2005 Asia-Pacific Conference on
Risk Management and Safety

The Comparison of CFD with a Traditional Method Used in an Incident Investigation Case Happened in Taiwan

Yet-Pole I* and Te-Lung Cheng

Department of Safety, Health, and Environmental Engineering
National Yunlin University of Science & Technology, Taiwan

Contents

- Introduction
- Background of the Accident
- Research Methods
  - Traditional methods
  - CFD method
- Results and Discussion
- Conclusions

Introduction

- On an afternoon of middle December 1997, a gas explosion happened in a 25,000 m^3 refrigerated storage tank for LPG at a local company, Taiwan. Three contactor workers were immediately killed at the accident. The hot fragments of the tank scattered allover the plant and hit pipe rack, a waste oil tank and the deck of an LPG discharge tanker and cause fires in four different site areas.

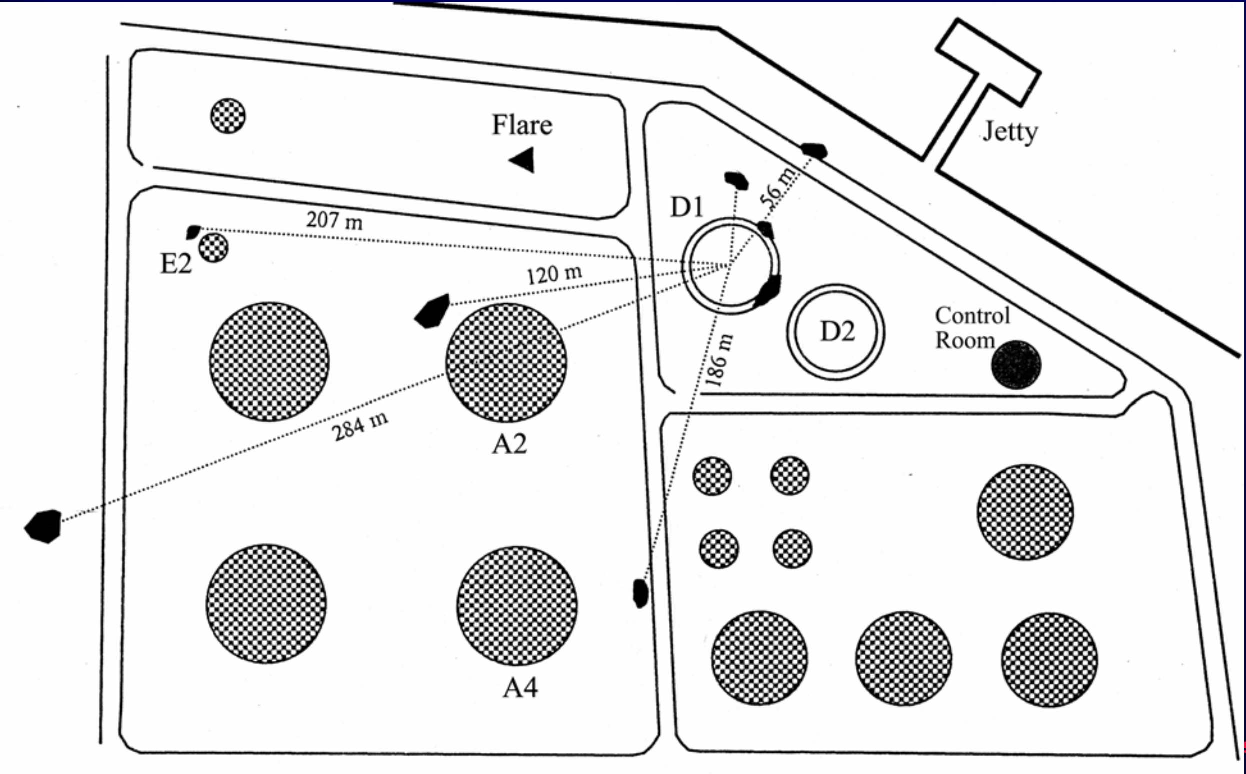


Figure 1: Explosion Distance of the LPG Tank Debris

Table 1. Tank Data of Accident Site

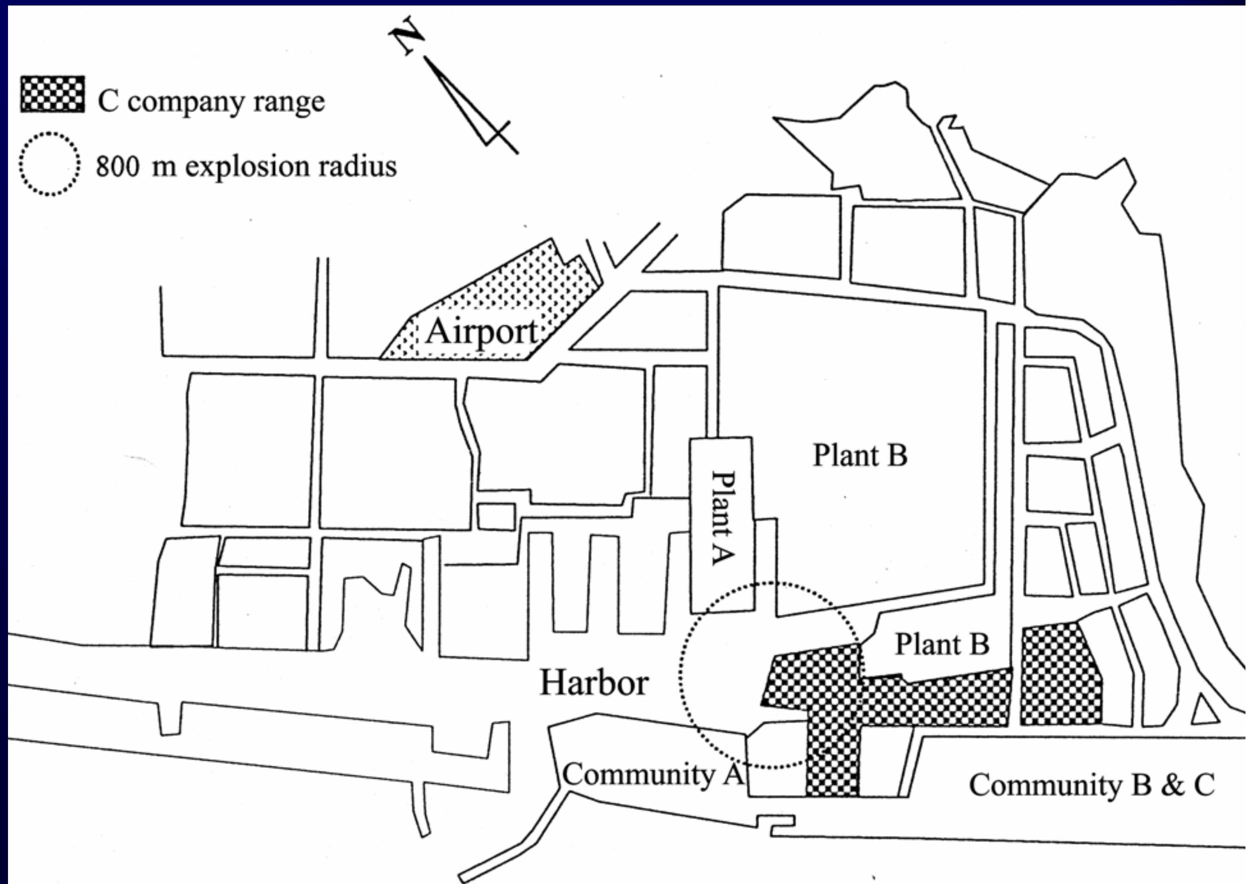
Tank No.	Contents	D (m)	H (m)
A1-A4	Petroleum	56.8	26.8
B1-B4	Petroleum	42.5	26.8
D1-D2	Refrigerated LPG	35.5	30.0
G1-G4	Pressurized LPG	17.4	17.4
E1	Waste oil	13.5	7.6
E2	Waste oil	15.5	8.8

Introduction (cont.)

- The fires were put out that evening. A hazard area with a radius of 800 m from the explosion center had been investigated after the accident; many window-glasses broken cases had been found within that limit.
- In this research, different consequence analysis methods such as TNT equivalent calculation and CFD technique were utilized and compared to investigate this LPG fire and explosion accident.

Background of the Accident

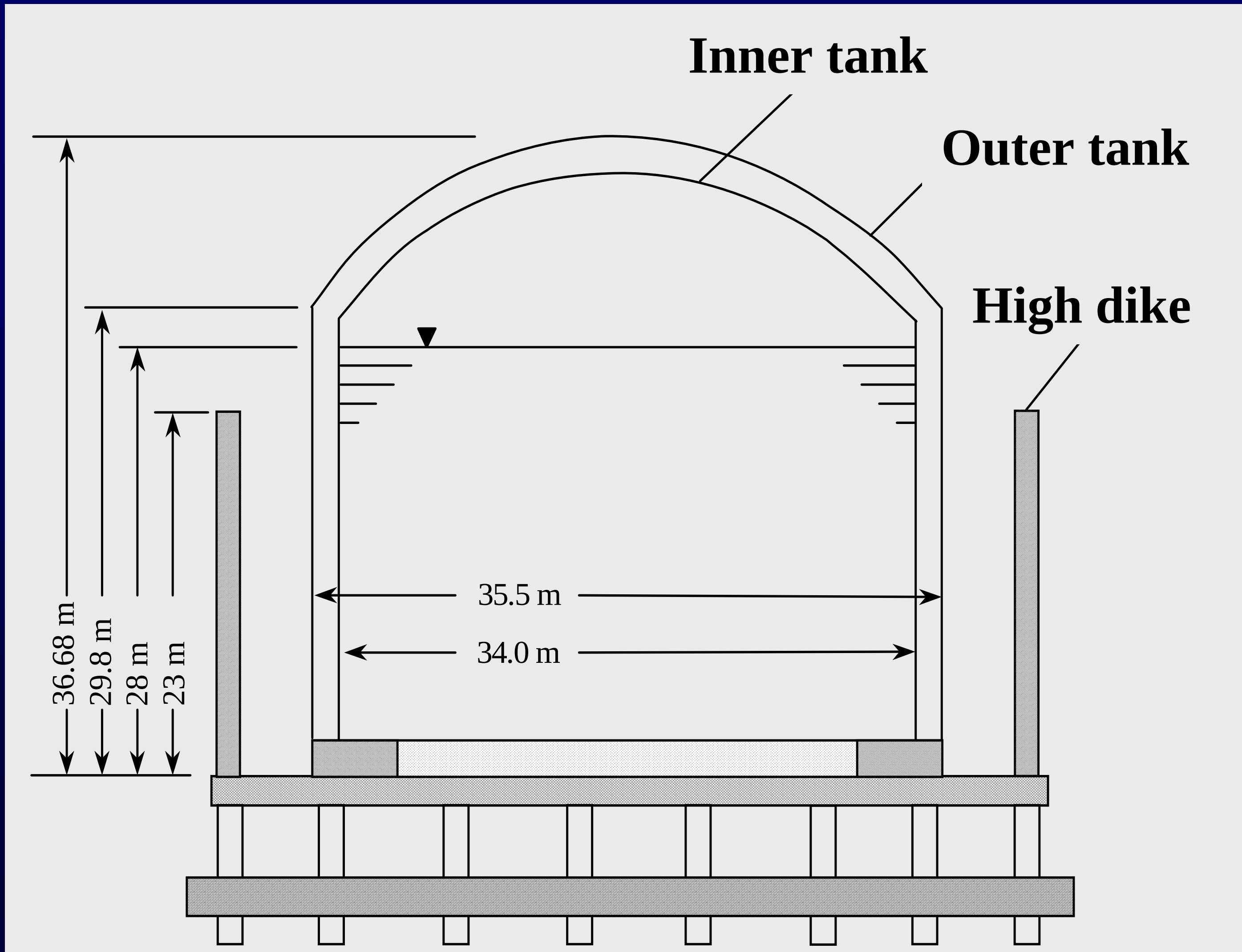
- The 300 hectares plant site owned by the C Company is located at a local harbor; it has more than a dozen process factories and five tank farms. Oil tankers less than 100,000 tons can directly come to anchor at the jetties along the tank farms.
- There are also three communities near by the plant site.
- The accident happened within the No. 2 tank farm.



Characteristics of LPG

- Liquefied petroleum gas (LPG) is mainly composed of propane and butane and is a common industrial or domestic fuel gas.
- It is estimated the volume of the refrigerated LPG will increase 322 times from its storage temperature (-43°C, 583.8 kg/m^3) to the ambient temperature (28°C, 1.81 kg/m^3) after vaporization.
- The fire and explosion limit of the LPG gas-air mixture is between 1.9% and 9.5%
- The minimum ignition energy (MIE) of the LPG gas-air mixture at 25°C is about 0.25 mJ
- The LPG gas-air mixture is quite easy to be ignited via static electricity, mechanical grinding or collision.

Description of the Exploded Tank



Empty procedure for the D1 tank

1) Pump remaining LPG → spherical tanks.
2) Until L→0, raise tank T → T_a
3) Purge LPG residue → flare.
4) Continuous purge until the tank P → 1,000 mmWg.
5) Repeat step 3) and 4) until C_{LPG} < 20% of LEL → stop.
6) Pump air → tank to replace N_2 until C_{O_2} > 19% → stop.

Empty procedure for D2 tank

- Different leak detecting techniques were employed by different units and were all failed to locate the leaking point, the methods include
  - high-pressure air with soap bubble
  - ACFM method
  - UT method
  - gastight test

Description by the Witnesses

- A very sharp and continuous "shoo—" sound existed for about 2 sec
- A 1/5 tank height jet fire happened at the D1 tank top near the harbor side of the end plate (this was postulated as the location of the No 3 manhole)
- A very loud "boom" sound accompanied with an emerging fire column, the tank roof (endplate) was disintegrated and many fireballs were scattered allover the tank farm

Traditional methods

- The refrigerated LPG tank's working volume: 25,000 m^3 (about 83% total inner tank's volume) and its design pressure: -50 ~ 1,500 kg/m^2G
- According to the previous researches, the explosion peak overpressure is about 8 times of the initial absolute pressure
- It is assumed
  - the LPG-air mixture has a maximum volume of 30,120 m^3
  - tank explosion pressure equals to 1.5×1,500 kg/m^2G (1.225 atm or 18 psia, assume 50% safety margin).
  - the LPG deflagration behaved like the physical explosion of a compressed gas container (between the explosion initiated and the tank ruptured)

Estimation of the Explosion Energy for Breaking the Tank

$$W = 1.4 \times 10^{-6} V \left(P_1 / P_0\right)\left(T_0 / T_1\right) R T_1 \ln\left(P_1 / P_2\right)$$

- W stands for the equivalent TNT mass of the explosion energy (lbm)
- V stands for the compressed gas volume (ft3)
- P1 stands for the compressed gas initial pressure (psia)
- P2 stands for the compressed gas final pressure (psia)
- P0 stands for the standard pressure (psia), which is 14.7 psia
- T1 stands for compressed gas temperature (°R)
- T0 stands for standard temperature (°R), which is 492°R
- R stands for ideal gas constant (1.987 Btu/lbmole·°R)

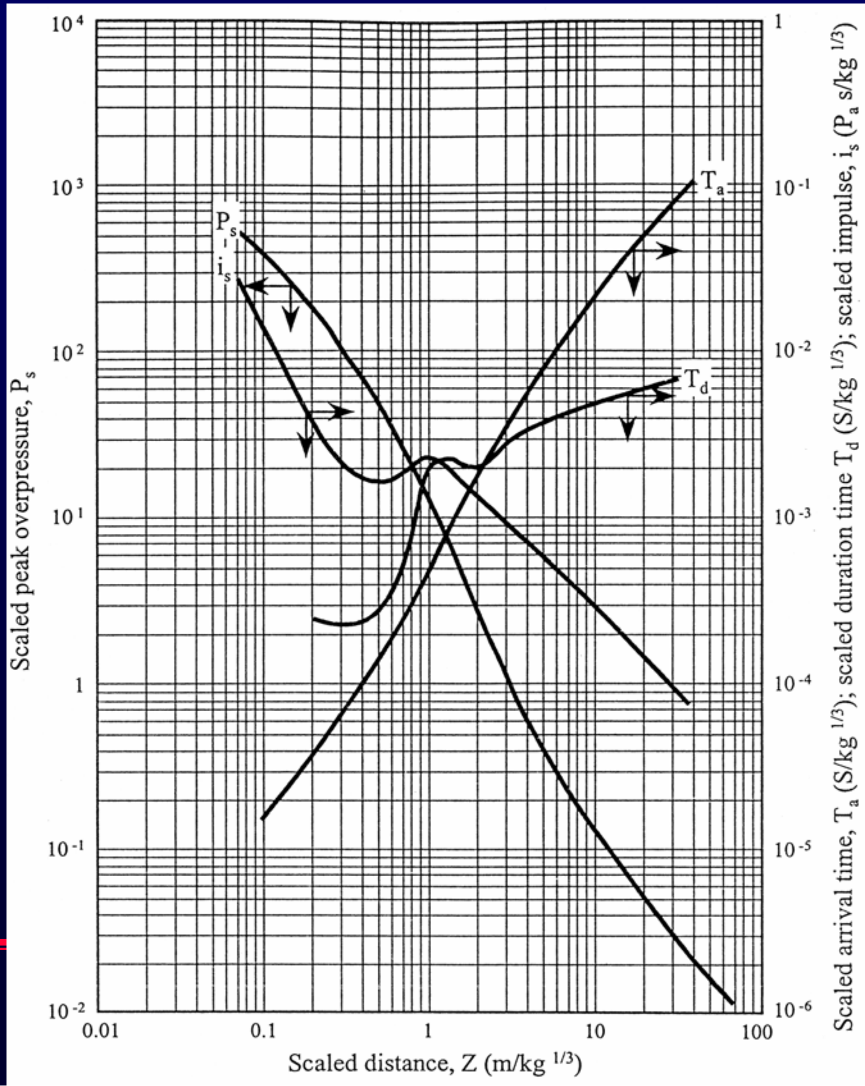
- The minimum required TNT equivalent mass that will destroy the D1 tank roof is **361 lbm** according to the calculation (the real explosion energy is larger than this)

Estimation of the Explosion Energy for Breaking the Glasses

- The explosion energy damaging nearby object can be estimated by:
  - "Damage Estimates for Common Structure Based on Overpressure" table
  - "Scaled Overpressure vs. Scaled Distance"

TABLE 2.18a. Damage estimates for common structures based on o
(Clancey, 1972). These values should only be used for approximate

Pressure		Damage
psig	kPa	
0.02	0.14	Annoying noise (137 dB if of low frequency 10–15 Hz)
0.03	0.21	Occasional breaking of large glass windows already under strain
0.04	0.28	Loud noise (143 dB), sonic boom, glass failure
0.1	0.69	Breakage of small windows under strain
0.15	1.03	Typical pressure for glass breakage
0.3	2.07	"Safe distance" (probability 0.95 of no serious damage below this value); projectile limit; some damage to house ceilings; 10% window glass broken
0.4	2.76	Limited minor structural damage
0.5–1.0	3.4–6.9	Large and small windows usually shattered; occasional damage to window frames
0.7	4.8	Minor damage to house structures
1.0	6.9	Partial demolition of houses, made uninhabitable
1–2	6.9–13.8	Corrugated asbestos shattered; corrugated steel or aluminum panels, fastenings fail, followed by buckling; wood panels (standard housing) fastenings fail, panels blown in
1.3	9.0	Steel frame of clad building slightly distorted
2	13.8	Partial collapse of walls and roofs of houses
2–3	13.8–20.7	Concrete or cinder block walls, not reinforced, shattered
2.3	15.8	Lower limit of serious structural damage
2.5	17.2	50% destruction of brickwork of houses
3	20.7	Heavy machines (3000 lb) in industrial building suffered little damage; steel frame building distorted and pulled away from foundations
3–4	20.7–27.6	Frameless, self-framing steel panel building demolished; rupture of oil



CPR Lab

Estimation of the Explosion Energy for Breaking the Glasses

- is 0.15 psig (Clancey's table); the window-glasses broken cases (found in r = 800m) can be used to calculate this explosion energy.
- Since the scaled peak overpressure is 0.15 psi/14.7psi = 0.01, its correspondent scaled distance is about 70 from Figure 3.

Pressure		Damage
psig	kPa	
0.02	0.14	Annoying noise (137 dB if of low frequency 10–15 Hz)
0.03	0.21	Occasional breaking of large glass windows already under strain
0.04	0.28	Loud noise (143 dB), sonic boom, glass failure
0.1	0.69	Breakage of small windows under strain
0.15	1.03	Typical pressure for glass breakage
0.3	2.07	"Safe distance" (probability 0.95 of no serious damage below this value); projectile limit; some damage to house ceilings; 10% window glass broken
0.4	2.76	Limited minor structural damage
0.5–1.0	3.4–6.9	Large and small windows usually shattered; occasional damage to window frames

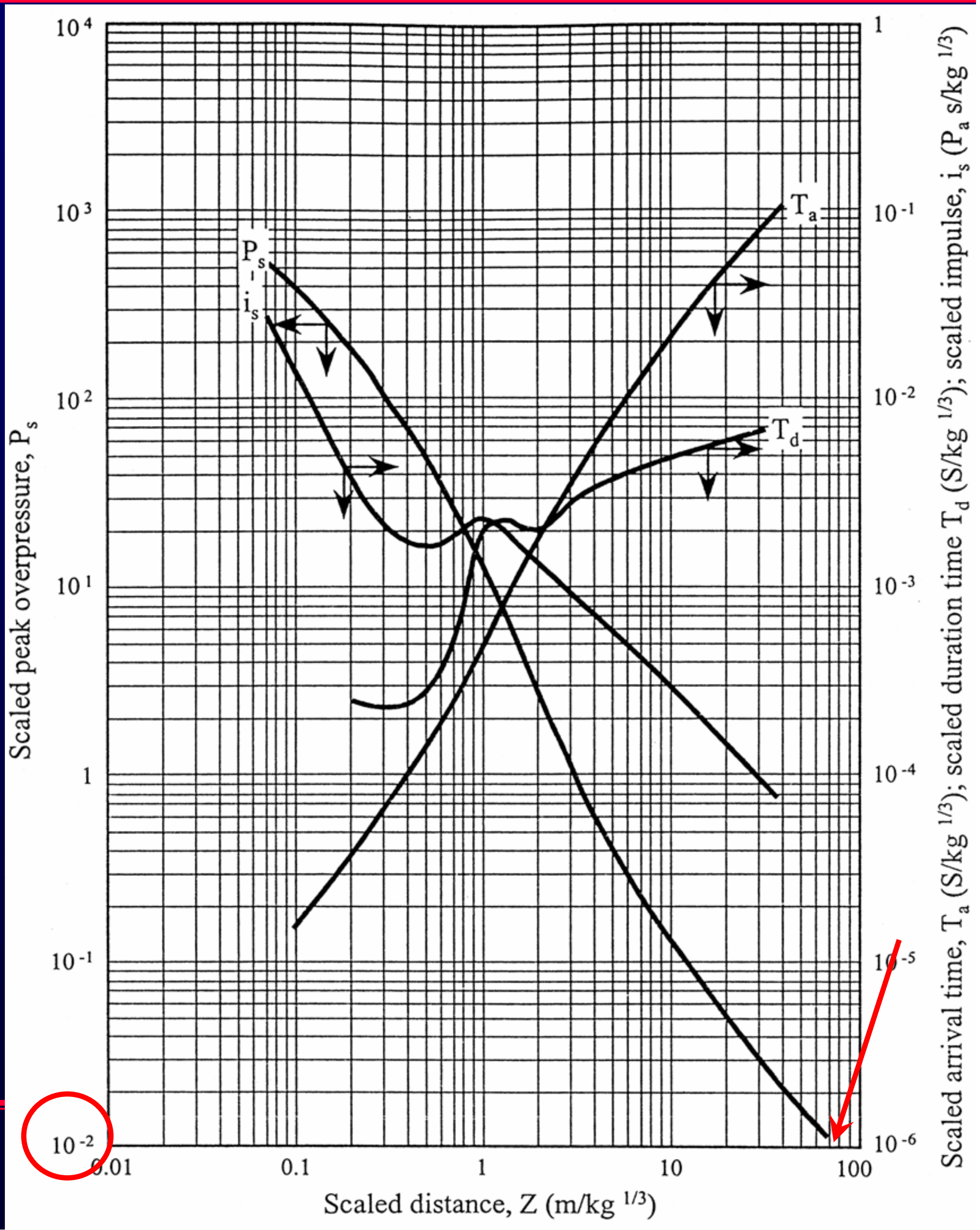
Estimate Energy Breaking the Glasses

- The scaled distance is defined as:

$$Z = R / W^{1/3}$$

  - Z represents scaled distance ($m/kg^{1/3}$) (= **70**)
  - R represents the distance from the explosion center (m) (= 800 m)
  - W represents equivalent TNT weight (kg)

- W is calculated as 1493 kg or **3288 lbm**



LPG Residual Amount inside the Refrigerated Tank

$$W = (NME_C)/E_{C,TNT}$$

- W represents the equivalent TNT mass (kg or lbm) (W = **361+3288 lbm**)
- M represents the flammable material mass (kg or lbm)
- N represents explosion effect factor (N=0.03 for propane, which is the main constituent of LPG gas)
- E_c represents the combustion heat of flammable gas (kJ/kg or Btu/lbm), E_c =19.8×103 Btu/lbm for LPG
- $E_{C,TNT}$ represents the combustion heat of TNT (kJ/kg or Btu/lbm), which is 1996 Btu/lbm

- The calculated residual LPG (M) = **5567 kg** or **3076 m^3**, which take up **10.2 %** total tank volume and all the other contents are air.

CFD Simulation Method

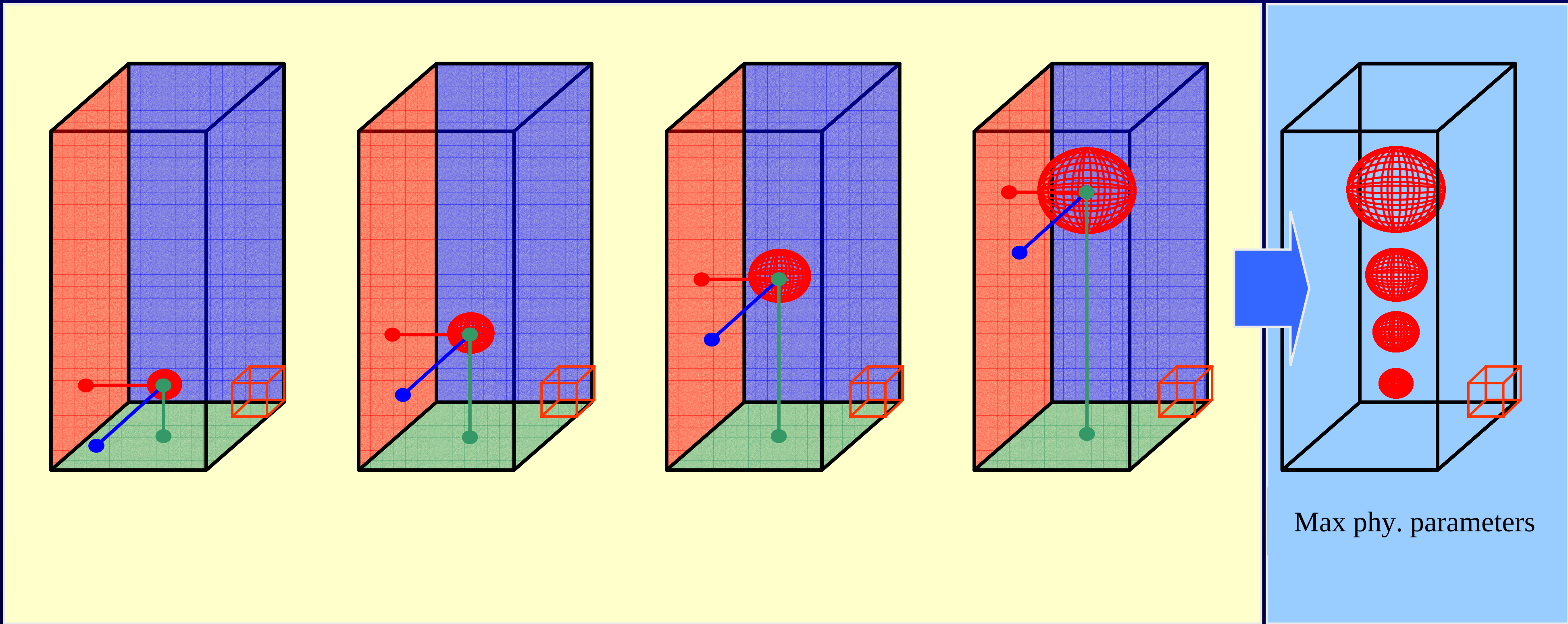
- Normally 1 volume of LPG (assume 50% C_3H_8 and 50% C_4H_{10}) needs 28.75 volume of air to form a stoichiometric reaction; therefore, only **3.36%** (=1/29.75) LPG gas composition can fulfill this purpose. The total LPG amount (10.2%) calculated by the traditional methods is more than 3 times of this value.
- Usually the stoichiometric concentration (or a little more denser) for a hydrocarbon in the air will produce the higher overpressure and pressure impulse during the explosion. It is assumed **1,832 kg** of LPG in its stoichiometric concentration (**3.36%**) with air is ignited inside of D1 tank (total **30,120 m^3**) during the simulation.
- The tank roof was removed in order to simulate the phenomena when the fire was erupted (this will also underestimate the explosion overpressure).

FLACS software

- FLACS software was employed as the physical model to calculate all kinds of fire & explosion consequences (P, J, T…)
- FLACS is a kind of CFD (computational fluid dynamics) software, it includes 3 parts:
  – CASD (computer aided scenario design)
  – flacs (flame acceleration simulator)
  – FLOWVIS (flow visualization)
- The 3D, real time simulation results can be shown in the movie files

Algorithm of Maximum Physical Parameters

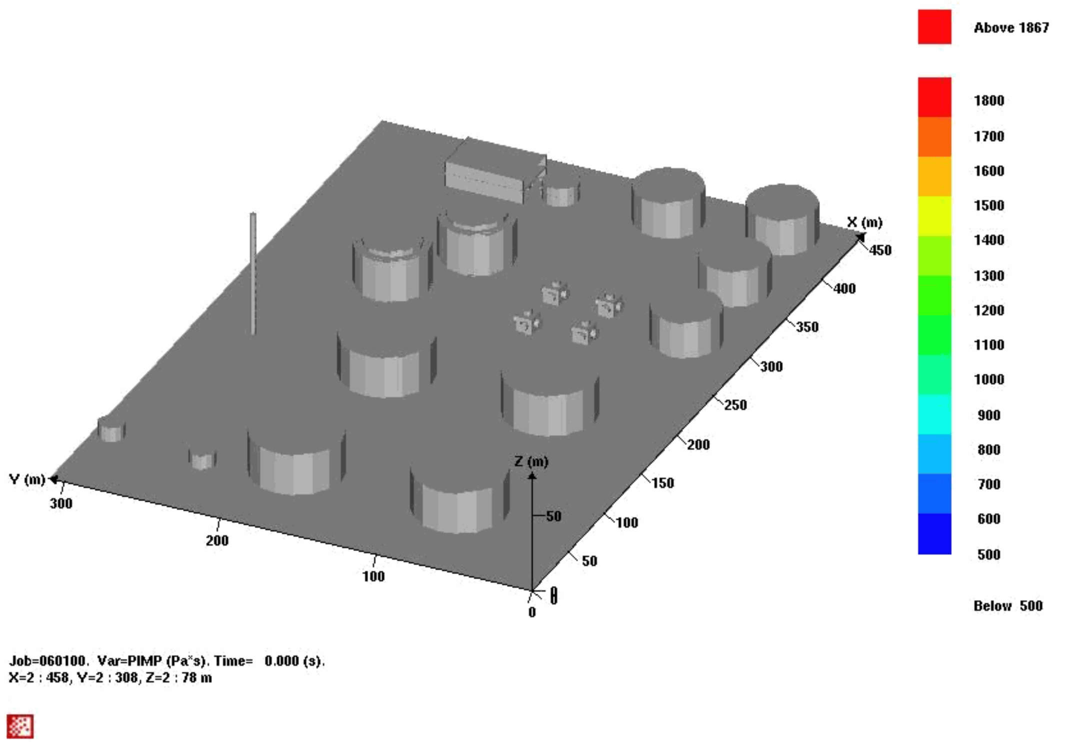
$$V_{\max}(x,y,z) = \underset{t=1\sim n}{Max} V(x,y,z,t)$$

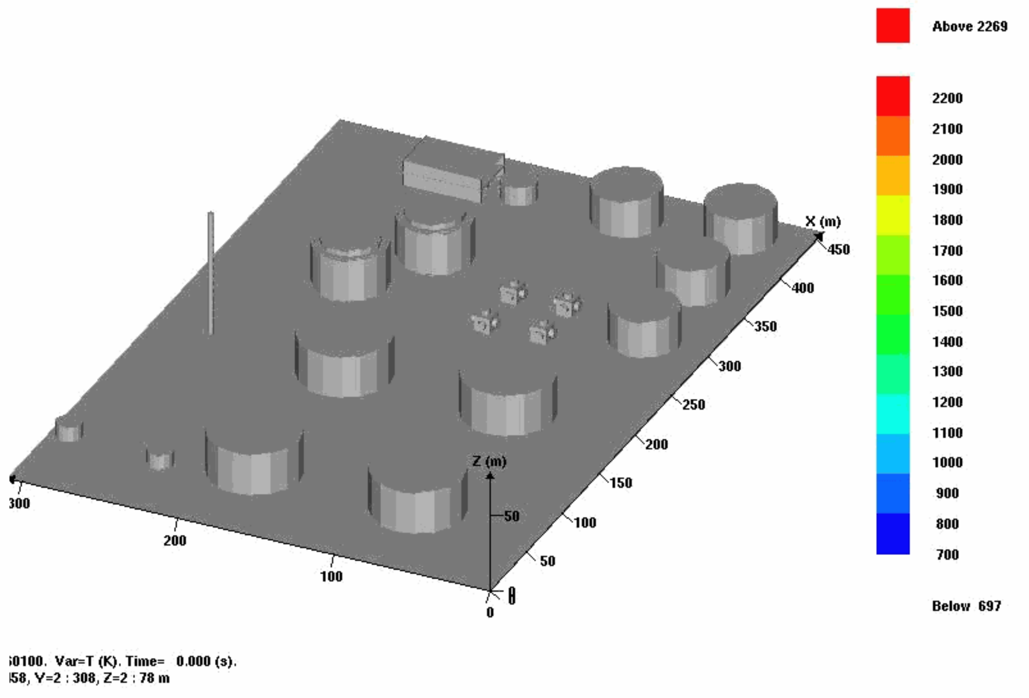


FLACS

Risk Analysis

Results and Discussion





Pressure Impulse Consequence

High-temperature Consequence

Results and Discussion (cont.)

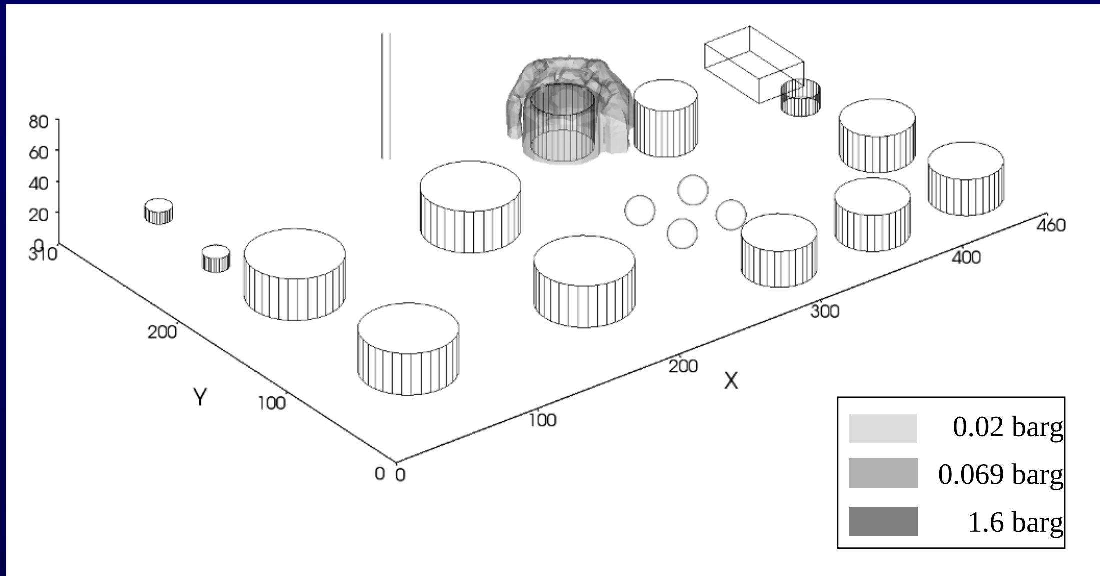
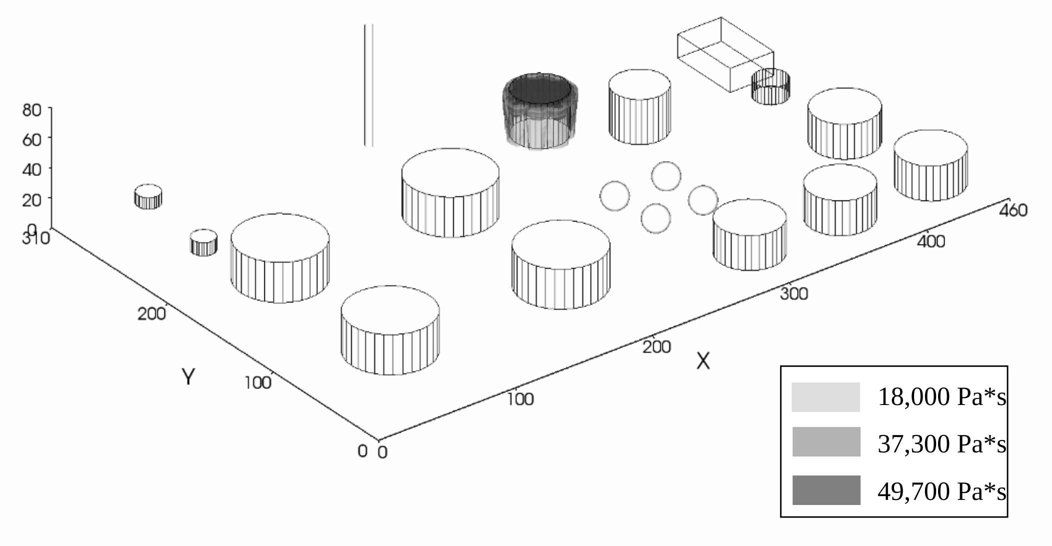


Figure 4: Overpressure Iso-surfaces of the Maximum Overpressure Effect

Results and Discussion (cont.)



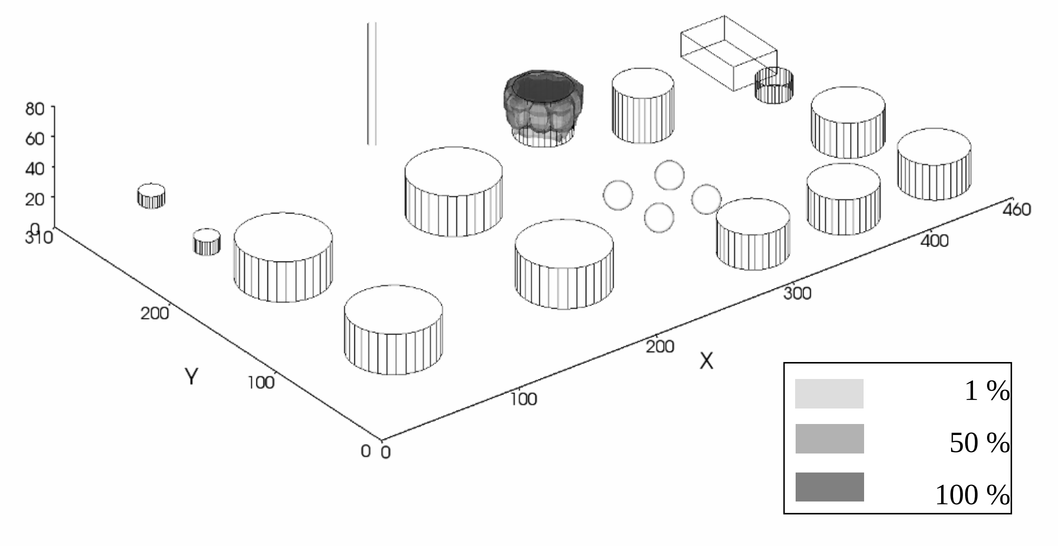


Figure 5: Pressure Impulse Iso-surfaces of the Maximum Pressure Impulse Effect

Figure 6: Death Percentage Iso-surfaces for Pressure Impulse

Results and Discussion (cont.)

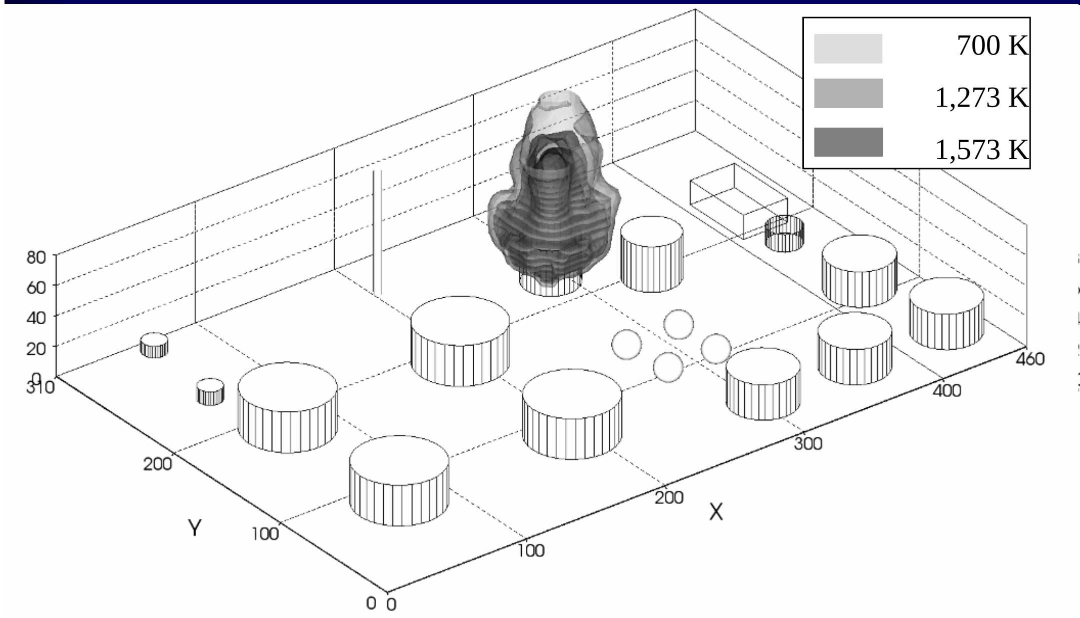


Figure 7: Temperature Iso-surfaces of the Maximum Temperature Effect

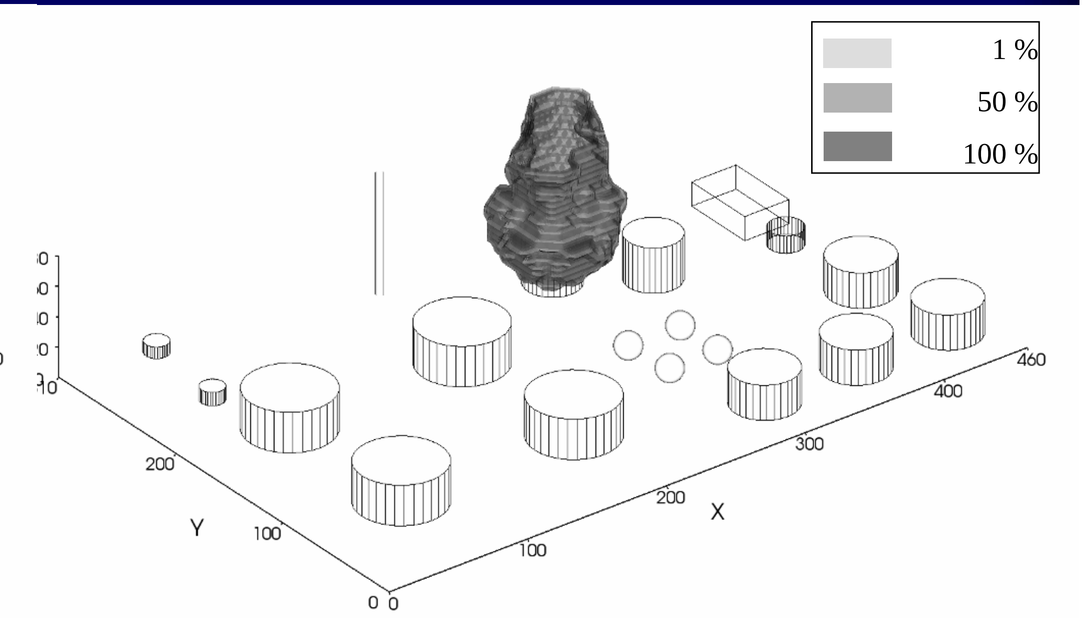


Figure 8: Death Percentage Iso-surfaces for Heat Radiation

Results and Discussion (cont.)

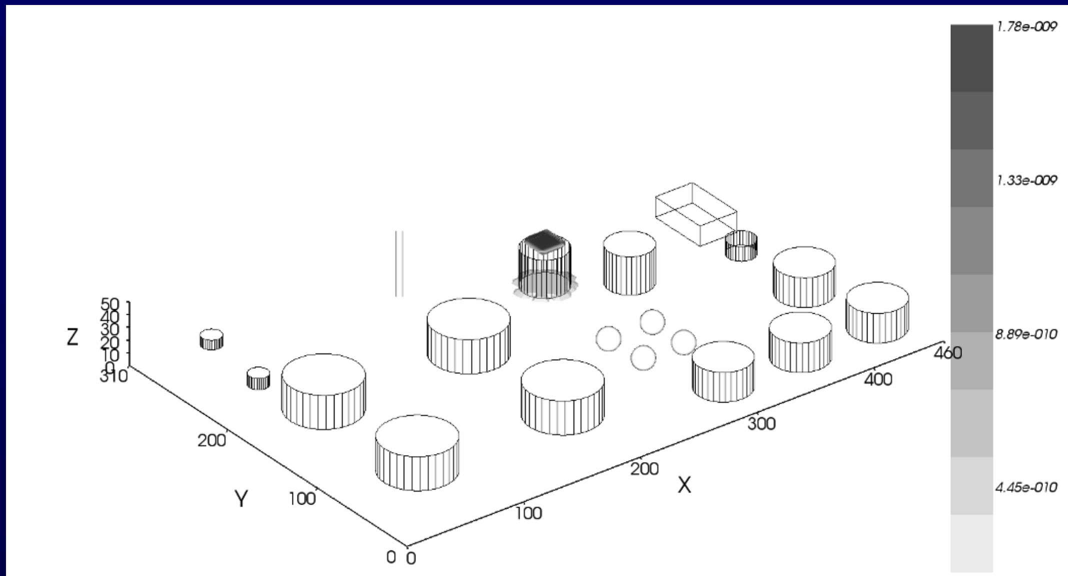


Figure 9: Individual Risk of the Combined Effects

Results and Discussion (cont.)

- Investigation shows the shortest distance from the inner tank floor to the bottom end of the level gauge well or to other pipe ends is 27 mm. This means although the level gauge indicated zero, there was still a lot of LPG inside the tank.
- Since the inner tank is quite large and all the nozzles are located on the roof, the common purging method is not suitable or efficient for this cleaning process; even though the sampling concentration of LPG (18 months before the accident) indicated it was within a safety range.
- CFD simulation shows the 1300°C temperature zone will soon covered the whole upper tank area for a very short period of time and produce heavy casualties to the employees under its coverage. The autopsy of one of the dead worker's body validate this phenomenon.

Results and Discussion (cont.)

- It is estimated the LPG residual amount is between **1832 and 5567 kg** due to an ineffective purging procedure.
- Since LPG is heavier than air, the sampling concentration either from manhole opening or from the tube outlet cannot guarantee all the LPG is expelled. After 18 months rest, all the concentrated LPG clouds that hidden in the dead corners which cannot be diluted or expelled are redistributed with air according to their concentration gradient.
- The concentration of LPG gas-air mixture at certain tank-height region is within the LEL and UEL. If this region was not very far from the slightly secured manhole cover and someone intended to remove the cover either by pushing (rubbing the cover with its iron flange) or by hitting with an iron hammer (was found at the site), an ignition source will be produced and the flammable zone will be ignited immediately.

Conclusions

- Usually the traditional method can only provide some calculation values, it is hard for us to imagine how the accident actually happened and progressed.
- By using the 3D dynamic feature of the CFD technique, all the possible accidental scenarios can be easily reconstructed and observed from any view angles, through any perspective cross-sectional planes and at any time point.
- Through the help of CFD method, investigators or researchers can not only understand the spatial and transient distribution of many physical parameters, but they can also use the results to postulate the possible causes and provide some prevention methods for the similar accidents that might happened in the future.

Thank you for your attention!

Acknowledgement

The authors are grateful to the National Science Council of Taiwan for financial support of this study under the project of “Development of a 3D risk analysis technique (NSC 94-2211-E-224-007-)”.