Technical Discussion
What is F Stability?

The worst-case meteorological condition in a toxic gas release situation is during the night when the air mass is stable and the toxic gas cloud is slow to disperse. This is the "F" atmospheric stability.

A Chlorine Release Incident

It was in the early morning hours of September 2, 1987, at the water treatment plant near Morristown, Tennessee. At 4:50 AM, the chlorine room monitor and alarm signaled employees that a leak had occurred. However, the chlorine concentrations in the room were so great that employees were unable to enter the area. The Morristown Fire Department was notified at 5:07 AM, but they were not able to cap the leak even wearing SCBA. The leak was described as a chlorine liquid jet escaping from one of two ton-capacity tanks connected with a manifold. The chlorine also corroded electrical equipment which resulted in a fire starting in the plant's chlorine room. Sometime around noon a team from the chlorine supplier successfully cap the leak. An estimated 2,400 to 3,000 pounds of chlorine had escaped before the leak was capped. By that time, almost all of the chlorine had escaped from the two tanks.

The resulting chlorine cloud was photographed about 3.5 hours after the spill, and the picture published in the February 1988 issue of Fire Engineering magazine (pages 22-29). The cloud at the time of the photograph was described as 5 miles long, 1 mile wide, and 30 feet high. The cloud forced the evacuation of 4000 people, including 131 patients from a nursing home.

During the early morning hours before the sun came up the weather was described as clear and calm. The chlorine plume hugged the ground and was only 2 feet high near the plant, and tended to follow the terrain. During the first 30 minutes, the cloud had advanced only ¼ mile from the plant. Before the sun began to heat the ground, the cloud was only about 10 feet high at a distance several miles from the plant. The cloud height increased to about 30 feet as solar heating began. Shortly afterwards, the winds picked up, and the cloud dissipated.

Weather Conditions and Terrain Affect Toxic Cloud Movement

The weather conditions were clear and calm and the air stable during the Morristown incident until the sun rose and began to heat the ground. During the night, the ground radiated heat off into space which resulted in the air near the ground to become cooler. Cool air is more dense than warm air, and with the cooler air near the ground the air layers do not mix and are therefore stable. Topography at Morristown TN also played a role in the spread of the chlorine cloud as it traveled downhill. The air was very stable at Morristown, as the chlorine height was initially shallow even some distance from the plant. Later, the sun rose and the ground began to heat up. The air began to become unstable, meaning that the warmer air near the ground began to rise and mixed with the cooler air above. The mixing also resulted in wind. The chlorine cloud mixed with the surrounding air and dissipated.

What are the things that affect the toxic cloud movement? One major factor is the wind. If the wind is strong, the air will be turbulent and the toxic cloud will tend to dissipate especially as the wind interacts with buildings and terrain. Also, the toxic cloud will arrive at some location downwind sooner. If the winds are light, solar heating during the day or cooling at night becomes important. The air becomes unstable during the day as the sun heats the ground and the heat is transferred to the air; unstable air results in the toxic cloud dissipating because the warm air near the ground rises. The opposite is true during a clear, calm night. Then the air is stable, the cold air remains near the ground, and the toxic cloud does not dissipate. If the weather conditions are overcast, heating and cooling of the ground does not take place, and the air is said to be neutral. Let’s make a list of those things which affect toxic cloud movement:

- Wind
- Solar heating and cooling (related to cloud cover and time of day)
- Humidity, precipitation
- Typography (hills, valleys, etc.)
- Terrain (flat, cropland/scrub, forests, buildings)

Also important is the amount and duration of the chemical release, the release elevation, and the temperature of the release. In the Morristown example, the chlorine evaporated as the chlorine escaped from the tanks. As the chlorine evaporated, the tank and gas became chilled, possibility down to –30ºF and even colder. We know this because there was some chlorine liquid and ice near the tank hole, and the boiling point for liquid chlorine is approximately –30ºF. The toxic gas was dense and cold and hugged the ground.

However, if a fire had occurred, the hot gases resulting from the fire could result in the chlorine toxic cloud rising high into the air. This happened with the chlorine fire on the afternoon of June 18, 1988, at Springfield, MA. The white to orange-brown colored toxic cloud was described as several city blocks wide and four to five miles long, with chlorine odors detected up to 15 miles downwind. Between 20,000 and 30,000 people were evacuated. The chlorine cloud was fairly high above the ground. The chlorine odors were more noticeable on hilltops rather than in valleys. The wind speed was 7 to 10 mph.

Modeling the Toxic Cloud Movement

Scientists have developed various mathematical models to describe the movement of the toxic cloud as it travels downwind. The models have been given names such as DEGADIS, SLAB, D2PC, HGSYSTEM, HEGADAS, etc., or any one of a number of passive dispersion models. The ALOHA model in CAMEO uses a combination of the DEGADIS dense gas model and a passive dispersion model. The PEAC tool uses a proprietary dense gas model related to SLAB and a passive gas dispersion model. All models must (or should be) calibrated against real data to determine how the toxic cloud spreads and disperses as it travels downwind for various weather situations. For example, Gary Briggs in the early 1970’s developed mathematical expressions (called “sigmas”) which described how a toxic cloud grew in size and became more dilute as it traveled downwind from a series of tests as sulfur dioxide was released over a field. Briggs’ sigma expressions are widely used in passive dispersion models today. Sometimes earlier models are “tweaked”, as they are tested and refined by comparison against actual releases. The adjusted models might be given version numbers, e.g. HEGADIS-1, etc.

The user of ALOHA or the PEAC tool does not have to worry about how the models calculate the results. Instead, ALOHA or the PEAC tool asks the user questions regarding the nature of the release, wind speed, cloud cover, and time of day. Calculations which would normally take perhaps an hour with a simple pocket calculator (perhaps days if a dense gas model is used), might be done in a second or less using today's computers or with the PEAC tool.

But how do these models work? From user input (wind speed, cloud cover, date, location, time of day) an atmospheric stability (A, B, C, D, E, or F) is assigned internally by the model (table 1). The A, B, and C Stabilities are reserved for daytime, low wind, sunny conditions when the air is unstable. The E and F Stabilities are reserved for nighttime including near sunrise or sunset conditions when the air is stable. The D stability is used for neutral atmospheric conditions, a situation which usually occurs during overcast conditions or windy conditions regardless of time of day. None of these stability classifications account for unusual weather situations such as a passing cold front, rain, or a zero wind situation.

Table 1. Pasquill-Gifford Stability Index.

Pasquill Stability Class	Description	Surface wind speed and cloud cover Wind measured (meters/second) at 10 meter height
A	very unstable	daytime; strong insolation and wind < 3 m/s or moderate insolution and wind < 2 m/s
B	Unstable	daytime; strong insolation with wind between about 3 and 5 m/s or moderate insolution with wind between 2 and 4 m/s or slight insolution and wind < 2 m/s
C	slightly unstable	daytime; strong insolation and wind > 5 m/s or moderate insolution with wind between 4 and about 5.5 m/s or slight insolution and wind between 2 and 5 m/s
D	Neutral	All overcast sky conditions, day or night; daytime and moderate insolation and wind> 5.5 m/s; daytime and slight insolation and wind > 5 m/s; nighttime and wind > 5 m/s; nighttime and more than 50% cloud cover or with thin overcast and wind > 3 m/s
E	slightly stable	nighttime; thin overcast or > 50% cloud cover and wind < 3 m/s; < 50% cloud cover and wind between 3 and 5 m/s
F	Stable	nighttime; < 50% cloud cover and wind < 3 m/s

When a user inputs a wind speed, the PEAC tool assumes it is at 2-meter height, and the PEAC computer tool calculates internally the wind speed at the 10 meter height. Solar heating and radiation cooling is determined by the time of day, latitude, date, and percent cloud cover. This is why the PEAC internal clock and location should be correctly set. The ALOHA model does essentially the same thing to determine the stability class.

Each model contains mathematical expressions (sometimes referred to as “sigmas”) that describe how the toxic cloud grows in size and becomes more dilute as it travels downwind. Under unstable air conditions, the toxic cloud disperses. Under stable air conditions, the toxic cloud remains essentially intact and if nothing disperses the cloud it can travel a long way from the source and remain for a long time. An intermediate condition exists under neutral conditions; the wind turbulence plays a major role in dispersing the toxic cloud.

The PEAC tool asks the user some basic information on the terrain: (1) flat, (2) cropland or light vegetation or (3) urban or forest. These ground structures/trees help disperse the toxic cloud under windy conditions. The effect of these structures/trees is not great (relative to stable vs. unstable conditions), but it is a way to fine-tune the model.

The boundary lines defining the stability classes are arbitrary, but many models follow the Pasquill-Gifford Stability classifications. The DOT initial isolation and protective action distances recognize only two classifications, daytime (incorporates A, B, C, and D stabilities) and nighttime (incorporates D, E, and F Stabilities). The numbers that DOT presents as protective action distances are based on a 90 percentile, that is, 90% of a large matrix of hypothetical spills will have protective action distances to a concentration level of concern equal to or less than the number presented in the DOT tables. The PEAC tool provides both the DOT protective action distance and the DOT level of concern that that number is based.

At the other extreme, some models provide the user the option of using a numerical scale to indicate atmospheric stability. The numerical scale most often used is the Obukhov length (sometimes called “Monin-Obukhov” length). The numerical scale allows the user to model say an intermediate D to E stability condition or an extreme far “F” stability condition where the winds virtually completely die down at night, by assigning an appropriate Obukhov length. Similarly, a surface roughness height can be assigned as a measure of the height of the structures on the terrain (instead of the three broad categories that the PEAC tool or ALOHA uses). This allows further fine tuning of the model predictions. SLAB is an example of a model where the user has the option of using a surface roughness length and a Obukhov length.

The emergency responder may ask, “I don’t care about modeling. What is the worst case?

The worst case is the “F Stability” condition. It is also the most controversial. It is also the case where models are most likely to disagree with each other. Under the F Stability condition, the toxic cloud is slow to disperse.

Modeling a Chlorine Release Incident at Different Stabilities

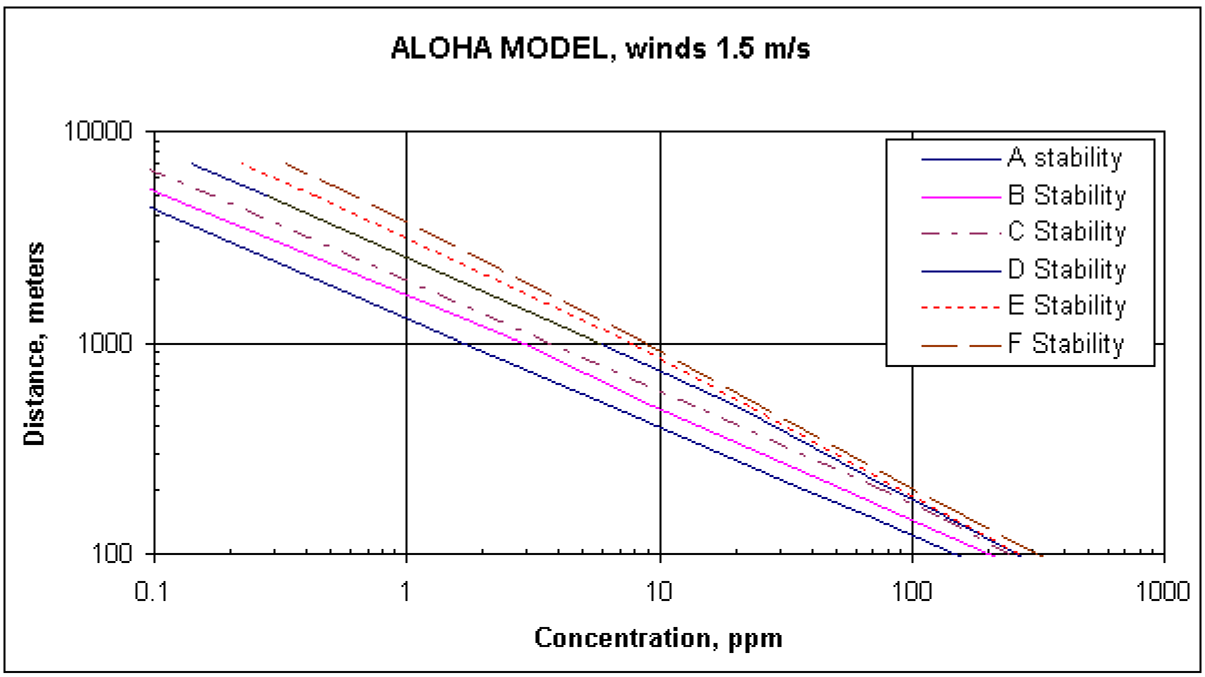
Let’s assume that 2000 lbs of chlorine escapes from a hole in a tank over a time period of two hours. We will model the incident for each of the atmospheric stabilities, A through F, and see which is the worst. We will do this exercise using ALOHA and the PEAC tool so we can get a comparison. We will input cloud cover and time of day based on table 1 to insure that the model selects the proper stability. We will use a wind speed of 1.5 m/s. The A through D stabilities will be done during the day, and the E and F stabilities will be done at night. Overcast (cloudy) skies will be selected for the D stability, and clear skies will be selected for the A and F stabilities. We will select open, flat terrain. The release rate averages 16.67 lbs/min (0.126 kg/s) over the two-hour period. The hole size in the chlorine tank corresponding to this release rate is 0.184 cm. We would like to graph the results, with distance from source on the vertical axis and concentration of chlorine in the toxic cloud on the horizontal axis. In order to get enough points to graph, we will need to run the model many times inputting different levels of concern and record the corresponding protective action distance.

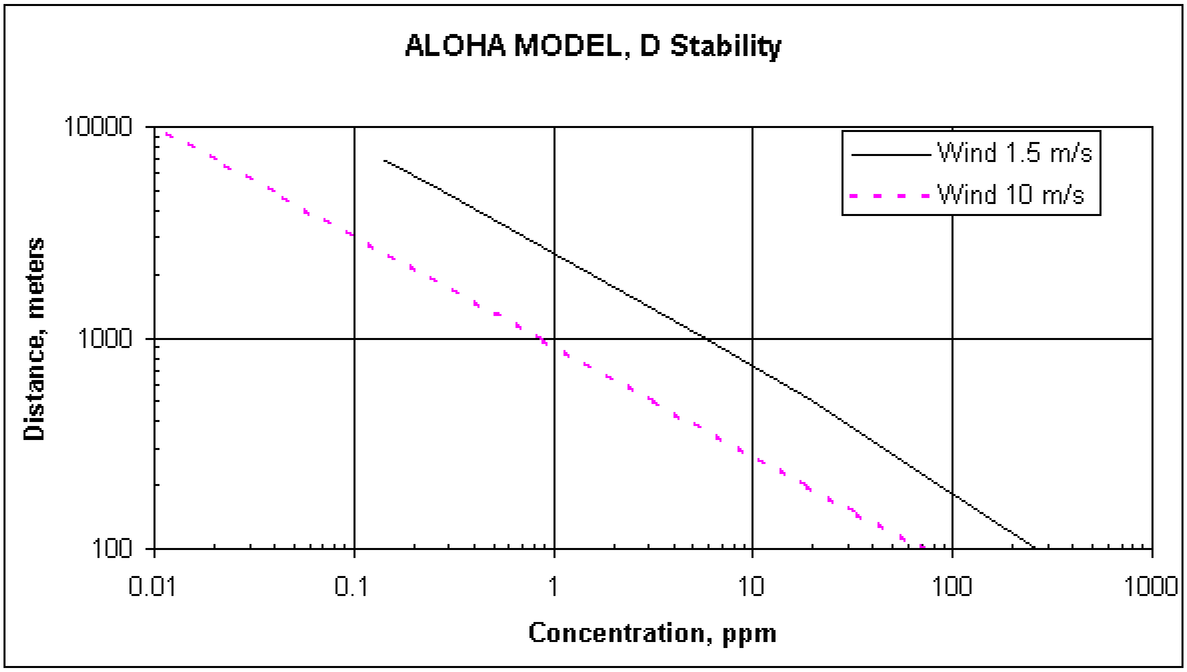
Wind also affects the chlorine cloud behavior. During windy conditions, the air is turbulent. The chlorine cloud disperses. Therefore we will do a comparison under D stability conditions at wind speeds of 1.5 m/s (3.35 mph) and 10 m/s (22.4 mph).

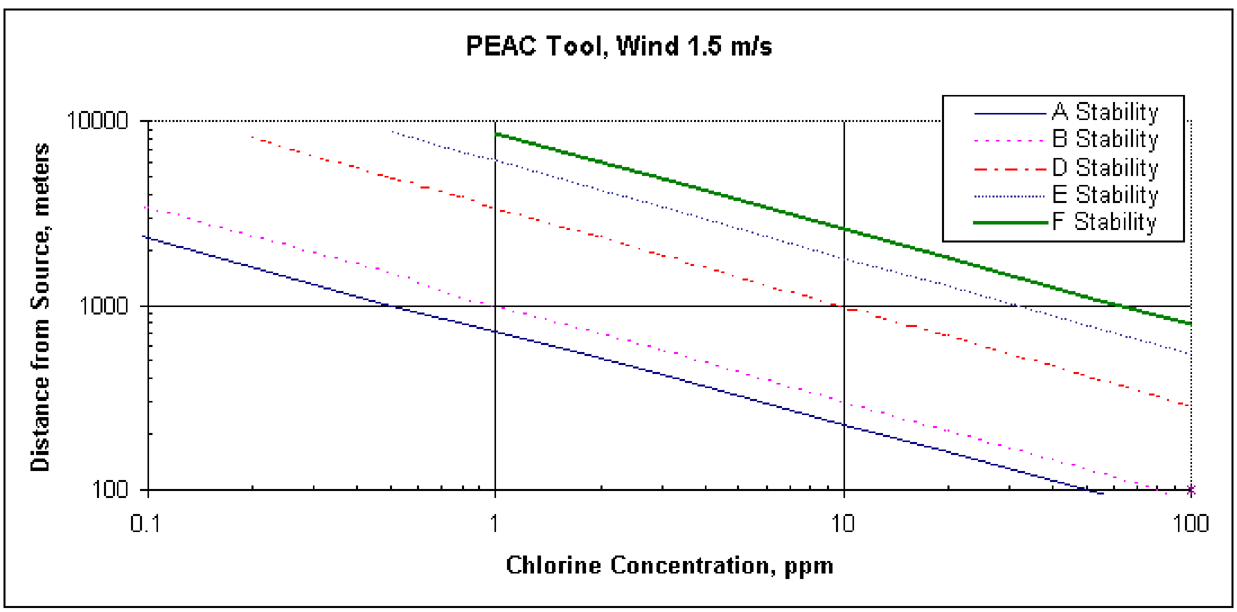
All these results as plotted on log-log paper are reproduced below. From the plots, a table was constructed listing the downwind distance corresponding to a chlorine concentration of 3 ppm, which is the ERPG-2 value.

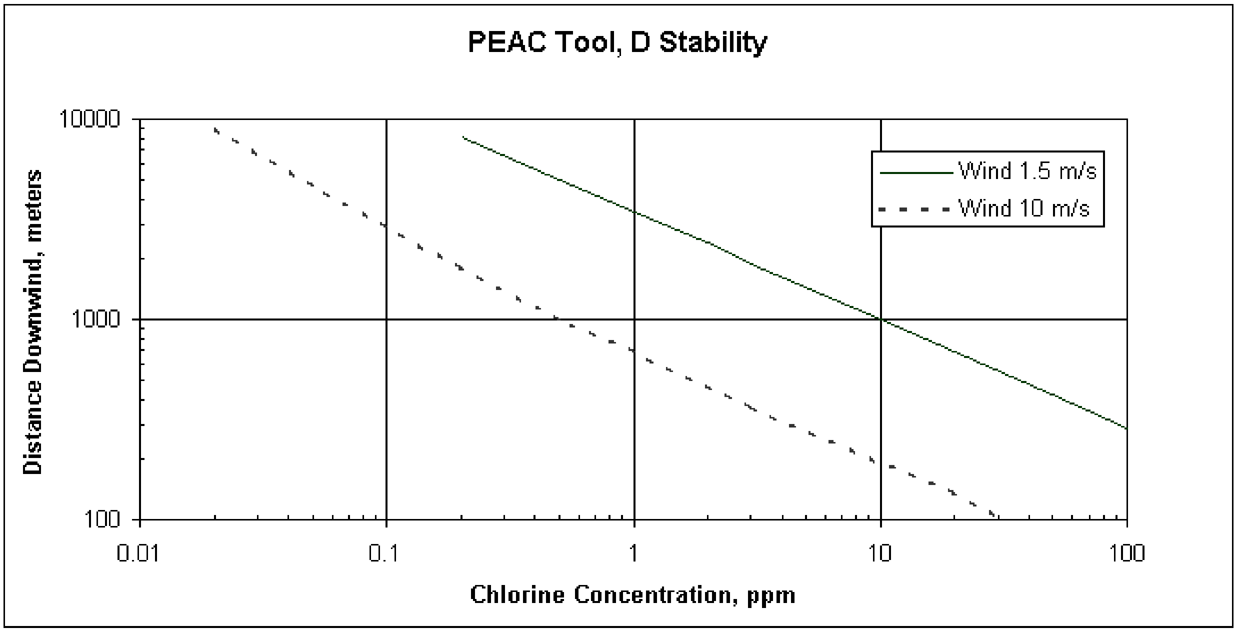
Table 2. Downwind Distance (meters) when Chlorine is 3 ppm

Model	Stability	Wind, m/s	Distance, meters
ALOHA	A	1.5	620
ALOHA	B	1.5	800
ALOHA	C	1.5	940
ALOHA	D	1.5	1250
ALOHA	E	1.5	1500
ALOHA	F	1.5	1800
ALOHA	D	10	520
PEAC	A	1.5	471
PEAC	B	1.5	571
PEAC	D	1.5	1900
PEAC	E	1.5	3500
PEAC	F	1.5	4900
PEAC	D	10	366




ALOHA MODEL, D Stability
Distance, meters
10000
1000
100
0.01
0.1
1
10
100
1000
Concentration, ppm
Wind 1.5 m/s
Wind 10 m/s


PEAC Tool, Wind 1.5 m/s
Distance from Source, meters
10000
1000
100
0.1
1
10
100
Chlorine Concentration, ppm
A Stability
B Stability
D Stability
E Stability
F Stability



Both the PEAC tool and the ALOHA model predict the same general trends, but the numbers are not quite the same. Before we discuss the reasons for differences between the two models, we need to consider a few other points.

Near F or Far F Stability

Under real-world conditions, atmospheric stability can change rapidly especially near sunset and sunrise. The transition between say an A and C stability or from D, E, to F stabilities can take place in minutes. In the Morristown TN chlorine release, at the time of the initial release, conditions could have been close to a "far F" stability condition. When the sun rose, conditions changed to possibility a B or C stability condition and the chlorine cloud dispersed.

What is a "near F" and "far F" stability? The boundaries between stability classes A through F are arbitrary. Some atmospheric modelers prefer to use an Obukhov Length as a measure of stability. The Obukhov Length has a negative value for unstable air conditions (A, B, and C Stabilities) and a positive value for stable air conditions (E and F stabilities). Under cropland conditions as listed in the PEAC tool (surface roughness 0. 1 meters), the F stability includes Obukhov lengths between 0 and 30 meters; an E stability includes Obukhov lengthes between 30 and 80 meters. For a far F condition, we could pick a small but positive Obukhov length. For a near F condition, we could pick a Obukhov length near the boundary between the E and F stability. For a mid F, we will pick an Obukhov length equal to 17.5 meters (which is the same as the Obukhov length which the PEAC tool internally uses under a clear night, low wind condition).

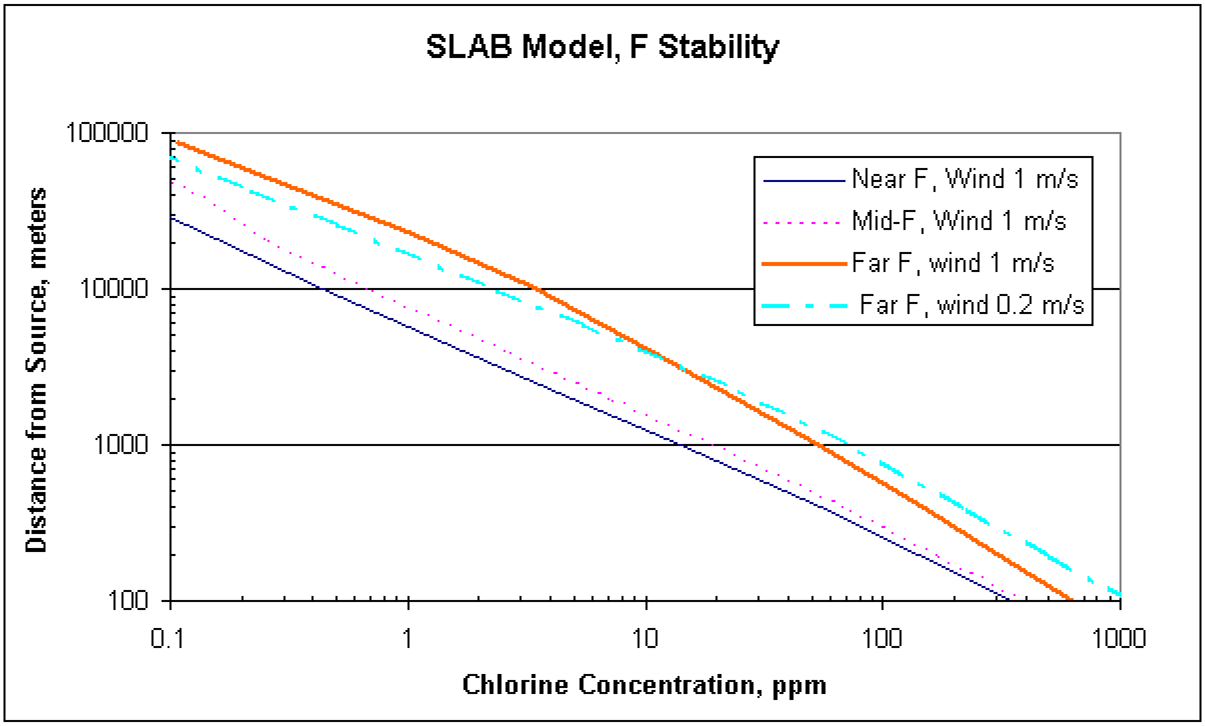
The calculation of an Obukhov Length requires very accurate measurements of temperature and wind velocity at several heights (from near ground level to about 10 meters), preferably using a sonic anemometer. These resources are not available when a chemical accident occurs. Best guesses are made from cloud cover, location, and time of day from which a stability class is assigned.

The SLAB model requires that the user input a surface roughness and an Obukhov length (Monin-Obukhov length). This is different from the PEAC tool or the ALOHA model where the user is asked questions on cloud cover, time of day, wind speed, and terrain, and the model internally assigns a stability class (A through F) and surface roughness. We will run the SLAB model under several F stability conditions and compare the results. We will do a (1) near F condition at 1 m/s wind speed and Obukhov length = 28 meters, (2) a mid F condition at 1 m/s wind speed and Obukhov length = 17.5 meters, (3) a far F condition at 1 m/s wind speed and Obukhov length = 5 meters, and (4) another far F condition at 0.2 m/s wind speed and Obukhov length = 5 meters. All computer runs will be done at a surface roughness = 0.1 meters and the wind speed measured at the 2 meter height. The chlorine release rate is 0.126 kg/s at ground level.

Table 3. Downwind Distance (meters) when Chlorine is 3 ppm, SLAB Model

Stability	Wind, m/s	Obukhov lenght, meters	Distance, meters
near F	1	28	2600
mid F	1	17.5	3200
far F	1	5	10200
far F	0.2	5	8000

In the Morristown TN chlorine accident, the toxic chlorine cloud initially traveled only 0.25 miles in 30 minutes, or 0.22 m/s. The Obukhov length could be 5 meters in the valley near the water treatment plant where cold air settles near the ground just before dawn. The five-mile downwind distance which the toxic cloud was observed is equivalent to approximately 8000 meters. The SLAB modeling predicted a 3 ppm chlorine concentration at 5 miles downwind for the far-F stability. However, the sun was also coming up which resulted in mixing of the chlorine cloud with the surrounding air. Chlorine concentrations were probably much less than 3 ppm by the time the toxic cloud traveled 5 miles.



The “F Stability” is not the only stability that behaves this way. We can have an A Stability sliding into B, then C, and D or D sliding into E, than F as sunset and night time approaches.

Comparisons of SLAB and ALOHA with PEAC Tool Predictions

Let us do some more modeling using ALOHA and SLAB and compare the results to what the PEAC tool predicts. We will stick with the 0.126 kg/s chlorine release at ground level as before. The terrain is cropland/brush with a surface roughness of 0.1 meters. The wind speed is assumed to be measured at the 2 meter height. The lastest(this hasn’t been released yet)version of the PEAC tool allows the user to input directly 0.126 kg/s as the release rate as an option. With older versions of the PEAC tool, the user must input a tank hole size, and direct input of a release rate is not possible. The model itself is the same with the two PEAC versions. Two meteorological situations will be compared: (1) a clear sky, daytime condition with a wind speed of 10 m/s, and (2) a nighttime clear sky with a wind speed of 1.5 m/s. The daytime condition represents a “D” stability and the nighttime condition represents an “F” stability. When using the SLAB model, an Obukhov length of 17.5 meters was selected for the F stability. A reciprocal Obukhov length of “0” was used for the D stability. We will graph the results as before and also list the downwind distances in meters corresponding to a 3 ppm chlorine concentration.

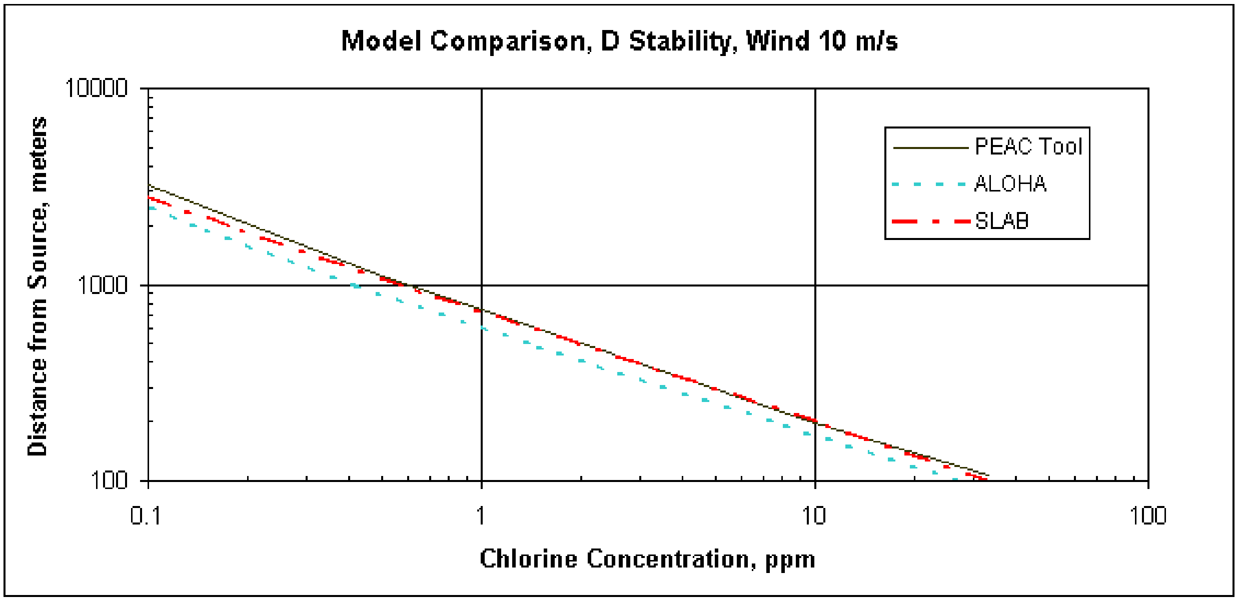
Table 4. PEAC Tool, SLAB, and ALOHA Model Comparisons for Two Conditions

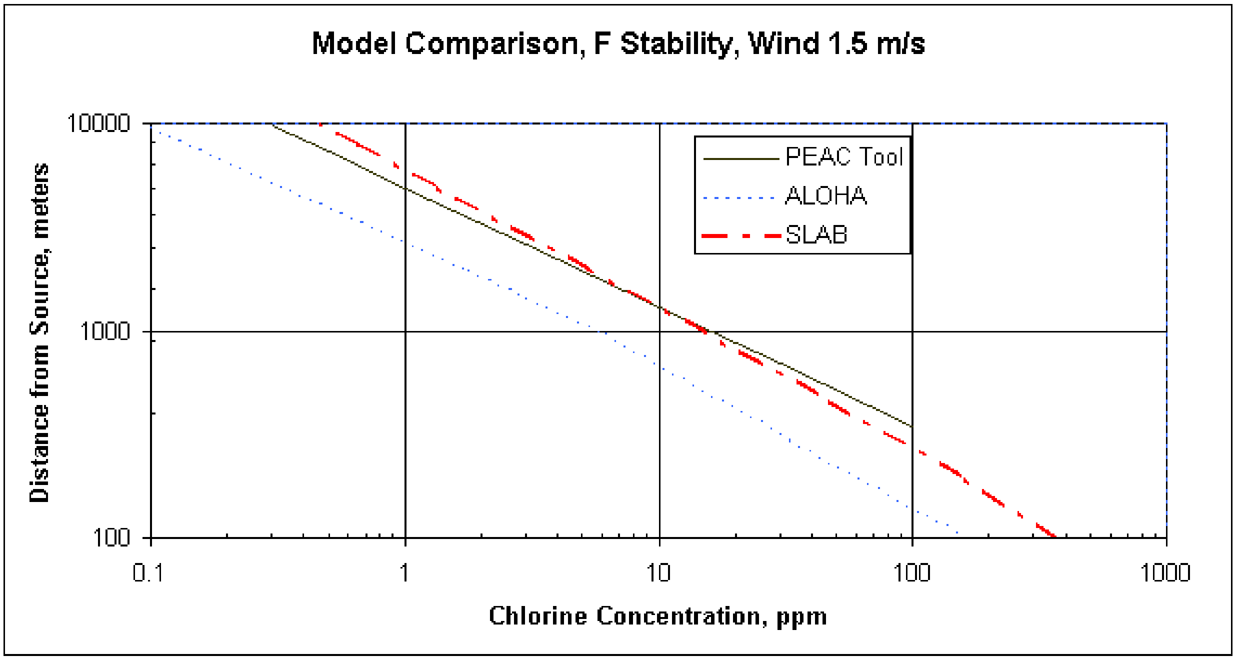
Stability	Wind Speed, m/s	Model	Distance Downwind, meters (at 3 ppm chlorine)

D	10	ALOHA	300
D	10	SLAB	396
D	10	PEAC tool	397
F	1.5	ALOHA	1475
F	1.5	SLAB	2900
F	1.5	PEAC tool	2600

In these examples, the PEAC tool predicts downwind distances fairly close to the SLAB model. Both SLAB and the PEAC tool predict downwind distances greater that what the ALOHA model predicts. The difference between the models is not very great for the D stability but is significant for the F Stability.

When chlorine is released at 0.126 kg/sec, it behaves as a dense gas. This means that it tends to sink and hug the ground. Chlorine has a molecular weight near 71 compared with air at 29. In addition, as the chlorine escaped from the hole in the tank at Morristown TN, the gas expanded and as it expanded the gas chilled. A cold gas with a molecular weight greater than air will sink. This was observed at Morristown TN. Therefore, a dense gas model was used. The ALOHA, PEAC tool, and SLAB models have the capability of operating in either a dense gas or passive mode. The model does the selection internally so the user does not have to think about it. The passive mode applies for release of a gas whose molecular weight is similar to air or if the release rate is small. The chlorine cloud from the Springfield MA, June 18, 1988, fire behaved passively because the heat from the fire caused the chlorine (and hydrochloric acid) to rise, with considerable mixing with the surrounding air.





Let us do some more modeling, this time with the models in the passive mode. To ensure passive behavior (i.e. the toxic cloud does not tend to sink), we will use a very small release rate. We could use chlorine again but select a very small release rate, or model some other toxic chemical. We will compare the PEAC tool with SLAB, ALOHA, and the military D2PC model. We will not display the results here (the results are displayed in the July issue of the newsletter in an article entitled "A Discussion on Gas Dispersion Models.) The models gave similar results for the "D" stability but different answers for the "F" stability. For the "F" Stability, the ALOHA model gave the least conservative result (smaller protective action distance) and the D2PC model gave the most conservative result. The PEAC tool and SLAB models gave answers between the ALOHA and D2PC model results.

Emergency Response Guidebook

The 2000 Emergency Response Guidebook lists Protective Action Distances for only four categories. For chlorine, the Protective Action Distances are based on 3 ppm concentration.

Category	Protective Action Distance
Small Spill, Daytime	0.2 miles (320 meters)
Small Spill, Nighttime	0.7 miles (1100 meters)
Large Spill, Daytime	1.7 miles (2700 meters)
Large Spill, Nighttime	4.2 miles (6800 meters)

Small spills are 55 gallons or less. It is primarily intended to be used where all of the contents are emptied in a short time as in a transportation accident rather than as a slow leak out of a tank hole over a two-hour period. Daytime includes A, B, C, and D Stabilities. Nighttime includes D, E, and F Stabilities. The numbers presented for Protective Action Distances are based on modeling many hypothetical release situations. The results for each chemical were tabulated in the four categories. A 90 percentile was selected for the listing of Protective Action Distances, meaning, that 90% of the accident scenarios modeled had a Protective Action Distance equal to or less than the distance listed.

Why Don't the Models Agree?

This was the subject of the before mentioned article in the July issue of the First Responder newsletter. The mathematical formulations upon which the models are based must be calibrated against test releases. There are very few full-scale releases of chemicals where concentrations are measured in the air as the chemical cloud travels downwind. There are a lot of small-scale tests in wind tunnels which mimic the "D" stability condition. Full scale, nighttime releases under "F" stability conditions are almost nonexistent. The models differ because they have different mathematical formulations and different data sets were used to calibrate the models. Also, one model's "F" stability might represent a "near F" condition and another model might represent a "far F" condition. There is a need to develop reliable data sets for model calibration.

What does this mean to the first responder? Use common sense. Gary Briggs, a meteorologist who specializes in gas dispersion models said that if modeling results agree by a factor of two, this is good agreement. There are too many unknowns in the real world, too many factors that affect toxic chemical cloud behavior to accurately pinpoint what happens. Get answers from a variety of sources. If using the model in the PEAC tool, run the model under different wind speeds and other conditions to get an idea of the toxic cloud behavior. Modeling is only a rough aid or tool to help in the decision making process.