Introduction to Natech risk:
Damage mechanisms, lessons learned and risk reduction

Elisabeth Krausmann
Collapse of 115 m stack at a refinery
- 63 product pipelines cut and heating unit damaged
- Fire in the crude oil unit; block valves unreachable to shut off fuel flow

Liquid sloshing of metallic tank roofs due to earthquake and creation of sparks
- Naphtha ignition
- Leak through damaged flange: flow through drainage channels and fire spread to other tanks

Ammonia venting at neighbouring fertilizer plant

Lifelines (water, power, communications) and many response personnel unavailable
Lessons-learning process:

- **Accident investigation**
  - why and how did the accident happen?

- **Accident reporting**
  - minimum of information according to a pre-defined set of criteria (incl. near misses)

- **Data collection**
  - relevant and structured information on accident and safety measures

- **Data analysis**
  - detect accident causation patterns (should include mitigation)

- **Generation of lessons learned and implementation**
  - technical/organisational LL
The quality of information in industrial accident databases is not uniform and exhibits different levels of detail and accuracy. The level of detail is particularly non-uniform for Natech accidents.
<table>
<thead>
<tr>
<th>No</th>
<th>Date</th>
<th>Country</th>
<th>Natural Hazard</th>
<th>Site</th>
<th>Ntech ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1923</td>
<td>Japan</td>
<td>Tokyo Earthquake</td>
<td>Yokosuka Naval Base</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>1989/09/20</td>
<td>United States</td>
<td>Hurricane Hugo</td>
<td>Amerada Hess Oil Co.</td>
<td>55</td>
</tr>
<tr>
<td>3</td>
<td>1994/01/17</td>
<td>United States</td>
<td>Northridge Earthquake</td>
<td>ARCO-Four Comers Pipeline</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>1994/02/22</td>
<td>South Africa</td>
<td>Merriespruit rain</td>
<td>Harmony Gold Mine</td>
<td>56</td>
</tr>
<tr>
<td>5</td>
<td>1994/07/24</td>
<td>United Kingdom</td>
<td>Lightning</td>
<td>Pembroke Refinery</td>
<td>47</td>
</tr>
<tr>
<td>6</td>
<td>1994/10/19</td>
<td>United States</td>
<td>San Jacinto River Flood</td>
<td>Pipeline</td>
<td>45</td>
</tr>
<tr>
<td>7</td>
<td>1995/10/24</td>
<td>Indonesia</td>
<td>Lightning</td>
<td>Pertamina Cilacap Refinery (Unit Pengolahan IV)</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>1998/02/27</td>
<td>Ecuador</td>
<td>Landslide</td>
<td>Trans-Ecuadorian Oil Pipeline</td>
<td>38</td>
</tr>
<tr>
<td>9</td>
<td>1998/04/25</td>
<td>Spain</td>
<td>Dofana Disaster/The Los Frailes tailings dam failure/Aznalcollar Disaster/Guadiamar Disaster</td>
<td>Los Frailes mine</td>
<td>27</td>
</tr>
<tr>
<td>10</td>
<td>1998/09/26</td>
<td>United States</td>
<td>Hurricane Georges</td>
<td>Chevron Pascagoula Refinery</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>1999/08/17</td>
<td>Turkey</td>
<td>Kocaeli Earthquake</td>
<td>TUPRAS Izmit Refinery</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>1999/08/17</td>
<td>Turkey</td>
<td>Kocaeli Earthquake</td>
<td>AKSA Acrylic Fiber Production Plant</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>2000/01/30</td>
<td>Romania</td>
<td>Heavy rainfall</td>
<td>Aurul Mine</td>
<td>28</td>
</tr>
</tbody>
</table>
- **Natural hazard**
  - Type and date
  - Location
  - Occurrence
    - Triggering hazard, parameters
  - Consequences

- **Industrial site**
  - Type and industrial activity
  - Location
  - Site description
  - Operator

- **Attachments**
  - Documents
  - Reference materials

- **Natech event**
  - **Event sequences**
    - Units, events (NH-specific initiating events), contributing factors, substances involved
  - **Emergency response**
    - Response planning, response to natural hazard, response to Natech
  - **Consequences**
    - Human health, environmental, economic losses, community disruption
  - **Remedial activities**
    - Decontamination, remediation, restoration
  - **Lessons learned**
    - Equipment, human, organizational, mitigation measures, emergency response
It is good practice during LPG tank inspections to leave the water for not more than 2-3 days in the tank. At the time of the earthquake the tank that collapsed had been filled with water for 12 days.

<table>
<thead>
<tr>
<th>Initiating Events</th>
<th>Critical Events</th>
<th>Major Events</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Component (Structural):</strong> Collapse of support columns</td>
<td>-</td>
<td><strong>Event Sequence:</strong> ES2 (Fire and explosions)</td>
</tr>
<tr>
<td>The earthquake shock caused the tank braces to fracture and eventually the legs to buckle. The measured PGA was 0.114g during the first earthquake shock. The aftershock was 0.99g.</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Component (Structural):</strong> Complete collapse</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**Name:** ES2 (Fire and explosions)

**Unit:** LPG storage tank farm

**Description:** The LPG leaking out from the ruptured pipes spread out and caught fire. As a consequence, the tank adjacent to Tank 364 exploded (BLEVE), spreading the fire from tank to tank and eventually throughout the whole LPG tank farm, leading to several explosions.

**Substances involved:** Liquefied Petroleum Gas – 5227 tons / 5227 tons, 27 atm, 50°C

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**Initiating Events**

**Event Sequence:** ES1 (Collapse of LPG storage tank)

**Component (Non-structural):** Pipe break / damage

**Contributing Factors**

**Prevention, Safety and Mitigation Measures:**
*Unavailable Emergency shut off / safety valves*

**Human:** Failure to carry out duties

Prior to the earthquake an emergency valve on the LPG pipes had been manually locked "open" to prevent it from actuating due to minor air leakages during repair work. Once LPG started to be released from the damaged pipe and the fire ignited, the valve could not be reached and closed, thereby continuously providing LPG to feed the fire. This exacerbated the fire and made it burn out of control. By manually overriding the emergency valve, the company was in violation of the High-Pressure-Gas law. In a personal communication, the Chiba Prefecture Fire Department expressed its belief that the accident might have been manageable had the safety valve not been open.

**Release:** Gas / vapour / mist release to air

**Explosion:** Vapour cloud explosion

The shock waves and debris from the explosions triggered fires in the adjacent premises of Maruzen Petrochemical Co., Ltd., and Chisso Petrochemical Corporation.

**Event Sequence:** ES2 (Fire and explosions)

**Fire:** Jet flame

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**Initiating Events**

**Event Sequence:** ES3 (Asphalt release)

**Name:** ES3 (Asphalt release)

**Unit:** Asphalt tanks
Accident Analysis

Objectives:

- Identify damage and failure modes of equipment due to natural hazards (incl. contributing factors)
- Identify consequences of releases of hazardous substances in Natech events
- Learn lessons and prepare recommendations to prevent future accidents or better mitigate their consequences

*In collaboration with the Department of Chemical Engineering, Bologna University, Italy, and the Disaster Prevention Research Institute, Kyoto University, Japan*
### Earthquakes

#### Damage/failure mechanisms:

<table>
<thead>
<tr>
<th>Direct shaking impact</th>
<th>Ground deformation due to liquefaction</th>
</tr>
</thead>
</table>

#### Structural damage without release

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor</td>
<td>Elephant-foot/diamond buckling, deformation of support structures, stretching of bolts, sloshing damage</td>
</tr>
<tr>
<td>Moderate</td>
<td>Detachment of bolts, failure of connections/welds, tank roof-top failure, failure of columns and support structures</td>
</tr>
</tbody>
</table>

#### Structural damage with release

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor</td>
<td>Partial failure of flanges and connections</td>
</tr>
<tr>
<td>Severe</td>
<td>Failure with loss from the tank roof top or shell</td>
</tr>
<tr>
<td>Catastrophic</td>
<td>Collapse or overturning of tank</td>
</tr>
</tbody>
</table>
Example: Equipment damage severity during earthquakes

*Figure based on 79 Natech accident records

Multiple and simultaneous releases frequent & high ignition probability (0.7) → increased risk of cascading effects
### Damage/failure mechanisms:

**Displacement due to buoyancy and water drag (water height & speed)**

**Impact of floating objects**

<table>
<thead>
<tr>
<th>Structural damage with release</th>
</tr>
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<tbody>
<tr>
<td>Minor</td>
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<tr>
<td>Severe</td>
</tr>
<tr>
<td>Catastrophic</td>
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</table>

Floodwaters can distribute the released toxic or flammable materials over wide areas, thereby increasing the risk to the surroundings.
Example: Type of damage to equipment during floods

2 specific accident scenarios for flood-triggered Natechs:
+ Severe WATER CONTAMINATION due to hazmat release
+ TOXIC and/or FLAMMABLE vapor formation and release due to reaction of chemicals with water
Examples of past Natech accidents incl. violent reactions of chemicals with water

<table>
<thead>
<tr>
<th>Flood target</th>
<th>Substances</th>
<th>Final scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warehouse</td>
<td>Calcium carbide (acetylene after water contact)</td>
<td>Fire</td>
</tr>
<tr>
<td>Atmospheric storage tanks</td>
<td>Nitric and sulphuric acids</td>
<td>Toxic gas cloud dispersion</td>
</tr>
<tr>
<td>Warehouse</td>
<td>Phosphorus</td>
<td>Fire, Explosion</td>
</tr>
<tr>
<td>Warehouse</td>
<td>Oleum</td>
<td>Toxic gas cloud dispersion</td>
</tr>
<tr>
<td>Warehouse</td>
<td>Calcium carbide (acetylene after water contact)</td>
<td>Explosion, Toxic gas cloud dispersion</td>
</tr>
<tr>
<td>Warehouse</td>
<td>Cyanide salts (hydrogen cyanide after water contact)</td>
<td>Fire, Explosion</td>
</tr>
</tbody>
</table>

From Cozzani, Campedel, Renni, Krausmann, *Industrial accidents triggered by flood events: Analysis of past accidents*, 2010
Lightning Damage/failure mechanisms:

Direct: Ignition of flammable vapours; structural damage

Indirect: Impact on electrical control systems

<table>
<thead>
<tr>
<th>Structural damage with release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor</td>
</tr>
<tr>
<td>Severe</td>
</tr>
<tr>
<td>Catastrophic</td>
</tr>
</tbody>
</table>
Example: Categories of process equipment damaged by lightning

Most vulnerable equipment: Storage tanks (60%) → non-negligible source of risk with high release probability

*Figure based on 485 Natech accident records*
Cold weather

Damage/failure mechanisms:

*Freezing of equipment* → *component malfunction and leaks (valve or control-system failures)*

*Falling ice and snow* → *physical loads (cracks, hazmat releases)*

*Ice formation in pipes* → *blockage and overpressure (rupture or tank overflow)*

*Frost heave* → *vertical ground displacement (pipeline buckling)*
Hazardous substances released during floods

<table>
<thead>
<tr>
<th>Category</th>
<th>Hazard</th>
<th>Num</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine</td>
<td>Toxic, dangerous for the environment</td>
<td>3</td>
</tr>
<tr>
<td>Oil, diesel fuel and gasoline</td>
<td>Extremely flammable, dangerous for the environment</td>
<td>142</td>
</tr>
<tr>
<td>Cyanides</td>
<td>Toxic, dangerous for the environment</td>
<td>5</td>
</tr>
<tr>
<td>Propane, butane and LPG</td>
<td>Extremely flammable, dangerous for the environment</td>
<td>12</td>
</tr>
<tr>
<td>Explosives</td>
<td>Reacts violently with water</td>
<td>3</td>
</tr>
<tr>
<td>Fertilizers</td>
<td>Dangerous for the environment, toxic</td>
<td>11</td>
</tr>
<tr>
<td>Acid products</td>
<td>Toxic, dangerous for the environment</td>
<td>7</td>
</tr>
<tr>
<td>Calcium carbide</td>
<td>Contact with water liberates extremely flammable gases</td>
<td>3</td>
</tr>
<tr>
<td>Soap and detergents</td>
<td>Dangerous for environment</td>
<td>1</td>
</tr>
<tr>
<td>Liquid hydrocarbons</td>
<td>Extremely flammable, dangerous for the environment</td>
<td>8</td>
</tr>
<tr>
<td>Liquid aromatics</td>
<td>Extremely flammable, dangerous for the environment</td>
<td>8</td>
</tr>
<tr>
<td>Oxides</td>
<td>Explosive with or without contact with air, reacts violently with water</td>
<td>5</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Toxic, dangerous for the environment</td>
<td>5</td>
</tr>
</tbody>
</table>
General lessons learned from the analysis of earthquake, flood and lightning Natech accidents

1) Atmospheric storage tanks, and in particular those with floating roofs, are particularly vulnerable to earthquake, flood and lightning impact.

2) Many Natech accidents involve hydrocarbon releases that often ignite and escalate into major fires or explosions.

3) During Natech accidents there is a high ignition probability and the likelihood of cascading events is significantly increased with respect to conventional technological accidents.
A database of 1085 events for statistical analysis of incidents with a natural-hazard trigger.
303 offshore incidents from natural causes in European waters:

• **Frequent but low consequences**

• **Main problem:** bad weather; also cases of lightning and earthquakes

• **Damage/failure modes:**
  → Floating infrastructure: loss of station keeping (mooring/anchors) due to high winds and rough seas
  → Fixed infrastructures: falling loads due to storms

• **Strong contributing factor fatigue and corrosion**
  → North Sea: highest number of incidents in Europe; highest number of incidents at semi-submersible units in the world

• **High number of incidents during towing**
  → Impact of natural hazards on safety of transfer operations
Pipeline Natech Study

• **Objective**
  Better understand the dynamics of onshore pipeline Natech accidents

• **Outputs**
  - Technical reports
    - JRC 83267, JRC 88410
    - JRC 90911, JRC 92700
  - Natech accident data analysis toolbox
• Methodology
  • Collection of historical incident data
    • Hazardous liquid (CONCAWE, PHMSA, NRC)
    • Natural gas (EGIG, PHMSA, NRC)
  • Unified relational database
    • Natural hazards + Incidents + References
  • Data analysis system
    • (Big) Data mining (> 1.7 million records)
    • Rule-based automated classification
    • Peer-review and correction
    • Statistical analysis
  • Reporting
Natechs occurred less frequently than accidents from other causes, but their consequences were more severe in terms of economic damage. (6% occurrence, 18% of economic cost)

The importance of Natechs appears to be increasing.

Pipeline performance is satisfactory for certain natural hazards (e.g. earthquakes), but for others (e.g. floods, freeze) further protection measures are required.

Natural hazards aggravated accidents from other causes by accelerating causes, facilitating transport of spilled substances, or hampering response and recovery operations.
<table>
<thead>
<tr>
<th>Lessons learned</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Earthquakes</strong></td>
<td>The risk associated with floating roof tanks in areas where an earthquake hazard exists needs to be re-evaluated</td>
</tr>
<tr>
<td>Floating-roof tanks are prone to fire scenarios during an earthquake. Liquid sloshing can result in bouncing of the metallic roof against the side wall which could create sparks and ignite the tank content if flammable</td>
<td>Liquid sloshing and the resulting dynamic loading on the tank wall needs to be taken into account in the risk assessment in earthquake-prone areas</td>
</tr>
<tr>
<td>Liquid sloshing can compromise the structural integrity of tanks which are full or nearly full</td>
<td>Specific connections should be used in earthquake-prone areas</td>
</tr>
<tr>
<td>Rigid connections between pipes and equipment are vulnerable to shaking damage and failure which can lead to the release of hazardous materials</td>
<td>Critical active and passive safety barriers in the facility need to be designed to withstand the forces of the expected earthquake</td>
</tr>
<tr>
<td>Safety barriers to prevent an accident or mitigate its consequences, such as e.g. catch basins around tanks or sprinkler systems, may fail under earthquake loading</td>
<td>Anchoring or restraining of equipment could effectively avoid displacement and keep the equipment intact</td>
</tr>
<tr>
<td>Non-anchored equipment can suffer damage through lateral displacement and/or uplifting</td>
<td>The characteristics of an earthquake impact on a chemical facility, and the possibility of a domino effect*, need to be considered in land-use-planning decisions and when preparing emergency response plans. In</td>
</tr>
</tbody>
</table>
Liquid sloshing can compromise the structural integrity of tanks which are full or nearly full.

Rigid connections between pipes and equipment are vulnerable to shaking damage and failure.

Safety barriers, e.g. catch basins around tanks or sprinkler systems, may fail under earthquake loading.

Liquid sloshing and the resulting dynamic loading on the tank wall need to be considered in the risk assessment in earthquake-prone areas.

Specific flexible connections should be used in earthquake-prone areas.

Critical active and passive safety barriers in the facility need to be designed to withstand the forces of the expected earthquake.
Waste oil in the plant drainage system can be lifted by the flood and cause fires and/or explosions upon contact with an ignition source.

Floods usually affect wide areas and can carry released substances over significant distances. Therefore, the risk of a domino effect in a densely industrialised area is elevated.

The drainage systems for waste flammable substances and surface run-off water should be segregated.

A flood-hazard management plan at plant and community level should incorporate the emergency evacuation due to the inundation of a facility and the Natech accidents triggered by it. Attention needs to be given to the impact of toxic or flammable substances on rescue operations.
The rim seal of atmospheric floating-roof tanks is the most likely point of ignition during a lightning strike.

Lightning can lead to partial or total on-site power outage and power dips which can result in process upsets and loss of containment.

The rim seal should be regularly checked and maintained in good condition to limit the escape of flammable vapours, which can be ignited by lightning.

Dangers due to power loss should be identified to determine which processes should receive power from backup systems. Emergency shutdown of hazardous processes and blow-down of pressurised equipment should be effected to put units into safe mode.
Obstacles to Natech risk reduction

**Lack of recognition** that industry is vulnerable to the impacts of natural hazards.

**Lack of guidance** on how to identify Natech hazards and assess the associated risk.

**Data availability** → incomplete knowledge of dynamics of Natech accidents and hence lack of scenarios.

**Questions about adequacy of design basis:**
- Design codes and standards aim at preservation of life safety, not prevention of loss of containment.
- Uncertainty as to which level of damage or failure is to be expected above the design-basis loading.

**Natech risk assessment is fundamentally a multi-disciplinary issue and cuts across traditional professional boundaries.**
1. The chemical industry is vulnerable to natural-hazard impact but this is not always recognized.

2. The most vulnerable equipment type are atmospheric storage tanks with a high storage capacity and a high likelihood of release during natural hazards.

3. The design basis of hazardous installations is not always adequate for natural-hazard loading and design limits need to be understood and acknowledged.

4. Natech risk reduction measures are available for several natural hazards and research is ongoing to fill existing data and knowledge gaps.


