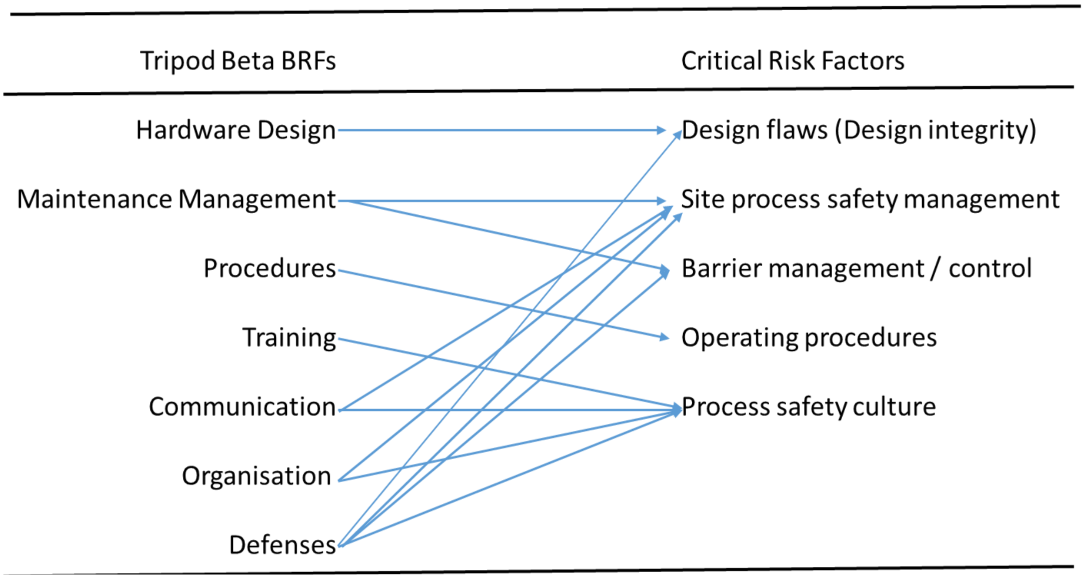
Fig. 5. Tripod beta tree for Macondo incident

Table 3. Mapping of the relevant tripod beta "basic risk factors" in each of the five major accidents

BRFs	Bhopal	Piper-Alpha	Buncefield	BP Texas Refinery	Macondo
Design (DE)					
Hardware (HW)	Improper design of reserve MIC tank Improper design of fixed water curtain to absorb MIC vapour	Wrong positioning of riser safety shutdown isolation valve (SSIV) Improper design of temporary refuge for fire and explosion protection	Poor design - automatic fire and gas detection system not provided on site	Improper design of relief system Improper design of emergency response system	Poor integrity of bottom hole cement and drilling mud Design flaw – differential pressure buckled blow out preventer (BOP) Inadequate mud diverter system Mud separator on drilling floor not fit for purpose (under-designed)
Maintenance Management (MM)	Inventory in MIC tank (degraded barrier) Faulty high temp alarm on MIC tank MIC refrigeration system shutdown MIC relief system shutdown for maintenance Flare system shutdown for repair	Use of condensate evacuation pump (degraded barrier) Inhibited firewater pumps to protect divers without interim mitigation measures	Automatic tank gauging system failed due to known maintenance issues Independent high-high level trip failed due to known maintenance issues	Faulty high level alarm on the raffinate tower Independent high level trip inoperable Inoperable shutdown system (fire and gas systems tied to obsolete shutdown system)	Physical barriers on well not tested for functionality, availability and reliability
House keeping (HK)					
Error-enforcing condition (EC)					
Procedures (PR)	Non-compliance with reserve MIC tank inventory management procedure	Wrong lining of condensate evacuation pump Improper permit-to-work management		Non-compliance with obsolete start-up procedure Non-compliance with access control procedure (ignition source in hazardous area)	Failure to divert well fluid to a safe location on the drilling floor
Training (TR)					Incompetence (many weak signals on disaster not picked up
Communication (CO)		Improper shift handover communication			
Incompatible goals (IG)					
Organisation (OR)	Production over safety consideration (refrigeration system shutdown for economic reasons) Poor site process safety management (inadequate risk assessment for impaired barriers; previous safety audit findings not implemented)	Poor site process safety management (inadequate risk assessments; previous safety audit findings recommending dedicated firefighting system to protect platform not implemented)	Poor site safety management (known failed barriers not addressed	Poor site process safety management (ignition source in hazardous area; poor risk appreciation; previous safety audit findings not implemented)	Poor site process safety management (very poor risk appreciation and risk assessment; ineffective barrier management)

BRFs	Bhopal	Piper-Alpha	Buncefield	BP Texas Refinery	Macondo
Incompatible goals (IG)					
Defenses (DF)	Insufficient protection of people and environment from consequences of MIC hazard release (no emergency response preparedness for Bhopal community	Insufficient protection of people from consequences of major hazard release on site (temporary refuge not designed for fire and explosion protection		Improper design of emergency response system (no automatic emergency response system)	Emergency response arrangement not fit for purpose (not understood and tested

Table 4. Mapping of the tripod beta BRFs to critical risk factors



Darbra et al. [15] that design flaw is one of the major accidents causal factors. Site process safety management in the main, relates to risk assessments and mitigation planning to ensure that there are adequate measures to protect the release of major hazards and limit consequences when the controls are lost. This agrees with the view of Ishola et al. [16] that risk assessment is at the heart of major accident prevention. Barrier management and control relates to all the activities required to ensure that barriers and protection layers are effective and fulfils the functionality at all times. This aligns with the view of Jonassen et al. [17] that effective barrier management is fundamental in preventing major accidents and that inadequate barrier management has been the main cause of major accidents in the oil and gas industry [18]. According to Lauridsen et al. [19], maintenance management plays a vital role in reducing the risk of major accidents and failure or weakening of barriers is a major cause of accidents. Behie et al. [20] supported this view by stating that the influence of various factors such as maintenance backlog, inhibits/bypasses, deferrals, overdue preventive maintenance, management of change programs, permit-to-work practices, conflicting work orders increase the risk of major accidents. According to Nwankwo et al. [21], 30% of major accidents in the oil and gas industry is due to inadequate maintenance. Operating procedures have to do with compliance with the procedures or even obsolescence of the procedures as a critical risk factor in major accidents. This aligns with the opinion of Nwankwo et al. [21] that the major reason why offshore accidents keep occurring is due to operational discipline and compliance with plant operating procedures. Major accident risk is also reduced by proper communication within the teams especially with respect to shift handovers. This aligns with the view of Norazahar et al. [22] that poor communication contributed to the organizational failure in BP Deep Water accident of 2010. Process safety culture represents all aspects of the values, norms, attitudes, perceptions, beliefs, actions and assumptions of any organization related to process safety [23]. The view that process safety culture as one of the critical risk factors in major accident causation aligns with the view of Nwankwo et al. [21] that (process) safety culture is one of the main causes of accidents in major hazard organizations

5. CONCLUSION

The aim of the study was to analyze five iconic accidents from the perspective of the risk factors and gather empirical evidence on the factors that influence the risk of major accidents. The study was conducted in three steps. (1) Review of the major accident reports was carried out. (2) Analysis of the major accidents using Tripod Beta methodology (3) Re-classification of the risk factors from Tripod Beta analysis. Through this study, five risk factors were identified: design flaws, site process safety management (risk assessment), barrier management / control, operating procedures and process safety culture. These findings highlight that major accident risks can accumulate “dangerous” from the impairment of safety-critical barriers and that the operators of petroleum and chemical facilities may be blind-sided to the cumulative risk of the impairments. The findings also highlight the need for a proactive risk assessment tool with the capability to check the health of safety-critical barriers on a real time basis, in an operating plant. The use of Tripod Beta as a tool in accident causation analysis is recommended.

CONSENT

As per University requirement, a written consent was sought and obtained from respondents and subsequently preserved by the Arthurs.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/101097