

**Bayesian Decision Analysis –  
A New Approach to an Old Problem**

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**Exposure Assessment Solutions, Inc.**

**AIHA Alberta Local Section  
Professional Development Conference**  
**Galgary, Alberta**  
**April 5, 2017**

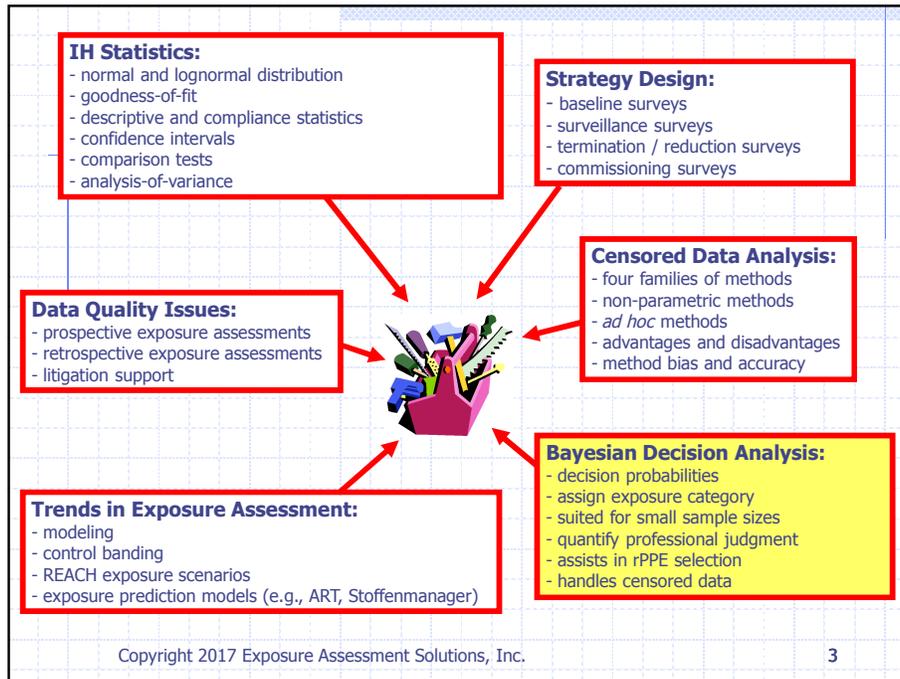
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## Learning Objectives

- ◆ Understanding of Bayesian Decision Analysis (BDA) methodology.
- ◆ Ability to quantify "professional judgment" using a Prior Decision Chart.
- ◆ Understanding of how BDA and the decision charts can be used to make IH decisions.
- ◆ Understanding of how BDA can be integrated into the AIHA or similar exposure assessment and management model.
- ◆ Ability to use the freeware program [IHDataAnalyst-Student](#) to calculate the Prior, Likelihood, and Posterior decision charts.

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## Agenda

- Introduction
- Review of the AIHA Model and IH Statistics
- Rule-of-thumb for Assigning AIHA Exposure Ratings

### Part I

- Introduction to Bayesian Calculations
- Bayesian Decision Analysis (BDA)
- Workshop 1 - BDA Examples
- Setting Informative Priors
- Managing Parameter Space
- Criticisms of the BDA Approach

### Part II

- Integrating BDA into the AIHA Model
- Workshop 2 - Assigning AIHA Exposure Ratings
- BDA and rPPE Selection
- BDA and Censored Data
- BDA and Noise Measurements

- Random Sampling Workshop (optional)
- Extra Slides and Handouts

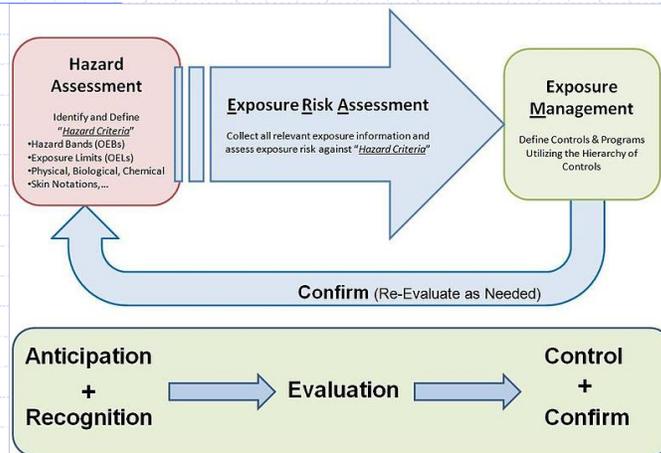
## Prerequisites

- ◆ Participation in the web PDC "IH Stats I - Basics" or a strong background in IH statistics
- ◆ Familiarity with the AIHA Exposure Assessment and Management Model (see Mulhausen and Damiano, 1998, or Bullock and Ignacio, 2006)
- ◆ A working knowledge of the IHDataAnalyst (IHDA; professional) or IHDA-Student.
- ◆ Recommended reading prior to the WebPDC:
  - Hewett, P. et al.: Rating Exposure Control Using Bayesian Decision Analysis. JOEH 3:568-581 (2006).
  - Chapter 22 in AIHA 4<sup>th</sup> Edition

## References

- ◆ Hewett, P., Logan, P., Mulhausen, J., Ramachandran, G., and Banerjee, S.: Rating Exposure Control Using Bayesian Decision Analysis. *Journal of Occupational and Environmental Health* 3:568-581 (2006).
- ◆ Logan, P.W. and Ramachandran, G. (2015): Chapter 22 - Bayesian Decision Analysis for Industrial Hygiene. in *A Strategy for Assessing and Managing Occupational Exposures, 4th edition*. American Industrial Hygiene Association, Falls Church, VA ([www.aiha.org](http://www.aiha.org)).
- ◆ AIHA (2015) - A Strategy for Assessing and Managing Occupational Exposures, Fourth Edition. Fairfax, VA: American Industrial Hygiene Association.

## What does an industrial hygienist (a.k.a, occupational hygienist) do?



Fundamental Elements of Industrial Hygiene (ERAM Model)

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**The Problem:** Employers want us to accurately assess "risk", but provide limited resources.

IHs assess risk with limited personnel, equipment, & budget for analyses.

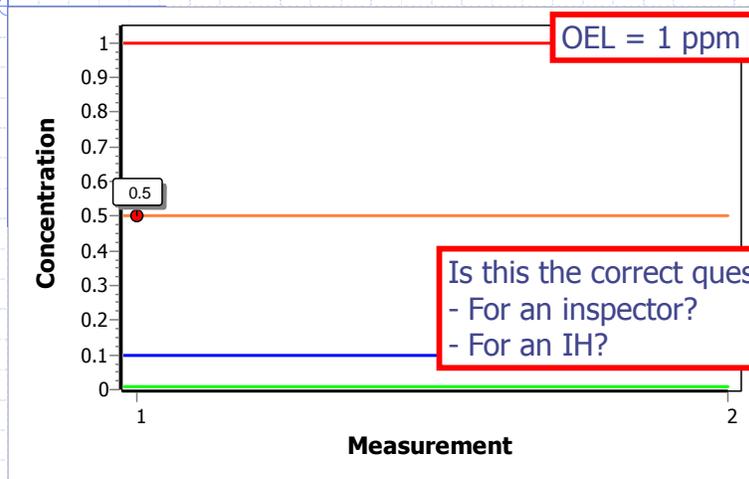
### Exposure Risk Assessment

Collect all relevant exposure information and assess exposure risk against "*Hazard Criteria*"

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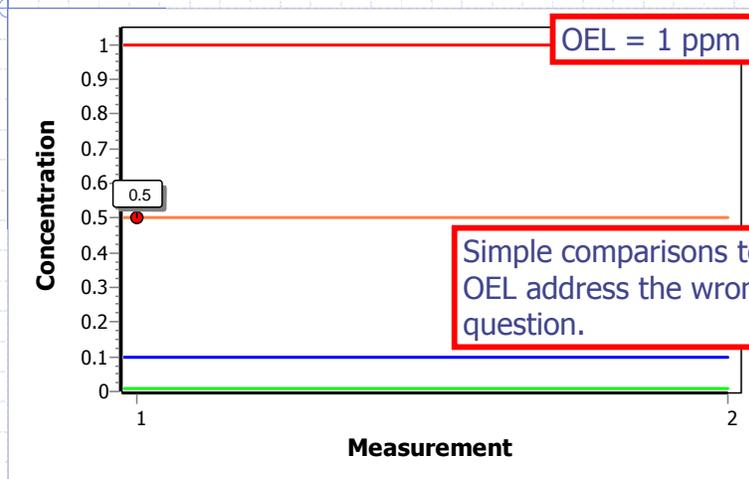
Was the TWA exposure on *that* day for *that* worker acceptable or unacceptable?



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Is the TWA exposure profile for the SEG acceptable or unacceptable?



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## John Tukey (1915-2000)

◆ "It is better to have an approximate answer to the right question than an exact answer to the wrong one."



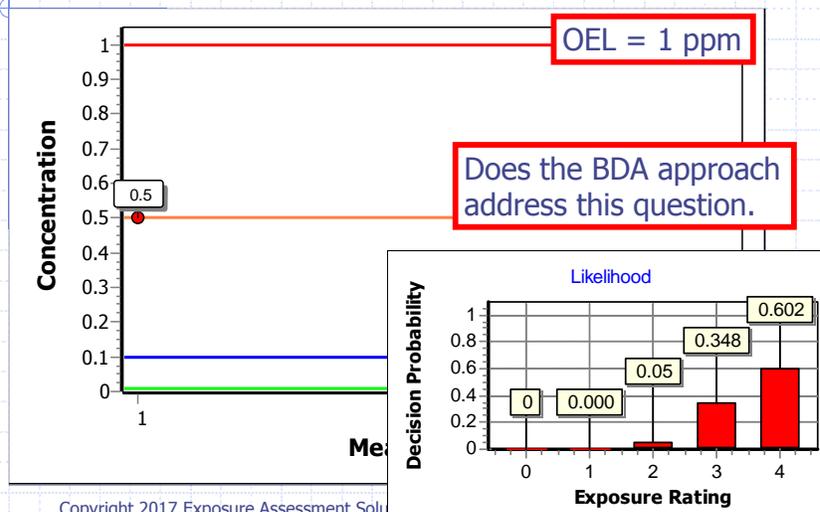
**Known for**

- Exploratory data analysis
- Projection pursuit
- Box plot
- Cooley–Tukey FFT algorithm
- Tukey's range test
- Tukey lambda distribution
- Tukey–Duckworth test
- Siegel–Tukey test
- Tukey's trimean
- Tukey's test of additivity
- Tukey's lemma
- Blackman–Tukey transformation
- Tukey mean difference plot
- Tukey median and Tukey depth
- Coining the term 'bit'

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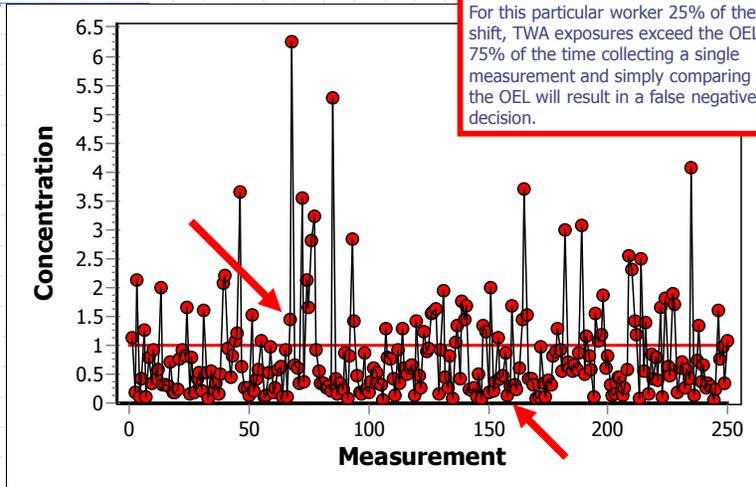
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Is the TWA exposure profile for the SEG acceptable or unacceptable?



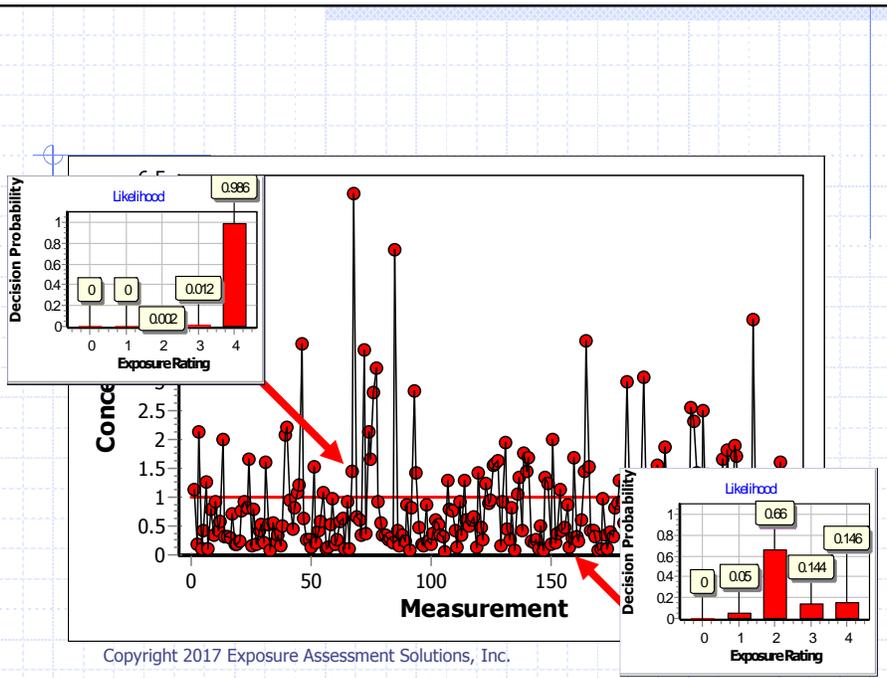
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Annual population of exposures for one worker: 250  
Worker-days per Year

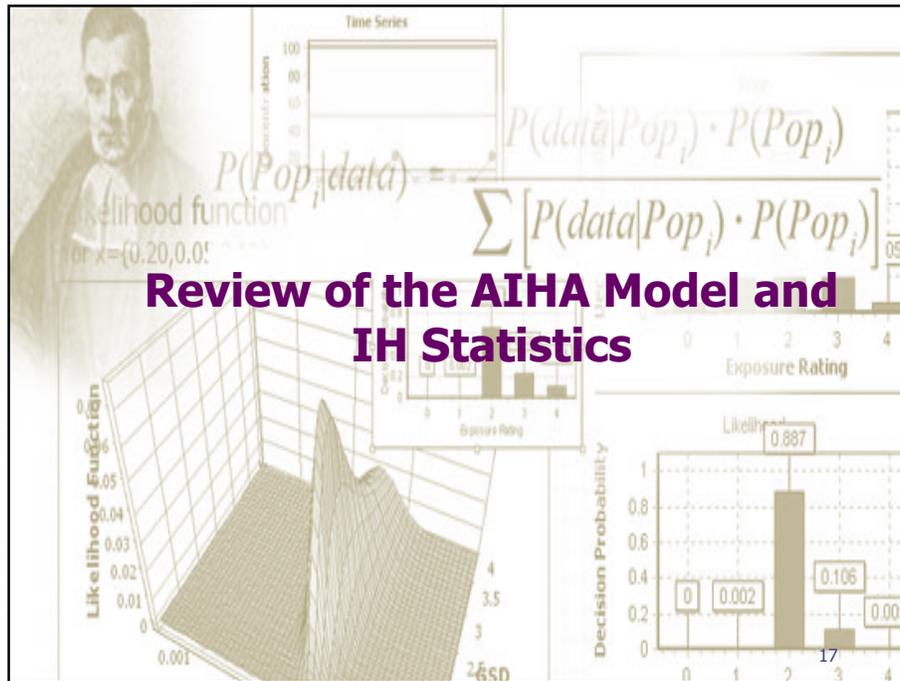


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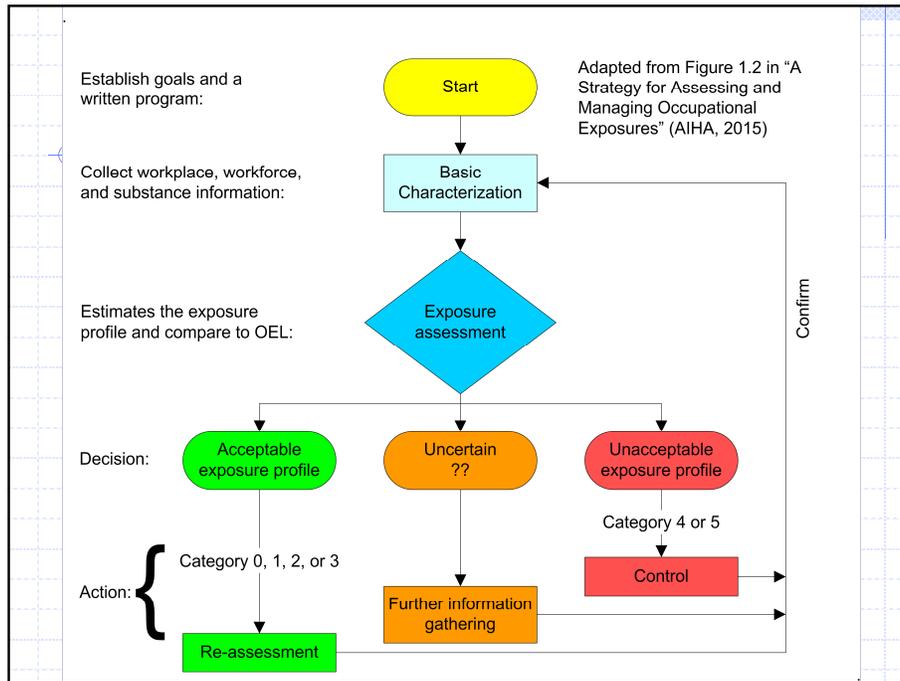


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## AIHA Exposure Assessment and Management Model

- ◆ *Comprehensive Exposure Assessment* :
  - Goal ≠ minimal compliance with OSHA PELs.
  - Goal = understand and manage all workplace exposures
  - Devise OELs when needed
  - Prioritize using both *qualitative* and *quantitative* exposure assessment
  - Assign Exposure Ratings to each SEG
  - Reassess all SEGs
  - Identify the *critical SEGs*
  - Document low or non-existent exposures
  - Anticipate change



- ◆ For each SEG ...
  - ◆ Develop and review **Background** information
  - ◆ Determine **Initial (exposure) Rating** and **Certainty Level**
  - ◆ Prioritize based on the Initial Rating, Certainty Level, and **Toxicity Category**
  - ◆ Using the company **Sampling Strategy**, devise and implement a process-specific **Sampling Plan**
  - ◆ Evaluate the data and assign a **Final Rating**
  - ◆ Recommend appropriate action
  - ◆ Reassess
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### AIHA Exposure Control Banding Model (cont'd)

Exposure Control Category (Exposure Rating)	Cutoff (%OEL)	Certainty Level
0	$X_{0.95}^* \leq 1\%$	High Medium Low
1	$1\% < X_{0.95} \leq 10\%$	
2	$10\% < X_{0.95} \leq 50\%$	
3	$50\% < X_{0.95} \leq 100\%$	
4	$X_{0.95} > 100\%$	

\* 90<sup>th</sup>, 95<sup>th</sup>, or 99<sup>th</sup> percentile

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### Typical "Actions" following Exposure Category Assignment

Exposure Control Category *	Recommended Control
0 (<1% of OEL)	No action
1 (<10% of OEL)	Procedures and training; general hazard communication
2 (10-50% of OEL)	+ Chemical specific hazard communication; periodic exposure monitoring
3 (50-100% of OEL)	+ Required exposure monitoring, workplace inspections to verify work practice controls; medical surveillance; biological monitoring
4 (>100% of OEL)	+ Implement hierarchy of controls;
4+ Multiples of OEL (e.g., based on respirator APFs)	+ Monitoring to validate respirator protection factor selection

\* Decision statistic = 95<sup>th</sup> percentile

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## IH Statistics

Substance Information

Substance: manganese fume (as Mn)

OEL: 0.2 mg/m<sup>3</sup>

Comments:
 

- TLV basis - CNS impairment
- PEL - 5 mg/m<sup>3</sup> Ceiling (1972)
- SMAW using medium steel welding wire
- controls: LEV

Data Entry

Sample #	Conc	LOD	Date	Group
1	0.056			Worker E
2	0.067			Worker F
3	0.067			Worker G
4	0.302			Worker H
5	0.097			Worker I
6	0.172			Worker J
7				

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Statistics GOF Graphs BDA Charts PPE Charts CDA

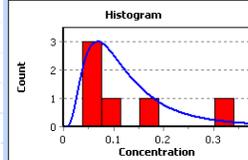
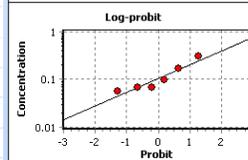
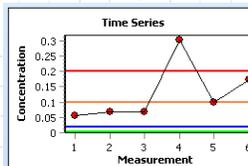
### Goodness-of-fit Test

Fillibens Test:

R = 0.943

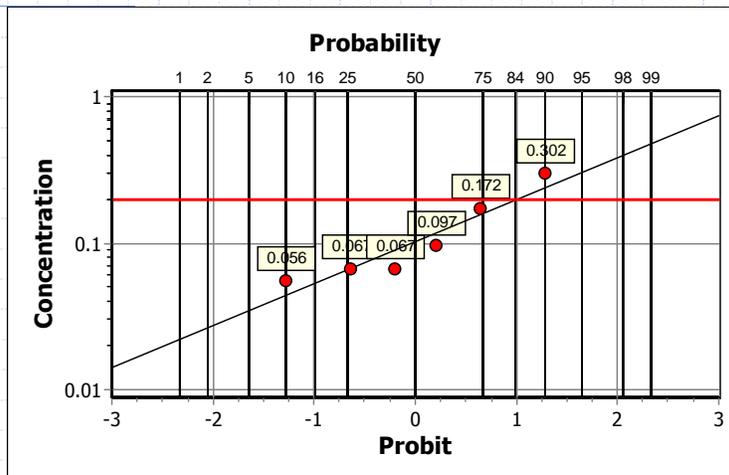
critical R = 0.889

Interpretation: the lognormal distribution hypothesis is not rejected.



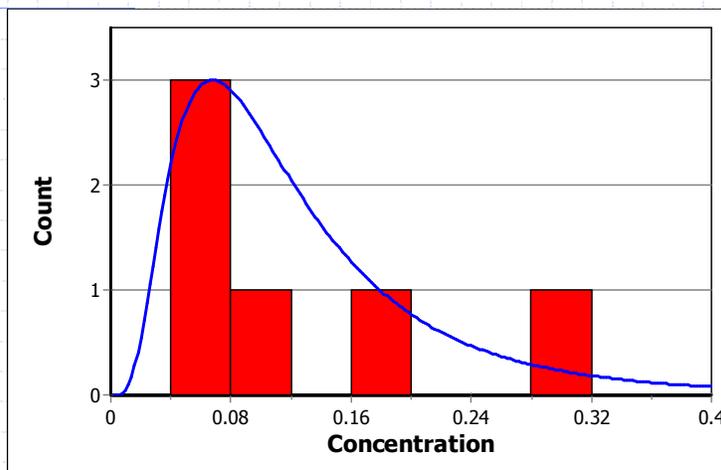
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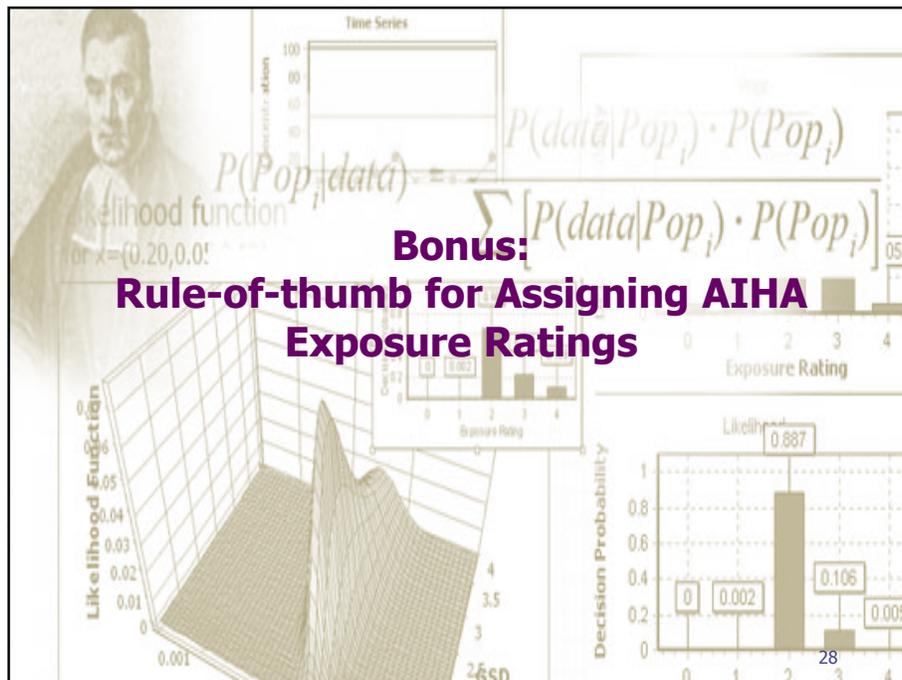
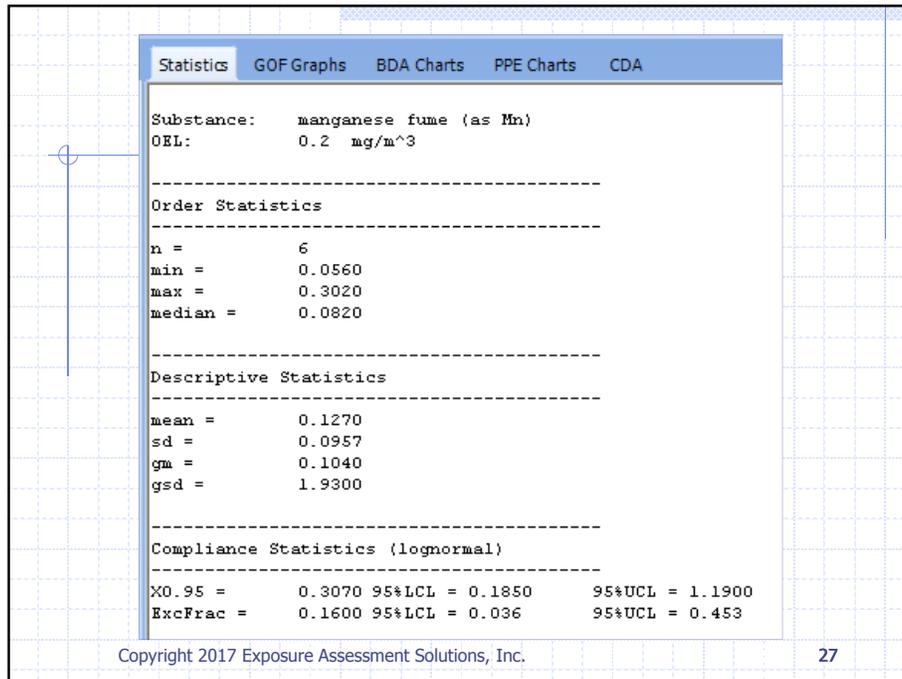
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## Rule-of-thumb for Assigning an AIHA Exposure Control Category Rating

◆ Given:

- GM = median
- $X_p = GM \times GSD^{Z_p}$  (e.g.,  $X_{0.95} = GM \times GSD^{1.645}$ )

◆ ... a Rule-of-thumb, or guideline, can be devised for quickly estimating from limited data the *range* in which the true 95<sup>th</sup> percentile might lie.

GSD	Multiple of GM (median)	
	$X_p = 95^{\text{th}}$ percentile	
	$Z_p = 1.645$	
1.5	1.95	<b>2X</b>
2.0	3.13	} <b>4X</b>
2.5	4.51	
3.0	6.09	<b>6X</b>

## Rule-of-thumb (Logan et al., AOH 53:311-324, 2009)

### ◆ Step 1:

- If n is small (i.e.,  $n < 10$ ) and one or more measurements  $> OEL$ , then decision = Category 4 ( $>OEL$ ).
- If a decision cannot be made, move to Step 2.

### ◆ Step 2:

- Estimate the **median** and use it as a **surrogate** of the sample GM:
  - ◆ Sort the data
  - ◆ If n is odd the median is the middle value.
  - ◆ If n is even the median is the average of two middle values.

## Rule-of-thumb

### ◆ Step 3:

- Multiply the median by 2, 4, and 6
- *The results can be considered approximate low, middle, and high estimates of the 95<sup>th</sup> percentile.*

### ◆ Step 4:

- Using the ROT estimates of the 95<sup>th</sup> percentile, pick the category that *most likely* contains the true 95<sup>th</sup> percentile.
  - ◆ Emphasis on 2 x Median if the data have little spread
    - e.g., min and max differ by a factor of 2
  - ◆ Emphasis on 6 x Median if the data have large spread
    - e.g., min and max differ by a fact of 10
- Note: A lower category is not an option if one or more measurements are in a higher category.

Variability	ROT Multiplier
Low	2
Medium	4
High	6

### Rule-of-thumb Workshop (assume OEL=100)

- A.  $X = \{30, 17, 7, 13, 63, 5\}$
- B.  $X = \{6\}$
- C.  $X = \{33, 37, 9, 109, 8, 5\}$
- D.  $X = \{5, 20, 3, 12\}$
- E.  $X = \{78\}$
- F.  $X = \{3, 1\}$
- G.  $X = \{31, 17, 18, 45\}$
- H.  $X = \{14, 5, 6, 12, 4, 36\}$

For each dataset, determine the appropriate AIHA Exposure Control Category – 1, 2, 3, or 4 – using the Rule-of-thumb.

## Rule-of-thumb Worksheet (assume OEL=100)

Data Set	Data	Median	Approximate $X_{0.95}$			Exposure Category (1-4)
			2x	4x	6x	
A	30, 17, 7, 13, 63, 5					
B	6					
C	33, 37, 9, 109, 8, 5					
D	5, 20, 3, 12					
E	78					
F	3, 1					
G	31, 17, 18, 45					
H	14, 5, 6, 12, 4, 36					

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## Rule-of-thumb Worksheet (sorted) (assume OEL=100)

Data Set	Data	Median	Approximate $X_{0.95}$			Exposure Category (1-4)
			2x	4x	6x	
A	5, 7, 13, 17, 30, 63	15	30	60	90	
B	6	6	12	24	36	
C	5, 8, 9, 33, 37, 109	21	42	84	126	
D	3, 5, 12, 20	8.5	17	34	51	
E	78	78	156	312	468	
F	1, 3	2	4	8	12	
G	17, 18, 31, 45	24.5	49	98	147	
H	4, 5, 6, 12, 14, 36	9	18	36	54	

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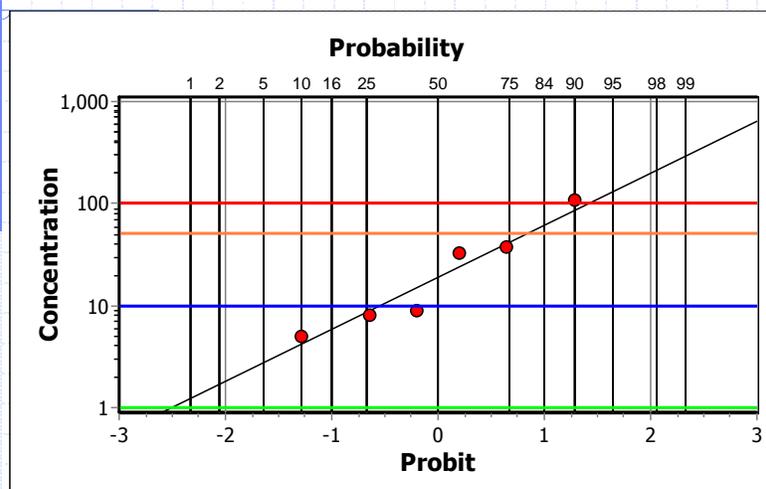
## Rule-of-thumb Worksheet (sorted) (assume OEL=100)

Data Set	Data	Median	Approximate $X_{0.95}$			Exposure Category (1-4)
			2x	4x	6x	
A	5, 7, 13, 17, 30, 63	15	30	60	90	3
B	6	6	12	24	36	2
C	5, 8, 9, 33, 37, 109	21	42	84	126	4
D	3, 5, 12, 20	8.5	17	34	51	2
E	78	78	156	312	468	4
F	1, 3	2	4	8	12	1
G	17, 18, 31, 45	24.5	49	98	147	3
H	4, 5, 6, 12, 14, 36	9	18	36	54	2

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## Traditional Log-probability Graph (Dataset C): Estimated 95<sup>th</sup> percentile > OEL

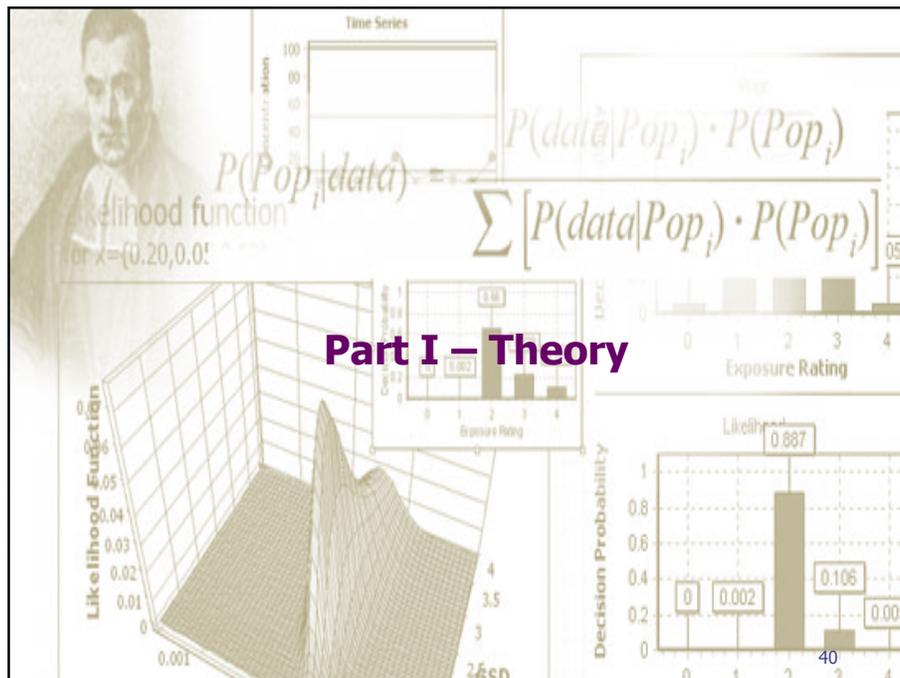


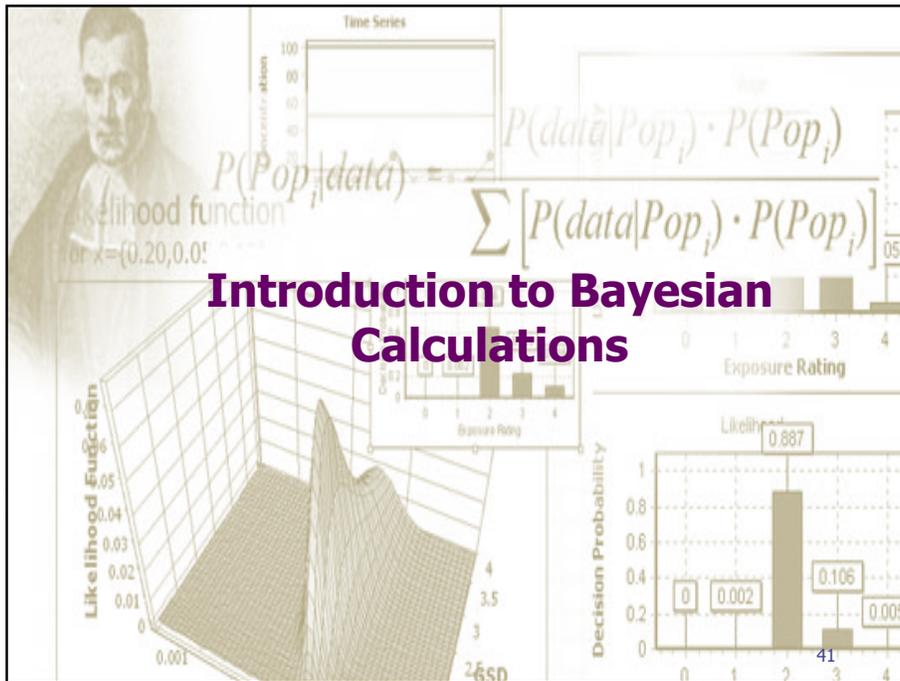
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## Comments

- ◆ For Dataset C, the preceding log-probability chart shows that the estimated 95<sup>th</sup> percentile exceeds the OEL. The calculated 95<sup>th</sup> percentile is 131.
- ◆ The Rule-of-thumb is useful in estimating the exposure category for an SEG, without the use of statistical or graphical tools.
- ◆ Bayesian Decision Analysis, covered in an upcoming web PDC, is a tool specifically designed for picking exposure categories.
- ◆ Later, we will determine the accuracy of the Rule-of-thumb by comparing the exposure categories determined using the Rule-of-thumb to those determined using Bayesian Decision Analysis.





### Bayes' Theorem – The Foundation of Bayesian Statistics



Posterior      Likelihood      Prior

$$P(Pop_i|data) = \frac{P(data|Pop_i) \cdot P(Pop_i)}{\sum [P(data|Pop_i) \cdot P(Pop_i)]}$$

Correction Factor

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## Who gave you the ugly tie?

- ◆ At your birthday party you receive a truly ugly tie. The wrapping was plain, with no label.
- ◆ Who gave you the tie?
- ◆ The choices are the stingy aunt and the weird uncle.
- ◆ Considering the two, the chances that your aunt or uncle would bring a *gift* are 1 in 4 and 3 in 4, respectively.
- ◆ The probability of your aunt giving you an ugly tie is low; for example, 1 in 10.
- ◆ The probability of your uncle giving you an ugly tie is high; for example, 1 in 2.

	A	B	C	D	E
1		Prior	Likelihood	Relative Probability	Posterior
2	Aunt	1/4	1/10	1/40	0.0625
3	Uncle	3/4	1/2	3/8	0.9375
4			Sum =	4/10	1.0000

- ◆ Given these two choices – and the Prior and Likelihood estimates/guesses - there is nearly a 94% probability that the your uncle gave you the tie.

$$P(\text{relative}|\text{tie}) = \frac{P(\text{tie}|\text{relative}) \cdot P(\text{relative})}{\sum_{i=1}^k [P(\text{tie}|\text{relative}_i) \cdot P(\text{relative}_i)]}$$

$$P(\text{Aunt}|\text{tie}) = \frac{1/10 \cdot 1/4}{1/10 \cdot 1/4 + 1/2 \cdot 3/4} = 0.06$$

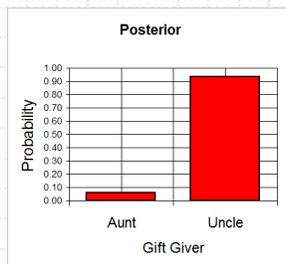
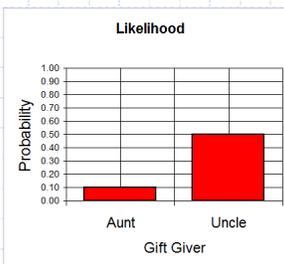
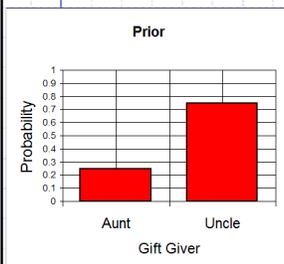
$$P(\text{Uncle}|\text{tie}) = \frac{1/2 \cdot 3/4}{1/10 \cdot 1/4 + 1/2 \cdot 3/4} = 0.94$$

## Decision Charts

Probability of getting a gift.

Probability of a gift in poor taste, given each relative.

Probability of getting "the" gift from each relative, factoring in the prior.



## Comments

- ◆ In principle, the decision options should be *exhaustive* and *exclusive*.
  - Exhaustive
    - ◆ The Aunt and the Uncle are the only possible choices.
    - ◆ i.e., "parameter space" contains the possible choices.
  - Exclusive
    - ◆ The Aunt and the Uncle did not jointly purchase the gift.
- ◆ That is, the decisions being considered should represent all possible decisions and there should be no overlap between possible decisions.

## Comments

- ◆ In order to apply Bayesian analysis to industrial hygiene "decision making" we need the following:
  - A model for classifying occupational exposures into exposure categories.
    - ◆ e.g., the AIHA Exposure Control Banding Model
  - A "distributional model"
    - ◆ e.g., the lognormal model
  - A "decision statistic"
    - ◆ e.g., the 95<sup>th</sup> percentile.
- ◆ Note:
  - BDA is used alongside the standard graphs and statistics that we have always displayed and calculated.

## Bayes' Theorem Applied to Exposure Profiles

Posterior      Likelihood      Prior

$$P(\ln G_p, \ln D_i | data) = \frac{P(data | \ln G_i, \ln D_i) \cdot P(\ln G_i, \ln D_i)}{\sum_{i=1}^k [P(data | \ln G_i, \ln D_i) \cdot P(\ln G_i, \ln D_i)]}$$

Equation 1

Correction Factor

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## Likelihood Function

- The relative probability of the data, given an exposure profile is calculated using the likelihood function ( $y = \ln(x)$ ):

$$P(data | \ln G_i, \ln D_i) \propto \prod_{j=1}^n pdf(y_j | \ln G_i, \ln D_i)$$

Equation 2

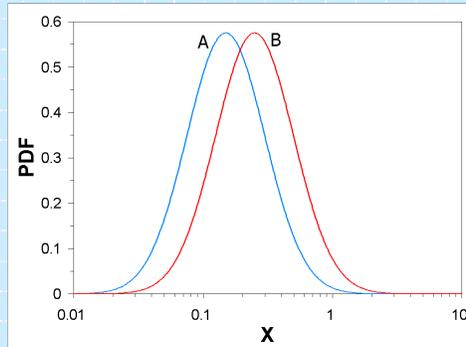
$$pdf(y | \ln G_i, \ln D_i) = \frac{1}{\ln D_i \sqrt{2\pi}} \cdot \exp\left(\frac{-(y - \ln G_i)^2}{2(\ln D_i)^2}\right)$$

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## Simple Example – Two Exposure Profiles

- ◆ Say we are interested in determining which of two exposure profiles is most likely.
- ◆ Exposure Profile A
  - GM = 0.15 ppm
  - GSD = 2
- ◆ Exposure Profile B
  - GM = 0.25 ppm
  - GSD = 2



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## Prior

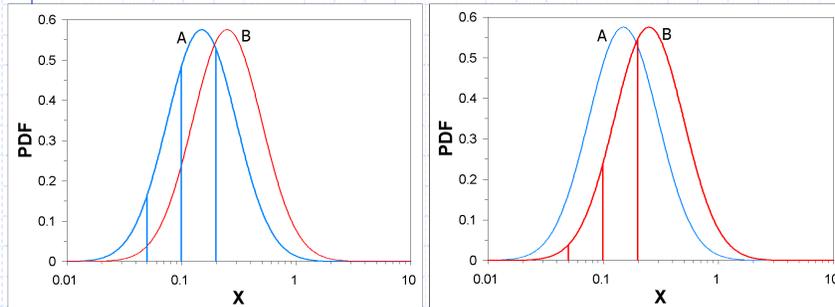
- ◆ Let us assign *a priori* probabilities of Exposure Profile A and B:
  - Prob(A) = 0.7
  - Prob(B) = 0.3
- ◆ Then collect some data:  
x={0.20, 0.05, 0.10} ppm



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- ◆ Calculate the PDF values for each exposure profile:



- ◆ Calculate the product of the PDF values for each exposure profile.

## Likelihood Function

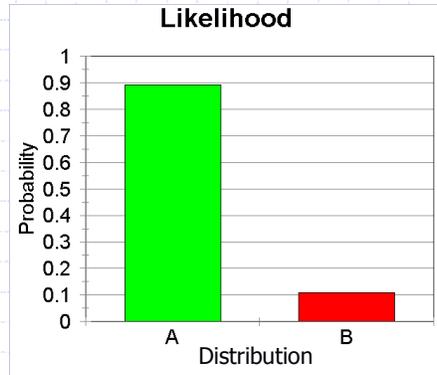
- ◆ To display the Likelihood Probabilities the Likelihood Function must be normalized:

$$P(\text{data} | \ln G_i, \ln D_i) = \frac{\prod_{j=1}^n pdf(y_j | \ln G_i, \ln D_i)}{\sum_{i=1}^k \left[ \prod_{j=1}^n pdf(y_j | \ln G_i, \ln D_i) \right]}$$

n = number of measurements  
k = number of exposure profiles

## Likelihood Function (cont'd)

- ◆ Display the Likelihood Decision probabilities in the Likelihood Decision Chart:



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## Posterior Function

- ◆ Combine the Prior and Likelihood functions using Bayes' Equation:

Equation 1

Equation 2

Prior

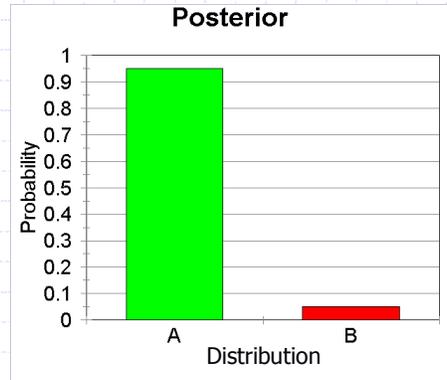
$$P(\ln G_i, \ln D_i | data) = \frac{P(data | \ln G_i, \ln D_i) \cdot P(\ln G_i, \ln D_i)}{\sum_{i=1}^k [P(data | \ln G_i, \ln D_i) \cdot P(\ln G_i, \ln D_i)]}$$

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## Posterior Function

- Display the Posterior Decision probabilities in the Posterior Decision Chart:



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## BDA example calc.xls

Pop	Prior	Data	PDF	ln(PDF)	Sum(ln(PDF))	LF	LF*Prior	Likelihood	Posterior	
A	0.7	0.20	0.528056	-0.63855	-3.170549	0.041981	0.029386	0.89	0.95	
A		0.05	0.163903	-1.80848						
A		0.10	0.485044	-0.72352						
B	0.3	0.20	0.546487	-0.60424	-5.278518	0.005100	0.001530	0.11	0.05	
B		0.05	0.038848	-3.2481						
B		0.10	0.240227	-1.42617						
Sum =							0.047081	0.030916		

**Prior**

**Likelihood**

**Posterior**

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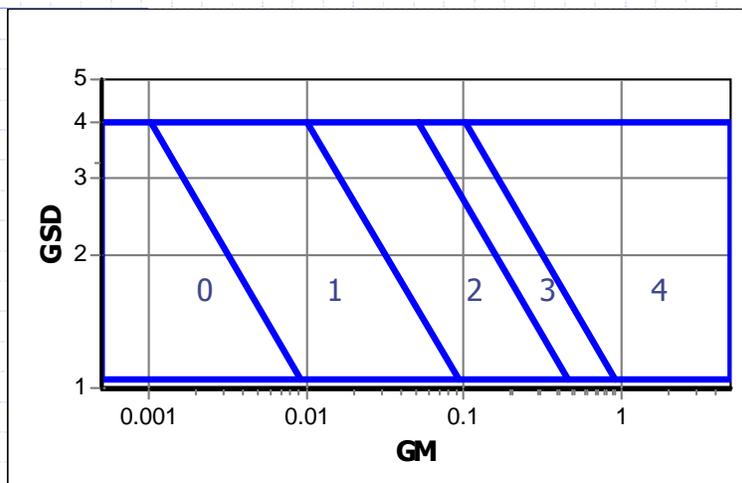
## Comments

- ◆ Bayes' Theorem directly applies to discrete choices.
  - e.g., Exposure Profiles A vs. B
- ◆ We are not interested in distinguishing between just two exposure profiles.
- ◆ Instead, we are interested in distinguishing between five *populations* of exposure profiles:
  - Exposure Zones 0, 1, 2, 3, and 4
- ◆ However, this example covers the basic BDA calculations.

## Exposure Ratings – A “rating zone” represents a population of exposure profiles

Exposure Rating	Cutoff (%OEL)
0	$X_{0.95} \leq 1\%$
1	$1\% < X_{0.95} \leq 10\%$
2	$10\% < X_{0.95} \leq 50\%$
3	$50\% < X_{0.95} \leq 100\%$
4	$X_{0.95} > 100\%$

## Exposure Ratings translated into *Parameter Space* for OEL=1ppm



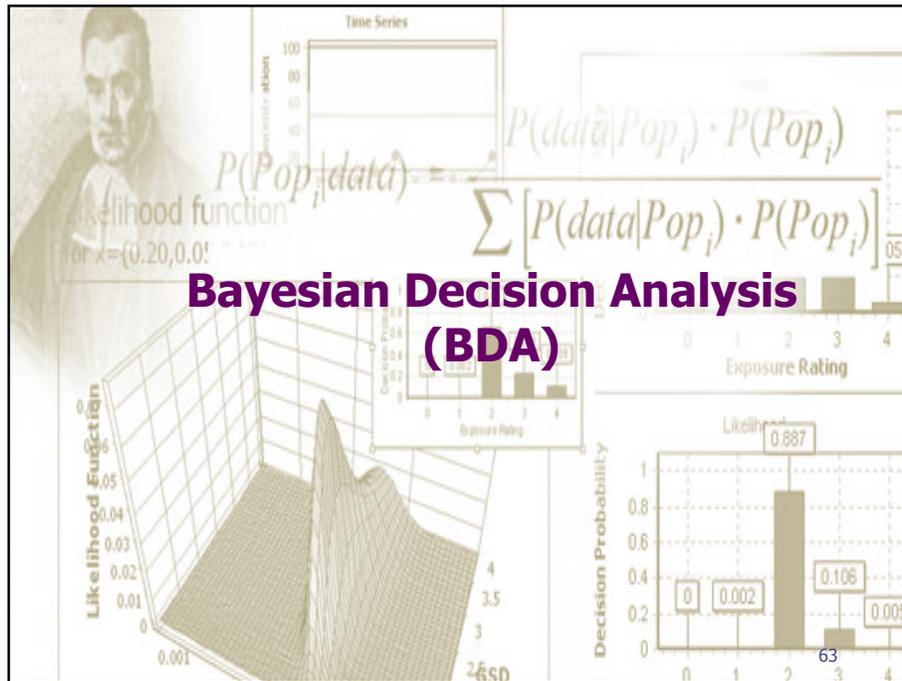
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- ◆ In principle, the exposure categories under consideration should be *exhaustive* and *exclusive*.
- ◆ That is, the exposure categories should represent all possible exposure profiles and there should be no overlap between categories.

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## Bayesian Decision Analysis

- ◆ An adjunct to the calculation and interpretation of traditional statistics.
- ◆ The goal of BDA is to estimate the **probability** that the *true* exposure profile falls into a particular category, or *Exposure Rating*.
- ◆ BDA can explicitly incorporate professional judgment.

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DOI: 10.1080/15459620600914641

### Rating Exposure Control Using Bayesian Decision Analysis

Paul Hewett,<sup>1</sup> Perry Logan,<sup>2</sup> John Mulhausen,<sup>2</sup> Gurumurthy Ramachandran,<sup>3</sup> and Sudipto Banerjee<sup>3</sup>

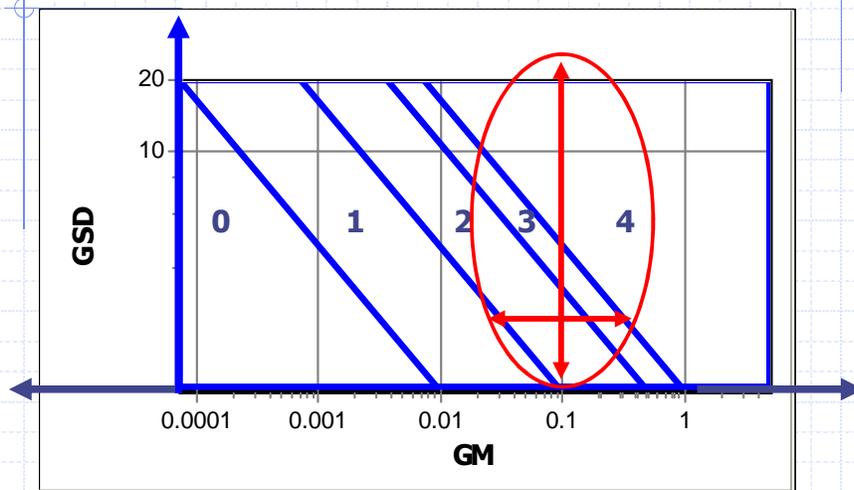
## Are IH's Bayesian Statisticians?

- ◆ Example "Traditional" Survey
  - OEL = 1 ppm
  - During a baseline/initial exposure assessment, an IH collected the following full-shift measurements from an SEG:
    - ◆ 0.20, 0.05, & 0.10 ppm
  - $n = 3$  ;  $gm = 0.10$  ;  $gsd = 2.00$
  - The sample 95<sup>th</sup> percentile was 0.31 ppm
  - but with a 95%UCL of 20 ppm

## When $n$ is small, confidence intervals are often extremely broad.

- ◆  $X = \{0.20, 0.05, 0.10 \text{ ppm}\}$
- ◆  $n = 3$
  
- ◆  $gm = 0.1 \text{ ppm}$      90%CI( 0.03, 0.32 )
- ◆  $gsd = 2.0$             90%CI( 1.5, 21 )
  
- ◆  $\hat{X}_{0.95} = 0.31 \text{ ppm}$      90%CI( 0.16, 20 )

## Parameter Space (for OEL =1)



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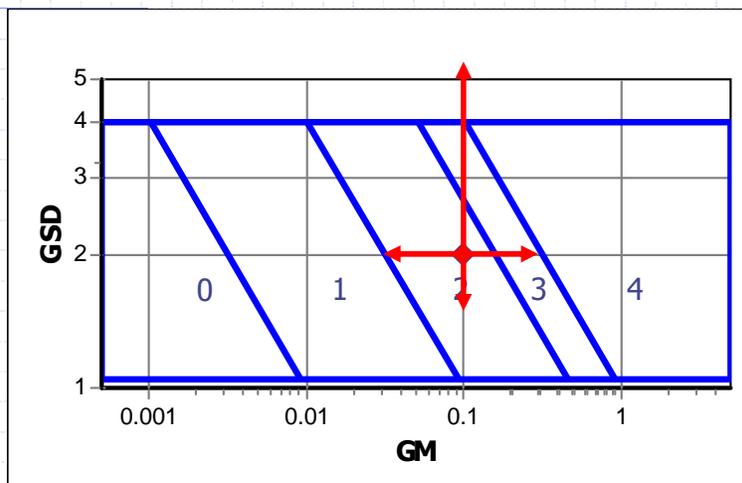
- ◆ The point estimate of the 95<sup>th</sup> percentile is < 50% of the limit.
- ◆ Exposures *appear* to be an AIHA Category 2 exposure.
- ◆ However, the 95%UCL( $X_{0.95}$ ) is considerably greater than the OEL.
- ◆ **What would you do?**
  - **Make a decision ?**
  - **Collect more data ?**

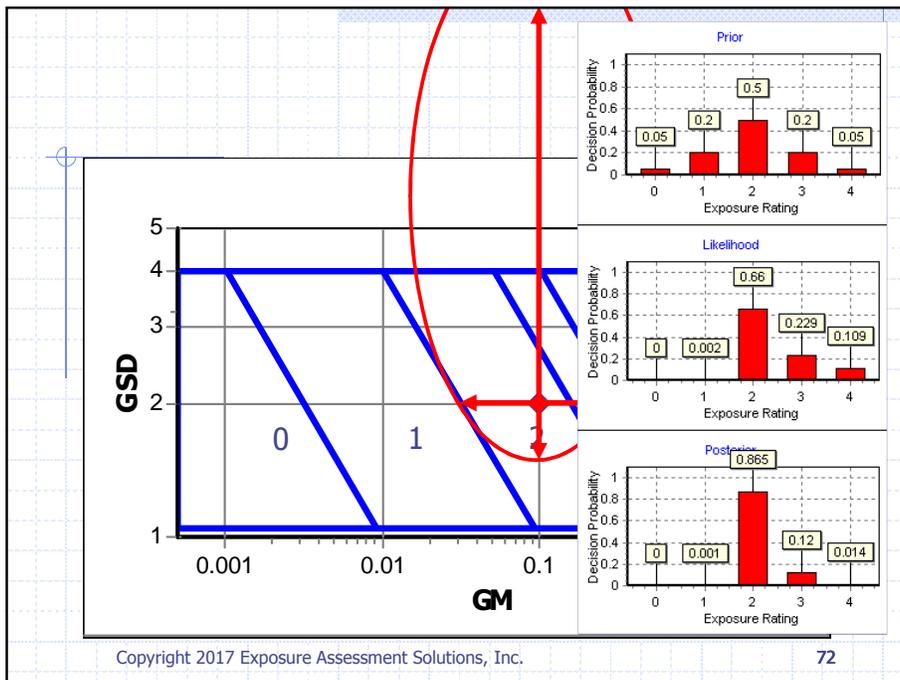
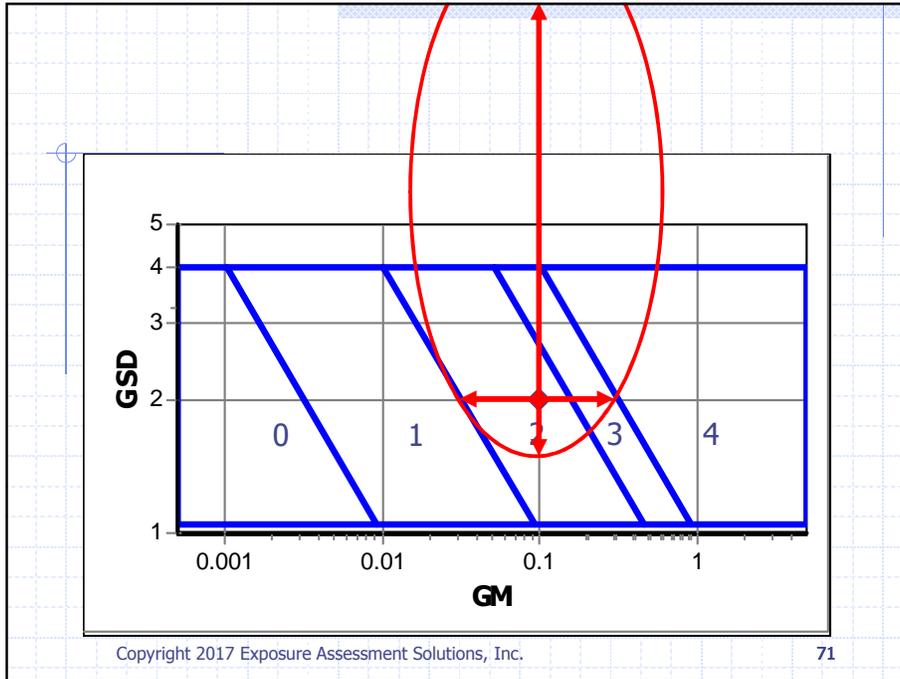
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- ◆ Our IH concludes:
  - This operation is well-controlled (i.e., Category 2) with just the existing dilution ventilation.
  - Although the 95%UCLs were excessive, our IH took into account his extensive past experience with this type of operation.
- ◆ His recommendations:
  - Further sampling is not necessary. Collect routine surveillance samples.
- ◆ **Is this decision making process a Bayesian analysis?**
- ◆ Can Professional Judgment be quantified?
- ◆ Can the confidence level for a *decision* composed of Data Analysis + Professional Judgment be quantified?

## Key Concept: Parameter Space (for OEL=1 ppm)





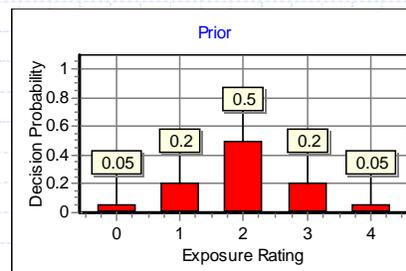
## Key Concept: "Decision" Distributions

- ◆ **Prior** decision distribution
  - Represents our professional judgment regarding the probability of each of the five Exposure Ratings.
- ◆ **Likelihood** decision distribution
  - The set of probabilities of each Exposure Rating *calculated using only the collected data (and part of Bayes' equation)*.
- ◆ **Posterior** decision distribution
  - The set of probabilities of each Exposure Rating *calculated using Bayes' equation*.

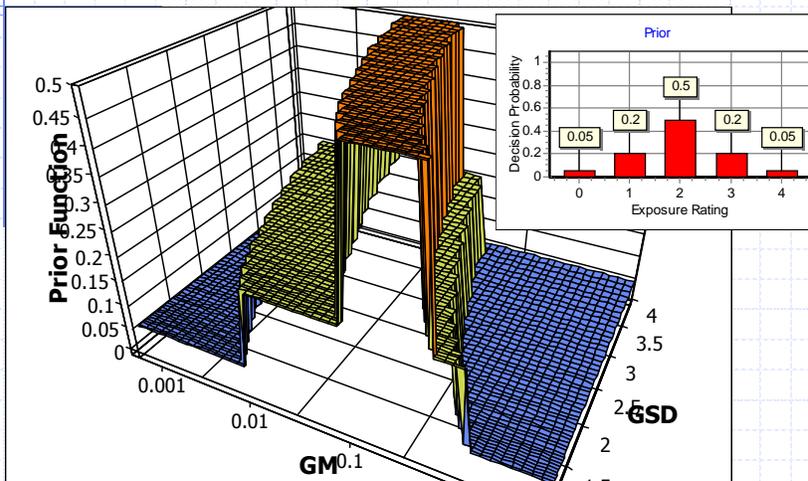
## Prior Decision Distribution

- ◆ Categorical
  - Assign an *a priori* probability to each Exposure Rating zone

- ◆ (Univariate)
- ◆ (Bivariate)



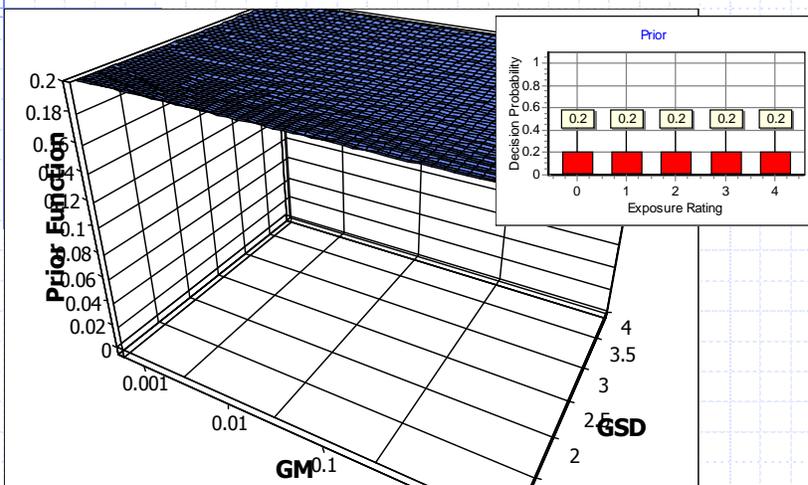
*Prior decision function (i.e., prior decision distribution spread across parameter space)*



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*Prior decision function (i.e., prior decision distribution spread across parameter space)*



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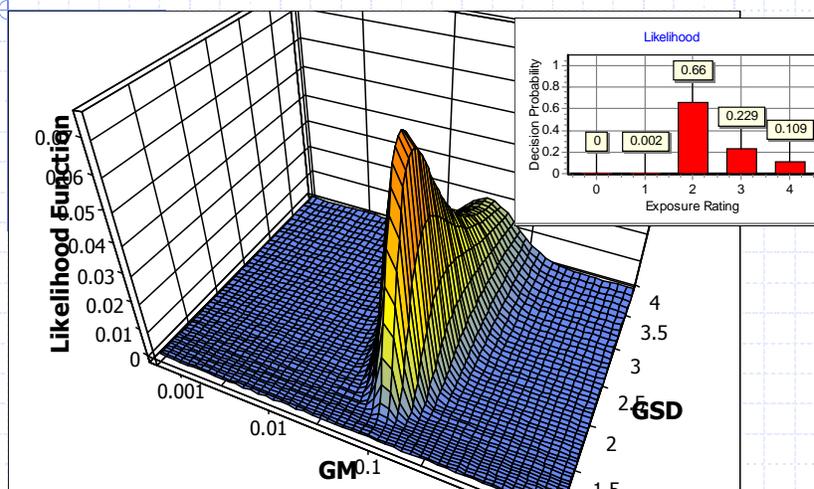
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## Likelihood Decision Probability Calculation

$$P(data|Pop_i) = \frac{\int_{\ln G_{\min}}^{\ln G_{\max}} \int_{\ln D_{\min}}^{\ln D_{\max}} P(data|\ln G, \ln D) d(\ln G) d(\ln D)}{\int_{\ln G_{\min}}^{\ln G_{\max}} \int_{\ln D_{\min}}^{\ln D_{\max}} P(data|\ln G, \ln D) d(\ln G) d(\ln D)}$$

Pop<sub>i</sub> = all combinations of GM and GSD within the *i*th Rating Zone.

## Likelihood function for x={0.20,0.05,0.10}

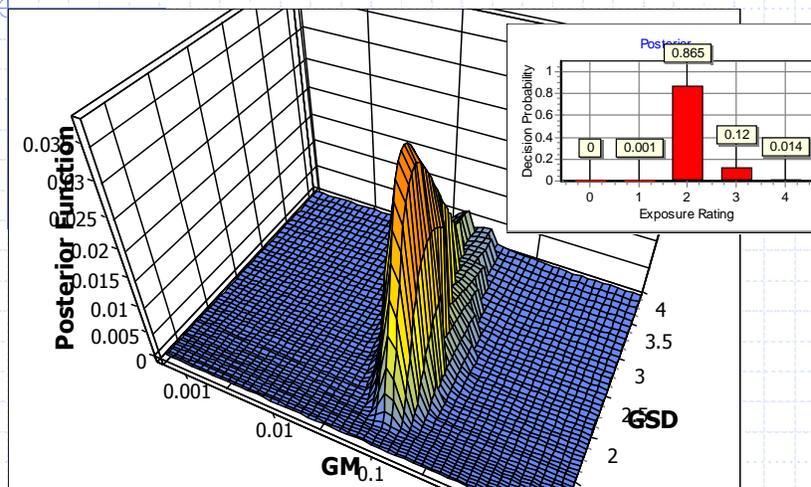


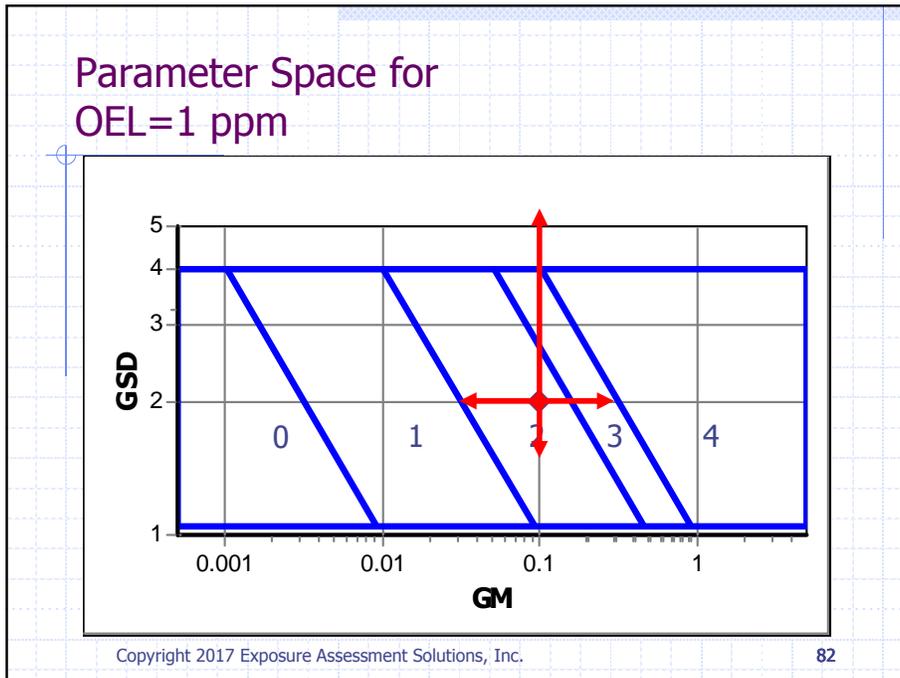
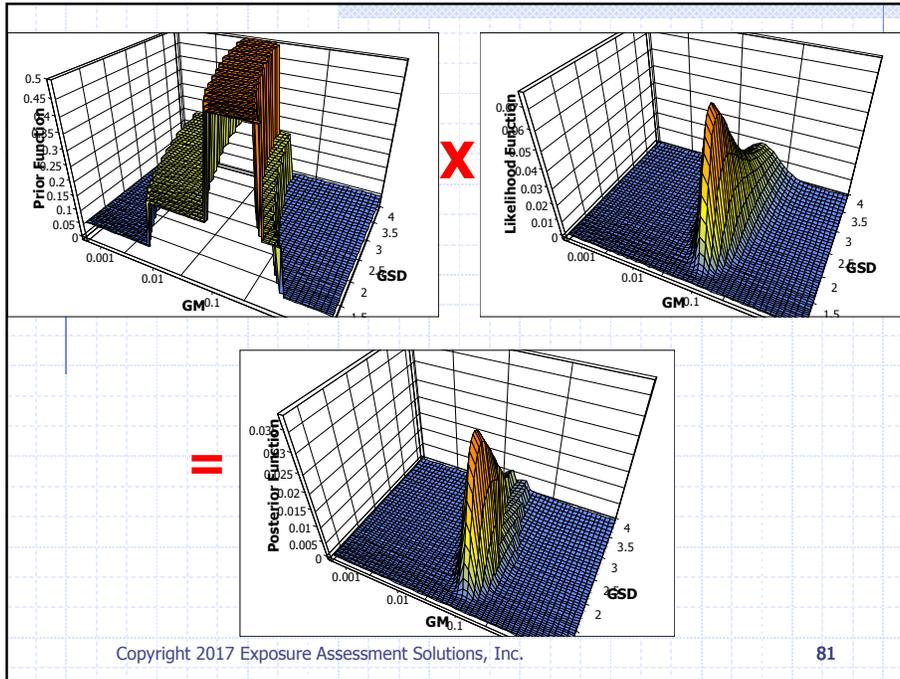
## Posterior Decision Probability Calculation

$$P(Pop_i|data) = \frac{\int_{\ln G_{\min}}^{\ln G_{\max}} \int_{\ln D_{\min}}^{\ln D_{\max}} [P(data|\ln G, \ln D) \cdot P(Pop_i)] d(\ln G) d(\ln D)}{\int_{\ln G_{\min}}^{\ln G_{\max}} \int_{\ln D_{\min}}^{\ln D_{\max}} [P(data|\ln G, \ln D) \cdot P(Pop_i)] d(\ln G) d(\ln D)}$$

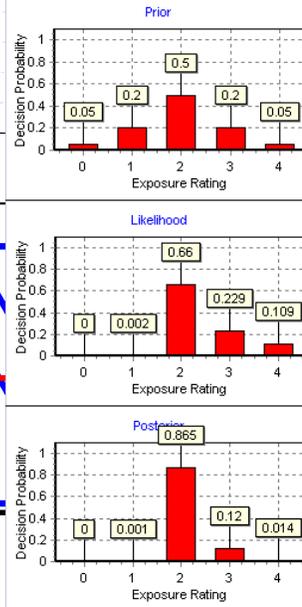
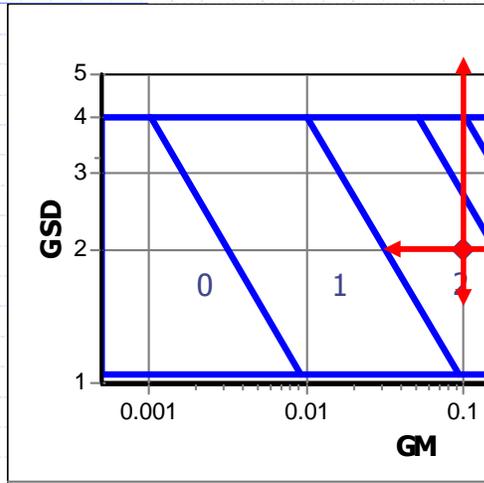
Pop<sub>i</sub> = all combinations of GM and GSD within the *i*th Rating Zone.

## Posterior function





## Parameter Space for OEL=1 ppm



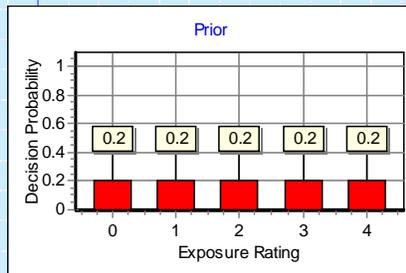
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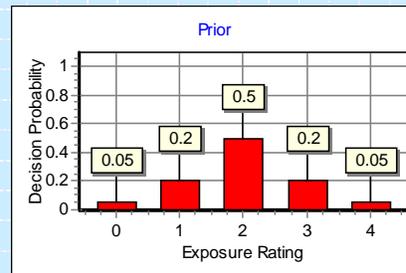
## Decision Charts

### ◆ Example *Prior* Decision Distributions

Non-informative prior

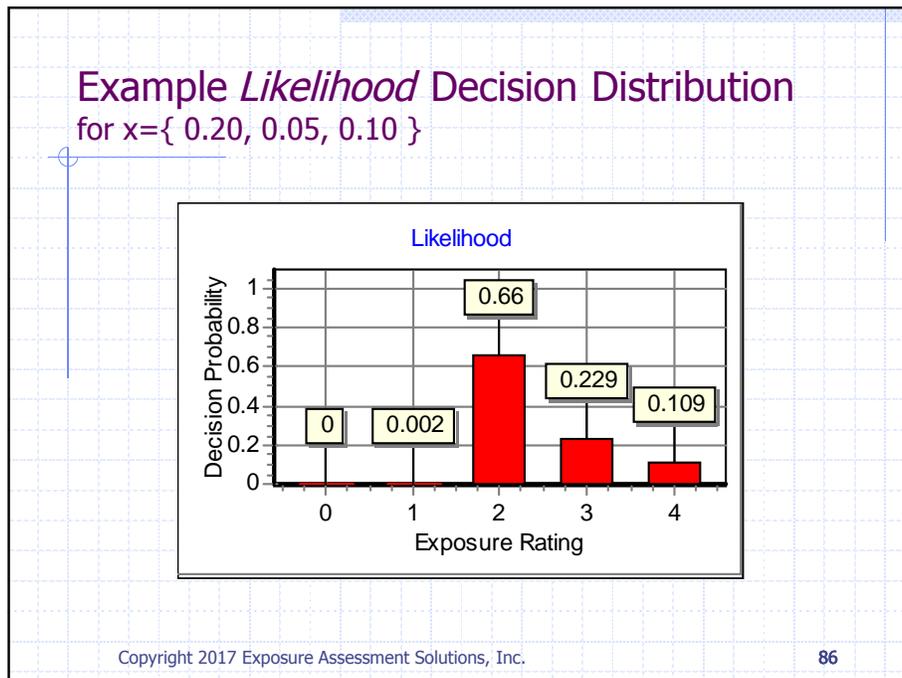
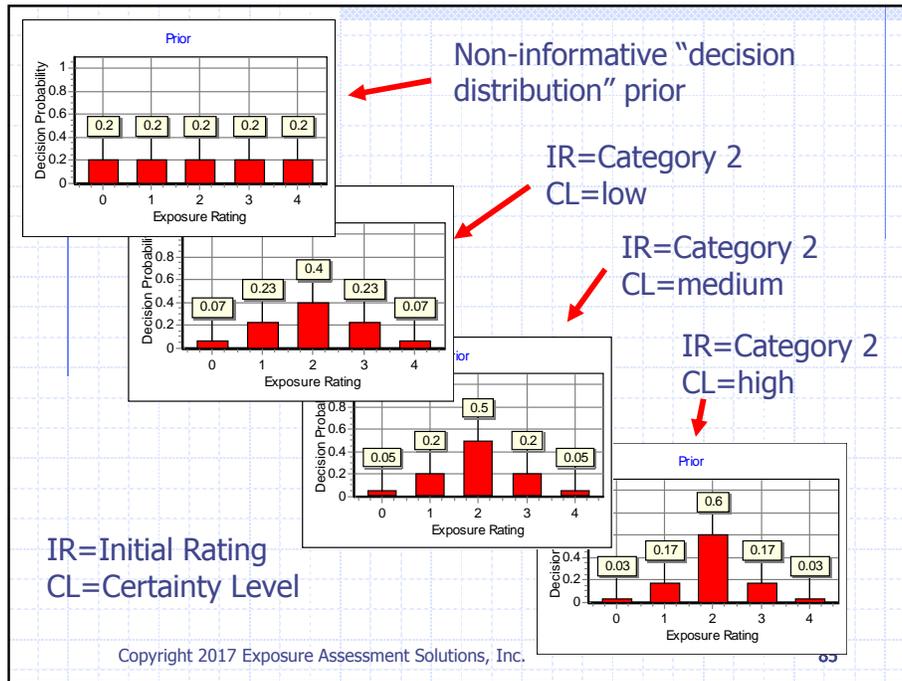


Informative prior



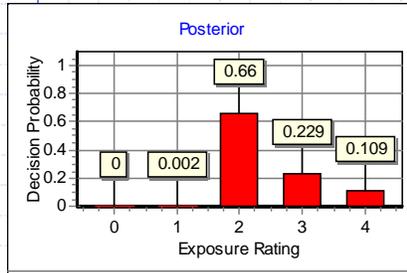
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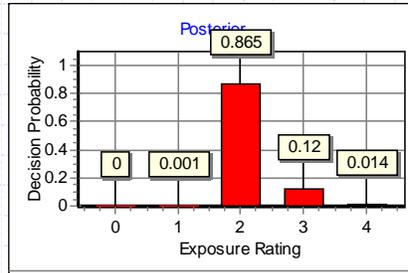


## Example *Posterior* Decision Distributions

Using the non-informative prior



Using the informative prior



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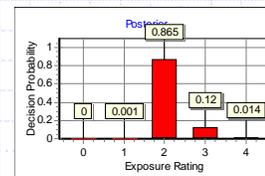
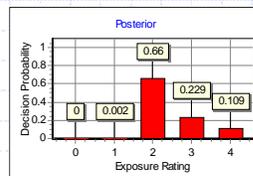
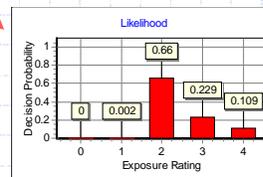
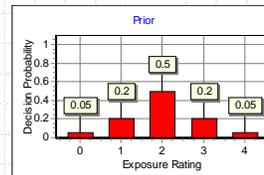
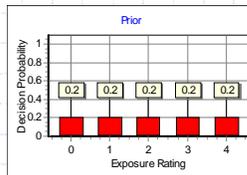
Prior

Likelihood

Posterior

Non-informative

Informative



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## BDA Rules-of-thumb

- ◆ When can we use an informative Prior Decision Distribution?
- ◆ What data should we use for the Likelihood Decision Distribution?

## When can we use an informative Prior Decision Distribution?

- ◆ Informative Priors can be used whenever we are confident in our Professional Judgment.
- ◆ Professional Judgment can be based upon...
  - Past experience with this or similar processes or tasks
  - Analysis of fairly recent data
  - Physical/chemical modeling
  
- ◆ Use a Uniform Prior if in doubt about the accuracy of Professional Judgment.

## What data should we use for the Likelihood Decision Distribution?

- ◆ Current data (<2 years old)
- ◆ Personal exposure data is preferred
- ◆ Same equipment & task

## Decision Making using BDA

- ◆ How much probability can we tolerate for the Category 4 exposure rating?
- ◆ This is a corporate policy decision.
  - A Posterior Decision Probability of  $\leq 0.05$  for Category 4 is analogous to a 95%UTL: "95% confidence that the true 95<sup>th</sup> percentile is less than the OEL".
  - A Posterior Decision Probability of  $\leq 0.10$  for Category 4 is analogous to a 90%UTL: "90% confidence that the true 95<sup>th</sup> percentile is less than the OEL".
  - A Posterior Decision Probability of  $\leq 0.25$  for Category 4 is analogous to a 75%UTL: "75% confidence that the true 95<sup>th</sup> percentile is less than the OEL".

## Advantages of BDA

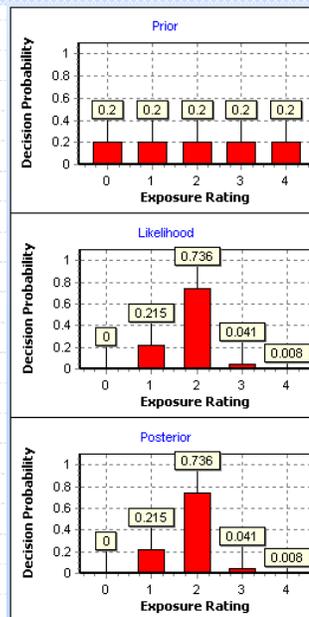
- ◆ Can set a plausible parameter space
- ◆ Output is a set of Decision Charts
- ◆ Can incorporate Professional Judgment
- ◆ Best applied to small datasets
- ◆ Provides feedback
- ◆ Consistent with ...
  - AIHA Exposure Banding Model
  - EU Control Banding Model
  - pharmaceutical Control Banding or PB-OEL Models
- ◆ Provides guidance for respirator selection
- ◆ Can be applied to *censored* datasets

## Example applications of Bayesian Decision Analysis

- ◆ General analysis of occupational exposure data
- ◆ Reach a decision when n is small
- ◆ Leverage professional judgment
- ◆ Provide feedback
- ◆ Analyze censored datasets
- ◆ Assist in respirator selection
- ◆ Risk Communication
  
- ◆ Note: BDA, as currently implemented in the IHDA, requires the assumption that the lognormal distribution is a reasonable approximation of the true exposure profile.

## General analysis of occupational exposure data

- ◆ OEL=0.2 mg/m<sup>3</sup>
- ◆ n = 4
- ◆  $x = \{0.015, 0.008, 0.006, 0.016\}$  mg/m<sup>3</sup>
- ◆ In principle, BDA can be applied to any sample size.

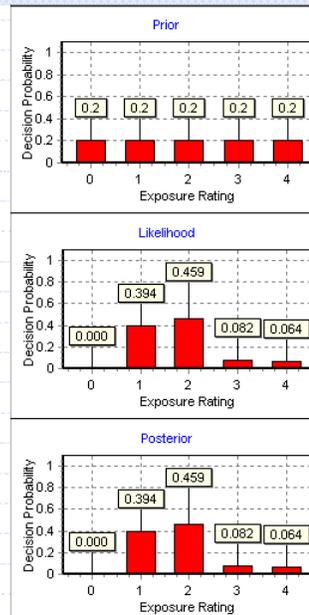


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## Reach a decision when n is small

- ◆ OEL=1 ppm
- ◆ n = 1
- ◆ x = 0.05 ppm
- ◆ BDA can be applied to sample sizes as low as n=1.

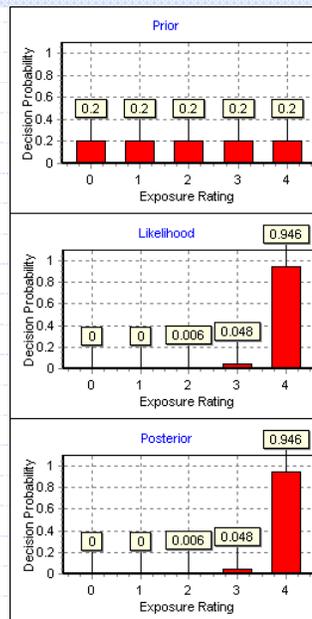


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## Reach a decision when n is small

- ◆ OEL=1 ppm
- ◆ n = 1
- ◆ x = 0.99 ppm
  
- ◆ "Yes, the measurement is <OEL. But I strongly suspect that that exposures are not acceptable."
- ◆ BDA would lead to the same conclusion.

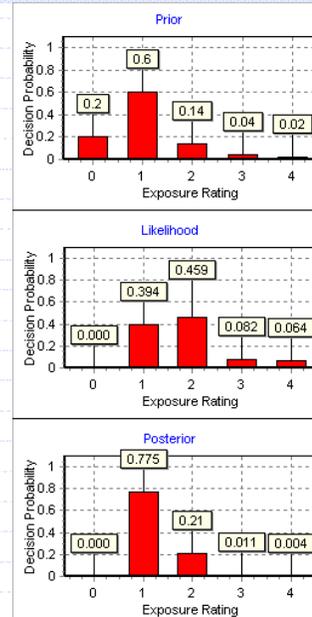


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## Leverage professional judgment

- ◆ OEL=1 ppm
- ◆ n = 1
- ◆ x = 0.05 ppm
  
- ◆ Professional judgment can sharpen the decision.

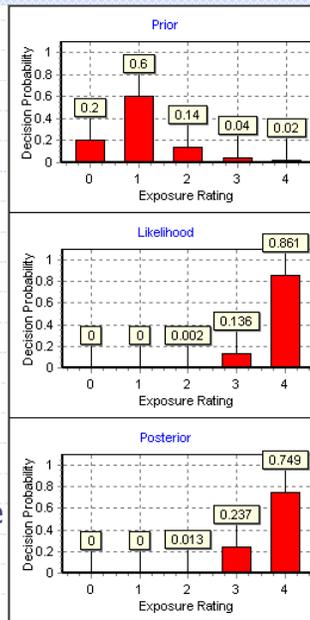


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## Provide feedback

- ◆ OEL=1 ppm
- ◆  $n = 3$
- ◆  $x_1 = 0.25$  ppm
- ◆  $x_2 = 0.50$  ppm
- ◆  $x_3 = 1.00$  ppm
  
- ◆ The Prior is inconsistent with the Likelihood.
- ◆ BDA can be used to help improve professional judgment.

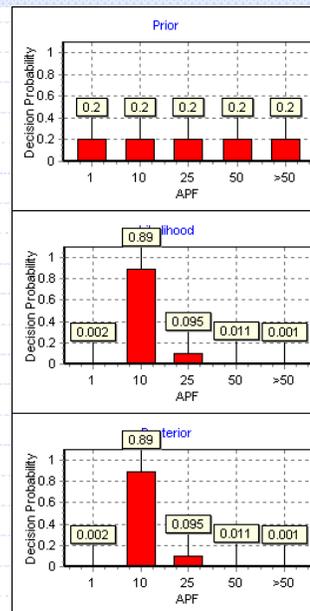


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## Assist in respirator selection

- ◆ OEL=1 ppm
- ◆  $n = 3$
- ◆  $x_1 = 0.99$  ppm
- ◆  $x_2 = 0.50$  ppm
- ◆  $x_3 = 2.0$  ppm
  
- ◆ Decision = Category 4
- ◆ BDA can be used to guide PPE selection.

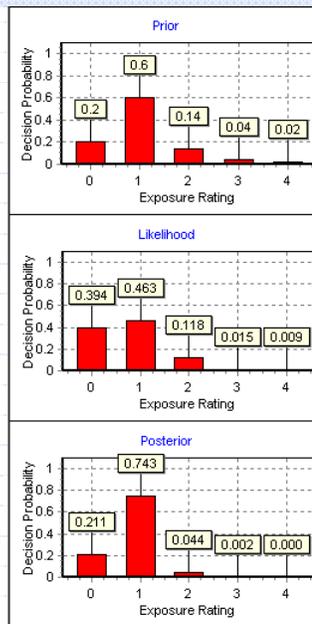


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## Analyze censored datasets

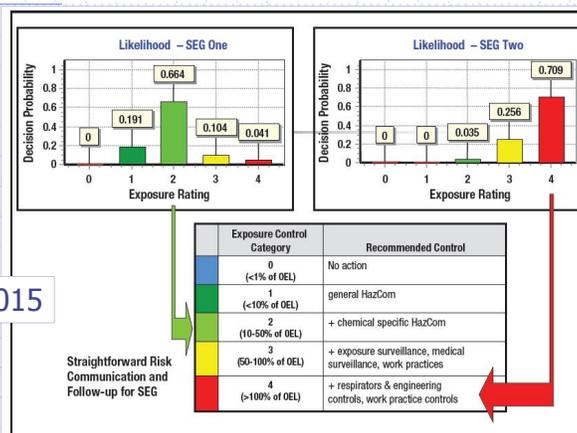
- ◆ OEL=1 ppm
- ◆ n = 1
- ◆  $x < \text{LOD}$
- ◆  $\text{LOD} = 0.05 \text{ ppm}$
  
- ◆ BDA can be applied to censored datasets, even 100% censored or w/ multiple LODs.



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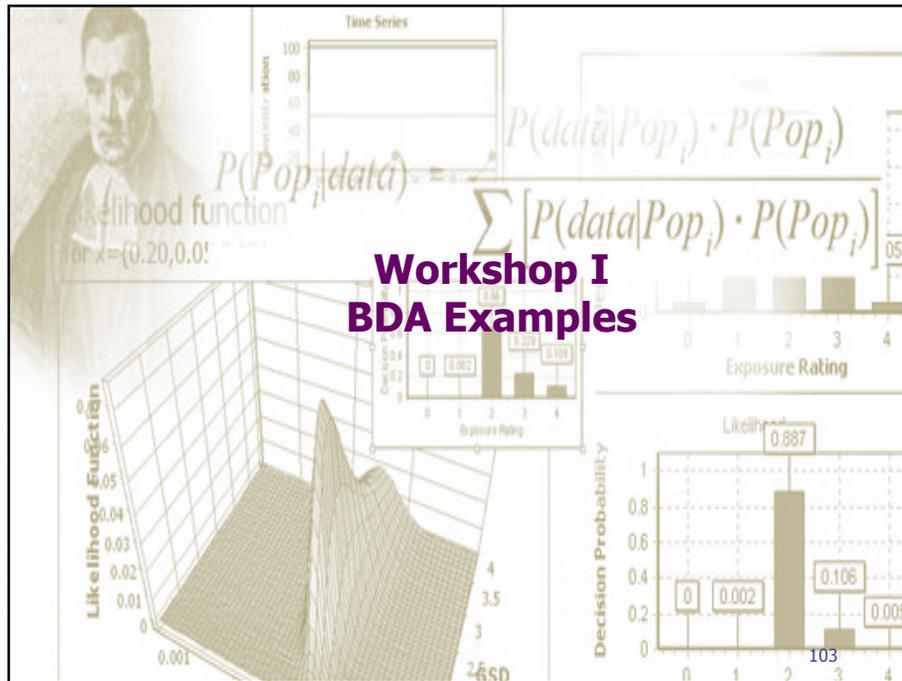
## Risk Communication



**Figure 10.3** – Bayesian Decision Charts Facilitate Risk Communication and Follow-up for SEG Exposure Data (from Mulhausen, J.R. in "Bayesian Statistics: Overview and Applications in Industrial Hygiene Data Interpretation and Exposure Risk Assessment." AIHce PDC 2013).

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## Baseline Survey Simulator V3

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## Steps in Data Analysis and Interpretation

1. Collect / Extract Data
2. Enter the Data into the IHDA (or other program)
3. Evaluate the Goodness-of-fit
4. Calculate Descriptive and Compliance Statistics
5. Calculate BDA Decision Charts (optional)
6. Assign a Final Rating and Certainty Level
7. Document the Analysis and Recommendations

### 3. Evaluate the Goodness-of-fit

What is the difference between min and max.

Do the data fall near a GM&GSD best fit line?

Outliers?

Odd clusters of data?

### 4. Calculate basic descriptive and compliance statistics

How variable are the data?

Compare the "decision statistic" to the OEL.

Compare the 95%UCL to the OEL.

Select a Censored Data Analysis (CDA) method for calculating statistics when there are non-detects.

◆ Hewett's Rule-of-thumb for assigning a Certainty Level

- Low: decision probability is less than 0.5
- Medium: decision probability is between 0.5 and 0.75
- High: decision probability is greater than 0.75

◆ If Exposure Rating  $\leq$  Category 3, check Category 4:

- $< 0.1$  - acceptable
- 0.1-0.25 - acceptable, provided the SEG has a surveillance plan
- $> 0.25$  but  $< 0.5$  - problematic, particularly if the SEG has no surveillance plan.

## Small Datasets

- ◆ IDHA – API 03
- ◆ IDHA – API 01
- ◆ IHDA - Manganese Fumes - Dept B.xls
- ◆ IHDA - Manganese Fumes - Dept C.xls
  
- ◆ Analyze with and without informative Prior Decision Charts.

## IHDA – API 03.xls

- ◆ Active Pharmaceutical Ingredient (API)
- ◆ OEL = 1  $\mu\text{g}/\text{m}^3$
- ◆  $X = \{0.014, 0.027, 0.030, 0.042, 0.101, 0.141\} \mu\text{g}/\text{m}^3$
- ◆ Use the Rule-of-thumb:

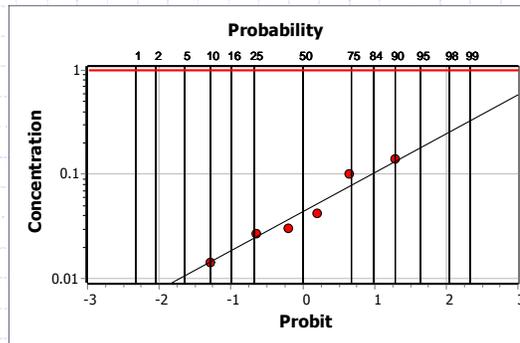
Data Set	Data	Median	Approximate $X_{0.95}$			Exposure Category (1-4)
			2x	4x	6x	
A	0.014, 0.027, 0.030, 0.042, 0.101, 0.141	0.036	0.072	0.144	0.216	2

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### ◆ GOF

- Subjective:



- Objective:

```

Statistics  GOF Graphs  BDA Charts  PPE Charts  CDA
-----
Goodness-of-fit Test
-----
Fillibens Test:
R = 0.978
critical R = 0.888
Interpretation: the lognormal distribution hypothesis is not rejected.
    
```

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Substance: Active Pharmaceutical Ingredient  
 OEL: 1 ug/m<sup>3</sup>

Descriptive Statistics			
mean =	0.0592		
sd =	0.0503		
gm =	0.0435	95%LCL = 0.0213	95%UCL = 0.0887
gsd =	2.3760	95%LCL = 1.7889	95%UCL = 6.1008

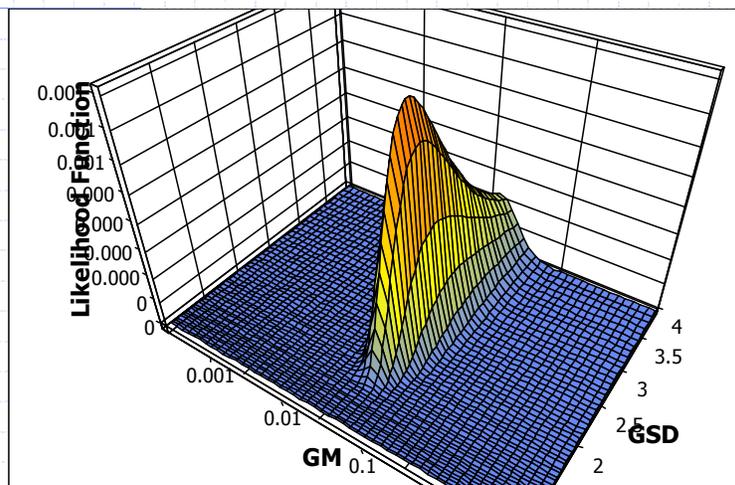
Compliance Statistics (lognormal)			
X0.95 =	0.1806	95%LCL = 0.0928	95%UCL = 1.0769
ExcFrac =	0.0001	95%LCL = <0.001	95%UCL = 0.055

Compliance Statistics (non-parametric)			
X0.95 =	NA	95%LCL = NA	95%UCL = NA
ExcFrac =	0.000	95%LCL = 0.000	95%UCL = 0.393

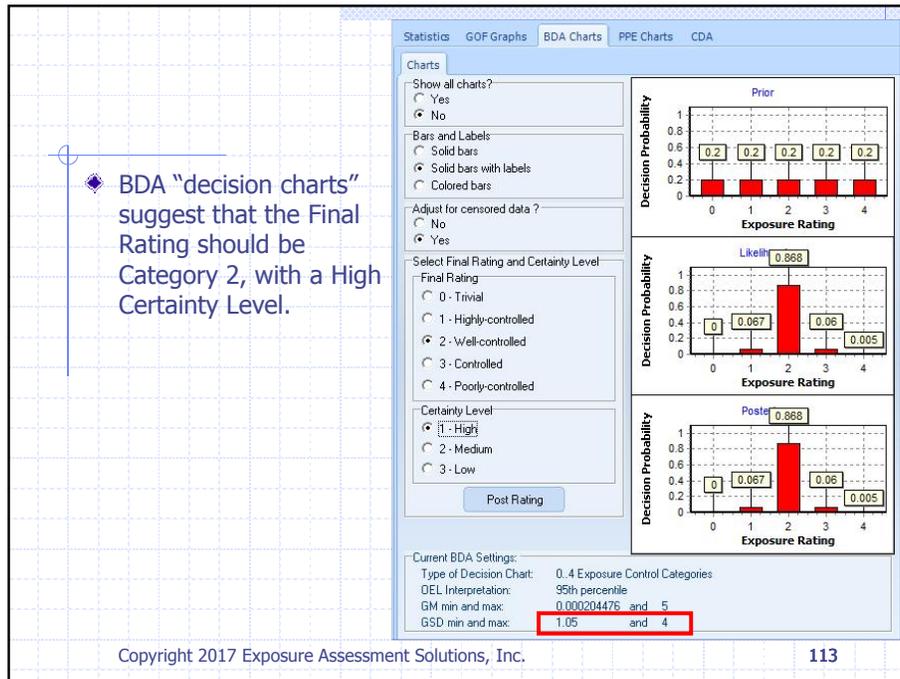
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Likelihood Function is well within Parameter Space, and mostly above the Category 2 zone.



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- ◆ Observations based on statistics:
- Sample 95<sup>th</sup> percentile ( $X_{0.95}$ ) is between 10% and 50% of the OEL: a low Category 2.
  - The 90% Confidence Interval for  $X_{0.95}$  extends from a high Category 1 to a low Category 4. (See 95%UCLs for the GSD.)
  - Confidence Level using statistics? Difficult to assign when the confidence interval spans several exposure categories.
- ◆ Observations based on BDA:
- BDA “decision charts” strongly suggest that the exposure profile is most likely a Category 2, High Certainty.
  - (Parameter Space forces the consideration of only *plausible* GSDs.)
- ◆ Final Rating and Certainty Level:
- Category 2, High Certainty.
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## IHDA – API 01.xls

- ◆ Active Pharmaceutical Ingredient (API)
- ◆ OEL = 1  $\mu\text{g}/\text{m}^3$
- ◆  $X = \{0.033, 0.097, 0.261, 0.432\} \mu\text{g}/\text{m}^3$
- ◆ Use the Rule-of-thumb:

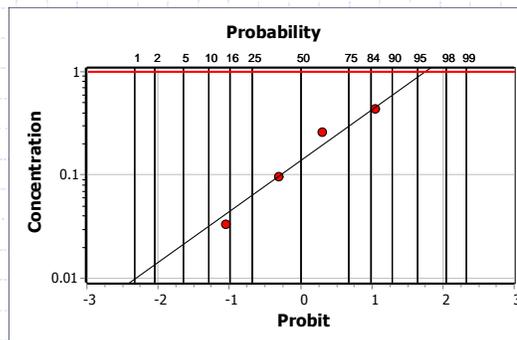
Data Set	Data	Median	Approximate $X_{0.95}$			Exposure Category (1-4)
			2x	4x	6x	
A	0.033, 0.097, 0.261, 0.432	0.179	0.359	0.716	1.07	3,4

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### ◆ GOF

- Subjective:



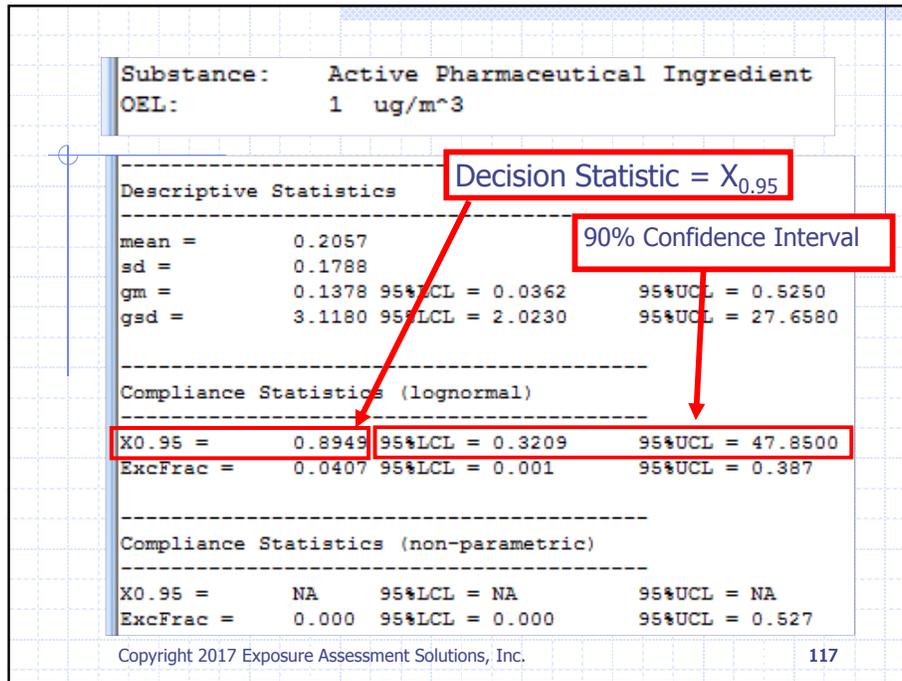
- Objective:

```

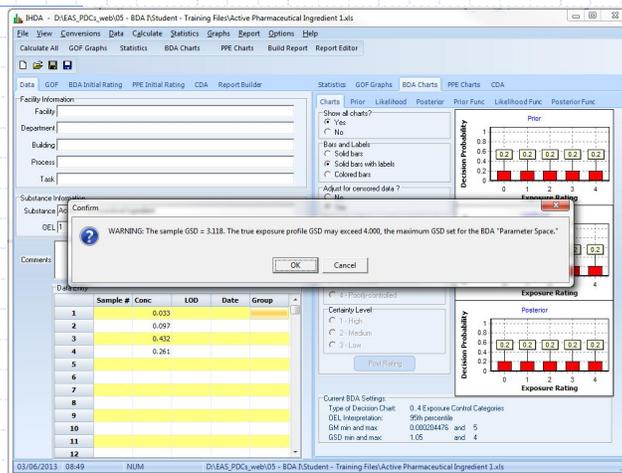
Statistics  GOF Graphs  BDA Charts  PPE Charts  CDA
-----
Goodness-of-fit Test
-----
Fillibens Test:
R = 0.985
critical R = 0.868
Interpretation: the lognormal distribution hypothesis is not rejected.
    
```

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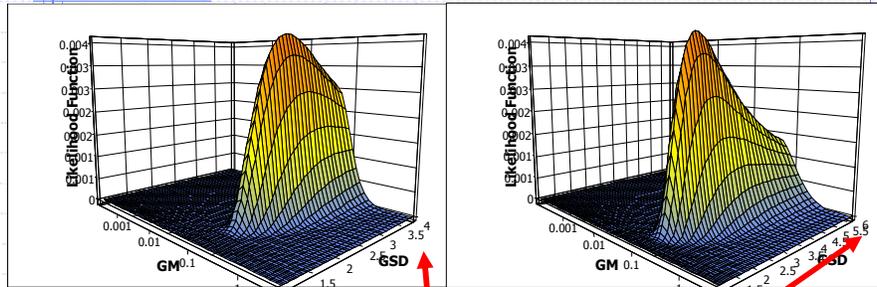
116



You will see this warning whenever the sample GSD is within 25% of the GSD<sub>max</sub> for Parameter Space:

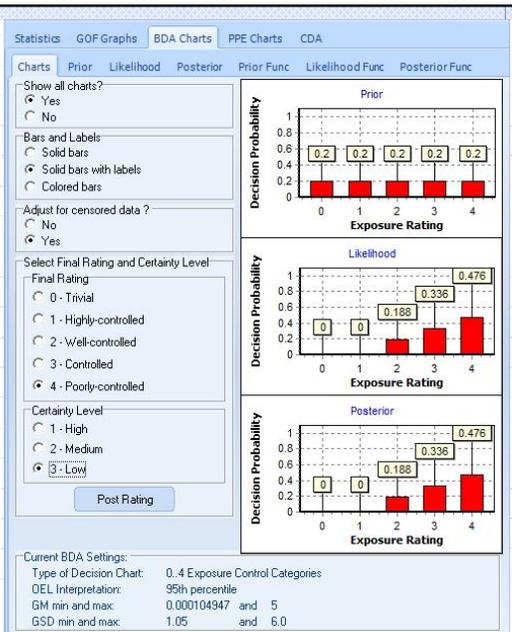


Extending the  $GSD_{max}$  captures more of the Likelihood Function, but should be done with caution.



$GSD_{max}$

- ◆ I extended Parameter Space to a GSD of 6.
- ◆ BDA "decision charts" suggest that the Final Rating should be either Category 3 or 4, most likely Category 4.
- ◆ The BDA Exposure Rating could be Category 4, but with a low Certainty Level.



- ◆ Observations based on statistics:
  - Highly variable data: sample GSD>3
  - Sample 95th percentile ( $X_{0.95}$ ) is a *high Category 3*.
  - The 90% Confidence Interval for the sample  $X_{0.95}$  extends from Category 2 to a high Category 4. (See 95%UCL for the GSD.)
  - The Confidence Level (or Certainty Level) is low for an exposure profile rating of Category 3. (True exposure rating could be a Category 4.)
- ◆ Observations based on BDA:
  - BDA suggests that the exposure profile may be either Category 3 or 4, but most likely a Category 4 (with the adjusted Parameter Space).
- ◆ Final Rating and Certainty Level:
  - A tentative 3 or even 4, Low Certainty.

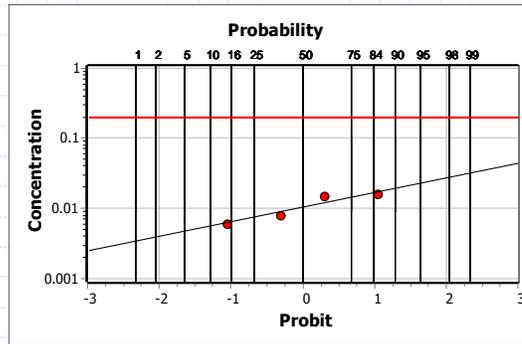
## IHDA - Manganese Fumes - Dept B.xls

- ◆ Welding fumes
- ◆ OEL = 0.2 mg/m<sup>3</sup>
- ◆  $X = \{0.015, 0.008, 0.006, 0.016\}$  μg/m<sup>3</sup>
- ◆ Use the Rule-of-thumb:

Data Set	Data	Median	Approximate $X_{0.95}$			Exposure Category (1-4)
			2x	4x	6x	
A	0.015, 0.008, 0.006, 0.016	0.011	0.022	0.044	0.066	2

◆ GOF

■ Subjective:



■ Objective:

Statistics	GOF Graphs	BDA Charts	PPE Charts	CDA
-----				
Goodness-of-fit Test				
-----				
Fillibens Test:				
R = 0.949				
critical R = 0.868				
Interpretation: the lognormal distribution hypothesis is not rejected.				

Substance: manganese fume (as Mn)  
OEL: 0.2 mg/m<sup>3</sup>

Descriptive Statistics

mean =	0.0112		
sd =	0.0050		
gm =	0.0104	95%LCL = 0.0059	95%UCL = 0.0182
gsd =	1.6160	95%LCL = 1.3463	95%UCL = 4.0598

Decision Statistic =  $X_{0.95}$

90% Confidence Interval

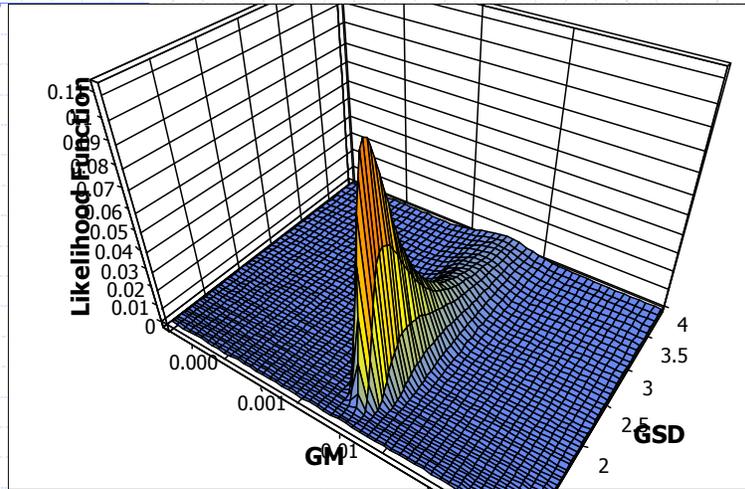
Compliance Statistics (lognormal)

$X_{0.95}$ =	0.0228	95%LCL = 0.0148	95%UCL = 0.1223
ExcFrac =	0.0000	95%LCL = <0.001	95%UCL = <0.025

Compliance Statistics (non-parametric)

$X_{0.95}$ =	NA	95%LCL = NA	95%UCL = NA
ExcFrac =	0.000	95%LCL = 0.000	95%UCL = 0.527

Likelihood Function is well within Parameter Space, and mostly above the Category 2 zone.

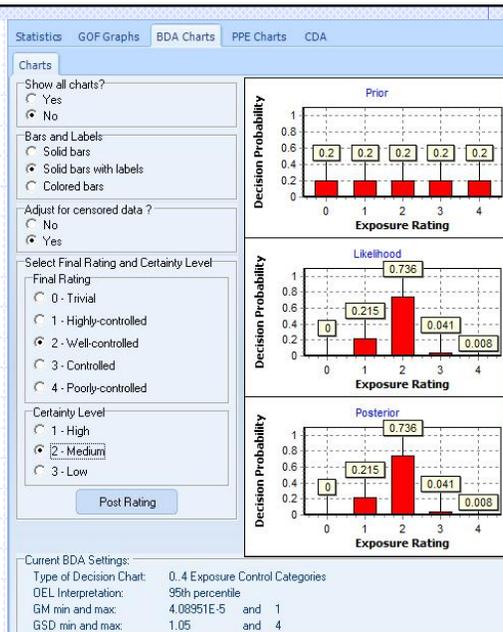


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◆ BDA “decision charts” suggest that the Final Rating should be Category 2.

◆ The BDA Exposure Rating could be Category 2, with a Certainty Level of Medium or High.



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◆ Observations based on statistics:

- The data appear to be reasonably lognormal and pass a formal GOF test.
- Medium variable data: sample GSD > 1.5 and < 2.5
- Sample 95th percentile ( $X_{0.95}$ ) is a *low Category 2*.
- The 90% Confidence Interval for the sample  $X_{0.95}$  extends from Category 1 to a low Category 3.
- The Confidence Level (or Certainty Level) is high for an exposure profile rating of Category 2.

◆ Observations based on BDA:

- BDA suggests that the exposure profile is likely a Category 2, with a Certainty Level of Medium or High.

◆ Final Rating and Certainty Level:

- Category 2, High Certainty. (Both stats+UCLs and BDA agree.)

◆ Comments:

- None of the measurements exceeded 10% of the OEL.
- Both the statistics and BDA suggest a Final Rating = Category 2.

- Analyze with and without made-up informative Prior Decision Charts. How does the Posterior Decision Chart respond to consistent and inconsistent Priors?

## IHDA - Manganese Fumes - Dept C.xls

- ◆ Welding fumes
- ◆ OEL = 0.2 mg/m<sup>3</sup>
- ◆ X={0.056, 0.067, 0.302, 0.097, 0.172} μg/m<sup>3</sup>
- ◆ Use the Rule-of-thumb:

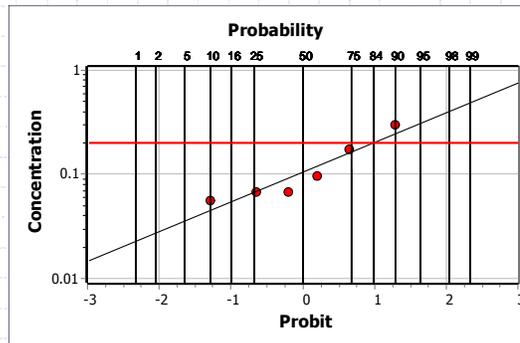
Data Set	Data	Median	Approximate X <sub>0.95</sub>			Exposure Category (1-4)
			2x	4x	6x	
A	0.056, 0.067, <b>0.302</b> , 0.097, 0.172	0.082	0.164	0.328	0.492	4

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### ◆ GOF

- Subjective:



- Objective:

```

Statistics  GOF Graphs  BDA Charts  PPE Charts  CDA
-----
Goodness-of-fit Test
-----
Fillibens Test:
R = 0.943
critical R = 0.888
Interpretation: the lognormal distribution hypothesis is not rejected.
    
```

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◆ Comments:

- The Category 4 decision probability will be large whenever n is small and one or more measurements approach or exceed the OEL.
- BDA assessments of small datasets tend to match our “gut feel”.
  - ◆ With small n, measurements approaching the OEL should a cause for concern.
  - ◆ Such measurements push the the decision probabilities towards Categories 3 and 4.
- 95<sup>th</sup> percentile is unlikely to exceed 10x the OEL. Therefore, a respirator APF of 10 might be appropriate.

Substance: manganese fume (as Mn)  
OEL: 0.2 mg/m<sup>3</sup>

Descriptive Statistics

mean =	0.1268		
sd =	0.0957		
gm =	0.1040	95%LCL = 0.0605	95%UCL = 0.1787
gsd =	1.9308	95%LCL = 1.5561	95%UCL = 3.9545

Decision Statistic =  $X_{0.95}$

90% Confidence Interval

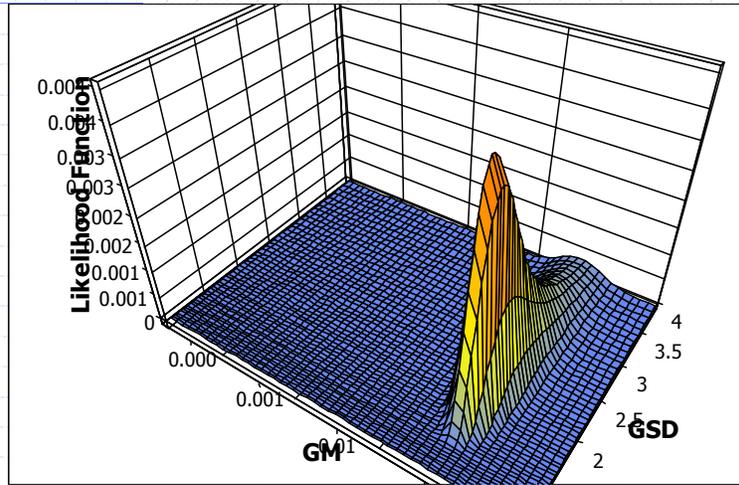
Compliance Statistics (lognormal)

$X_{0.95}$ =	0.3070	95%LCL = 0.1850	95%UCL = 1.1929
ExcFrac =	0.1602	95%LCL = 0.036	95%UCL = 0.453

Compliance Statistics (non-parametric)

$X_{0.95}$ =	NA	95%LCL = NA	95%UCL = NA
ExcFrac =	0.167	95%LCL = 0.009	95%UCL = 0.582

Likelihood Function is well within Parameter Space, and mostly above the Category 4 zone.

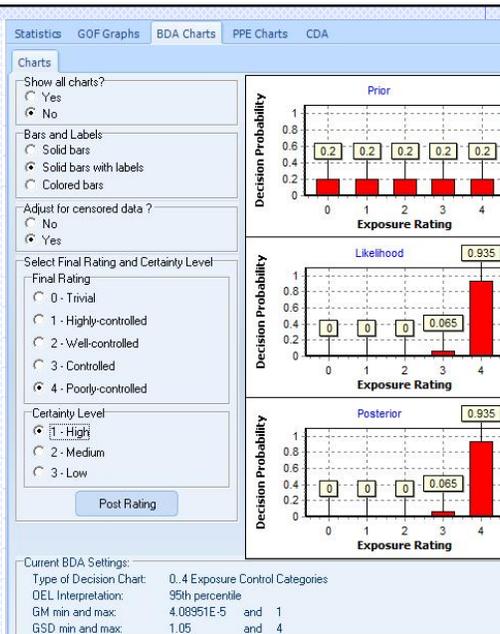


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◆ BDA "decision charts" suggest that the Final Rating should be Category 4.

◆ The BDA Exposure Rating should be Category 4, with High Certainty Level.



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- ◆ Observations based on statistics:
  - The data appear to be reasonably lognormal and pass a formal GOF test.
  - Medium variable data: sample GSD > 1.5 and < 2.5
  - Sample 95th percentile ( $X_{0.95}$ ) is a *high Category 4*.
  - The 90% Confidence Interval for the sample  $X_{0.95}$  extends from a high Category 3 to a high Category 4.
  - The Confidence Level (or Certainty Level) is high for an exposure profile rating of Category 4.
- ◆ Observations based on BDA:
  - BDA suggests that the exposure profile is likely a Category 4, High Certainty.
- ◆ Final Rating and Certainty Level:
  - Category 4, High Certainty.
  - Even though the sample size was small, a decision can be made with high certainty.

- ◆ Comments:
  - Neither statistics nor BDA is needed with this dataset.
  - 95<sup>th</sup> percentile is highly unlikely to exceed 10x the OEL. Therefore, a respirator APF of 10 might be appropriate.
  - ... but there is a 10% probability that the true 95<sup>th</sup> percentile exceeds 10x the OEL.
    - ◆ Ignore, considering the conservatism built into the APF?
    - ◆ Collect more data?

## Large datasets

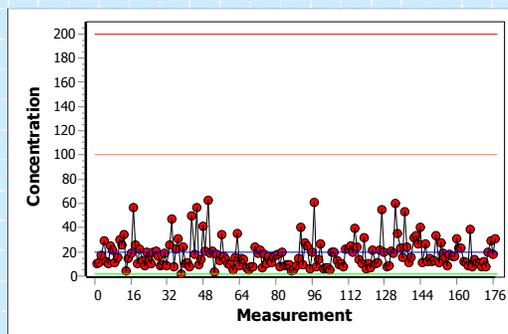
- ◆ IHDA - CopeDataset - All.xls
- ◆ IHDA - CopeDataset - Worker F.xls
- ◆ Comment: For large sample sizes – e.g.,  $n > 15$  – the conclusions derived from an analysis of the statistics and BDA tend to converge.
- ◆ Note: The IHDA-S program is limited to 25 measurements.

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## IHDA - CopeDataset - All.xls

- ◆ Inorganic Lead
- ◆ OEL =  $200 \mu\text{g}/\text{m}^3$  (mid-1970s)
- ◆  $X = \{10.4, \dots, 30.6\} \mu\text{g}/\text{m}^3$  ( $n=177$ )

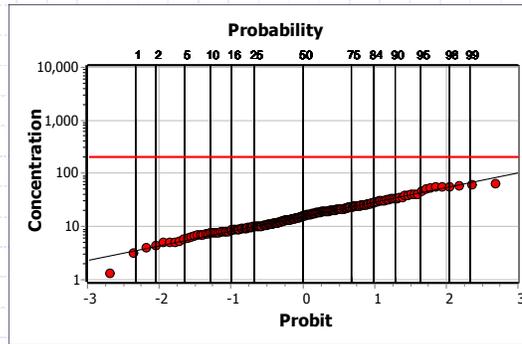


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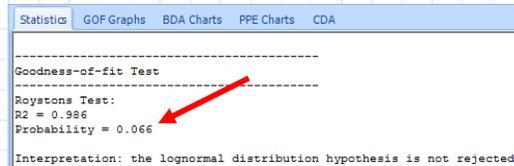
138

◆ GOF

■ Subjective:



■ Objective:

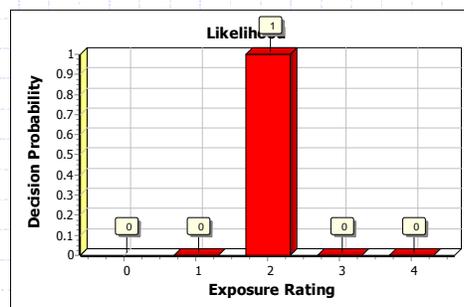


Descriptive Statistics

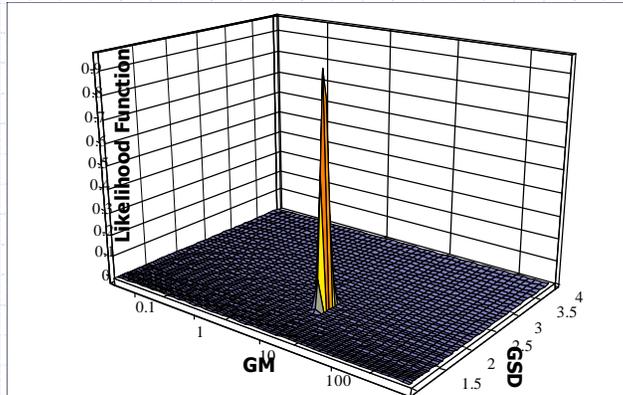
gm = 15.3 95%LCL = 14.2 95%UCL = 16.6  
gd = 1.88 95%LCL = 1.79 95%UCL = 2.00

Compliance Statistics (lognormal)

X0.95 = 43.2 95%LCL = 38.6 95%UCL = 49.1  
ExcFrac = 0.00 95%LCL = <0.001 95%UCL = <0.001



- ◆ Likelihood function is extremely sharp, sitting almost entirely in the Category 2 slice of Parameter Space.



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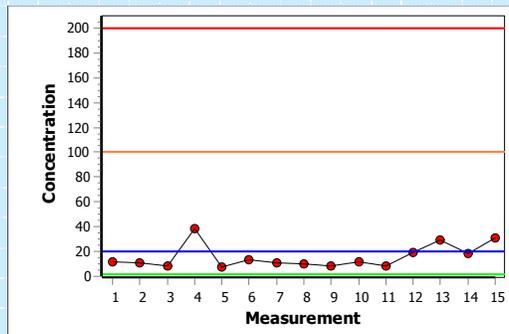
- ◆ Observations based on statistics:
  - The data appear to be reasonably lognormal and pass a formal GOF test (barely).
  - Medium variable data: sample  $GSD > 1.5$  and  $< 2.5$
  - Sample 95th percentile ( $X_{0.95}$ ) is a Category 2.
  - The 90% Confidence Interval for the sample  $X_{0.95}$  is entirely within the Category 2 range.
  - Based on statistics: Category 2, High Certainty
- ◆ Observations based on BDA:
  - BDA suggests that the exposure profile is likely a Category 2, High Certainty.
- ◆ Final Rating and Certainty Level:
  - Category 4, High Certainty.
  - Statistics and BDA agree

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## IHDA - CopeDataset - Worker F.xls

- ◆ Inorganic Lead
- ◆ OEL = 200  $\mu\text{g}/\text{m}^3$
- ◆  $X = \{12.0, \dots, 30.6\} \mu\text{g}/\text{m}^3$  (n=15)

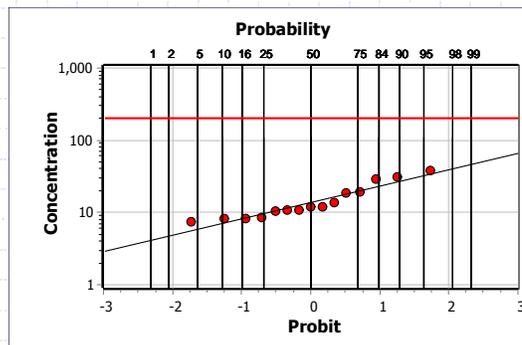


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### ◆ GOF

- Subjective:



- Objective:

```

Statistics  GOF Graphs  BDA Charts  PPE Charts  CDA
-----
Goodness-of-fit Test
-----
Fillibens Test:
R = 0.957
critical R = 0.939
Interpretation: the lognormal distribution hypothesis is not rejected.
    
```

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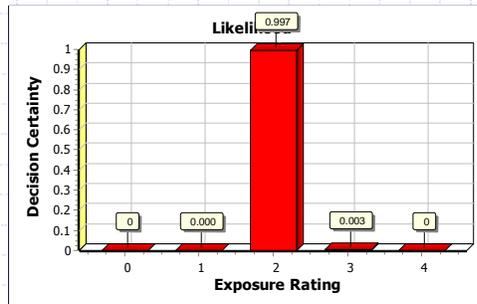
144

-----  
Descriptive Statistics  
-----

gm = 13.8 95%LCL = 10.8 95%UCL = 17.5  
gsd = 1.690 95%LCL = 1.50 95%UCL = 2.15

-----  
Compliance Statistics (lognormal)  
-----

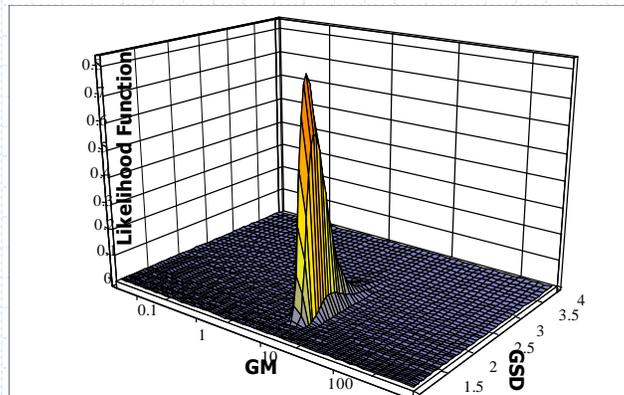
X0.95 = 32.6 95%LCL = 24.7 95%UCL = 52.9  
ExcFrac = 0.000 95%LCL = <0.001 95%UCL = <0.001



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- ◆ Likelihood function is extremely sharp, sitting almost entirely in the Category 2 slice of Parameter Space.



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- ◆ Observations based on statistics:
  - The data appear to be reasonably lognormal and pass a formal GOF test.
  - Medium variable data: sample GSD > 1.5 and < 2.5
  - Sample 95th percentile ( $X_{0.95}$ ) is a Category 2.
  - The 90% Confidence Interval for the sample  $X_{0.95}$  is entirely within the Category 2 range.
  - Based on statistics: Category 2, High Certainty
- ◆ Observations based on BDA:
  - BDA suggests that the exposure profile is likely a Category 2, High Certainty.
- ◆ Final Rating and Certainty Level:
  - Category 4, High Certainty.
  - Statistics and BDA agree

- ◆ Comments:
  - For large  $n$  – e.g., > 10 to 15 - the decisions made using standard statistics (using UCL's) and BDA tend to converge.
  - In the IHDA program BDA is not permitted on datasets exceeding 250 measurements.

## Single measurement scenarios

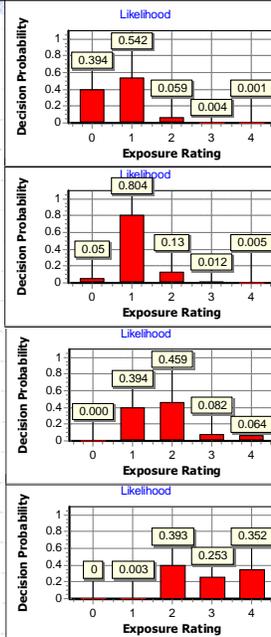
- ◆ OEL = 1 ppm
  - ◆ X = {0.005} ppm
  - ◆ X = {0.01} ppm
  - ◆ X = {0.05} ppm
  - ◆ X = {0.25} ppm
  - ◆ X = {0.49} ppm
  - ◆ X = {0.99} ppm
  - ◆ X = {1.50} ppm
- ◆ Analyze with and without informative Prior Decision Charts.
- ◆ Comments: A BDA assessment of small datasets tend to match our "gut feel".

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OEL = 1 ppm

- ◆ X = {0.005} ppm
- ◆ X = {0.01} ppm
- ◆ X = {0.05} ppm
- ◆ X = {0.25} ppm



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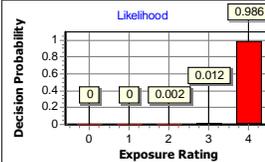
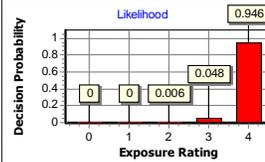
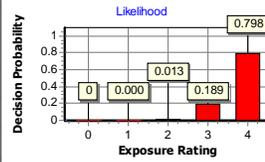
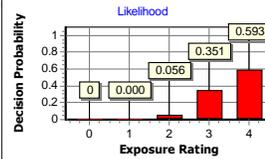
OEL = 1 ppm

◆ X = {0.49} ppm

◆ X = {0.75} ppm

◆ X = {0.99} ppm

◆ X = {1.5} ppm



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◆ Comments:

- As the measurements approach the OEL the BDA decision probabilities for Categories 3 and 4 increases, forcing us to consider the possibility that the true exposure profile is a Category 3 or 4.
- A category 4 decision does not convey the severity of the exposure profile.
  - ◆ Look at the sample 95<sup>th</sup> percentile.
  - ◆ Is it barely above the OEL or multiples of the OEL?
  - ◆ Use BDA PPE selection function to help determine the severity of the Category 4 exposure profile.
- Analyze with and without made-up informative Prior Decision Charts. How does the Posterior Decision Chart respond to an inconsistent Prior? ... such as Initial Rating = 1, High Certainty.

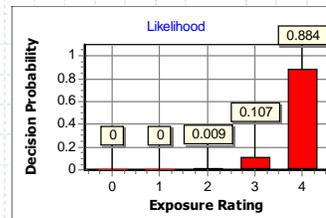
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### OSHA Compliance Issues Exposure to Crystalline Silica During a Foundry Ladle Relining Process

- ◆ “The sampling results reported by the consultant found that the collected samples contained 11 percent crystalline silica. The eight-hour time weighted average exposure was 0.67 mg/m<sup>3</sup>, and the calculated OSHA PEL was 0.77 mg/m<sup>3</sup>. The company was found to be in compliance with the PEL, and OSHA closed the investigation.”
- ◆ Would a BDA analysis support OSHA’s conclusion?

- ◆ BDA suggests that this single “commissioning” measurement most likely came from a Category 4 exposure profile.
- ◆ Either additional measurements are needed to conclusively demonstrate compliance or the engineering controls need to be further improved.



## Comparison of the Rule-of-thumb Method and BDA

- ◆ Compare the exposure ratings determined using the Rule-of-thumb (ROT) method from the IH Statistics training.
- ◆ The ROT methods compares favorably to the results of BDA.
- ◆ However, if BDA is more accurate and consistent, why not use the BDA tool and save the ROT for those assessments where the computer is not available.

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## Apply BDA and compare the Rule-of-thumb exposure rating to the BDA exposure rating:

Data Set	Data	Approximate $X_{0.95}$				ROT Category (1-4)	BDA Category (1-4)
		Median	2x	4x	6x		
A	5, 7, 13, 17, 30, 63	15	30	60	90	3	3
B	6	6	12	24	36	2	2
C	5, 8, 9, 33, 37, 109	21	42	84	126	4	4
D	3, 5, 12, 20	8.5	17	34	51	2	2
E	78	78	156	312	468	4	4
F	1, 3	2	4	8	12	1	1
G	17, 18, 31, 45	24.5	49	98	147	3	3
H	4, 5, 6, 12, 14, 36	9	18	36	54	2	2

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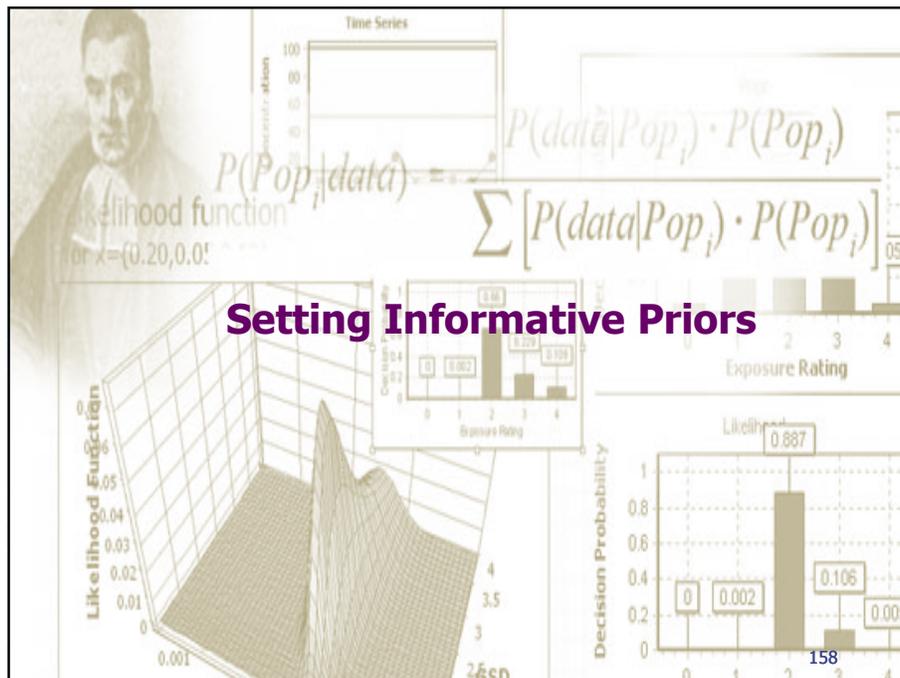
156

## Summary

- ◆ BDA is new tool for IHs.
- ◆ Use it in conjunction with your other tools:
  - goodness-of-fit figures and tests
  - descriptive statistics
  - compliance statistics.
- ◆ Do the BDA results suggest a different interpretation your datasets?
- ◆ Which interpretation is most likely correct? The BDA interpretation or that reached using your existing data analysis tools?

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## IHDA permits three types of Categorical Priors

- ◆ Generic Professional Judgment Prior
- ◆ Custom Professional Judgment Prior
- ◆ Uniform (i.e., flat) Prior

Rating	Probability
0 - Trivial	0.03
1 - Highly-controlled	0.17
2 - Well-controlled	0.60
3 - Controlled	0.17
4 - Poorly-controlled	0.03

Sum = 1.000

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## What is "Professional Judgment"?

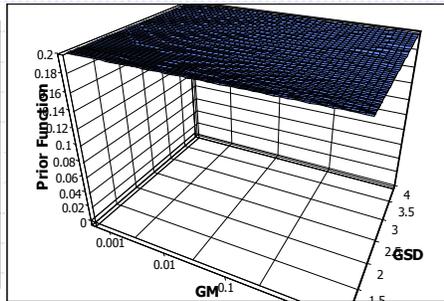
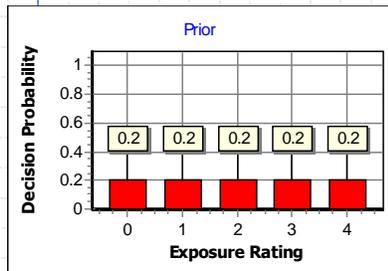
- ◆ In the context of AIHA model, "professional Judgment" represents your opinion regarding the probability that the true exposure profile falls into one of the exposure categories *before exposure data are collected*.
- ◆ The basis for a "professional judgment" can be ...
  - personal "exposure monitoring" experience
  - company, industry or trade organization experience
  - historical or surrogate exposure data
  - exposure modeling predictions
  - ... any combination of these and other sources of information
- ◆ The basis shouldn't be ...
  - a guess (WAG ?)
  - based upon the *current* data

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## Rules for Setting Categorical Priors

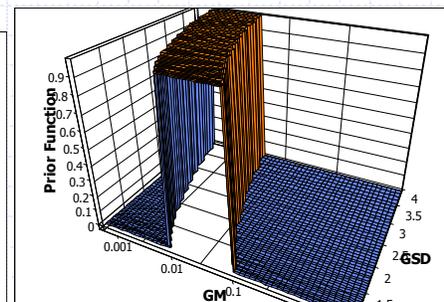
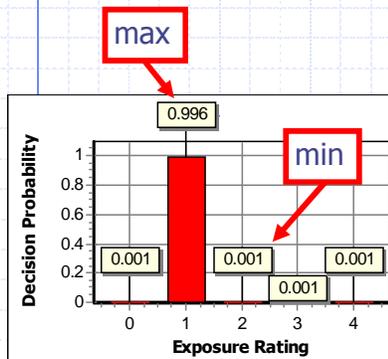
1. The prior is generally set prior to collecting the data.
2. The prior is always set before observing the data.
3. A flat prior is permissible.



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4. Do not assign 0% to any exposure category.
5. Do not assign 100% or near 100% to a category.



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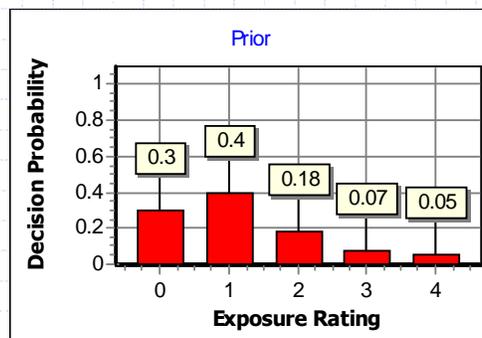
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◆ Notes:

- The maximum and minimum probabilities permitted by IHDA are 0.996 and 0.001.
- This ensures that there no areas within Parameter Space having a zero probability.
- All areas *outside* of Parameter Space do have a zero probability.

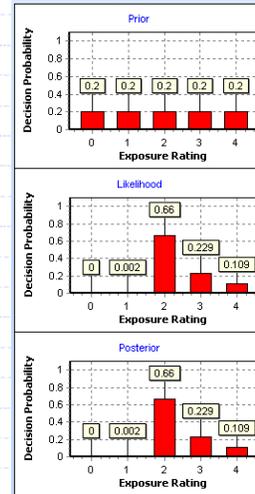
6. The category fractions must sum to 1.

7. Categories distant from the primary category should have progressively less probability.



## Flat or Non-informative Priors

- ◆ Is a flat, non-informative prior conservative?
  - Yes, in the sense that the Posterior Decision Chart will reflect only the Bayesian analysis of the data.
  - Therefore, the Posterior will be identical to the Likelihood Decision Chart.
  - Any decision is based on the data and the Likelihood Decision Chart.



IHDA - 00 manuscript data.xls

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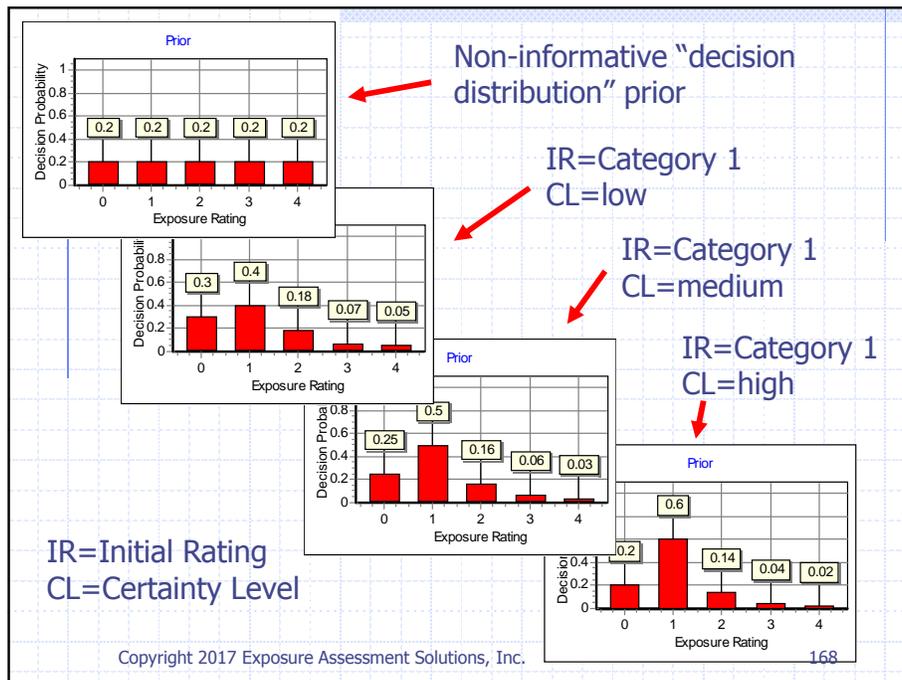
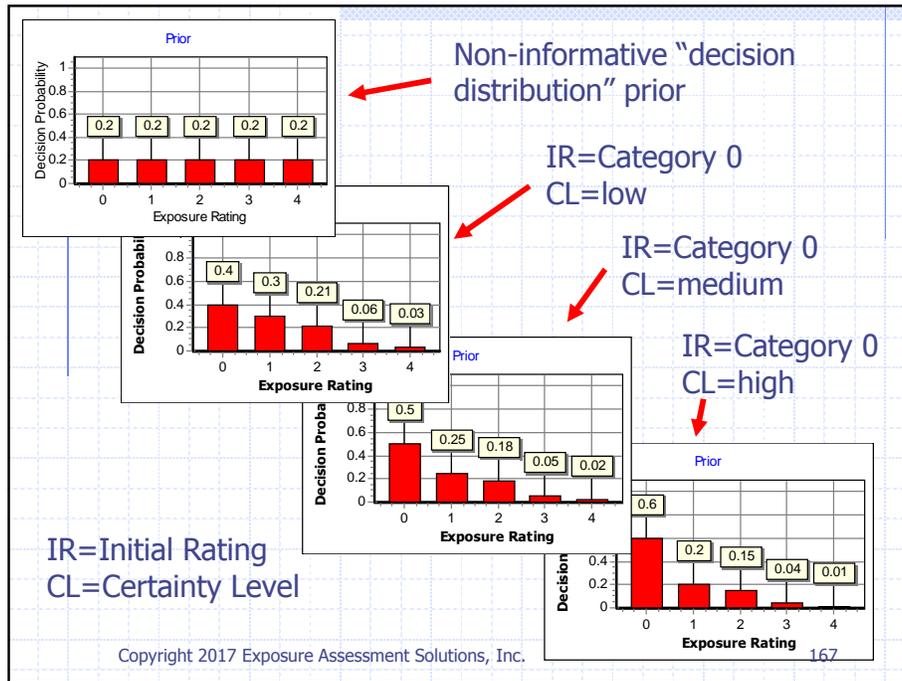
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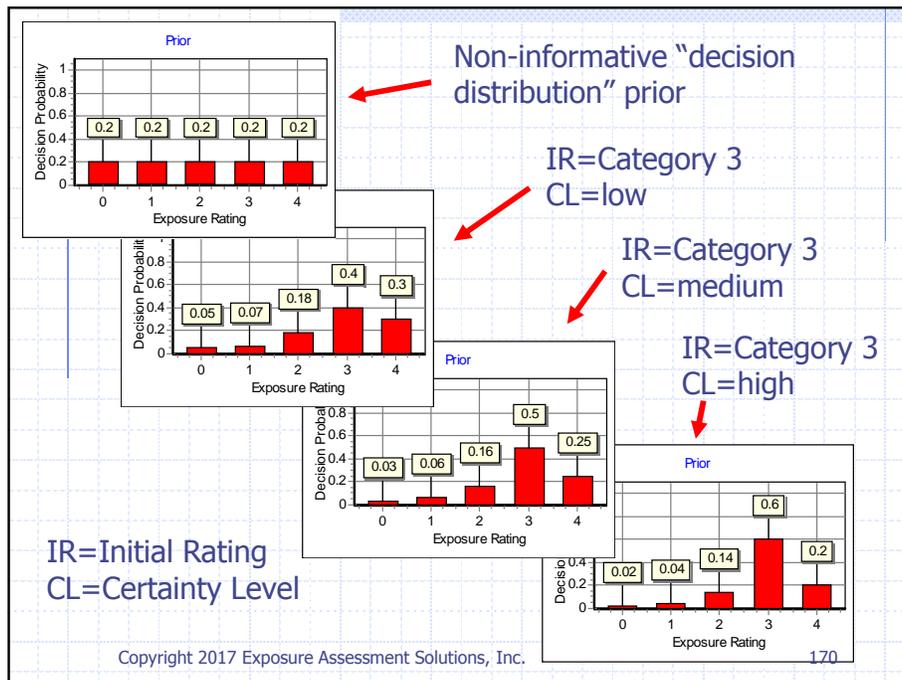
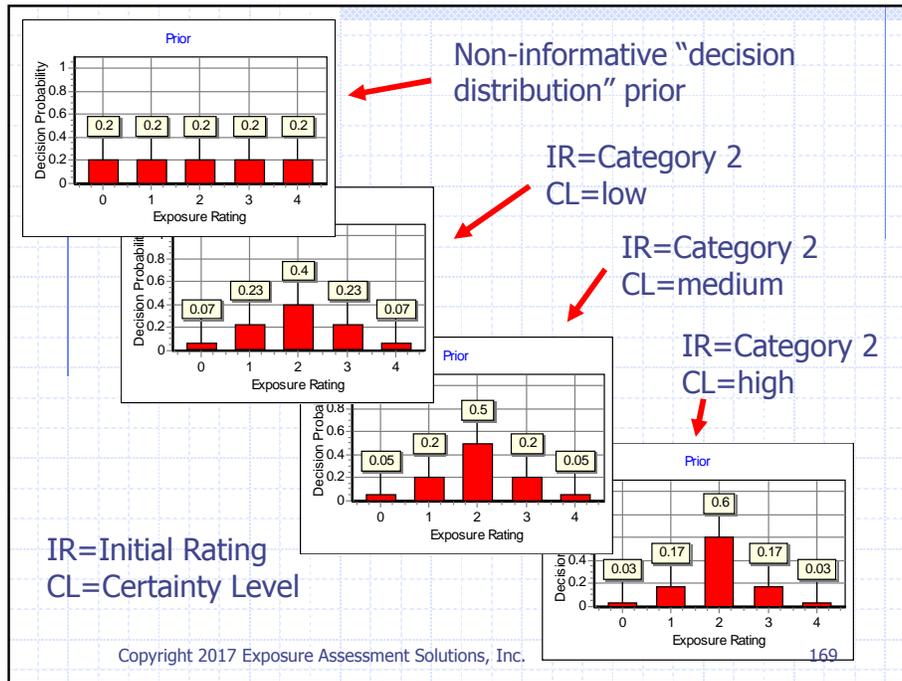
## Generic "Prior Decision Charts"

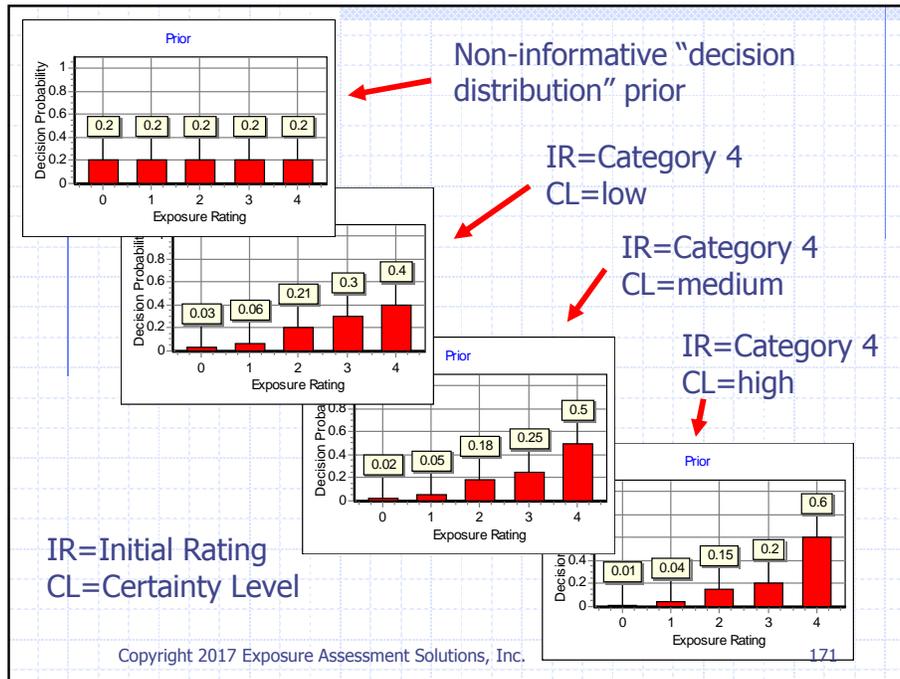
- ◆ Professional Judgment prior
  - When the user picks an **Initial Rating** and **Certainty Level** a *recommended* Prior Decision Chart is shown.
  - *The default category probabilities represent an example or "best guess" as to what a generic prior should look like.*
- ◆ What is the source of the generic Prior Decision Charts built into the IHDA?
  - We devised *reasonable* examples.
  - In other words, we made them up.
  - However, you can devise your own and, using the IHDA, save them as your corporate "generic priors".

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- ◆ In Options/BDA, the IHDA user can modify the category probabilities for any IHDA *built-in* Professional Judgment Prior.
- ◆ First, select the Type of Decision Chart.

Type of Decision Chart

- 0.4 Exposure Control Categories
- 1.5 Exposure Control Categories
- EU Control Bands - Particulates
- EU Control Bands - Vapors
- Noise (percent dose)
- Custom Exposure Control Categories

DEL Interpretation

- 90th Percentile
- 95th Percentile
- 99th Percentile

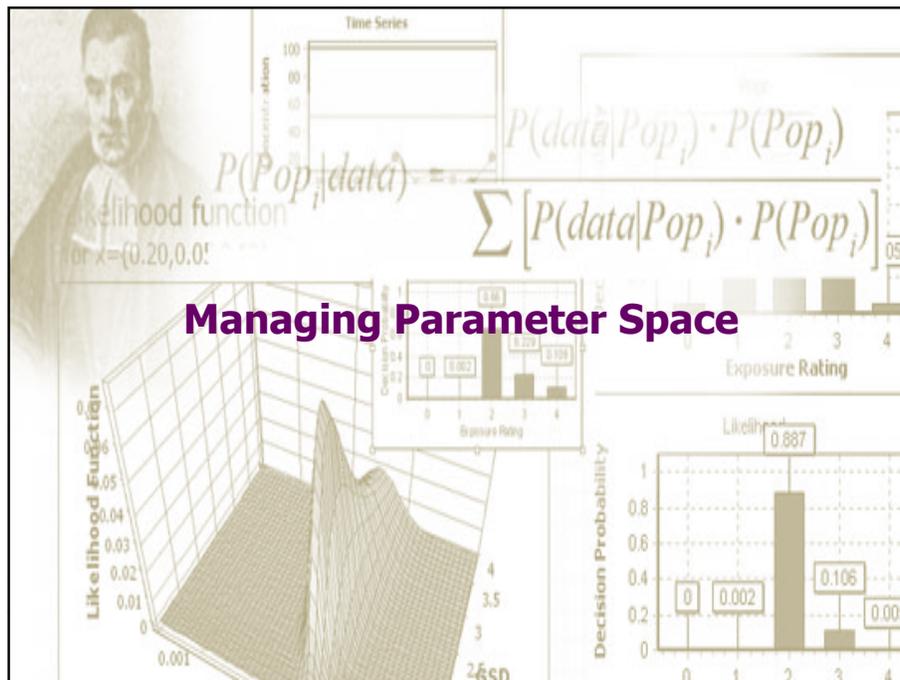
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## Comments

- ◆ The use of Prior Decision Chart permits the user to quantify and use professional judgment in a transparent and reproducible manner.
- ◆ The *prior* could be misused by making the Prior Decision Chart **too** sharp.
- ◆ Try to avoid being overly confident. Avoid putting more than 60% in the primary category.
- ◆ Do not assume that the current conditions – process, equipment, controls, personnel, and work practices – precisely and exactly match the previous conditions.
- ◆ In other words, be judicious in quantifying your professional judgment.

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## BDA Advantage and Disadvantages

### ◆ Traditional statistics:

- The range of possible values for the true GM includes virtually zero and extends to infinity.
- The range of possible values for the true GSD includes one and extends to infinity.
- Such ranges are not only implausible, but impossible.

### ◆ Advantage of BDA:

- The user can define a plausible Parameter Space.

### ◆ Disadvantage of BDA:

- The user has to define a plausible Parameter Space.

### ◆ BDA allows us to restrict the analysis to the range of GMs and GSDs that make sense, ... are plausible. But what ranges are plausible?

### ◆ The boundaries of Parameter Space represent the expected or probable min and max values for the true GM and GSD.

- Defaults:
- GM:  $\sim 0.0002 \times \text{OEL}$  to  $5 \times \text{OEL}$
- GSD: 1.05 to 4

### ◆ The min and max values can be changed for a particular SEG or SET.

## Options/Bayesian Decision Analysis

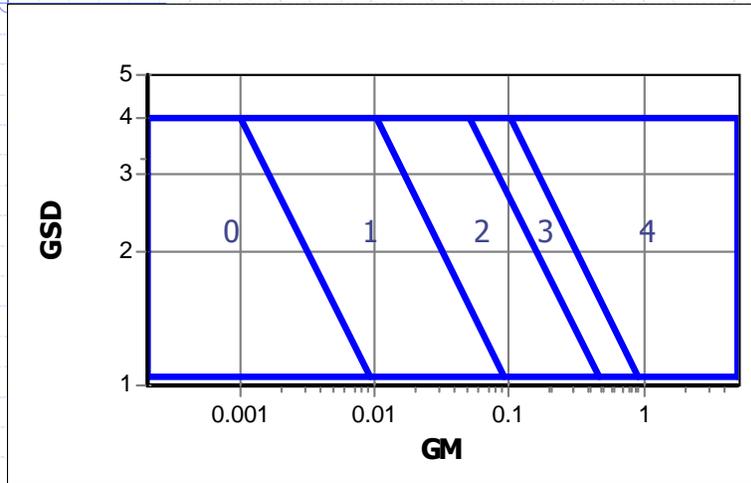
Exposure Category Cutoffs   Parameter Space   Integration

OEL =

Default

GM minimum = <input type="text" value="0.0002044"/>	0.000204476
GM maximum = <input type="text" value="5"/>	5 x OEL
GSD minimum = <input type="text" value="1.05"/>	1.05
GSD maximum = <input type="text" value="4"/>	4

## Default Parameter Space for OEL = 1



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**Criticisms of the BDA Approach**

...malicious censurers, which ever,  
As ravenous fishes, do a vessel follow  
That is new-trimmed...  
Henry VIII

The image contains several charts and mathematical formulas related to the BDA approach. The formulas shown are:

$$P(Pop_i | data) = \frac{P(data | Pop_i) \cdot P(Pop_i)}{\sum [P(data | Pop_i) \cdot P(Pop_i)]}$$

The charts include:

- A "Time Series" plot showing a fluctuating line graph.
- A "Likelihood function" plot showing a 3D surface.
- A "Decision Probability" plot showing a bar chart with values 0, 0.002, 0.887, 0.106, and 0.005.
- An "Exposure Rating" plot showing a bar chart with values 0, 1, 2, 3, and 4.

### ◆ Rock (2013)

- Rock, J.C. (2013): Bayesian Analysis for Industrial Hygiene Applications. American Conference of Governmental Industrial Hygienists.
- Recommended creating a "BDA Region 5" that sits above the BDA Parameter Space. It's purpose is to check for evidence that the true GSD is greater than the default  $GSD_{max}$  of 4.
- My response:
  - ◆ We encourage users to compare the sample GSD against  $GSD_{max}$  and either enlarge Parameter Space or break the dataset into more logical subgroups.

### ◆ Quick et al. (2017)

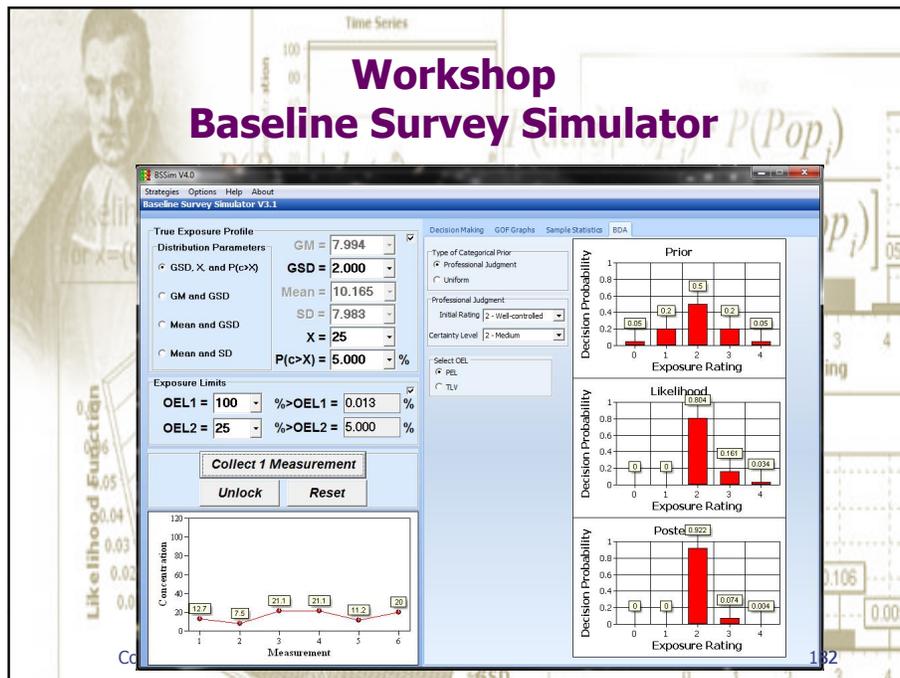
- Quick, H., Huynh, T., and Ramachandran, G. (2017): A Method for Constructing Informative Priors for Bayesian Modeling of Occupational Hygiene Data. *Annals of Work Exposures and Health* 61:67-75.
- Recommended a triangular shaped Parameter Space and the use of traditional Bayesian conjugate priors.
- My response:
  - ◆ Their "version" of BDA requires proficiency in the R programming language and (in my view) requires considerable statistical expertise.
  - ◆ Is the extra complexity worth the effort? Will a different "decision" result?

## Conclusions

- ◆ BDA is an additional tool to help guide “decision making”.
- ◆ Use alongside your traditional IH statistics and goodness-of-fit graphs.
- ◆ BDA was explicitly designed for use with the AIHA exposure control banding scheme.
- ◆ BDA charts improve risk communication.
- ◆ Additional uses for BDA:
  - Analysis of censored datasets (contain non-detects)
  - Respirator Selection

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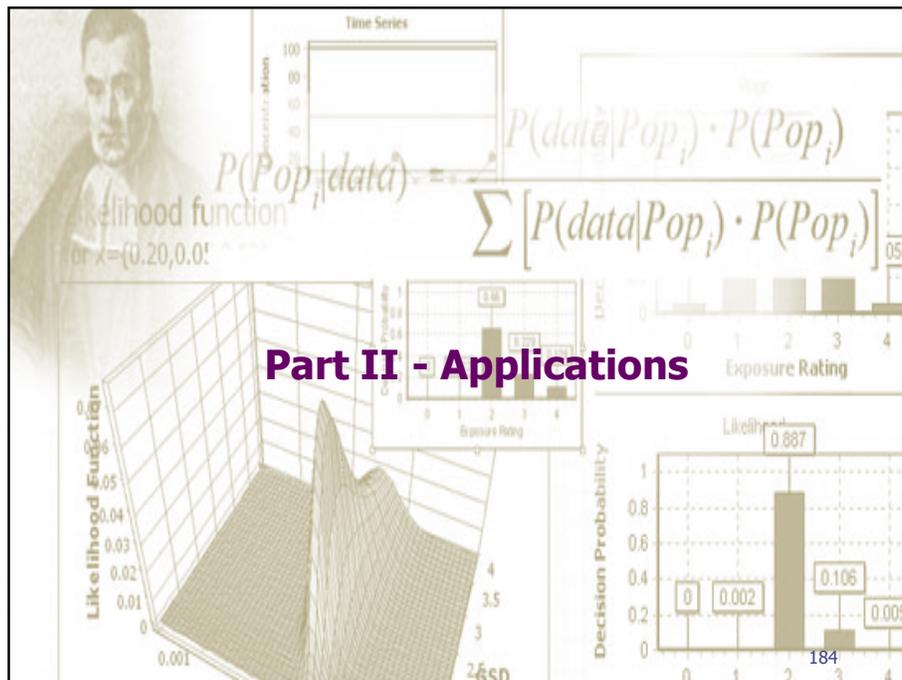
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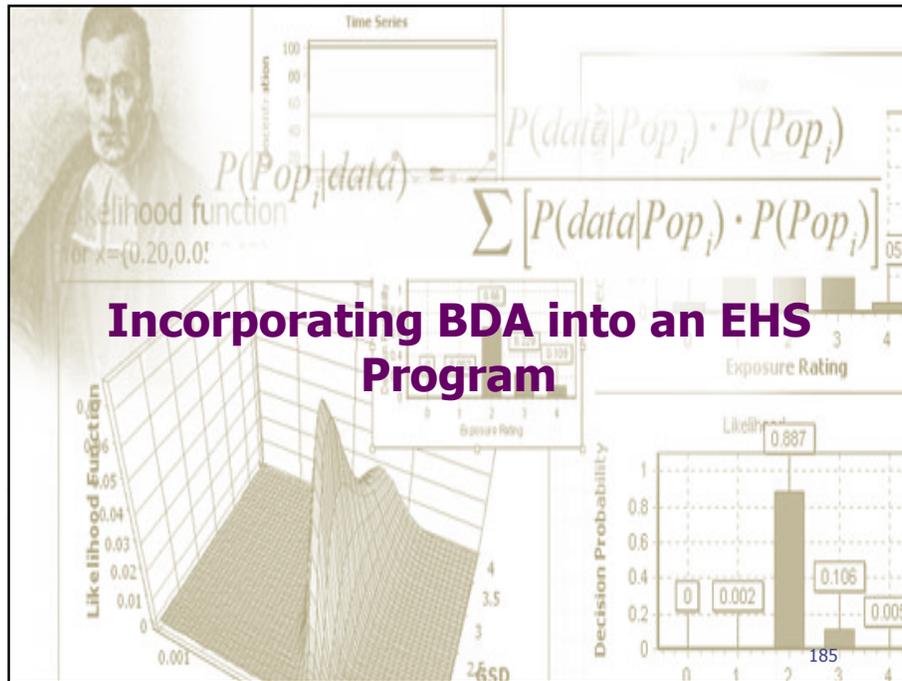
# [ End of Part I ]

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## Part II - Applications



## Incorporating BDA into an EHS Program

AIHA exposure categorization scheme (adapted from AIHA, 1991, 2015). An Exposure Control Category (ECC) can be assigned to a SEG whenever the true 95<sup>th</sup> percentile exposure ( $X_{0.95}$ ) falls within the specified range.

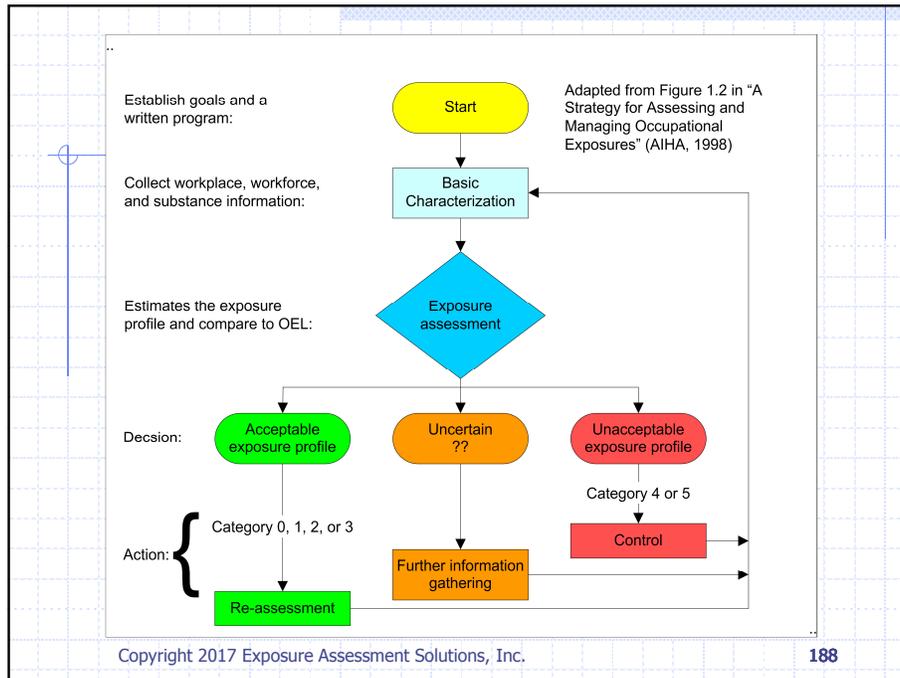
ECC	Rule-of-thumb Description*	Qualitative Description	Statistical Interpretation**	Notes
0	Exposures are <i>de minimis</i> , trivial, or non-existent. Employees have little to no exposure.	Exposures, if they occur, infrequently exceed 1% of the OEL.	$X_{0.95} \leq 0.01 \cdot \text{OEL}$	a, b
1	Exposures are <i>highly-controlled</i> . Employees have minimal exposure.	Exposures infrequently exceed 10% of the OEL.	$0.01 \cdot \text{OEL} < X_{0.95} \leq 0.1 \cdot \text{OEL}$	b
2	Exposures are <i>well-controlled</i> . Employees have frequent contact at low concentrations and rare contact at high concentrations.	Exposures infrequently exceed 50% of the OEL and rarely exceed the OEL.	$0.1 \cdot \text{OEL} < X_{0.95} \leq 0.5 \cdot \text{OEL}$	b, c
3	Exposures are <i>controlled</i> . Employees have frequent contact at low concentrations and infrequent contact at high concentrations.	Exposures infrequently exceed the OEL.	$0.5 \cdot \text{OEL} < X_{0.95} \leq \text{OEL}$	b, c
4	Exposures are <i>inadequately to poorly-controlled</i> . Employees often have contact at high or very high concentrations.	Exposures frequently exceed the OEL.	$X_{0.95} > \text{OEL}$	b, c

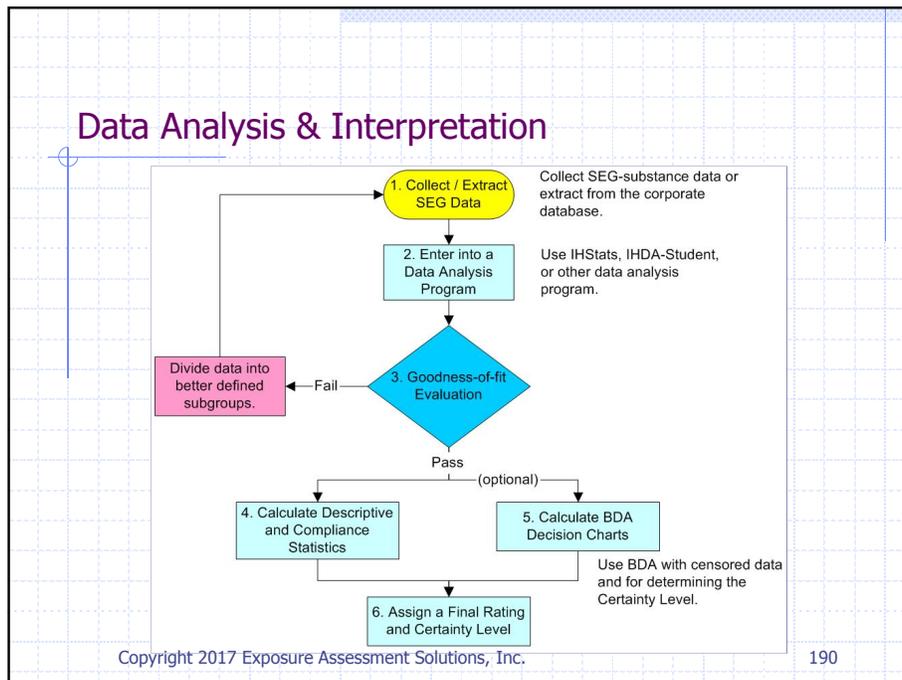
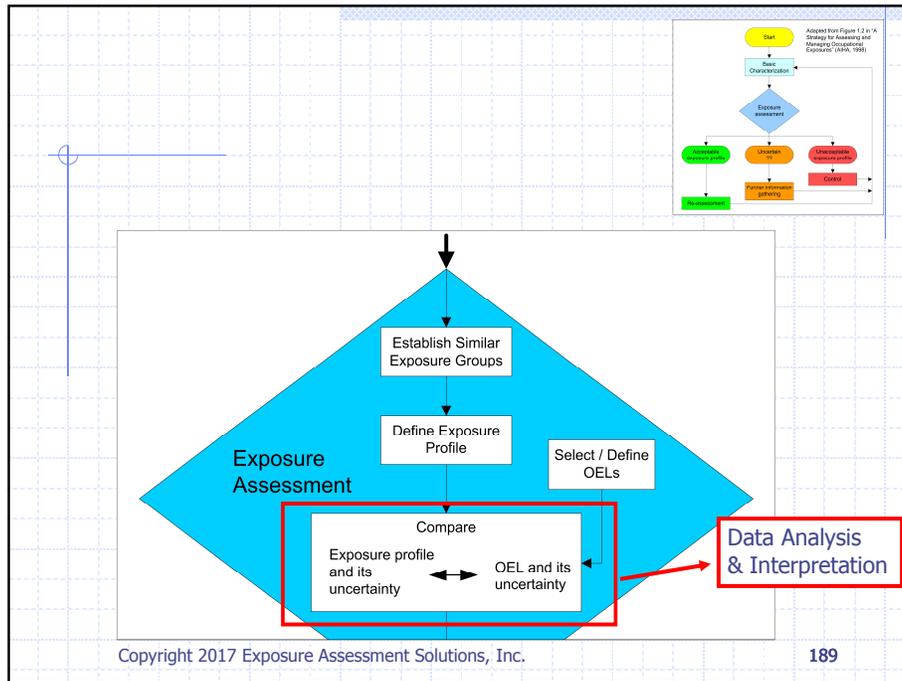
\* The "Rule-of-thumb" descriptions were adapted from AIHA (1991).  
 \*\*  $X_{0.95}$  = the true 95<sup>th</sup> percentile exposure  
 a Category 0 category is used to distinguish between highly-controlled exposures and scenarios where exposures are either nonexistent or trivially low.  
 b "Infrequently" and "rarely" refers to events that occur no more than 5% and 1% of the time, respectively.  
 c "High concentrations" are defined as concentrations that exceed the TWA OEL.

Typical actions or controls that result for each Final Rating, adapted from Figure 23.1 in AIHA (2015).

Final Rating	Action or Control
0	No action
1	Procedures and training, general hazard communication
2	+ Chemical specific hazard communication, periodic exposure monitoring
3	+ Required exposure surveillance, workplace inspections to verify work practice controls, medical surveillance, biological monitoring
4	+ Implement the hierarchy of controls
4+ *	+ Monitoring to validate respirator protection factor selection

\* The 95<sup>th</sup> percentile is several multiples of the OEL (e.g., based on respirators APFs)





## What is the objective of "Data Analysis and Interpretation"?

- ◆ Assign an *accurate* Exposure Control Category (ECC) to each SEG:
  - Category 0
    - ◆ de minimis, extremely low, or virtually non-existent exposures
  - Category 1
    - ◆ Highly Controlled exposures
  - Category 2
    - ◆ Well Controlled exposures
  - Category 3
    - ◆ Controlled exposures (minimally controlled)
  - Category 4
    - ◆ Poorly Controlled exposures (worker protective measures are required)

## AIHA 4<sup>th</sup> Edition

SEG Exposure Control Category**	Applicable Management/ Controls
0 (<1% of OEL)	no action
1 (<10% of OEL)	procedures and training, general hazard communication
2 (10-50% of OEL)	+ chemical specific hazard communication, periodic exposure monitoring.
3 (50-100% of OEL)	+ required exposure monitoring, workplace inspections to verify work practice controls, medical surveillance, biological monitoring.
4+ (>100% of OEL, Multiples of OEL; e.g., based on respirator APFs)	+ implement hierarchy of controls, monitoring to validate respirator protection factor selection.

▶ \*\* - Upper Tail Decision statistic = 90<sup>th</sup>, 95<sup>th</sup>, 99<sup>th</sup> percentile

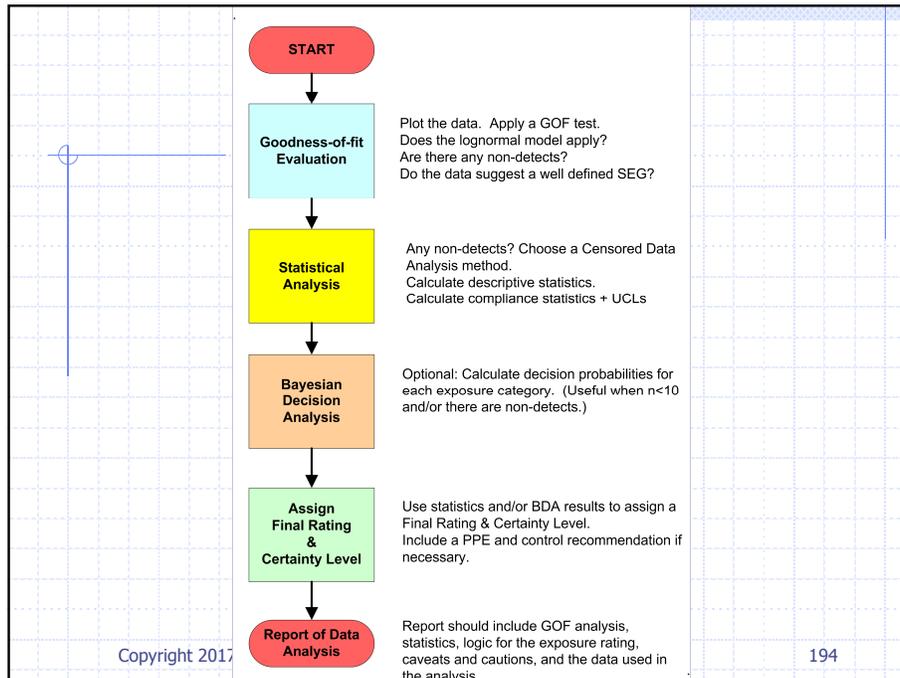
Management of Exposures through programs and training

Implement Hierarchy of Controls

**Figure 23.1** – Applicable Management Actions and Controls for Exposure Categories

## Steps in Data Analysis and Interpretation

1. Collect / Extract Data
2. Enter the Data into the IHDA (or other program)
3. Evaluate the Goodness-of-fit
4. Calculate Descriptive and Compliance Statistics
5. Calculate BDA Decision Charts (optional)
6. Assign a Final Rating and Certainty Level
7. Document the Analysis and Recommendations



## Step 1 – Collect / Extract Data

- ◆ Database → identify the data → Excel .xls file
- ◆ Medgate → Select the SEG or task → Statistical Analysis Query
  
- ◆ Example dataset:  $x = \{0.10, 0.05, 0.20\}$  (OEL=1)

## Step 2 – Enter the Data into the IHDA (or other program)

- ◆ Manually enter or copy/paste → IHDA
- ◆ Excel .xls file → IHDA
  
- ◆ Medgate:
  - → “Lognorm” → basic IH statistics + GOF
  - → “Run Bayesian Analysis” → BDA charts

The screenshot shows the IHDA software interface with the following data and statistics:

**Facility Information:**  
 Facility: AMCE Plant A  
 Department: Widget Manufacturing  
 Building: West Complex, Building 100  
 Process: Fabrication of Part 1  
 Task: Tank Charging

**Substance Information:**  
 Substance: DTM (Dimethyl Death)  
 DEL: 1 ppm  
 Exposure Control Categories: 0.4

**Data Entry Table:**

Sample #	Conc	LOD	Date	Group
1	0.2			
2	0.05			
3	0.1			
4				
5				
6				
7				
8				
9				
10				

**Statistics:**  
 Substance: DTM (Dimethyl Death)  
 DEL: 1 ppm

**Order Statistics:**  
 n = 3  
 min = 0.0500  
 max = 0.2000  
 median = 0.1000

**Descriptive Statistics:**  
 mean = 0.1167  
 sd = 0.0764  
 gs = 0.1000 95%LCL = 0.0311 95%UCL = 0.3217  
 gad = 2.0000 95%LCL = 1.4930 95%UCL = 21.3400

**Compliance Statistics (Lognormal):**  
 XO.95 = 0.3127 95%LCL = 0.1557 95%UCL = 20.1700  
 ExcFrac = 0.0004 95%LCL = <0.001 95%UCL = 0.296

**Compliance Statistics (non-parametric):**  
 XO.95 = NA 95%LCL = NA 95%UCL = NA  
 ExcFrac = 0.000 95%LCL = 0.000 95%UCL = 0.632

**Goodness-of-fit Test:**  
 Fillibens Test:  
 R = 1.000  
 critical B = 0.794  
 Interpretation: the lognormal distribution hypothesis is not rejected.

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## Step 3 – Evaluate the Goodness-of-fit (GOF)

- ◆ The calculation of statistics and BDA decision charts should be preceded by a goodness-of-fit evaluation.
- ◆ Objectives:
  - Verify that a single mode, lognormal model applies to the dataset.
  - For BDA, verify that the true GSD is likely to be within Parameter Space.
- ◆ The assumption behind both lognormal statistics and BDA is that the underlying exposure profile is reasonably well described by a lognormal distributional model.
- ◆ A GOF evaluation requires 3 or more detects.

$x = \{0.10, 0.05, 0.20\}$  (OEL=1)

- ◆ There are three steps to a GOF analysis
  - 1. Trend analysis
  - 2. Subjective GOF analysis
    - ◆ look at the log-probability graph
  - 3. Objective GOF analysis
    - ◆ a formal GOF statistical test

Statistics GOF Graphs BDA Charts PPE Charts CDA

---

Goodness-of-fit Test

---

Filibens Test:  
 $R = 1.000$   
 critical  $R = 0.794$   
 Interpretation: the lognormal distribution hypothesis is not rejected.

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### Comments

- ◆ Rarely are sufficient data available for a formal trend analysis.
- ◆ If the exposures are “trending” upwards the current sample 95<sup>th</sup> percentile will tend to underestimate a future 95<sup>th</sup> percentile.
- ◆ Professional judgment is required whenever  $n < 3$  or many of the measurement are non-detects.
- ◆ GOF test failure
  - Dataset may represent a mixture of SEGs, different tasks, different work practices &/or use of controls.
  - Divide the data into better defined subgroups and analyze separately.

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## Step 4 – Calculate Descriptive and Compliance Statistics

- ◆ Calculate ...
  - Order Statistics
  - Descriptive Statistics
  - Compliance Statistics
- ◆ Compare...
  - the "decision statistic" (e.g., sample 95<sup>th</sup> percentile) to the OEL.
  - the 95%UCL to the OEL.
- ◆ Objective:
  - Assign the most appropriate Exposure Rating (ER).
  - Determine the Certainly Level (CL) for the Exposure Rating.
- ◆ Issues:
  - How variable are the data?
    - ◆ Look at the GSD

$x = \{0.10, 0.05, 0.20\}$  (OEL=1)

```

-----
Order Statistics
-----
n =          3
min =       0.0500
max =       0.2000
median =    0.1000
-----
Descriptive Statistics
-----
mean =       0.1167
sd =        0.0764
gm =        0.1000  95%LCL = 0.0311      95%UCL = 0.3217
gsd =       2.0000  95%LCL = 1.4930      95%UCL = 21.3400
-----
Compliance Statistics (lognormal)
-----
X0.95 =     0.3127  95%LCL = 0.1557      95%UCL = 20.1700
ExcFrac =   0.0004  95%LCL = <0.001      95%UCL = 0.295
  
```

## Comments

### ◆ Always look at the sample GSD:

AIHA 4<sup>th</sup> Edition

	Exposure Profile Variability	GSD
SEG or group	Low	$GSD \leq 2.0$
	Medium (moderate)	$2.0 < GSD \leq 3.5$
	High	$GSD > 3.5$
Individual worker	Low	$GSD \leq 1.5$
	Medium (moderate)	$1.5 < GSD \leq 3.0$
	High	$GSD > 3.0$

A high GSD may indicate a poorly specified SEG or a mixture different tasks.

## Comments

- ◆ A Censored Data Analysis method *must* be selected whenever the dataset contains non-detects. Statistics and confidence limits tend to be less reliable when a dataset is censored.
- ◆ Parametric statistics (normal and lognormal) cannot be calculated for some severely and all completely censored datasets.
- ◆ Severely datasets and 100% censored datasets should be analyzed using BDA.

## Step 5 – Calculate BDA Decision Charts (optional)

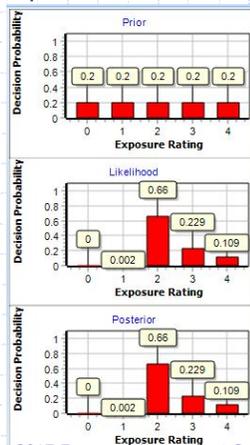
- ◆ An exposure rating can often be assigned using the standard statistics, but BDA may be needed to determine the certainty level of the decision, as well as the certainty levels of the other possible decisions (i.e., the other exposure categories).
- ◆ BDA was designed for the AIHA Exposure Control Category (ECC) method.
- ◆ Objective:
  - Assign the most appropriate Exposure Rating (ER).
  - Determine the Certainty Level (CL) for the Exposure Rating.
- ◆ If a non-informative, flat prior is used, the ER and CL are determined using the Likelihood Decision Chart.
- ◆ If an informative prior is used, the *user* must decide to base the ER and CL on either the Likelihood Decision Chart or the Posterior Decision Chart.

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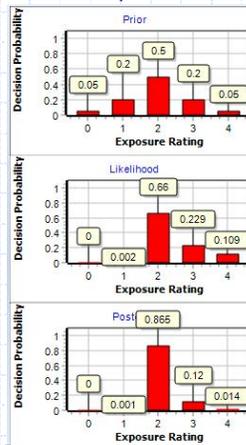
205

Example:  $x=\{0.10, 0.05, 0.20\}$  (OEL=1)

flat prior



informative prior



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## Comments

### ◆ CAUTION:

- BDA is not a substitute for a standard statistical analysis.
- Whenever possible, calculate the GM and GSD, and from these the sample 95th percentile (and its 95%UCL).
- BDA is used whenever it is not clear from the sample 95th percentile (and its UCL) which exposure category should be selected.
- BDA is particularly useful when the sample size  $n$  is small (e.g.,  $<5$ ), but can be applied to medium size (6-10) and large datasets ( $>10$ ).

- ◆ BDA can be applied to severely or completely censored datasets.

## Step 6 – Assign a Final Rating and Certainty Level

### ◆ Using IH Statistics

- Final Rating:
  - ◆ Compare the sample 95<sup>th</sup> percentile to the Exposure Control Categories and select a category.
- Certainty Level:
  - ◆ Compare the 95%UCL to the ECCs:
    - Low certainty if  $\geq 2$  categories above the chosen ECC
    - Medium certainty if only 1 category above
    - High certainty if within chosen category
- Example:
  - ◆  $x = \{0.10, 0.05, 0.20\}$  (OEL=1)
  - ◆ Sample GSD = 2
  - ◆ Sample 95<sup>th</sup> percentile = 0.31 (95%UCL=20)
  - ◆ Final Rating = Category 2, Low Certainty

Hewett's  
ROT



## Comments

- ◆ When  $n$  is small the 95%UCL for the sample 95<sup>th</sup> percentile is often large (usually extending into Category 4), making it difficult to determine the Certainty Level for exposure ratings of 3 and below.
- ◆ A Censored Data Analysis method *must* be selected whenever the dataset contains non-detects. The resulting statistics and confidence limits are less reliable.

## ◆ Using BDA Charts:

- Final Rating
  - ◆ ECC = category with highest bar
- Certainty Level \*
  - ◆ Low Certainty - category probability < 0.5
  - ◆ Medium Certainty - category probability between 0.5 and 0.75
  - ◆ High Certainty - category probability greater than 0.75.
- Example:  $x = \{0.10, 0.05, 0.20\}$  (OEL=1)
  - ◆ Final Rating:
    - Non-informative (flat) prior – Category 2, Medium Certainty
    - Informative Prior – Category 2, High Certainty

\*It is permissible to combine adjacent categories, and sum their decision probabilities, to create a composite rating: e.g., Category 1-2, High Certainty, or Category 3-4, High Certainty.

◆ If  $ECC \leq 3$ , check Category 4:

- < 0.1 - acceptable
  - 0.1-0.25 - acceptable, provided the SEG has a surveillance plan
  - > 0.25 but < 0.5 - problematic, particularly if the SEG has no surveillance plan.
- 
- As a rule-of-thumb, Category 4 decision probabilities up to 0.25 are tolerable, provided the SEG is regularly checked as part of an ongoing surveillance strategy. On the other hand, appreciable Category 4 decision probabilities indicate that the true 95th percentile may exceed the OEL and therefore should be a cause for concern whenever the SEG is unlikely to be reevaluated for an extended period.

## Comments

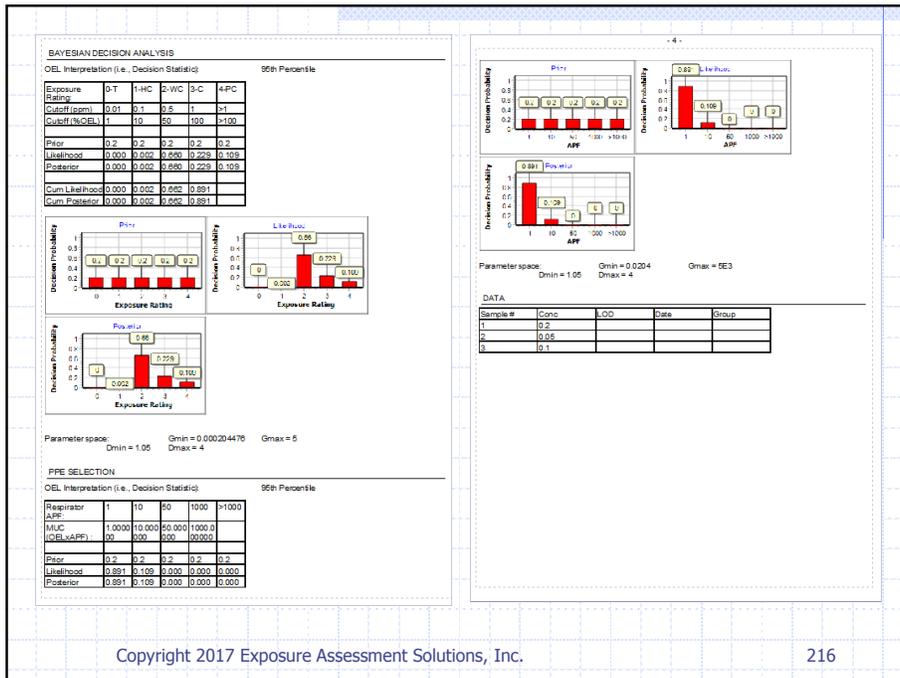
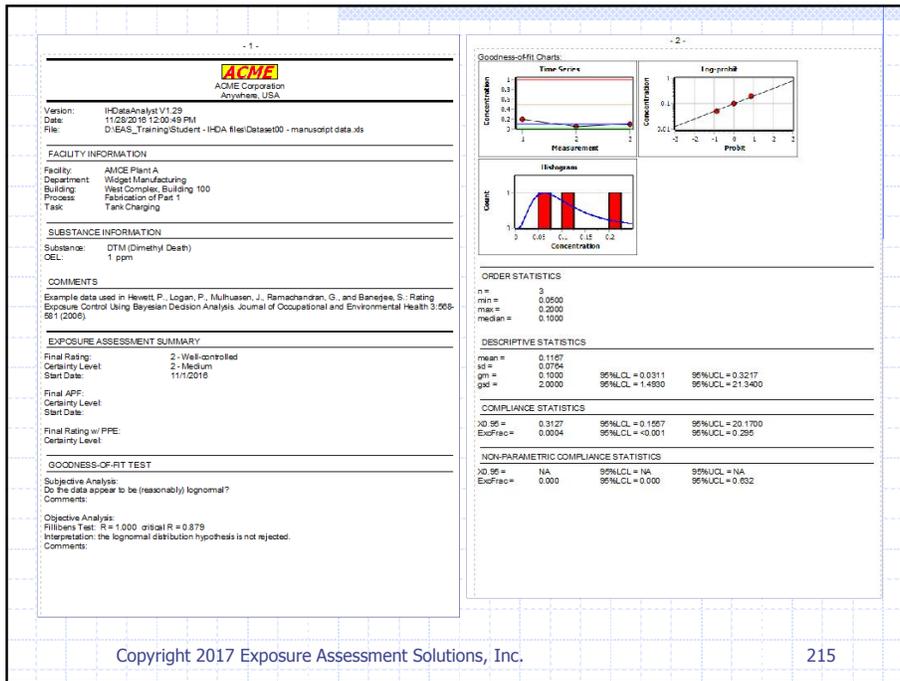
- ◆ Final Rating and Certainty Level – flat prior
  - The Likelihood decision chart is always used whenever a flat prior is specified.
- ◆ Final Rating and Certainty Level – informative prior
  - The Posterior chart can be used when the Prior and the Likelihood charts are in general agreement regarding the most likely exposure rating *and* you have confidence in the prior.
  - Otherwise, use the Likelihood decision chart (which reflects only the current data).
  
- ◆ Many companies are more comfortable using flat priors.

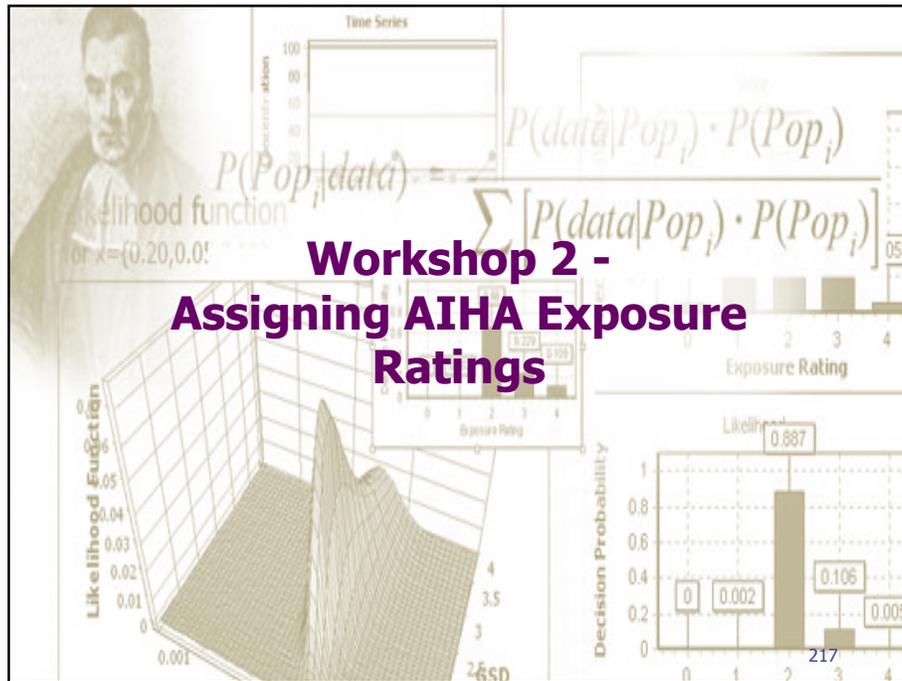
## Comments

- ◆ A small n dataset does not lead to a “data driven” decision.
- ◆ Use of BDA will not lead to a “data driven” decision.
- ◆ BDA simply provides additional information that is relevant for IH decision making: i.e., selection an exposure category.
- ◆ Uncertainty in any decision can be reduced by collecting additional measurements.

## Step 7 – Document the Analysis and Recommendations

- ◆ Any data analysis that leads to a Final Rating and Certainty Level should be documented.
- ◆ The IHDA program has a report feature that captures all of the statistics, GOF graphs, BDA analysis and decision charts, as well as the data.





## Types of Exposure Assessment Surveys

### ◆ Baseline

- The exposure potential for a SEG is unknown or known with low certainty: e.g., the process is similar, but not identical, to processes previously evaluated or the SEG that has changed significantly since the previous survey.
- The goal is "to collect sufficient exposure measurements to accurately characterize and judge the exposure profile of an exposure group". (Hewett, 2007)

### ◆ Surveillance

- A surveillance strategy is intended for SEGs that have already been evaluated and the AIHA Exposure Category has been validated using quantitative data.
- Periodically collect sufficient measurements so that trends are identified in timely manner and the initial exposure rating of the exposure group can be verified.

### ◆ Termination / Reduction

- Exposure controls (and/or work practices) have been improved to the point that policies or services to the employees - such as required PPE, exposure surveillance, medical surveillance, or enrollment in a hearing conservation program - could be reduced or terminated, and the company needs to be highly confident that the decision to do so is correct.
  
- ◆ BDA can be used to assist in the interpretation of quantitative data collected for any of these surveys, particularly when n is small (e.g., < 10).

## Examples

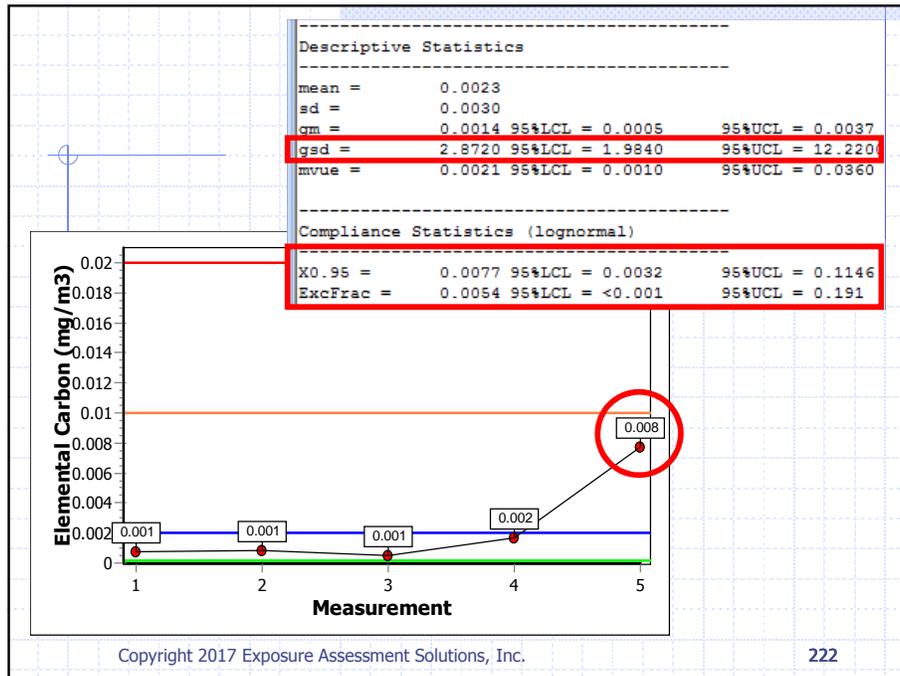
- ◆ Baseline Exposure Assessment
- ◆ SEG rated Category 1
- ◆ SEG rated Category 2
- ◆ SEG rated Category 3
- ◆ SEG rated Category 4
- ◆ SEG previously rated Category 4, but with new LEV

## Baseline Exposure Assessment

- ◆ Diesel emissions – measured as “elemental carbon” – were evaluated in a rail yard.
  - IHDA - Diesel emissions - NIOSH HHE - rail yard.xls
- ◆ Data:
  - $X = \{0.00077, 0.00085, 0.00054, 0.0017, 0.0077\}$  mg/m<sup>3</sup>
- ◆ OEL = California guideline of 0.020 mg/m<sup>3</sup>
- ◆ Statistics:
  - Suggest a Category 2 rating, but UCL is in Category 4
- ◆ BDA
  - Final Rating = Category 2, Medium Certainty

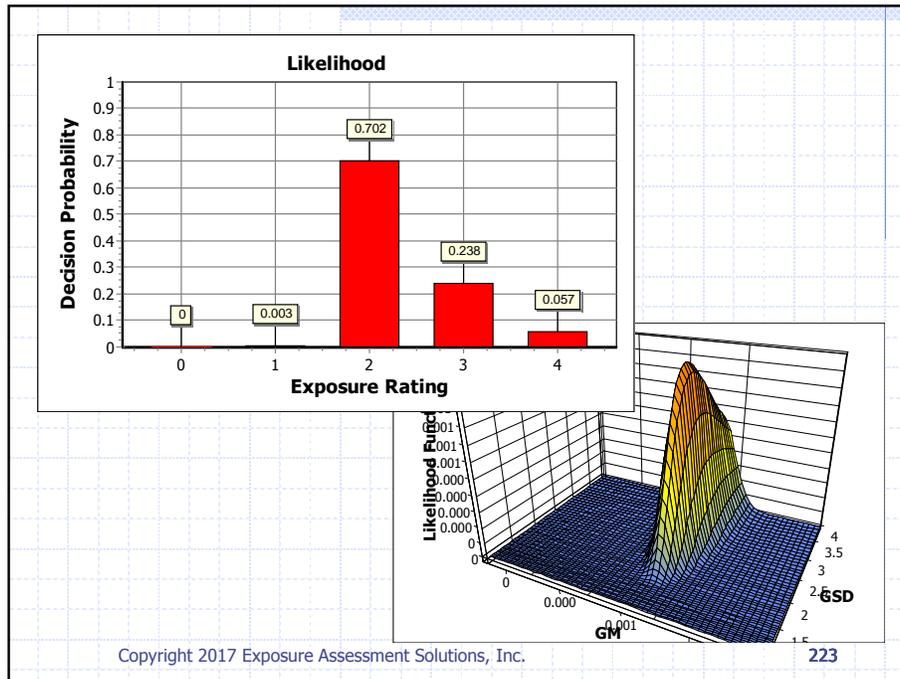
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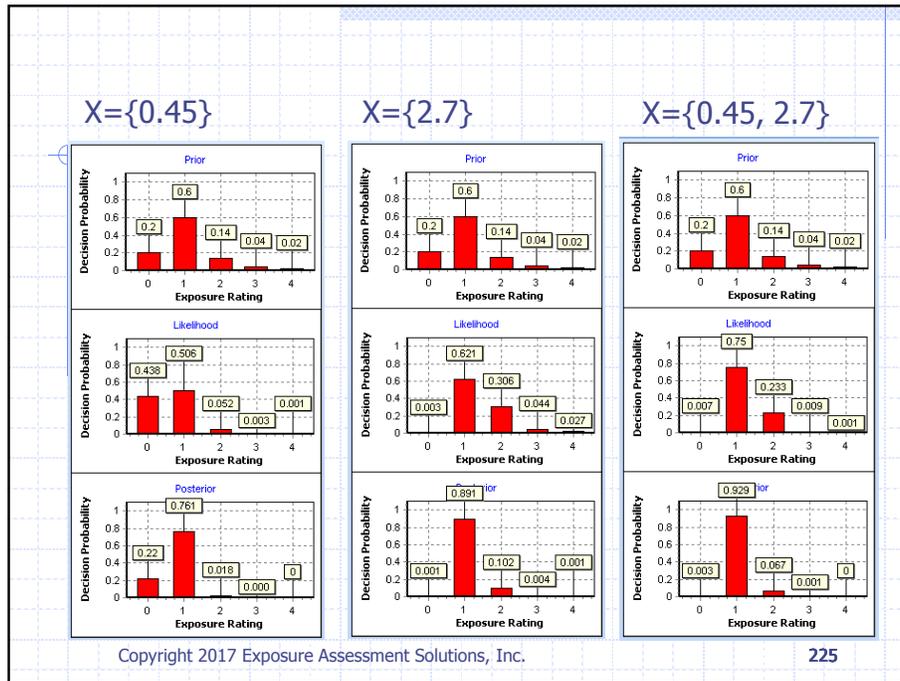
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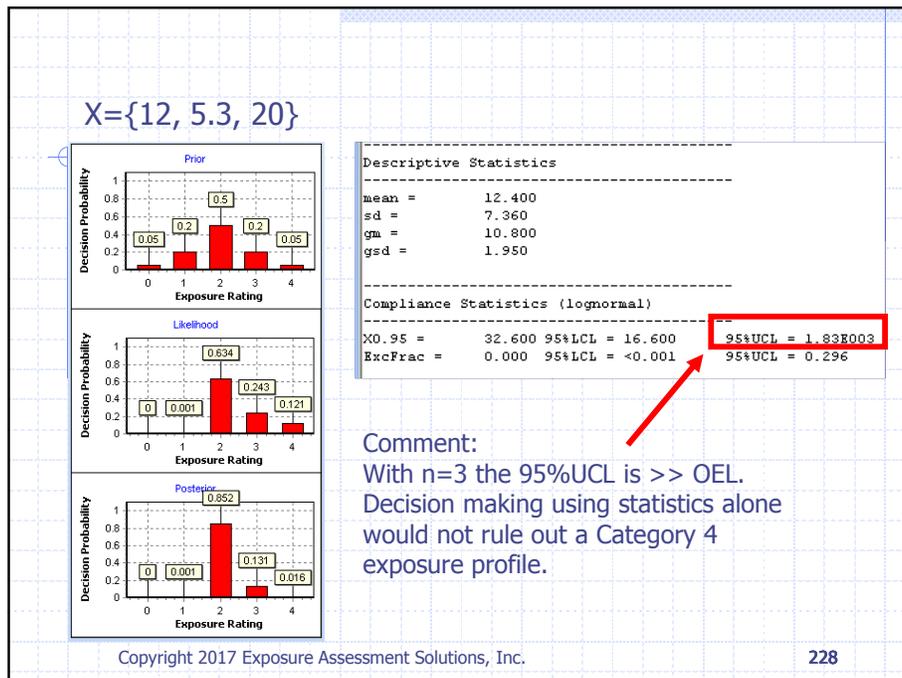
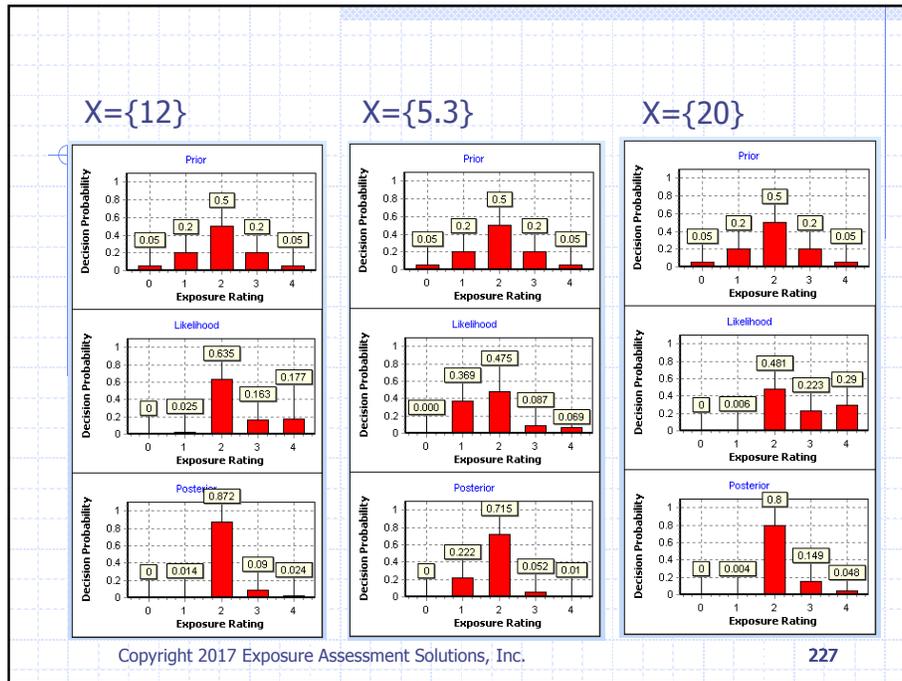
## SEG rated Category 1 (OEL = 100 ppm)

- ◆ The previous sampling cycle (i.e., the previous year) an SEG was rated Category 1, High Certainty.
- ◆ For a Category 1 SEG, one to two measurements are collected at random intervals during the year.
- ◆  $X_1 = 0.45$
- ◆  $X_2 = 2.7$
- ◆ Final Rating = Category 1, High Certainty



## SEG rated Category 2 (OEL = 100 ppm)

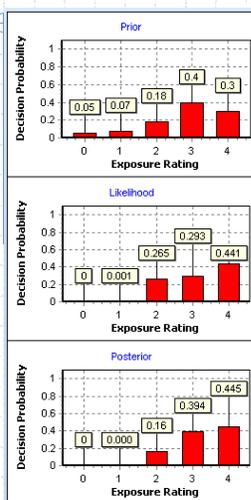
- ◆ The previous sampling cycle (i.e., the previous year) an SEG was rated Category 2, Medium Certainty.
- ◆ For a Category 2 two to three measurements are collected at random intervals during the year.
- ◆  $X_1 = 12$
- ◆  $X_2 = 5.3$
- ◆  $X_3 = 20$
  
- ◆ Final Rating = Category 2, High Certainty



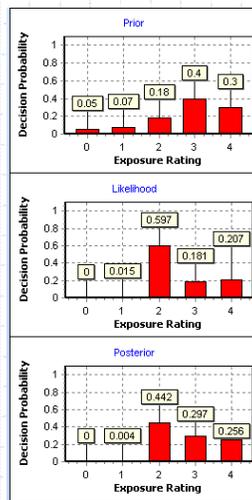
## SEG rated Category 3 (OEL = 100 ppm)

- ◆ The previous sampling cycle (i.e., the previous year) an SEG was rated Category 3, Low Certainty.
- ◆ For a Category 3 three to six measurements are collected at random intervals during the year.
- ◆  $X_1 = 33$                        $X_2 = 14$
- ◆  $X_3 = 25$                        $X_4 = 66$
  
- ◆ Final Rating = Category 3, Low Certainty

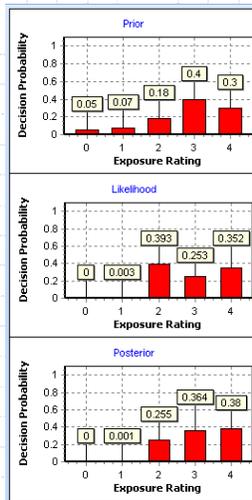
$X = \{33\}$



$X = \{14\}$

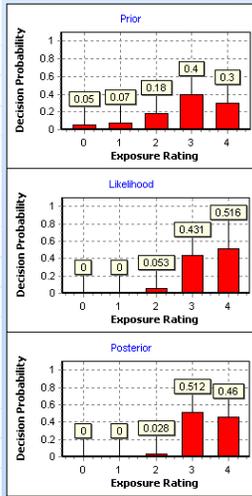
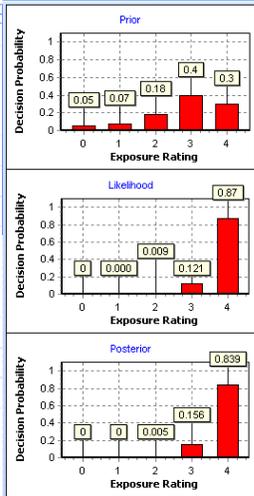


$X = \{25\}$



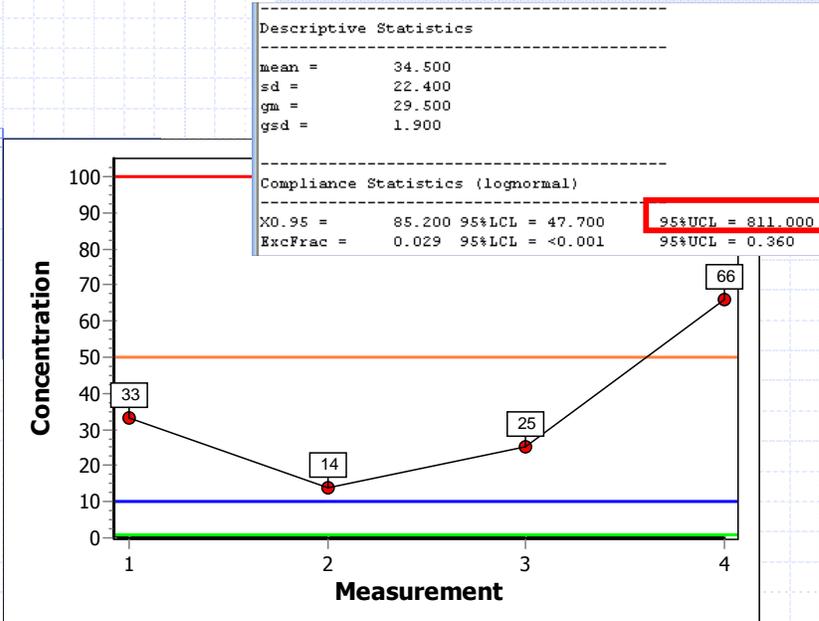
$X=\{66\}$

$X=\{33, 14, 25, 66\}$



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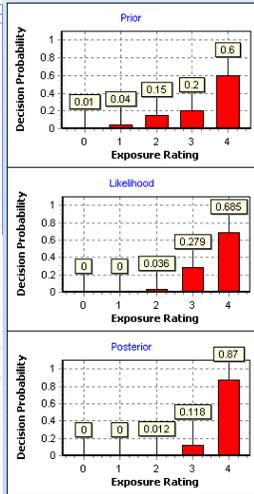
◆ Comments:

- Category 3 is the transitional exposure category: neither clearly acceptable nor clearly unacceptable.
- Category 3 exposure profiles can be difficult to rate with High Certainty.
- Generally, large sample sizes and/or low sample GSD's are required for a Final Rating of "Category 3, High Certainty".

**SEG rated Category 4  
(OEL = 100 ppm)**

- ◆ The previous sampling cycle (i.e., the previous year) an SEG was rated Category 4, High Certainty.
- ◆ For a Category 4 three measurements are collected at random intervals during the year.
  - ◆  $X_1 = 87$
  - ◆  $X_2 = 14$
  - ◆  $X_3 = 23$
- ◆ Final Rating = Category 4, High Certainty  
(The SEG has not changed. Even if the data are low – e.g., < OEL - the Exposure Rating remains Category 4.)

$X = \{87, 14, 23\}$



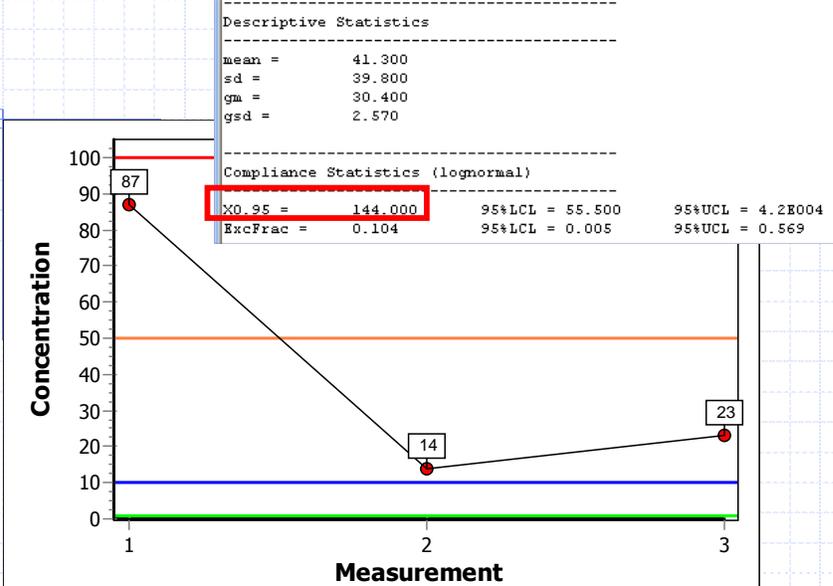
Comments:

Analysis of *each* measurement is not necessary, unless it is unexpectedly high.

Measurements are collected to validate the choice of PPE and to determine if the exposure profile is moving upwards.

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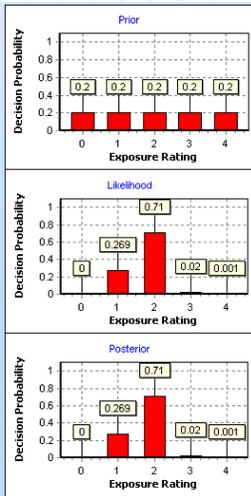
◆ Comments:

- A true Category 4 exposure profile is will often produce measurements less than the OEL ... measurements that can mislead the unwary.
- Lowering the exposure rating should be considered ...
  - ◆ only when the SEG has changed – presumably for the better: new or improved LEV, improved work practices, etc.
  - ◆ ...not because several measurements in a row happen to be less than the OEL.
- Given a true GSD=2 and true 95<sup>th</sup> percentile=2xOEL, we would still expect approximately 75% of the measurements to be less than the OEL.

**SEG previously rated Category 4  
(OEL = 100 ppm)**

- ◆ The previous sampling cycle (i.e., the previous year) an SEG was rated Category 4, High Certainty.
- ◆ LEV was recently installed
- ◆ For a Termination / Reduction strategy six measurements are collected.
  - ◆  $X_1 = 6.3$                        $X_2 = 1.4$
  - ◆  $X_3 = 7.1$                        $X_4 = 1.7$
  - ◆  $X_5 = 6.2$                        $X_6 = 3.2$
- ◆ Final Rating = Category 2, High Certainty

$X = \{6.3, 1.4, 7.1, 1.7, 6.2, 3.2\}$



Descriptive Statistics			
mean =	4.320		
sd =	2.520		
gm =	3.580		
gsd =	2.040		
Compliance Statistics (lognormal)			
X0.95 =	11.600	95%LCL = 6.680	95%UCL = 50.300
ExcFrac =	0.000	95%LCL = <0.001	95%UCL = 0.016

**Comments:**  
 A flat prior was used.  
 Both the statistics and a BDA evaluation point towards an Exposure Rating of Category 2, High Certainty.

**BDA and rPPE Selection**

$P(Pop_i | data) = \frac{P(data | Pop_i) \cdot P(Pop_i)}{\sum [P(data | Pop_i) \cdot P(Pop_i)]}$

Time Series

Likelihood function for  $x = (0.20, 0.0)$

Decision Probability

Exposure Rating

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## Selection of Respiratory PPE

- ◆ OSHA provides little guidance on selecting the target APF:
  - 1910.134(d)(1)(i) The employer shall select and provide an appropriate respirator based on the respiratory hazard(s) to which the worker is exposed and workplace and user factors that affect respirator performance and reliability.
  - 1910.134(d)(1)(ii) The employer shall select a NIOSH-certified respirator. The respirator shall be used in compliance with the conditions of its certification.
  - 1910.134(d)(1)(iii) The employer shall identify and evaluate the respiratory hazard(s) in the workplace; this evaluation shall include a reasonable estimate of employee exposures to respiratory hazard(s) and an identification of the contaminant's chemical state and physical form. Where the employer cannot identify or reasonably estimate the employee exposure, the employer shall consider the atmosphere to be IDLH.
  - 1910.134(d)(1)(iv) The employer shall select respirators from a sufficient number of respirator models and sizes so that the respirator is acceptable to, and correctly fits, the user.

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OSHA Assigned Protection Factors <sup>5</sup>

Type of Respirator	Quarter mask	Half mask	Full facepiece	Helmet / hood	Loose-fitting facepiece
1. Air Purifying Respirator (APR) <sup>1,2</sup>	5	10 <sup>3</sup>	50	-----	-----
2. Powered Air Purifying Respirator (PAPR)	-----	50	1000	25 / 1000 <sup>4</sup>	25
3. Supplied Air Respirator (SAR) or Airline Respirator					
• Demand mode	-----	10	50	-----	-----
• Continuous flow mode	-----	50	1000	25 / 1000 <sup>4</sup>	25
• Pressure demand or other positive pressure mode	-----	50	1000	-----	-----
4. Self-Contained Breathing Apparatus (SCBA)					
• Demand mode	-----	10	50	50	-----
• Pressure-demand or other positive pressure mode	-----	-----	10,000	10,000	-----

<sup>1</sup> Employers may select respirators assigned for use in higher workplace concentrations of a hazardous substance for use at lower concentrations of that substance, or when required respirator use is independent of concentration.

<sup>2</sup> The assigned protection factors are only effective when the employer implements a continuing, effective respirator program as required by 29 CFR 1910.134, including training, fit testing, maintenance, and use requirements.

<sup>3</sup> This APF category includes filtering facepieces, and half masks with elastomeric facepieces.

<sup>4</sup> The employer must have evidence provided by the respirator manufacturer that testing of these respirators demonstrates performance at a level of protection of 1000 or greater to receive an APF of 1000. This level of performance can best be demonstrated by performing a WPF or SWPF study or equivalent testing. Absent such testing, all other PAPRs and SARs with helmets/hoods are to be treated as loose-fitting facepiece respirators, and receive an APF of 25.

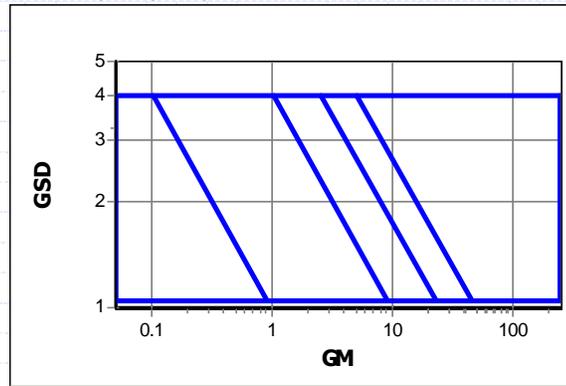
<sup>5</sup> These APFs do not apply to respirators used solely for escape. For escape respirators used in association with specific substances covered by 29 CFR 1910 subpart Z, employers must refer to the appropriate substance-specific standards in that subpart. Escape respirators for other IDLH atmospheres are specified by 29 CFR 1910.134 (d)(2)(ii).

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## Parameter Space and APFs

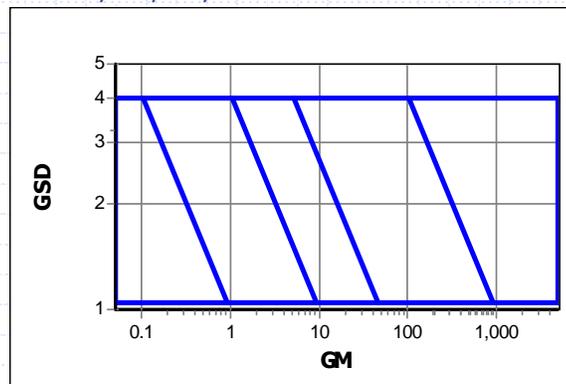
- ◆ OEL = 1
- ◆ APFs set at 1, 10, 25, and 50



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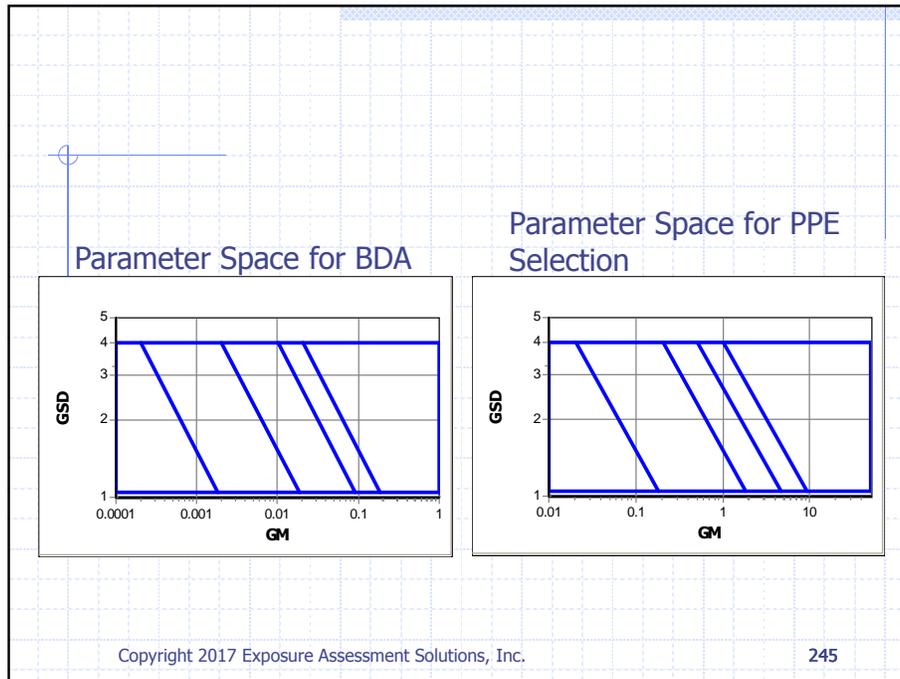
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- ◆ OEL = 1
- ◆ APFs set at 1, 10, 50, and 1000



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## Comments

- ◆ The category cutpoints or boundaries correspond to respirator Assigned Protection Factors.
- ◆ Selection of the *target* APF is an initial step.
- ◆ Fit testing and an ongoing, effective respiratory PPE program helps ensure that the “Effective Protection Factor” (EPF) exceeds (or at least equals) the *target* APF for each employee.

Note: The EPF is the protection factor actually reached by an employee, taking into account both fit and actual usage (and non-usage).

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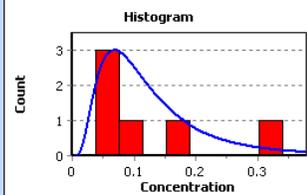
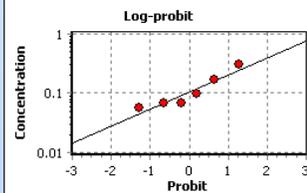
## Effective Exposure Category

- ◆ What is the *effective* Exposure Category if the "Effective Protection Factor" equals the *target* APF for each employee?
- ◆ The *effective* Exposure Category can be estimated:
  - Reduce the dataset exposures by the target APF
  - Redo the Bayesian analysis.

## Example

- ◆ IHDA - Manganese Fumes - Dept C.xls
- ◆ OEL = 0.2  $\mu\text{g}/\text{m}^3$

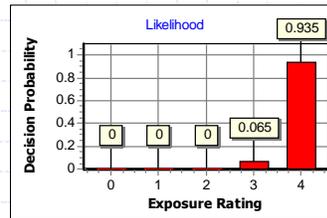
Substance Information				
Substance: manganese fume (as Mn)				
OEL: 0.2 $\text{mg}/\text{m}^3$				
Comments: <ul style="list-style-type: none"> <li>- TLV basis - CNS impairment</li> <li>- PEL - 5 <math>\text{mg}/\text{m}^3</math> Ceiling (1972)</li> <li>- SMAW using medium steel welding wire</li> <li>- controls: LEV</li> </ul>				
Data Entry				
Sample #	Conc	LOD	Date	Group
1	0.056			Worker E
2	0.067			Worker F
3	0.067			Worker G
4	0.302			Worker H
5	0.097			Worker I
6	0.172			Worker J



◆ Calculate IH statistics

Compliance Statistics (lognormal)			
X0.95 =	0.307	95%LCL = 0.185	95%UCL = 1.190
ExcFrac =	0.160	95%LCL = 0.036	95%UCL = 0.453

◆ Apply BDA:



◆ Final Rating:

- Category 4, High Certainty

◆ What respirator APF is most appropriate?

- ◆ The 95<sup>th</sup> percentile is most likely <10xOEL.
- ◆ An APF of 10 is appropriate.
- ◆ If PPE is used properly, what will be the Effective Exposure Rating?

Statistics GOF Graphs BDA Charts PPE Charts CDA

PPE Selection Charts

Data Labels  
 Yes  
 No

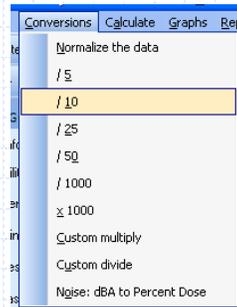
Adjust for censored data?  
 No  
 Yes

Professional Judgment  
 PPE Selection  
 APF1 - 1  
 APF2 - 10  
 APF3 - 50  
 APF4 - 1000  
 > APF4 - 1000

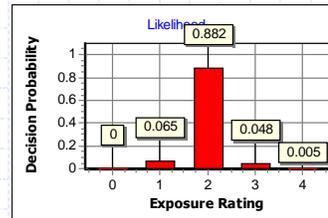
Certainty Level  
 1 - High  
 2 - Medium  
 3 - Low

Post APF

◆ Divide the data by 10:

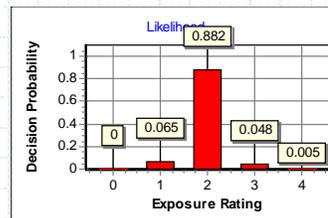


◆ If the EPF = APF the Effective Exposure Rating will be Category 2.



◆ Using the IHDA-Student

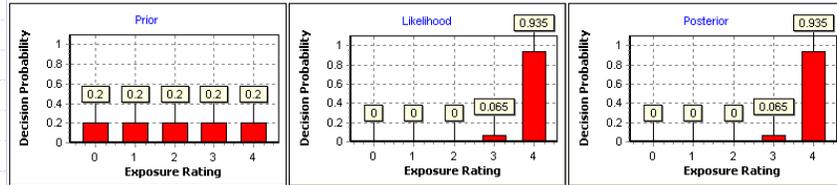
- Let the OEL =  $10 \times 0.2 \mu\text{g}/\text{m}^3$  (which is the MUC)
- So, the 95<sup>th</sup> percentile is most likely  $< 10 \times \text{OEL}$ .
- An APF of 10 is appropriate.



## Summary:

### BAYESIAN DECISION ANALYSIS

Exposure Rating:	0-T	1-HC	2-WC	3-C	4-PC
Cutoff (mg/m <sup>3</sup> )	0.002	0.02	0.1	0.2	>0.2
Cutoff (%OEL)	1	10	50	100	>100
Prior	0.2	0.2	0.2	0.2	0.2
Likelihood	0.000	0.000	0.000	0.065	0.935
Posterior	0.000	0.000	0.000	0.065	0.935
Cum Likelihood	0.000	0.000	0.000	0.065	
Cum Posterior	0.000	0.000	0.000	0.065	



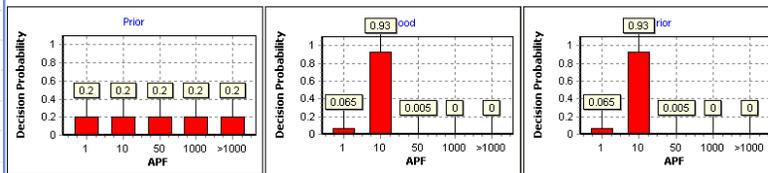
Parameter space:  $G_{min} = 4.09E-5$   $G_{max} = 1$   
 $D_{min} = 1.05$   $D_{max} = 4$

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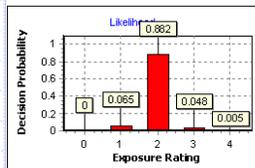
### PPE SELECTION

Respirator APF:	1.00	10.00	25.00	50.00	>50.00
Prior	0.2	0.2	0.2	0.2	0.2
Likelihood	0.065	0.930	0.005	0.000	0.000
Posterior	0.065	0.930	0.005	0.000	0.000



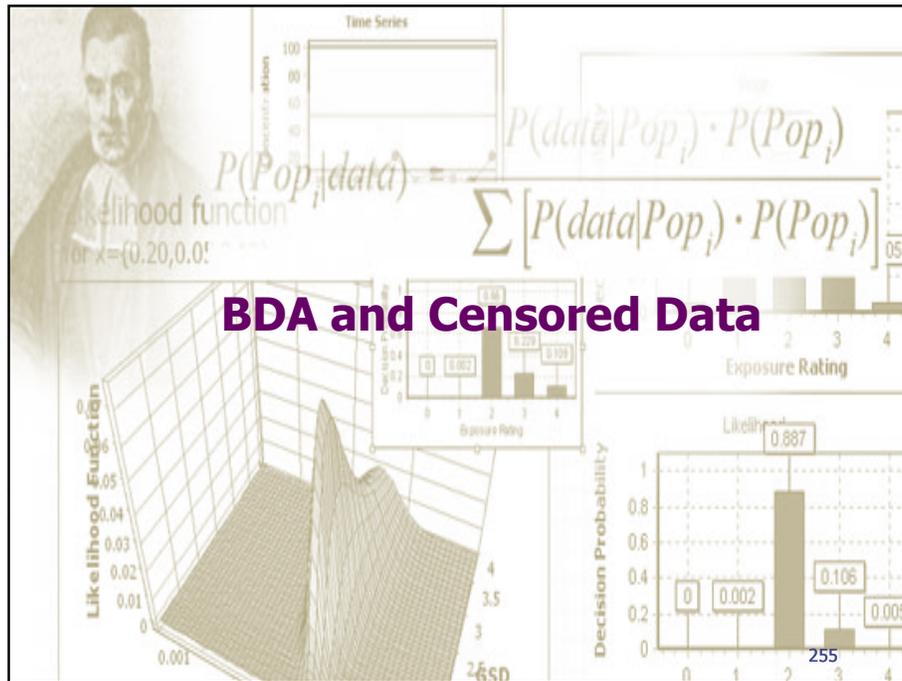
Parameter space:  $G_{min} = 0.01$   $G_{max} = 50$   
 $D_{min} = 1.05$   $D_{max} = 4$

If the Effective Protection Factor at least equals the APF the Effective Exposure Rating should be Category 2:



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◆ **NOTE:**

- The version of BDA in the commercial IHDA uses a Bayes's algorithm designed to use non-detects as well as detects.
- The BDA module in the freeware IHDA-Student *does not adjust for censored data*.
- It treats all nondetects as if they detects. In other words, the IHDA-Student BDA algorithm ignores the "LOD" indicator column. The IHDA-LE results may be misleading.

## Censored Data Analysis vs BDA

- ◆ Traditional
  - Goal: To extract the best possible estimate of the true GM and GSD, and then calculate the 95th percentile.
  - Methods:
    - ◆ Simple substitution methods
    - ◆ Log-Probit Regression methods
    - ◆ Maximum Likelihood Estimation (MLE) methods
    - ◆ Non-parametric approaches
- ◆ BDA
  - Determine the probability that the dataset came from a Category 0, 1, 2, 3, or 4 exposure profile.
  - Advantages:
    - ◆ BDA is based upon the MLE equations.
    - ◆ Can handle complex censored datasets, datasets as small as n=1 and 100% censored datasets.

## Theory

- ◆ BDA is based on the use of the Maximum Likelihood Equation.
- ◆ MLE methods are the preferred methods for analyzing censored datasets (when the data are well described by a lognormal distribution).
- ◆ Find the GM and GSD that maximize the Likelihood Function:

$$LF = \prod_{i=1}^n pdf(\ln x_i | \ln G, \ln D) \cdot \prod_{j=1}^m cdf(\ln x_j | \ln G, \ln D)$$

where:

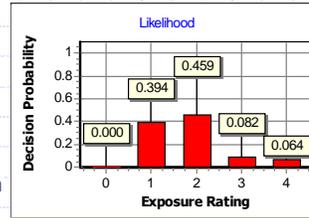
- n - number of measurements  $\geq$ LOD
- m - number of measurements  $<$ LOD
- pdf – probability density function
- cdf – cumulative density function

## Example - N=1, 100% censored

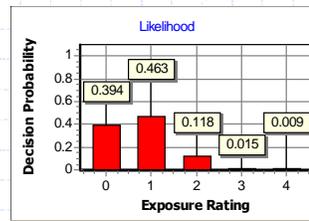
◆ OEL = 1  $\mu\text{g}/\text{m}^3$

Case	Example 1* ( $\mu\text{g}/\text{m}^3$ )
1	<0.05

w/o adjustment  
for censored data

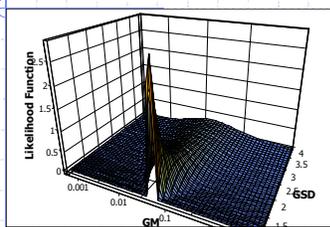


w/ adjustment  
for censored data

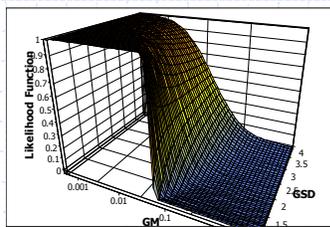
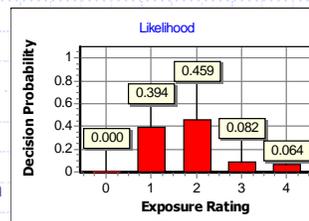


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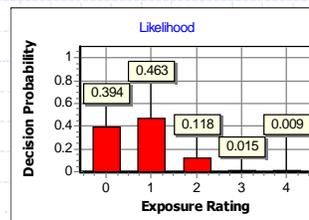
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w/o adjustment  
for censored data

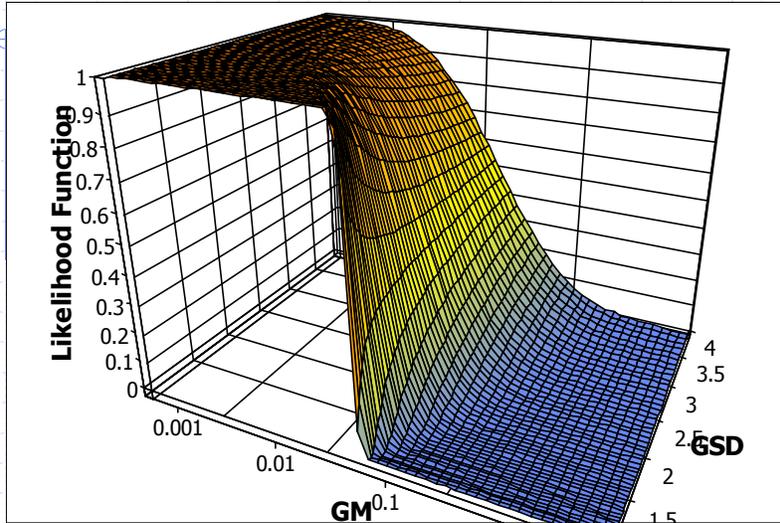


w/ adjustment  
for censored data



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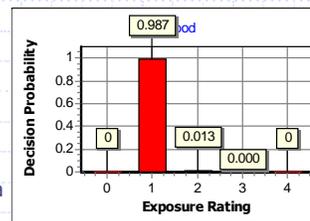
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## Example - N=4, 100% censored

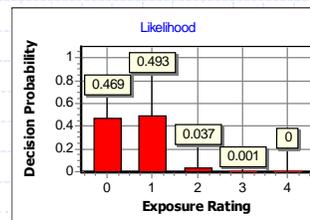
◆ OEL =  $1 \mu\text{g}/\text{m}^3$

Case	Example 1* ( $\mu\text{g}/\text{m}^3$ )
1	<0.05
2	<0.05
3	<0.05
4	<0.05

w/o adjustment  
for censored data

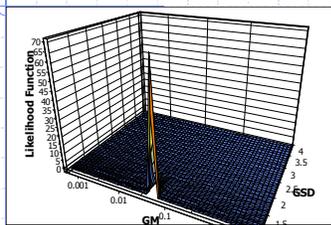


w/ adjustment  
for censored data

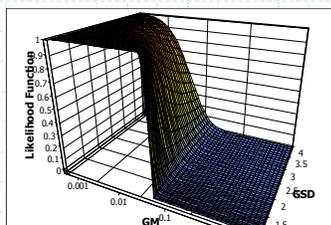
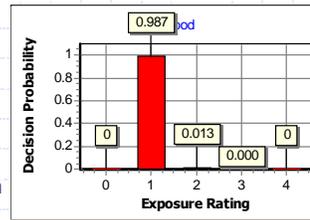


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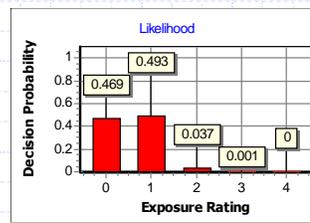
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w/o adjustment for censored data



w/ adjustment for censored data



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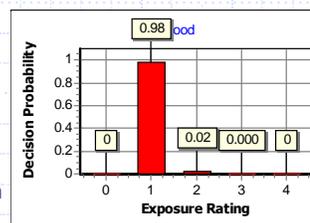
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## Example - N=5, 80% censored

◆ OEL = 1  $\mu\text{g}/\text{m}^3$

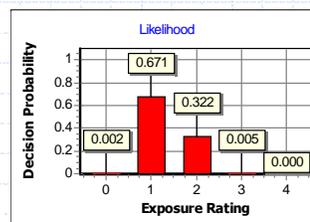
Case	Example 1* ( $\mu\text{g}/\text{m}^3$ )
1	<0.05
2	<0.05
3	<0.05
4	<0.05
5	0.06

w/o adjustment for censored data



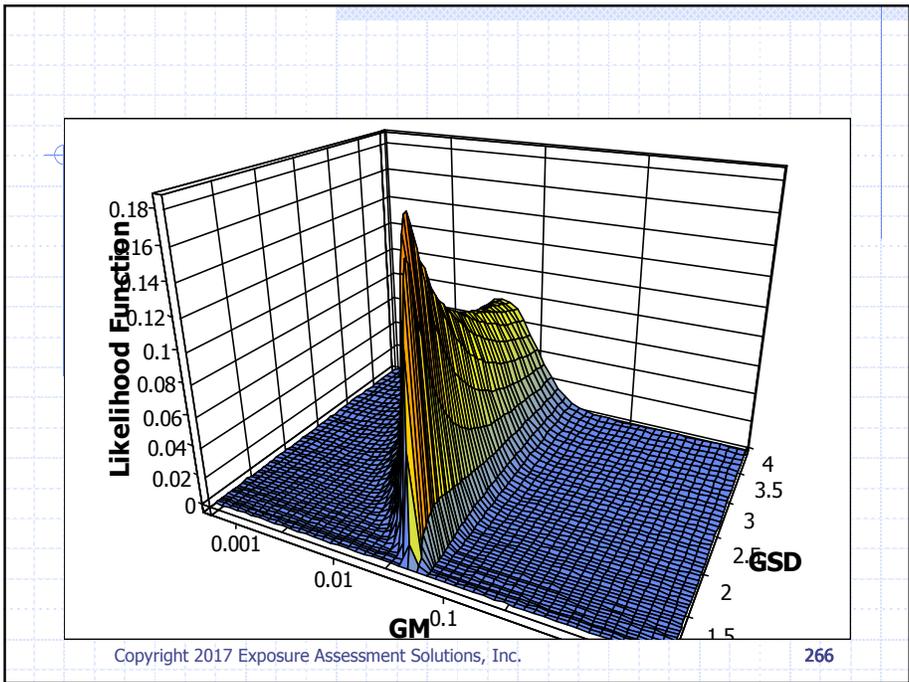
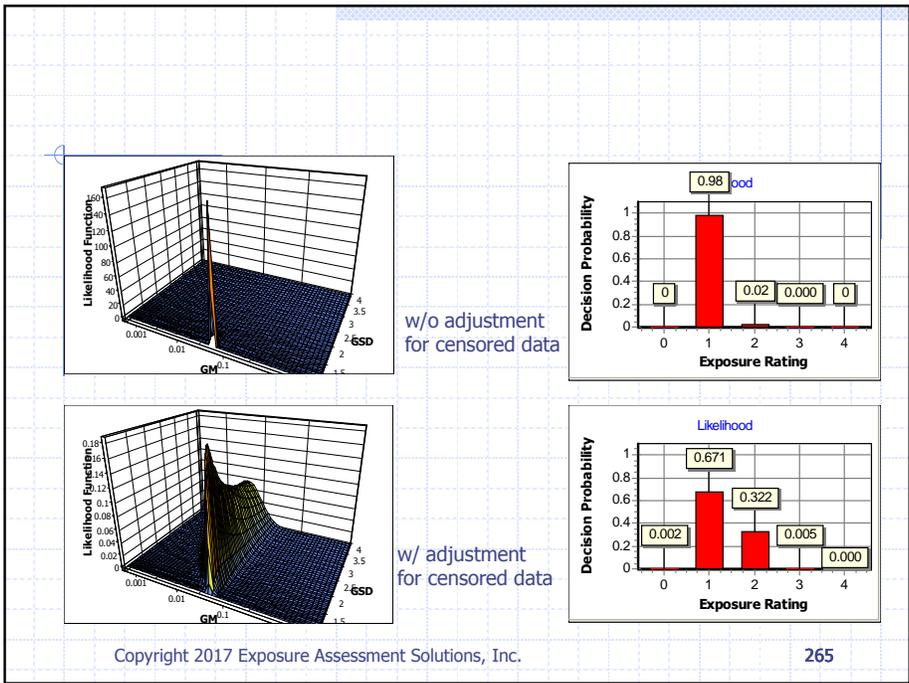
Now we have a detect!!

w/ adjustment for censored data



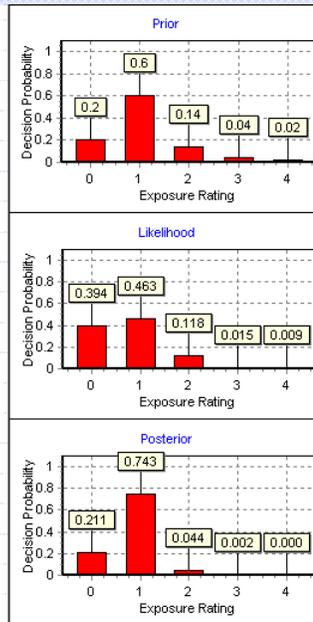
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## Using an Informative Prior

- ◆ OEL=1 ppm
- ◆  $n = 1$
- ◆  $x < \text{LOD}$
- ◆  $\text{LOD} = 0.05 \text{ ppm}$
- ◆ BDA can be applied to censored datasets, even 100% censored or w/ multiple LODs.

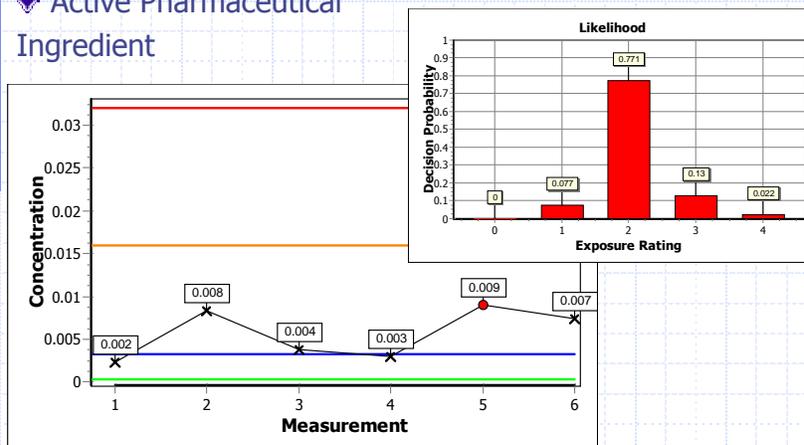


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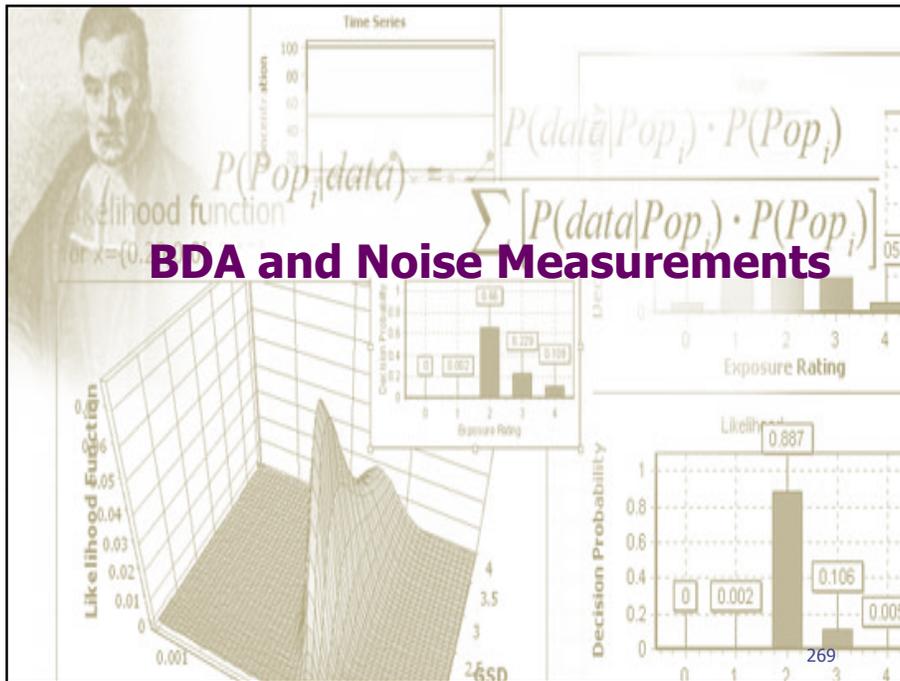
## Active Pharmaceutical Ingredient

- ◆ Active Pharmaceutical Ingredient



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## BDA Exposure Categories for Noise (Hager and Johnson (2015): Chapter 14 – Noise Stressors)

Table 14.2 – Noise SEG Exposure Control Categories

TWA8 and Noise Dose	SEG Exposure Control Category**	Applicable Management/ Controls
<56.8 dBA <1%	0 (<1% of OEL)	Hearing loss prevention awareness training optional
56.8–73.4dBA 11-10%	1 (<10% of OEL)	Hearing loss prevention awareness training optional
73.4–85 dBA 10-50%	2 (10–50% of OEL)	+ Hearing loss prevention awareness training, periodic exposure monitoring
85–90 dBA 50-100%	3 (50–100% of OEL)	+Hearing Conservation Program inclusion, exposure monitoring, medical surveillance, PPE requirements begin, consider hierarchy of controls
90–101.6dBA 100-500%	4 (>100% of OEL)	+Implement hierarchy of controls, implement engineering controls
>101.65dBA >500%	5 (Multiples of OEL)	+ Implement hierarchy of controls, validation of hearing protection sufficiency, dual HPD, priority engineering control

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(Original) BDA Exposure Categories for Noise  
(cutoffs are suggested and can be modified)

- ◆ OEL = 100% dose
- ◆ Which control zone is appropriate?

Exposure Control Ratings *	Cutoff (%OEL)	Confidence level
0	$X_{0.95} \leq 12.5\%$	High
1	$12.5\% < X_{0.95} \leq 25\%$	
2	$25\% < X_{0.95} \leq 50\%$	Medium
3	$50\% < X_{0.95} \leq 100\%$	Low
4	$X_{0.95} > 100\%$	

\* Adapted from Tables 5.2 and 6.2; rating 0 taken from 1991 version

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- ◆ Exposure categories and corresponding dBA level category cutoffs.

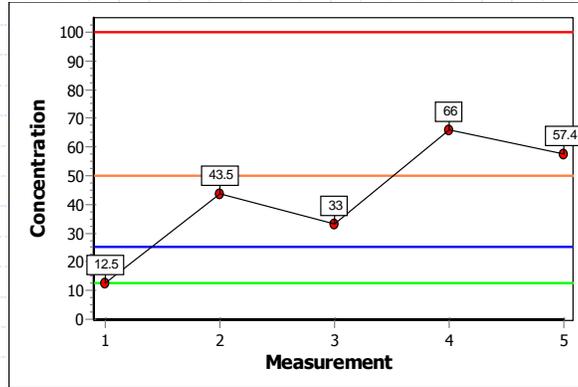
Exposure Category	Cutoff (%OEL)	5db ER	3db ER	Measurement Threshold?
		OSHA (dBA)	ACGIH (dBA)	
0	$X_{0.95} \leq 12.5\%$	75	76	}
1	$12.5\% < X_{0.95} \leq 25\%$	80	79	
2	$25\% < X_{0.95} \leq 50\%$	85	82	
3	$50\% < X_{0.95} \leq 100\%$	90	85	
4	$X_{0.95} > 100\%$	> 90	> 85	

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### Example (IHDA - Noise - in percent dose.xls)

- ◆ Data:  $x = \{12.5, 43.5, 33.0, 66.0, 57.4\}$  percent dose  
(compare to OSHA PEL = 90 dBA, Exchange Rate = 5 db)

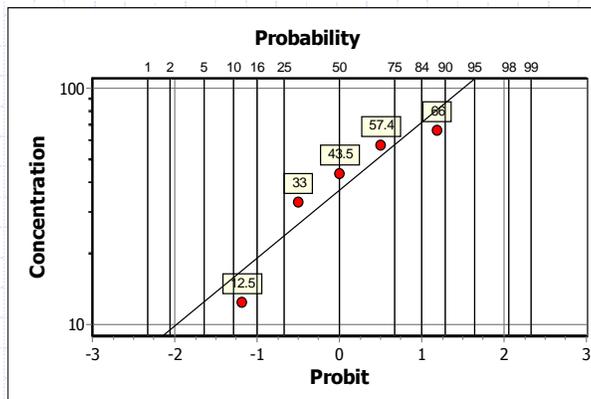


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#### Compliance Statistics (lognormal):

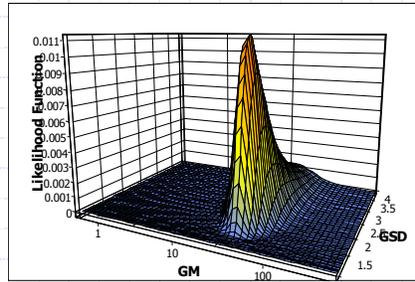
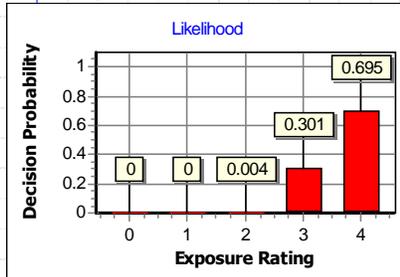
X0.95 =	109.000	95%LCL =	63.300	95%UCL =	592.000
ExcFrac =	0.065	95%LCL =	0.005	95%UCL =	0.369



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◆ BDA results: This dataset was most likely produced by a Category 4 exposure profile:



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