650V GaN HEMT Reliability for Automotive Applications

Ronald Barr VP Quality & Reliability

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Five Stages of Automotive Qualification

1. Product Qualification (Q101: Cookbook standard)
2. Extended Qualification (Beyond Q101)
3. Intrinsic Reliability (Lifetime/acceleration)
4. Extrinsic Reliability (FIT/PPM/MTBF)
5. Field Reliability

Note: this applies equally to commercial qualification

Product Qualification

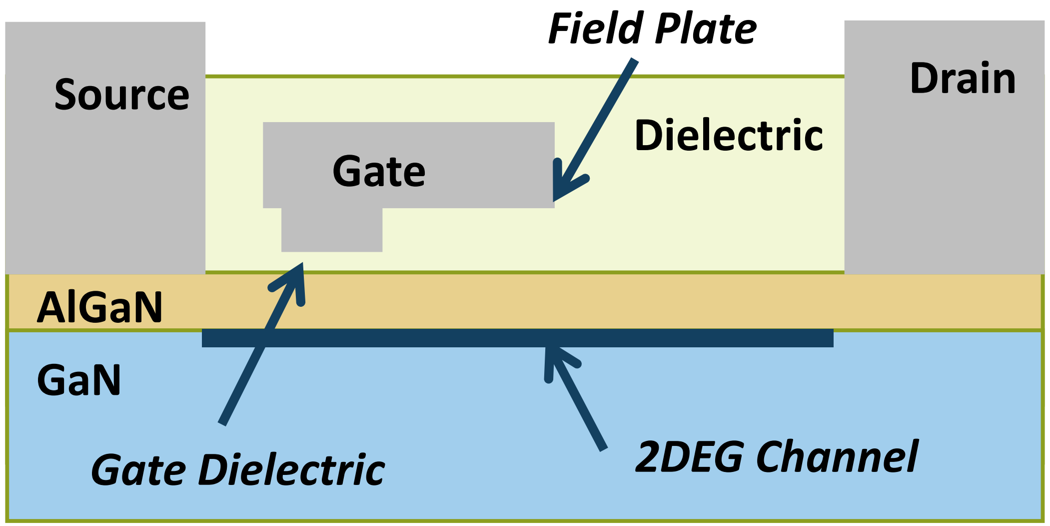
1. AEC Q101
2. Testing beyond qualification

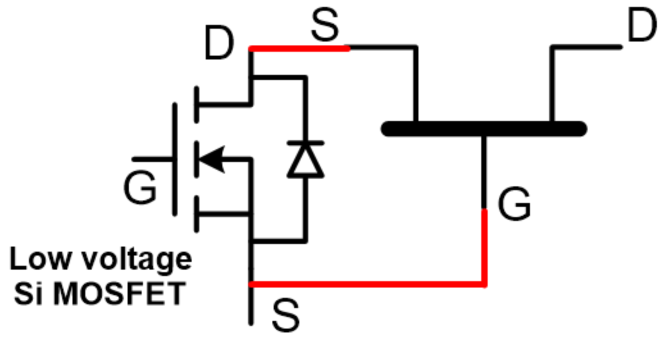
Most data from: TPH3205WSQA: Two Chip Normally-off, AEC-Q101

- D-mode GaN HEMT in series with an E-mode low voltage silicon FET.
- Package: TO-247
- $V_{DS(min)}$ = 650 V,
- $V_{(TR)DSS}$ = 800 V,
- $R_{DS(on)eff}$ = 62 mΩ,

Some data is also presented on TP65H035WSQA, qualified to 175C/650V

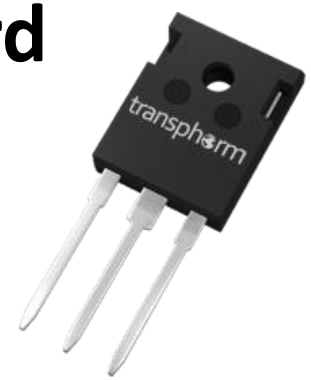
Simplified Cross Section of GaN HEMT





Normally Off

TPH3205WSQA: Qualified to AEC-Q101 Standard



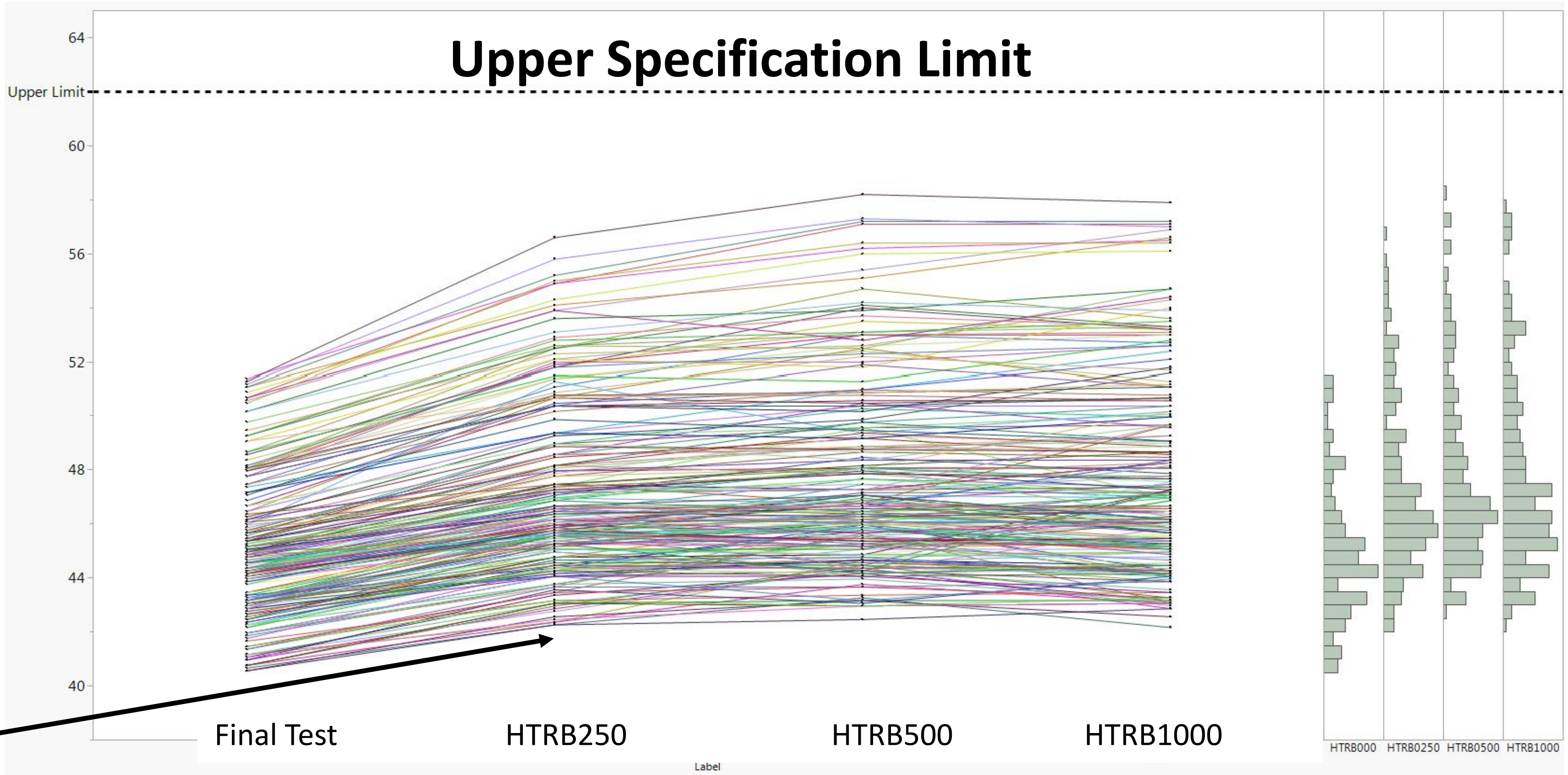
- **First step towards producing products for automotive market**

TEST	SYMBOL	CONDITIONS	SAMPLE	RESULT
High Temperature Reverse Bias	HTRB	TJ=150ºC V_{DS} = 650V 1000 HRS	3 lots – 77 parts per lot 231 total parts	0 Fails PASS
Highly Accelerated Temp and Humidity Test	HAST	130ºC 85% RH 33.3 PSI Bias = 100V 96 HRS	3 lots 77 parts per lot 231 total parts	0 Fails PASS
Temperature Cycle	TC	-55ºC / 150ºC 2 Cycles / HR 1000 Cycles	3 lots 77 parts per lot 231 total parts	0 Fails PASS
Temperature Cycling Hot Test	TCHT	125ºC Test After TC	3 lots 77 parts per lot	0 Fails PASS
Wire Bond Integrity	WBI	150ºC, 500 hours	3 lots 5 parts per lot	0 Fails PASS
Power Cycle	PC	25ºC / 125ºC ΔT = 100ºC 15,000 Cycles	3 lots 77 parts per lot 231 total parts	0 Fails PASS
High Temperature Storage Life	HTSL	150ºC 1000 HRS	3 lots 77 parts per lot 231 total parts	0 Fails PASS
High Temperature Gate bias (Cascode)	HTGB	150ºC 1000 HRS V_{GSS}=18V	3 lots 77 parts per lot 231 total parts	0 Fails PASS
High Temperature Gate bias (HEMT ONLY)	HTGB#2	150ºC 1000 HRS V_{GSS}=-35V	3 lots 77 parts per lot 231 total parts	0 Fails PASS
High Humidity High Temp Reverse Bias	H3TRB	85ºC/85% RH 1000 HRS 100V	3 lots 77 parts per lot 231 total parts	0 Fails PASS
Unbiased Accelerated Stress Test	UHAST	130ºC 85% RH 96 HRS	3 lots 77 parts per lot 231 total parts	0 Fails PASS
Destructive Physical Analysis	DPA	Post TC & HAST	3 lots 2 Parts Per Lot	0 Fails PASS

Post HTRB Dynamic Ron key reliability test for GaN

1000 Hours HTRB
Vds = 650V
150 Deg C

Ron shift <20%
for all parts

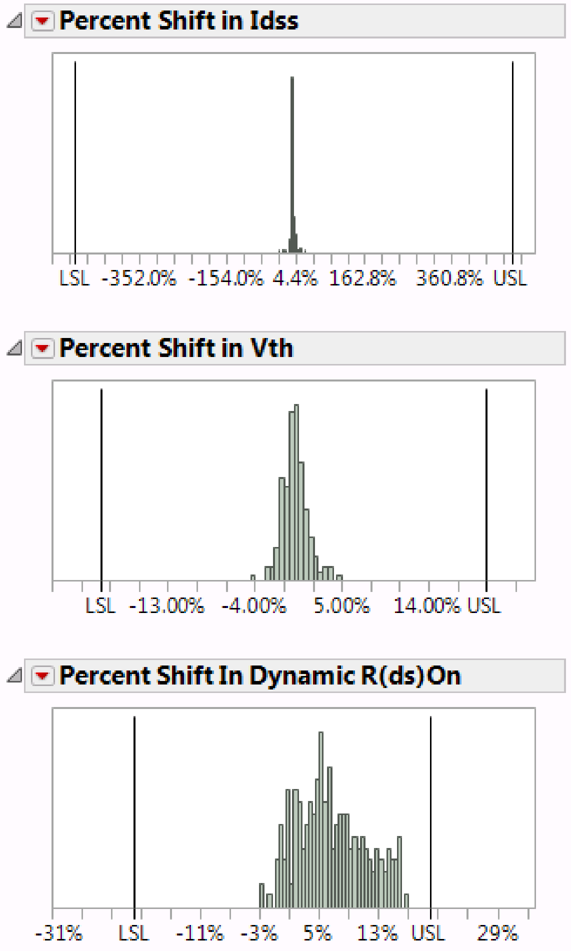


Dynamic R_{on} changes saturates after 250 hours

TP65H035WSQA
175C Q101 Automotive Qualification Test Data
Includes electrical, package and functional testing

- Key Qualification Tests @ **175C**
  - HTRB @ 650v
  - HTGB
  - Temperature Cycle (TC)
    - -55C to **175**C
  - HTOL

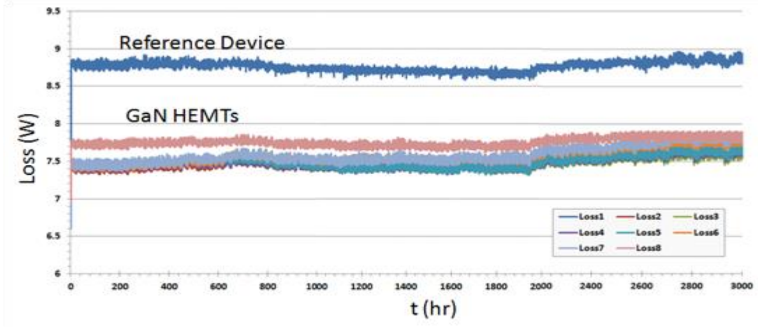
HTRB TEST DATA



Data showing the percent shift in Idss, Vth and Dynamic R(ds)on before and after 1000 hours of **<u>HTRB, at 650Volts, 175C</u>**

This meets and exceeds the requirements for passing automotive qualification per the Q101 Rev. D1 specification

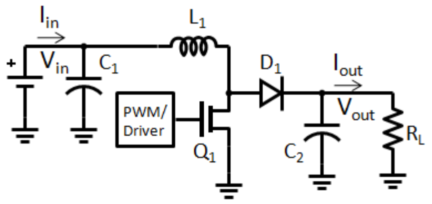
Qualification testing “beyond” Q101 includes HTOL, Gate Robustness, Radiation , HV Switching.

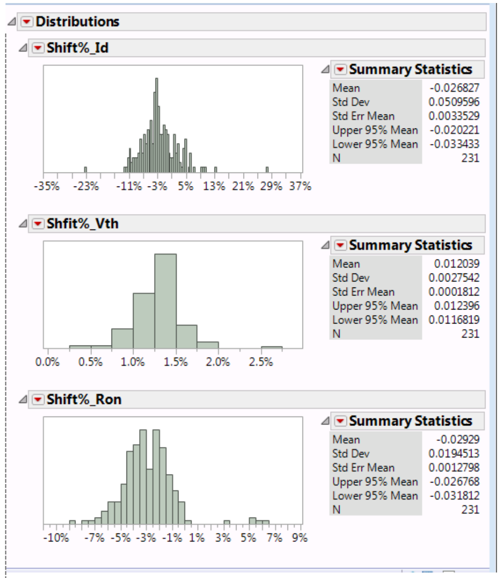


HTOL TESTING AT 175C

Circuit: Boost converter

- Input / Output voltage: 200V / 400 V
- Operating frequency: 300kHz
- Operating temperature: Tj = 175°C
- Output power: 410W
- Test time: 3000 hours

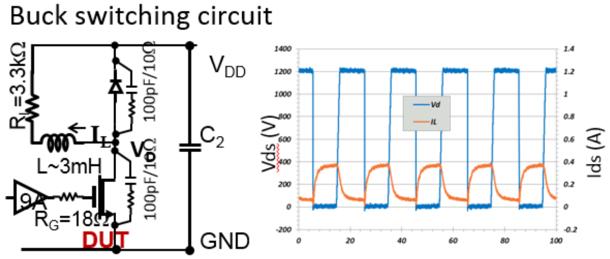




GaN HEMT Only HTGB 175C
Vg = -35 volts

Removes “protective” effect of SiFET on HEMT stress

Performed to Q101 standard

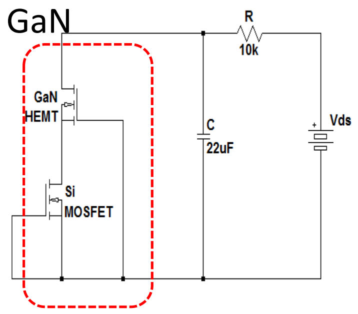


Vdd=1000V to 1200V
f=50KHz, 150KHz

1000V Switching for 1000 Hours

Accelerated Single Event Burn Out

- Facility: RCNP at Osaka University
- Neutron source: White beam compliant with JEDEC JESD89A
- Total fluence: 1.3E+09 neutron/cm2
- Results: **<1.5 fit(CL60) @Vds=600V with no failure**

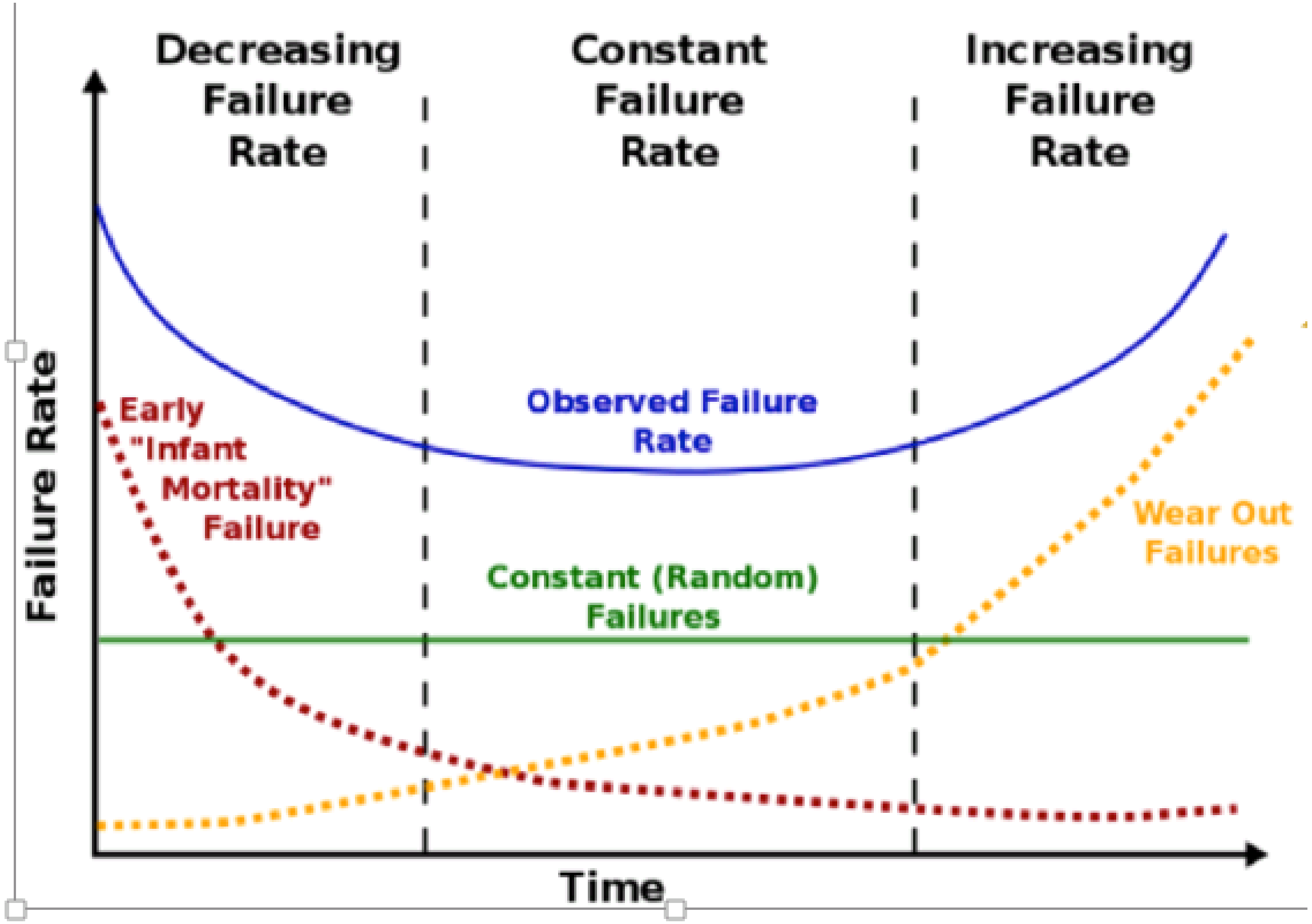


Intrinsic vs Extrinsic Testing

Extrinsic vs Intrinsic Testing
Both are required to be able to publish FIT/PPM/MTBF Data

EXTRINSIC RELIABILITY

Early Life Failure



INTRINSIC RELIABILITY

Wearout

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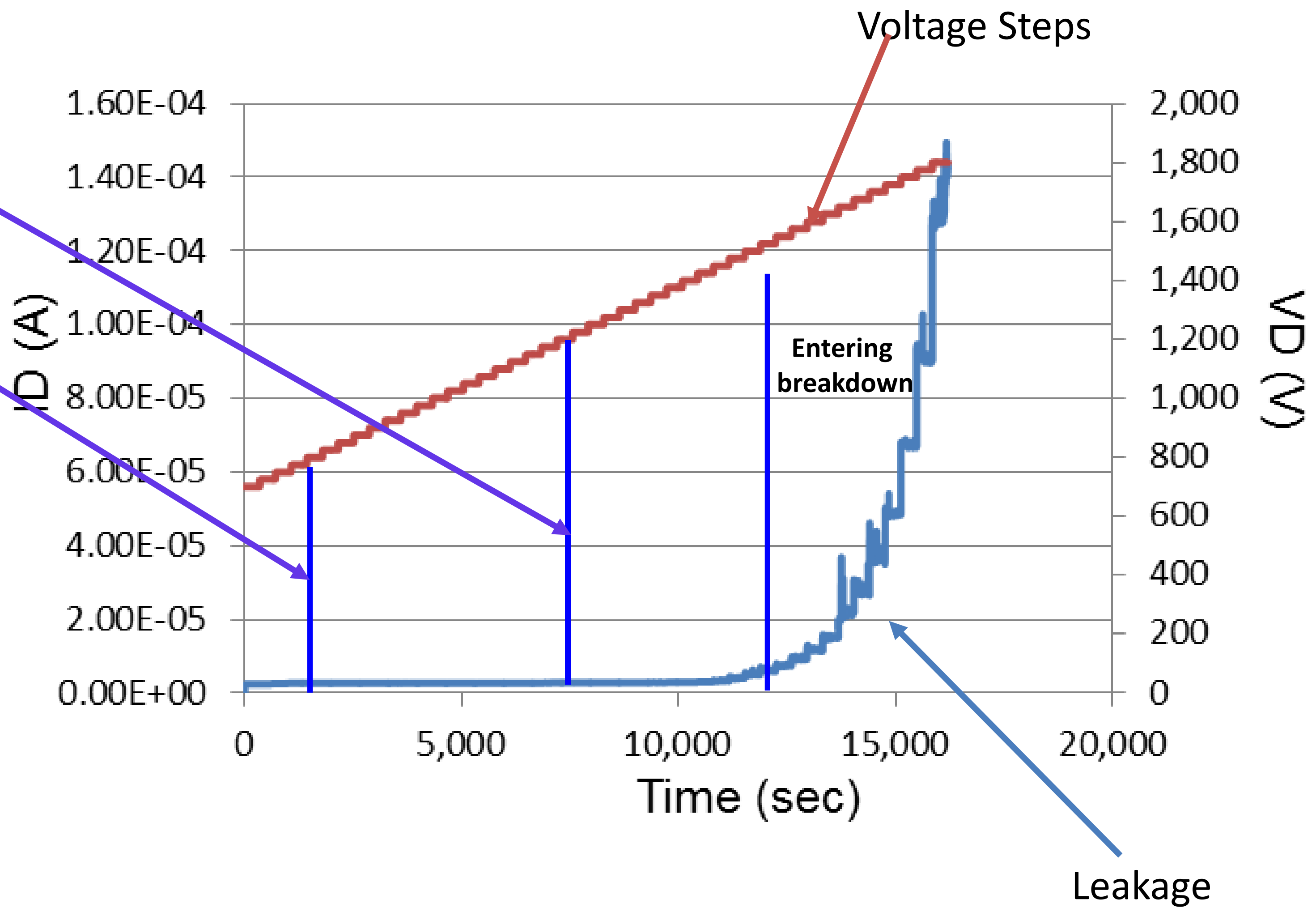
Pick the correct conditions for the test you need to run

Intrinsic Testing ~1200V

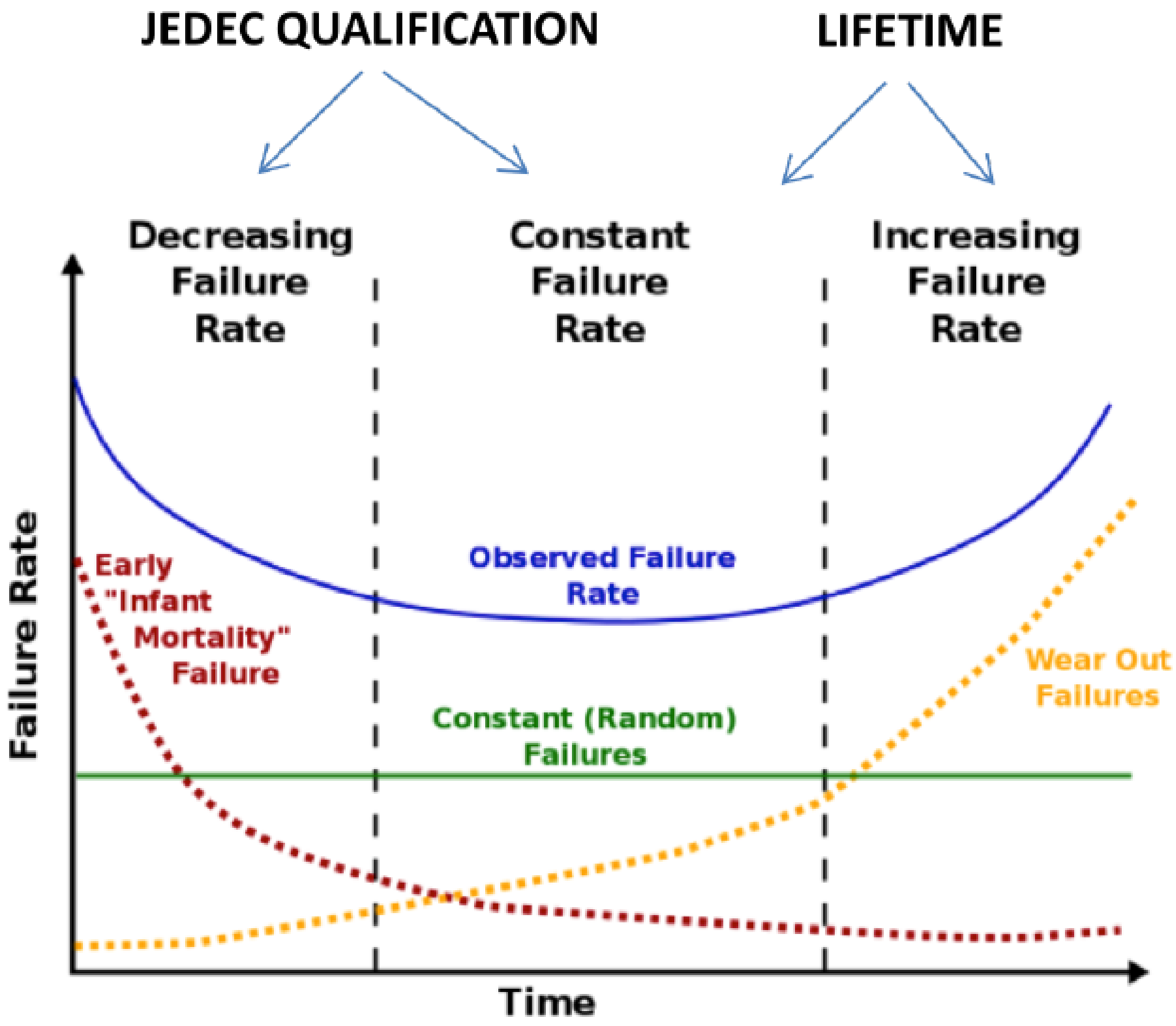
Extrinsic Testing ≤ 900V

Keep out of breakdown region!



Intrinsic Reliability

Intrinsic Failure focuses on Wear out



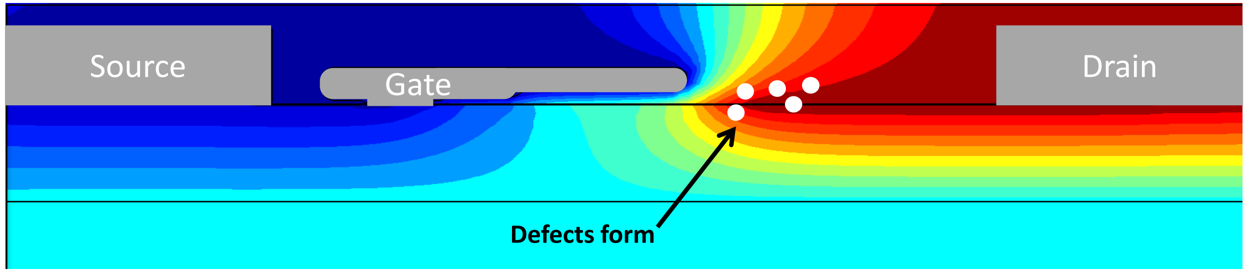
Wear out testing only addresses end of life

m = shape parameter of Weibull, also called β

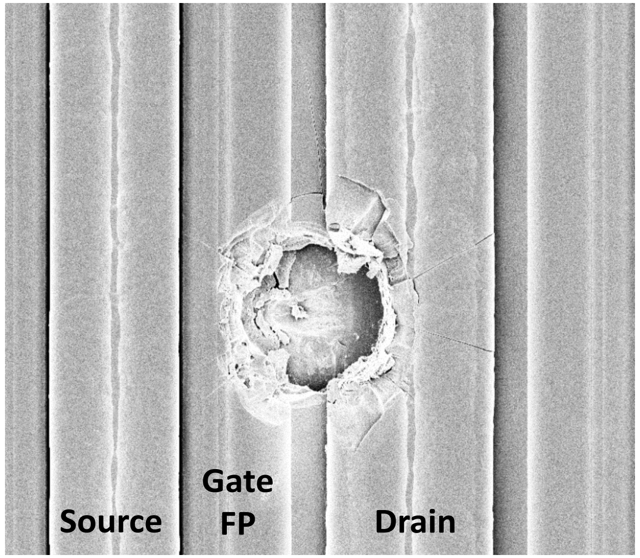
High Temperature Reverse Bias Primary Failure Mode
Lateral breakdown from Field Plate to Drain

- Under high electric field defects form in the dielectric
- Dielectric failure allows short from Gate-to-Drain
- Same mode observed in Infant Mortality, Useful Life and Wear out
- Failure mode limits the lifetime of the device in most mission profiles

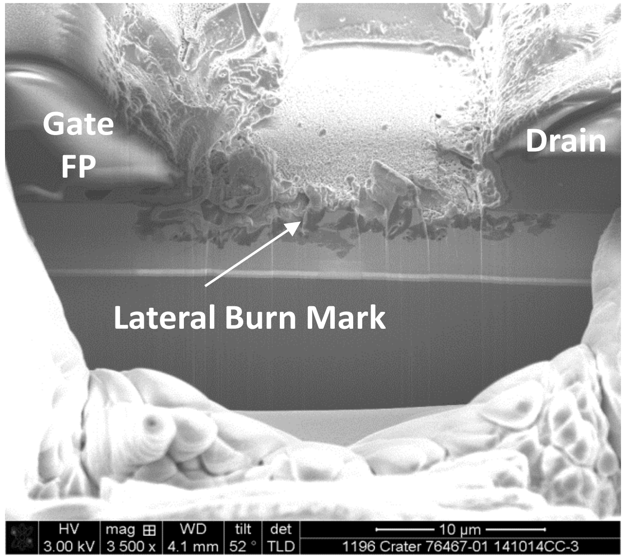
High Electric Field



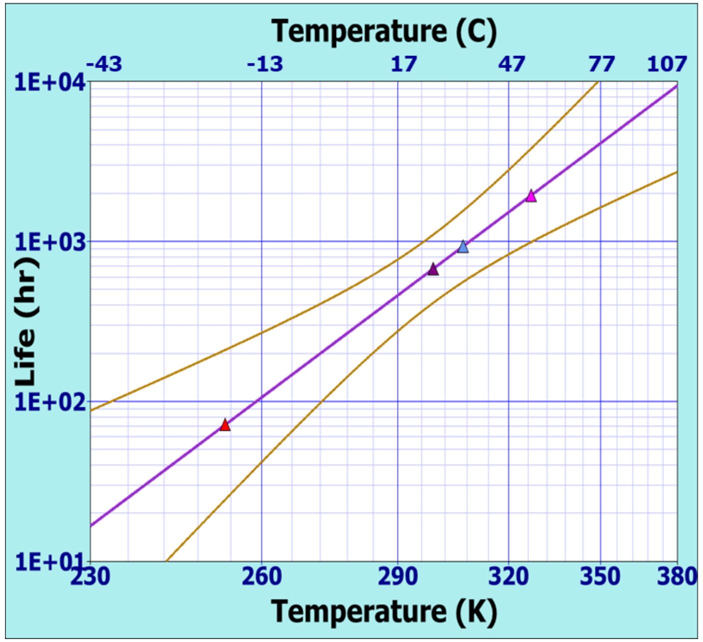
Overhead View

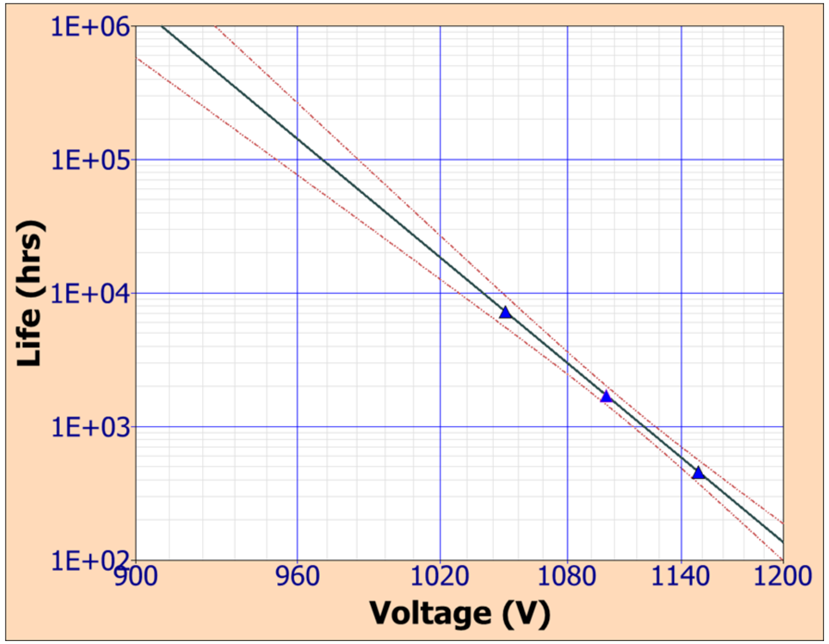


Cross Section



Determination of voltage and temperature acceleration factors: Physics of Failure
Three temperature/Three voltages





HVOS Testing to Failure:

- Voltage: 1000 V to 1200 V
- Temperature: -20°C to 150°C

- **Temperature Acceleration**
- Arrhenius : Eaa=-.30 eV

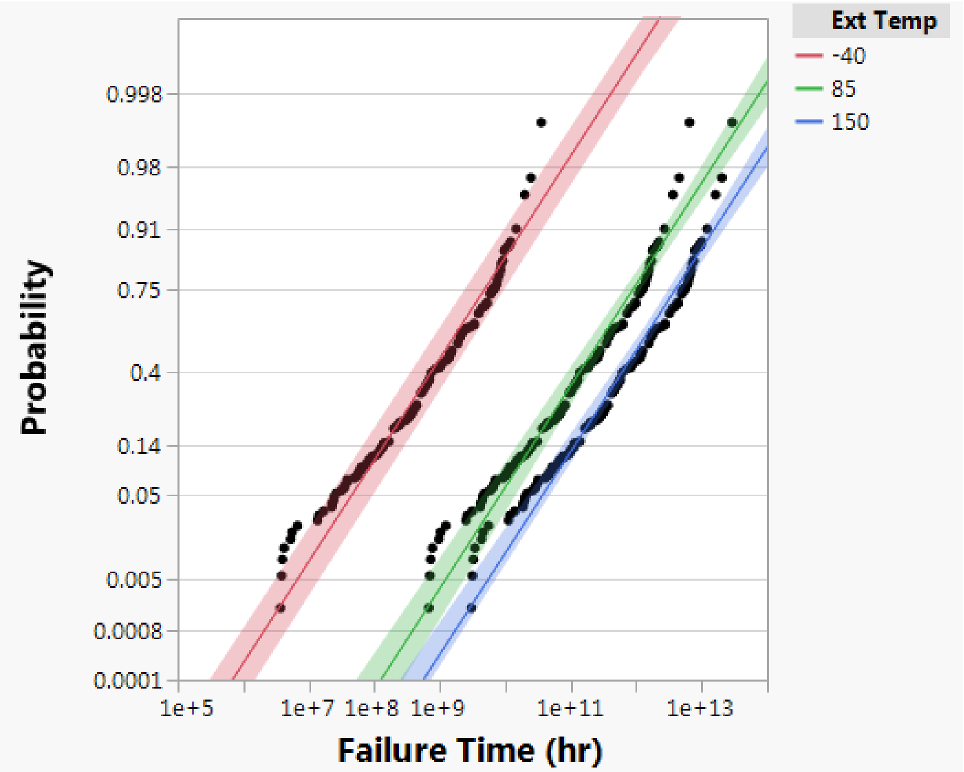
- **Voltage Acceleration**
- V Model: e $^{-(ϒ*ΔV)}$
- ϒ=.026

Note: the standard calls for the use of the V model for voltage acceleration unless there is data supporting an alternative: V model results in the "shortest" lifetime

HVOS: Wear out lifetime exceeds typical 10 year customer requirement by large factors

Acceleration factor and wear out are very important parameters for understanding device reliability.

This data should not be used to report FIT rates or PPM quality!



Typical Use conditions lifetime ~10^8 hours

Extrinsic Reliability: *Early Life Failure (ELF)*
Field Reliability Data

Parts Per Million (PPM)
Failure in Time (FIT): Failures per billion device hours
Mean Time Between Failure (MTBF)

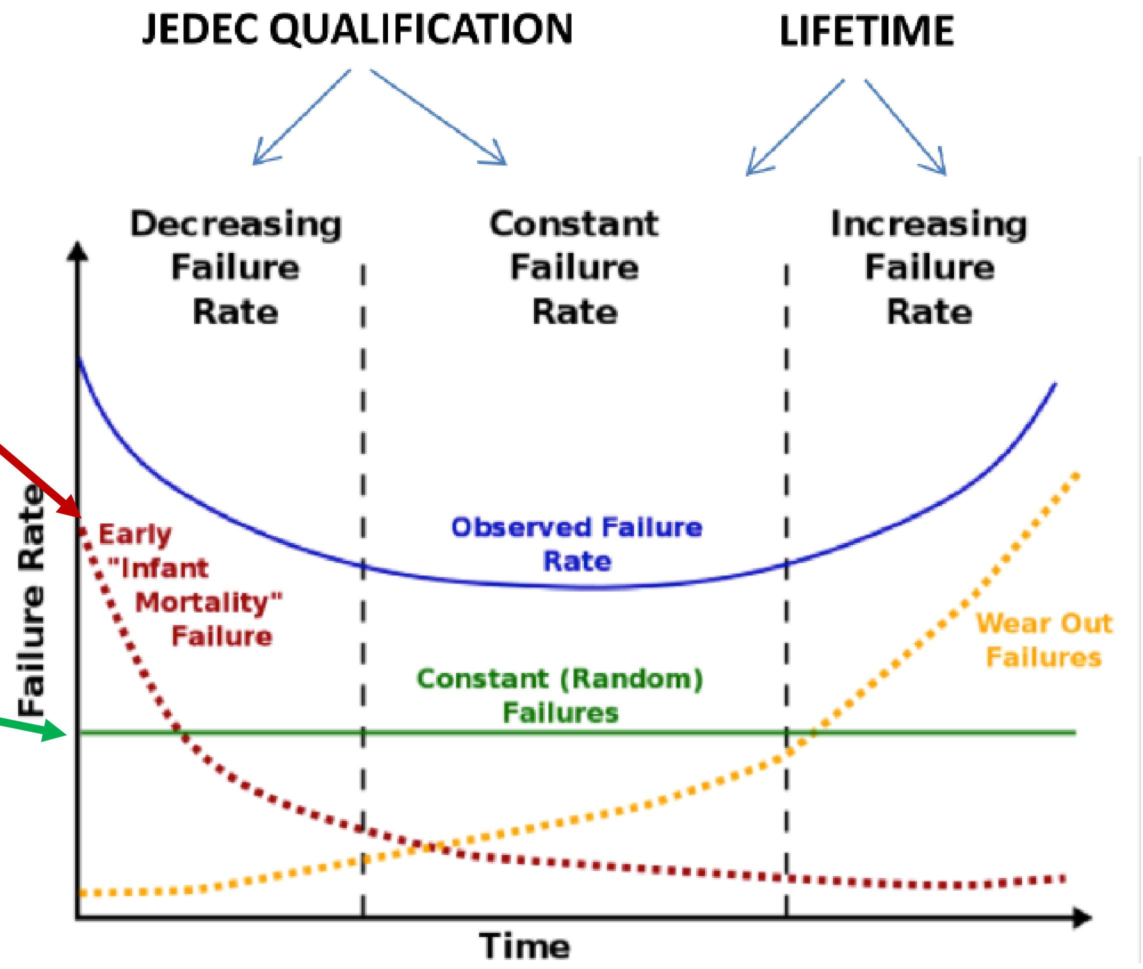
PPM Method vs. FIT Method

All definitions are from JEDEC Standard JESD74A

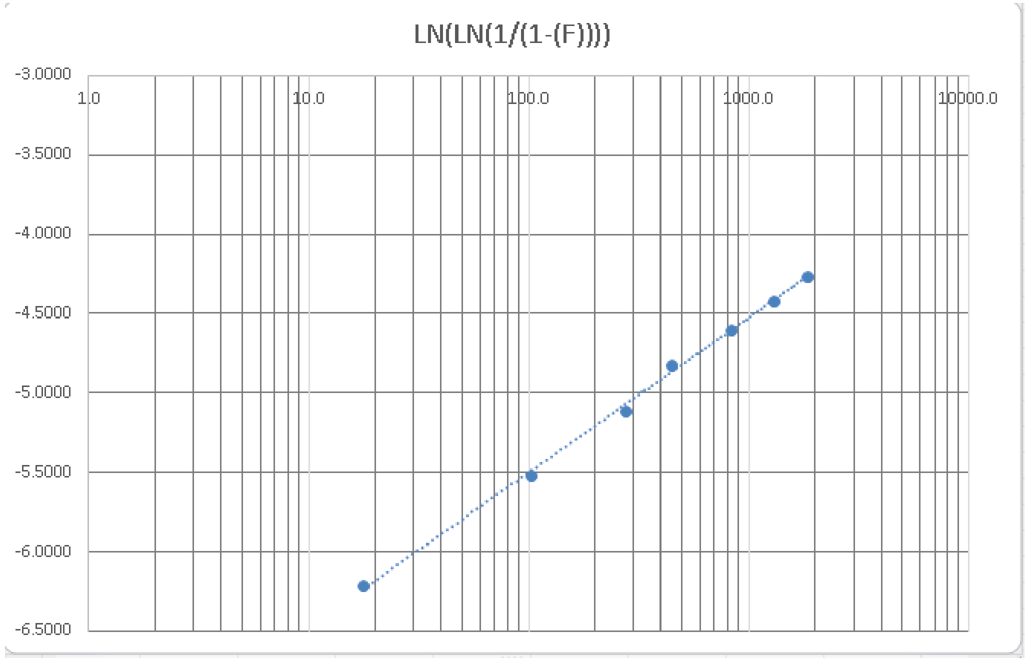
m = shape parameter of Weibull, also called β

PPM Method assumes infant mortality failures will continue: Weibull m < 1

FIT Method assumes constant failure rate: Weibull m = 1
Exponential Distribution



900V test data shows constant failure rate validates use of exponential model



900 V test to failure confirms that m = 1, justifying use of exponential function

Do not assume exponential distribution without supporting data!

- Stress parts at high voltage until some small percentage failed
  - Calculate Weibull parameters
  - Confirm m=1

Setting ELF Targets: ~1 FIT

- **MTBF (Mean Time Between Failures)**
- Do not confuse MTBF with time to first failure
    - Parts remaining = $e^{-(\text{expected lifetime/MTBF})}$
    - **100 year MTBF**
    - **10,000 PPM/Year**
    - **1,142 FIT**
- **87 million hour MTBF = 100 PPM/Year=11 FIT**

FIT = 10^9/$MTBF_{hours}$

88 PPM/Year = 10 FIT

8.8 PPM/Year = ~ 1 FIT

Note: MTBF units always seem really large. Do not let the numbers lull you into a false sense of security

Problem: Use of Temperature Acceleration Alone to demonstrate ELF FIT<1 requires large number of parts/resources. Even for Silicon!

Sample Size Required for 1 FIT @ 85C	
Eaa	# Parts
1.0	6,286
0.7	28,008
0.5	75,839
0.3	205,355
0.1	556,052
0.0	915,000
-0.1	1,505,659
-0.3	4,076,974
-0.5	11,039,493
-0.7	29,892,371
-0.9	80,941,563
-1.0	133,191,711

Assumes "standard" HTRB Qual Conditions: 150C/650V/1000 hrs per test

Power Electronics run at relatively high temperatures, reduces acceleration factor of standard HTRB testing

Voltage Acceleration is required

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Early Life Failure
Industry First for High Voltage GaN

- 4000 Devices Tested
- 1e^9 accelerated device hours
- Voltage Range: 520V – 900V
- Temp Range: 25C – 175C

Temperature and voltage conditions can be used to generate lifetime estimates based upon mission profile

ELF @ 150C

Voltage	FIT	MTBF hrs	PPM/Yr
520 V	0.42	2E+09	3.6
480 V	0.15	7E+09	1.3
400 V	0.02	5E+10	0.2

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Field PPM Rates showing excellent reliability in line with other WBG devices in production

- >400k production parts shipped to date
  - 3 Billion device hours
- To calculate field return rate we "discount" the number of device hours by ½ (so that we do not take "credit" for parts that have not actually shipped to users yet)
- Field failure rate:
  - 20 PPM/Year
  - FIT =2.2

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Pitfalls to avoid in reliability testing

- Acceleration testing: pick reasonable conditions and if using voltage acceleration stay out of the breakdown region
- Use the appropriate voltage acceleration model
  - V model is generally appropriate unless you can justify a different one
  - 1/V Model may give you false sense of security
- Do not use wear out data to predict field reliability
  - Early Life Failure Testing: JESD74A

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Conclusion: Five stages in automotive qualification demonstrated

1. Product Qualification (Q101:Cookbook standard)
2. Extended Qualification (Beyond Q101)
3. Intrinsic Reliability (Lifetime/acceleration)
4. Extrinsic Reliability (FIT/PPM/MTBF)
5. Field Reliability