Using HAZOP and LOPA Methodologies to Improve Safety in the Coke Drums Cycles

Authors:
Gilsa Pacheco Monteiro
Francisco Carlos da Costa Barros
Edson Romano Marins
Marcelo Teixeira Halasz

BR Petrobras
Hazards of DCU Hazards of DCU

Batch Operations Batch Operations

Permissive Permissive
Logics Matrix Logics Matrix

Coke Drums Hazard Coke Drums Hazard
Evaluation Process Evaluation Process
(General View) (General View)

Coke Drum Coke Drum
Switching Switching

HAZOP HAZOP
Study Study
Selecting HAZOP scenarios for LOPA

Coke Drums HAZOP Study Coke Drums HAZOP Study
Integrated HAZOP and LOPA Analysis

Coke Drums Coke Drums
LOPA Study LOPA Study
(Main Results) (Main Results)
HAZARDS OF DCU BATCH OPERATIONS

The Coke Drum Switching

The Problem:
“The batch stage of the operation (drum switching and coke cutting) presents unique hazards and is responsible for most of the serious accidents attributed to DCUs”.


<table>
<thead>
<tr>
<th>Step</th>
<th>Duration (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling</td>
<td>20.0</td>
</tr>
<tr>
<td>Purge with steam</td>
<td>1.5</td>
</tr>
<tr>
<td>Quench</td>
<td>6.0</td>
</tr>
<tr>
<td>Drain</td>
<td>1.5</td>
</tr>
<tr>
<td>Unhead</td>
<td>1.0</td>
</tr>
<tr>
<td>Decoke</td>
<td>3.0</td>
</tr>
<tr>
<td>Rehead and Test</td>
<td>2.0</td>
</tr>
<tr>
<td>Warm-up</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Why does drum switching create unique hazards, resulting in relatively frequent and serious accidents?

- The batch operations involve a series of opening and closing of valves by the operators;
- The high frequency of the drum sequence contributes to increase the likelihood of a human error.
- The inadvertent valve operation can lead to loss of containment scenarios with: release of hydrocarbon from an in-service or open drum to atmosphere, fire, release of H2S.
- High operator exposure during drum sequence.

Risk of operating:
- The wrong valve on the right drum
- The right valve on the wrong drum
(A unit with more than one pair of drums presents even more risks.)

The Goal:
Improve operator safety, reducing the risk of loss of containment!

How?
How to improve safety in the coke drums cycles?

- With these logics, some conditions must be met to allow a valve to be opened or closed.

- These conditions can be based either on other valves positions or on process parameter values (e.g., a permissive logic where the coke drum pressure must be lower than a pre-determined value to allow a valve to open).

- All normally operated sequence valves are automated and the instrumentation allows to verify valves position.

---

Permissive Logics Matrix

<table>
<thead>
<tr>
<th>Valve Command</th>
<th>Valve and Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open HV-002A</td>
<td>Drilling Stand (Docking)</td>
</tr>
<tr>
<td></td>
<td>O</td>
</tr>
<tr>
<td>Open HV-007A</td>
<td>B</td>
</tr>
<tr>
<td>Close HV-007A</td>
<td>Out of drum</td>
</tr>
</tbody>
</table>

HV-001 A: Switch valve
HV-002 A: Feed from the heater to coke drum A
HV-003 A: Coke drum overhead to fractionation tower first blockage
HV-004 A: Coke drum overhead to fractionation tower second blockage
HV-007 A: Automatic top head valve
HV-008 A: Automatic bottom head valve
HV-009A / 010A / 027 A: Coke drum vent valves
PT-016 A: Coke drum pressure
HAZARDS OF DCU BATCH OPERATIONS

Permissive Logics Matrix (PLM)

<table>
<thead>
<tr>
<th>Valves and Instruments</th>
<th>Valve Command</th>
<th>Drilling Steam (I-cooking)</th>
<th>HV-001A</th>
<th>HV-002A</th>
<th>HV-003A</th>
<th>HV-004A</th>
<th>HV-007A</th>
<th>HV-008A</th>
<th>HV-009A / 010A / 027A</th>
<th>PT-016A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open HV-002A</td>
<td>B</td>
<td>O</td>
<td>O</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>O</td>
<td>&lt;9.8 kPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open HV-007A</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>O</td>
<td></td>
<td></td>
<td></td>
<td>&lt;9.8 kPa</td>
<td></td>
</tr>
<tr>
<td>Close HV-007A</td>
<td>Out of drum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>O</td>
</tr>
</tbody>
</table>

HV-001 A: Swith valve
HV-002 A: Feed from the heater to coke drum A
HV-003 A: Coke drum overhead to fractionation tower first blockage
HV-004 A: Coke drum overhead to fractionation tower second blockage
HV-007 A: Automatic top head valve
HV-008 A: Automatic bottom head valve
HV-009A / 010A / 027 A: Coke drum vent valves
PT-016 A: Coke drum pressure

The team responsible to build the matrix included: experienced DCU operators, automation specialists and process engineers involved in the DCU design and operation.

This matrix was developed during brainstorming sessions.

• What type of incidents these logics can prevent?
• What is the availability or the PFD (Probability to Fail on Demand) acceptable for these logics?
• How safe is enough?

HAZOP and LOPA
This hazard evaluation procedure was applied to a Petrobras DCU during Basic Design Phase.

Preferably, the experts responsible for the matrix development integrate the HAZOP team.

Preferably, HAZOP and LOPA are performed in an integrated approach, with only one facilitated session.

**Main Results:**
- The permissive logics defined in the matrix were assessed using a risk basis through HAZOP;
- The logics that need to be defined as SIF (Safety Instrumented Function) were identified with a target SIL (Safety Integrity Level).
Understanding HAZOP through the Anatomy of a Process Incident

- **NORMAL**: All process hazards are contained and controlled.
- **ABNORMAL**
- **EMERGENCY**: 1) Keep the facility in normal operation mode.
  2) Optimize production.

**Key Systems:**
1. Primary Containment (pipes & vessels)
2. BPCS (Basic Process Control System)
3. Process Equipment
4. Operational Procedures

**Goals:**
1) Keep the facility in normal operation mode.
2) Optimize production.
Coke Drum A inlet feed isolation valve inadvertently closed during Filling step

Overpressure of the Charge Heater with potential for loss of containment and fire.

Loss Event

Operation Modes

NORMAL

ABNORMAL

EMERGENCY

DEVIATION
("No Flow" of Heater effluents)

Goals:
1) Return to Normal Operation Mode
2) If it’s not possible, bring the plant to a safe state (shutting down the unit before a loss event occurs).
Coke Drum A inlet feed isolation valve inadvertently closed during Filling step.

Overpressure of the Charge Heater with potential for loss of containment and fire.

**Operation Modes**

- **NORMAL**
- **ABNORMAL**
- **EMERGENCY**

**DEVIAITION**

“No Flow” of Heater effluents to Coke Drum

**Goals:**

The goal changes to the minimization of injuries and losses.

**MITIGATE**
PREVENTIVE SAFEGUARDS: any device, system or action that can interrupt the chain of events following an initiating cause and prevents the loss event from ensuing.

MITIGATIVE SAFEGUARDS: the likelihood of occurrence of the loss event.

the severity of consequences.
Coke Drum A inlet feed isolation valve inadvertently closed during Filling step

Overpressure of the Charge Heater with potential for loss of containment and fire.

Loss Event

Operation Modes

NORMAL

ABNORMAL

EMERGENCY

Possible safeguards for this scenario:

• Permissive logic that allows the closure of Coke Drum A feed isolation valve only if the Switch valve is turned to Coke Drum B.

• PSV located on Heater outlet, sized for the blocked flow scenario;

• Heater Low Low Flow Trip
For the switch valve inadvertently switched into a closed inlet isolation valve, some permissive logics were also defined in order to avoid dead-heading the heater.
For each “NODE”:
(each step of drum sequence)

**DEVIATION** → **CAUSE** → **CONSEQUENCES** → **SAFEGUARDS**

- **Parameter**
- **Temperature**
- **Guide-Word**
- **More**

**Deviations**

- High Temperature
- Low Temperature
- High Level
- Low Level
- High Pressure
- Low Pressure
- High Flow
- Low Flow
- No Flow
- Reverse Flow
- Contamination

**Process Parameter + Guide-Word = Deviation**
“NODES” Definition:

- Each step of the drum sequence is a “NODE” of analysis.
- The node is defined considering the drum and all alignments needed to perform that phase.
- When explaining the design intention of the node, the valves position to perform the step under analysis are clearly defined.

Node – Filling Step: from the switch valve, passing through the coke drum, as far the Fractionator, including: the anti-foaming and quench injection lines.
For each “NODE”:
(Each step of drum sequence)

Qualitative Approach

<table>
<thead>
<tr>
<th>DEVIATION</th>
<th>CAUSE</th>
<th>CONSEQUENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAFEGUARDS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- How safe is enough?
- How many safeguards are needed?
- What is the SIL target required for the SIFs?

Semi-Quantitative Approach

LOPA
Layer of Protection Analysis
The worse the consequence, the lower the tolerance for the incident!

**CONSEQUENCE SEVERITY CATEGORY**

The IPL provides a Risk Reduction Factor (RRF).

**F_{SCENARIO} \leq F_{TOLERABLE}**

IPL = Independent Protection Layer

PFD = Probability to Fail on Demand
**COKE DRUMS LOPA STUDY**

**CONSEQUENCE**

**SEVERITY**

CATEGORICAL = 4

*(Fatality within the unit)*

**F** TOLERABLE = 1 in 10,000 years

---

**Coke Drum A inlet feed isolation valve inadvertently closed during Filling step**

**F** CAUSE = 1 in 10 years

**PFD** = 0.01

**RRF** = 100

---

**PSV**

**Permissive Logic** (in the BPCS)

**PFD** = 0.1

**RRF** = 10

---

**Overpressure of the Charge Heater with potential for loss of containment and fire.**

**F** Scenario = **F** CAUSE * PFD\(_1\) * PFD\(_2\) = 1 in 10,000 years

**F** Scenario = **F** CAUSE * PFD\(_1\) = 1 in 1,000 years
COKE DRUMS LOPA STUDY

CONSEQUENCE SEVERITY CATEGORY = 4
(Fatality within the unit)

FTOLERABLE = 1 in 10,000 years

Permissive Logics (in the BPCS)

Rapid vaporization with potential overpressure on drum and Coke Drum A Quench Water Valves inadvertently opened in an “in-service” drum

PFD=0,1 RRF = 10

• Risk reduction required of two orders of magnitude to eliminate Risk Gap!

F_scenario = F_cause * PFD_1 = 1 in 100 years
SIF = Prevents the drum quench water valve from opening if drum bottom temperature is too high.  
SIL target = SIL 2 (PFD of 0.01)

**COKE DRUMS LOPA STUDY**

**CONSEQUENCE**

**SEVERITY**

**CATEGORY = 4**

(Fatality within the unit)

**F_{TOLERABLE} = 1 in 10,000 years**

SIF: Prevents the drum quench water valve from opening if drum bottom temperature is too high.

**SIL target = SIL 2 (PFD of 0.01)**

Rapid vaporization with potential overpressure on drum and Coke Drum A Quench Water Valves in an “in-service” drum.

**Permissive Logics (in the BPCS)**

PFD = 0.1

**RRF = 10**

**CAUSE SCENARIO**

F_{CAUSE} = 1 in 10 years

**SIF (in the SIS)**

PFD = 0.01

**RRF = 100**

**F_{Scenario} = F_{Cause} * PFD_1 * PFD_2 = 1 in 10,000 years**
**What does SIL mean?**

<table>
<thead>
<tr>
<th>SIL</th>
<th>AVAILABILITY REQUIRED (%)</th>
<th>PFD (Probability to fail on demand)</th>
<th>RRF = 1/PFD (Risk Reduction Factor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90,00 - 99,00</td>
<td>0,01 – 0,1</td>
<td>100 – 10</td>
</tr>
<tr>
<td>2</td>
<td>99,00 - 99,90</td>
<td>0,001 – 0,01</td>
<td>1000 – 100</td>
</tr>
<tr>
<td>3</td>
<td>99,90 – 99,99</td>
<td>0,0001 – 0,001</td>
<td>10.000 - 1000</td>
</tr>
<tr>
<td>4</td>
<td>&gt; 99,99</td>
<td>0,00001 – 0,0001</td>
<td>100.000 – 10.000</td>
</tr>
</tbody>
</table>

The SIL (Safety Integrity Level) indicates the availability or the PFD of a SIF (Safety Instrumented Function) when a process demand occurs.

E.g.: The acceptance of a SIL 1 means that the risk is sufficiently low that a function with an availability of 90% (or 10% chance of failure) is acceptable.
A SIS (Safety Instrumented System) is a combination of sensors, logic solvers and final elements that performs one or more safety instrumented functions (SIFs), which are installed for the purpose of mitigating the hazard or bringing the process to a safe state in the event of a process upset.

(*) The SIS is used for any process in which the process hazard analysis has determined that the mechanical integrity of the process equipment, the process control, and other protective equipment are insufficient to mitigate the process hazard.

SISs are covered by:


ANSI/ISA 84.00.01-2004 (IEC 61511 modified)

ISA TR84.00.04.04 – 2005 – Guidelines for the Implementation of ANSI/ISA 84.00.01-2004 (IEC 61511 modified)

Do I have to apply LOPA to all HAZOP scenarios?

- One way to define the events of interest for LOPA is to determine the scenarios that result in release of hydrocarbon and H₂S from an in-service or open drum during switch and unheading.

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>Initiating Events</th>
</tr>
</thead>
</table>
| In-Service     | - Vent valve opening  
                 - Drain valve opening  
                 - Top head opening  
                 - Bottom head opening |
| Open Drum      | - Overhead to Fractionator valve opening  
                 - Inlet feed valve opening  
                 - Blowdown valve opening  
                 - Condensate Vessel valves opening |

When to move beyond qualitative risk judgment?

- Besides this list, Petrobras Coke drums analysis identified some other initiating events, not necessarily directly related to hydrocarbon release to atmosphere.

### Other Initiating Events Identified with Petrobras Coke Drums Analysis

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Quench water valve opening to an in-service-drum</td>
<td>(leading to a coke drum overpressure due to the rapid water vaporization, with potential for loss of containment, hydrocarbon leakage and equipment damage);</td>
</tr>
<tr>
<td>- Coke drum inlet feed valve closing</td>
<td>(with potential overpressure to the upstream segment, which includes the heater; loss of containment, fire and equipment damage);</td>
</tr>
<tr>
<td>- Switch feed valve inadvertently turned to a blocked segment</td>
<td>(out-of service drum “B” or coke drums by-pass line to fractionation tower);</td>
</tr>
<tr>
<td>- Coke drum to Fractionator valve closing</td>
<td>(with potential drum overpressure);</td>
</tr>
<tr>
<td>- Coke drum to Blowdown valve opening</td>
<td>(with potential Blowdown System overpressure);</td>
</tr>
</tbody>
</table>
### Other Initiating Events Identified with Petrobras Coke Drums Analysis

<table>
<thead>
<tr>
<th>Event Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>coke cutting operational error, raising the drilling stem out of the drum</td>
<td>potentially exposing the operator to high pressure water jet;</td>
</tr>
<tr>
<td>out-of-service coke drum safety relief valve leaking</td>
<td>(with potential hydrocarbon release to the atmosphere from the</td>
</tr>
<tr>
<td></td>
<td>fractionation tower, which this relief valve discharge is aligned to);</td>
</tr>
<tr>
<td>high pressure drilling water delivery hose failure</td>
<td></td>
</tr>
</tbody>
</table>

- A similar solution was recommended during HAZOP to the water hose disconnection or rupture scenario.

---

**Decoking Hose Failure - A Safety Threat**

There was a near miss incident in our coker unit about a year back. One of our decoking water hoses had failed from its top rotary joint end and fell down on the cutting platform. There was no indication that it was about to rupture (that’s why “near miss”). The hose had failed from its coupling portion due to improper bonding/curing of the glue used. Fortunately, nobody was beneath the falling hose when it failed and a major accident got avoided. We replaced the hose with a new one of another manufacturer, in addition to providing 2 strong safety clamps with chains fastened to the top flange to prevent falling down for the other potential hoses.

Anand C Haridas/JAMNAGAR/RIL@RELIANCE  
mailto: anand_c_haridas@ril.com
Do I have to apply LOPA to all HAZOP scenarios?

- Qualitative Study (E.g.: HAZOP scenario)
  - Is consequence severity > III?
    - Yes: LOPA
    - No: Complete Study based on qualitative judgment

When to move beyond qualitative risk judgment?

- Is frequency of consequence > 1/10 years?
  - Yes: Is a SIL required for one or more SIFs?
    - Yes: Complete Study based on qualitative judgment
    - No: Complete Study based on qualitative judgment
  - No: Complete Study based on qualitative judgment

### Other Results

**Typical scenario when there are multiple coke drums with its PSVs discharge aligned to Blowdown system or to Fractionator.**

Possible backflow of blowdown (or fractionator) vapors to an open drum, leading to release of hydrocarbons / H₂S with potential fire.

<table>
<thead>
<tr>
<th>Deviations</th>
<th>Frequency Evaluation</th>
<th>Possible Effects</th>
<th>Conseq. Severity</th>
<th>RRF Required</th>
<th>Safeguards</th>
<th>IPI (Independent Protection Layers)</th>
<th>IPL Type</th>
<th>RRF</th>
<th>Overall RRF</th>
<th>RRF Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse Flow</td>
<td>Open Drum PSV leaking</td>
<td>100</td>
<td>4</td>
<td>100</td>
<td>- Provide limit switches for the block valves located on PSV discharge and a permissive logic that prevents these blockages from opening if the top head valve is opened.</td>
<td>BPCS</td>
<td>10</td>
<td>100</td>
<td>TR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Provide a permissive logic that prevents the top and bottom head valves from opening if the blockages located on PSV discharge are opened.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Operator by procedure closes the block valves located on PSV discharge before opening the drum.</td>
<td>Operat. Procedure</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Other design alternative:**

- Motorized block valves located on the discharge of the coke drum PSVs.
Integrated HAZOP and LOPA/SIL Analysis

Only one facilitated session is required and only one database is generated.

The integrated approach is less time consuming and more consistent, since the HAZOP and LOPA teams are the same.
Conclusions

• “No one system has proven effective in eliminating all incidents associated with incorrect valve activation due to mistaken coke drum operation.”


• However, the definition of a set of permissive logics that prevent inadvertent valve operations during the coke drums batch steps has been an improvement adopted by some refiners. The set of logics are defined based on operational procedures, during brainstorming sessions involving a multidisciplinary team.

• HAZOP and LOPA methodologies can provide a risk decision basis to assess the set of permissive logics, defining what accident scenarios these logics can prevent, the amount of risk reduction needed to achieve a scenario tolerable frequency of occurrence and the availability or SIL required for those logics which will be defined as SIFs.

• The integrated HAZOP and LOPA Analysis is presented as a more consistent and less time consuming approach.