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The Development of a 3D Risk Analysis Method

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Background

- Due to the increasing of scale and complexity of a plant, the disasters of chemical process industries become more and more severe during past decades.

- Lots of efforts had been made in order to decrease the scale and possibility of chemical accident. Quantitative risk analysis (QRA) methodology that was originally used in aerospace, electronics, and nuclear power industries, has also been employed in the chemical process industries (CPI).

- Many recent regulations, such as Risk Management Program (RMP) of US EPA and SEVESO II Directive of EU, all include part or most of the QRA techniques in order to predict the severity or the possibility of the potential hazards.

Background (cont.)

- The traditional risk analysis technique (such as SAFETI etc.) can only predict 2D individual risk (IR) within certain process area; it usually neglected the influence of building blockage and terrain effect therefore its simulation results were quite different from the real situations.
- A more rigorous model such as CFD (computational fluid dynamics) can resolve the previous limitations; however, it didn't find out a proper way to handle the complexity of risk calculation.
- A 3D risk analysis technique was developed in this research via combing the results of CFD simulations with some post-processing procedures and was applied on a fire and explosion simulation within a petrochemical plant's tank area.

Introduction to the Simulation Site

- The simulation site used for testing fire and explosion results is a petrochemical plant's tank area (460m x 310m)
- The layout and contents of the storage tanks were shown in Fig.1 & Tab.1.

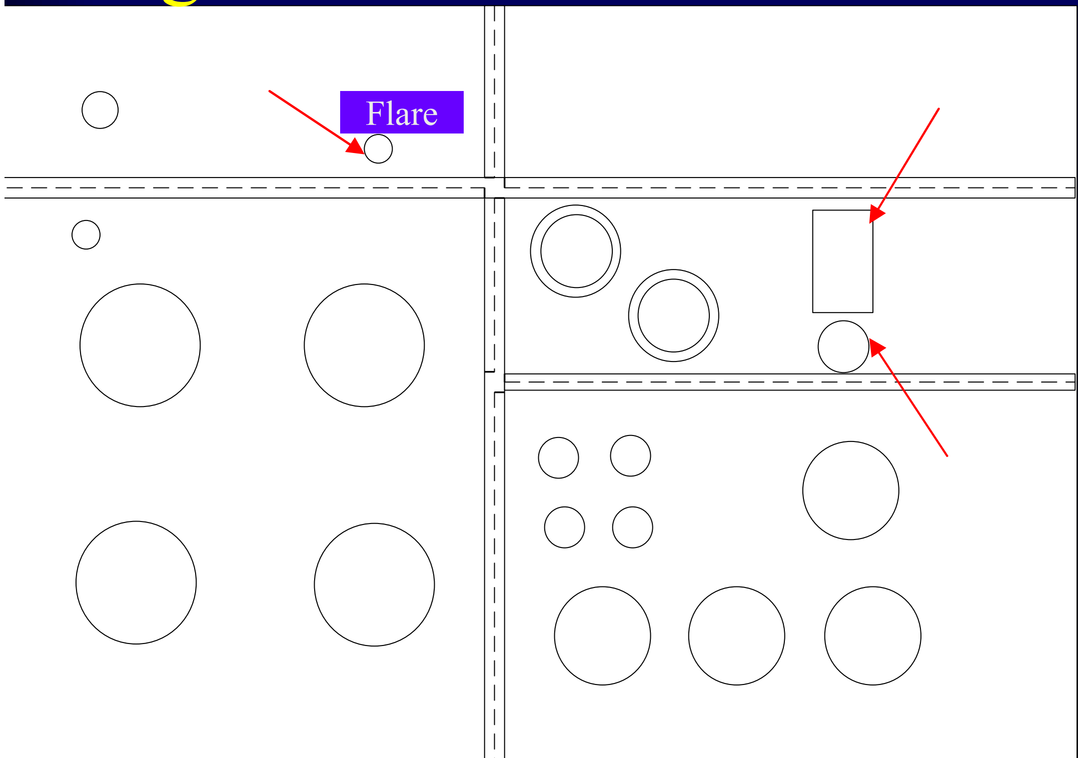


Figure 1. Equipment Layout of Simulation Site

Table 1. Tank Data of Simulation 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 to the Simulation Site (cont.)

Figure 2

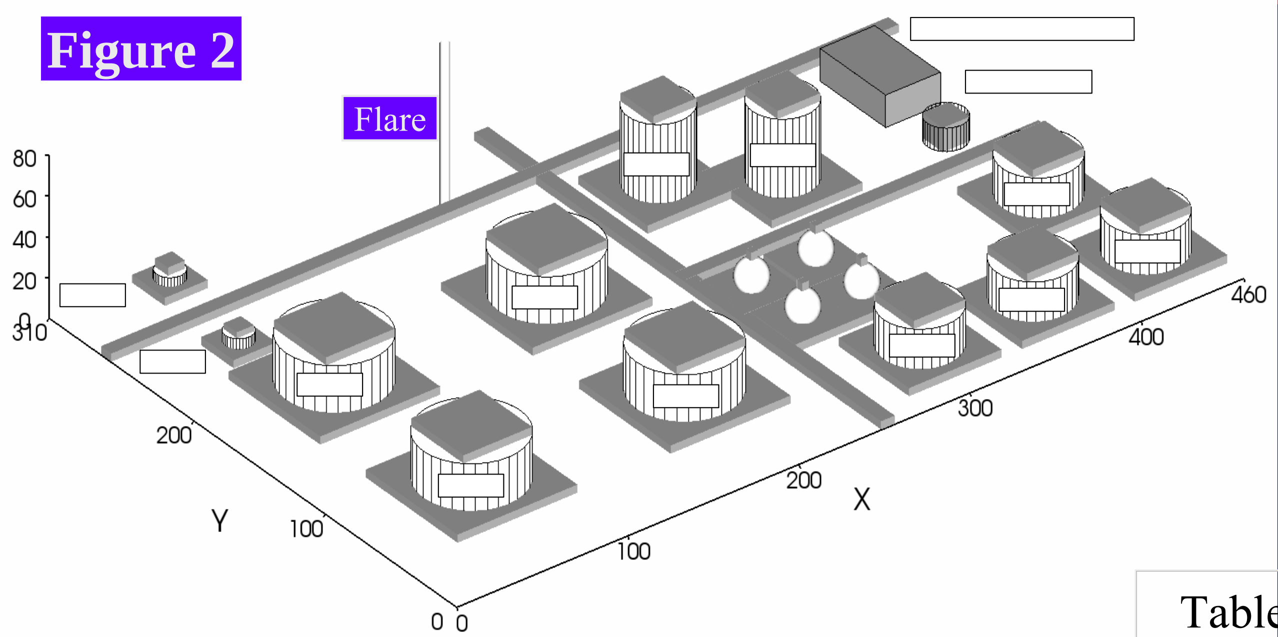


Table 3: Population Distribution & Probability

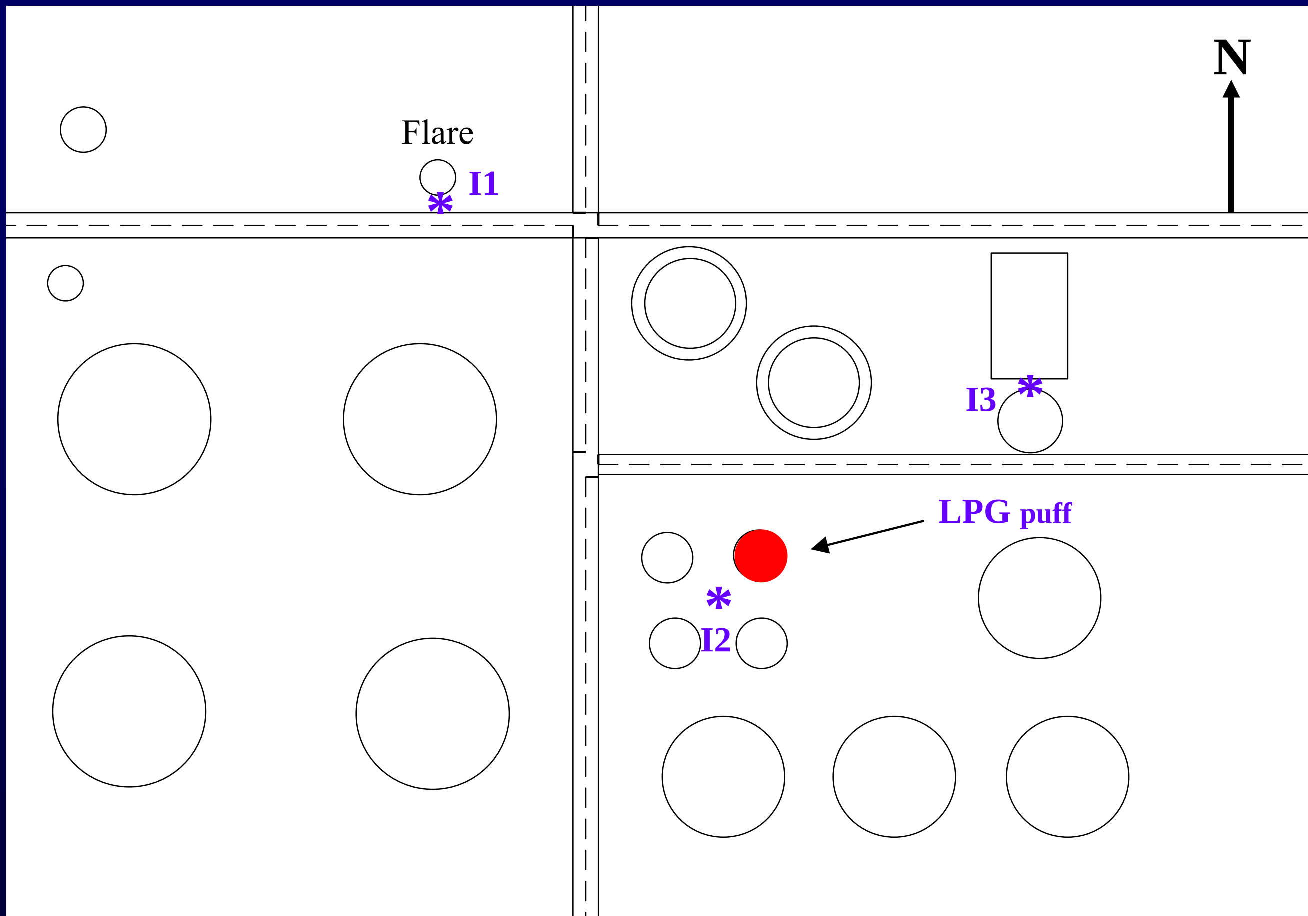
Location	Number of Person ①	Probability of Appearance, P_Z ②	①×②
Vacant lots	6	0.1	0.6
Site roads	10	0.5	5
Tanks	2×16	0.2	6.4
Factory	8	1	8
Control room	15	1	15
Nominal total person	71	Real total person number onsite	35

- Table 3 also lists the ranking of the P_Z value from high to low as: control room ≥ factory > site roads > tank surrounding area > vacant lots

Wind Effects

Table 2: Wind Rose Data at the Simulation Site								
Wind(m/s)	N	NE	E	SE	S	SW	W	NW
< 1.0	0.04	0.04	0.021	0.008	0.01	0.01	0.010	0.017
1.0 - 2.0	0.09	0.07	0.038	0.011	0.02	0.02	0.030	0.045
2.0 - 3.0	0.06	0.02	0.008	0.009	0.03	0.02	0.044	0.051
3.0 - 4.0	0.03	0.00	0.002	0.007	0.02	0.01	0.036	0.043
4.0 - 5.0	0.01	0.00	0.000	0.004	0.01	0.00	0.016	0.028
5.0 - 6.0	0.00	0.00	0.000	0.002	0.01	0.00	0.007	0.012
6.0 - 7.0	0.00	0.00	0.000	0.001	0.00	0.00	0.002	0.005
7.0 - 8.0	0.00	0.00	0.000	0.000	0.00	0.00	0.001	0.002
SUM	0.23	0.13	0.07	0.04	0.10	0.06	0.15	0.20

Locations of Leakage and Ignition Points



The Flowchart of Risk Management

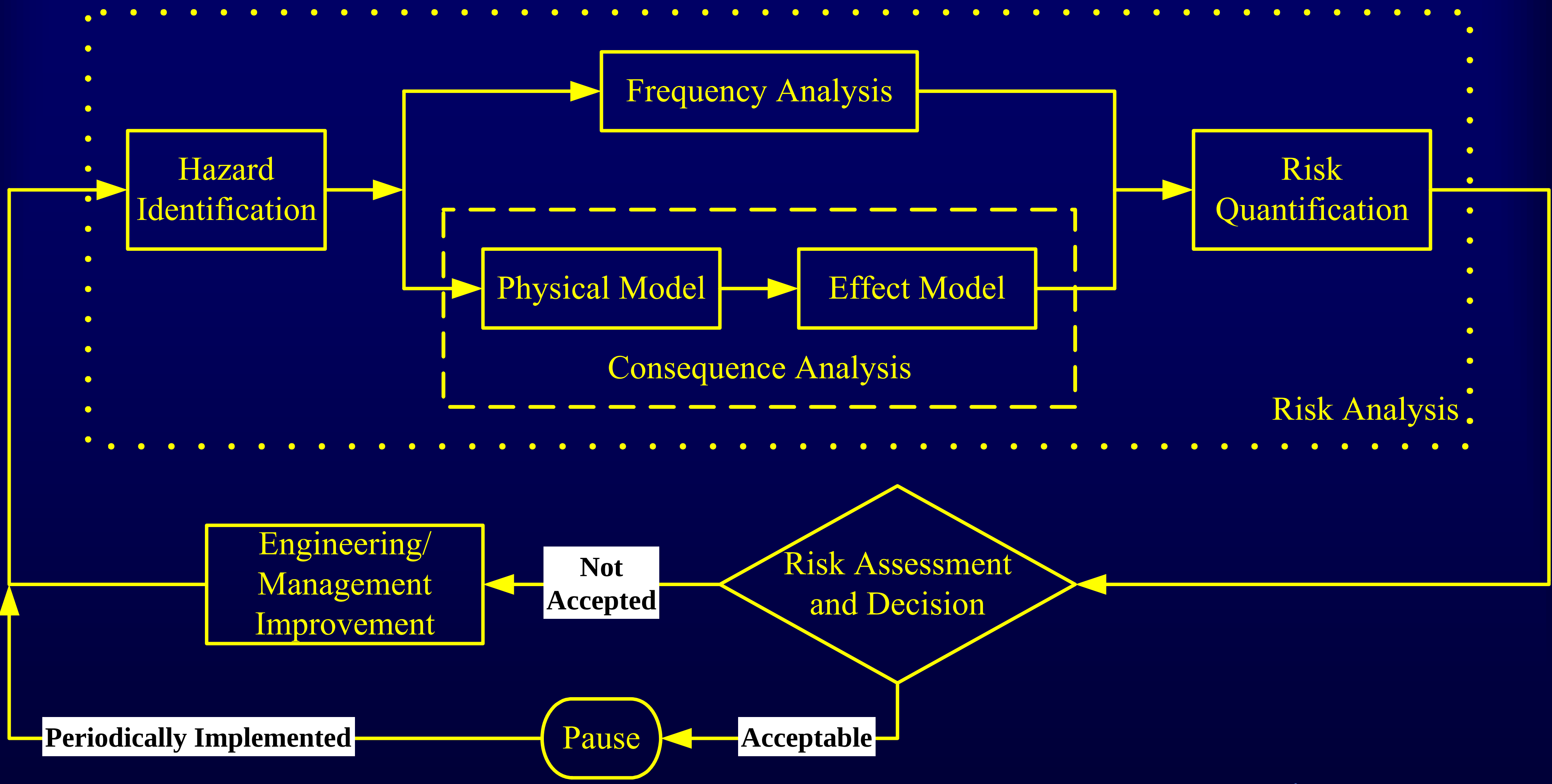


Figure 4

(1) Physical Model

- 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

List of Simulation Scenarios

No	Wind	Speed	Scenario	LPG conc.	Vol. (m^3)	Ig. Time
1	N	1.5 m/sec	G2 rupture	100 %	60×60×60	17 sec
2	NE	1.5 m/sec	G2 rupture	100 %	60×60×60	17 sec
3	E	1.5 m/sec	G2 rupture	100 %	60×60×60	41 sec
4	SE	1.5 m/sec	G2 rupture	100 %	60×60×60	15 sec
5	S	2.5 m/sec	G2 rupture	100 %	60×60×60	12 sec
6	SW	2.5 m/sec	G2 rupture	100 %	60×60×60	10 sec
7	W	2.5 m/sec	G2 rupture	100 %	60×60×60	12 sec
8	NW	2.5 m/sec	G2 rupture	100 %	60×60×60	13 sec

(2) Effect Model

- This research used CVF6.6 and MATFOR graphical library to develop the "effect model" and the "risk analysis module"
- In order to predict the maximum hazard impact degree within the hazard impact area, the "maximum physical effects" in each coordinate (x, y, z) within hazard elapse time were selected to convert the time dependent variables (P(x, y, z, t), J(x, y, z, t), and T(x, y, z, t)) into time independent variables via Eq(1)

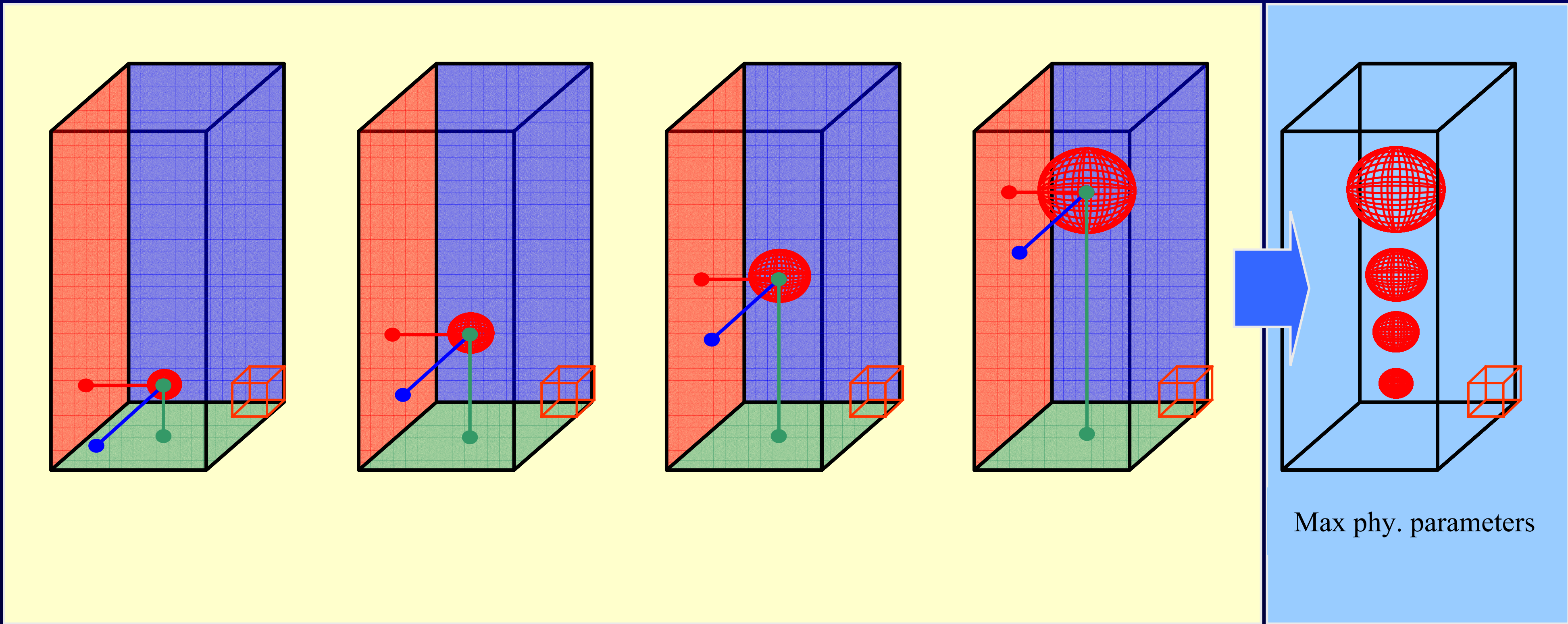
$$F_{\max}(x,y,z) = \underset{t_0 \le t \le t_f}{Max} F(x,y,z,t) \qquad (1)$$

- $T_{max}(x, y, z)$ will later be converted into "radiation heat" via Eq(2).

$$I_{\max}(x,y,z) = 5.67 \times 10^{-8}\left(T_{\max}^{4}(x,y,z) - T_{a}^{4}\right) \qquad (2)$$

Algorithm of Maximum Physical Parameters

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



FLACS

Risk Analysis

(2) Effect Model (cont.)

- The effect model converted the "maximum physical effects (P, J, and I)" into the personnel death probit value via Eq(3)

$$Y_i(x,y,z) = K_1 + K_2 \ln\left[F_{\max}(x,y,z)\right] \qquad (3)$$

- The probit value (Y) can be further converted into the personnel death probability (P_D) at specific 3D coordinate (x,y,z) via Eq(4).

$$P_{D,i}(x,y,z) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{Y_i(x,y,z)} \exp\left(-\frac{u^2}{2}\right) du \qquad (4)$$

(2) Effect Model (cont.)

Physical Hazard Effect	Probit Equation
Overpressure Effect	$Y_1(x,y,z) = -77.1 + 6.91\ln\left(P_{\max}(x,y,z)\right)$
Pressure Impulse Effect	$Y_2(x,y,z) = -46.1 + 4.82\ln\left(J_{\max}(x,y,z)\right)$
Heat Radiation Effect	$Y_3(x,y,z) = -14.9 + 2.56\ln\left[\frac{t_e I_{\max}^{4/3}(x,y,z)}{10^4}\right]$

Frequency Analysis

- According to the previous research [I *et al.*, 1999], the common LPG tank rupture frequency is between $2\times10^{-6}\sim 1\times10^{-5}$/yr
- Based on the published document and the experience, this research divided the incident frequency (F_I) into 3 categories, possible ($F_I = 1\times10^{-5}$/yr), impossible ($F_I = 1\times10^{-6}$/yr), and extremely impossible ($F_I = 1\times10^{-7}$/yr)
- Four hazard incident top events were enumerated in this research: (1) high-pressure tank BLEVE, (2) refrigerated tank gas explosion, (3) semi-confined factory pipe leak, and (4) high-pressure tank disaster breakage; the ranking of the F_I value from high to low is (3) > (1) > (2) > (4)

Quantitative Risk Analysis

- Individual risk (IR) is used to predict the employees' yearly death rate within a plant site that has been influenced by certain hazard incidents
- 3D death percentage generated from effect model can be applied to predict the IR value by combining incident frequency, atmospheric conditions, and ignition probability, etc.; the total IR value is the cumulative summation of IR values under different hazardous physical effects from certain enumerated incidents as Eq(5)

$$IR(x,y,z) = \sum_{i=1}^{n} F_I P_I P_{WIND} P_{Z,i}(x,y,z) P_{D,i}(x,y,z) \qquad (5)$$

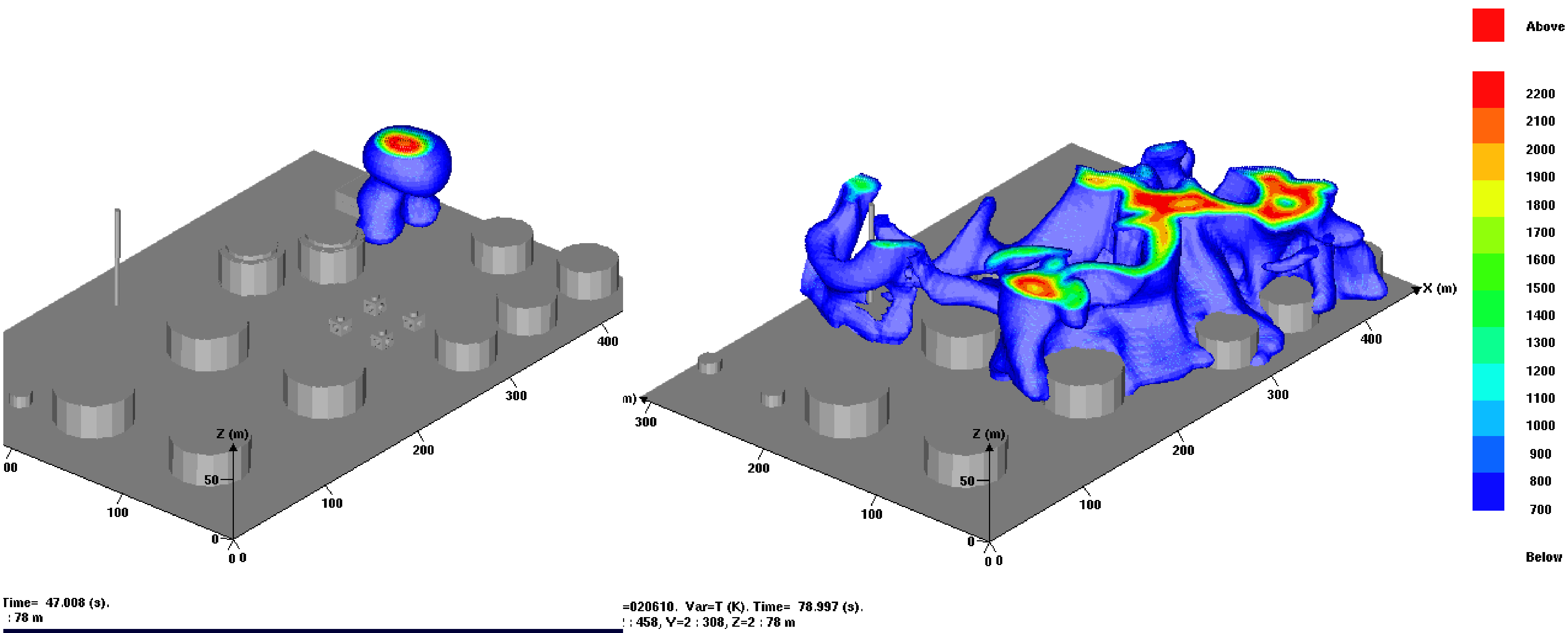
  - IR(x,y,z): the individual risk at specific location (x, y, z)
  - n: the number of the hazardous physical effect, the default effects are explosion overpressure (P), pressure impulse (J), and heat radiation (I)
  - F_I: incident frequency; P_I: ignition probability of the released cloud
  - P_{WIND}: probability of 8 different wind directions
  - $P_{Z,i}$ and $P_{D,i}$: personnel appearance probability & death percentage at coordinate (x, y, z)

Results and Discussion

- Worst-case scenario (WCS) is commonly employed in a risk management program for analyzing the most severe hazard that might happen within a certain process area.
- A disastrous rupture of G2 LPG pressurized tank is chosen as the study case. The incident frequency was set as 1×10^{-7}/year since such case is nearly impossible to happen.
- Assumed 60 m^3 LPG puff is formed from the G2 tank rupture scenario; later the dispersed gas cloud encountered 3 continuous ignition points that locate beside flare (I1), high-pressure spherical tank (I2), and semi-confined factory (I3).
- Since there are 8 wind directions/probabilities in this study and their results are quite lengthy; therefore, only the results of east-wind scenario were demonstrated here.

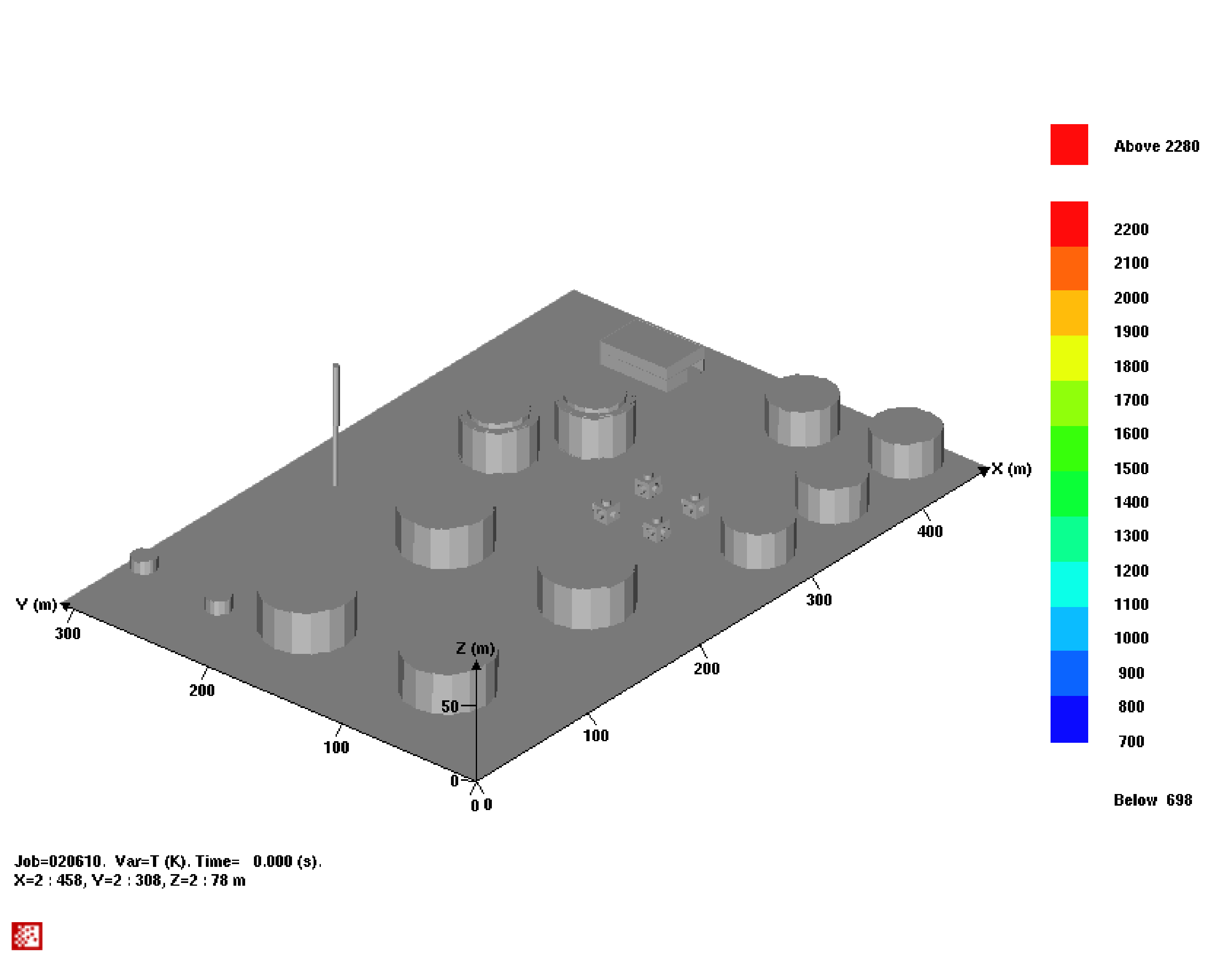
Radiation Heat Effect

Figure 4: High-Temperature Consequence and Its Related Calculation Effects

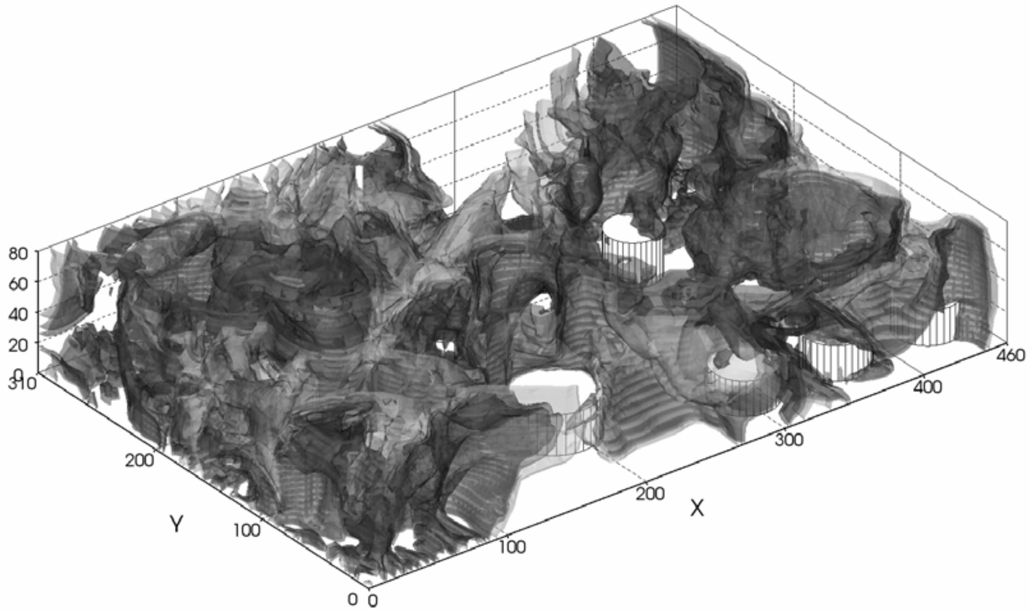


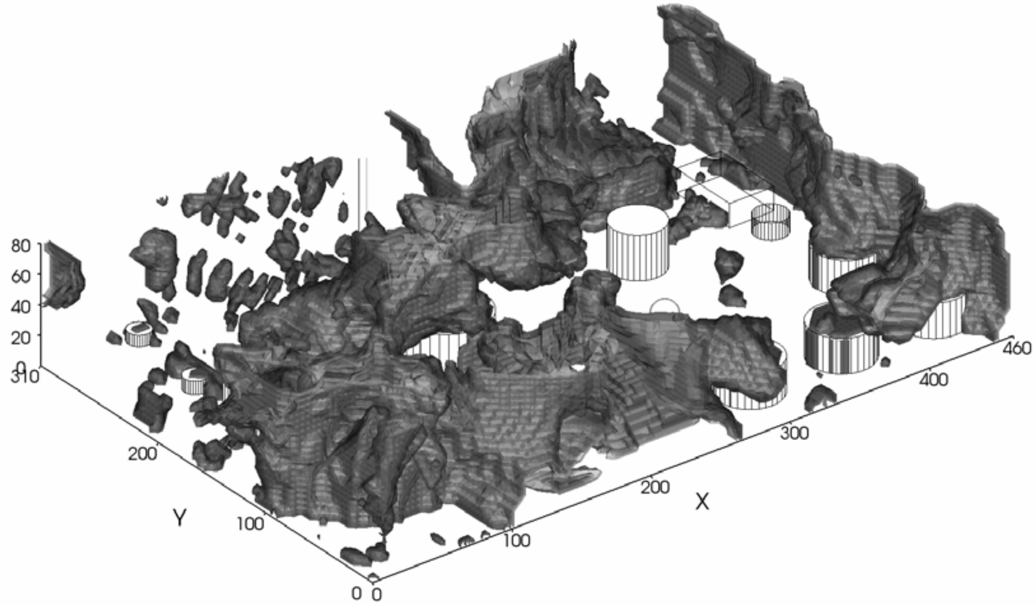
(A) The Flame-Front Progression (47 sec)　(B) The Flame-Front Progression (79 sec)

Radiation Heat Effect (cont.)



Radiation Heat Effect (cont.)

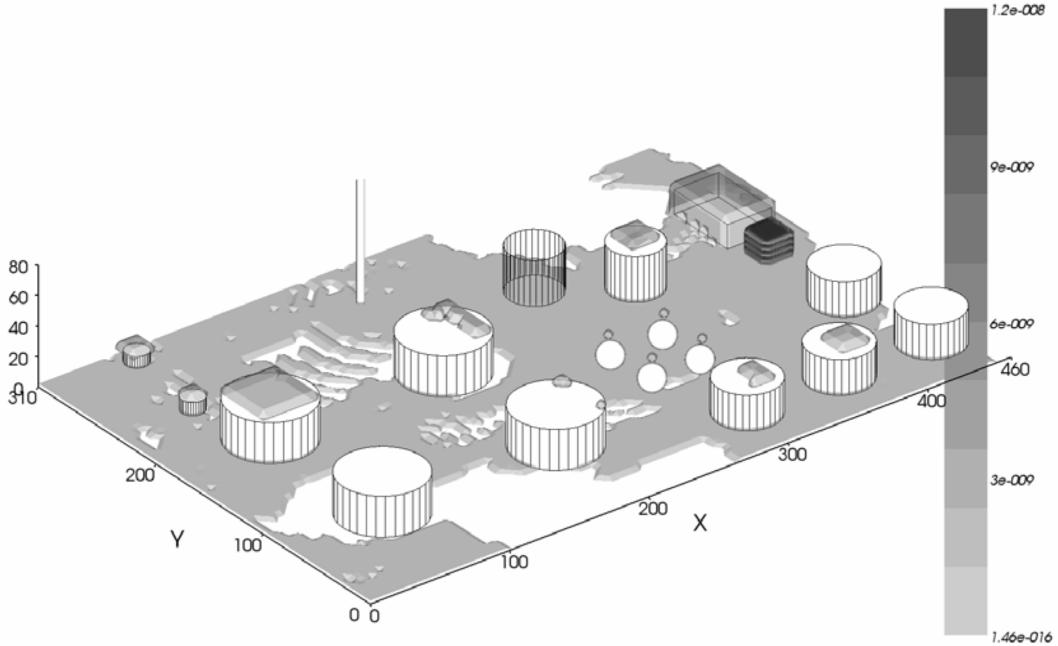


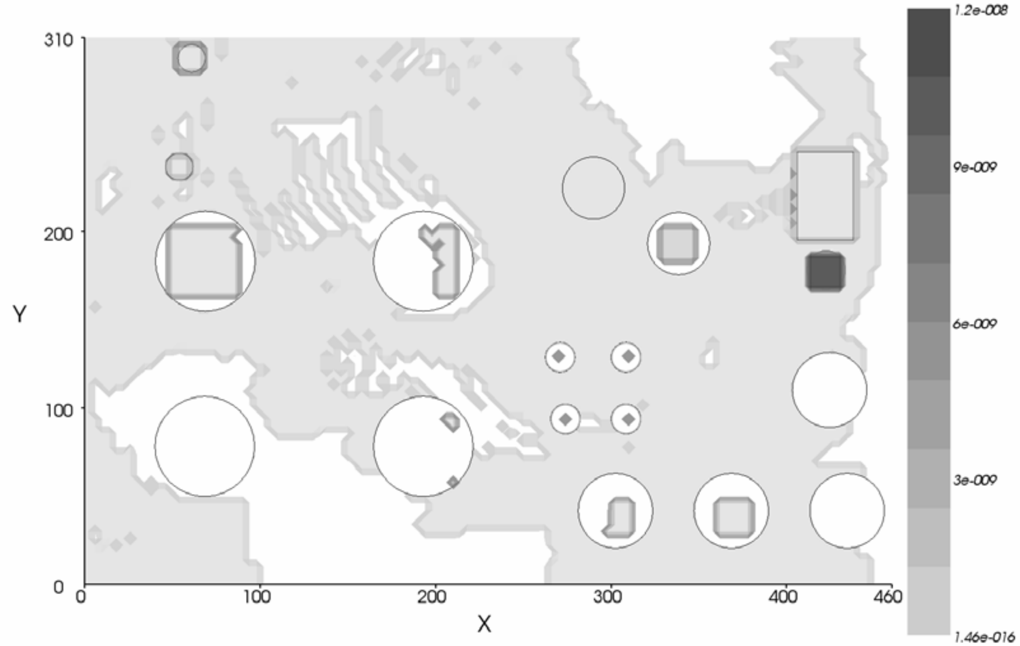


(C) Temperature Iso-surfaces (700 K, 1273 K, and 1573 K) of the Max. Temp. Effect

(D) Iso-surfaces of the Personnel Death Percentage (1%, 50%, and 100%)

Radiation Heat Effect (cont.)





(E) Individual Risk of Heat Radiation under East Wind Condition (3D View)

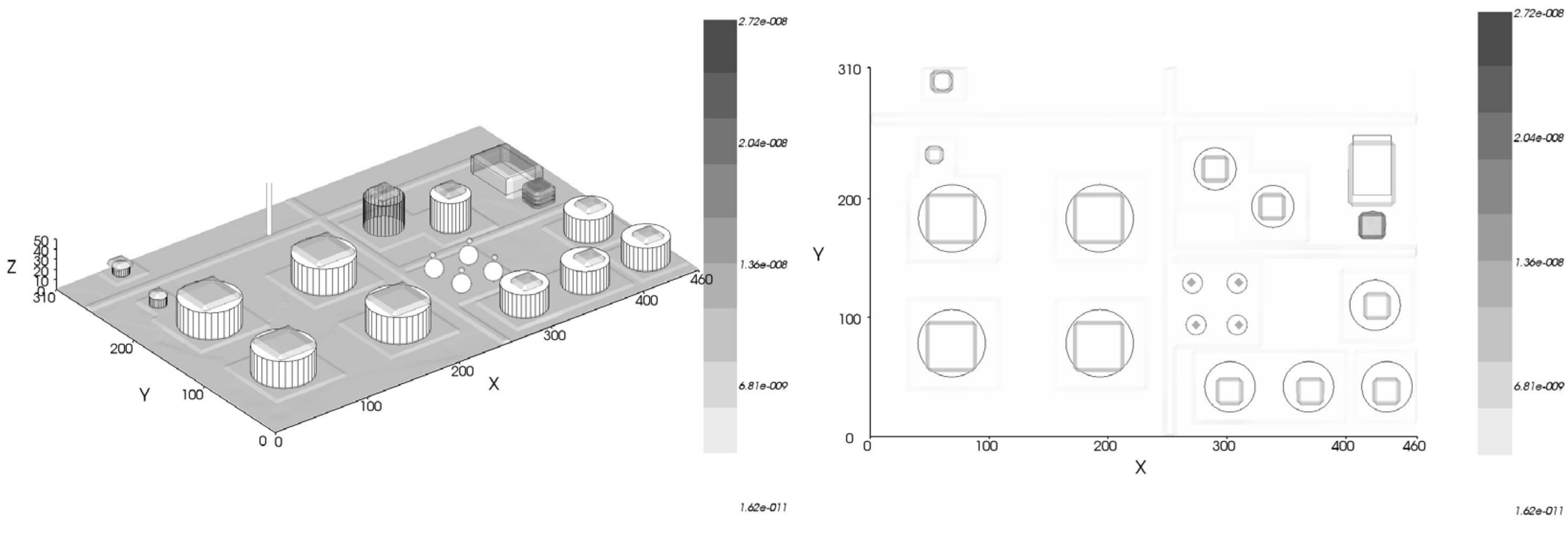
(F) Individual Risk of Heat Radiation under East Wind (E) Condition (Projective View of X-Y Plane)

Pressure Impulse and Overpressure Effect

- During the development of a large-scale deflagration period, the ambient pressure changed drastically thus the pressure impulse in the whole simulation area were almost larger than 18,000 Pa·s, which will cause a serious damage to the personnel and the equipments.
- According to the simulation results (not shown here), except for the top of tank B1 and B3, almost all the plant's ground areas were covered by the death percentage iso-surfaces that higher than 90%. The death toll reached 21 persons under the influence of this physical effect.
- The overpressure effect around the plant area were all below 0.015 barg. Since the deflagration overpressure in an unconfined space will do limited harm to the human being; therefore, no death percentage zone or death toll was found in this case.

3D Individual Risk Contour

Figure 5: IRC for the G2 Tank Accident under the Influence of 8 Wind Directions



(A) 3D View

(B) Projective View of X-Y Plane

Risk ranking: control room (2.5×10^{-8} person/yr) > semi-confined factory (2.5×10^{-9} person/yr) > site roads (1.4×10^{-9} person/yr) > surrounding of tanks (from 1.4×10^{-9} to 1.5×10^{-10} person/yr) > vacant sites (3.1×10^{-11} person/yr).

Conclusions

- In this research, a conceptual ***3D risk analysis technique*** was proposed via the combination of the CFD simulation results with self-developed codes for calculating effect model and individual risk. This technique has been successfully implement on the fire & explosion risk analysis task within a petrochemical plant's tank area.
- The ***3D risk analysis technique*** can not only improve the drawback of the traditional methods which usually neglect the terrain, the obstacle, and concentration fluctuations effects but also extend the risk analysis region from 2D into 3D domain

Conclusions (cont.)

- A spherical tank rupture accident was chosen to investigate the influence of wind directions on the flammable concentration range, the ignition priority, the fire and explosion consequence, and the individual risk distribution.
- The simulation results show employees in control room will receive the highest risk (2.5×10^{-8} person/year) while the risk in the vacant lots will be the lowest (3.1×10^{-11} person/year). An apparent risk difference exist between different heights at the same location.
- The 3D risk analysis technique proposed in this research can not only used in chemical industry but can also be extended to other industries (aerial, submarine, or ever space risk analysis) where height (depth) has a critical meaning with them.

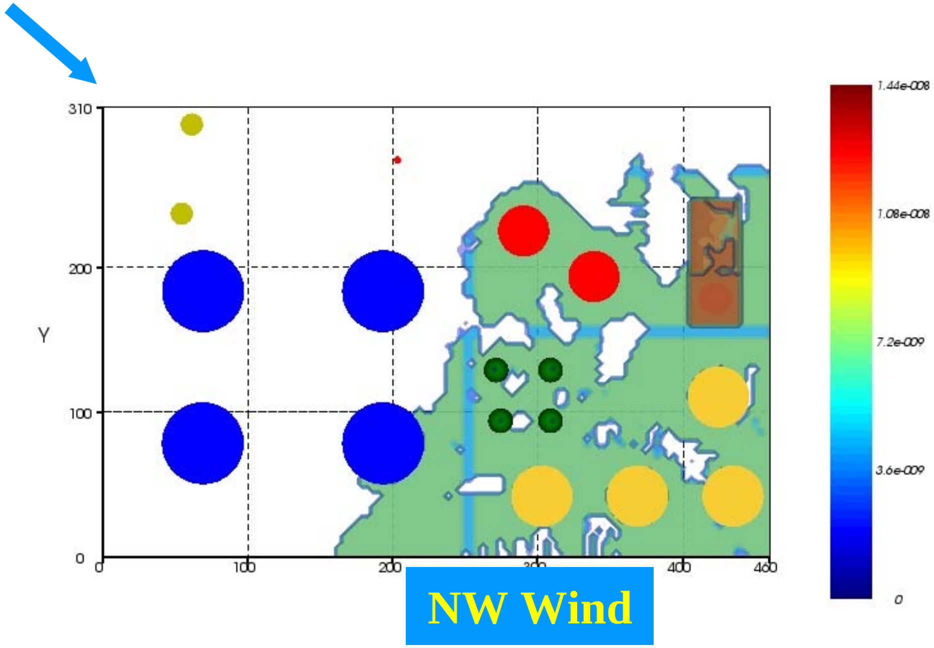
Thank you for your attention!

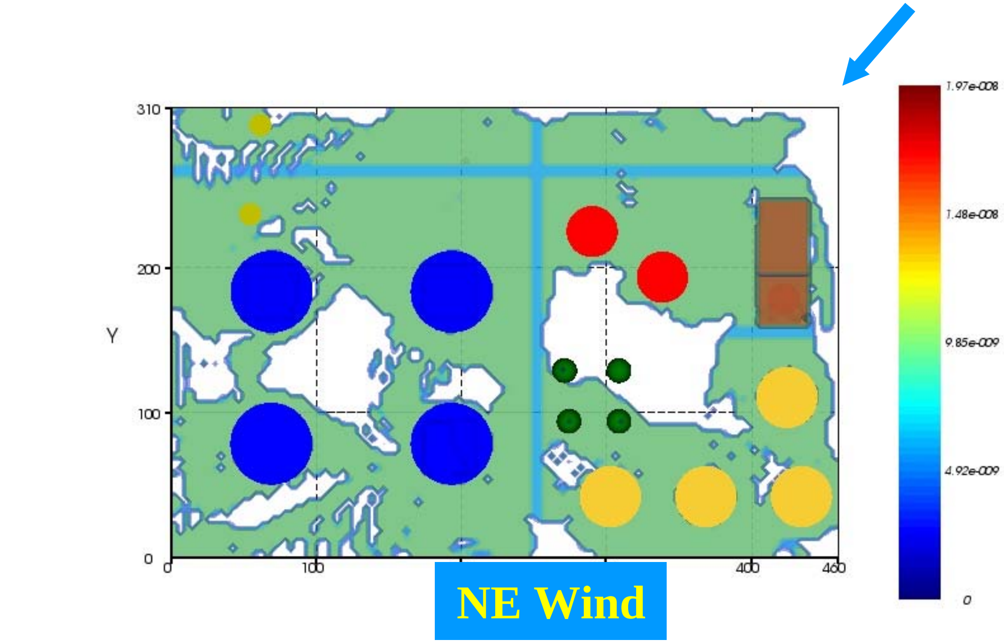
Acknowledgement

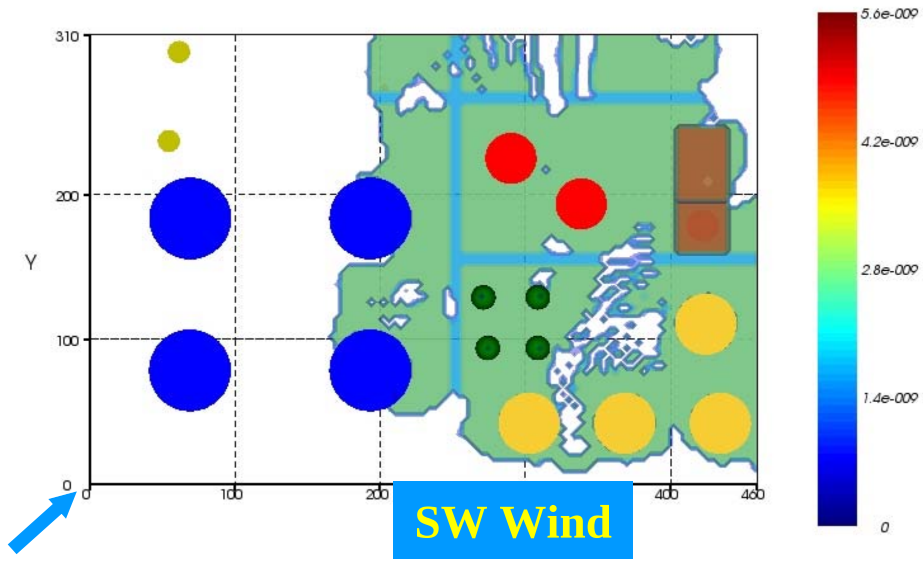
The authors are grateful to the National Science Council of Taiwan for financial support of this study under the project of “Development of a 3D risk analysis technique (NSC 94-2211-E-224-007-)”.

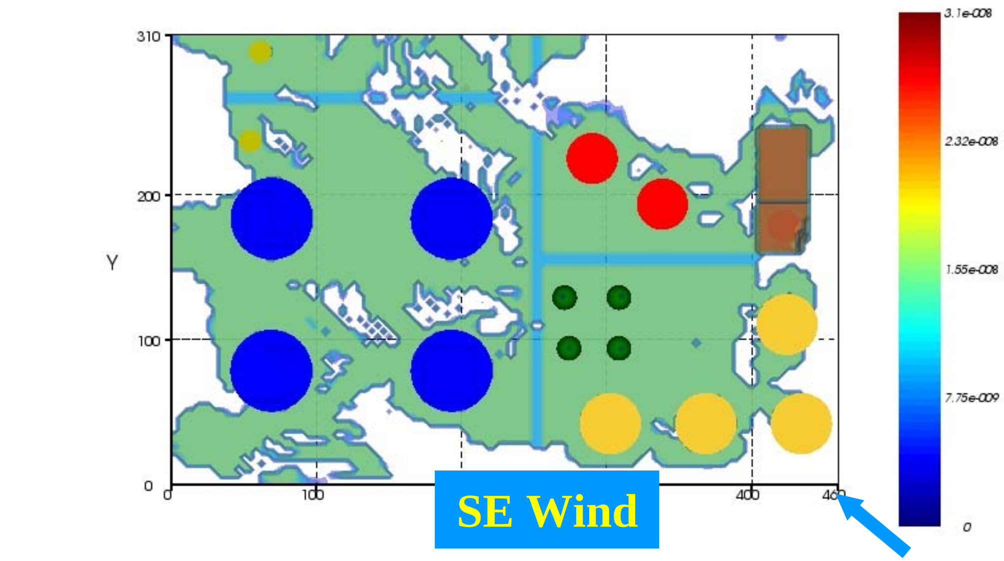
CPR Lab

IR of Scenarios 2, 4, 6, 8

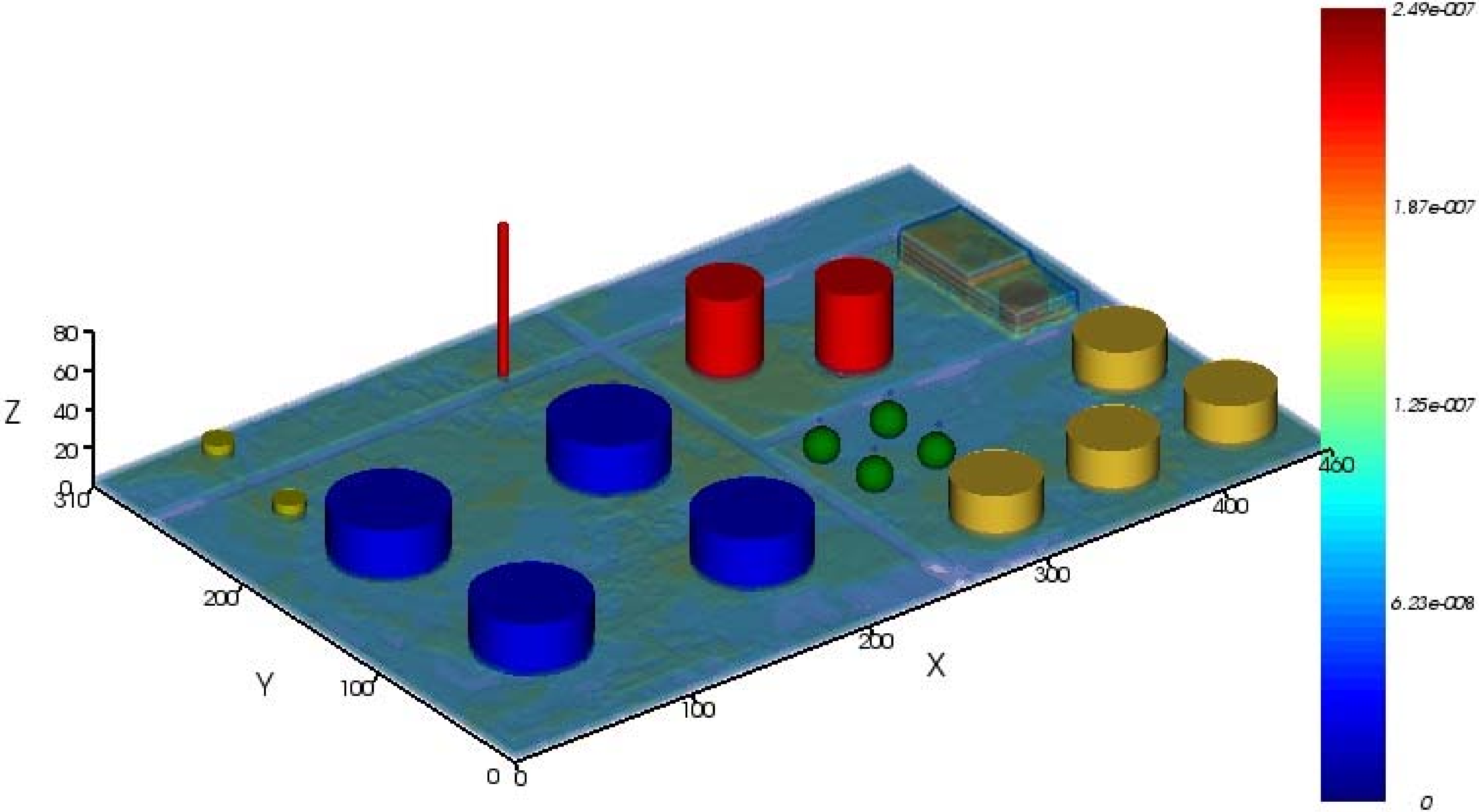




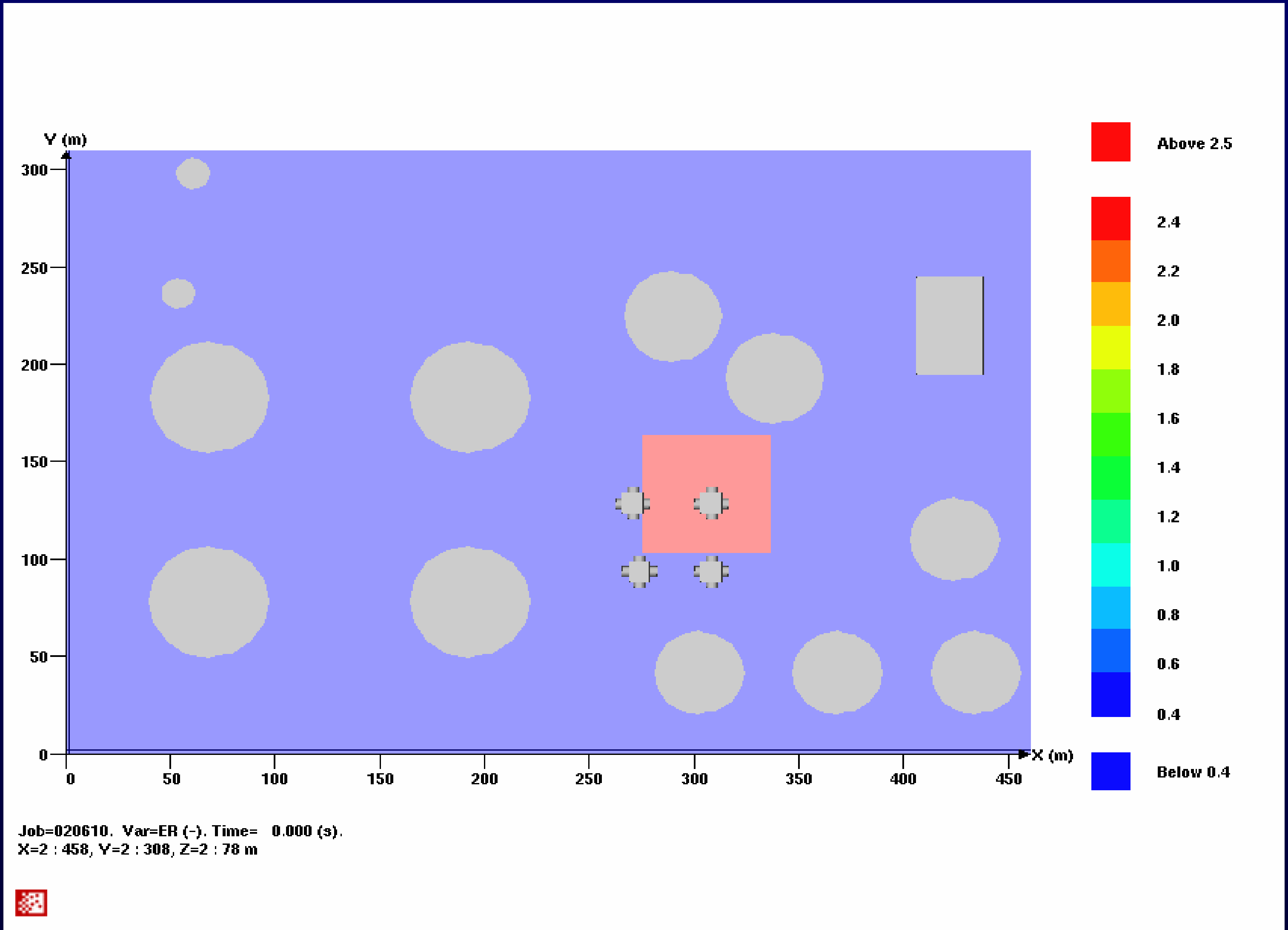




IR of G2 Tank Rupture

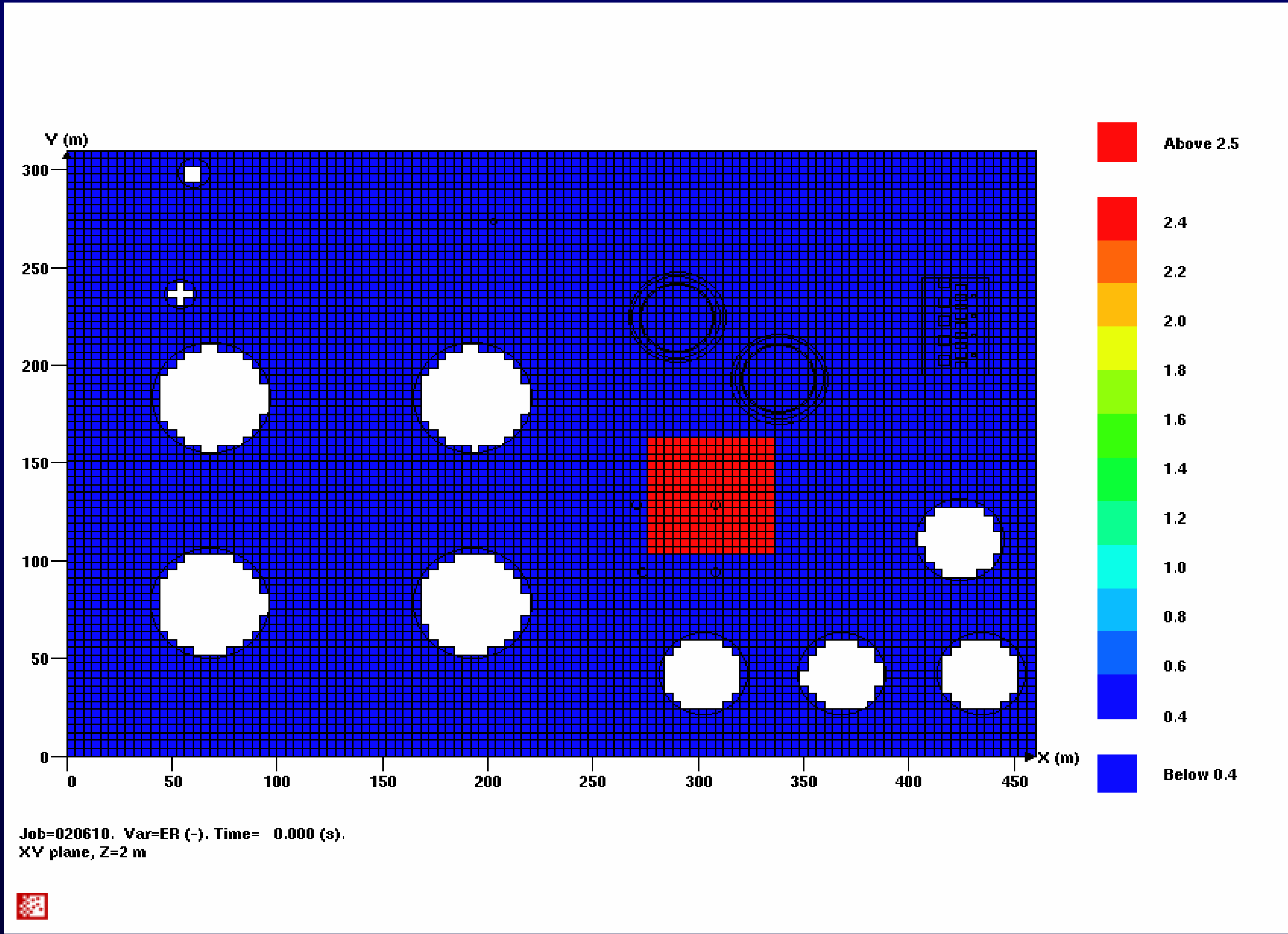


G2 Tank Rupture – Ignited



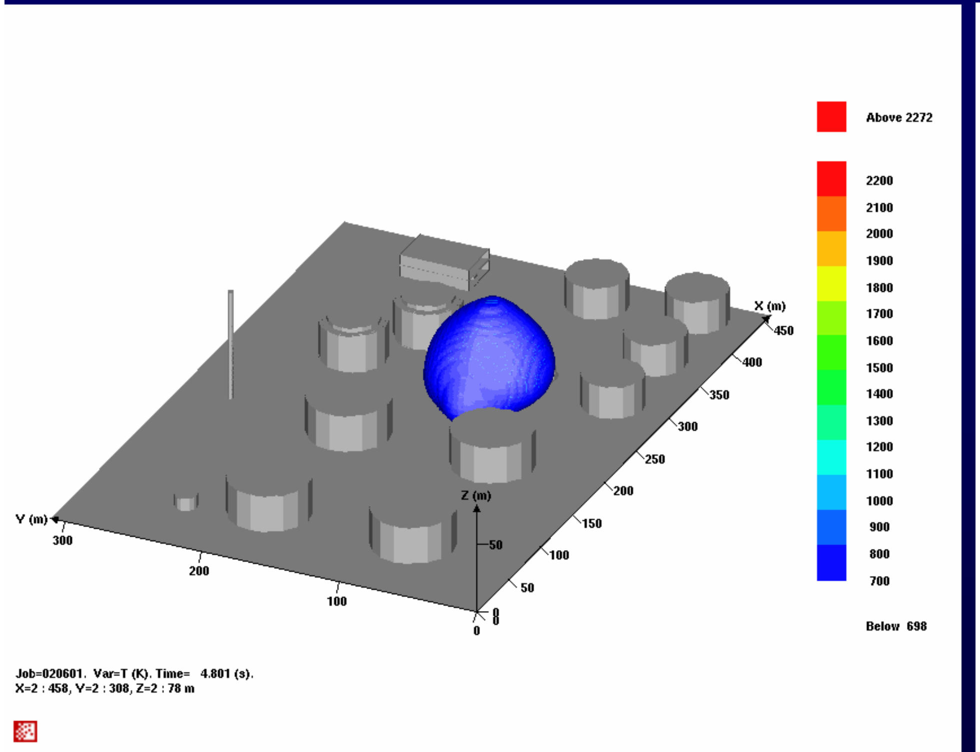
LPG gas dispersion

G2 Tank Rupture – Not Ignited

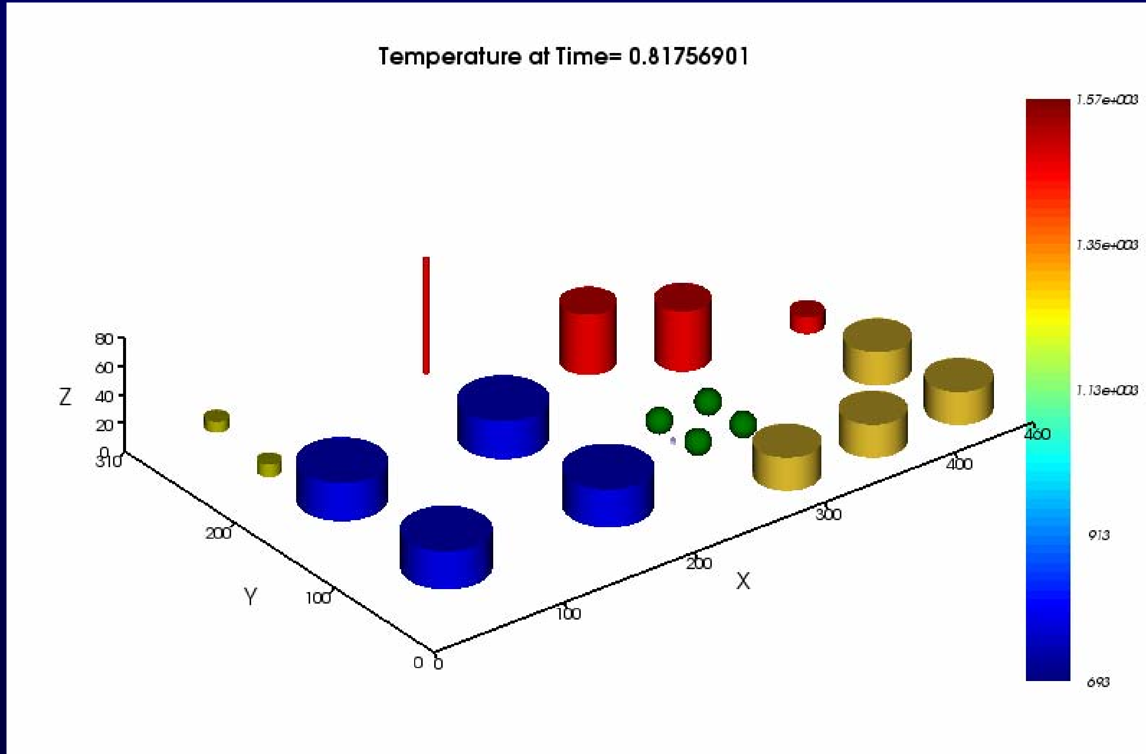


LPG gas dispersion

Connection between FLACS & Risk Analysis Module



FLACS Simulation



3D Contour Simulation