Q_{50}: Quantifying Chemical-Biological Threats

By Mr. Reid Kirby

There is a military adage which states that "Amateurs talk tactics; generals talk logistics." While it is true that chemical-biological (CB) weapons are area weapons, they are also mass-action weapons that require hundreds of tons of chemicals or hundreds of pounds of biological agents to represent a significant threat. Lesser amounts are generally considered more of a destabilizing nuisance than an actual combat power; the minor amounts attributed to potential terrorism merely signify fringe criminality.

In hopes of establishing international agreements and controls that would eliminate CB weapons, the disarmament and counterproliferation communities have concerned themselves with determining the threshold above which CB agents are considered excessive for legitimate research or commercial activities. These threshold levels signify points of concern—not points where developing CB arsenals are considered an appreciable threat. What does it mean when information indicates that Libya has 100 tons of mustard gas (H) or North Korea has 1,000 to 5,000 tons of a variety of chemical agents? A generalized means of assessing such "threats" is necessary.

One means of assessing the threat is to compare the logistics required for various CB weapons. By determining the quantity of CB agent necessary to produce an effect threat and by understanding potential enemy doctrine and battlefield constraints, it may be possible to estimate the area and the number of targets that could be impacted by an emerging CB arsenal. This article presents a workable method for this analysis.[1]

Calder's Legacy

The English physicist Sir Geoffrey Taylor initiated the first systematic treatment of eddy motion in the atmosphere in 1915. Following World War I, the British Chemical Warfare Establishment at Porton Down attempted to improve upon chemical warfare meteorology through controlled experiments with smoke on Salisbury Plain. This work, in turn, led to O.G. Sutton's theory of eddy diffusion and the birth of atmospheric diffusion modeling as we know it today. Sutton's understudy at Porton Down was meteorologist Kenneth L. Calder. In the 1950s, the Army Biological Warfare Laboratories (BWL) at Camp Detrick (now Fort Detrick), Maryland, managed to employ Calder to work out biological weapon expenditure problems based on atmospheric diffusion modeling.

It is apparent from Calder's reports that he was brilliant, but isolated from the rest of the atmospheric diffusion analysis community working on chemical warfare problems. His work in biological warfare led him to use exponential dose-response relationships (i.e., independent action), rather than traditional probit analysis, further alienating his work from mainstream chemical weapon effects modeling.

Calder often reduced the complexity of his calculations by making general comparisons. He also relied on small samples of field trial data to represent typical employment conditions. His vast field experience likely allowed him to make decisions that the insufficiently accurate models lacked the complexity to make. With a scarcity of computers in the 1950s, Calder produced a series of tables used to estimate biological weapon coverage. The biological warfare community continued to use these tables into the 1990s (Gulf War).

In the 1990s, William Patrick and Richard Spertzel developed a graph which plotted the toxicity of an agent against the quantity of that agent required to produce an effective exposure. This graph (Figure 1), which was based on Calder's tables in BWL Technical Study #3 and widely distributed in *Defense Against Toxin Weapons*, illustrates that by knowing the lethal dose, 50 percent (LD_{50})—the dose required to kill half the members of a tested population—of a potential CB agent, it is possible to theoretically determine the quantity of the agent necessary (Q_{50}), under ideal meteorological conditions, to achieve a 50 percent casualty rate for an open-air exposure in a 100-square-kilometer (km^2) area. The following equation can be derived from the graph:

Q_{50} *(kilograms [kg]/km²) = 32,000 ·* LD_{50} *(milligrams [mg]/kg)*

At first glance, this appears to be a useful means of identifying the logistics associated with various CB weapons; however, in practice, there are limitations to this methodology that prevent its usefulness beyond the illustrative purposes for which it was originally intended.[2]

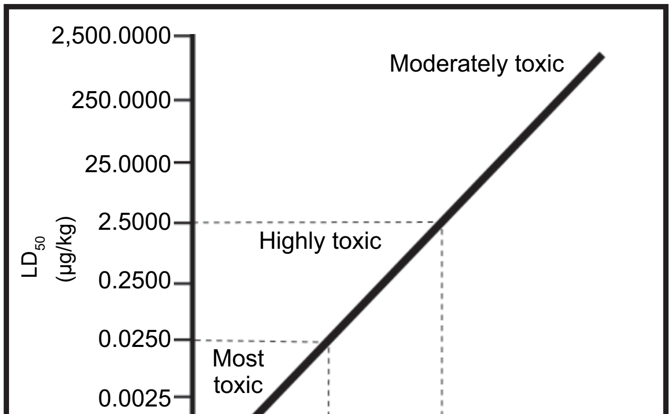

Figure 1. Toxicity (LD_{50}) versus quantity of toxin required (Q_{50}) to provide a theorectically effective open-air exposure under ideal meteorological conditions (after Franz, 1997)

Posological Theorem

CB warfare is, in essence, the delivery of a quantity of agent to a target, subjecting those within the target to a dosage that results in a casualty-causing dose. There is a mathematically transitive relationship among dose, dosage, and quantity; so doubling the dose corresponds to doubling the dosage and the quantity. Further, a dose may have multiple dosages, and these dosages may have multiple quantities, owing to the refinements of added conditions.

The relationship between the dose and the percent of resultant casualties can be described using a probit analysis or an independent-action model. An expected casualty rate can be inferred from the dose received or the dosage of exposure. It is the relationship between the dosage and the quantity that requires a method of calculation.

To calculate quantity, the issue of CB weapon coverage can be simplified by considering a square target area oriented squarely to the release of the CB agent along the upwind side (Figure 2). As a rule, when half the target area is covered with a median dosage, the integrated casualty rate for the entire target area is about equal to the casualty rate associated with that particular dosage. Therefore, the quantity of agent required to achieve a 50 percent casualty rate depends on the amount of agent that must be released on the upwind side to attain a median dosage halfway through the target.

This method is mathematically derived from the reduction of atmospheric diffusion models. The Gaussian model for a point source expands to that for a finite line source, which reduces to that of an infinite line source by extending the source length toward infinity. Assuming that the source height and sampling height are both at the surface (z = 0), then it follows that—

$$\frac{D\bar{u}}{\Lambda q} = \frac{\sqrt{2}}{\sqrt{\pi}\,\delta_z}$$

Where—

D = *dosage (mg.min/m³)*

$\bar{u}$ = *wind speed (m/min)*

Λ = *conditional adjustment factor*

q = *quantity released on a line (in mg/meter [m])*

δ_z = *atmospheric diffusion parameter*

With some algebra, some adjustments to convert quantity per meter of line source to total quantity, and

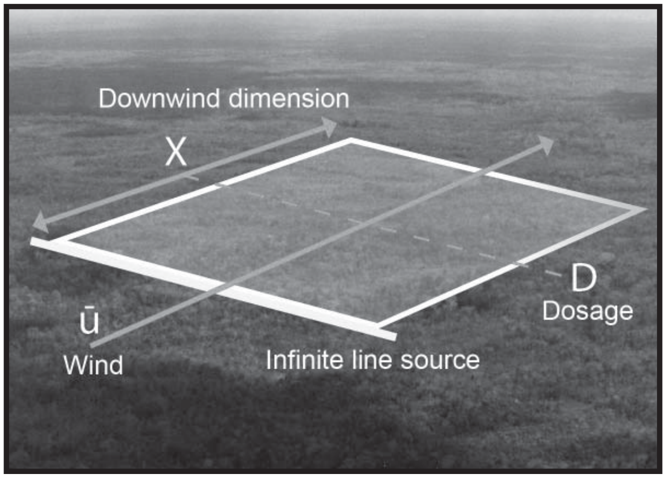

Figure 2. A notional CB target

some adjustments of units, the equation takes on the form—

$$Q = \frac{D\bar{u}}{\Lambda\left(\frac{\sqrt{2}}{\sqrt{\pi}\delta_z}\right)X}$$

Where—

Q = quantity of CB agent needed (kg/km²)

X = windward dimension of a target (m)

This model can be adapted to produce figures for different target sizes (Figure 3), target conditions (Figure 4, page 44), wind speeds, and atmospheric stabilities (Figure 5, page 44).

Evaluation

As a test of the model presented, Field Manual (FM) 3-10 was used to calculate the Q_{50} for sarin (GB), assuming an effects component of 3.22 that corresponds to 0- to 5-knot winds, open terrain, no precipitation, and high temperatures. This method indicated that 40 M121 155-millimeter (mm) projectiles would be needed to produce a 50 percent casualty rate on a 1-km² target area. This translates to a Q_{50} of 118 kg/km².

The method described by Patrick and Spertzel yields a result of 214 kg/km² for the same scenario, assuming a median incapacitating dose (ID_{50}) for GB of 0.0067 mg/kg. Using the Posological Theorem with a dosage required to incapacitate half the members of an exposed population (ICt_{50}) of 50 mg·min/m³ resulted in a Q_{50} of 119 kg/km². The dose-only methods of determining the Q_{50}, by definition, fail to explain the differences between dose and dosage, and, thence, dosage and quantity.[3]

Application

In the 1960s, the United States purchased 100,000 pounds of the incapacitating agent BZ—probably one of the most expensive military chemicals ever standardized by the United States; 10,000 pounds went to research and development, leaving about 90,000 pounds for filling chemical weapons. What was the chemical combat power associated with this purchase?

Using the Patrick-Spertzel method, an ID_{50} of 0.0116 mg/kg for BZ, yields a Q_{50} of 371 kg/km². Dividing 90,000 pounds (or 40,823 kg) by this result suggests that the Cold War arsenal of BZ would have been capable of producing 50 percent casualties over a 110-km² area.

From the information in FM 3-10B, BZ weapons were intended to cover half of a 1- to 2-hectare target area with an ICt_{50} of 110 mg·min/m³ under neutral atmospheric stability and 10-knot winds. This indicates a Q_{50} of 1,284 kg/km² in the open and 4,246 kg/km² in an urban terrain complex. Therefore, the BZ arsenal was capable of

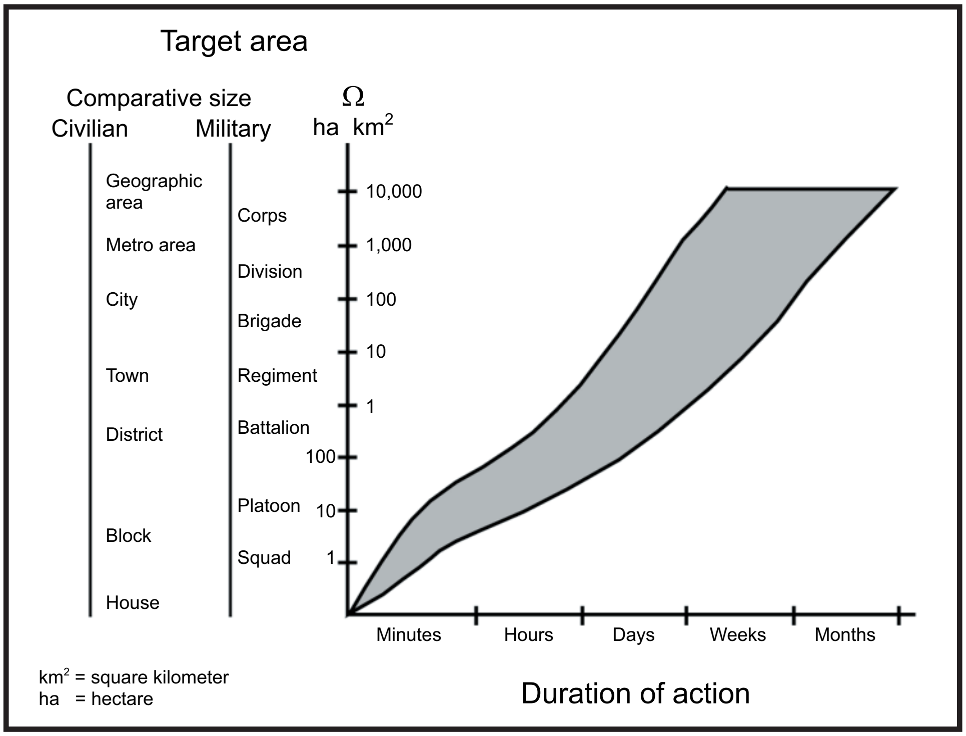

Figure 3. The approximate size of a notional target is proportional to the duration of a CB agent.

Condition	Factor
None	1.0
Wooded	0.8
Hilly	0.5
Indoor	0.5
Rainy	0.4
Jungle	0.2

Figure 4. Effects adjustment factors, Λ[4]

neutralizing 32 km^2 (open) and 10 km^2 (urban), though expanding the target size to that which is reasonable for the rate and duration of action indicates that the BZ arsenal was actually capable of neutralizing an open area up to 40 km^2.

The usefulness of this approach is that it indicates the quantities of CB agents needed under different doctrinal assumptions. It applies when determining the amount of agent that must be successfully disseminated to achieve a casualty effect; therefore, it can also be used to judge the potential threat from a developing CB arsenal. This approach is internally and externally consistent, and its application conforms to the added conditions of extending dose, through dosage, to quantity.

Pasquill-Gifford Class	Terrain Complex	
	Open	Urban
A	$1.35(x/20)^{2.82}$	$0.24(1+0.001x)^{0.5}$
B	$1.35(x/20)^{1.86}$	$0.24(1+0.001x)^{0.5}$
C	$1.35(x/20)^{1.18}$	$0.24(1+0.001x)^{0.5}$
D	$1.35(x/20)^{0.88}$	$0.20x$
E	$1.35(x/20)^{0.76}$	$0.14x(1+0.0003x)^{-0.5}$
F	$1.35(x/20)^{0.66}$	$0.08x(1+0.00015x)^{-0.5}$
G	$1.35(x/20)^{0.60}$	$0.08x(1+0.00015x)^{-0.5}$

Figure 5. Atmospheric diffusion parameters, δ_z, for open and urban terrain. Pasquill-Gifford stability classes usually used in analysis are B (lapse), D (neutral), and F (inversion). Here x = 0.5X. (After Milly, 1957, and Hanna, et. al., 1982.)[5]

Endnotes:

[1] This work was the result of a special study on the military potential of prions.

[2] Patrick and Spertzel were not attempting to create a method for analysts to calculate Q_{50}; their purpose was merely illustrative.

[3] Comparisons with other quantity figures verified the reasonable accuracy of these methods. However, similar attempts with infective agents and agents with aerobiological decay rates proved to yield grossly inaccurate results.

[4] These adjustments factors were from University of Pennsylvania, Project SUMMIT, for the U.S. Arms Control and Disarmament Agency (1962).

[5] For puff diffusion, it is customary to take the next highest stability classes' plume diffusion deviation as an approximation.

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