Statistics and Physics in Reliability.

You Can’t Have One Without the Other

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Statistics and Physics in Reliability.

Just like a Horse and Carriage

You Can’t Have One Without the Other

- Not necessarily a packaging issue, but applies to all of reliability physics evaluations
- There is an infinity of distributions
- We need to pick one from the physics, not merely because it “fits the data”
  - We have a finite number of samples

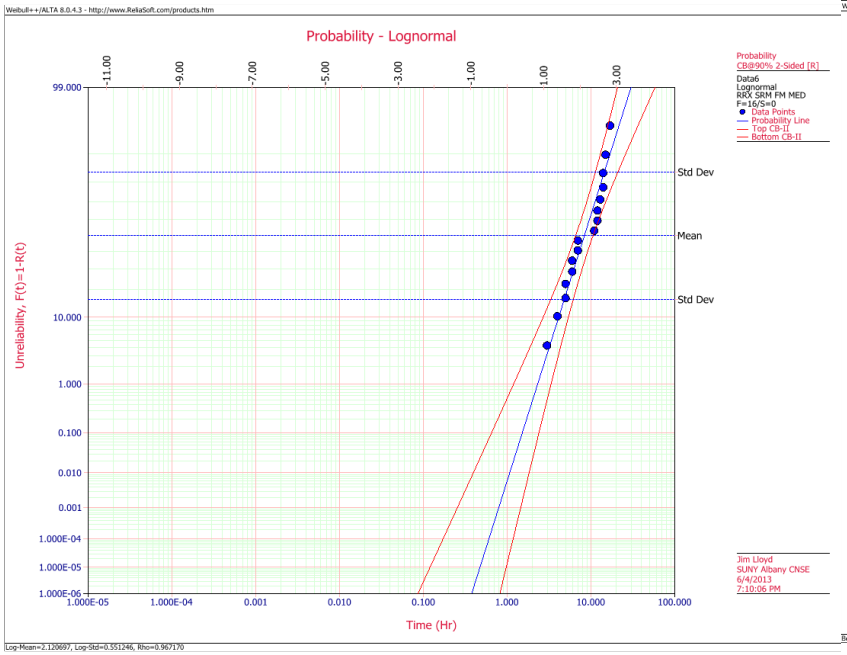
Distributions

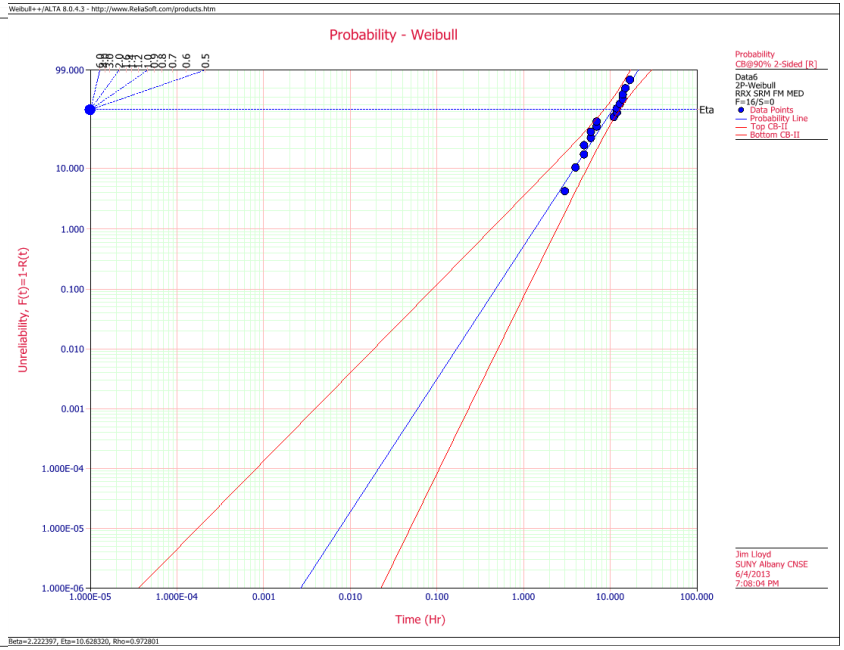
- Of all the distributions out there, only some can be failure distributions
  - The normal distribution CANNOT be a failure distribution
    - It goes negative
  - Lognormal, Weibull, Gumbel, Exponential can all be viable failure distributions
    - But their choice is based on the physics of failure
  - But, sometimes the statistics suggest the physics

What do we do

- We generally use one of two failure distributions
  - Lognormal
    - Because it fits the data reasonably well
      - Most of the time
    - There is theoretical justification for its use
  - Weibull
    - “Because it can be made to fit a wide range of data”
      - Not a good enough reason

Comparison Lognormal to Weibull





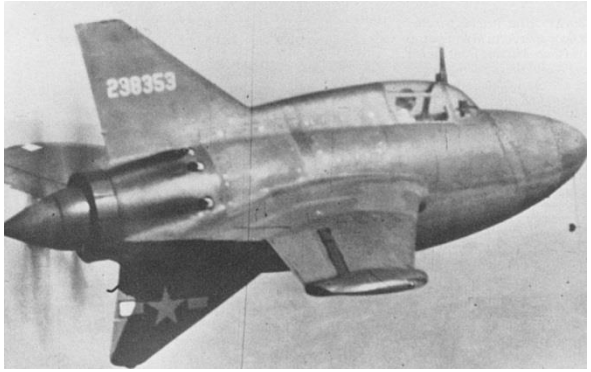
Taking the same data that fit equally well to Lognormal or Weibull distributions in the small (16) sample limit, they extrapolate very differently

Weibull vs Lognormal

- Extrapolating to 1ppm
  - Correlation Coefficient the same (rho = 0.97)
  - The difference in projected $t_{.000001}$ is 130X
  - To 90% confidence level it is **3000X**
    - **Weibull more conservative**

So it is to your advantage

to know what distribution you should be using



Weibull vs Lognormal

- The regimes of application are very different
  - Weibull is an extreme value distribution
    - Weakest link in a chain
  - Lognormal is not
    - For many test structures this is the right choice

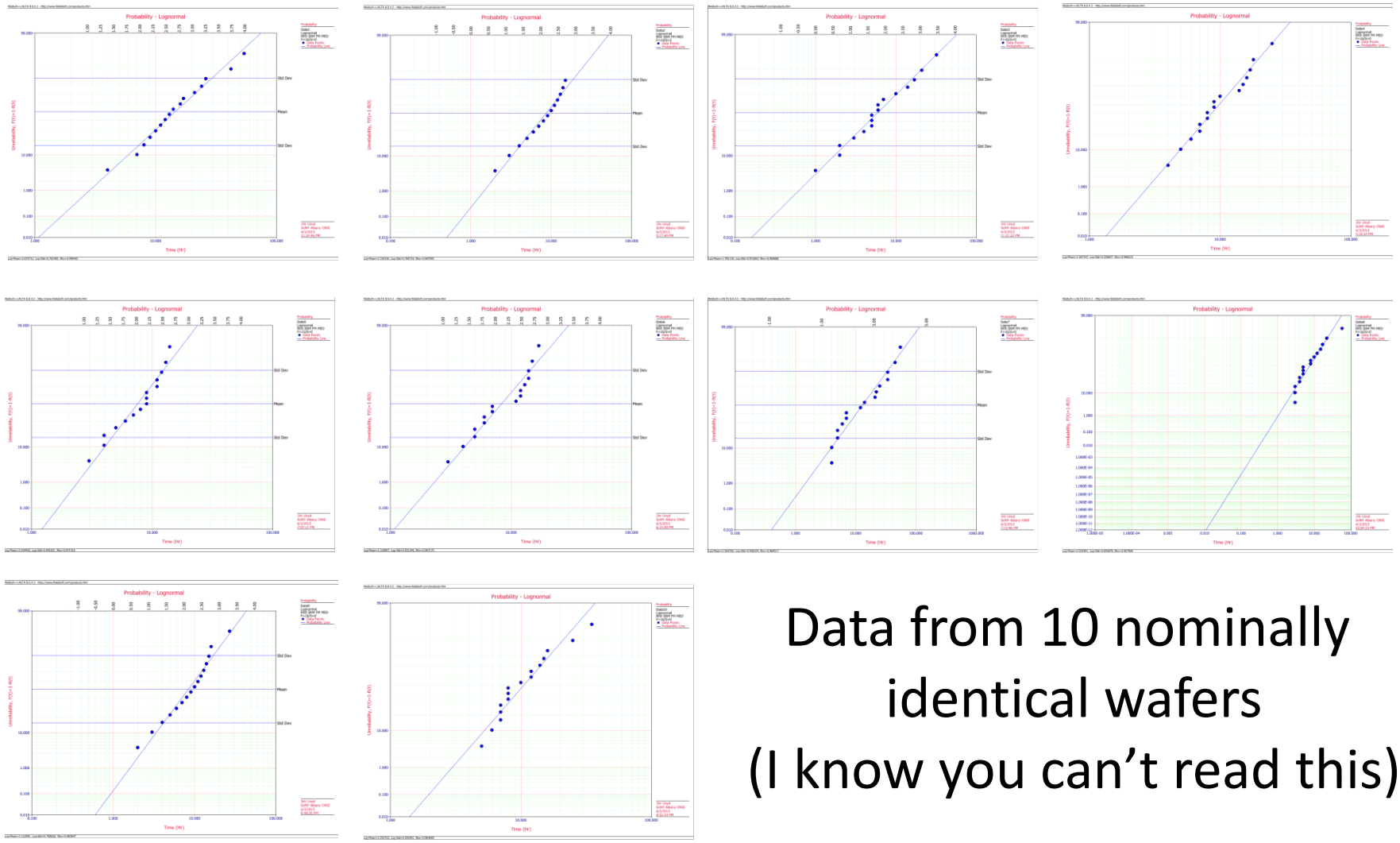
What are we interested in?

- The user/customer is not interested in the Median Time to Failure t_{50} (Lognormal) or the t_{63} (Weibull), but in the $t_{.000001}$ or so.
  - So what is the distribution of failures for the 2 sigma value

All devices are not created equal

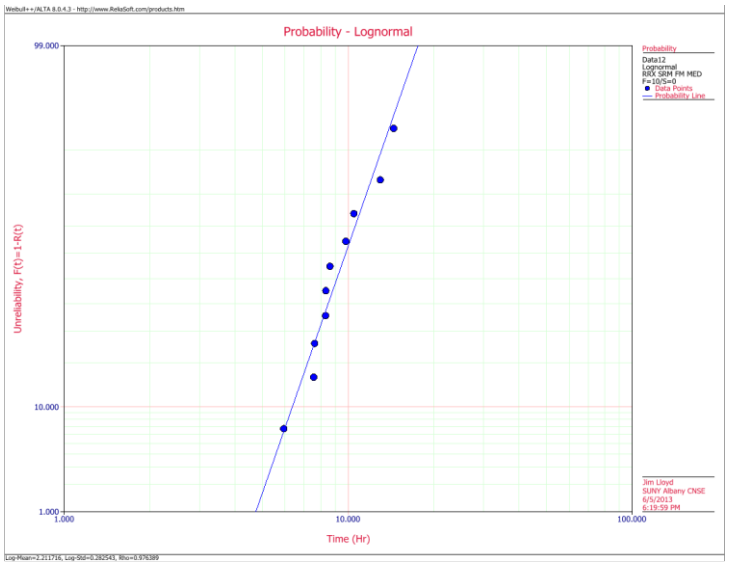
- As we can see, given nominally identical structures, they will not all fail at the same time.
  - Above
- Given nominally identical lots, the median time to failure and the deviation in the time to failure will vary.
  - Considerable lot to lot variation
  - Sometimes as much as 10X

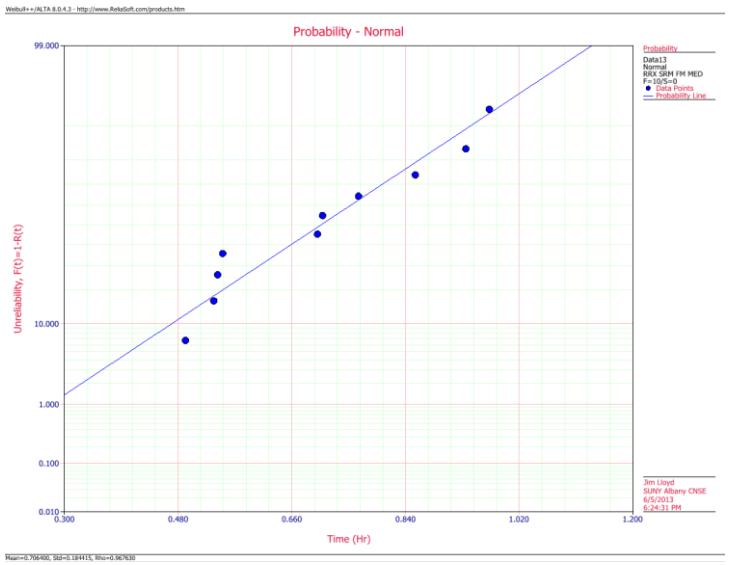
Data



Data from 10 nominally identical wafers
(I know you can’t read this)

Real Data
(electromigration test structures)





t_{50} lognormally distributed

median t_{50} = 9.2hrs $\sigma_{t50} = 0.28$

μ Normally distributed

median μ = 2.21 $\sigma_{\mu} = 0.28$

σ normally distributed

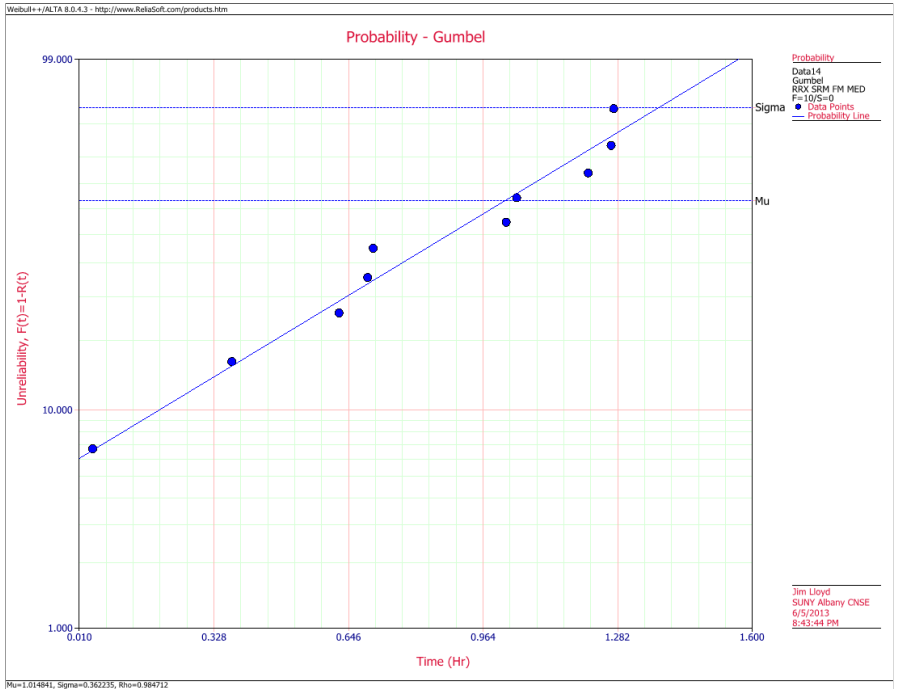
$\sigma_{50} = 0.70$ $\sigma_{\sigma} = 0.18$

Failure Distribution Chip Scale

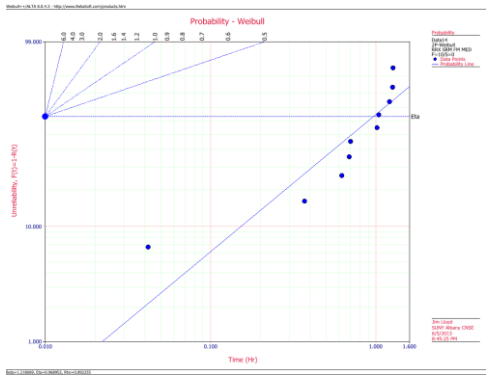
- The Gumbel is the extreme value distribution for the Normal
  - Thus if you have a chain of normally distributed links, the chain will fail by a Gumbel distribution
    - Used commonly for flood predictions
  - Experiment and theory have shown that for individual elements (test structures) the lognormal distribution is appropriate
  - Since the lognormal distribution is a normal distribution of the logarithms of a quantity, the appropriate failure distribution for a lognormal chain (an integrated circuit) should be a Gumbel distribution of the logs of the links, hence a log-Gumbel distribution

Distribution of extreme value

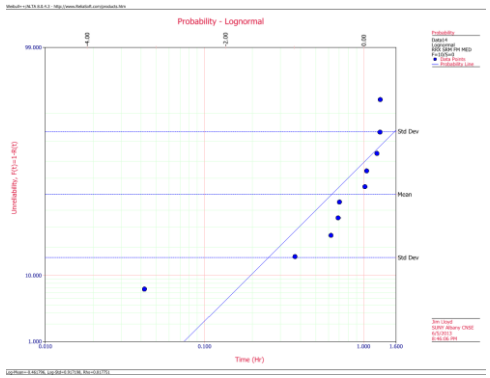
- This is the distribution of 2 sigma values of the logs of experimental t_{50} 's (not individual failures)



Gumbel



Weibull



Lognormal

Using the Weibull

- Even if it is not the right distribution, plotting failures with a Weibull can be informative
  - Increasing or decreasing failure rate characterized by the beta (equivalent to sigma for a lognormal/normal distribution)
  - Where are you in the bathtub?

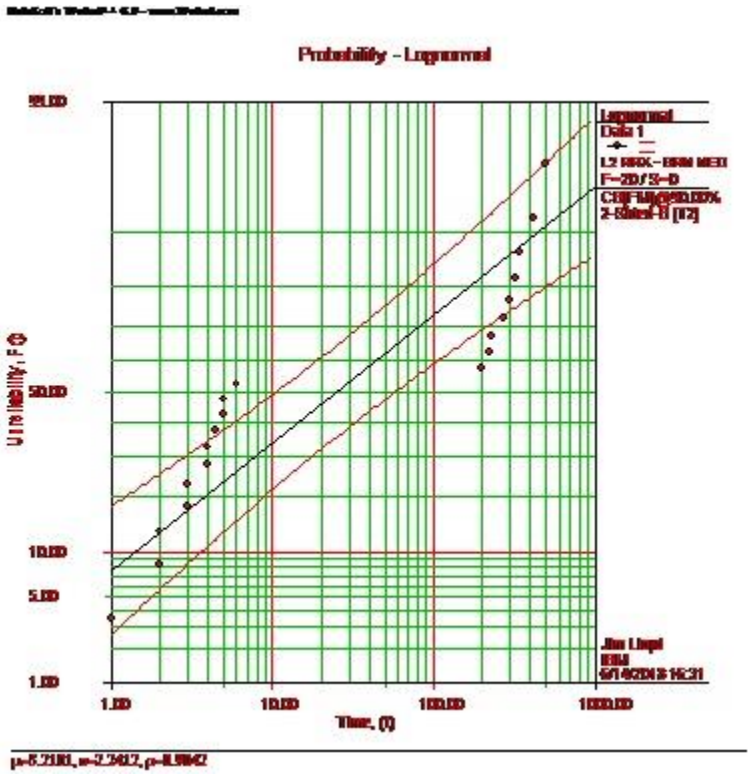
Not Wearout

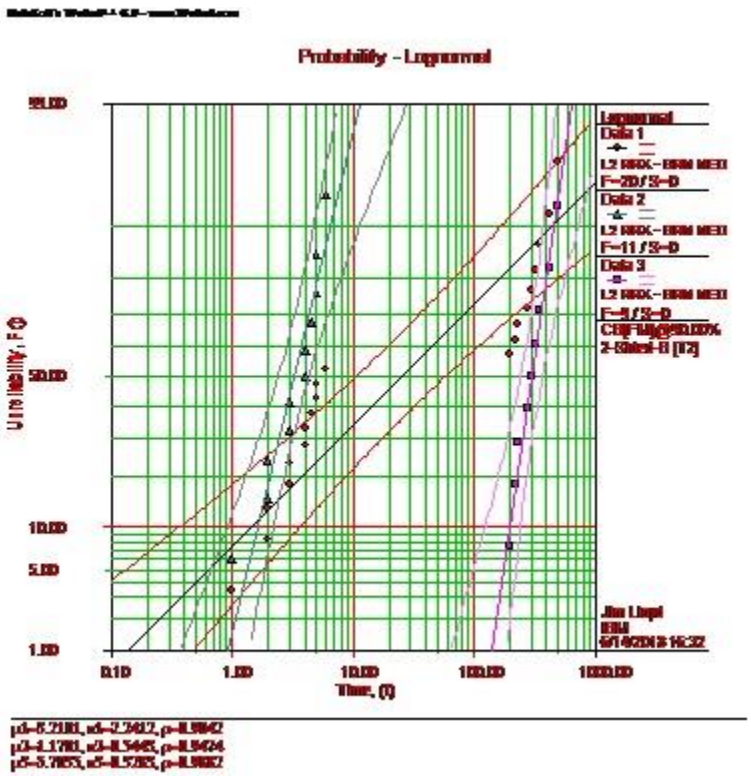
- If the Weibull distribution has a beta of 1
  - It is not a Weibull distribution
- It is an Exponential distribution
  - Constant failure rate
  - Not wearout
  - MTBF
  - Physics
    - Radioactive Decay

Multi-Modal Failure

- Mixed populations generally observed
  - Bimodal failure distributions are common
    - Defect population
  - Intrinsic material characteristics
    - Electromigration in Cu
    - Electromigration in Sn
- Misinterpreting a bimodal distribution will produce gross errors
  - Generally very pessimistic

Bimodal Failure Distribution
(A fake one)





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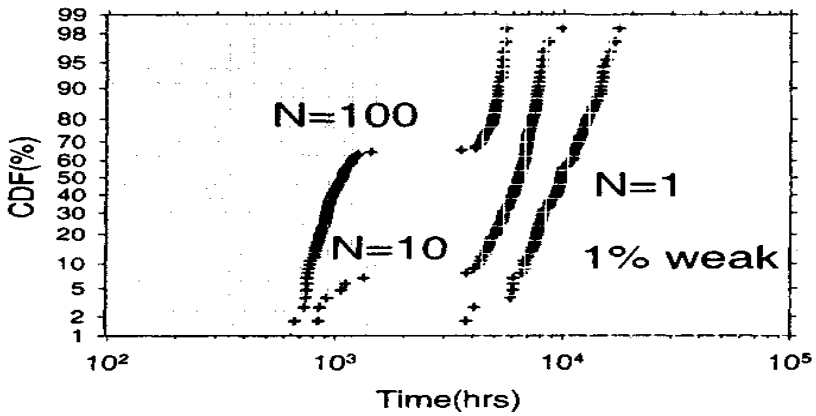
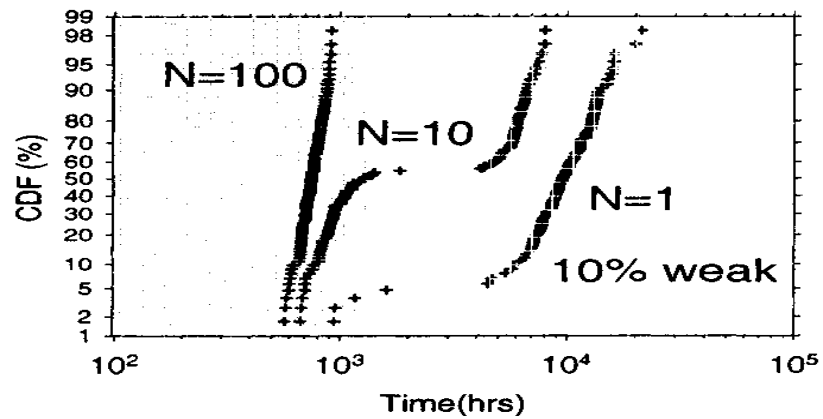
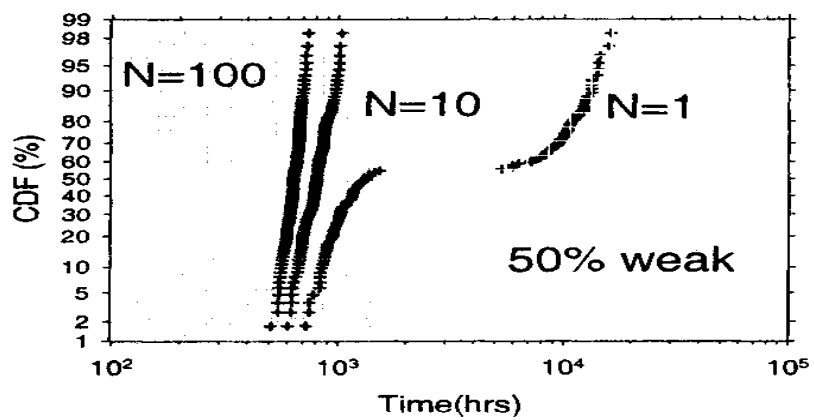
6th International Workshop on Stress-Induced Phenomena in Metallization
Ithaca NY 2001







Monte Carlo

Strong Mode t_{50} = 1000 hrs
Weak Mode t_{50} = 50 hrs
$\sigma = 0.3$

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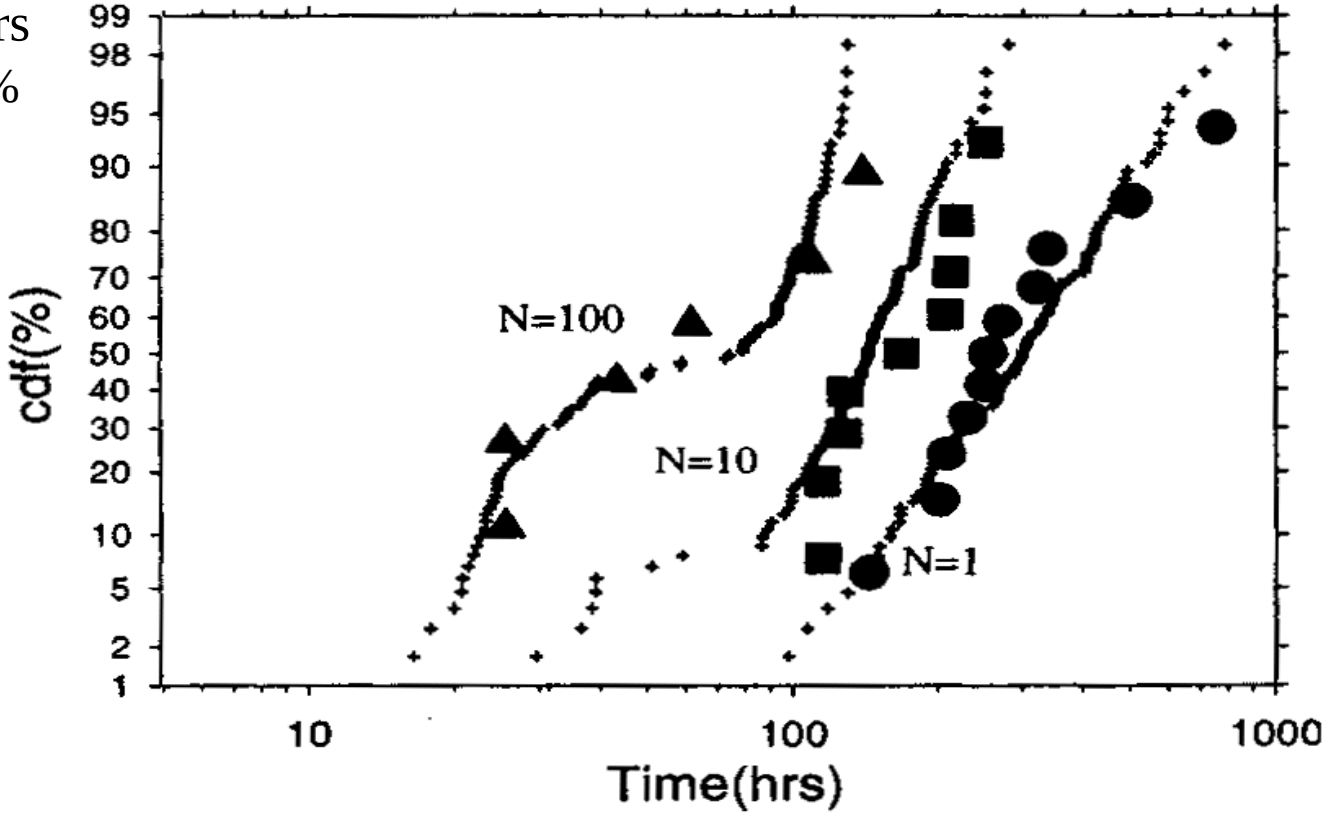
Actual Data

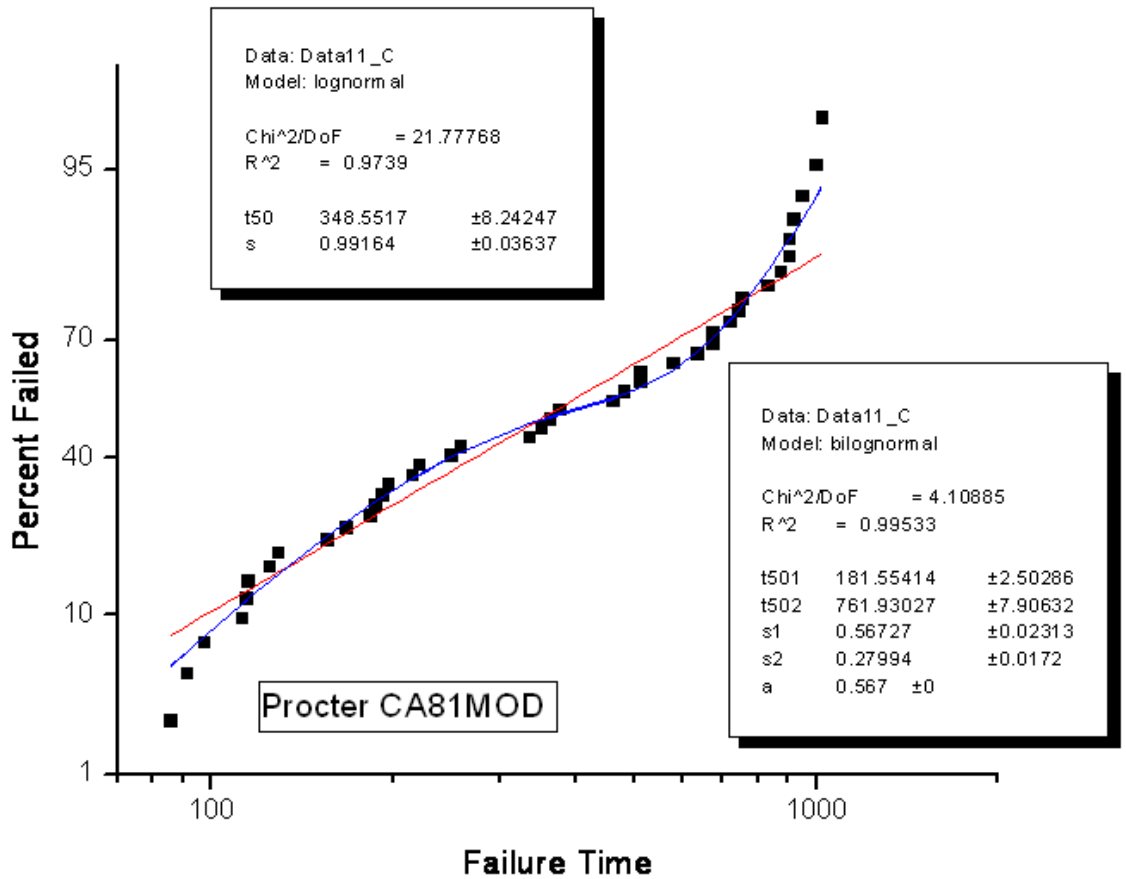
Strong Mode t_{50} = 300 hrs

Weak Mode t_{50} = 30 hrs

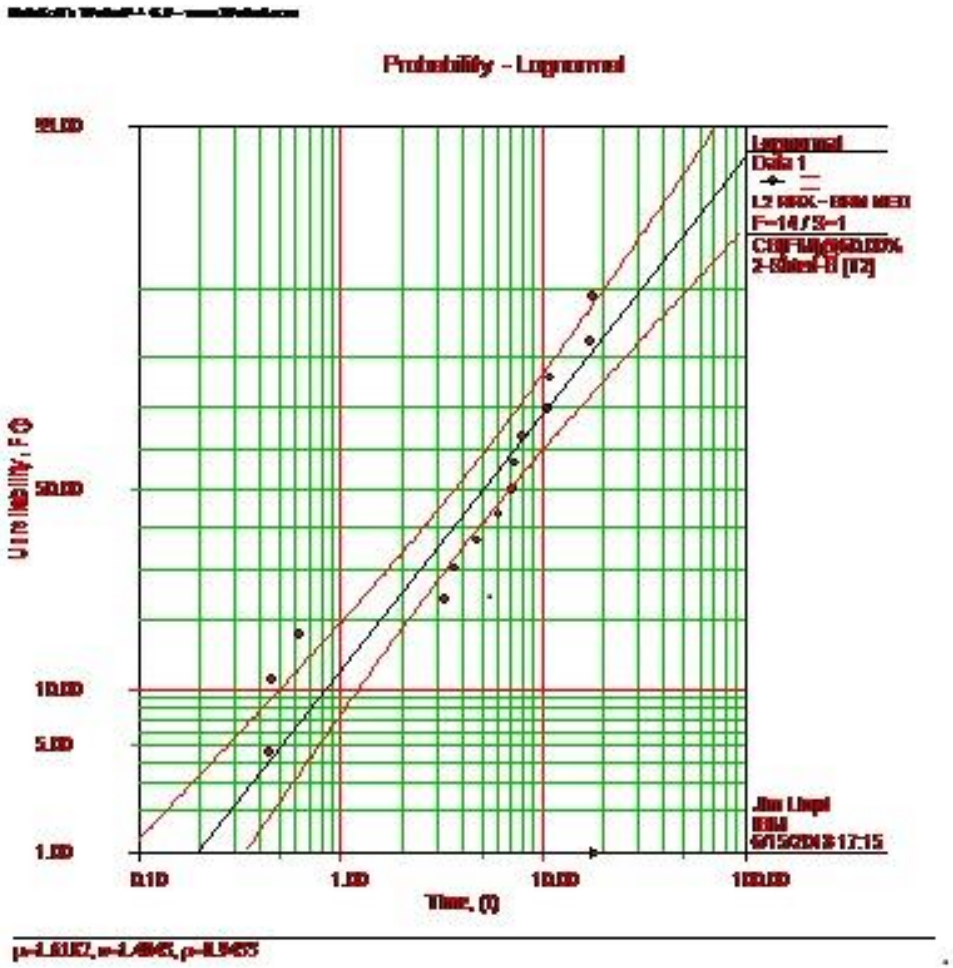
Fraction Weak = ~ 0.6%



Real Data
More what a bimodal distribution looks like

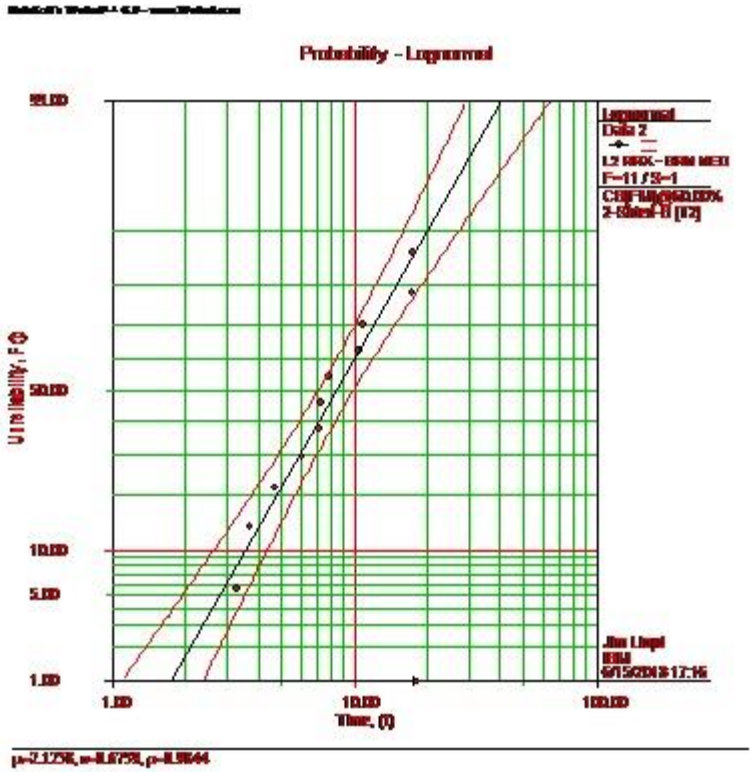


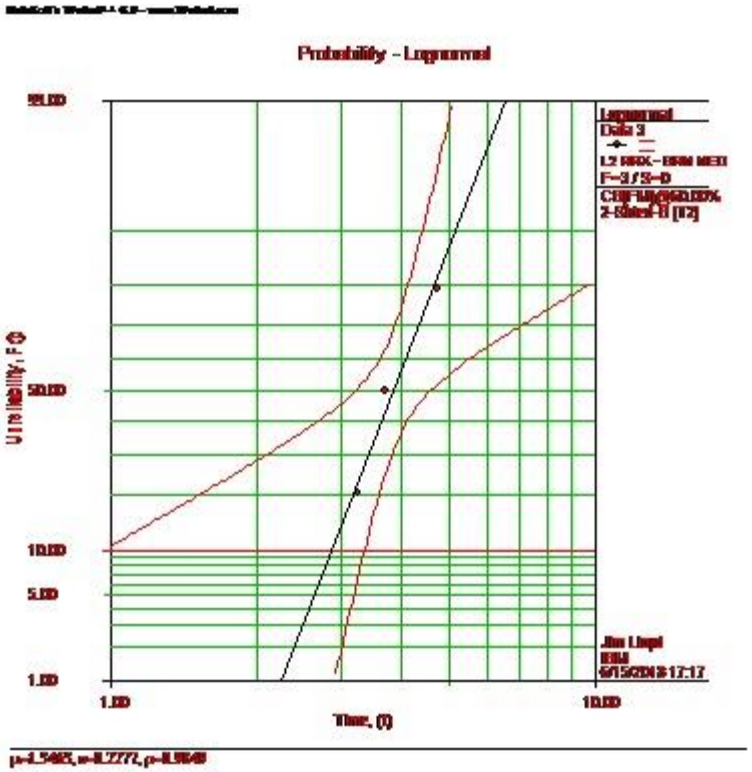
What we typically get
(Real data from my student)



Note “eyeball integrator” shows clear bimodality

Bimodality





Note tighter distributions and the huge uncertainty in the early fail distribution
Due to small sample size
The minimum number of points for a line is 3, not 2

Sn based solder

- Sn is a very anisotropic material
  - Body Centered Tetragonal
    - Sn really wants to be a semiconductor with DC structure
  - Elastic modulus can vary over 3X due to orientation
  - Diffusion can vary orders of magnitude
    - Fast Diffusers
    - Depends upon orientation

BLM Dissolution

- Fast Diffusers
  - Interstitial in Sn and Pb
    - All the Noble Metals
    - Many Transition Metals
  - Very small solubility
    - ppm or less

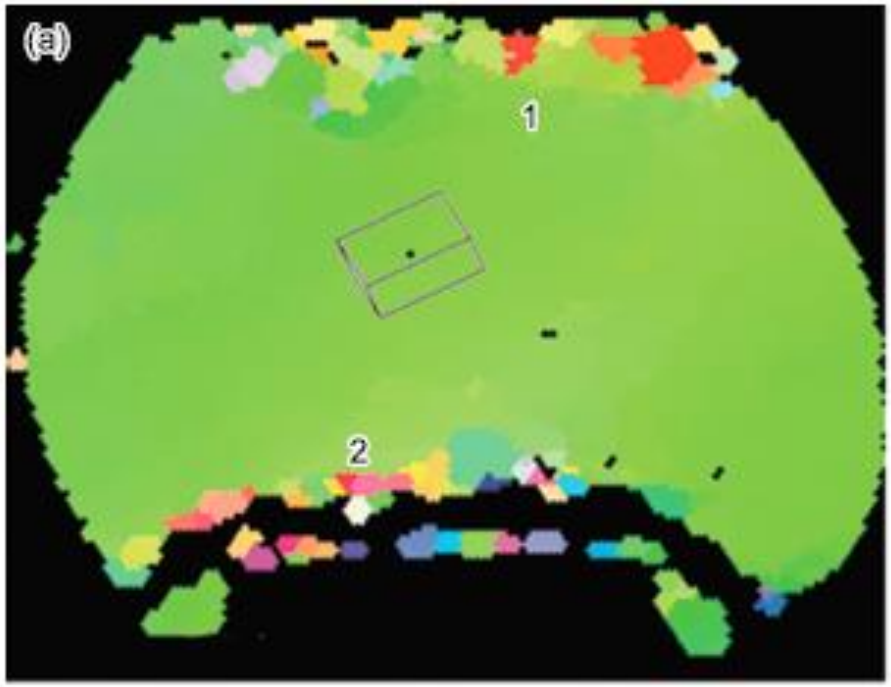
Ni in Sn is the fastest Solid State Diffusion Known
(Extrapolates to faster than in liquid state)
In the c direction only

Suggests possibility of Ni BLM being eaten away on upstream side

Sn Solder Balls

- Due to very low solubility, if you just look at Fickian diffusion you will not see anything.
  - Ni forms an IMC and appears to be a good diffusion barrier.
  - But it's not in real applications.
  - Must add another driving force
  - Electromigration or Soret Effect
- Grain size of Sn can be comparable to the size of the solder ball
  - In some cases the solder ball is a single crystal
  - Orientation of the large grains will determine reliability
  - If the c direction is parallel to current flow, you have a problem
  - With 1,000+ solder balls, a bad guy is almost guaranteed
  - Bimodal failure distribution
  - Intrinsic, not due to defects

Lead Free Solder



Summary

- It is important to use the proper failure distribution
  - Extrapolation
  - Based on physics and not just how it looks
  - Data obtained from test structures will in general not have the same distribution as a complex part
  - For a “real” part an extreme value distribution should be used
    - Significantly different from test structure distribution

Summary

- Many failure distributions are bimodal at least
  - Due to mechanical and kinetic anisotropy bimodal failure distributions are intrinsic
  - The user/customer is not interested in t_{50}
  - The mainstream distribution will never be observed
    - Need enough data to characterize the weak distribution

Thank You for your Indulgence