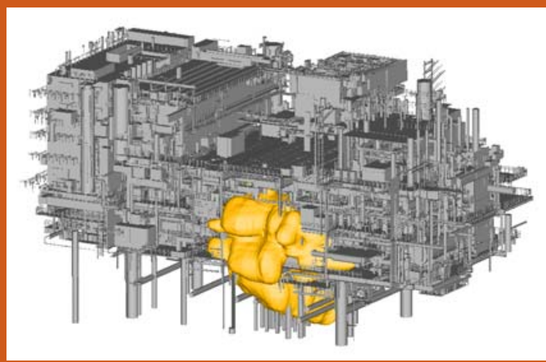
FLACS Course Handouts



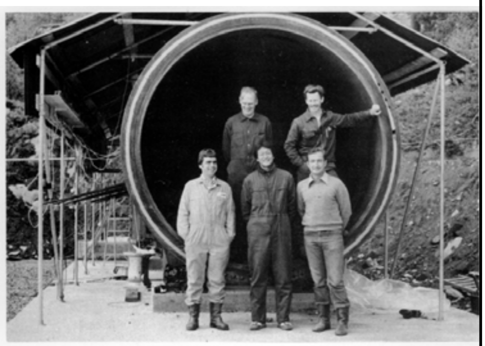
Introduction

Outline

- Presentation of GexCon
- Gas explosions and affecting parameters
- Simplified methods for blast loads evaluation
- Requirements for suitable gas explosion loads prediction tools
- Presentation of FLACS code
- Risk assessment methodologies

The beginning

- 1857-1925: **Christian Michelsen**
  - Lawyer, ship owner, …
  - Prime minister of Norway from 1905 to 1907
- 1930 → : **Chr. Michelsen Institute** (CMI)
  - Independent research foundation in Bergen
  - Science, medicine, the humanities, etc.
- 1970 → : **Dust explosions activities** at CMI
  - Grain dust explosion at Stavanger Port Silo, 9 June 1970
  - Silicon powder grinding plant in Bremanger, October 1972
  - Aluminium flake & sulphur explosion, Gullaug, August 1973
- 1977 → : **Gas & mist explosion activities** at CMI
  - Gas & oil mist explosions hazards on offshore platforms
  - Large-scale gas explosion experiments at Raufoss
  - The Gas Safety Programs (GSP)
  - FLACS (FLame ACceleration Simulator)

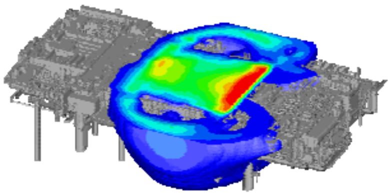


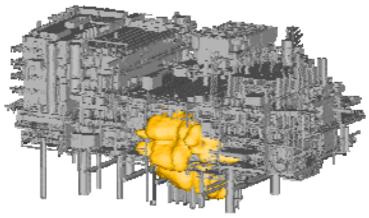
R.K. ECKHOFF K. FUHRE
J.E. VINNEM J.H.S. LEE O. KREST

LARGE EXPLOSION TUBE READY FOR EXPERIMENT

CMR & GexCon

- 1992: **Christian Michelsen Research** (CMR)
  - Formed in a split from CMI
- 1998: **GexCon** – Global Explosion Consultants
  - Currently owned by CMR (100%)
  - About 50 employees: Bergen, US, UK & Sweden
  - Five departments:
    - **R&D** – developing, maintaining and validating FLACS
    - **Software** – marketing and sale of FLACS
    - **Gas Consultants** – consultancy services with FLACS
    - **Process safety** – risk assessments and ATEX
    - **Labs** – laboratory & large-scale experimental testing





GexCon in short

- ~50 employees with more than 350 man years of explosion experience
- R&D-projects, FLACS based consulting, accident investigation, laboratory testing
- Annual turnover ~ NOK 50 mill
- ~ 150-200 projects per year
- Main office in Bergen, Norway

Software Dept | R&D Dept | Gas Risk Consulting Dept | Process Safety Dept | Laboratories Dept

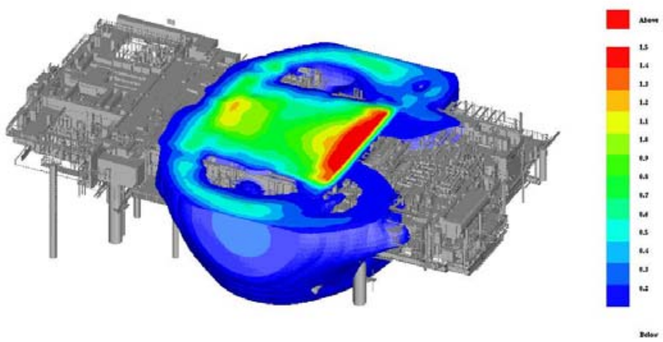
GexCon AS

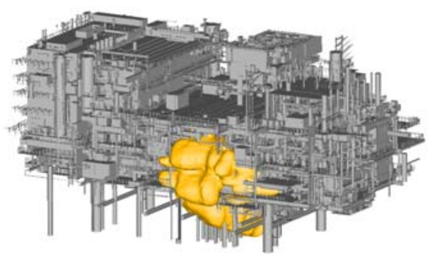
GexCon Sverige | GexCon UK | GexCon USA | GexCon Australia

Italy Agent | China Agents | Korea Agent | Japan Agents | Taiwan Agent | India Agent | Indonesia Agent

Consulting

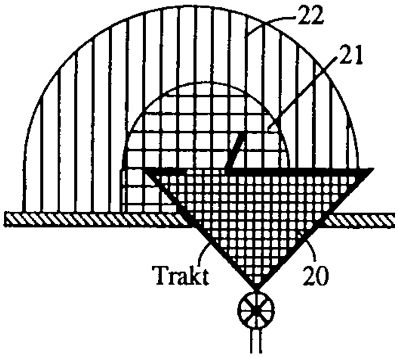
- Dispersion, location of gas detection, simulations
- Explosion effects, prediction, QRAs
- Limitation of effects, design, lay-out, mitigation (water/gas)
- Accident investigations





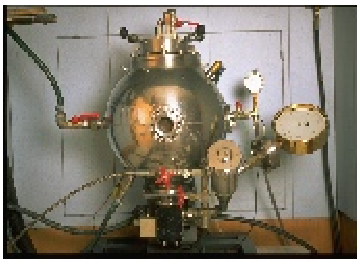
Process Safety/Labs

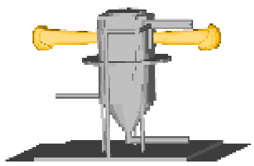
- Standard tests dusts
- Explosion properties gas/dust
- ATEX-certification (together with DNV)
- ATEX Risk assessments
- Ignition source identification
- Plant inspections
- Prevention and protection



Dust explosions

- Establishment of dust explosion test laboratory (1975)
- Large-scale dust explosion research (Boge 1980, Sotra 1984)
  - venting
  - flame free venting
  - explosions in connected vessels
- Ignition sources
  - mechanical sparks
  - electrostatic discharges
- Development of numerical computer code for dust explosion (DESC)

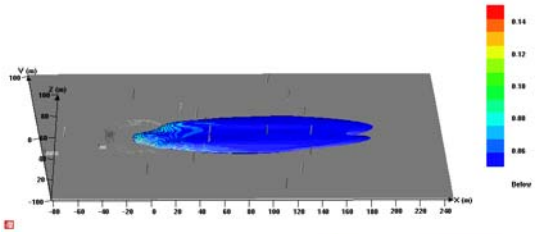


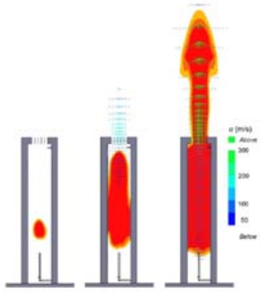


Medium-scale test site

- ATEX testing and approval
- Explosion properties
- Testing of protection systems
- Research and validation
- Tailor-made tests

Software & R&D





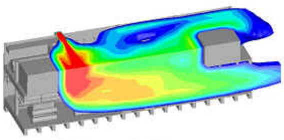
Contract research/New functionality

- LNG modelling
- Flashing releases
- Dust explosion simulator (DESC)
- Hydrogen safety
- JIP: FLACS 2011 and beyond
- CO_2 Pipe Hazards

Software sale, product development and maintenance

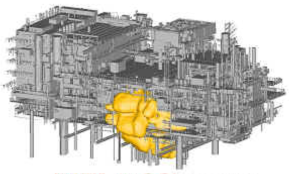
- Marketing and sale of FLACS based products
- Support and maintenance for existing users
- Training courses
- New products and interfaces

Software spectrum

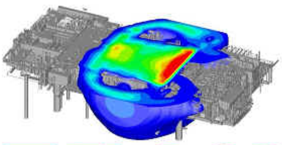


FLACS-DISPERSION

FLACS-AEROSOL



FLACS-GASEX

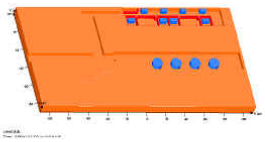


FLACS®

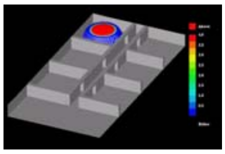
DESC

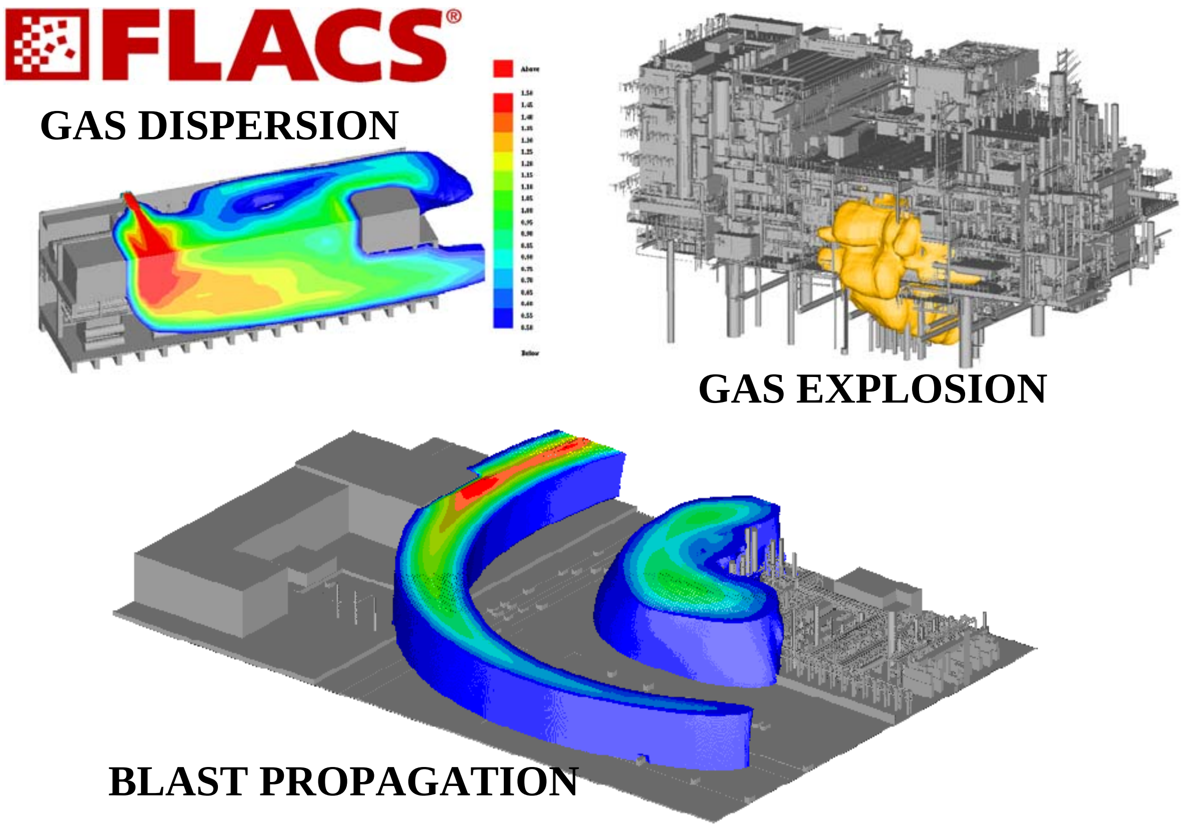
FLACS-HYDROGEN

FLACS-ENERGY

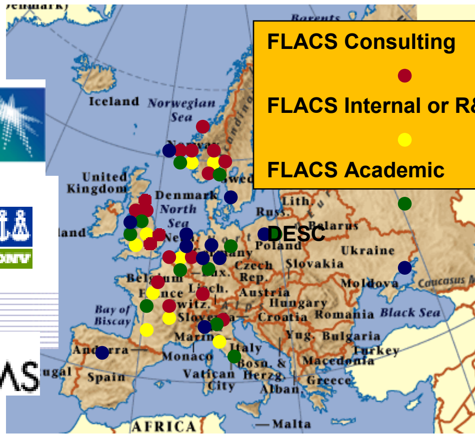


FLACS-TNT




FLACS®
GAS DISPERSION
GAS EXPLOSION
BLAST PROPAGATION

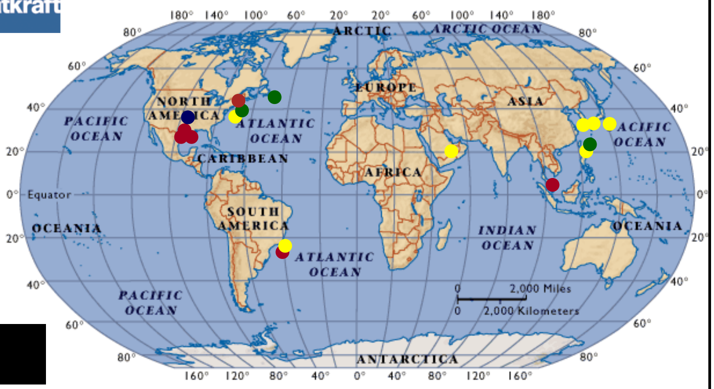
Clients



FLACS Consulting

FLACS Internal or R&D

FLACS Academic



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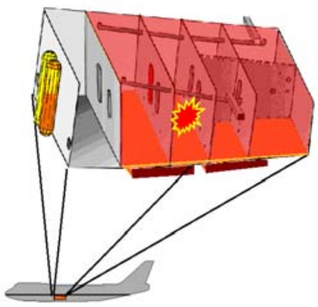
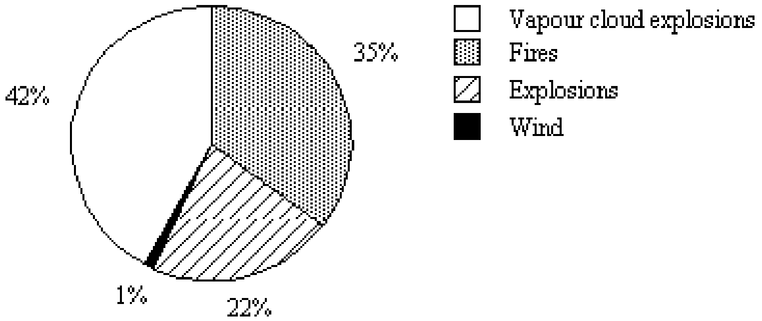
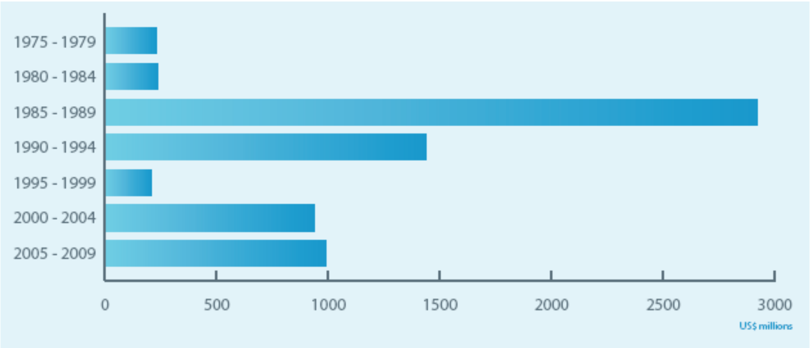
Explosion accidents are found ”everywhere”

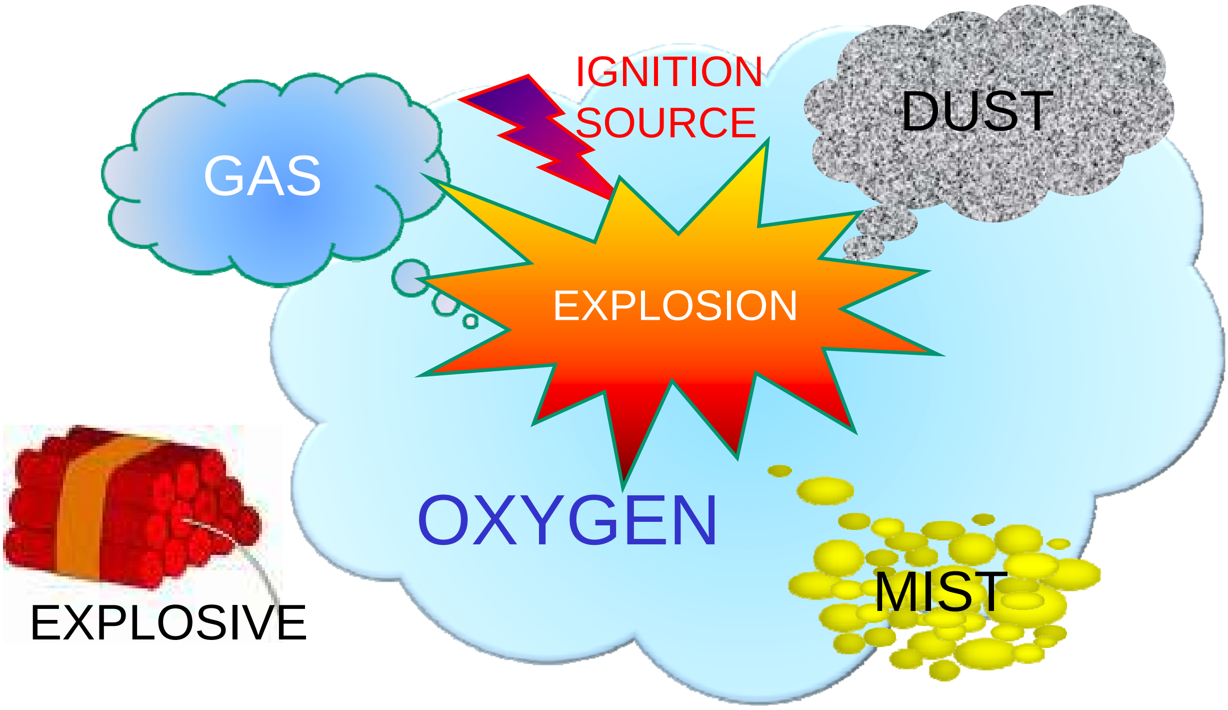


Statistics


42%
35%
1%
22%
Vapour cloud explosions
Fires
Explosions
Wind


1975 - 1979
1980 - 1984
1985 - 1989
1990 - 1994
1995 - 1999
2000 - 2004
2005 - 2009
0
500
1000
1500
2000
2500
3000
US$ millions

Chemical explosion (combustion)



FUEL + OXYGEN + IGNITION SOURCE = Explosion

Gas explosion loading mechanism

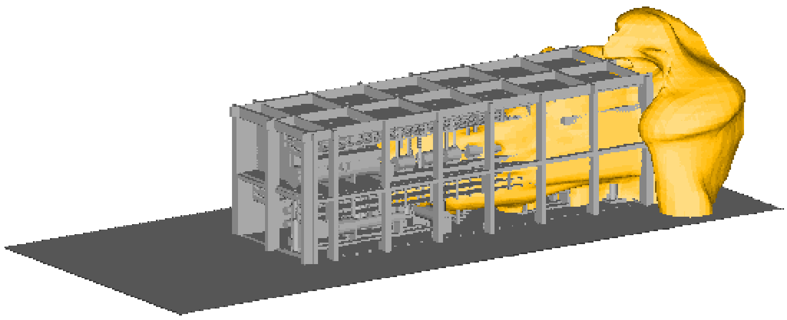
- Burning gas is hot and expands
- Overpressure is generated if expansion is hindered by
  - ✓ walls
  - ✓ equipment
  - ✓ surrounding air
- Confinement extreme conditions:
  - ✓ completely confined (closed vessel)
  - ✓ completely open
- Expansion rate extreme conditions:
  - ✓ low expansion rate (complete confinement)
  - ✓ high expansion rate (no confinement)

$$p=\rho RT/M$$

Gas explosion loading mechanism

- Typically explosions occur somewhere in between the extremes confinement conditions (open/closed geometries)
- The overpressure level is determined by the balance between the rates of expansion and venting

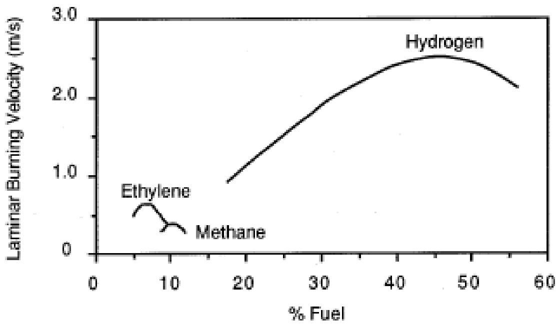
Flame velocity X Flame area → Expansion rate
Gas flow velocity X Vent area → Rate of venting

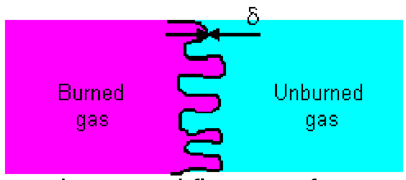


Parameters influencing the explosion evolution

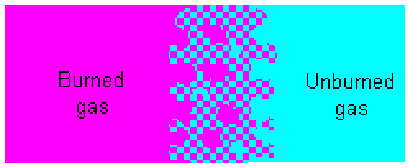
- Flame velocity depends on:
  - ✓ turbulence (interaction between gas flow and obstacles)
  - ✓ gas type
  - ✓ gas concentration

- Flame area depends on:
  - ✓ flame folding (interaction between flame and obstacles)





increased flame surface

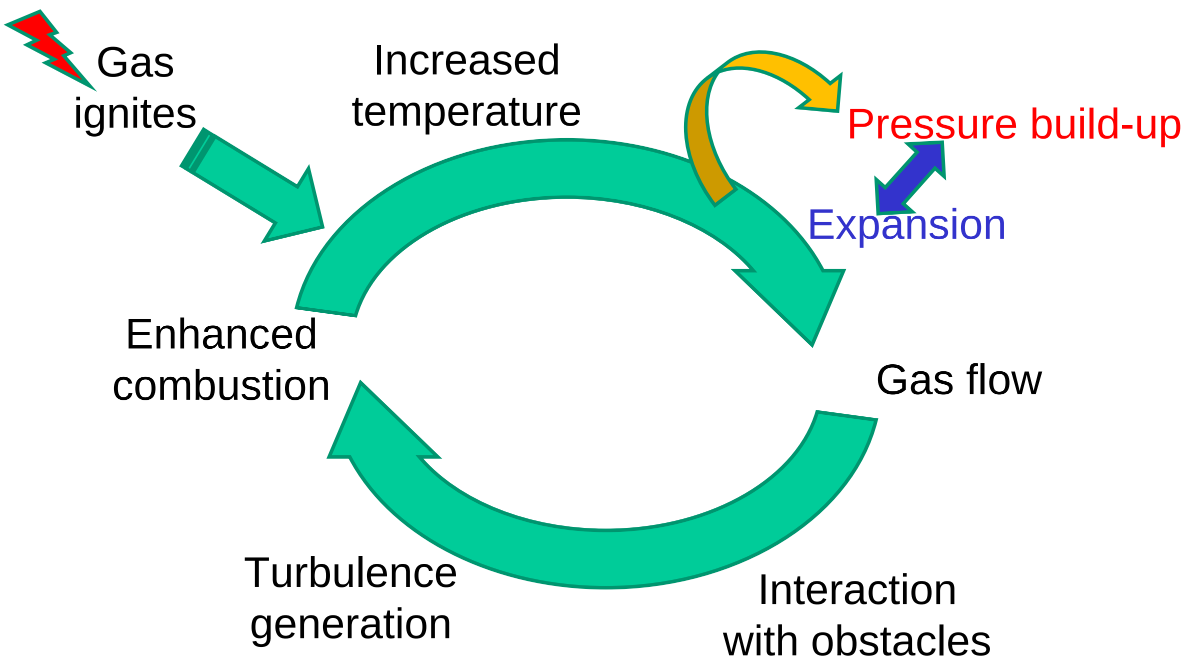


increased diffusion of heat and mass

Parameters influencing explosion evolution

- Flame velocity depends on:
  - ✓ turbulence (interaction between gas flow and obstacles)
  - ✓ gas type
  - ✓ gas concentration
- Flame area depends on:
  - ✓ flame folding (interaction between flame and obstacles)
- Vent area depends on:
  - ✓ design layout
- Gas velocity depends on:
  - ✓ rate of expansion
  - ✓ limited by the sound speed

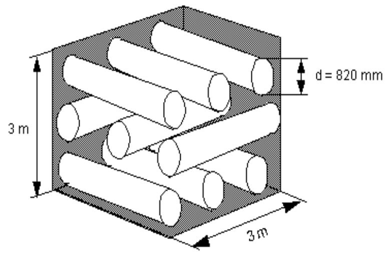
Explosion feedback loop



Explosion feedback loop

- Strongly influenced by congestion degree

EXAMPLE: CMR 3D-CORNER EXPERIMENTS ($27m^3$) WITH PROPANE VBR=0.50

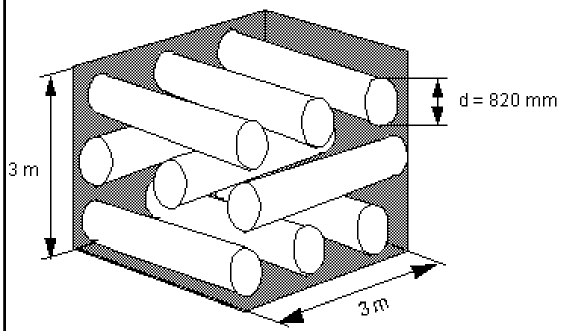


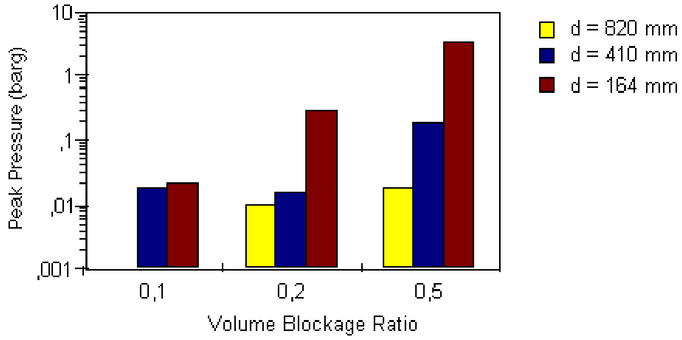
3x3x3 820mm pipes

15x15x15 164mm pipes

Explosion feedback loop

- Strongly influenced by congestion degree
- Very good representation of geometry is required





Same volume blockage, 15x15 thin pipes give > 100 times higher pressure than 3x3 larger

Explosion feedback loop

- Strongly influenced by congestion degree
- Very good representation of geometry is required

EXAMPLE: 45m ENCLOSURE WITH CYCLOHEXANE; LONG ARRAY OF CROSS FLOW OBSTRUCTIONS; NO CONFINEMENT

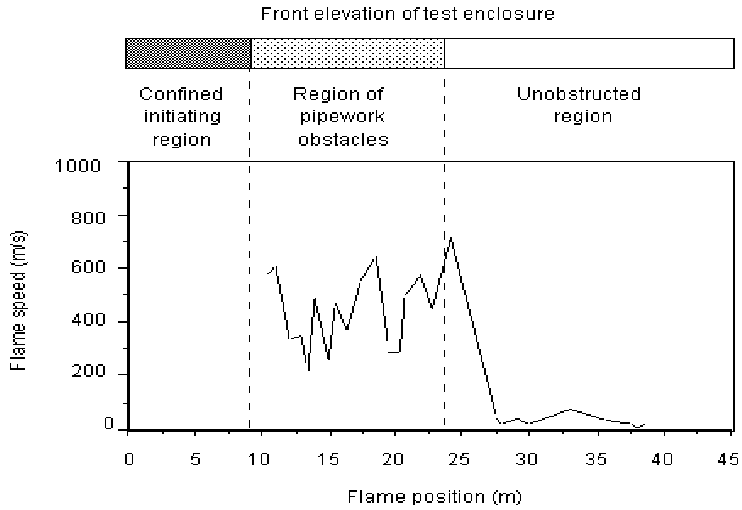
obstacles along the whole enclosure

obstacles along half enclosure

Explosion feedback loop

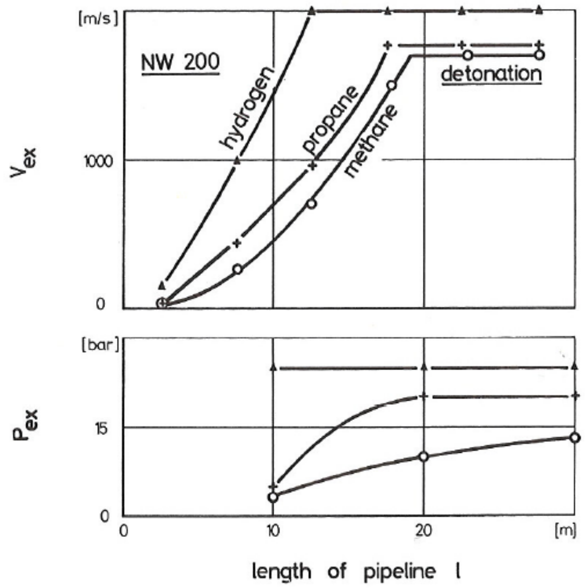
- Strongly influenced by congestion degree
- Very good representation of geometry is required

EXAMPLE: 45m ENCLOSURE WITH CYCLOHEXANE; LONG ARRAY OF CROSS FLOW OBSTRUCTIONS; NO CONFINEMENT



Deflagration to Detonation Transition (DDT)

- Strong deflagrations can transit into a detonation
- Pipes: explosion generated turbulence at walls results in flame accelerations and possibly DDT



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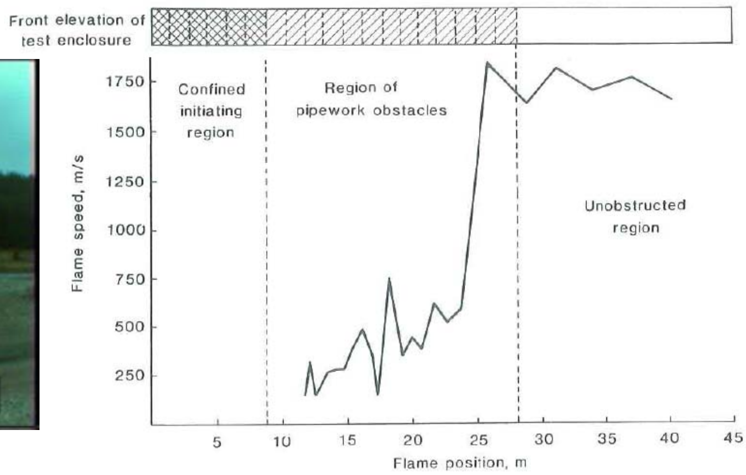


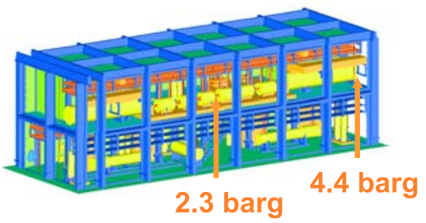
Effect of confinement (venting degree)

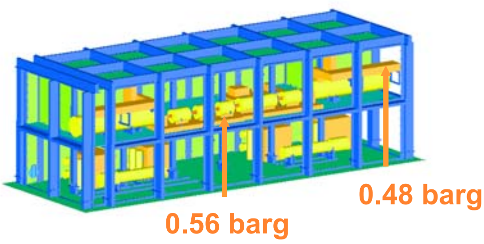
0.1 barg

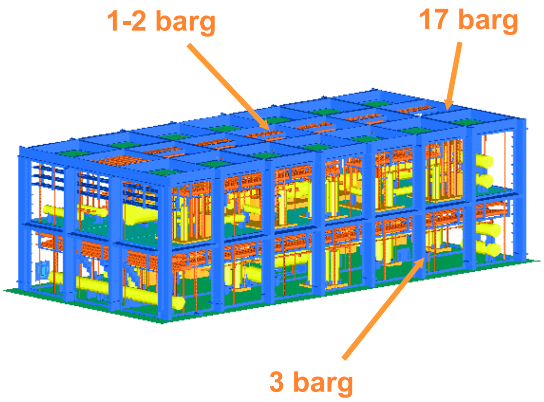
2 barg

Effect of Ignition Location

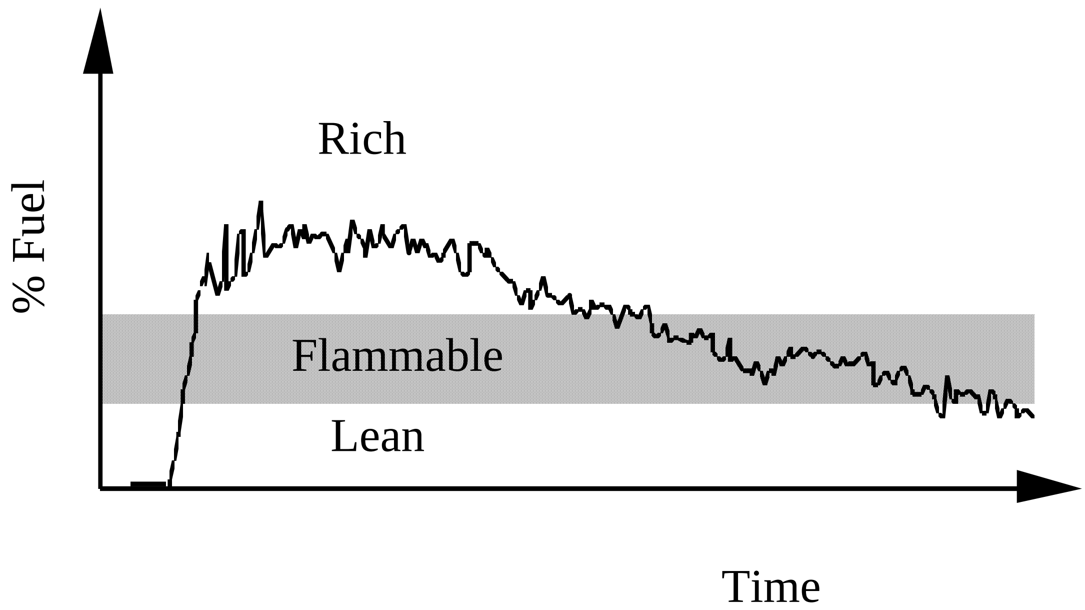
- Pressure varies with congestion and ignition location





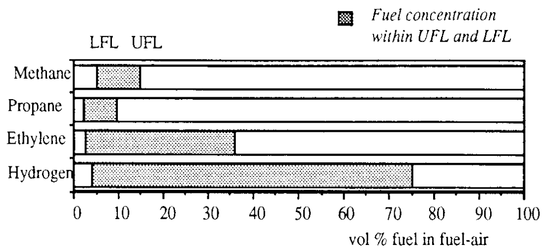


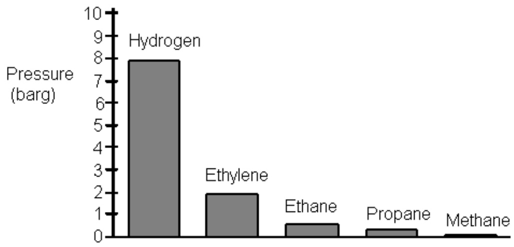
Concentration of gas cloud

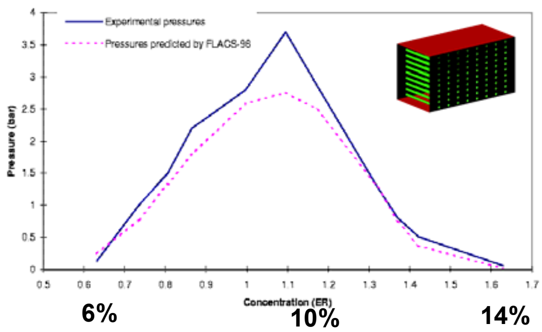


Gas Type and Reactivity

Significant difference in reactivity among gases and concentrations

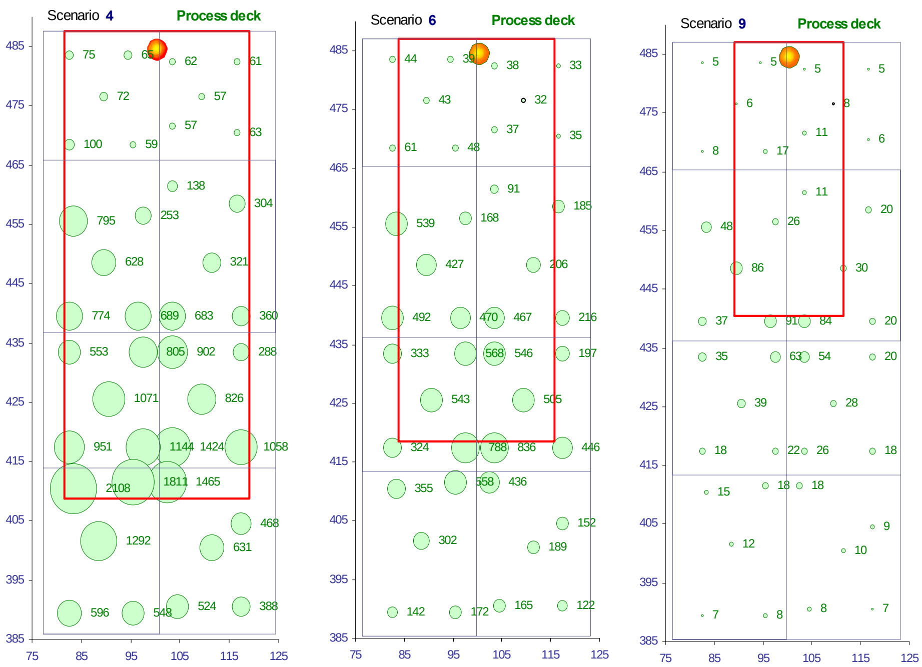






Example difference between propane and hydrogen

Effect of gas cloud size



"Bubble" –size proportional to overpressure

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- Presentation of GexCon
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- Methods for blast loads evaluation
- Requirements for suitable gas explosion loads prediction tools
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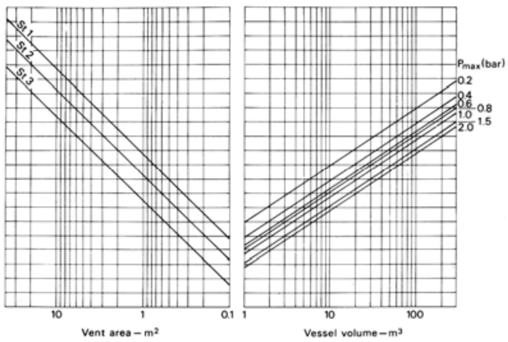
How can explosion loads be estimated?



- Nomograms (guidelines e.g. NFPA-68):
  - ✓narrow application range
  - ✓real situations often under-predicted
- Blast decay methods (e.g. Multi-energy method)
  - ✓simple and useful if applied conservatively
  - ✓limitations (good for far field)
- Experimental scaling
  - ✓expensive and inaccurate in a general situation
  - ✓limited value (Pmax can be approximated, not duration)
- Phenomenological models
  - ✓can give reasonable results in certain situations
  - ✓explosion phenomena too complex in general
- **CFD simulations (e.g. FLACS)**
  - ✓potential for accurate estimates
  - ✓complicated physics → **validation** important

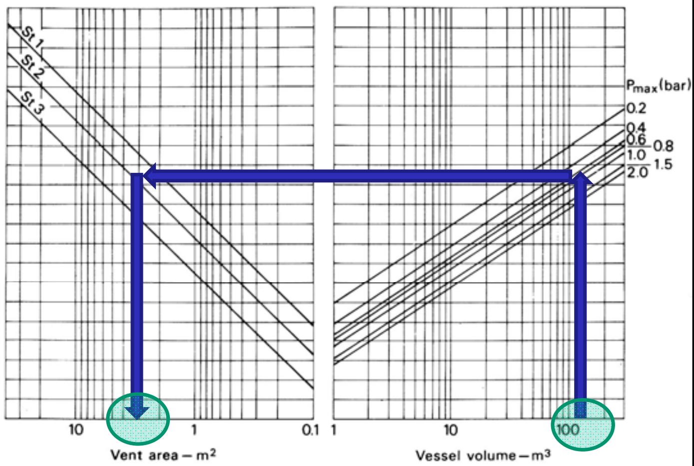
How can explosion loads be estimated?

NFPA-68: explosion venting

- ✓ nomograms for vent area dimensioning
- ✓ design parameters: vessel volume, maximum internal pressure
- ✓ parameterization with respect to:
  - gas/dust reactivity
  - vent opening pressure

Relationship between K_{st} values and explosion class

K_{st} (bar m/s) Strong ignition source (10 kJ)	Explosion class	K_{st} (bar m/s) Weak ignition source (10 J)
0	St 0	0
< 200	St 1	< 100
> 200-300	St 2	> 100-200
> 300	St 3	> 200

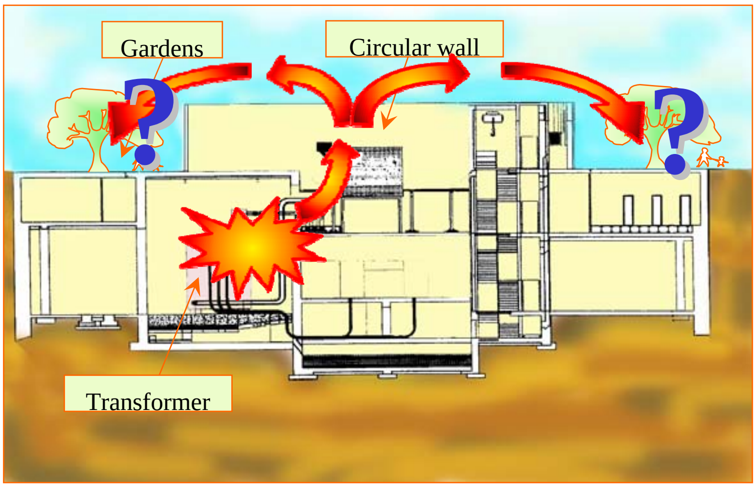


Nomograph to determine vent areas for combustible dusts subjected to weak ignition conditions, vent opening pressure 0.1 bar
P_{max} = maximum pressure obtained in the vessel during venting [178]
(reproduced by permission, from NFPA 68, Guide for Explosion Venting, © NFPA, 1978)

How can explosion loads be estimated?

NFPA-68: explosion venting

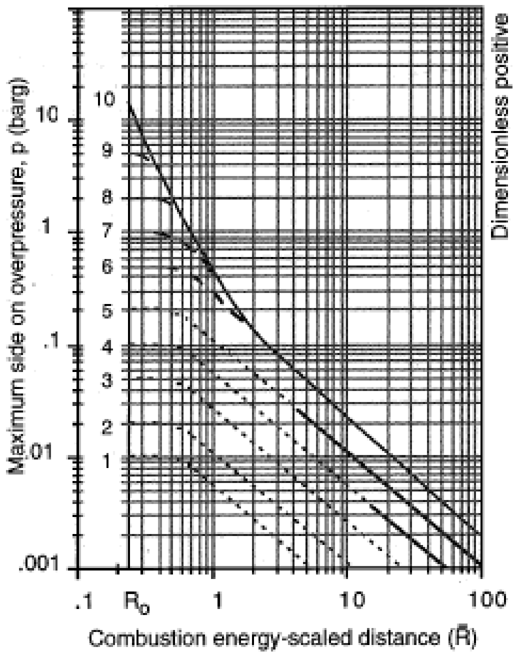
- ✓ nomograms for vent area dimensioning
- ✓ design parameters: vessel volume, maximum internal pressure
- ✓ parameterization with respect to:
  - gas/dust reactivity
  - vent opening pressure
- ✓ correction for partially filled vessels
- ✓ correction for vent duct (questionable?)
- ✓ interpolation of experimental results for given test set-ups: be careful in using it for different layouts!
- ✓ no information about what happens outside the vented vessel



How can explosion loads be estimated?

MultiEnergy method: far field effects

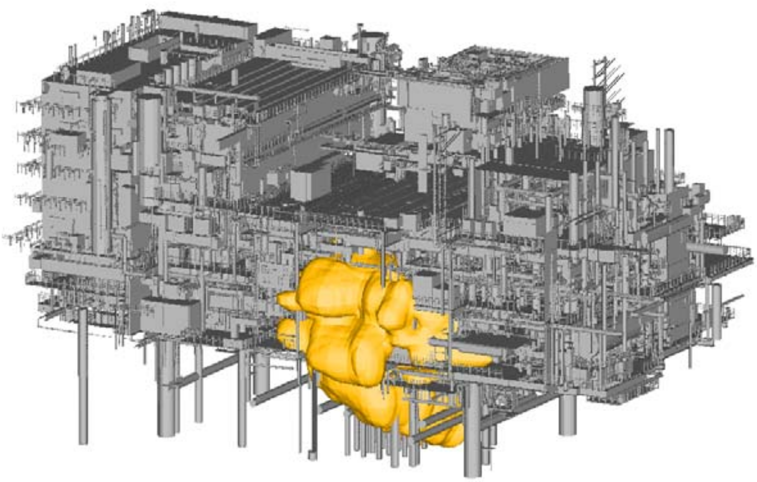
- ✓ nomograms for overpressure estimation
- ✓ parameterization with respect to:
  - gas/dust reactivity
  - area congestion degree
- ✓ allows good predictions for damage potential in the far field
- ✓ semi analytical - empirical basis: be careful in using it beyond its scope!
- ✓ no reliable information about what happens in the near field



How can explosion loads be estimated?

CFD simulations

✓good potential for accurate estimates in industrial applications
✓complicated physics → **validation** is important



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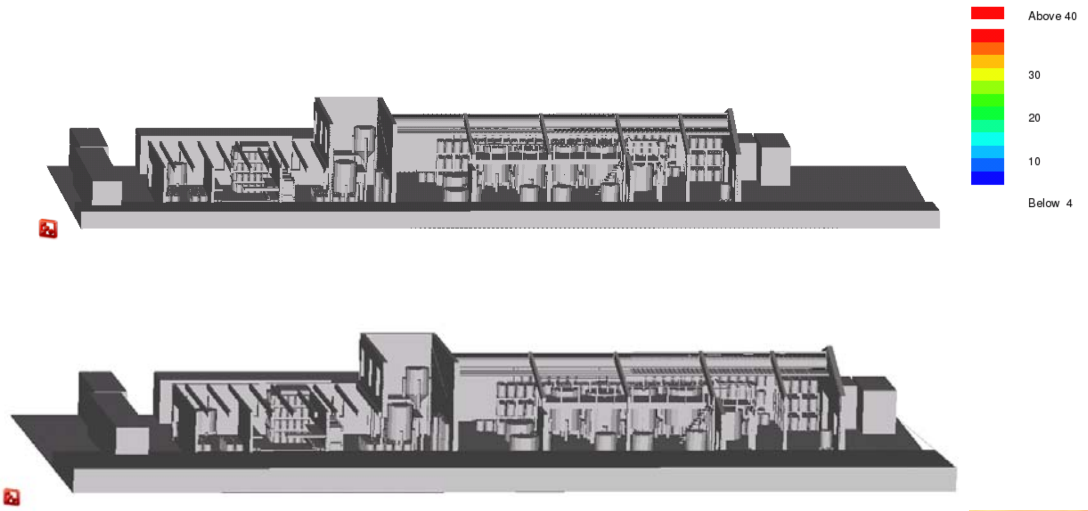
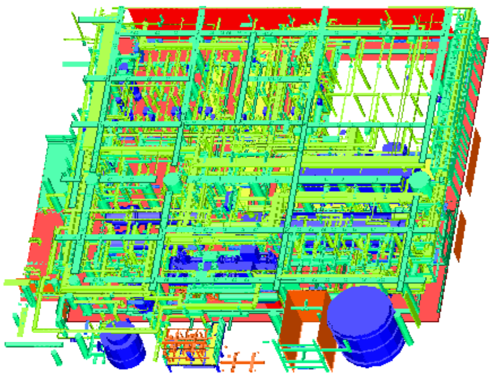
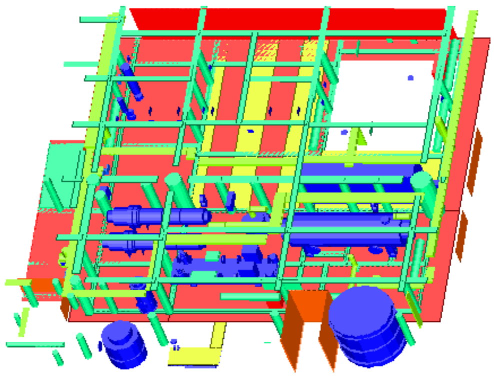
Parameters affecting explosion strength

- Obstacle density (flow across obstacles accelerates flames)
- Confinement and vent areas (removal of walls reduces pressures)
- Reactivity, size and concentration of flammable cloud
- Flame distance / ignition location (severity may increase with scale)



Requirements for suitable gas explosion load prediction tools





➢congestion degree (location and size of structural elements and equipment)

Geometry details are very important: Tools that ignore details can overpredict ventilation by a factor 2 and underpredict explosion load by a factor 5 or more

Requirements for suitable gas explosion load prediction tools

Gas explosions may be very sensitive to changes in several factors: a proper tool for gas explosion load prediction should permit to properly take into account all these aspects, which can be resumed within the following requirements:

- geometry based formulation
- capability in describing complex 3D geometries (up to hundreds of thousands primitives for real plants)
- full Navier-Stokes fluid dynamic formulation for the estimation of turbulence field
- laminar and turbulent burning velocity model
- validated gas library (explosion properties database for a given, clearly stated set of gases)

Requirements for suitable gas explosion load prediction tools

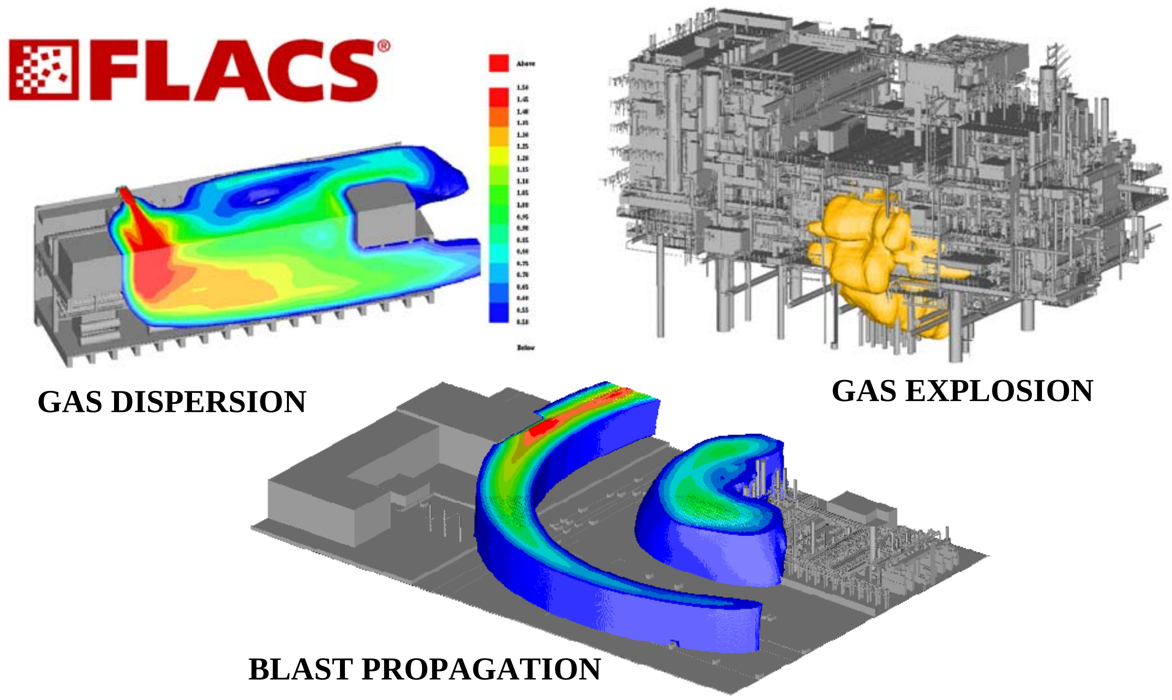
A complete and versatile tool for gas explosion quantitative risk analysis should include:

- a ventilation module for proper description of environmental conditions
- a dispersion module for proper description of gas cloud formation
- an explosion module for proper description of flame and pressure wave propagation

Outline

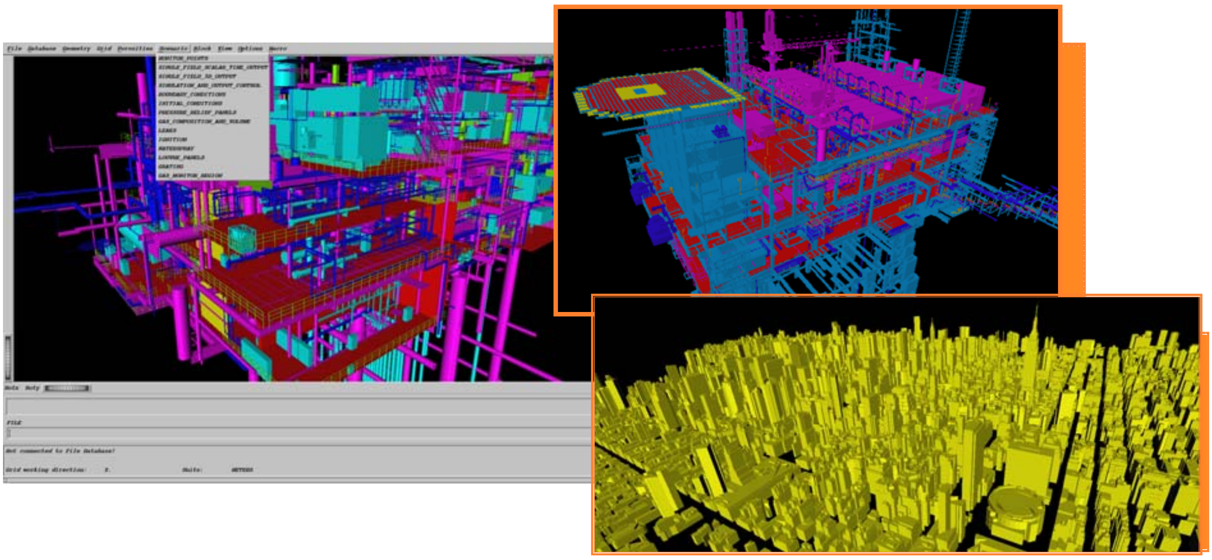
- Presentation of GexCon
- Gas explosion and affecting parameters
- Simplified methods for blast loads evaluation
- Requirements for suitable gas explosion loads prediction tools
- Presentation of FLACS code
- Risk assessment methodologies

FLACS – (FLame ACceleration Simulator)



Geometry representation

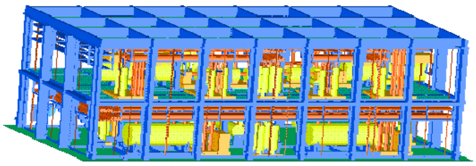
Recent dispersion tests in geometries of "real" congestion confirmed importance of geometry representation also for dispersion analyses



FLACS has advantages to traditional "state-of-the-art" CFD-tools due to more efficient geometry handling (including import)

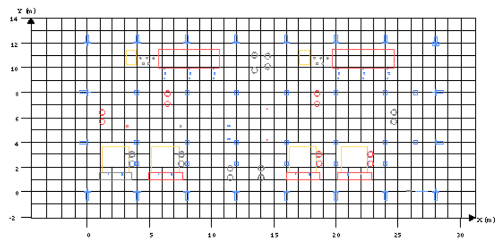
Geometry representation

Explosions require very good representation of geometry



All objects are built from **box** or **cylinder** primitives (including minus operations)

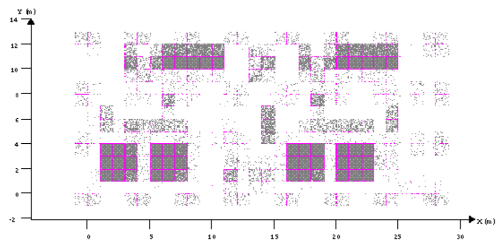
Geometry is mapped to the CV's using a **distributed porosity concept**



A control volume or CV-face may be open / partly blocked / fully blocked

In addition to porosities, **sub-grid turbulence factors** are calculated

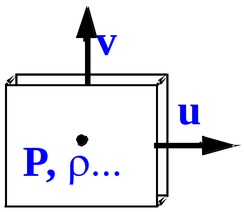
Efficient CAD-import systems exist
GexCon imports about 40-50 offshore geometries from PDMS and **PDS (Microstation)** every year



Range of geometries includes

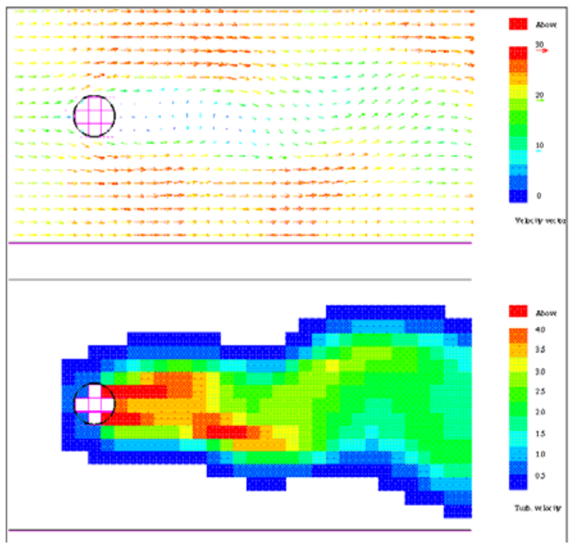
- simple geometries easily defined by hand
- full offshore platforms/FPSO (~ 400.000 objects)

FLACS equations



Flow solver:

- Full 3D Cartesian N-S flow solver
- SIMPLE method, compressible extension
- Implicit/explicit 2nd order accuracy
- BICGSTAB-solver
- Transport equations for fuel/fuel mix.
- Distributed porosity concept (PDR)
- Source terms for chemical reactions



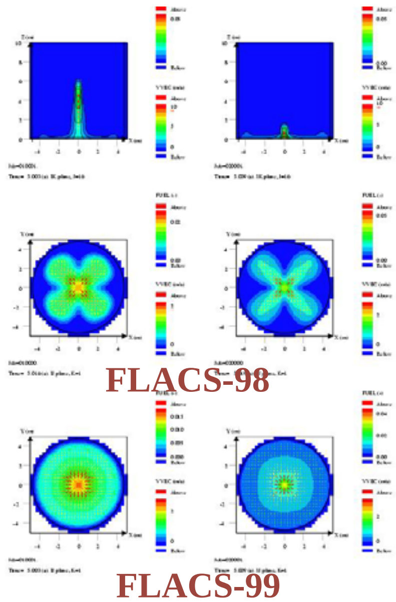
Turbulence:

- k-ε model
- wall functions
- sub-grid contributions

Numerical methods

High accuracy and efficiency in solver is required

Optimisation between
- Solver accuracy
- Convergence rate/criterion
- Numerical schemes describing physics



Example of dispersion case, change of discretisation needed to obtain physically correct results

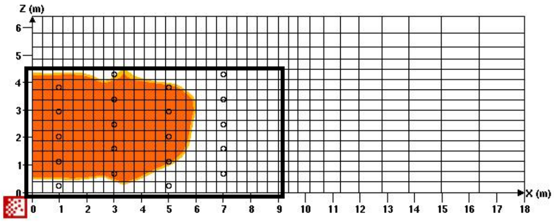
Indications that FLACS solves explosions faster than competitors
- Usually good answers within minutes (< 30 minutes)
- Extensive explosion calculations (1-5 hours)

Sub-grid Modeling

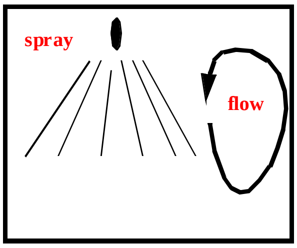
Several scales must be solved on realistic grid sizes (0.1-2m)

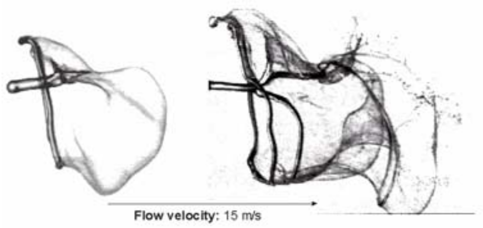
Turbulence model is one of several SUB-GRID models in FLACS

- Initial combustion model
- Flame model
- Flame folding around objects
- Water deluge model
- Models for panels



Subgrid pipes increase pressure factor of 6





Development and validation of sub-grid models are time consuming easy to make a model, difficult to make a good model

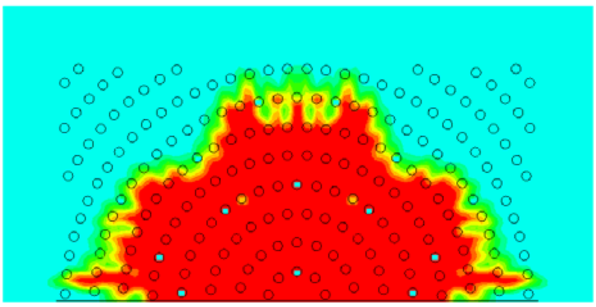
Flame Modeling

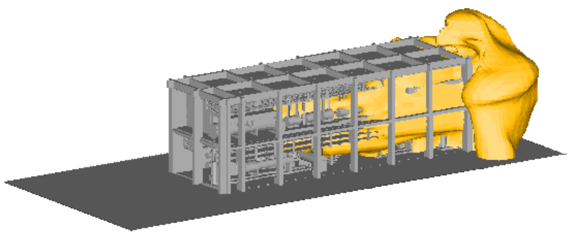
FLACS flame models:

Beta model, force fuel equation to give specified burning velocity (S_{lam}, S_{turb})

=> reaction zone has a certain thickness (3-5 control volumes)

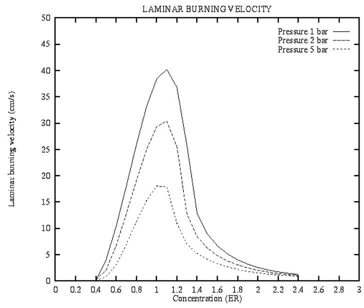
Must be adjusted when high curvature / laminar phase (wrinkling low with thick flame)





Any flame model (3D) will be grid dependent!

Burning velocity Models



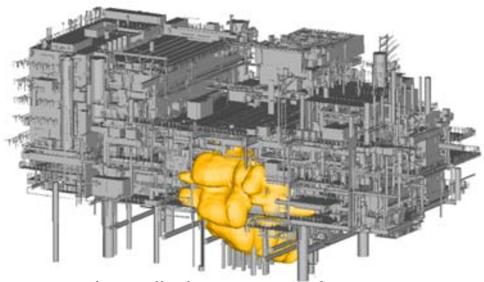
- Flame library, Slam(ER), for all gases
- For gas mixtures properties are interpolated
- Corrections for actual T, P, oxygen content in air
- Quasilaminar model for initial flame wrinkling
- Correlation for S_{turb}
- Turbulent quenching
- Mitigation of inert gas / deluge will influence
- Subgrid objects enhances the flame area (flamefolding)

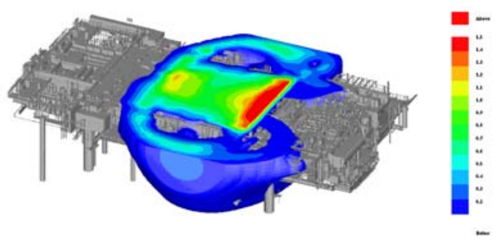
Enthalpy Models

- Energy release from combustion => increased temperature
- Temperature increase depends on reaction products generated
- FLACS calculates this from equilibrium conditions based on reactant composition, ER, presence of inert gases, ambient T / P
- Hydrocarbon gases burn into H_2 + CO + OH + H_2O + CO_2
- Fraction of CO increases with temperature, fuel concentration

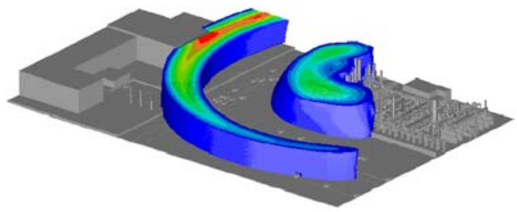
Wide Applicability

Ventilation, gas dispersion and explosion onshore/offshore





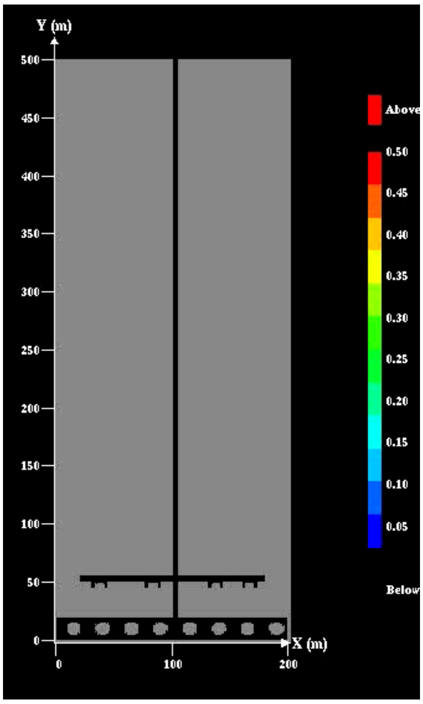
- natural ventilation, HVAC, fans
- dispersion, low and high momentum releases
- practically any type of geometry
- variable gas cloud size (defined / from dispersion)
- variation of ignition location
- hydrocarbon gases + H_2S + hydrogen+CO
- any mixture and concentration of the above gases
- pressure relief panels
- effect of water deluge, inert gases, CO_2 and nitrogen, O_2
- prediction of blast strength in far field
- initial condition: temperature / pressure / turbulence
- liquid particles / oil mist
- Fire functionality under development

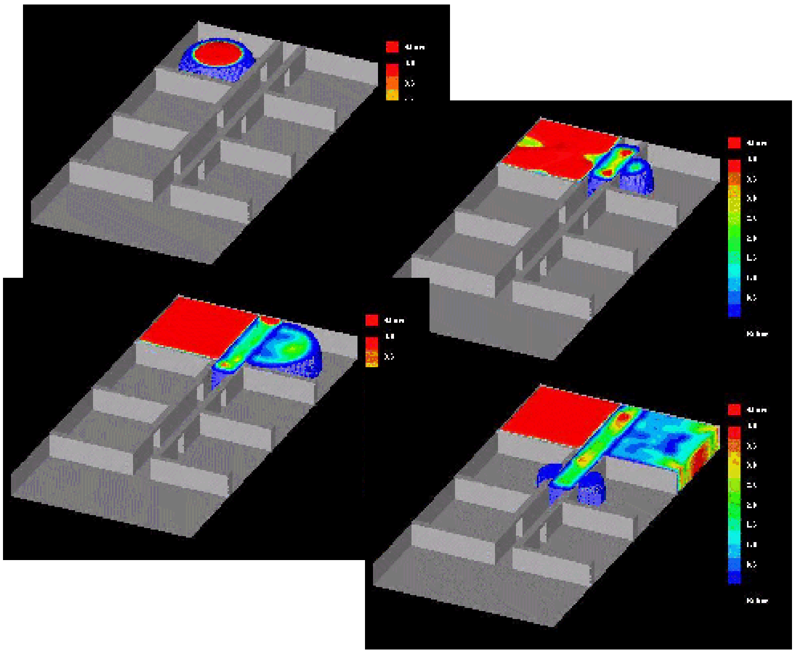


Blast wave propagation
effect of buildings

Wide Applicability

Explosion in tunnel systems (hydroelectric plant)

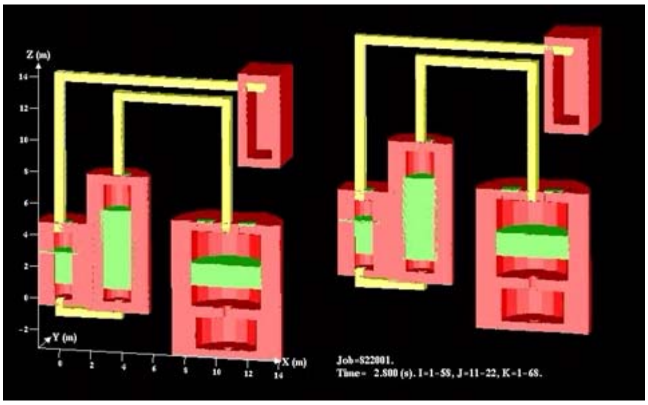


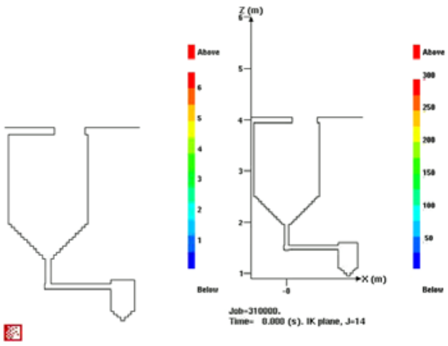


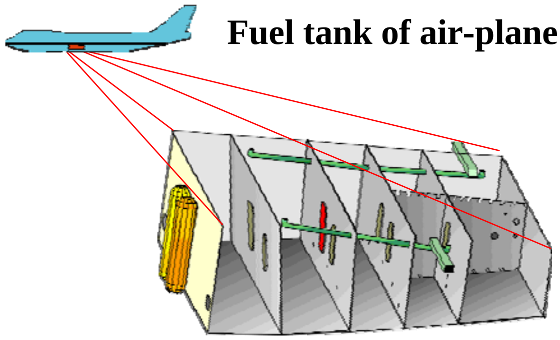
Explosives in storage facility

Wide Applicability

Chemical process, sizing/location of rupture discs







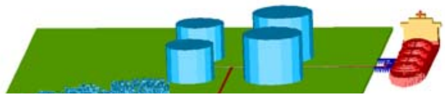
Fuel tank of air-plane

- Process flow turbulence
- Fuel concentration & oxygen amount
- Elevated pressure & temperature
- Rupture discs with inertia
- Connected vessels / pressure piling
- Effect of internal geometry

Wide Applicability

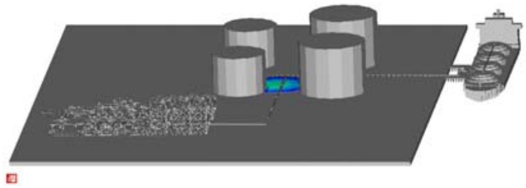
Similar consequence studies for other industries, e.g.

- Hydrogen safety, new energy or nuclear plant
- Coal mines, transformer explosions in substations
- Transportation, pipelines, LNG-carriers (storage/leaks and exhaust-pipe explosions)



GexCon did safety study for
Gas fuelled ferries (natural gas)

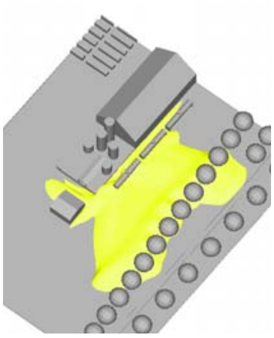
In Norway there is also work with hydrogen ships



Wide Applicability

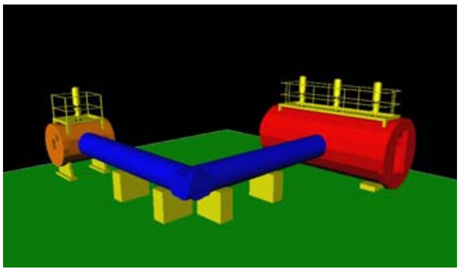
Dispersion of toxic gases

- Tracer gas in urban areas
- Chlorine releases from railcars
- H_2S from reservoirs, CO_2 injection issues

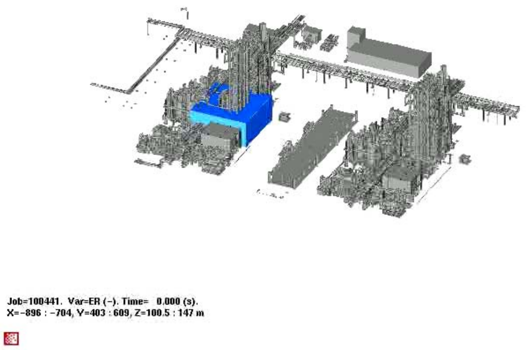


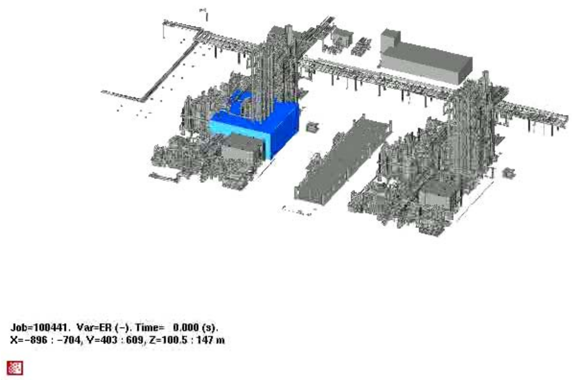
DESC tool (based on FLACS)

- Dust explosion modeling for process industry and more



FLACS applications – Onshore Gas Explosion

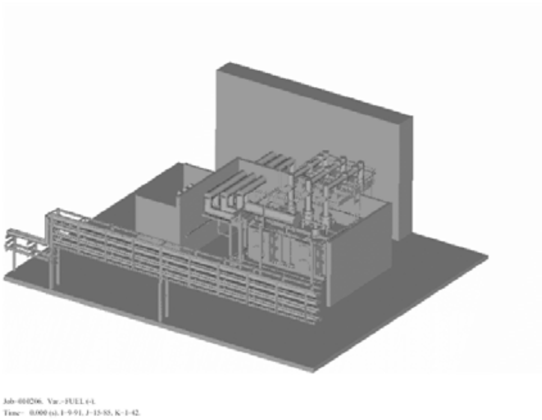


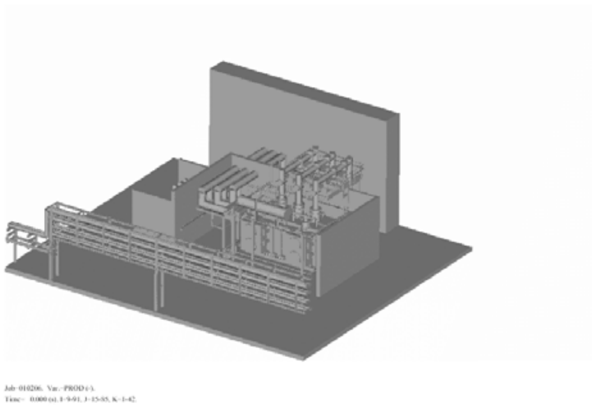


Pressure wave propagation

Flame propagation

FLACS applications – Transformer explosion thermal powerplant

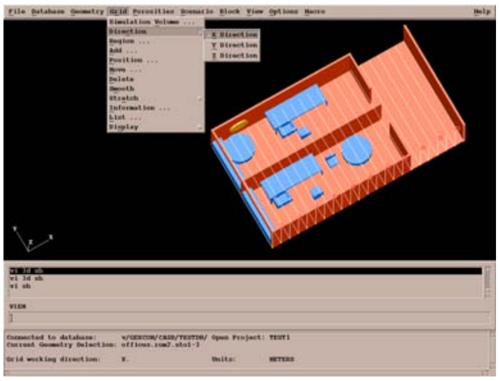




Fuel dispersion **Flame propagation**

Efficient Preparation and Reporting

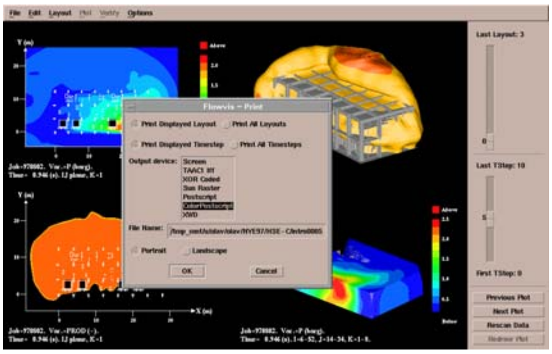
Preprocessor CASD can be used both with menus and command line

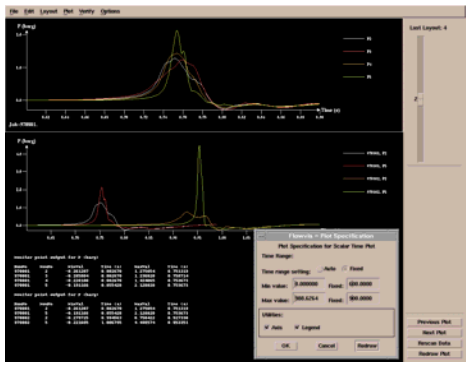


Utility programs
Expert users use manual editing

Multiple simulations can be prepared and started by use of scripts

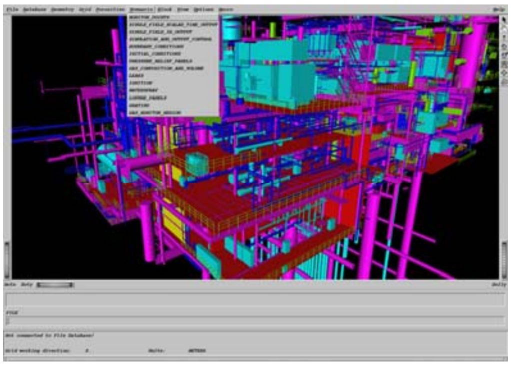
Efficient result processing with Flowvis



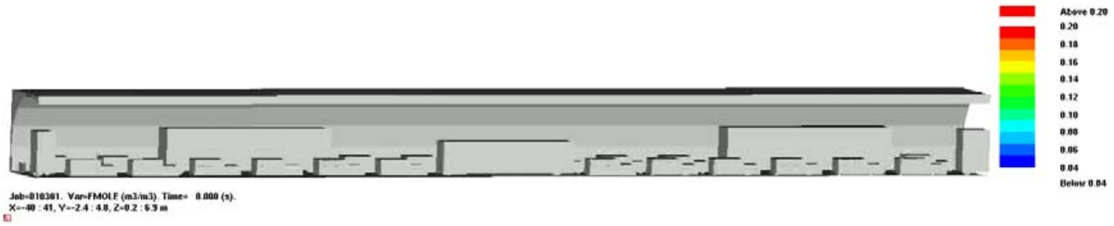


Efficient Preparation and Reporting

More recent features:
3D-walk through options in preprocessor
(result viewer partly developed)



Automatic generation of video-files (mpg)



Outline

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Explosion hazard management

Risk reduction measures should focus on:

- preventing incidents (i.e. reducing the probability of an explosion occurring)
- controlling incidents (i.e. limit the extent and duration of a hazardous event, reducing explosion loads to acceptable levels)
- mitigating the effects (i.e. reducing the consequences of an explosion and reduce the likelihood of escalation as a result of explosion loads).

Risk Analysis provides useful information for taking decisions within the hazard management process.

Risk assessment methodology

using suitable tools for gas explosion loads quantification

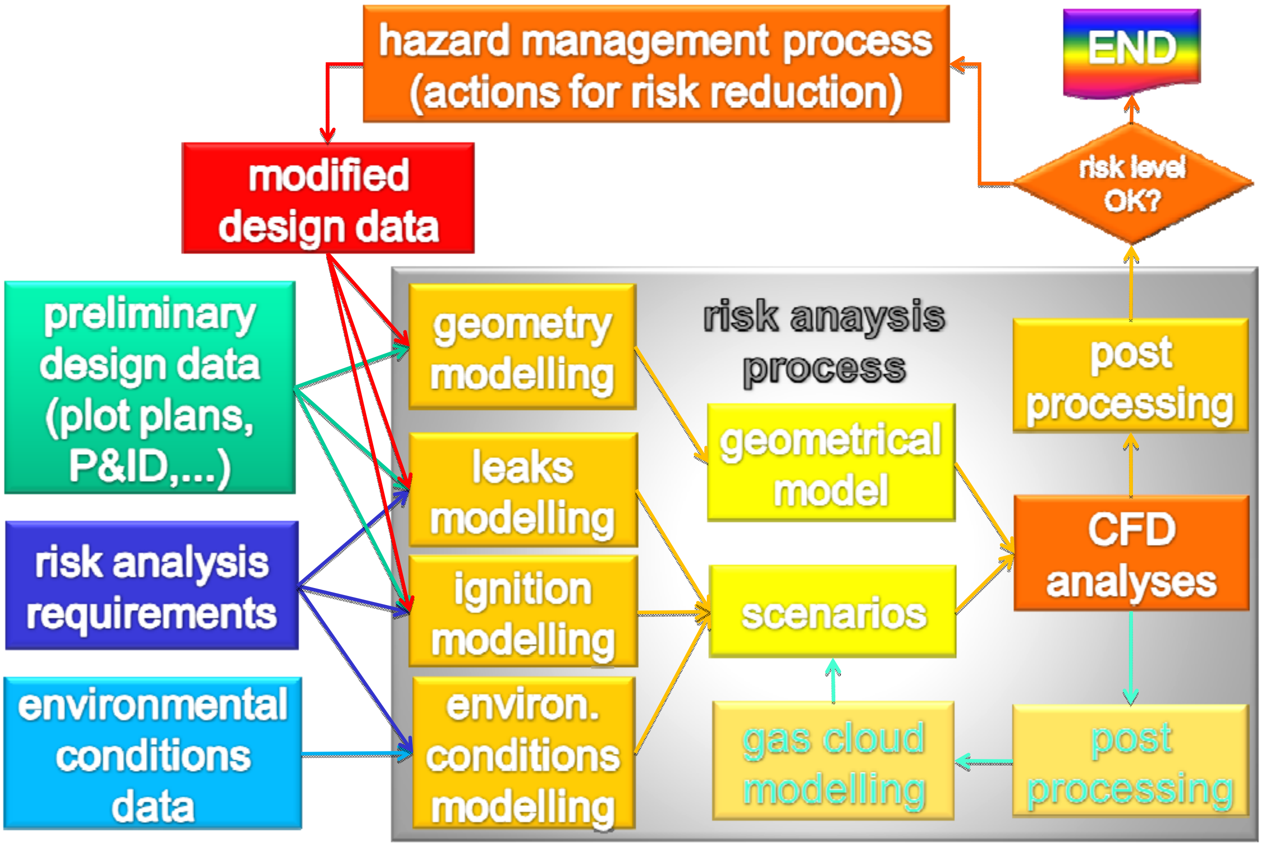
→ key requirement in a risk analysis process ←

→ **not sufficient** ←

suitable risk assessment methodology is needed

✓collecting and integrating input/output information relevant to different task for proper modelling

✓producing synthetic output information suitable for final assessment


hazard management process
(actions for risk reduction)
END
risk level OK?
modified design data
preliminary design data (plot plans, P&ID,...)
risk analysis requirements
environmental conditions data
risk anaysis process
geometry modelling
leaks modelling
ignition modelling
environ. conditions modelling
geometrical model
scenarios
gas cloud modelling
post processing
CFD analyses
post processing