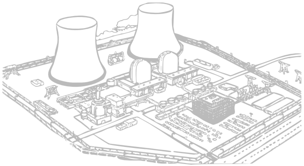

# Consequence modelling: overview of hazards


Eric Marsden

<eric.marsden@risk-engineering.org




> *From little spark may burst a mighty flame.*
>
> *— Dante, Paradise*

# Consequence assessment

- Many things can go wrong on a hazardous industrial facility, leading to an **unintended release of hazardous material** or an **uncontrolled release of energy**

- Consequence assessment is a rigorous and methodical examination of the direct undesirable impacts of a *loss of containment* of material or energy
  - impacts on people, the environment and the process

- Applications:
  - design of new facilities: suggest optimal separation distances
  - risk assessment of a facility for safety case
  - emergency planning and land use planning: estimate impact distances for major accident scenarios

- Highly technical area, requiring detailed process safety expertise
  - this presentation: an overview of major hazards in the process industries

# Chemical plants

# Steel works

# Power plants

Image source: Cruas-Meysse nuclear power plant, `flic.kr/p/neGatj`, CC BY licence

# Storage depots

# Offshore oil rigs

# Offshore oil complexes

3 km from one edge to the other...

Photo credit (Ekofisk complex, North Sea): ConocoPhillips

# FPSO

FPSO: Floating Production, Storage and Offloading unit

Floating vessel used by the offshore oil & gas industry to extract, process and temporarily store hydrocarbons.

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# Offshore oil complexes

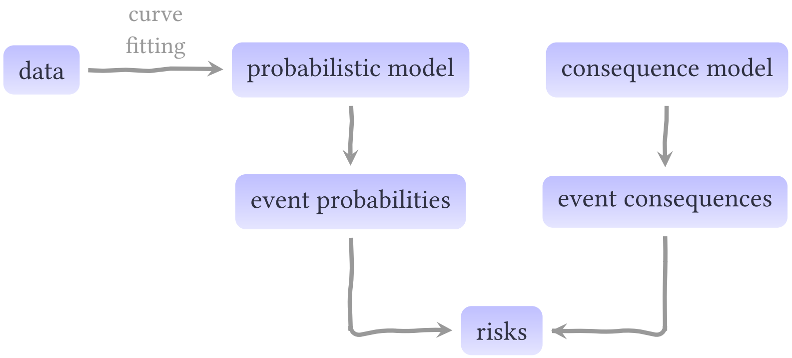

Photo credit: Total

# Hazmat pipelines

Hazmat: hazardous material

# Underground gas storage sites

# Where does this fit into risk engineering?



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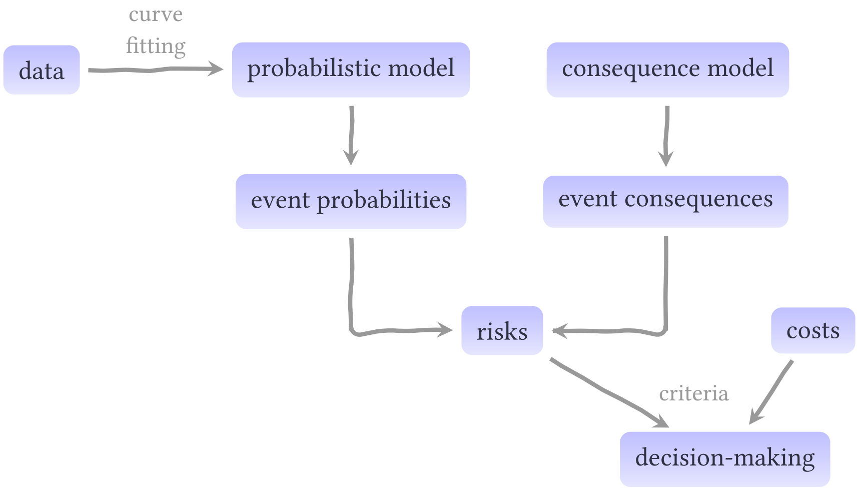
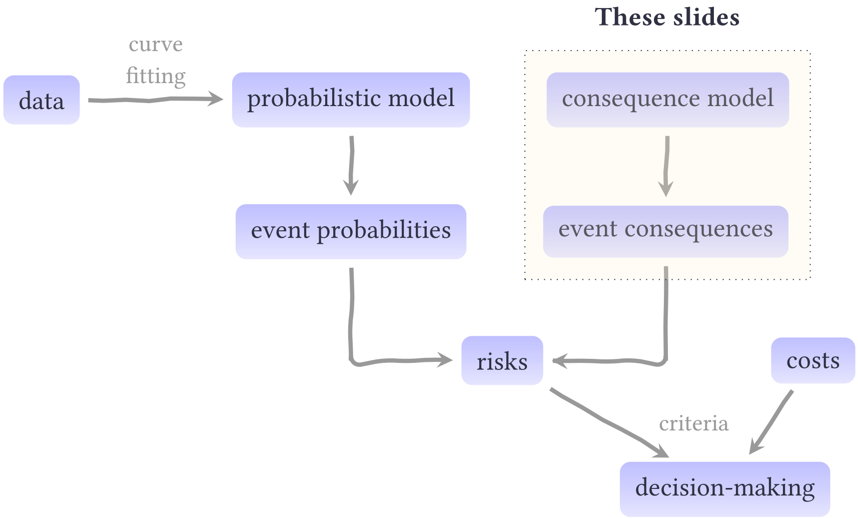
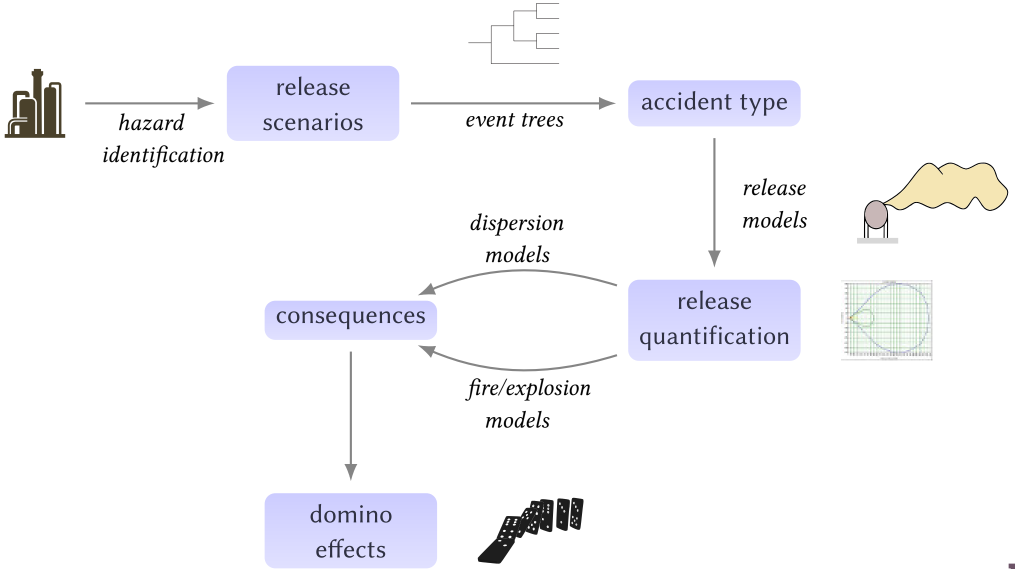


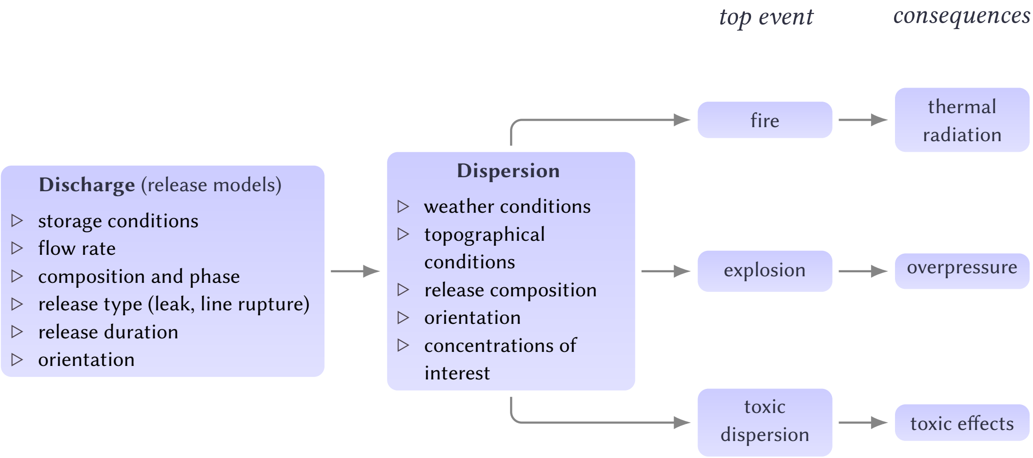
# Where does this fit into risk engineering?



# Consequence modelling

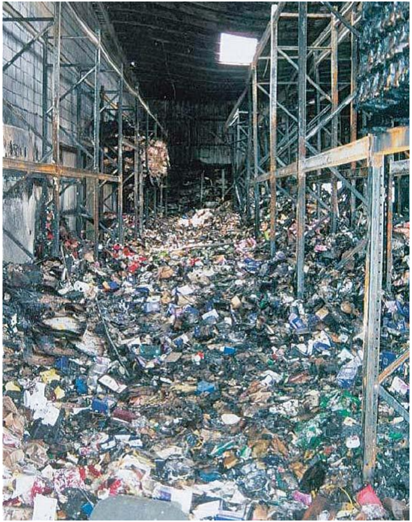


# Modelling stages



# Flammable hazards

# Ordinary fire



Left: results of fire in a perfume warehouse

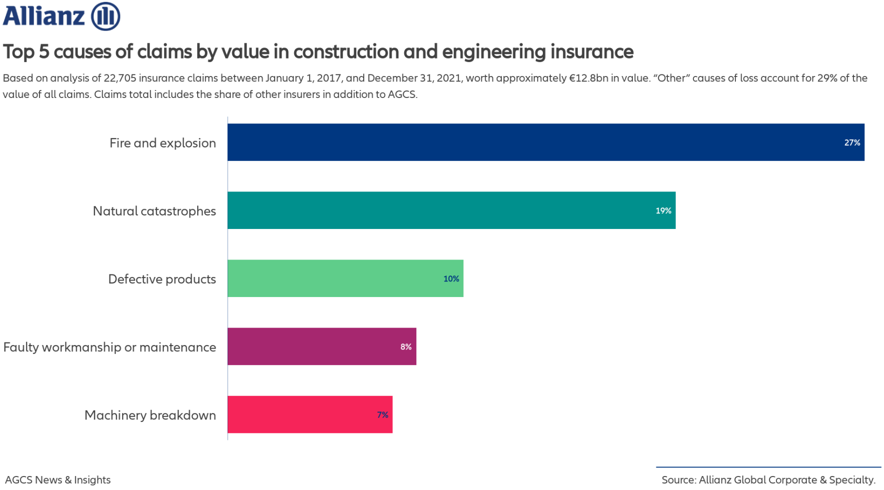
Ordinary fires are a major source of losses (material damage, lost production, sometimes injured workers) in industry.

Large amounts of information available from:

- US National Fire Protection Association (NFPA), at `nfpa.org`
- Insurers and reinsurers (Munich Re, Swiss Re, Allianz, Mapfre, Marsh…)

Image source: Munich Re

# Ordinary fire



# Jet fire

- Jet fire: turbulent diffusion flame resulting from combustion of a continuous release of flammable liquid or vapour with some significant momentum in a particular direction
  - may arise from release of gaseous, flashing liquid (two phase) and pure liquid inventories
  - may be affected by wind
  - high heat flux on impinging objects can lead to structural failure and escalation (domino effects)
  - high pressure jet fires are significant hazards for oil & gas industry

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# Well fire in Irak

# Gas flare on offshore oil platform

Flare stacks (or gas flares) are used to burn natural gas associated with oil production on offshore platforms which aren't equipped with gas transportation infrastructure.

They lead to a controlled jet fire.

# Gas flare on a refinery

Gas flares or flare stacks are used to burn flammable gas and petroleum products during emergency shutdowns of refineries and chemical plants.

They are also used to burn products during shutdowns and startups.

Image source: Wikimedia Commons, CC BY-SA licence

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# Jet fire: Piper Alpha platform

- Piper Alpha: a North Sea oil production platform north of Aberdeen, accounting for 10% of North Sea production at the time
- Poor information transmission during maintenance and bad use of permit-to-work led to gas leak (July 1988)
- Explosion and resulting fire destroyed platform, killing 167 people
- Flames over 100 m high, visible from 100 km

# Pool fire

- Pool fire: a turbulent diffusion fire burning above a horizontal pool of vapourizing hydrocarbon fuel
  - fuel may be spilled on land, on water, on a building
  - pool may be confined (tank, containment bund) or unconfined
- Heat radiation depends on product burning
  - heavier hydrocarbons burn with smoky flame
  - light hydrocarbons burn with much brighter flame
- Significant hazard for oil and gas industry

# Pool fire


Sitapura, India (2009) storage fire accident

# Pool fire

Buncefield fire (UK, 2005)

# Pool fire

Buncefield fire (UK, 2005)

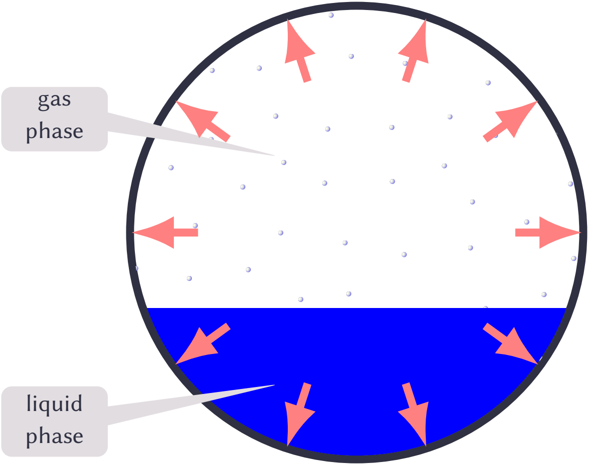
# Pool fire

Aftermath of Buncefield fire (UK, 2005)

# Explosion hazards

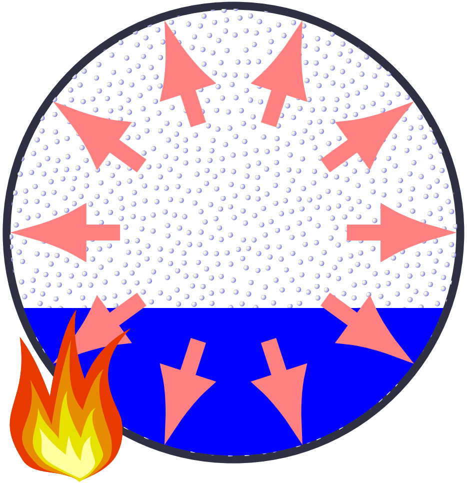
# BLEVE

- BLEVE: Boiling Liquid Expanding Vapor Explosion
- Failure of pressure vessel containing pressurized liquid
- Pressure drop causes violent boiling, rapid expansion and vaporization
- Typically occurs due to external heat source from other process emergency (*e.g.* jet fire) impinging on vessel
- Flammable liquids lead to fireball
- Flame spreads through 360°




Fuels such as butane and propane are generally stored as pressurized liquids at a temperature higher than their boiling point.

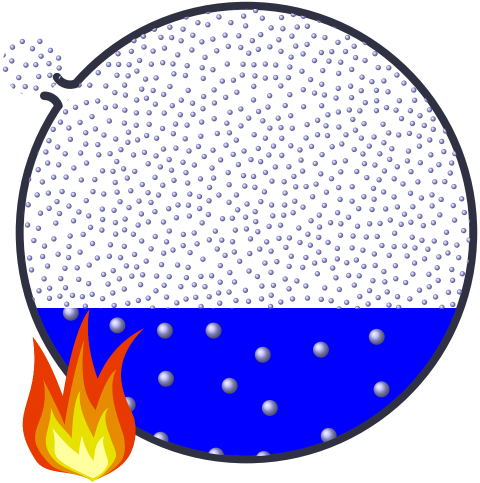
Typical pressures: 17 bar (1700 kPa).



An initial event (often a jet fire) leads to **heat impinging on the storage vessel**.

**Pressure** inside the tank increases.

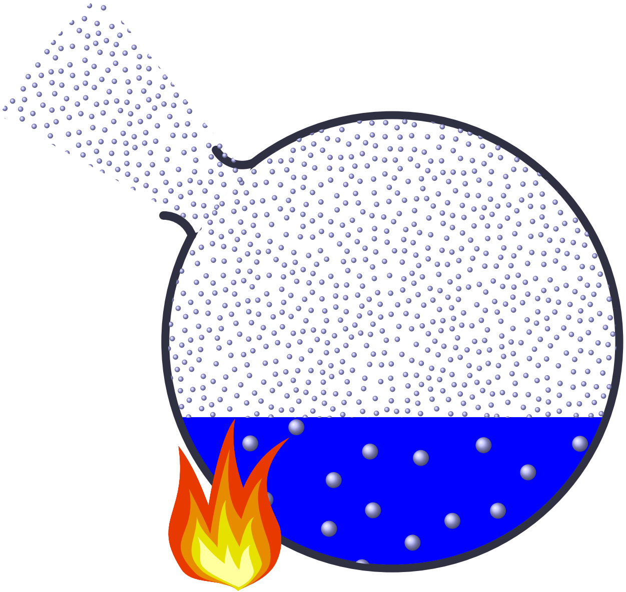
The liquid in the tank cools down the metal in the lower part of the vessel, but the upper part of the tank may become weaker due to heat.



The vessel fails, initially with only a small hole.

Gas **leaks** from the hole, rapidly lowering the pressure inside the tank.

The liquefied gas **boils** violently (its boiling point is pressure-dependent).



**BLEVE**: Boiling Liquid Expanding Vapour Explosion

The boiling liquid **vapourizes**, increasing pressure in the vessel and ripping it open. A huge volume of gas is ejected into the atmosphere.

Massive **blast**. If material is flammable, a huge **fireball** forms with massive heat radiation.

BLEVE after train derailment in Casselton, North Dakota (2013)

# BLEVE: explanatory video

Explanatory video: `youtu.be/UM0jtD_OWLU`

# Preventing BLEVEs in LPG tanks

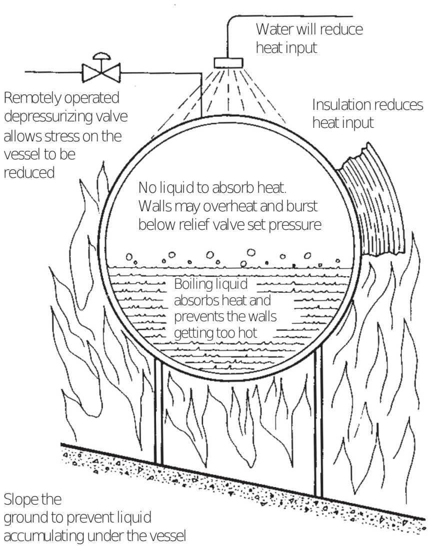



Image source: *Loss Prevention Bulletin* 077, 1987

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# Vapour cloud explosion (VCE)

- Typical steps leading to a VCE:
  1. release of a large quantity of flammable vapor (often after rupture of a pressure vessel)
  2. vapour disperses on the site and mixes with air
  3. one part of the cloud reaches an ignition source (heat, static electricity) and ignites
- Major hazard for plants processing liquefied gasses and high pressure gasses
  - potentially very destructive…
- Controls:
  - prevent leaks from all process equipment
  - (last resort) zones that are particularly susceptible to leaks are classified “ATEX” (explosive atmosphere: any equipment installed is designed not to become an ignition source)

# Related CSB safety video


US CSB safety video *Filling blind*, 2015

Watch the video: `youtu.be/41QMaJqxqIo`

# Flammable consequences: radiation

| Radiation intensity ($kW/m^2$) | Observed effect |
|---|---|
| 37.5 | Sufficient to cause damage to process equipment |
| 12.5 | Minimum energy for piloted ignition of wood, melting of plastic tubing |
| 4 | Sufficient to cause pain to personnel if unable to reach cover within 20 seconds |
| 1.6 | Will cause no discomfort for long exposure |

Note: normal sunny day = $1\,kW/m^2$

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# Explosion consequences

- Flammable vapor cloud which is within the flammable limits of the fluid
- Explosions can be confined or unconfined
  - confinement increases flame speed
  - confined explosions are far more hazardous
- Air burst or ground burst depending on cloud buoyancy

# Explosion consequences

# Explosion consequences

# Explosion consequences




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# Explosion consequences

# Gas explosion at Ghislenghien (2004)

- High pressure (70 bar) pipeline transporting natural gas from Zeebrugge towards France
- Pipeline probably damaged during terracing works in the area
- Leak and explosion in town of Ghislenghien, Belgium, July 2004
- 24 people killed in explosion
- Flames from jet fire reach almost 100 m into the sky

More info: www.aria.developpement-durable.gouv.fr/fiche_detaillee/27681/

# Flammability hazards in risk assessment

- FERA: Fire and Explosion Risk Analysis
- Undertaken during concept development and design phases
  - mostly for offshore oil and gas projects
- Identify major accident scenarios (dimensioning/credible worst case)
- Estimate probability of fire/explosion scenarios and their consequences
- Verify the suitability of the planned fire safety/explosion equipment

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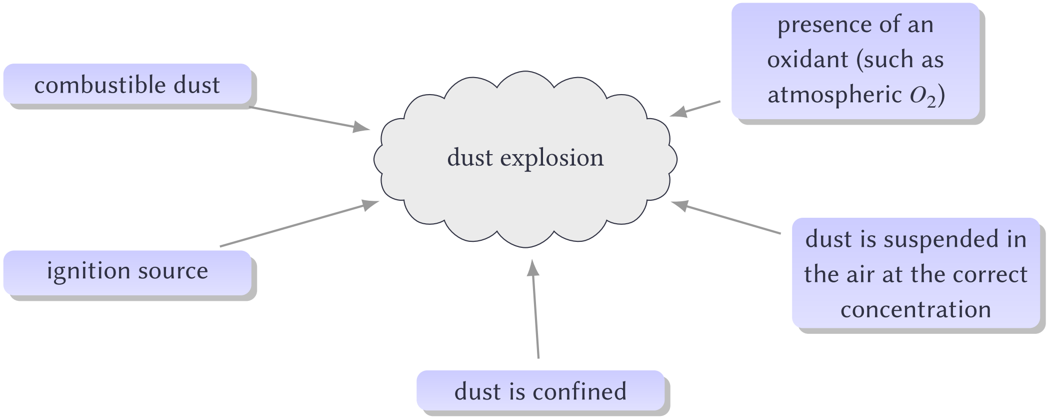
# Dust explosions

- ▷ The dust of a combustible material can be explosible if suspended in air at certain concentrations
- ▷ Even materials that don't burn in larger pieces can be explosible in dust form (*e.g.* aluminium, iron)
  - in many accidents, employers and employees unaware of the existence of a hazard
- ▷ Dust explosions can destroy buildings and kill people
- ▷ Often a small primary explosion raises dust in the air and leads to larger secondary explosions
- ▷ Many industries concerned
  - food, grain storage, plastics, wood, paper, rubber, textiles, pharmaceuticals, coal, metals, fossil fuel power generation

# Causes of a dust explosion



# Related CSB safety video

US CSB safety video *Inferno: dust explosion at Imperial Sugar*, 2008

Watch the video: `youtu.be/Jg7mLSG-Yws`

# Related CSB safety video


US CSB safety video *Combustible Dust: Solutions Delayed*, 2014

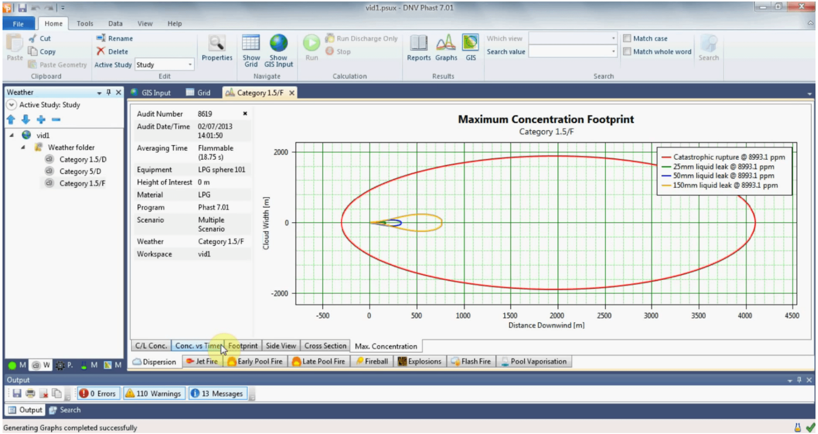
Watch the video: `youtu.be/ADK5doMk3-k`

# Relevant modeling software

# Using modeling tools

- Consequence assessment can make use of:
  - equations taken from professional literature
  - numerical charts calculated from equations or from experimental data
  - software models
- Effective use of these tools requires **good knowledge** of the **physical phenomena** involved
  - to select an appropriate model
  - to understand whether results are physically plausible
- Users of these tools should always keep **uncertainty** in mind when presenting results

# Phast (DNV GL Software)




Commercial tool which is widely used for consequence assessment in the chemicals, energy and offshore sectors. Can model a range of hazards, uses a 2D dispersion model.

Source: DNV GL Software

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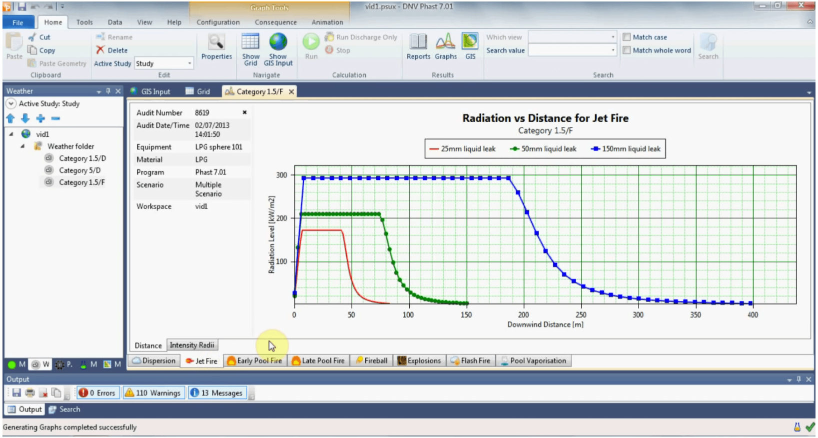


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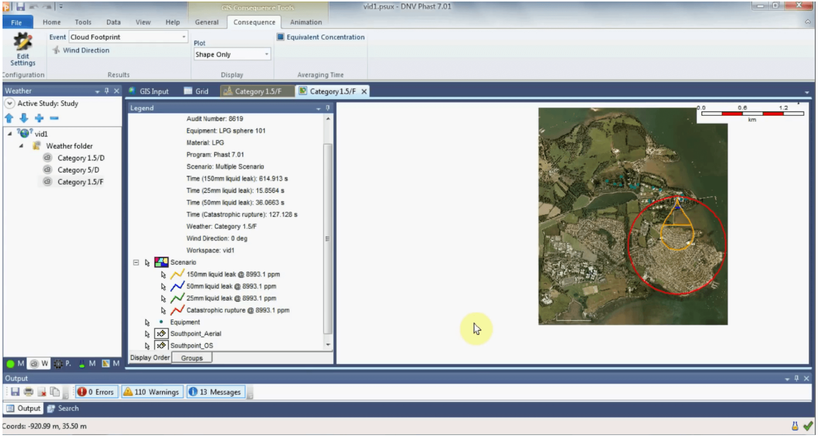


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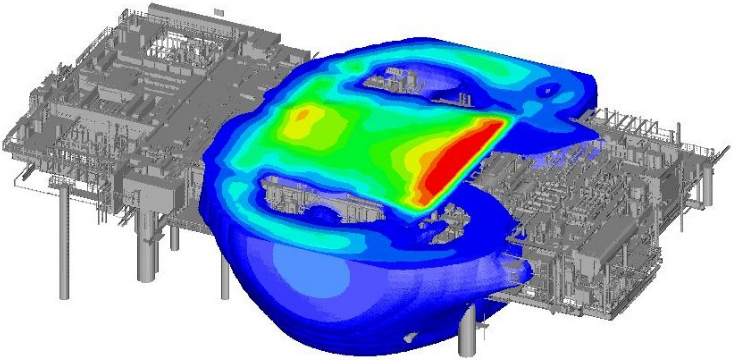
Source: DNV GL Software

# FLACS-CFD (GexCon)

*CFD: computational fluid dynamics*

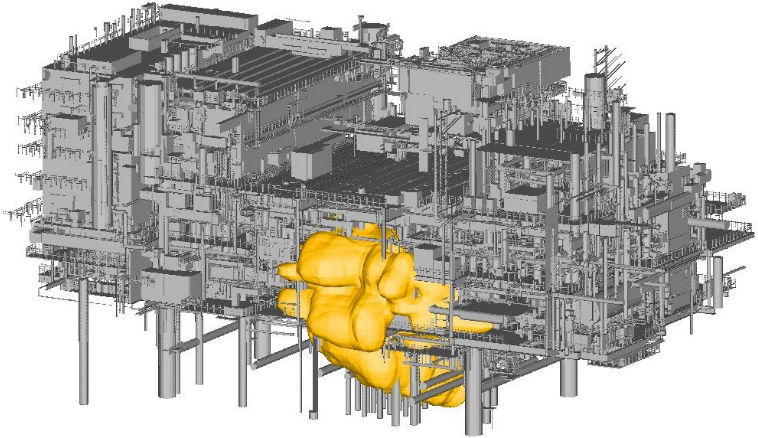


A commercial CFD tool for modelling dispersion, explosion and fire effects. Is widely used in the offshore oil and gas sector.

Source: GexCon, `gexcon.com`

# FLACS-CFD (GexCon)

*CFD: computational fluid dynamics*



A commercial CFD tool for modelling dispersion, explosion and fire effects. Is widely used in the offshore oil and gas sector.

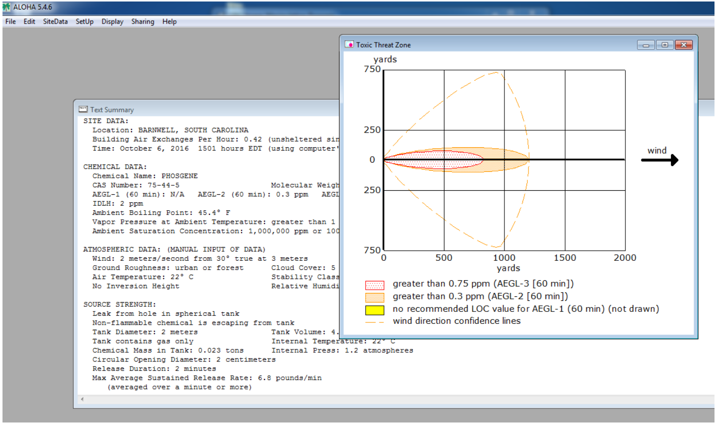
Source: GexCon, `gexcon.com`

# Kameleon FireEx KFX (DNV)


Watch evolution of a hydrocarbon jet fire predicted by KFX: `youtu.be/HxZ5E23ZXHo`

Source: ComputIT

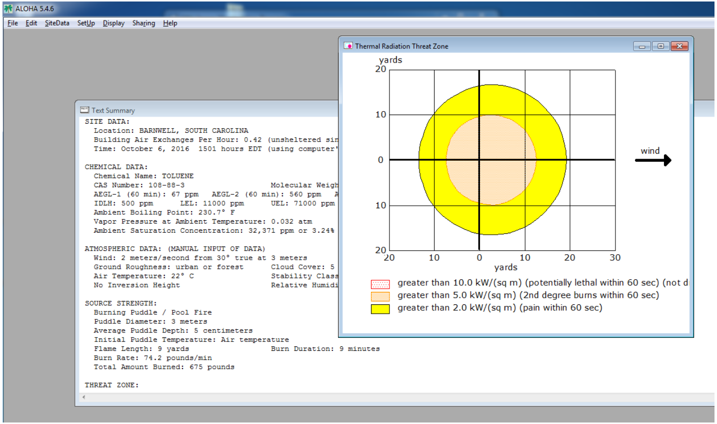
# Aloha (US EPA)




Simple tool which can estimate threat zones for toxic gas releases, flammable gas releases, BLEVEs, jet fires, pool fires, vapor cloud explosions. Free software from US EPA.

Web: epa.gov/cameo/aloha-software

# Aloha (US EPA)




Simple tool which can estimate threat zones for toxic gas releases, flammable gas releases, BLEVEs, jet fires, pool fires, vapor cloud explosions. Free software from US EPA.

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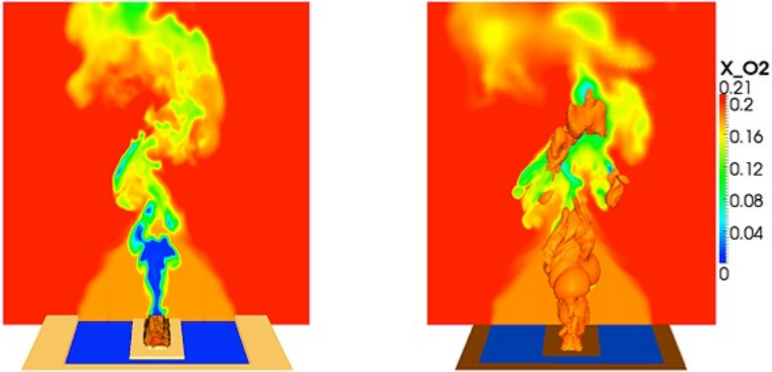
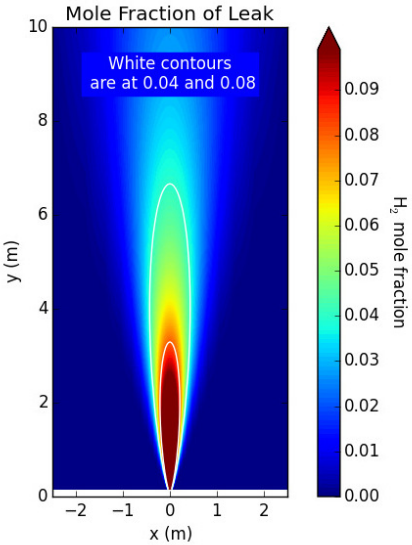
# FDS (NIST)




The Fire Dynamics Simulator is a sophisticated CFD tool for modelling fire propagation and atmospheric dispersion. Free software from the US NIST.

Web: `nist.gov/services-resources/software/fds-and-smokeview`

# HyRAM (Sandia)

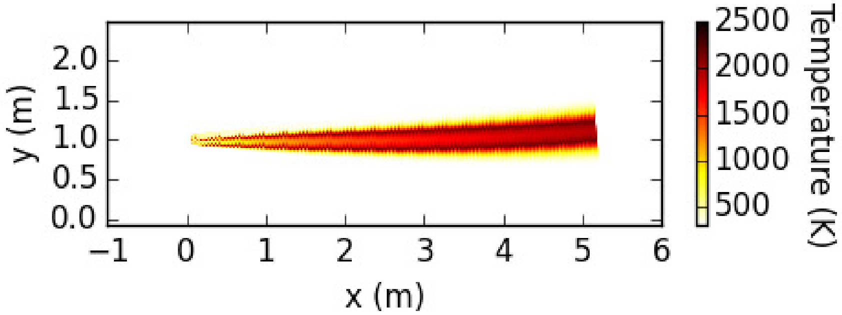



HyRAM is a tool for estimating the consequences of accidents involving hydrogen. It can estimate likelihood of equipment failures and includes sophisticated models for hydrogen release and flame physics.

Free software from Sandia National Laboratories.

Web: `hyram.sandia.gov`

# HyRAM (Sandia)




Web: `hyram.sandia.gov`

# Applications

# What are consequence modelling outputs used for?

- **Design of new facilities**
  - example: suggesting optimal separation distances between units, to avoid domino effects
- **Risk assessment** of a facility to provide input to a safety case
- **Emergency planning**:
  - estimate impact distances for major accident scenarios to develop evacuation scenarios
  - calculate quantity of firefighting equipment necessary (fire water, sprinklers, lances…)
- **Land use planning**: decide on zoning restrictions for land use, siting of public facilities (schools…), location of infrastructure (roads, railways…)

# Emergency planning

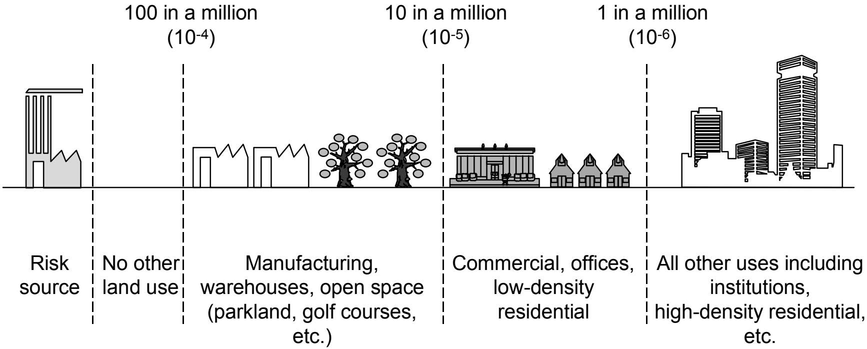
- Typically, start with a list of **maximum credible accident scenarios**
- Identify on-site and off-site **consequences of each scenario**
  - quantity of hazardous materials that could be released as a result of an accident (including smoke effluent from fires), rate of release, effect of explosions, effect of thermal radiation from fires, effect of hazardous materials that could be released
- List **control and containment measures**
  - firefighting equipment, groundwater capture systems, alerting mechanisms, protective equipment such as gas masks, emergency power systems, evacuation plans…
- Define command structure and **communication channels in case of emergency**
  - roster of on-call personnel defined
  - link with off-site emergency services defined

# Emergency planning

- All personnel should receive **training** on their responsibility in case of an emergency
- Emergency plan should be **regularly tested**
  - test *readiness to respond*
  - for example, one scenario every three years, ideally with external emergency response teams
- Plan should be **reviewed periodically** and whenever significant changes are made to the facility

# Land use planning: MIACC guidelines

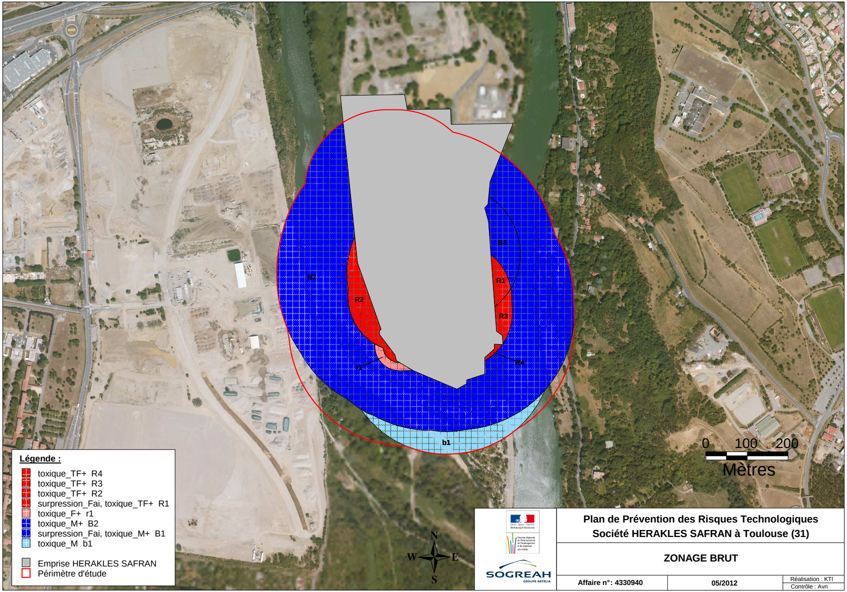
**Annual Individual Risk**
**(chance of fatality per year)**




**Allowable Land Uses**

Source: Major Industrial Accidents Council of Canada (MIACC) risk acceptability criteria

# Land use planning: PPRT legislation in France



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- Pipeline (slide 10): rickz via `flic.kr/p/4dJLmX`, CC BY-NC-ND licence
- Gas storage site: GorissenM via `flic.kr/p/sjwAE6`, CC BY-SA licence
- Flames (slide 15), `flic.kr/p/a6qFq2`, CC BY-NC-ND licence
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- Explosion (slide 25), `flic.kr/p/5menMy`, CC BY-NC-ND licence
- Emergency response (slide 46), U.S. Army Corps of Engineers via `flic.kr/p/9gGtxK`, CC-BY licence

THANKS!

# Further reading

- *Fire, Explosion and Risk Assessment Topic Guidance* from the UK Health and Safety Executive's Hazardous Installations Directorate, `hse.gov.uk/foi/internalops/hid/manuals/pmtech12.pdf`
- OGP report *Risk Assessment Data Directory*, available at `www.iogp.org`
- The famous *Yellow Book* published by TNO contains large amounts of information on hazardous phenomena

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