Canadian Upstream Oil and Gas Industry
Fire and Explosion Incident Analysis

Based on the Investigative Work of
the IRP18 Committee
working with the
University of Calgary
Department of Chemical and Petroleum Engineering

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1. Methodology: Incident Investigation and Analysis

1.1 Gathering Real-life Examples

The Canadian upstream oil and gas industry committee convened to address “Explosive Atmospheres in Wellbores, Vessels, Tanks, and Piping Systems” pursued one aspect of this task by requesting that industry and regulators across Western Canada provide real-life examples of relevant field incidents. This analysis examines 40 incidents gathered by the Committee since June 2003. This group is known as the IRP18 Committee as it is developing an Industry Recommended Practice about this issue. Information about IRP18 is available on the Canadian Petroleum Safety Council website: www.psc.ca/irp_summary/irpvol_18.htm.

1.2 More Incidents Needed

The IRP18 Committee believes that an ongoing effort must be made to identify and document related incidents and close calls. Anecdotal accounts highlight that there are a significant number of events not yet factored into this analysis. The Committee encourages anyone with information about an incident or near miss to submit it through this website or by contacting the Co-chairs:

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1.3 Document Overview

This report discusses the findings and conclusions of the analysis of the 40 case studies gathered by the IRP18 Committee. It also identifies issues that require further research and investigation. The first sections of the document, Understanding the Problem and Applying Accident Theory Models outline how the incidents were assessed. A list of the references used throughout the text is provided in Appendix 7.1. This analysis was done by Walter Tersmette, P. Eng. in consultation with the University of Calgary’s Department of chemical and Petroleum Engineering.
1.4 Understanding the Problem

The development of an effective strategy to address fire & explosive hazards requires extensive knowledge of the items listed below [1]. The incidents on this website were examined according to these criteria:

A. The nature of the “fire and explosion” mechanics and the substances involved.
B. The physical operations being undertaken.
C. The physical site layout, equipment and protection features.
D. The ability of operations personnel to avoid errors.

The findings and conclusions pertaining to each one of these headings are found in the Incident Analysis section of this report.

1.5 Applying Accident Theory Models

The combination of two accident theory models was viewed as the most appropriate way to assess the 40 case studies reviewed in this report. They are: James Reason’s “Swiss Cheese” model [2] and Edward Adam’s “Organizational Responsibility Model” [3].

- Reason’s “Swiss Cheese” model sets out the basic relationships between hazards, defenses and losses. The model identifies three levels of defenses based on organizational, local workplace and human factors. Reason’s theory reminds us that in most situations these defenses are likely in place. However, the theory cautions that there also likely will be holes in these defenses. The number and size of these holes will determine the likelihood of a fire or explosion event.

- Adam’s “Organizational Responsibility Model” takes a more people-oriented approach by examining the activities of the key people in every management system - managers, supervisors and workers. More importantly, this theory reminds us that addressing a problem involves a shift in thinking from “blame the worker or blame management” to “how can we attack the problem simultaneously on all fronts”.

The following diagram illustrates the combination of these models. It is the belief of those involved in this analysis, that creating a sustainable improvement in industry safety depends on understanding each dimension highlighted by these theories.
2 Incident Analysis

2.1 Nature of “Fire and Explosion” Mechanics and the Substances Involved

This section of the report analyzes the incidents based on an expanded view of the fire triangle which resulted from the research done by the University of Calgary’s Department of Petroleum Engineering. A diagram of the Expanded Fire Triangle follows. A detailed explanation of its elements is provided in Expanding the Understanding of the Fire Triangle in Appendix 7.2.

It is widely accepted that you need to eliminate one of the three sides of the fire triangle to eliminate the potential of a fire or explosion. The analysis revealed that this was not as simple as it seemed for these reasons:

1. There was always potential for flammable/combustible substances to be present. More importantly, their properties varied greatly given a range of operating conditions.
2. There was a wide range of oil and gas operations with an equally wide range of circumstances in which oxygen or air could be introduced into the system.
3. There was a wide range of ignition sources, some ignition sources such as static electricity and adiabatic compression, are not well understood and even more difficult to control.
4. Having all three parts of the fire triangle does not guarantee that an explosion will occur. The complex mechanics involved in combustion never guarantees that the same result happens every time. The probability of an explosion occurring in certain situations can be very high; however it is never absolutely certain.

Based on these factors, the identification of fire and explosion hazards can be challenging.
Heat / Ignition Sources
1. Hot Work
2. Other Open Flames (i.e. Flare Stacks, Burners, Torches)
3. Electric Arcs and Sparks (i.e. non-explosion proof equipment)
4. Static Electricity
5. Hot Surfaces
6. Friction and Mechanical Sparks
7. Chemical Reactions and Sparks
8. Spontaneous Combustion
9. Pyrophors (i.e. Iron Sulphide)
10. Pressure / Compression Ignition (Dieseling)
11. Sudden Decompression
12. Catalytic Reactions

Oxygen Sources
Planned Introduction of Air
- Air-based operations
- Air Purging
Unplanned Introduction of Air
- Underbalanced operations
- Swabbing & other operations that create a vacuum
- Pockets of air created during the installation and servicing of Equipment
- Oxidized (Weathered) Hydrocarbons
- Oxidizers
- Chemical Reactions
- On-Site Generated Nitrogen
- Tank Drawdown

Release of Hydrocarbons into Air

Gases
- Natural Gas
- Hydrogen Sulphide
- LPG Gases (Including propane and butane)
- Are the other relevant gases (i.e. hydrogen, acetylene)

Liquids / Vapours
- Crude oil / Condensate
- NGL liquids
- Hydrocarbon based frac fluids
- Gasoline, Diesel & other fuels
- Methanol

Chemicals
- Solvents and cleaning agents
- Special compounded hydraulic fluids & lubricants
- Chemicals used for well servicing and stimulations

Solids
- Lubricants
- Sealants,
- Packings, “O” rings, diaphragms and valve seats
- Paints and Coatings

Preventing Fires and Explosions: Understanding the Fire Triangle
2.2 Key Findings

*It was difficult to conclusively identify ignition sources in many incidents. In these cases, the most likely or apparent ignition source was used. The diagrams following the findings provide a detailed break-down of the air-hydrocarbon mixtures and ignition sources identified in the case studies reviewed. Detailed descriptions of each case study can be found on this website.*

- The ignition of hydrocarbons released into the air was a factor in close to 50% of the incidents. A lack of understanding of ignition sources was evident. Some of the more specific problem areas included:
  - Hydrocarbons released from rig tanks, storage tanks and tank truck vents
  - Hydrocarbons released from closed piping systems while thawing frozen lines
  - Hydrocarbons released from piping and other oilfield equipment
- A lack of understanding of liquid-hydrocarbon properties was apparent in the incidents involving oxidized hydrocarbons and the loading of liquid hydrocarbons.
- A lack of understanding of the requirements for purging a system before proceeding with work was a factor in 9 of the 40 incidents reviewed.
- The inadvertent introduction of air into a system, while a concern, was not as significant a factor as originally believed. The deliberate use of air was identified as a primary contributing factor in only one of the incidents reported. This could be attributed to the extra care and attention used while working with air in operations.

**Fuel – Air Mixtures Identified in Case Studies**
2.3 Conclusions

- The ability to improve fire and explosion safety depends on the industry developing a much better understanding of each arm of the fire triangle.
- The nature and circumstances of the incidents clearly pointed to the need for improved training and awareness. In many cases, there were clear indications that something was not right yet work activities continued with no corrective measures being taken. This suggested an incomplete understanding of the hazards and the need for controls.
- More real-life examples of relevant incidents and close calls are needed. A better understanding of the number and nature of fires and explosions is required to ensure that the conclusions reached in this analysis are valid and can be substantiated.
- Based on the findings, there is a strong need to establish an improved technical understanding in critical areas. Additional research work is required to better understand the following.
  - The ignition of air – hydrocarbon mixtures through compression and decompression.
  - LEL’s of complex hydrocarbon mixtures at subsurface pressures and temperatures.
3 Understanding the Physical Operations

This section of the analysis examines the physical operations undertaken in the incidents studied and the range of organizational factors that contributed to their cause. A detailed summary of each of the factors referred to in the information below is provided in Understanding Organizational Factors in Appendix 7.3.

3.1 Key Findings

- Trucks and trucking operations were a critical factor in 16 of the 40 incidents reviewed as this diagram categorizing the case studies shows.

- The majority of the incidents involved operations [7] that were either routine or where it could reasonably be assumed that personnel should have received some training pertinent to the task. Only a small percentage of the incidents were viewed as novel or high-risk operations.
For the majority of the incidents, the operational control modes \[^8\] were either normal or maintenance operations. Only a small percentage of the incidents occurred during emergency situations.

**Assessment of Operations Control Mode**

<table>
<thead>
<tr>
<th>Control Mode</th>
<th>Drilling and Completions</th>
<th>Operations</th>
<th>Trucking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency Control</td>
<td>5</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Normal Control</td>
<td>15</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Maintenance Control</td>
<td>20</td>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>

Human performance factors include both job planning and field execution activities. Intention storage or retention, meaning the worker knew what needed to be done but failed to act at the appropriate time, was identified as a factor in a large number of events.

**Assessment of Human Factors**

<table>
<thead>
<tr>
<th>Human Factor</th>
<th>Drilling and Completions</th>
<th>Operations</th>
<th>Trucking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workload Limitation</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Steps Not Recalled</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Physical / Mental Limitation</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Unintended Actions</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Critical Step Deliberately Omitted From Plan</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Deliberate Risk Taken</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Task / Situation Not Covered by Procedure</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Undetected Omission</td>
<td>7</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Wrong Design</td>
<td>8</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Training / Experience Insufficient</td>
<td>9</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Procedure Unworkable / Unavailable</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Critical Steps Overlooked</td>
<td>11</td>
<td>11</td>
<td>5</td>
</tr>
</tbody>
</table>

The assessment included an analysis of organizational factors that may have contributed to the incidents. As the graph on the following page shows, added attention to work procedures and job instruction was the highest priority organizational factor in the cases studied. The selection and use of safety and protective equipment as well as the selection and layout of operations equipment were also noteworthy considerations.
3.2 Conclusions

- Both job planning and field execution activities must be considered equally to effectively address the problems encountered.
- To improve the overall level of safety, focus needs to be directed to routine operations; an increased emphasis on maintenance operations is also required.
- The fact that in some cases workers knew what needed to be done but failed to act in a timely manner, suggests that the scope and effectiveness of current training needs examination. This may also point to concerns about the effectiveness of enforcement processes.
- Workers in trucking and maintenance operations are two important target groups for training.
- At the writing of this analysis, there is no mandatory requirement for training Canadian oil and gas industry workers about the hazards and controls related to air – hydrocarbon mixtures.
4 Physical Site Layout, Equipment & Protection Features

To assess physical site layout as well as equipment and protection requirements, an understanding of the workplace factors [11] that contributed to the fire and explosion incidents is required. These are highlighted in the following graph. A more detailed explanation of these factors is provided in Understanding Workplace Factors in Appendix 7.5.

### Assessment of Workplace Factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Drilling and Completions</th>
<th>Operations</th>
<th>Trucking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incompatible Goals</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Housekeeping</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Error-enforcing Conditions</td>
<td>0</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Communication</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Design</td>
<td>15</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Maintenance Management</td>
<td>20</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Defences (PPE/Barriers)</td>
<td>25</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Training and Awareness</td>
<td>30</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Procedures</td>
<td>35</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

#### 4.1 Key Findings

Insufficient information in this area prevented a detailed analysis; however, a number of critical information gaps were identified as a result of the review:

- What steps is industry taking to address the four fire extinguishing principles and how are these steps being applied to each type of operation? These principles apply to both planned operations and unplanned incidents. The four fire extinguishing principles [12] are:
  - A. Controlling the fuel
  - B. Controlling the oxygen
  - C. Controlling the heat (read: ignition sources)
  - D. Inhibiting chemical chain reactions

- What is the role of detection and suppression systems? Some of the factors cited in fire and explosion related literature [13] include:
  - Isolation
  - Cooling combustibles
  - Reaction inhibitor
  - Water (sprays, steam, salts)
  - Gas extinguishants (CO2, Nitrogen, Foams, Soaps & Surfactants)
  - The nature and extent of LEL detection and its role?
4.2 Conclusions

- This examination suggests that an improved understanding of existing procedures and operations controls is required. Even with this, however, the work completed to date suggests that it will not be possible to identify a prescriptive solution that can be universally applied. This is because any solution must be site specific and will be different for each type of operation.

5 The Ability of Operations Personnel to Avoid Errors

Human factors engineering is a growing field and the processes for identifying and applying effective strategies are not well understood. Yet clearly, industry must address the issues related to human performance factors \cite{14}, if the level of safety is to improve. Those considered in this evaluation are further explained in Understanding Human Performance Factors, Appendix 7.5.

5.1 Key Trends

The depth of the information provided for the Case Studies evaluated made it difficult to draw specific findings regarding human performance factors. Nevertheless, some interesting trends were identified:

- As illustrated in the graph on page 12, human performance factors came into play at each level of the operations and included: project management and planning, engineering and design, field supervision and job - task execution.

- There are six basic types of human error \cite{15} as summarized in the figure below. This preliminary analysis highlighted the need to also address human performance factors.
  - The number of knowledge-based mistakes and skill-based errors indicated that worker training must be improved.
  - The number of rule-based errors suggested that adding more rules and procedures may not result in the desired safety improvement.

\begin{center}
\begin{figure}
\centering
\includegraphics[width=\textwidth]{human_performance_factors.png}
\caption{Human Performance Factors}
\end{figure}
\end{center}
A summary of human performance factors identified during a review of the fire and explosion case studies is summarized in the graph below. These performance factors indicate that the main areas requiring attention are improved planning and ensuring those plans are in fact executed.

### Summary of Human Performance Factors

- Insufficient Planning: 39%
- Planned but Forgot: 29%
- Poor Execution: 21%
- Lack of Monitoring: 11%

### 5.2 Conclusions

- The results of this analysis suggest that an improved understanding of human performance factors is required.
- More detailed information relative to human performance factors needs to be sought when future incident information is gathered.

### 6 Closing

The information obtained to date through this analysis reveals that the oilfield workers involved in many of the fire and explosion incidents had a fundamental lack of understanding of the basic principles related to the detection and control of flammable substances. More effective, comprehensive training is required. The issues surrounding work procedure requirements are less clear. What is clear from this review is that it will not be possible to identify a prescriptive solution that can be universally applied. Any solution will need to be operation and role specific and will differ for each level of personnel involved from managers, engineers, field supervisors through to operations staff.
7 Appendices

7.1 References
7.2 Expanding the Understanding of the Fire Triangle
7.3 Understanding Organizational Factors
7.4 Understanding Workplace Factors
7.5 Understanding Human Performance Factors
Appendix 7.1  References

The following references were used to prepare this analysis.


Appendix 7.2   Expanding the Understanding of the Fire Triangle [4]

7.2.1 Behavior of “fuels”
- The behaviors and properties of flammable materials & hydrocarbons including:
  - Gases
  - Flammable and combustive liquids/vapours
  - Chemicals
  - Flammable solids
- Do we understand how well operations affect behaviors and properties at both surface and subsurface conditions:
  - Temperature
  - Pressure
  - Mists and sprays
- Expand discussion on flammable materials – do we also need to discuss the “Fire Tetrahedron” FSM page – 15
- Other substances not considered but may be playing a factor include:
  - Solvents and cleaning agents
  - Special compounded hydraulic fluids and hoses
  - Chemicals used for servicing and stimulations
  - Lubricants
  - Sealants, packing “o” rings, diaphragms and valve seats
- Additional research will be required to address knowledge gaps.

7.2.3 Understanding Ignition Mechanics
- Need to provide a more comprehensive discussion of the range of ignition sources. Key questions include:
  - How do they work? – Are there differences in behavior people need to understand?
  - What can be done to identify and eliminate potential ignition sources?
- The summary of the relevant ignitions sources we need to consider include:
  - Electric arcs and sparks including static electricity
  - Hot surfaces
  - Friction and mechanical sparks
  - Chemical action and sparks
  - Spontaneous combustion
  - Hypergols
  - Pyrophors
  - Adiabatic compressor (dieseling)
  - Sudden decompression
  - Catalytic and other chemical reactions
- The implications of ignition delay also need to be discussed.

7.2.3 Completing the Fire Triangle > oxygen
- Understanding how oxygen gets into the “system”
- Also need to discuss factors with respect to escape of hydrocarbons to mix/combine in air at atmospheric conditions.
Primary process subsystems underlying organizational safety
It will be seen that training is represented as a universal feature rather than as a localized cluster of related items.

A recent review of a number of safety process measures identified five broad clusters, as listed below:

- **safety-specific factors** (for example, incident and accident reporting, safety policy, emergency resources and procedures, off-the-job safety and so on)
- **management factors** (for example, management of change, leadership and administration, communication, hiring and placement, purchasing controls, incompatibilities between production and protection and so on)
- **technical factors** (for example, maintenance management, levels of automation, human-system interfaces, engineering controls, design, hardware and so on)
- **procedural factors** (for example, standards, rules, administrative controls, operating procedures and so on)
- **training** (for example, formal versus informal methods, presence of a training department, skills and competences required to perform tasks and so on).
Appendix 7.4  Understanding Workplace Factors

After observing operations in a number of operating companies and studying their accident records, the following 11 workplace factors were chosen as best reflecting those most likely to contribute to unsafe acts and hence create lost time injuries. They are listed below:

- **Hardware.** This relates to the quality and availability of tools and equipment. Its principal components would include policies and responsibilities for purchase, quality of stock system, quality of supply, theft and loss of equipment, short-term renting, compliance to specifications, age of equipment, non-standard use of equipment and so on.

- **Design.** Design becomes a workplace factor when it leads directly to the commission of errors and violations. There are three main classes of problem: a failure on the part of the designer to provide external guidance (the knowledge gulf); designed objects are often opaque with regard to their inner workings, or to the range of safe actions (the execution gulf); and the failure of designed items to provide feedback to the user (the evaluation gulf).

- **Maintenance management.** This workplace factor is concerned with the management rather than the execution of maintenance activities (that are covered by other workplace factors). Was the work planned safely? Did maintenance work or an associated stoppage cause a hazard? Was maintenance carried out in a timely fashion?

- **Procedures.** This relates to the quality, accuracy, relevance, availability and workability of procedures.

- **Error-enforcing conditions.** These are conditions relating either to the workplace or to the individual that can lead to unsafe acts. They break down into two broad (and, to a degree, overlapping) categories: error-producing conditions and violation-promoting conditions. Error-enforcing conditions, receive influences from many of the “upstream” workplace factors.

- **Housekeeping.** This constitutes a workplace factor when problems have been present for a long time and when various levels of organization have been aware of them but nothing has been done to correct them. Its “upstream” influences include: inadequate investment, insufficient personnel, poor incentives, poor definition of responsibility, and poor hardware.

- **Incompatible goals.** Goal conflicts can occur at any of three levels:
  - Individual goal conflicts caused by preoccupation or domestic concerns
  - Group goal conflicts, when the informal norms of a work group are incompatible with the safety goals of the organization
  - Conflicts at the organizational level in which there is incompatibility between safety and productivity goals.

- **Communications.** Communication problems fall into three categories:
  - System failures in which the necessary channels of communication do not exist, or are not functioning, or are not regularly use
  - Message failures in which the channels exist but the necessary information is not transmitted
  - Reception failures in which the channels exist, the right message is sent, but it is either misinterpreted by the recipient or arrives too late.
• **Organization.** This concerns organizational deficiencies that blur safety responsibilities and allow warning signs to be overlooked. The three main components are: organizational structure, organizational responsibilities and the management of contractor safety.

• **Training.** Problems include the failure to understand training requirements, the downgrading of training relative to operations, the obstruction of training, insufficient assessment of results, poor mixes of experienced the inexperienced personnel, poor task analyses, inadequate definition of competence requirements and so on.

• **Defences.** These comprise failures in detection, warning, personnel protection, recovery, containment, escape and rescue.
Appendix 7.5  Understanding Human Performance Factors \cite{14}, \cite{15}, \cite{16}

<table>
<thead>
<tr>
<th>Nature</th>
<th>Type of Error</th>
<th>Human Performance Issue</th>
<th>Job Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Errors</td>
<td>Knowledge based mistakes</td>
<td>1. Task or situation not covered by procedures or training.</td>
<td>Planning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. A necessary step in unknowingly overlooked.</td>
<td>Retention</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. A wrong decision or an inadequate response to a critical situation.</td>
<td>Execution</td>
</tr>
<tr>
<td></td>
<td>Rule based errors</td>
<td>1. Training or experience was not appropriate for the planned task.</td>
<td>Planning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Work procedure for the planned task was unavailable or unworkable.</td>
<td>Planning</td>
</tr>
<tr>
<td></td>
<td>Skill based ‘slips’ or ‘trips’</td>
<td>1. Actions did not proceed as intended.</td>
<td>Execution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Site personnel were unable to detect or correct a procedural omission.</td>
<td>Monitoring</td>
</tr>
<tr>
<td></td>
<td>Skill based fumble</td>
<td>1. Worker unable to complete required work due to job design or workload related issues.</td>
<td>Planning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Worker unable to complete required work due to physical or mental limitations.</td>
<td>Execution</td>
</tr>
<tr>
<td></td>
<td>Lapse</td>
<td>1. Intention to carry out a planned action not recalled or completed at the appropriate time.</td>
<td>Retention</td>
</tr>
<tr>
<td>Violations</td>
<td>Key step deliberately left out of action plan.</td>
<td></td>
<td>Planning</td>
</tr>
<tr>
<td></td>
<td>Worker deliberately took risk.</td>
<td></td>
<td>Execution</td>
</tr>
</tbody>
</table>