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Microwave Device Reliability Characterization -The Mechanics of Life Test Execution and Analysis

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Microwave Device Reliability Characterization -The Mechanics of Life Test Execution and Analysis

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Reliability Lab Charter

- Perform All Due Diligence Testing to Establish and Maintain the MMIC Fab Process Reliability to ensure 'NoDoubt' Mission Assurance
- Provide Reliability Expertise Within RFC, IDS and Company Wide
- Anticipate Test Capability and Capacity Needs to Enable Nimble Response to Programs' Needs
- Search for New Paradigms in Testing and Reliability Benchmarks Industry Wide
- Implement Lean Methods and Automation to Optimize Quantity and Enhance the Quality of Test Execution and Data Analysis

Reliability Lab Test Capabilities

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- Life Testing:
- Process Reliability Monitoring
- DC Biased Temperature Accelerated Life Test
- RF Operational Life Test (S & X-Band)
- RF Temperature Accelerated Life Test (X-Band)
- Pulsed DC Electromigration (DC TALT)
- Current Density Testing (DC TALT)

- Characterization:
- Capacitor Time Dependent Dielectric Breakdown Testing
- LabVIEW Based Parametric Characterization
- Resistor TCR Characterization
- Light Emission Microscopy
- Liquid Crystal Failure Analysis

What Affects Reliability?

- Technical or lay, we all know that the reliability or longevity of “things” is driven by stress
- The list of life reducing stresses include: temperature, temperature cycling, humidity, voltage/electric field, current density, mechanical stress, thermo-mechanical stress cycling, radiation etc
- The dominating stresses depend on the application environment.
- Most of us would instinctively recognize Temperature as a common stress for many “things”.

Temperature is a common stress driver of reliability

The Focus of Today's Presentation

- Our "things" of interest are microwave devices made of compound semiconductor materials (GaAs, GaN etc)
- Temperature and voltage/electric field are the important stresses in the application of microwave devices
- In the space/defense environment many of the others are mitigated by the application environment.
- This presentation will focus on temperature activated degradation. The reliability metrics from the statistical formalism will be introduced and the procedures to obtain them will be detailed

Main Theme: Thermally activated reliability metrics

Elements of the Statistical Formalism

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- The Lognormal Lifetime Distribution
  – Failures are distributed 'normally' when plotted on log time scale

- The Cumulative Failure Fraction Plot
  – A linear plot can be taken as evidence for lognormal lifetime distribution

- The Arrhenius Reaction Rate Model - $t=to*e^{Ea/kT}$
  – The Arrhenius acceleration relationship is then

  – $ML1/ML2 = e^{Ea/kT1}/e^{Ea/kT2}$

- The Reliability Metrics from above are:
  – Median Life (ML) or MMTF
  – Sigma (σ) the dispersion – standard deviation of the log of lifetimes
  – Activation Energy

The Metrics: Median Life, Sigma and Activation Energy

The Lognormal Failures Distribution

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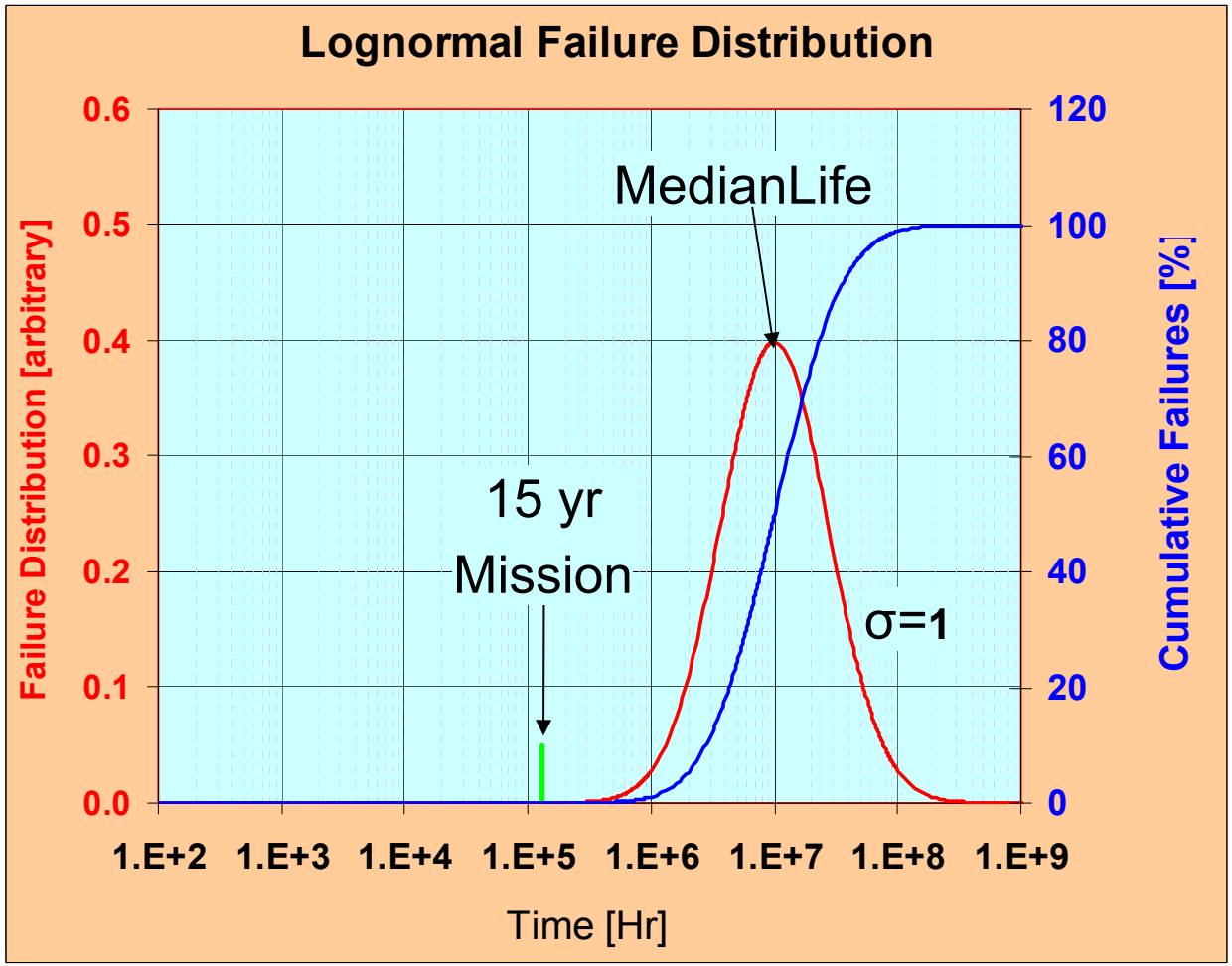

Distribution is 'normal' when plotted on log time scale

Trade Off Between ML and σ

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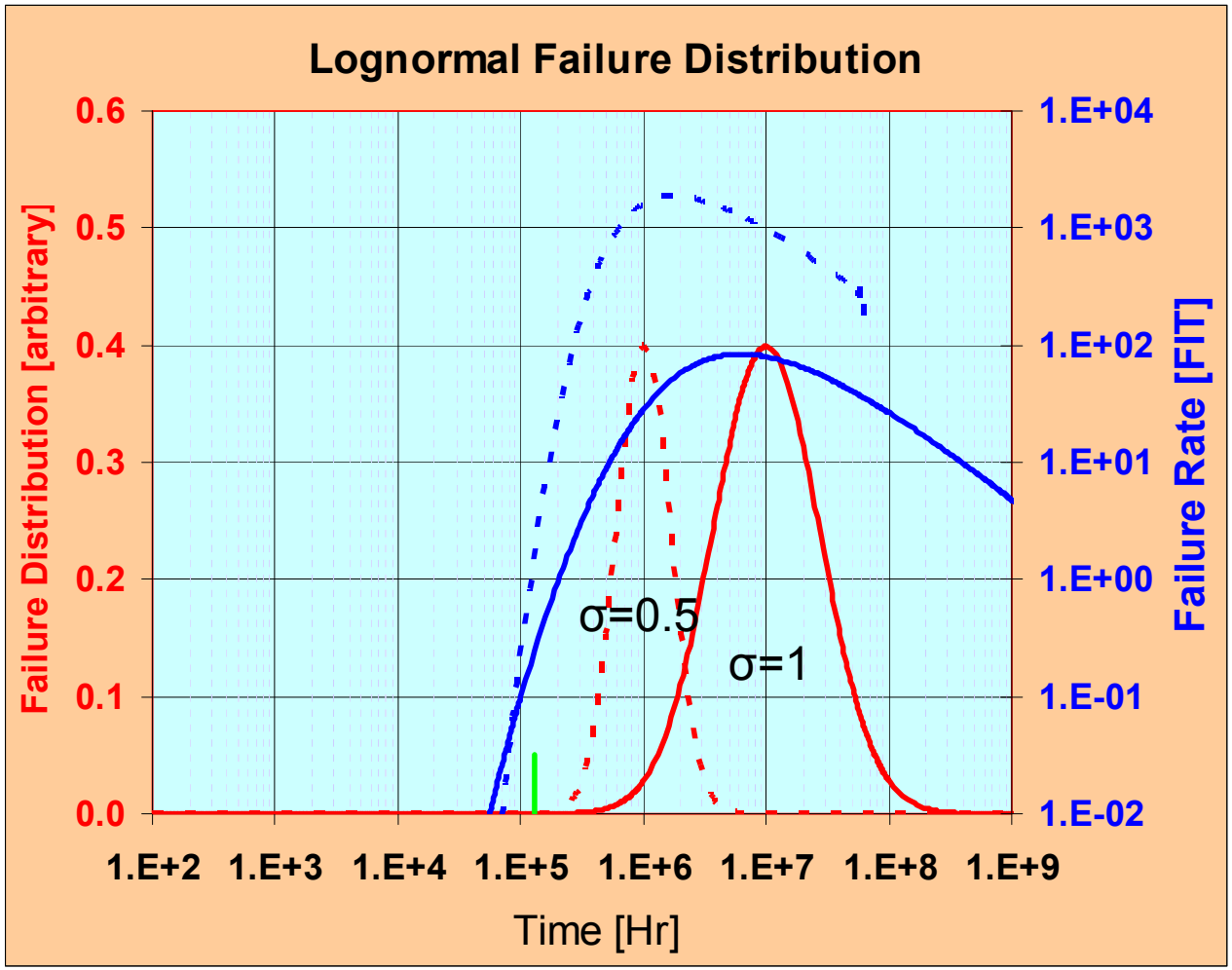
Failure Rate in FITs through mission time is negligible

FIT is a failure unit

And it is equivalent with 1 failure/10^9 hr



To maintain 'Same' Reliability at lower ML, σ has to be smaller

The Lognormal Failures Distribution

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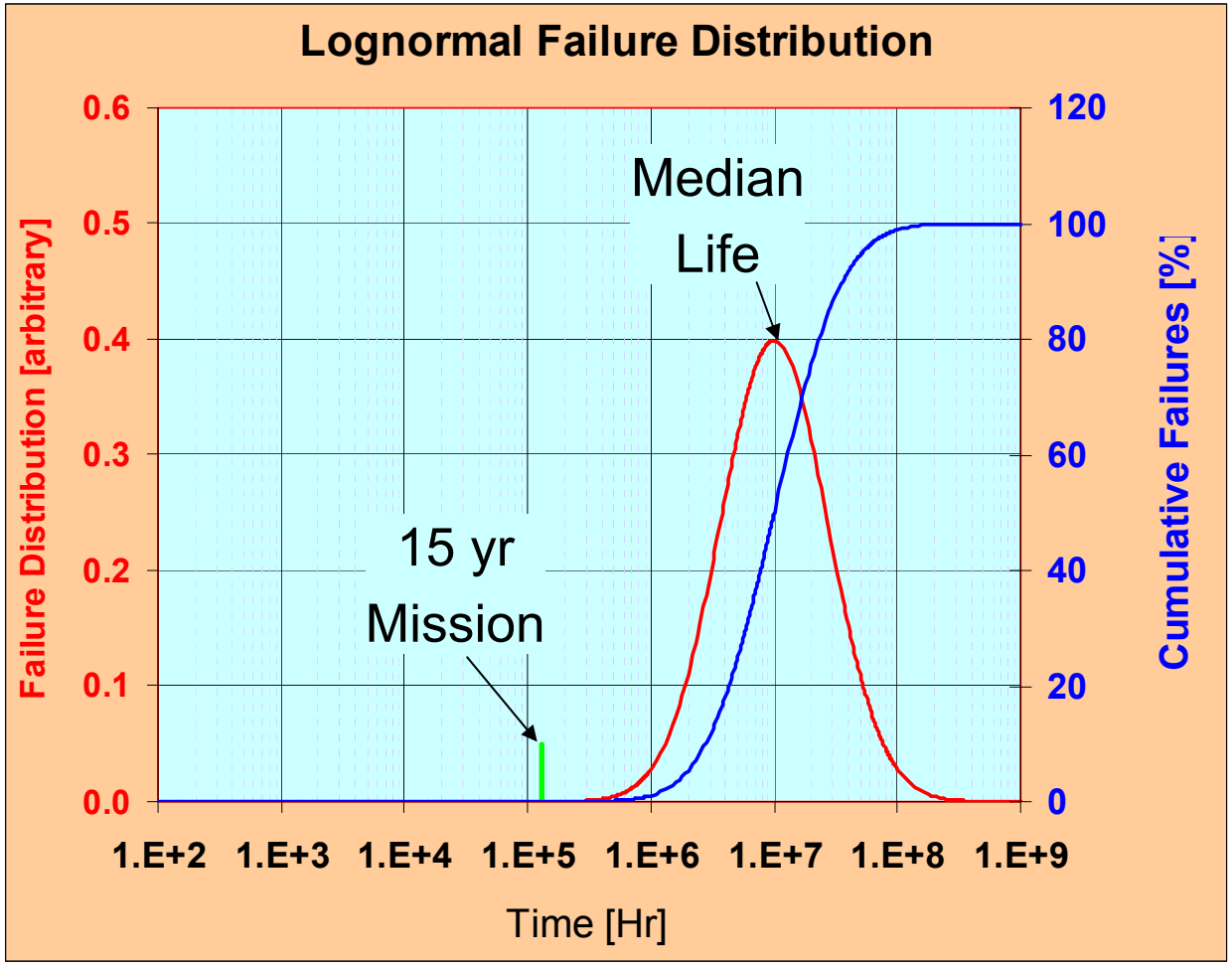


Note Margin Between Distribution Tail and Mission Time

The Cumulative Failure Fraction Plot

Note on the X scale both the Probability and Score scales are shown

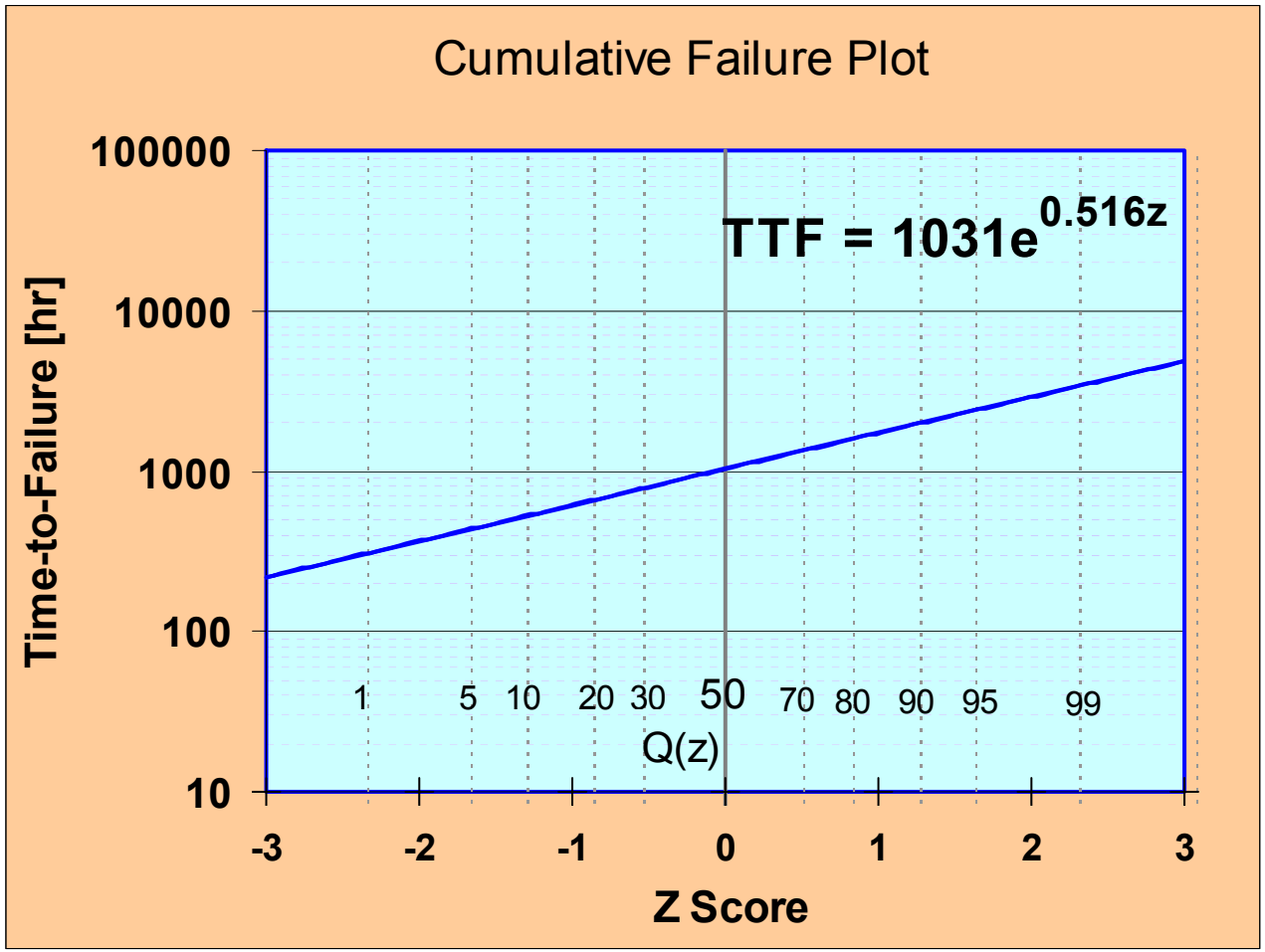
The Plot is linear

$Ln(TTF) = \sigma * z + Ln(ML)$

The exponential curve fit in Excel returns the form

$TTF = ML * e^{\sigma * z}$

The extraction of ML and σ is direct



A linear plot is taken as evidence for lognormal lifetime distribution

The Arrhenius Reaction Rate Model

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$ML=C * e^{Ea/kT}$

Or

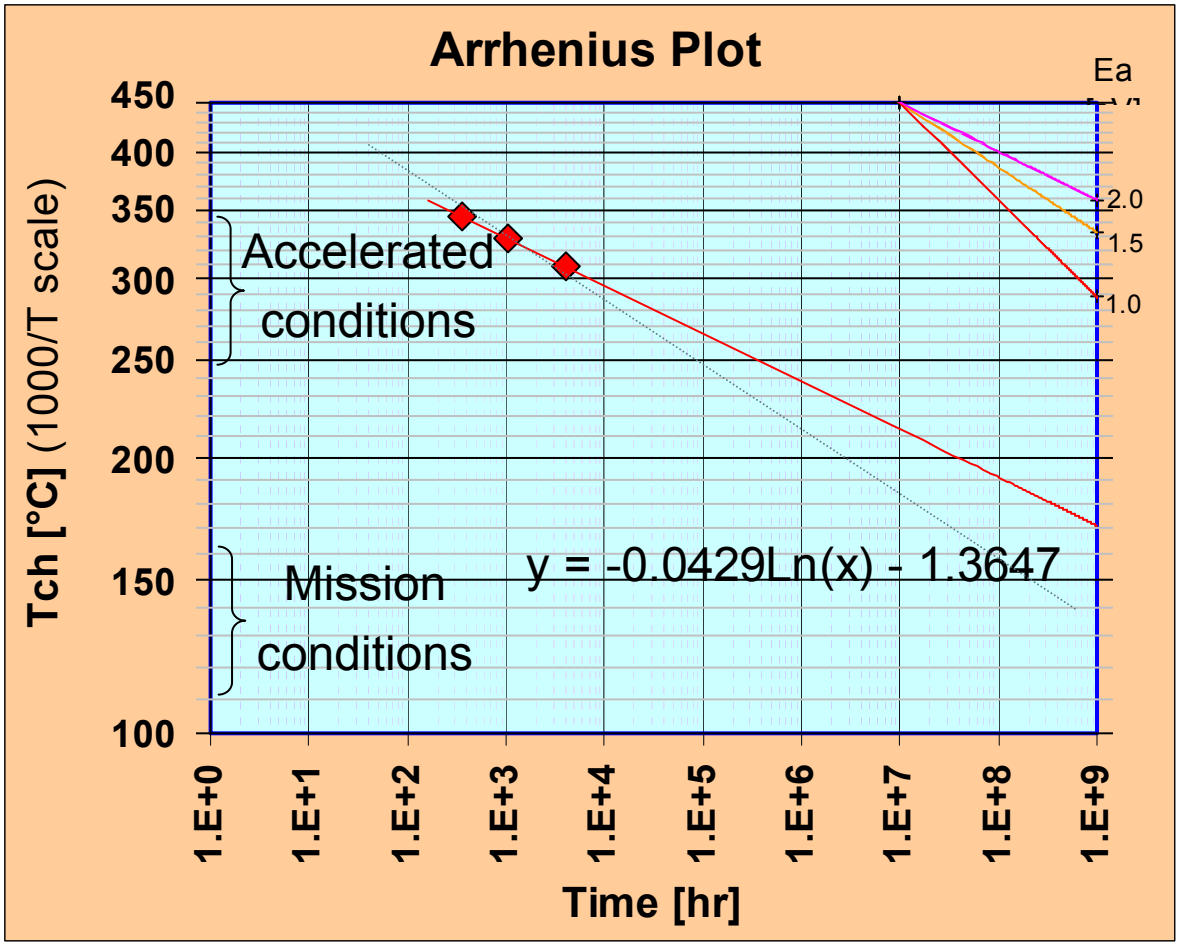
$1000/T= A*\ln(ML)+C$

The Plot is a straight line using these scales

The logarithmic curve fit in Excel returns this form and from the slope A the Activation Energy

$Ea=1000k/A=0.0862/A$

k is Boltzman's constant in $eV*K^{-1}$



The Ability to Thermally Accelerate Aging is Key to the Process

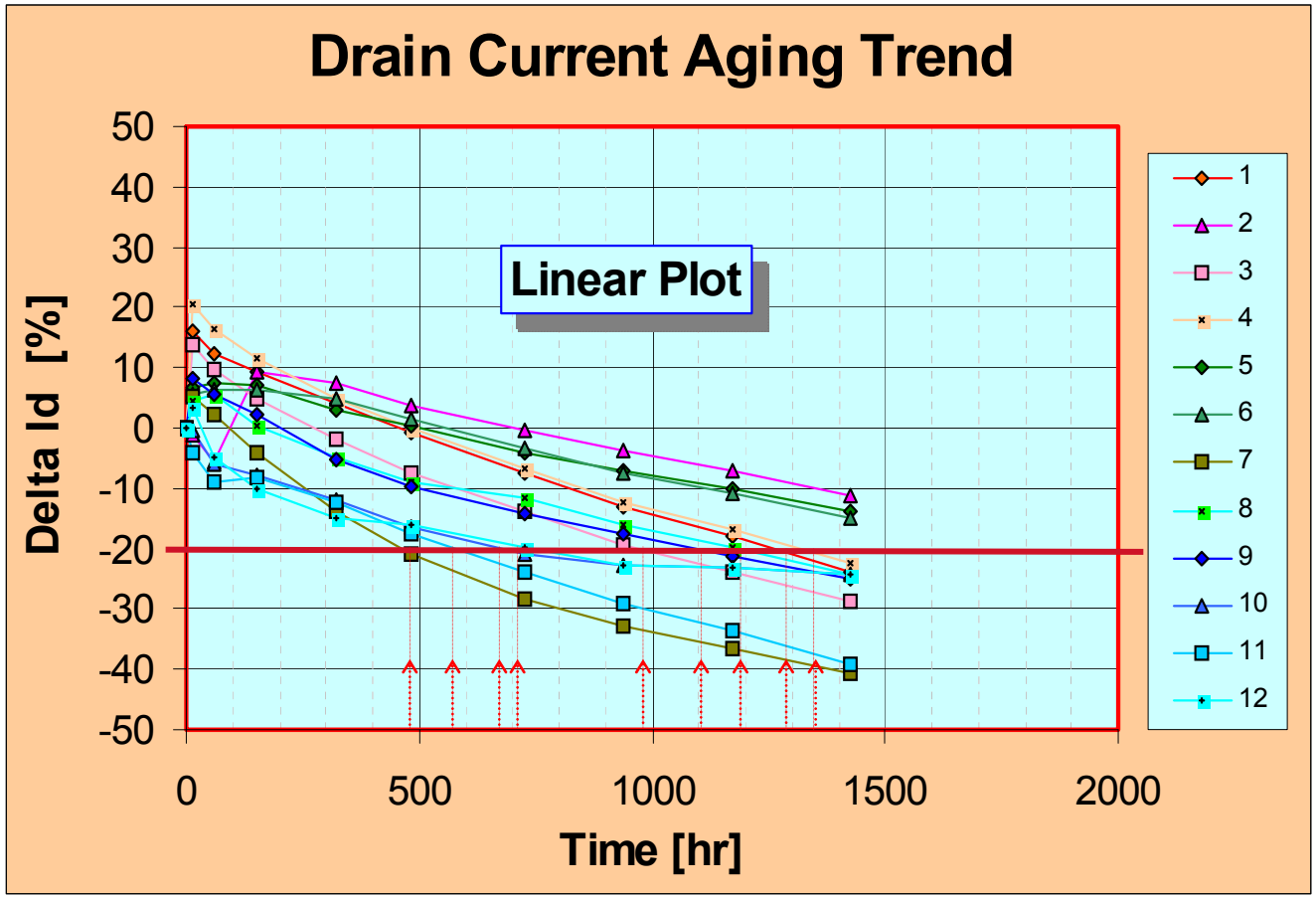
Life Test Scope

- Life Tests at minimum 3 temperatures are required to establish a credible trend
- Tch for the Life Tests is determined from self heating due to DC operating power dissipation and base plate temperature setting
- Test Vehicles are 12 Schottky Gate Field Effect Transistors per temperature group
- 20% Decrease in Drain Current is the Failure Criterion
- Drain Current is a key performance parameter and it is correlated with RF Power output capability

FET Test Vehicles and -20% ΔId Failure Criterion

Life Test Data Analysis

- Drain Current aging at Tch=329°C - Linear trend plot

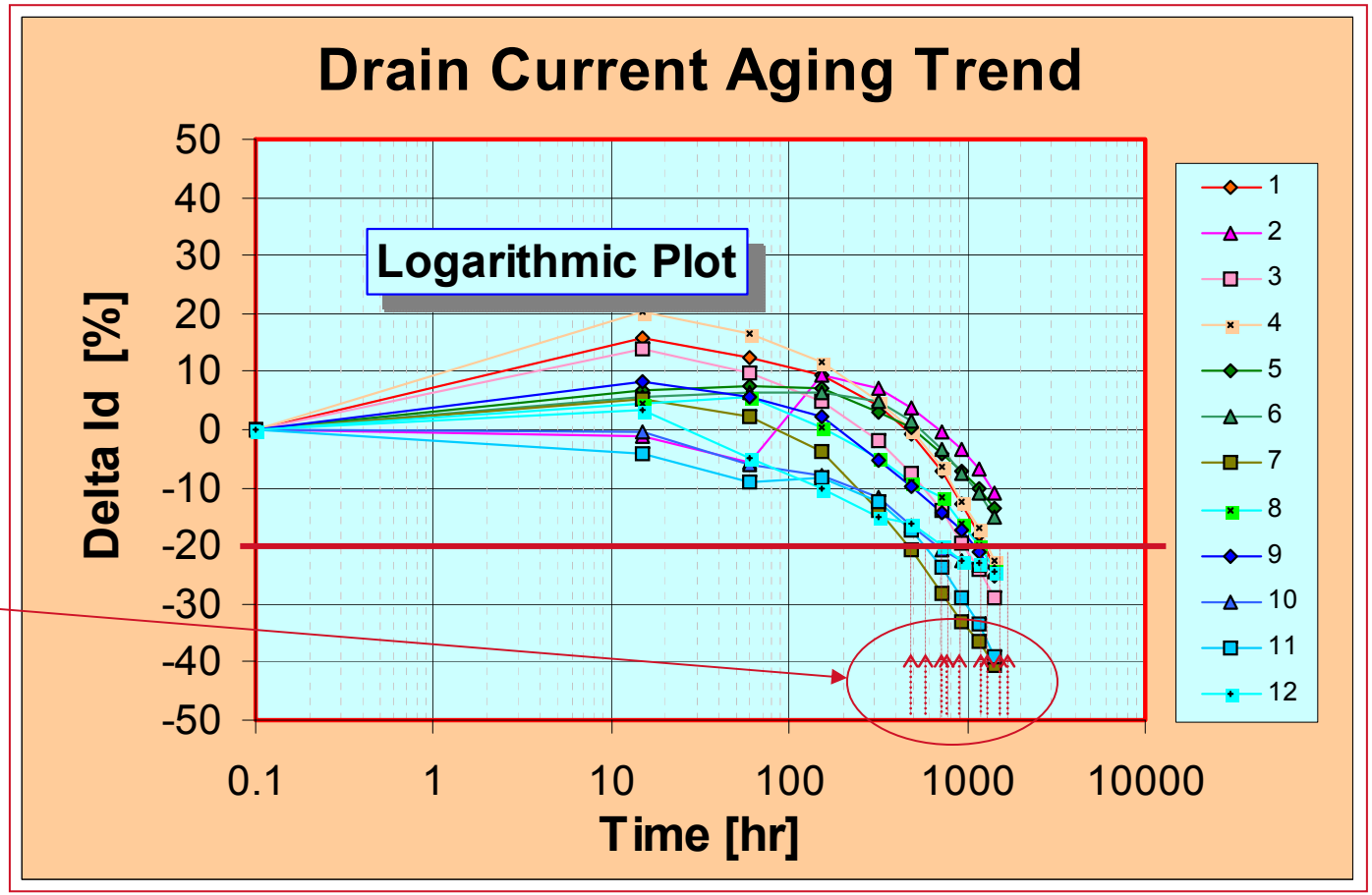


Times to Failure are indicated by arrows on the Time Scale

Life Test Data Analysis

- Drain Current aging at Tch=329°C - Logarithmic trend plot

The Times-to-Fail are tabulated and ranked and used in the next step



Logarithmic trend plot is a better visual indicator of ML

Life Test Data Analysis

- The Time-to-Fail values are tabulated and ranked
- For each failure the cumulative failed fraction, Q, is calculated using the median ranking formula:
  $Q=(F-0.3)/(N+0.4)$ F is the number of failed parts; N is the number of parts in the test
- Q is converted to the z score using NORMSINV function in Excel

The resulting z-score and TTF data is plotted using the Cumulative Failure Fraction Plot

F cum # failures	Q [fraction] (F-0.3)/(N+0.4)	Z score	TTF [hr] sorted
1	0.05645	-1.58528	450
2	0.13710	-1.09346	570
3	0.21774	-0.77984	670
4	0.29839	-0.52904	700
5	0.37903	-0.30802	950
6	0.45968	-0.10125	1100
7	0.54032	0.101246	1174
8	0.62097	0.308024	1200
9	0.70161	0.529045	1200
10	0.78226	0.779842	1700
11	0.86290	1.093456	1900
12	0.94355	1.585278	2100

The Id trend plot is reduced to the TTF and Z-score data array

The Cumulative Failure Plot: Tch=329°C

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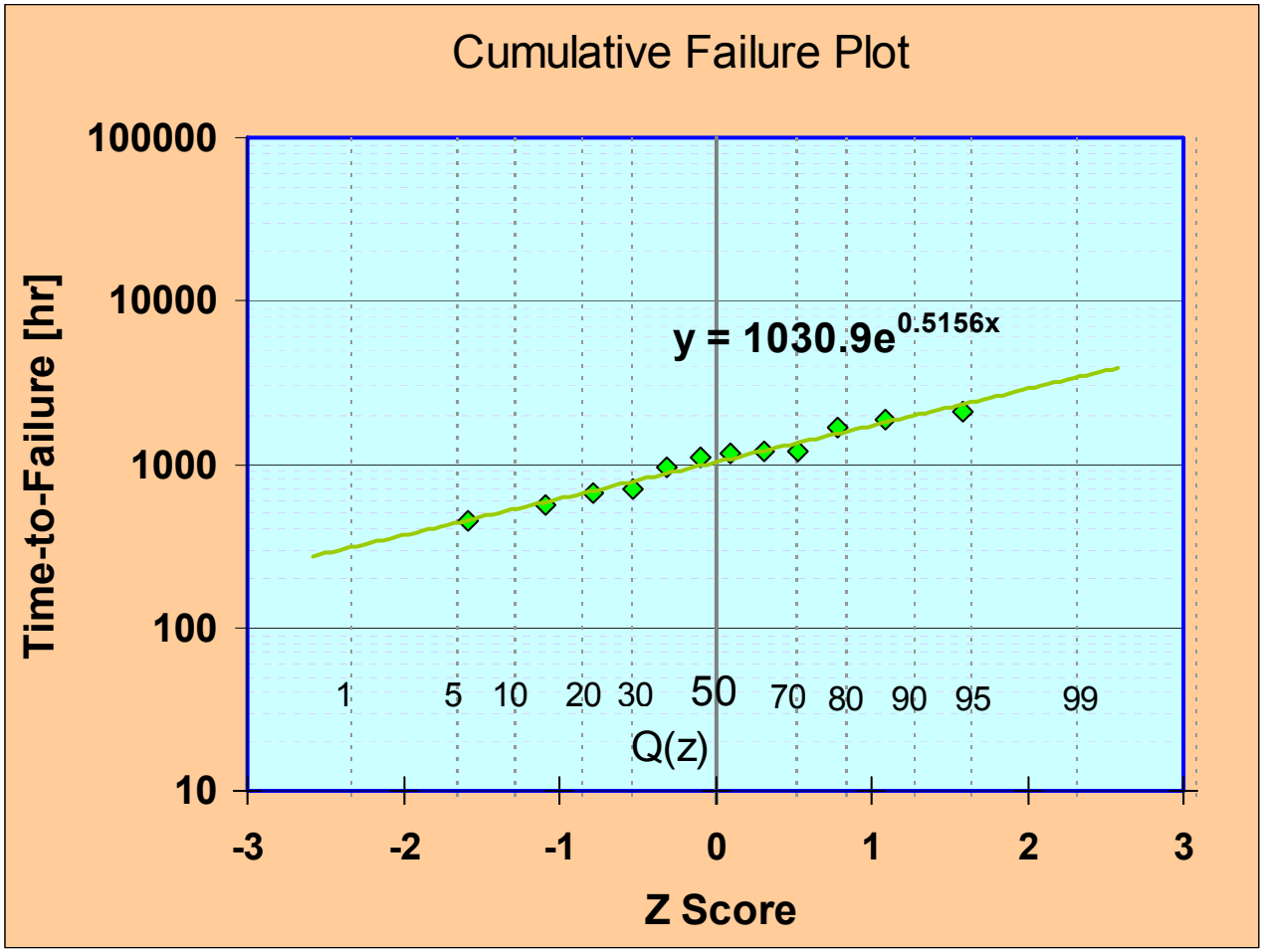
The exponential curve fit in Excel returns the form

$TTF = ML^* e^{\sigma^* z}$

The extraction of ML and σ is direct

ML=1031hr

σ=0.52



The Cumulative Failure Plot Provides ML and σ Directly

All 3 Cumulative Failure Plots

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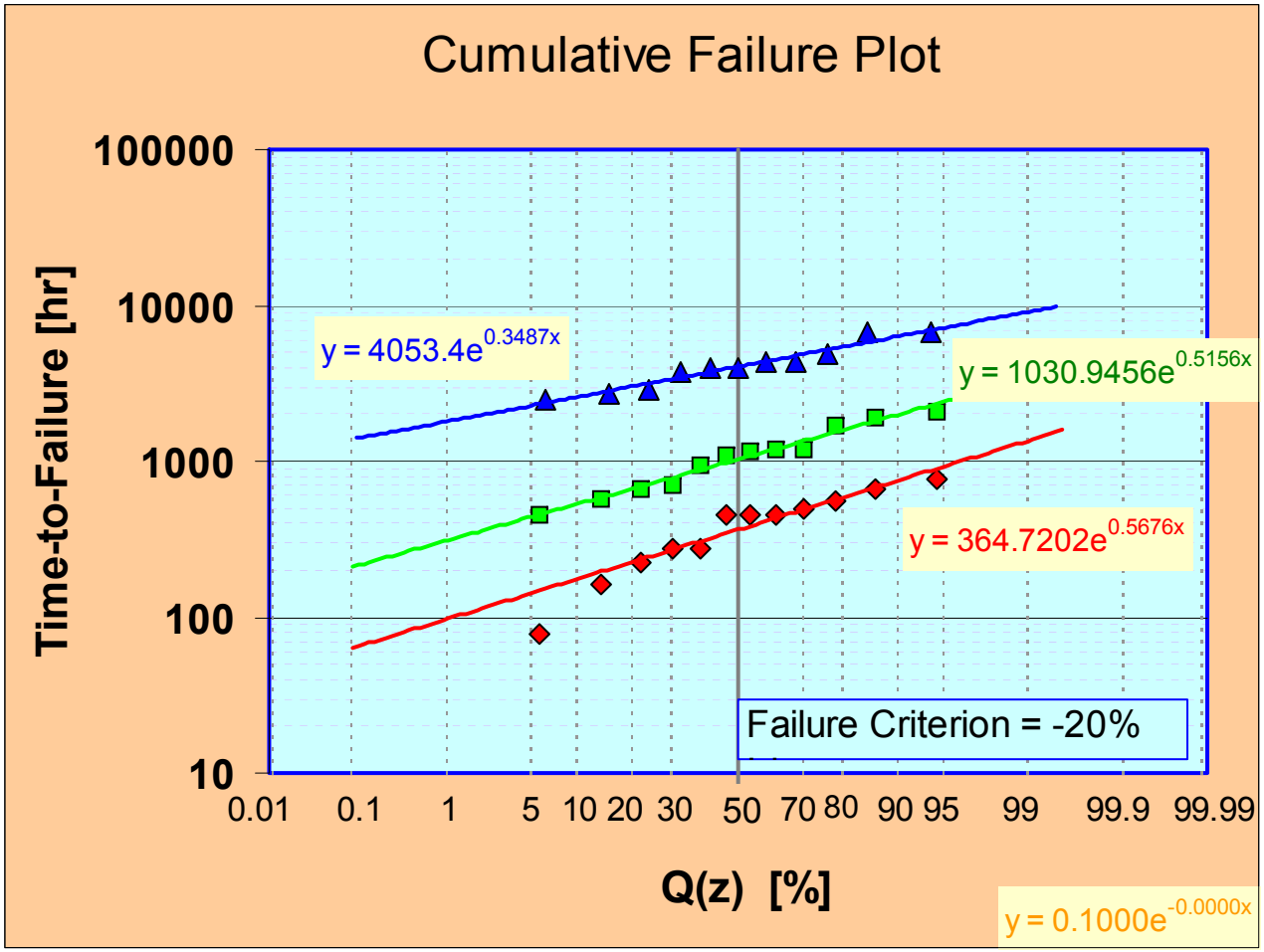
The extraction of ML and σ is direct for all 3 temperature groups

Tch[°C]	ML[hr]	σ
345	365	0.57
329	1031	0.52
308	4053	0.35

Tch and ML are ready to be plotted on the Arrhenius coordinates



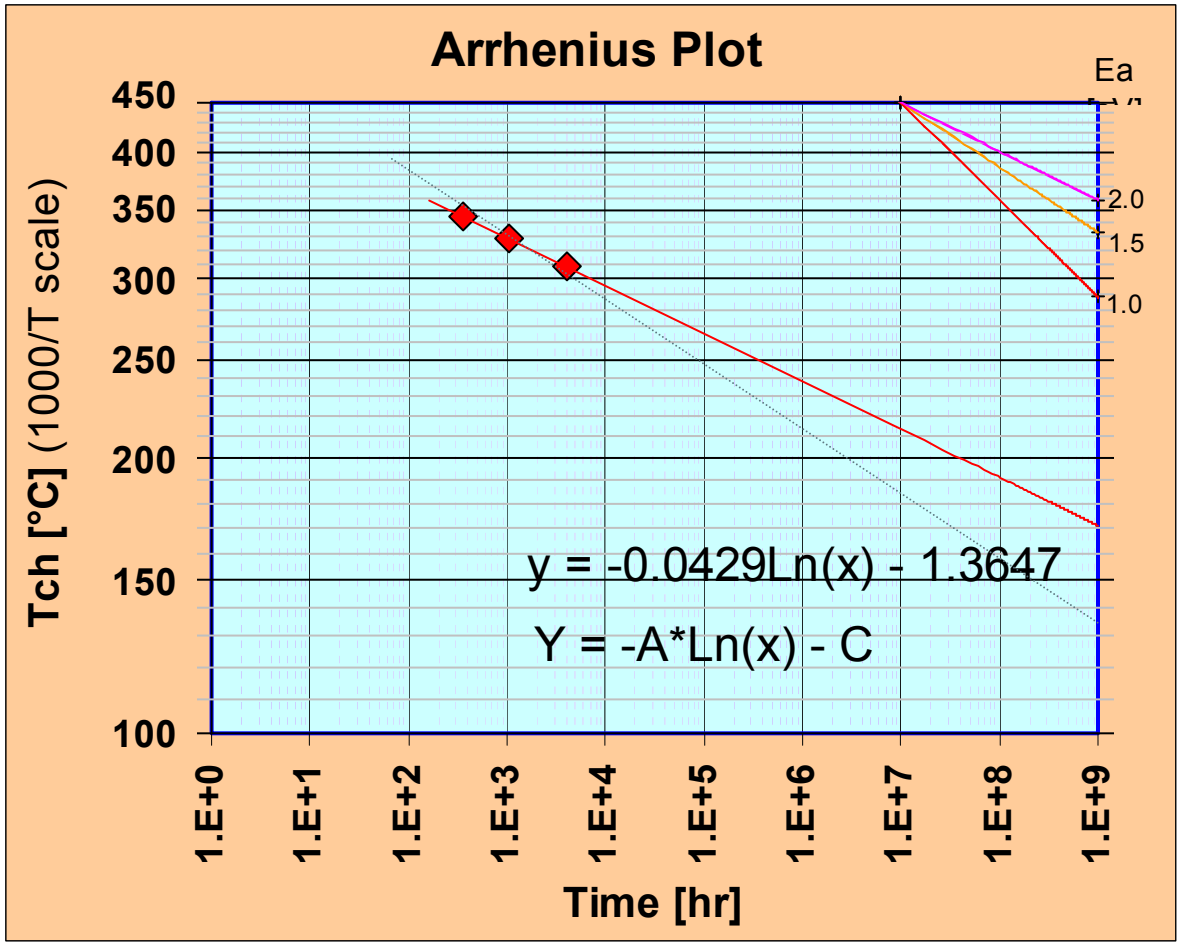
The Cumulative Failure Plot Provides ML and σ Directly

The Arrhenius Plot for the 3 Life Tests

- Tch is converted to 1000/Tch in [°K^{-1}]
- Note negative sign forces Temperature increase bottom to top

Tch [°C]	ML [hr]	1000/Tch [°K^{-1}]
345	365	-1.618
329	1031	-1.661
308	4053	-1.721

- ML and 1000/Tch are plotted on the Arrhenius Coordinates
- Ea=0.0862/A
- Ea=2.01eV



The Arrhenius Plot Provides Ea Directly

Reliability Metrics Summary

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The Reliability Metrics based on all 3 temperature groups used in this example are

Tch[°c]	ML[hr]	σ	Ea[eV]
345	365	0.57	
329	1031	0.52	2.01
308	4053	0.35	

Projections are based on the Arrhenius relationship

$ML1/ML2 = e^{Ea/kT1}/e^{Ea/kT2}$

Extrapolate Time				
			Unknown	
Ea (eV)	t1 [hr]	T1 [°C]	t2=?? [hr]	T2 [°C]
2.01	**4.05E+03**	**308**	1.313E+10	**150**
1.50	**1.03E+03**	**329**	2.116E+08	**150**

The 2.01eV Arrhenius Line Projects ML= 1.3E10 at a Mission Tch=150°C
The Conservative 1.5eV Arrhenius Line Projects ML= 2.1E8 at Tch=150°C

Reliability Metrics Summary

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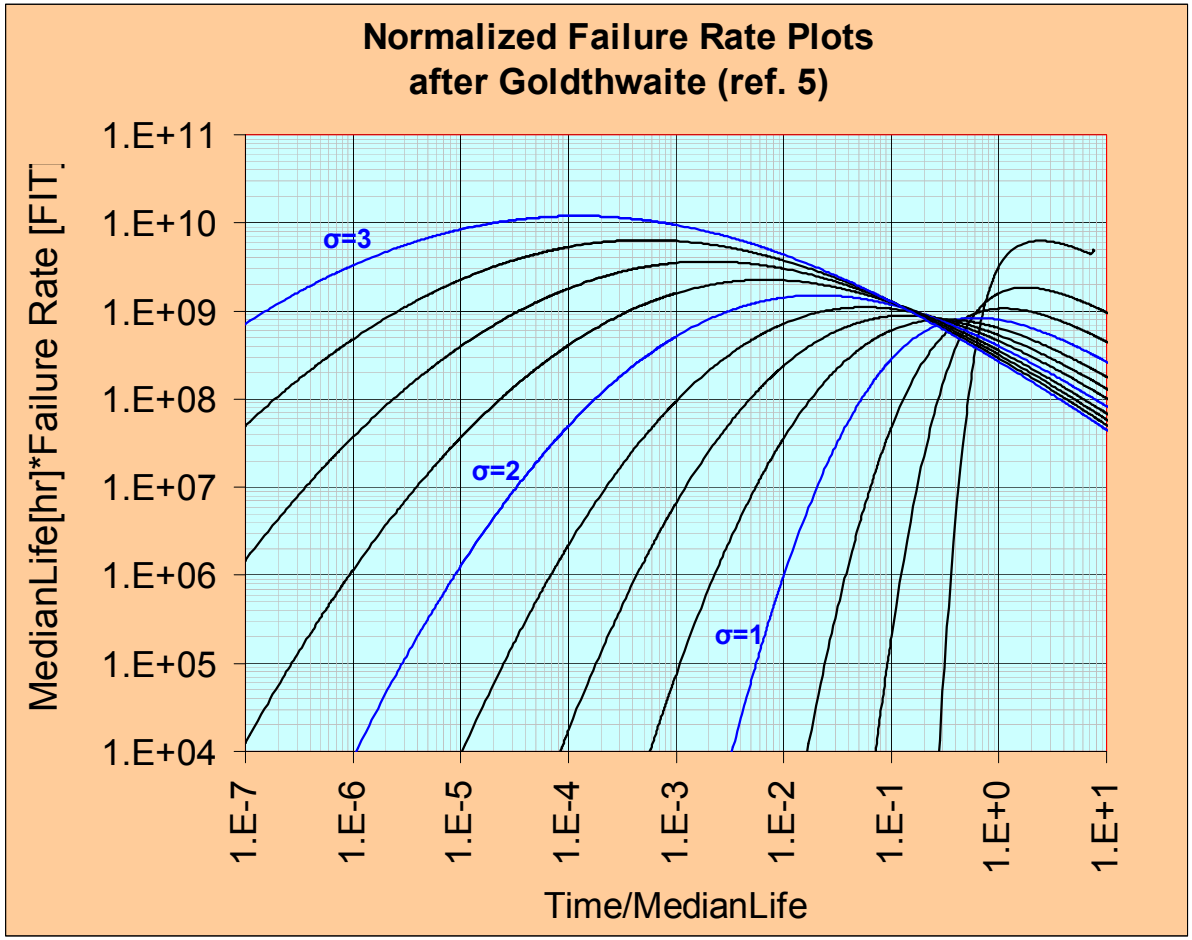

Normalized Failure Rate Plot is Used to Validate Our Extraction and Calculation Protocols

The Equipment/Set Up

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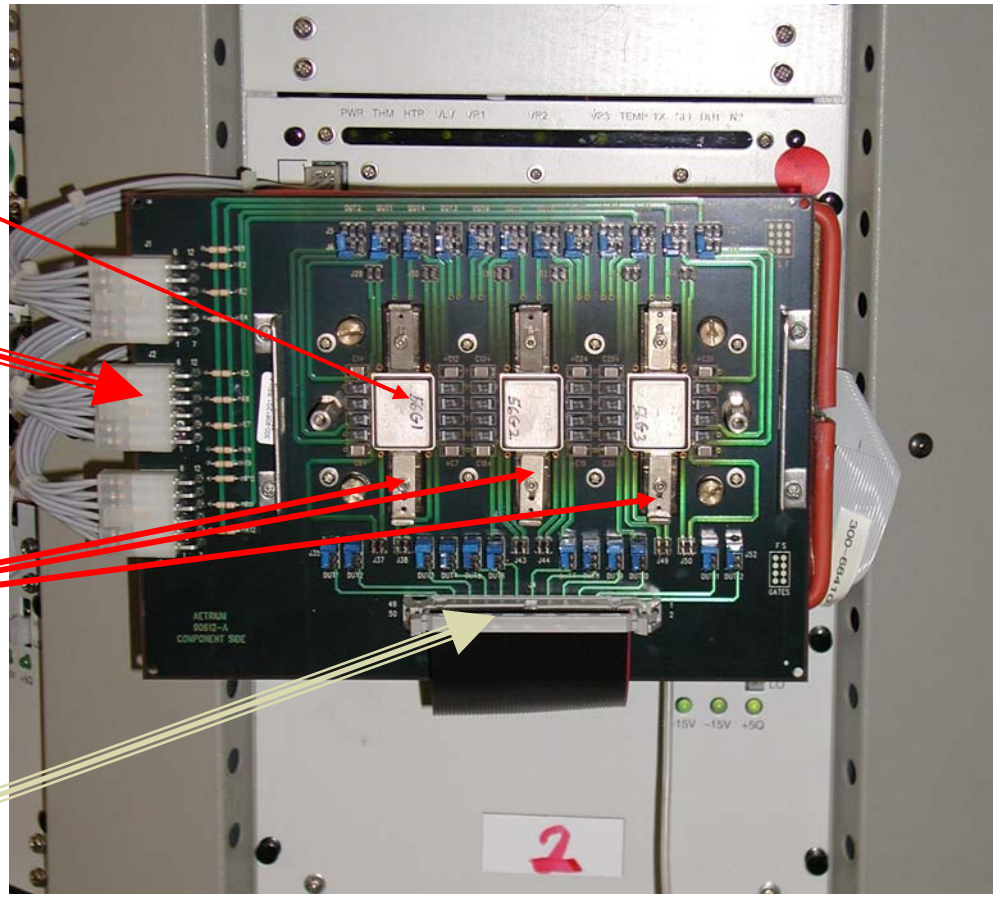
Device Package

4 DUTs Inside

Drain Bias

Heater Stage

Gate Bias



The Equipment Uses a Servo Feedback Loop Which Adjusts the Gate Voltage to Keep Constant Drain Current

The 2nd Key Stress in the application of microwave devices - Voltage/Electric field

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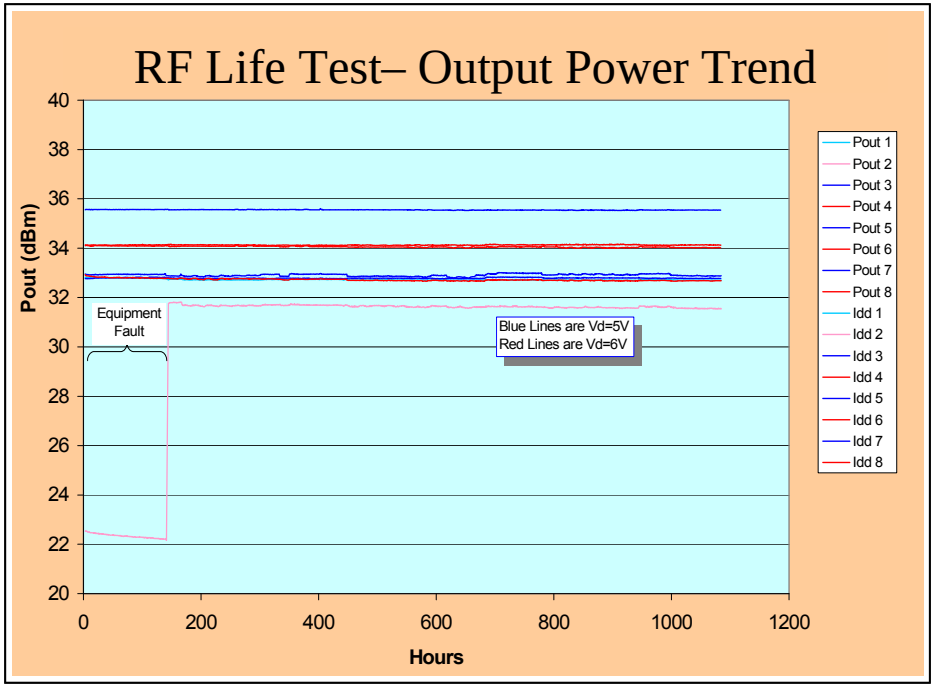
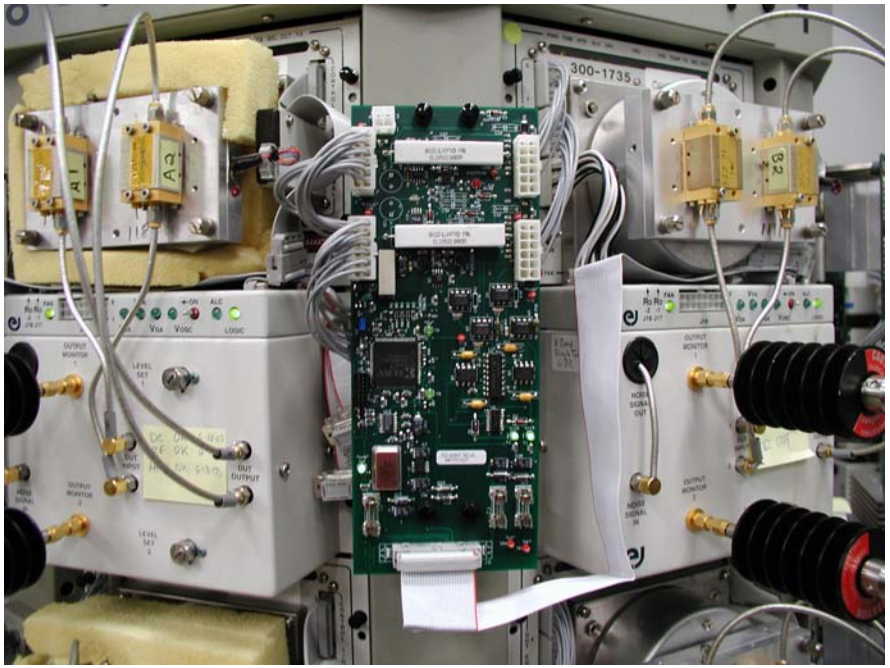


Stable Po during RF Life Test

RF Life Test Equipment



RF Operational Life Tests Are Used to Mitigate High Field Effects Also Known as Hot Electron Effect

References

1. F.H. Reynolds, “Thermally Accelerated Aging Of Semiconductor Components”, Proceedings of the IEEE, Volume 62, No2, Feb., 1974

2. D.S. Peck and C.H. Zierdt, Jr, “The Reliability of Semiconductor Devices in the Bell System”, Proceedings of the IEEE, Volume 62, No2, Feb., 1974

3. P.A. Tobias and D.C. Trindade, “Applied Reliability”, Van Nostrand Reinhold Company, Copyright 1986

4. W. B. Nelson, Accelerated Testing Statistical Models, Test Plans, and Data Analysis”, John Wiley & Sons, Inc, Copyright 1990, 2004

5. L. R. Goldthwaite, “Failure Rate Study for the Lognormal Lifetime Model”, Proceedings of the 7th Symposium on Reliability and Quality Control, 1961 p. 208-213

6. B.S. Hewitt and M. Benedek, “Decipher The Mystery of Reliability Statistics, MicroWaves, October, 1978