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Research on emergency evacuation at the leakage of toxic substances in Mitsubishi Chemical Corporation

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KAITEKI Value for Tomorrow
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Background and aim

Background : The regulation for consequence management of toxic leakage is not exist in Japan unlike US and Europe, and the level of emergency response plan is not enough. Our company has the emergency evacuation plan, but following problems are identified.

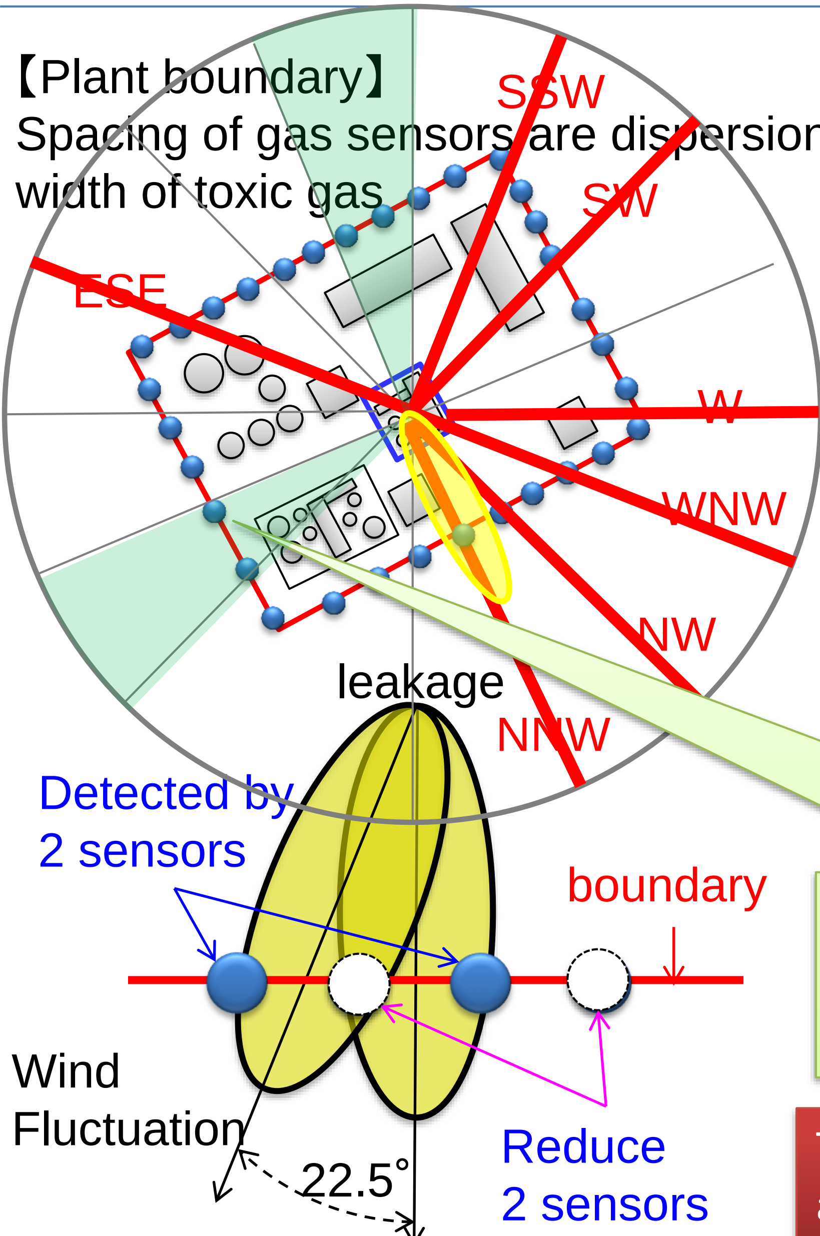
	Problems of current evacuation system	Improvement studies
Detection	• Accurate detection for the leakage of toxic substances	• Optimization of location of gas sensors –plant boundary and manufacturing area
Estimation of leakage rate	• A diameter, which is an input parameter of current model, is not appropriate in accidents	• The estimation of leakage rate by image analysis (kg/min) (Python-OpenCV)
Estimation of dispersion area	• Case study is unable, because estimation results calculated by TRACE are prepared and refer nearest situation	• Making dispersion model which is easy to use and is able to predict evacuation area in near future
Evacuation	• The rule is not decided for the evacuation zone and emergency operation zone to shut down of chemical plant	• Decide threshold for evacuation • Make a rule for evacuation zone and emergency operation zone

Introduction of summary

Today's topics

Aim : Solving all problems from leak detection to evacuation comprehensively, developing the emergency response plan, and deploying it to other factories to improve safety.

Optimization of locations of gas sensors



Collect data from JMA (for 10 years, every 10 min)

Time	2018/6/11
0:10	ENE
0:20	ENE
0:30	ENE
0:40	ENE
0:50	ENE
1:00	ENE
1:10	ENE
1:20	ENE
1:30	ENE
1:40	NE
1:50	NE
2:00	NE
2:10	NE
2:20	NE
[illegible]	NE
3:50	ENE

The analysis of possibility of wind fluctuation

Direction	Possibility(%)
N	65.1
NNE	60.6
NE	58.8
ENE	54.1
E	71.0
ESE	76.6
SE	60.9
SSE	68.4
S	42.4
SSW	78.3
SW	90.5
[illegible]	67.1
[illegible]	75.5
[illegible]	94.7
[illegible]	85.7
[illegible]	75.4

If gas sensors in manufacturing area can detect these directions, gas sensors at plant boundary would be reduced.

The combination of gas sensors in manufacturing area and plant boundary is effective.

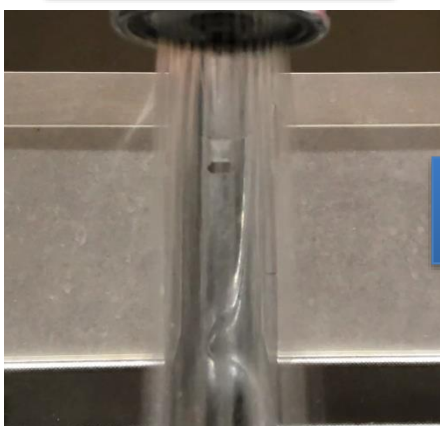
Estimation of leakage rate by motion analysis

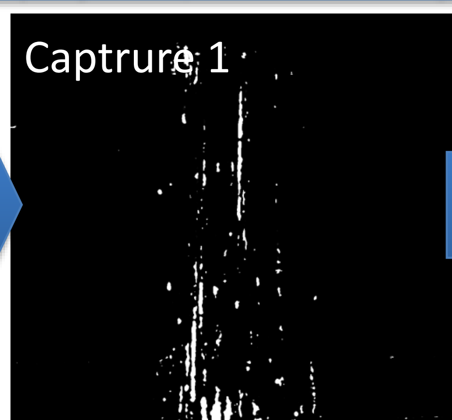
Procedure for evacuation

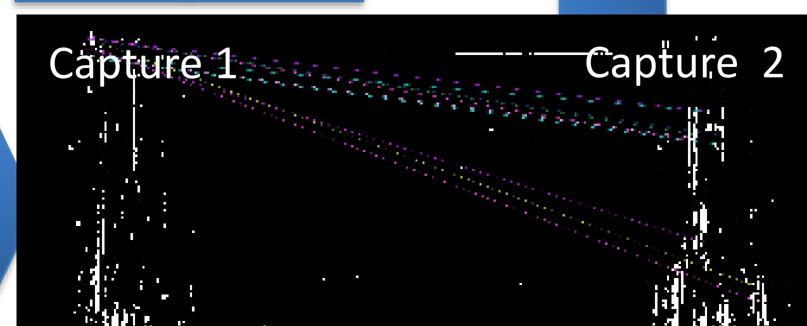
Leakage → Gas / Two phase (flash) / Liquid → Dispersion Analysis → Emergency Evacuation

Motion analysis by OpenCV- Python (Raspberry Pi zero w)

Movie → Preprocessing (Capture, binarization) → Tracking of droplet → Calculation of leakage rate







Comparison of change of each coordinate point in frame rate -> calculate linear velocity

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Calculation by emergency evacuation model

Evacuation calculation model (Excel) : Everybody can use easily and obtain same result

Explanation of color

(yellow)	select from pull down
(red)	input value
(blue)	output value

Obtain atm data

Cal dispersion

Draw consequence

Evacuation, Isolation

Plant	A	
Equipment	T-101	
Substance	toxic	
Leakage rate	10	kg/min
Hole diameter	3.0	mm
Wind direction	SE	
Wind speed	1.5	m/sec
Atmospheric sta	F	

YELLOW : Select values

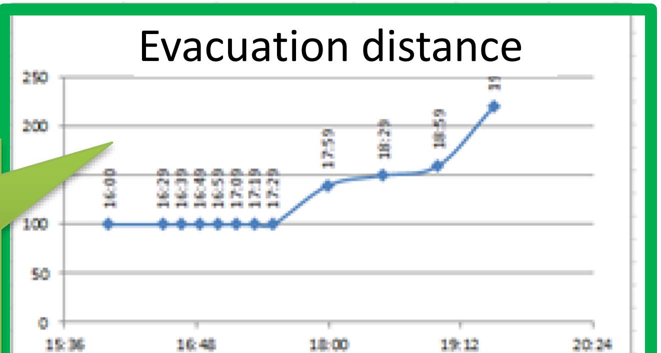
RED : Input parameter <u>Leakage rate only!</u>

BLUE : Obtain or estimate automatically

After input parameter, RED, push 4 buttons for calculation

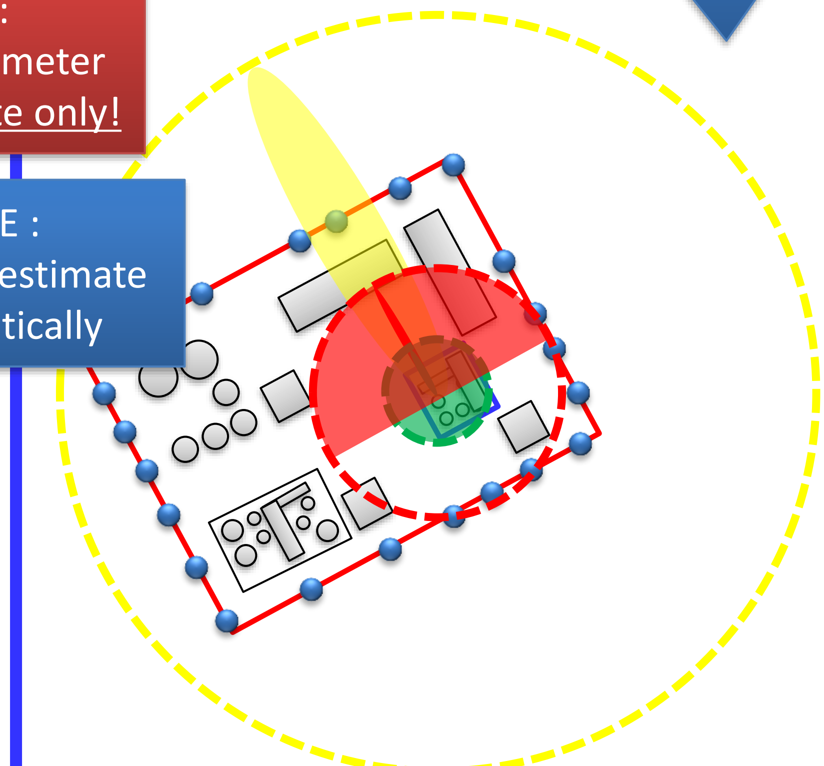
Calculation results

Thresholds	Concentration		Distance	
PAC-3	500	ppm	100	m
PAC-2	100	ppm	250	m
PAC-1	10	ppm	800	m



Prediction of evacuation distance in near future

Display of current dispersion and evacuation area



The model has online and offline mode, and online mode is introduced today

Dispersion model – Pasquill Gifford Equation

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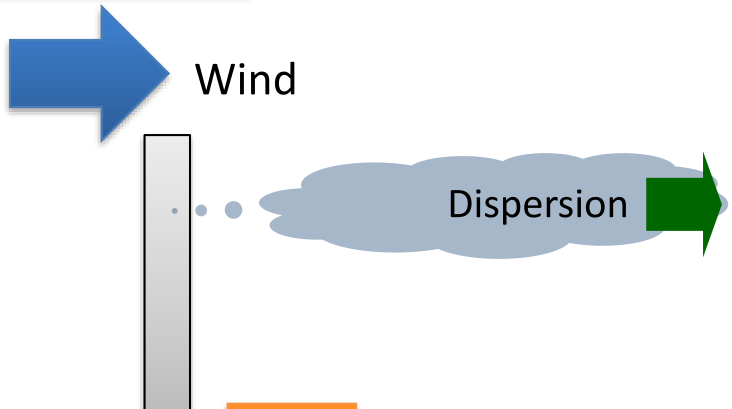
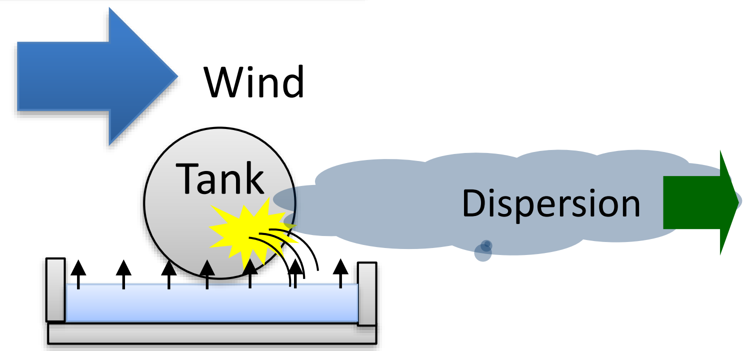
Dispersion model is assumed release phase and pool evaporation

Leak as gas phase



Leak as liquid phase



Calculation of dispersion

$$C = \frac{Q}{2\pi\sigma_y\sigma_z u}F(y)F(z)$$

$$F(y) = \exp\left(\frac{-y^2}{2\sigma_z^2}\right)$$

$$F(z) = \exp\left\{-\frac{(H_e - z)^2}{2\sigma_z^2}\right\} + \left\{-\frac{(H_e + z)^2}{2\sigma_z^2}\right\}$$

Pasquill-Giford
(only passive dispersion)

Calculation of vaporization rate

$$\frac{\overline{Sh} - 0.45}{0.6774\phi_m^{1/2}} = \left[1 + \left(\frac{\phi_m}{12{,}500}\right)^{3/5} \Big/ \left[1 + \left(\frac{300{,}000}{\phi_m}\right)^{7/2}\right]^{2/5}\right]^{1/2}$$

$$\varphi_m = Re\,Sc^{2/3} \Big/ \left[1 + \left(\frac{0.0468}{Sc}\right)^{2/3}\right]^{1/2}$$

Automatic acquisition of parameter for calculation

Data acquisition from HP of Japan Meteorological Agency
-> Decreasing required input parameters make everybody obtain same results

Time	Press(hPa) Land	Press(hPa) Sea	Rain (mm)	Temp (C)	Dew (C)	Pvap (hPa)	Moist (%)	Wind Speed	Wind Direc	Sun (hr)	TASR (MJ/m²)
7	1015.8	1019.2	--	13.1	3.2	7.7	51	6.1	N	0.3	0.52
8	1016.6	1020.0	--	13.9	1.5	6.8	43	7.7	N	1.0	1.56
9	1017.0	1020.4	--	14.5	1.4	6.8	41	8.0	N	1.0	2.29
10	1017.4	1020.8	--	15.4	1.2	6.6	38	6.1	NNE	1.0	2.85
11	1017.5	1020.9	--	15.3	1.8	7.0	40	7.0	NNE	1.0	3.22
12	1017.3	1020.7	--	15.3	1.4	6.8	39	7.1	NNE	1.0	3.38
13	1017.3	1020.7	--	15.1	1.6	6.9	40	6.6	NNE	1.0	3.28
14	1017.1	1020.5	--	15.3	3.5	7.8	45	6.3	NE	1.0	2.94
15	1017.3	1020.7	--	15.4	3.2	7.7	44	6.1	NNE	1.0	2.30
16	1018.0	1021.4	--	15.4	3.5	7.9	45	6.0	NNE	1.0	1.69
17	1018.7	1022.1	--	14.7	2.9	7.5	45	5.8	NNE	1.0	0.95
18	1019.6	1023.0	--	13.7	4.3	8.3	53	7.2	NNE	0.5	0.27

TASR ← Total amount of solar radiation

Solar radiation (0.01kW/m²)
48.1
43.3
63.6
79.2
89.4
93.9
91.1
81.7
63.9
46.9
26.4
15.0

Obtain meteorological data with one button by excel macro

Decide atmospheric stability and dispersion calculation are carried out automatically

Atmospheric stability

Wind Speed (m/s)	Daytime: Solar radiation (0.01kW/m²) 60<Q	30~59	15~29	1~14	Night 0
U<2.0	A	A-B	B	D	F
2.0~2.9	A-B	B	C	D	E
3.0~3.9	B	B-C	C	D	D
4.0~5.9	C	C-D	D	D	D
6.0<	C	D	D	D	D

Dispersion parameters for estimation

Table 5-2 Recommended Equations for Pasquill-Gifford Dispersion Coefficients for Plume Dispersion[a,b] (the downwind distance x has units of meters)

Pasquill-Gifford stability class	σ_y (m)	σ_z (m)
Rural conditions		
A	$0.22x(1 + 0.0001x)^{-1/2}$	$0.20x$
B	$0.16x(1 + 0.0001x)^{-1/2}$	$0.12x$
C	$0.11x(1 + 0.0001x)^{-1/2}$	$0.08x(1 + 0.0002x)^{-1/2}$
D	$0.08x(1 + 0.0001x)^{-1/2}$	$0.06x(1 + 0.0015x)^{-1/2}$
E	$0.06x(1 + 0.0001x)^{-1/2}$	$0.03x(1 + 0.0003x)^{-1}$
F	$0.04x(1 + 0.0001x)^{-1/2}$	$0.016x(1 + 0.0003x)^{-1}$
Urban conditions		
A–B	$0.32x(1 + 0.0004x)^{-1/2}$	$0.24x(1 + 0.001x)^{+1/2}$
C	$0.22x(1 + 0.0004x)^{-1/2}$	$0.20x$
D	$0.16x(1 + 0.0004x)^{-1/2}$	$0.14x(1 + 0.0003x)^{-1/2}$
E–F	$0.11x(1 + 0.0004x)^{-1/2}$	$0.08x(1 + 0.0015x)^{-1/2}$

Equation of dispersion

$$C = \frac{Q}{2\pi\sigma_y\sigma_z u}F(y)F(z)$$

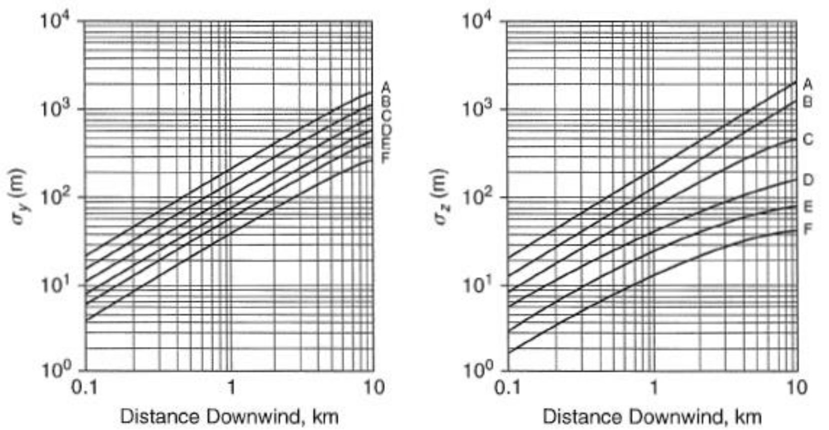


Figure 5-10 Dispersion coefficients for Pasquill-Gifford plume model for rural releases

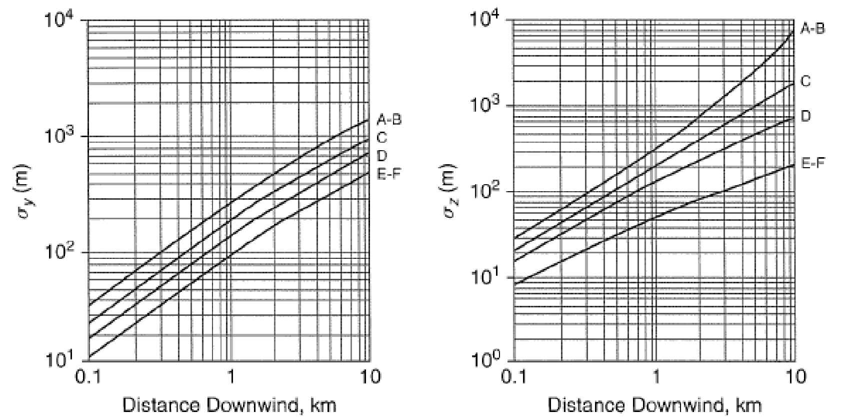
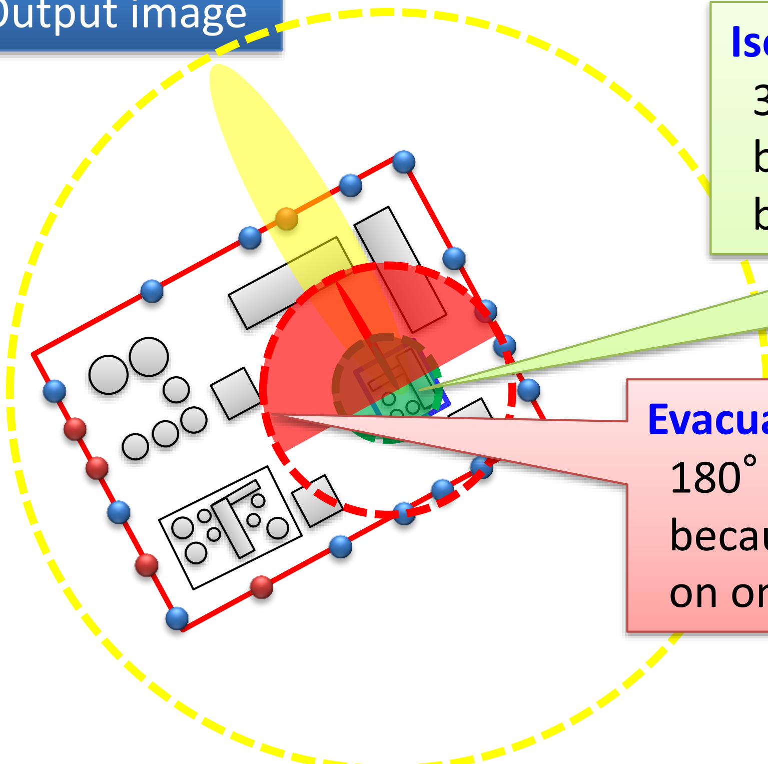


Figure 5-11 Dispersion coefficients for Pasquill-Gifford plume model for urban releases.

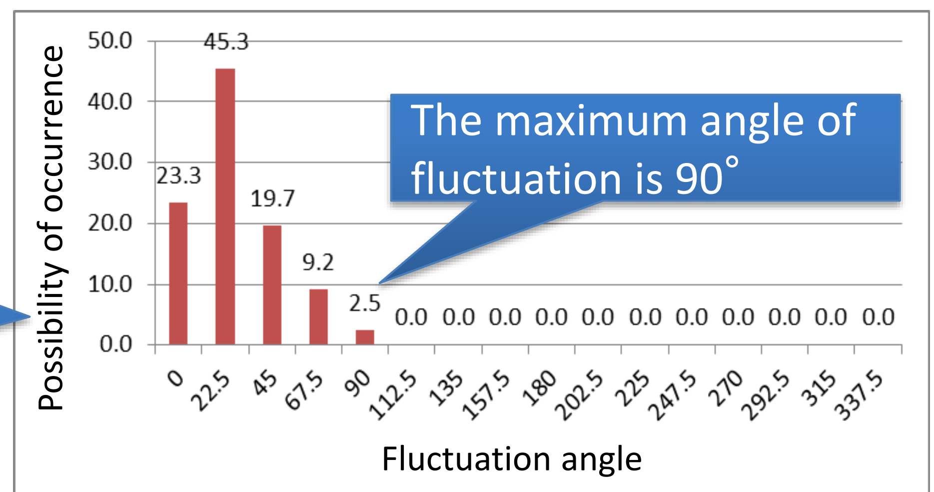
Output image- isolation and evacuation area

Output image



Isolation area: PAC-3 (threat to human life)
360° zone as isolation area
because diffusion in near field is tend to be influence
by existing structures of chemical plant

Evacuation area: PAC-2 (irreversible influence on human)
180° zone of downwind
because the wind may fluctuate in the range of 90°
on one side from the analysis of past 10 years



The maximum angle of fluctuation is 90°

Collect wind direction data every 10min for the past 10yrs from JMA, and analyze 60 min of wind fluctuation

Calculation by emergency evacuation model

Evacuation calculation model (Excel) : Everybody can use easily and obtain same result

Explanation of color

(yellow)	select from pull down
(red)	input value
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Obtain atm data

Cal dispersion

Draw consequence

Evacuation, Isolation

Plant	A	
Equipment	T-101	
Substance	toxic	
Leakage rate	10	kg/min
Hole diameter	3.0	mm
Wind direction	SE	
Wind speed	1.5	m/sec
Atmospheric sta	F	

Calculation results

Thresholds	Concentration		Distance	
PAC-3	500	ppm	100	m
PAC-2	100	ppm	250	m
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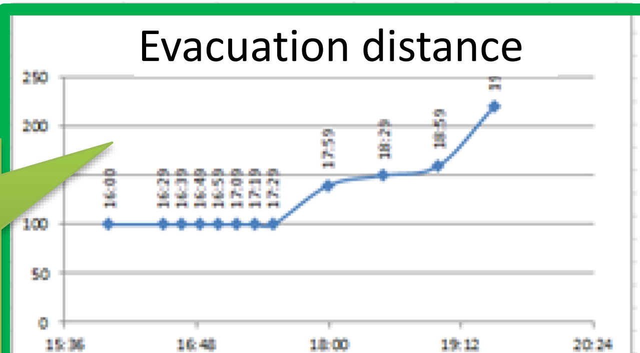
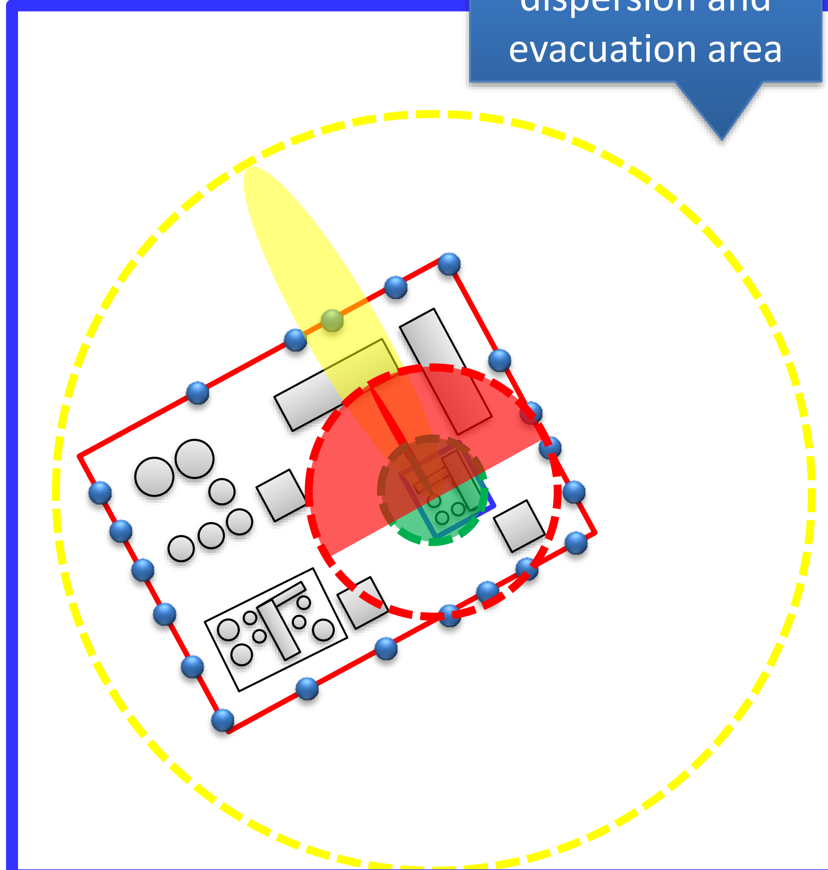


Prediction of evacuation distance in near future

Display of current dispersion and evacuation area

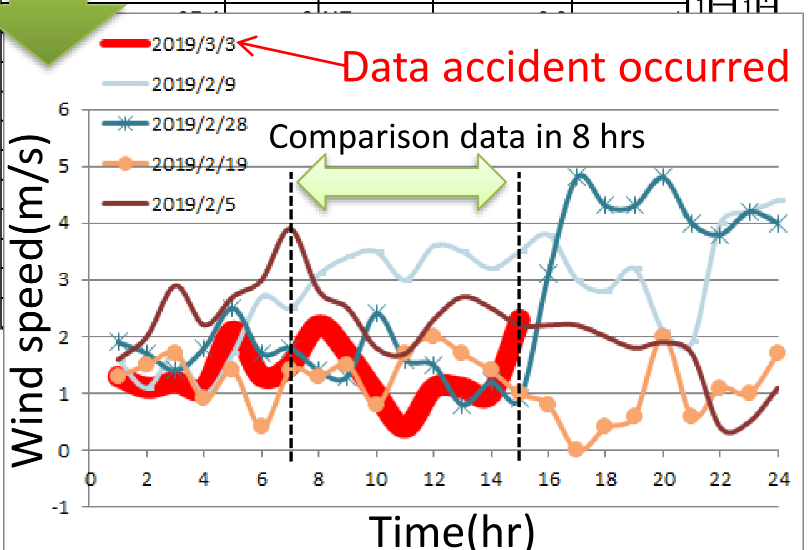


The model of prediction in future evacuation distance is introduced in following slides

Prediction of evacuation distance in future

Collect wind speed and duration of sunshine in 30 days automatically, and estimate them in 3 hrs. in future by cluster analysis

Time	Temperature deg.C	Rainfall mm	Wind Direction	Wind Speed m/s	Sunshine Duration
1	23.8	0	ENE	2.4	–
2	23.5	0	NE	1.3	–
3	23.6	0	NNE	1.1	–
4	23.7	0	NNE	1.5	0
5	23.5	0	NE	1.5	0
6	23.9	0	NE	2	0
7	24.4	0	N	2.5	0
8	25.2	0	NNE	2.8	0.5
9	26.2	0	N	2.9	0.7
10	26.5	0	NNE	2.6	0.7
11	26.1	0	NNE	2.2	0.1
	27.1	0	NE	3	0.8
	27.1	0	NE	2.9	0.8



Preprocessing of cluster analysis

Derivative wind speed is taken on the analysis instead of wind speed absolute value, because of strengthen of correlation to estimate wind speed in future.

Min-Max Normalization was carried out and data sets from 0 to 1 were created to use different dimensions data such as wind speed and sunshine duration.

$$X_{Norm} = \frac{X_{data} - x_{min}}{x_{max} - x_{min}}$$

The data used for cluster analysis is the data up to 8 hours before the current time, because the latest data is important. The period of wind speed change was about 4 hours, so 8 hours for 2 periods is used for the calculation.

Cluster analysis

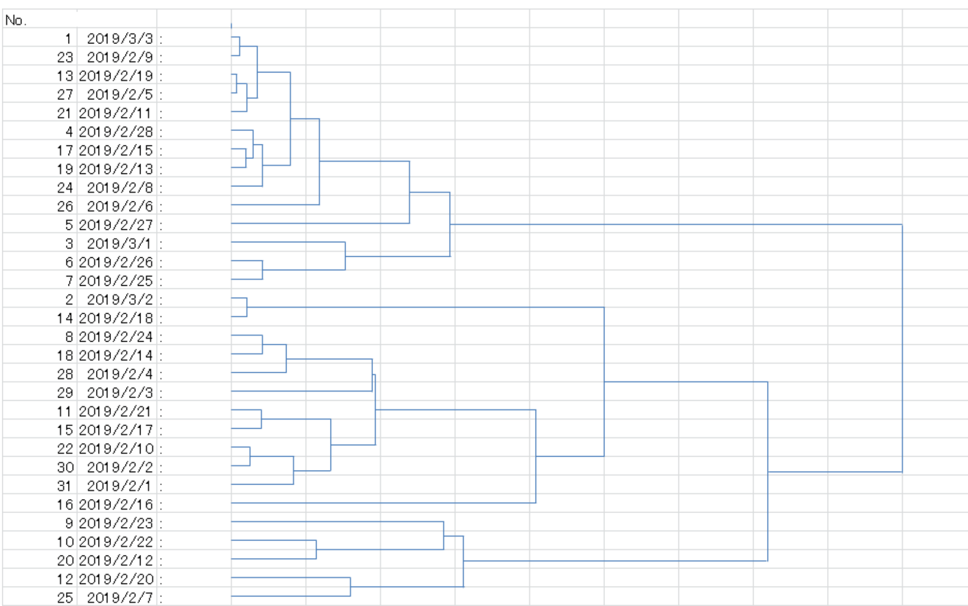
The study of luster analysis is carried out by Ward method, minimum distance method and centroid method

- Euclid distance is taken on similarity distance
- Cluster analysis is carried out by following equation

  Weighting is carried out by among current time and reference time, because data of nearer time is more important.

$$d(A,B)=\sqrt{\sum_{n=0}^{8}\frac{1}{t-(t-n)+1}(A_{t-n}|ws-B_{t-n}|ws)+\sum_{n=0}^{8}\frac{1}{t-(t-n)+1}(A_{t-n}|sd-B_{t-n}|sd)}$$

ws: wind speed
sd: sunshine duration

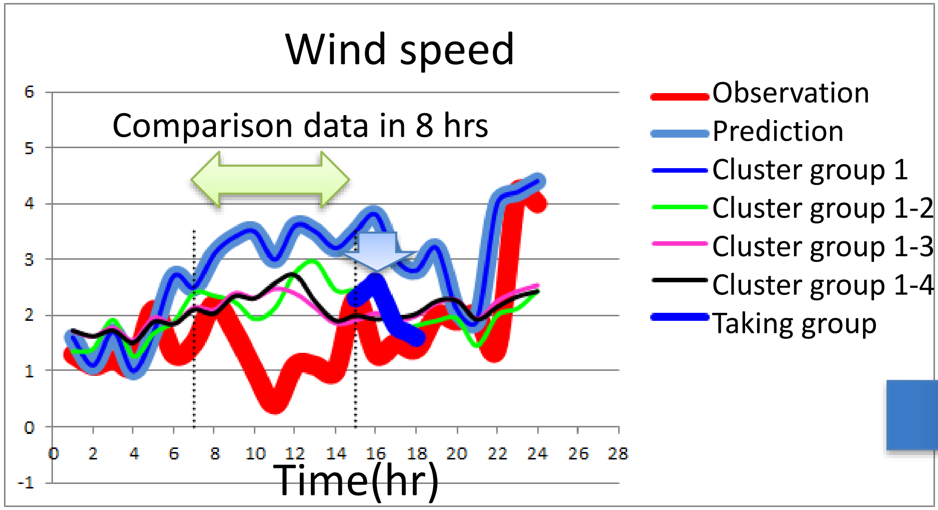


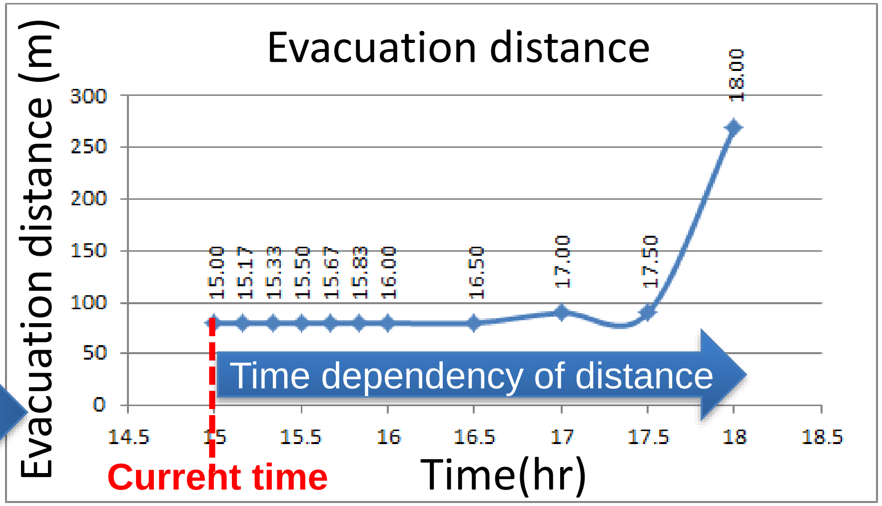
Analysis method	RMSE (m/s)
Ward	0.82
Min. distance	1.12
Centroid	1.06

Ward method is taken for cluster analysis by the result of RMSE.

The prediction of evacuation distance by 3 hours in future

The cluster group having correlation to current wind speed and duration of sunshine is adopted for the prediction model.





Estimated value is deviation of wind speed, and absolute value of wind speed should be corrected corresponding to current wind speed.

Estimate evacuation distance by 3 hours in future, and recognize necessity of preparation for increase of evacuation distance

Especially, the atmospheric condition is stable at sunset and the evacuation distance is increased, so it is considered that the prior prediction is very effective.

Accuracy of predicted wind speed

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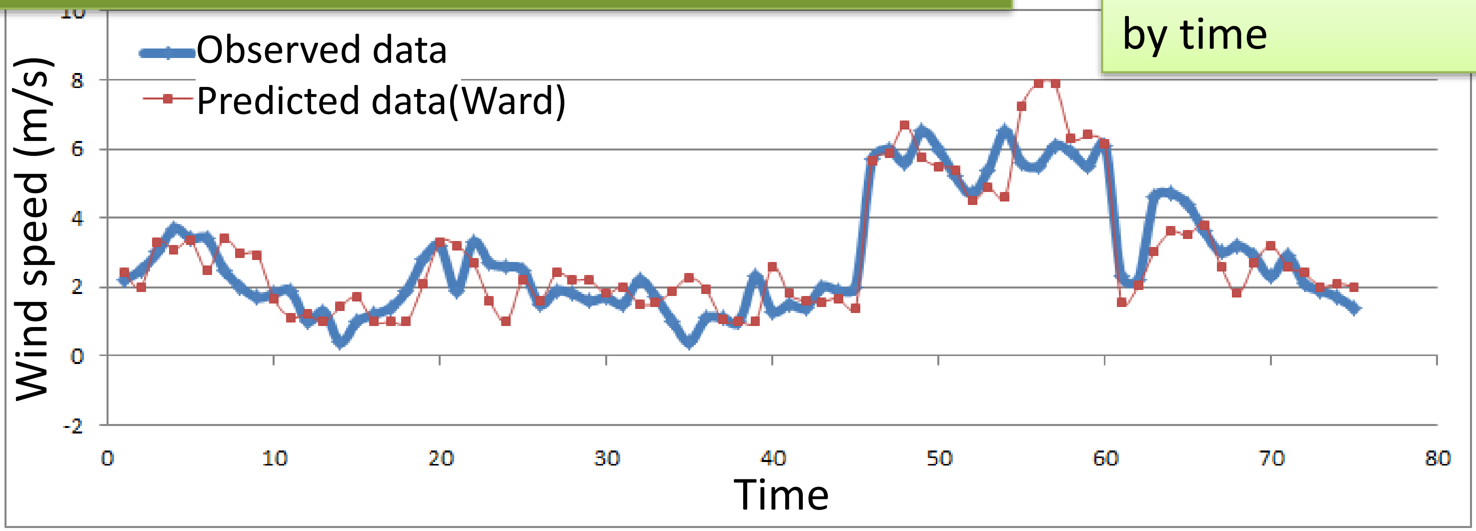
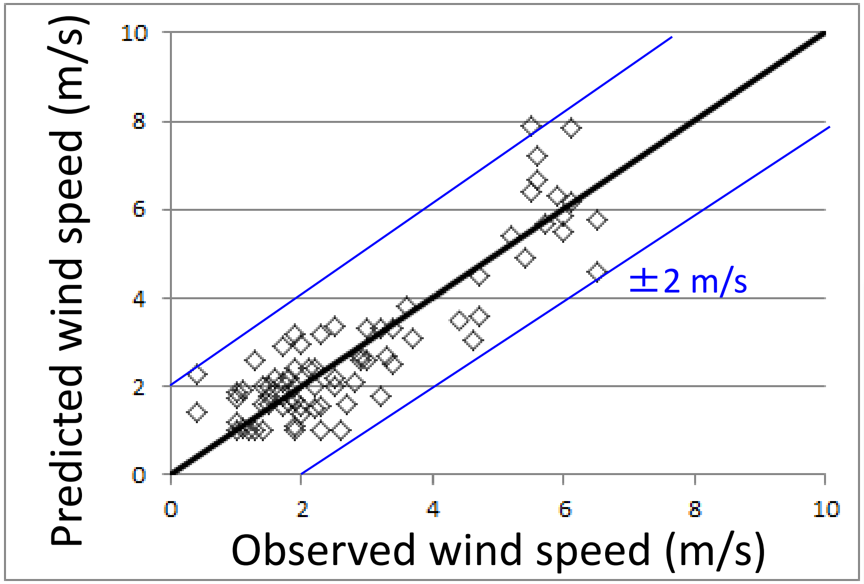
Comparison of predicted wind speed with observed one

Plotted continuously by time





The tendency of wind speed almost can be estimated

However, the accuracy of prediction is about ± 2 m/s at maximum
⇔ If the wind speed is low, the relative error will increase. It becomes a factor to deteriorate the accuracy of evacuation distance estimation

Accuracy of predicted atmospheric stability

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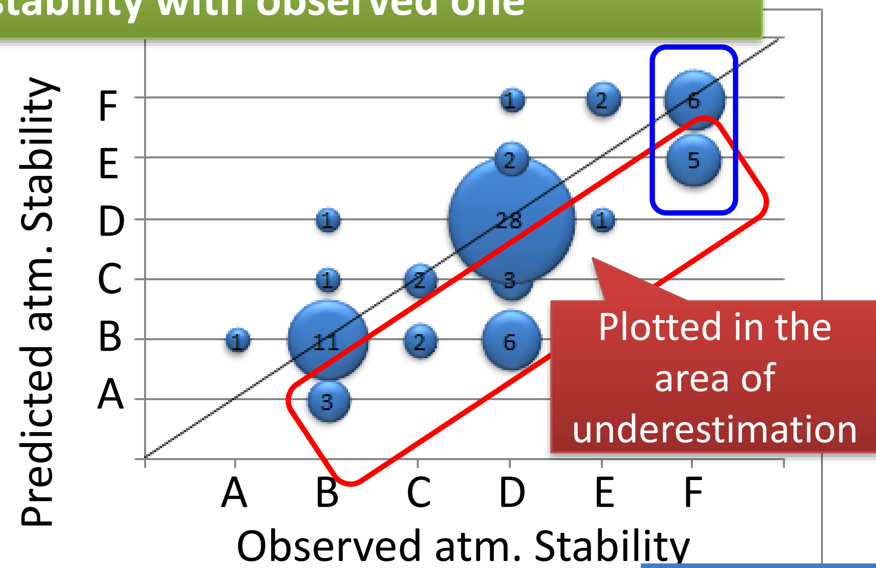
Comparison of predicted atmospheric stability with observed one



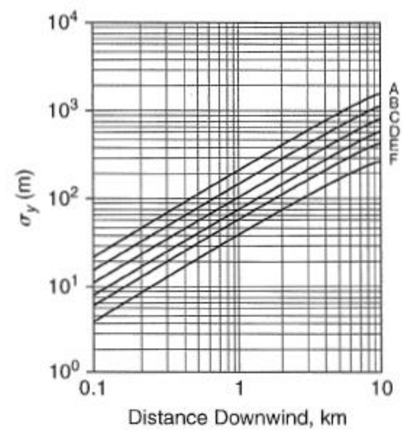
Equation of gas dispersion

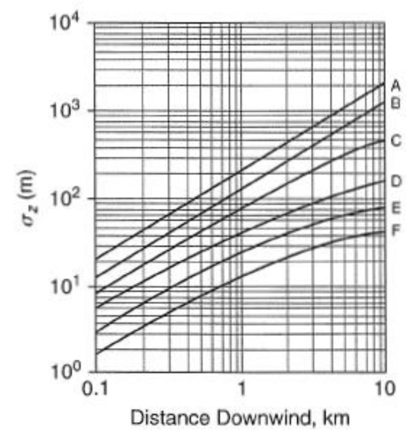
$$C = \frac{Q}{2\pi\sigma_y\sigma_z u} F(y)F(z)$$

$$F(y) = \exp\left(\frac{-y^2}{2\sigma_z^2}\right)$$

$$F(z) = \exp\left\{-\frac{(H_e - z)^2}{2\sigma_z^2}\right\} + \left\{-\frac{(H_e + z)^2}{2\sigma_z^2}\right\}$$

Evacuation distance increases as A → F





Judgment of atm. Stability

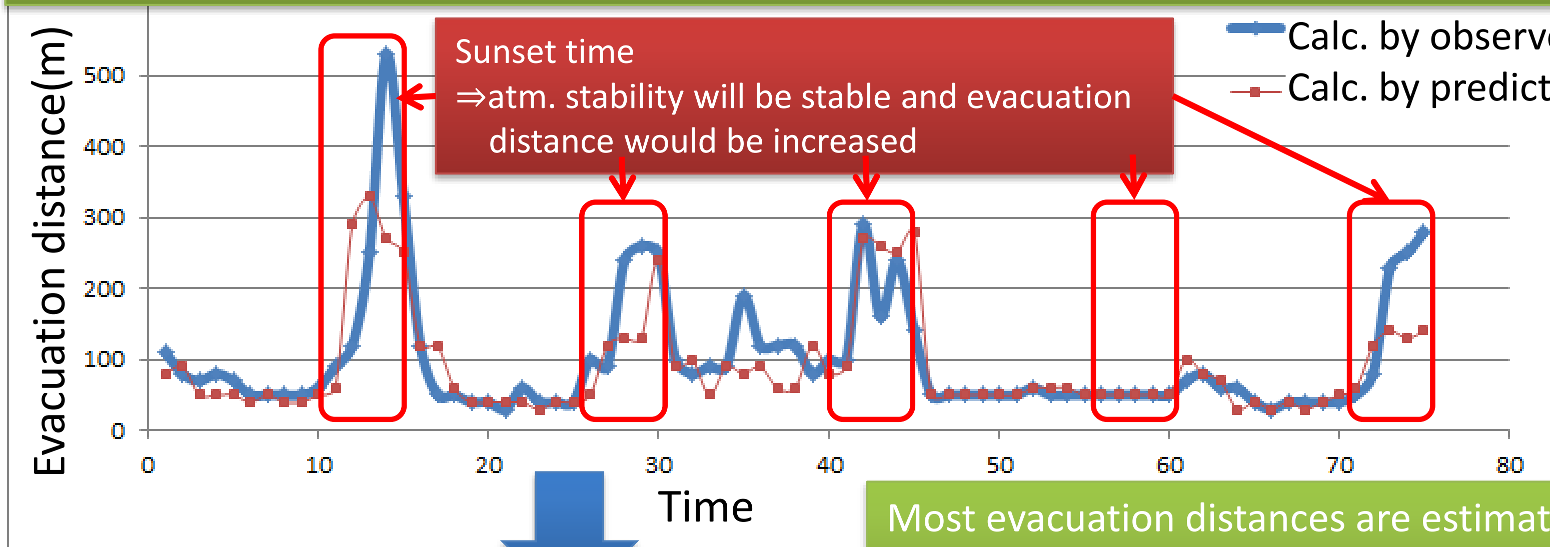
This is the biggest error factor

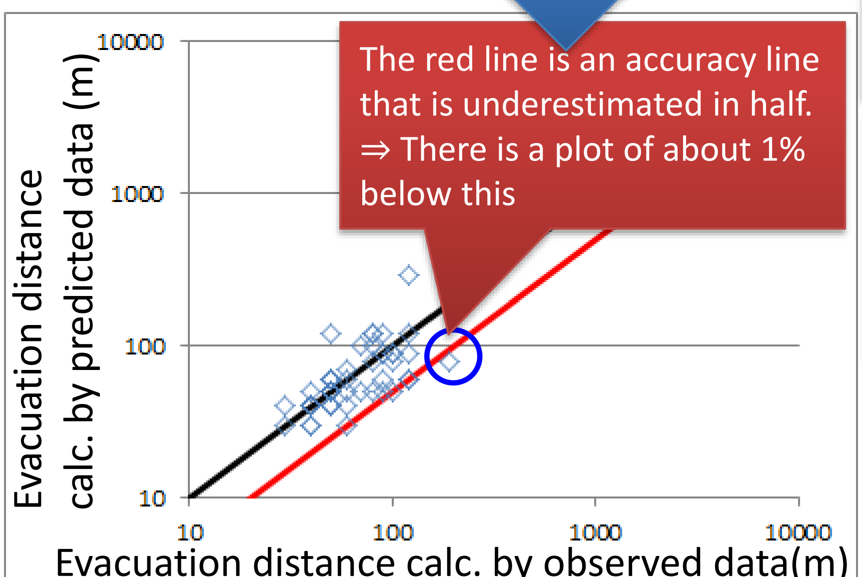
Wind Speed (m/s)	Daytime: Solar radiation (0.01kW/m²)				Night
	60<Q	30~59	15~29	1~14	0
U<2.0	A	A-B	B	D	F
2.0~2.9	A-B	B	C	D	E
3.0~3.9	B	B-C	C	D	D
4.0~5.9	C	C-D	D	D	D
6.0<	C	D	D	D	D

Accuracy of predicted atm. stability is important, because parameter taken for calculation is changed by it.

Accuracy of predicted evacuation distance

Comparison of evacuation distance calculated by predicted atm. condition with observed one





Most evacuation distances are estimated accurately, but there are some plots not matching in case of sudden change of wind speed

【Current operation】

It is possible to estimate the evacuation distance in advance with an accuracy of approximately 99% without underestimation, by adopting a distance that is twice the predicted distance as the evacuation distance as the safety factor.

【Future plan】

The study of increasing accuracy about data set having large predicting error, especially atmospheric stability F.

Summery and future plans

Technical approaches are studied for each problems in order to construct comprehensive emergency response plan. The problems are still remain for completion and continue to study below items.

	Problems of current evacuation system	Improvement studies	Future plans
Detection	• Accurate detection for the leakage of toxic substances	• Optimization of locations of gas sensors –plant boundary and manufacturing area	• Study many case studies and make some simple dispersion model to implement them easily
Estimation of leakage rate	• A diameter, which is an input parameter of current model, is not appropriate in accidents	• The estimation of leakage rate by image analysis (Python-OpenCV)	• (same as left)
Estimation of dispersion area	• Case study is unable, because estimation results calculated by TRACE are prepared and refer nearest situation	• Making dispersion model which is easy to use and is able to predict near future evacuation area	• Improving prediction model and check accuracy for various conditions
Evacuation	• The rule is not decided for the evacuation zone and zone of emergency operation for shut down of chemical plant	• Decide threshold • Make a rule for evacuation zone and emergency operation zone	• (Finished)

This presentation (Red area)

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Thank you for your attention!

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Mitsubishi Chemical