Safety Aspects of Floating LNG: Preliminary Inherent Safer Design Selection of Liquefaction Process


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67th Canadian Chemical Engineering Conference
Outline

• What is Inherently Safer Design (ISD)?
• General Principles of ISD.
• Need for ISD in Current industry and FLNG
• Hazards associated with FLNG
• Application of step-wise methodology for selection of Inherently Safer Design of Natural Gas liquefaction process
• Discussion and Result
• Conclusion
• Future Scope for application
What is Inherently Safer Design?

- What is “Inherent”? 
- Inherently Safer Design is to eliminate or minimize hazards rather than control hazards

- This is best done at the very beginning of a project
Hazard Reduction Strategy (Principles of ISD)

- Minimization
- Moderation
- Simplification
- Substitution

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Need for ISD in Current industry

Bhopal Disaster in 1984

Bhopal Disaster in 1984
Need for ISD in Current Industry

Flixborough Disaster in 1974

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Need for ISD in Current industry

Piper Alpha in 1988

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Need for ISD in Current industry

Fukushima Incident in 2011

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Need for ISD in FLNG Structure

- Offshore structure
- Limited escape space
- Limited plot area
- Complexity
- Not much operational experience
- Remote location
- Many Hazards involved

Need for ISD in FLNG Structure (Hazards Associated)
Layer of protection analysis (LOPA) for FLNG

1) Hazards elimination and minimization
   (Inherently Safer Design)

2) Prevention (Reduction of likelihood)

3) Detection and control (Limitation of scale, intensity and duration)

4) Consequences mitigation (safeguards for effects)

5) Emergency response arrangements
Step-wise Methodology for ISD

1. List out all technologies of interest
2. Identify the chemicals involved in each technology
3. Identify the process hazards characteristics in each technology
4. Calculation of Inherent Process Safety Index ($I_{PSI}$)
5. Calculation of Inherent Chemical Safety Index ($I_{CSI}$)
6. Calculation of Total Inherent Safety Index ($I_{TSI}$)
7. Comparison of $I_{TSI}$ for all technologies
8. Evaluate the safety sub-indices for chemicals and process hazards for each technology
9. Selection of most Inherently Safer process with lowest $I_{TSI}$
### ISD Application to Natural Gas Liquefaction Processes

#### Propane Mixed Refrigerant (C3MR) Process

- **Liquefied Natural Gas (LNG)**
  - \( T = -160 ^\circ C, P = 1.1 \text{ Bar} \)

### Calculation of Inherent Process Safety Index (I\(_{PSI}\))

<table>
<thead>
<tr>
<th>SI Code</th>
<th>SI Name</th>
<th>Severity Score</th>
<th>Compressor and Cooler (Propane)</th>
<th>Precooling System</th>
<th>Compressor and Cooler (MR System)</th>
<th>MCHE</th>
<th>MR Vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_p )</td>
<td>Pressure SI</td>
<td>0 - 4</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>( l_T )</td>
<td>Temperature SI</td>
<td>0 - 4</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>( l_{PM} )</td>
<td>Process mode SI</td>
<td>1 - 3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( l_v )</td>
<td>Boiling point SI</td>
<td>0 - 3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

**Inherent process safety index**:

\[ I_{PSI} = 30 + 24 + 39 = 93 \]

**Total Inherent Process Safety Index (I\(_{PSI}\))**:

\[ I_{PSI} = 205 \]

### Calculation of Inherent Chemical Safety Index (I\(_{CSI}\))

#### Natural Gas

- **Methane** (95%)
- **Ethane** (5%)

#### Propane Mixed Refrigerant

- **Propane** (70%)
- **Ethane** (20%)
- **Methane** (10%)

<table>
<thead>
<tr>
<th>SI Code</th>
<th>SI Name</th>
<th>Severity Score</th>
<th>(95%) Methane</th>
<th>(5%) Ethane</th>
<th>Propane (70%)</th>
<th>Ethane (20%)</th>
<th>Methane (10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_c )</td>
<td>Corrosiveness SI</td>
<td>0 - 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( l_{EL} )</td>
<td>Exposure limit SI</td>
<td>0 - 4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( l_T )</td>
<td>Toxic SI</td>
<td>0 - 4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( l_R )</td>
<td>R-phrases SI</td>
<td>0 - 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( l_F )</td>
<td>Flammability SI</td>
<td>0 - 4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>( l_{RM} )</td>
<td>Chem. React. SI</td>
<td>0 - 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Inherent chemical safety index**:

\[ I_{CSI} = 6.65 + 0.3 = 6.95 \]

**Total Inherent Chemical Safety Index (I\(_{CSI}\))**:

\[ I_{CSI} = 19.05 \]

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### ISD Application to Natural Gas Liquefaction Processes

**Calculation of Inherent Process Safety Index (IPSI)**

<table>
<thead>
<tr>
<th>SI Code</th>
<th>SI Name</th>
<th>Severity Score</th>
<th>MCHE</th>
<th>Compressor and Cooler (MR System)</th>
<th>Cooled MR Vessel</th>
<th>Warm MR Vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 Comp.</td>
<td>3 HEs</td>
<td></td>
</tr>
</tbody>
</table>

**Calculation of Inherent Chemical Safety Index (ICS)**

<table>
<thead>
<tr>
<th>SI Code</th>
<th>SI Name</th>
<th>Severity Score</th>
<th>Natural Gas</th>
<th>Mixed Refrigerant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(95% Methane)</td>
<td>(5% Ethane)</td>
</tr>
<tr>
<td>I_p</td>
<td></td>
<td></td>
<td>0 - 2</td>
<td>0</td>
</tr>
<tr>
<td>I_T</td>
<td></td>
<td></td>
<td>0 - 4</td>
<td>1</td>
</tr>
<tr>
<td>I_PM</td>
<td></td>
<td></td>
<td>0 - 4</td>
<td>2</td>
</tr>
<tr>
<td>I_v</td>
<td></td>
<td></td>
<td>0 - 4</td>
<td>0</td>
</tr>
<tr>
<td>I_MS</td>
<td></td>
<td></td>
<td>0 - 4</td>
<td>0</td>
</tr>
<tr>
<td>I EQ</td>
<td></td>
<td></td>
<td>0 - 4</td>
<td>0</td>
</tr>
<tr>
<td>I_T</td>
<td></td>
<td></td>
<td>0 - 4</td>
<td>1</td>
</tr>
<tr>
<td>I_R</td>
<td></td>
<td></td>
<td>0 - 4</td>
<td>0</td>
</tr>
<tr>
<td>I_F</td>
<td></td>
<td></td>
<td>0 - 4</td>
<td>4</td>
</tr>
<tr>
<td>I_RM</td>
<td></td>
<td></td>
<td>0 - 4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Chemical severity index</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inherent chemical safety index</td>
<td>6.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Inherent Chemical Safety Index (ICSI)</td>
<td>13.05</td>
</tr>
</tbody>
</table>
ISD Application to Natural Gas Liquefaction Processes

Nitrogen Refrigerant Process

<table>
<thead>
<tr>
<th>SI Code</th>
<th>SI Name</th>
<th>Severity Score</th>
<th>MCHE</th>
<th>Nitrogen Cold Box</th>
<th>Sub-cooler (HE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC</td>
<td>Corrosiveness</td>
<td>0 - 4</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>IL</td>
<td>Exposure limit</td>
<td>0 - 4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>IF</td>
<td>Toxic SI</td>
<td>0 - 4</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>IR</td>
<td>R-phrases</td>
<td>0 - 3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>IIC</td>
<td>Flammability</td>
<td>0 - 3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>IIR</td>
<td>Chemical reaction</td>
<td>1 - 3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>IP</td>
<td>Pressure SI</td>
<td>0 - 4</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>IT</td>
<td>Temp. SI</td>
<td>0 - 4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>IPM</td>
<td>Pro. mode SI</td>
<td>1 - 3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>IV</td>
<td>Boiling point SI</td>
<td>0 - 3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>IMS</td>
<td>Material phase SI</td>
<td>1 - 3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>IET</td>
<td>Eq. safety SI (ISBL)</td>
<td>0 - 4</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>IIP</td>
<td>Inventory SI</td>
<td>0 - 5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>I</td>
<td>Total Chemical severity index</td>
<td>14</td>
<td>15</td>
<td>13</td>
<td>15</td>
</tr>
</tbody>
</table>

Inherent Chemical Safety Index (I_{CSI}) = 6.65

Inherent process safety index (I_{Psy}) = 14

Total Inherent Process Safety Index (I_{Psy}) = 85
## Discussion and Result

### Comparison of Total Inherent Safety Index (I\textsubscript{SI}) FLNG liquefaction technologies

<table>
<thead>
<tr>
<th>FLNG liquefaction technologies</th>
<th>C\textsubscript{3}MR</th>
<th>SMR</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Inherent Chemical Safety Index (I\textsubscript{CSI})</td>
<td>19.05</td>
<td>13.05</td>
<td>6.95</td>
</tr>
<tr>
<td>Total Inherent Chemical Safety Index (I\textsubscript{PSI})</td>
<td>205</td>
<td>102</td>
<td>85</td>
</tr>
<tr>
<td>Total Inherent Safety Index (I\textsubscript{SI}) (Round figure)</td>
<td>224.05</td>
<td>115.05</td>
<td>91.95</td>
</tr>
<tr>
<td>Total Inherent Safety Index (I\textsubscript{SI}) (Round figure)</td>
<td>224</td>
<td>115</td>
<td>92</td>
</tr>
</tbody>
</table>

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Conclusion

• FLNG is offshore structure and hence very crucial from safety point view.
• ISD methodology is a good approach for the upcoming projects to select the preliminary inherently safer design amongst many technologies available.
• It generally applies at the pre-design stage and hence many later cost and safety concerns can be avoided in advance.
• Mathematical evaluation
• Nitrogen Refrigerant Process is the most inherently safer process comparatively for Natural Gas Liquefaction for FLNG.
Future Scope for application

- ISD can be implemented to any field
- A software can be developed to help performed this evaluation at research stage with ease
- Safety indices can be customized based on need as they are limited to relative comparison amongst alternatives
References


- **Edwards & Lawrence**


- **Hurst, L. C.** (February 2008). The Terrorist Threat to Liquefied Natural Gas: Fact or Fiction? Washington, Maryland USA: Institute for the Analysis of Global Security (IAGS).


- **Kletz, T. A.** 1978. What you don’t have, can’t leak. *Chemistry and Industry*, 6, 287-292

- **Kletz, 1996**


• Prevention is better than Cure...
Similarly Inherently Safer Design is always better than operating and managing hazards...

Thank you &

Email ID: Dhaval.p.eng@gmail.com