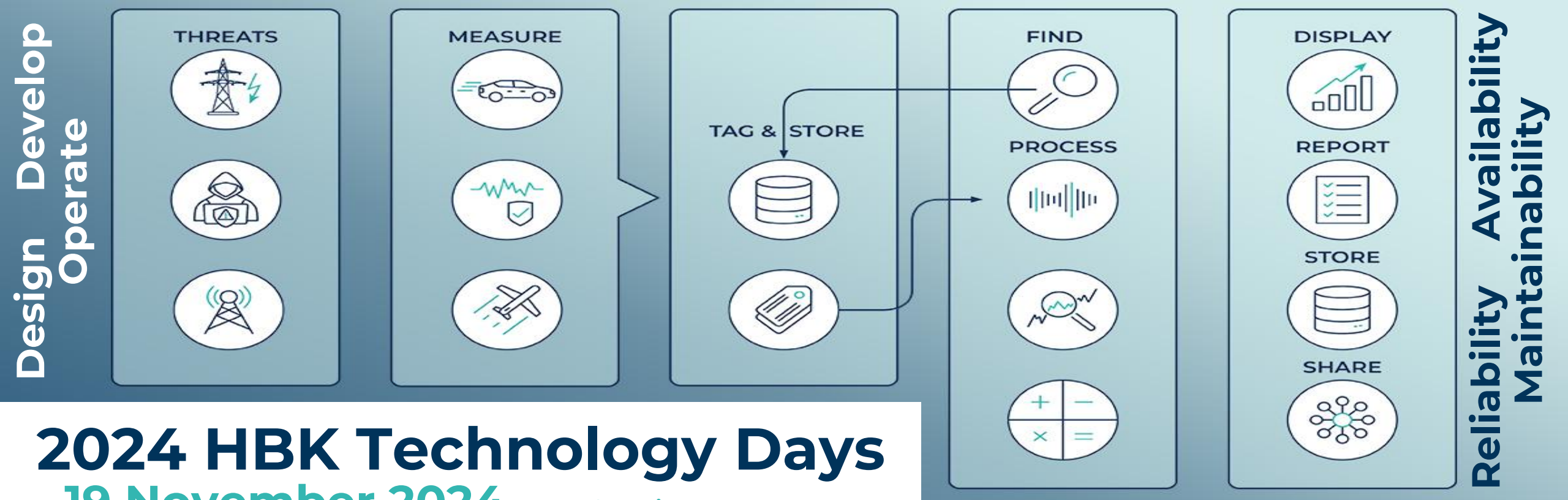




2024 HBK Technology Days

19 November 2024

Session 5: Reliability Engineering from Limited Failure Data

Accelerated Life Testing

Three approaches:

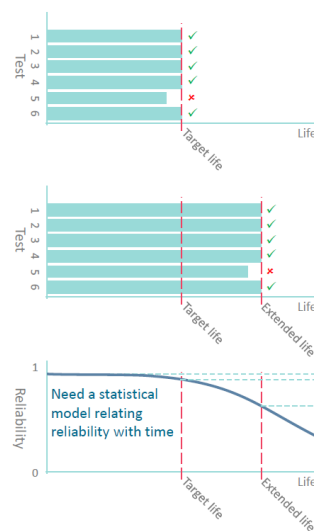
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2. Load amplification
3. Extended life testing (testing beyond target life)

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$$C_L = 1 - \alpha_L^n$$

but target reliability on test α_L is now smaller 😬

The new α_L (called α_L), depends on the reliability vs. time model
e.g. Weibull, log normal, etc.



- Statistical qualification of complex systems based on zero-failure evidence

Dr. Andrew Halfpenny,
Director of Technology – nCode Products, HBK

Statistical qualification of complex systems based on zero-failure evidence

Abstract

- Complex systems are susceptible to numerous failure modes. Conveniently, their reliable lifespan is often determined by a relatively small number of 'critical' modes. Often it is uneconomical to conduct separate reliability tests for each failure mode, designers typically focus on evaluating the critical ones. This raises the question: how confident can we be that those deemed 'non-critical' are truly non-critical?
- This presentation explores how one might estimate confidence in a specified reliability target when no failures have been observed during testing. This approach is valuable because zero failures are common among non-critical failure modes, given that test articles usually fail due to a critical failure mode first. The method involves using simulations of the tests (Virtual Testing) to calculate the damage ratio for each non-critical failure mode relative to the target lifespan of the component.

Statistical qualification of complex systems based on zero-failure evidence

- ▲ About the presenter, Dr. Andrew Halfpenny,
Director of Technology – nCode Products, HBK
 - Dr. Halfpenny has a PhD in Mechanical Engineering from University College London (UCL) and a Master's in Civil and Structural Engineering. With over 25 years of experience in structural dynamics, vibration, fatigue and fracture, he has introduced many new technologies to the industry including: FE-based vibration fatigue analysis, crack growth simulation and accelerated vibration testing. He holds a European patent for the 'Damage monitoring tag' and developed the new vibration standard used for qualifying UK military helicopters.

Statistical qualification of complex systems based on zero-failure evidence

How confident are we in our assessment of non-critical failure modes



Dr. Andrew Halfpenny

Director of Technology – nCode Products

Motivation

e.g. Automotive OEM:

*“In the past,
if we had reliability issues,
we’d swap components early under warranty.*

*But EV batteries contain thousands of
unservicable components.*

*There’s a mandatory 10 year / 150,000 mile warranty.
A reliability issue here could sink the company!”*

And

*“In the past, we would select a warranty period based on **market forces** and **over 50 years** of historical maintenance data.*

*Today, warranties are dictated by **politicians** for **brand new concepts** with **no historical data** whatsoever!”*



“For a **duty cycle** of 10 years (150,000 miles),
I require a **reliability** exceeding 95%
(i.e. fewer than 5% failures),
at a **confidence level** of at least 90%”

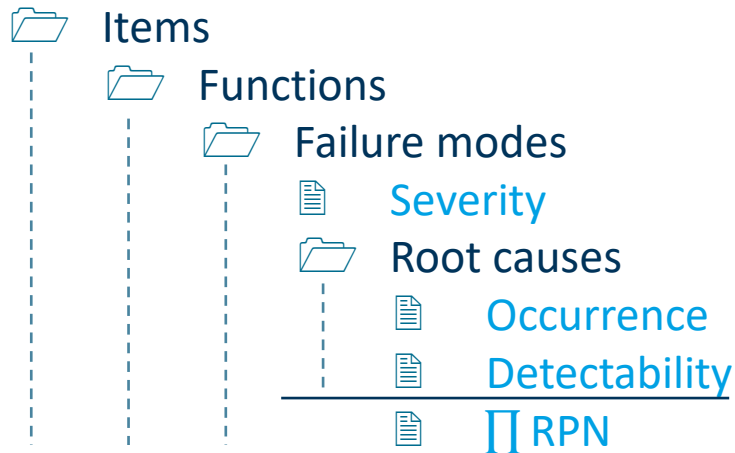
How do we find this?

Identifying failure modes

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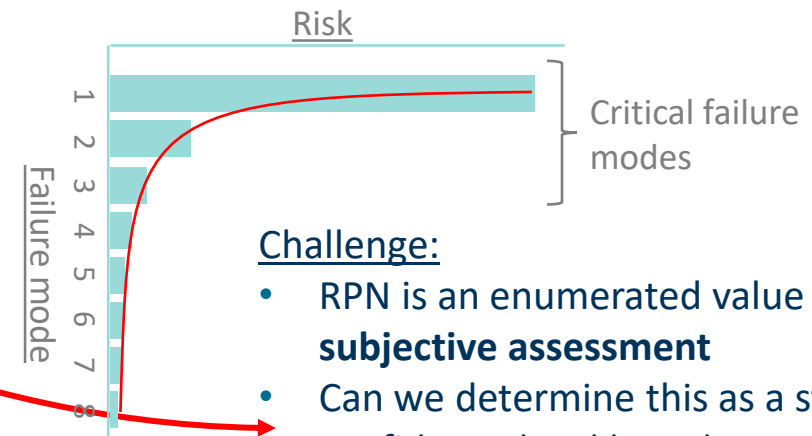
How do we find this?

FMEA – risk discovery and prioritization



What does it do
What prevents it doing that
How bad is it (1-10)
What causes that
Likelihood of that (1-10)
How hard is it to spot (1-10)
Risk Priority Number (1-1000)

	Function	Potential Failure Mode	Potential Effect(s) of Failure	SEVt	Potential Cause(s) of Failure	OCCI	Current Design Controls	DETI	RPNI	Recommended Action(s)
1	Supply Voltage 1.2v for 85Ah	Thermal runaway	Lost of primary function for a single cell (7,-) Propagation beyond individual cell, catastrophic failure of the entire pack and potential damage to surroundings (9,-)	9	Short circuit due to overcharge or overdischarge	3	Current limiting by fuse	2	54	
2					Internal short circuit due to battery recharging in low temperature	2	Module temperature monitoring	2	36	
3					Electrolyte vaporization due to high storage temperature	3	Pressure detection	4	108	
4					Failure of the separator due to repeated charge-discharge cycling	4	Charge discharge current monitoring	2	72	
5					External short circuit	4		2	72	
6					External mechanical abuse	3		4	108	
7					Aging due to electrochemical cycling	2	SOH monitoring	2	36	
8		Does not supply specified voltage of 1.2v	Sub optimum performance (7,-)	7	Aging due to degradation of electrode properties caused by electrochemical cycling	6	SOH monitoring	2	84	
9					Accelerated degradation due to trace contaminants	2	Quality control	5	70	
10					Residual mechanical stress induced by the packaging the cell	5	Durability test	3	105	



Challenge:

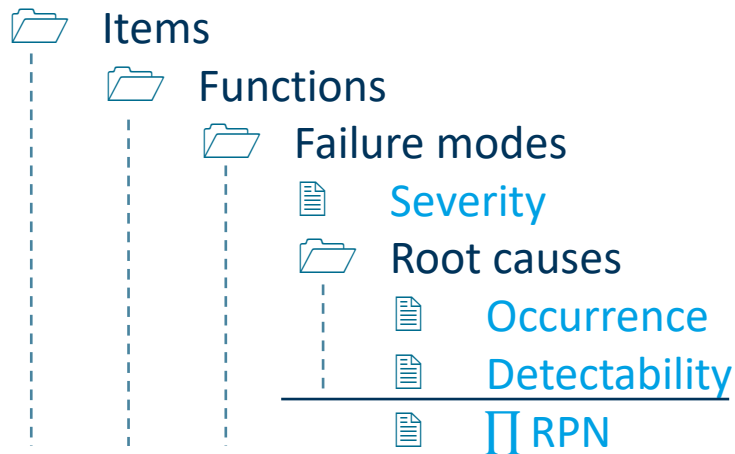
- RPN is an enumerated value based on **subjective assessment**
- Can we determine this as a statistical confidence level based on **test evidence**?

Identifying failure modes

“For a **duty cycle** of 10 years (150,000 miles),
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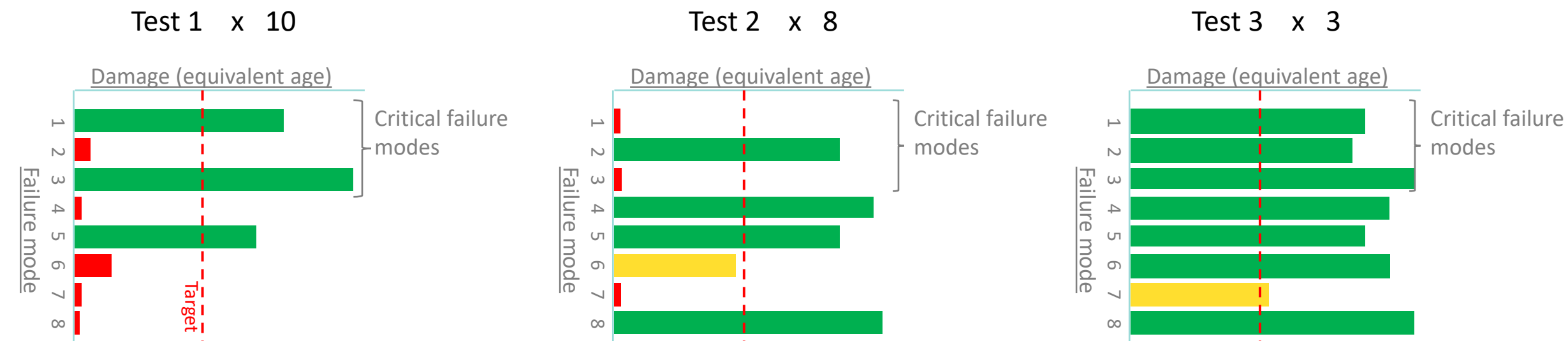
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Possible outcomes:

- Confidence is **high**, RPN is **low** 😊
- Confidence is **high**, RPN is **high** 😊
May have sufficient evidence to reduce RPN
- Confidence is **low**, RPN is **low** 😐
Need to confirm we are happy with RPN or might need more testing
- Confidence is **low**, RPN is **high** 😞
Definitely need more testing!

Validation testing



Test damage matrix for each failure mode

Test type	Full structure										Component			Element				Coupon/Supplier					Confidence
	Proving Ground 1					Proving Ground 2																	Level
Failure Mode	T1	T2	T3	T4	T1	T2	T3	T4	T5	T6	T1	T2	T3	T1	T2	T3	T4	T1	T2	T3	T4	T5	CL
Ribbon to cell endcap failure	0.7	2.4	1.0	1.9	2.5	1.6	1.7	1.5	1.5	1.8	0.4	1.2	1.7	1.6	1.5	1.1	0.3	1.2	2.7	0.3	1.7	0.9	92.44%
Ribbon connector failure	3.6	0.6	2.4	0.7	2.4	0.8	2.9	1.0	2.9	2.3	1.7	1.5	0.4	1.7	1.0	0.8	1.6						94.46%
Ribbon to busbar failue	1.6	2.2	3.8	3.4	1.0	0.8	1.5	2.9	2.3	0.1	1.3	0.9	1.3	0.1	0.1	1.8	0.4	2.4	0.3	2.8	2.8	2.0	98.04%
Busbar failure	2.1	3.1	1.0	0.4	2.1	2.9	1.9	0.6	2.7	1.4	1.9	0.0	1.3	0.8	0.5	1.7	0.1	1.5	0.3	3.0	1.6	2.3	96.27%
Busbar to module plug failure	3.6	3.1	0.5	3.9	1.2	0.6	1.4	2.3	2.2	2.7	0.2	0.4	1.9										94.56%
Module plug failure	2.1	2.0	2.5	0.4	0.3	1.0	2.2	2.2	0.9	2.5	0.8	0.5	0.8										80.48%
Busbar fixing screw failure	1.1	1.4	3.5	4.0	2.0	0.2	2.8	0.7	2.7	2.5	0.7	0.4	2.2										94.53%
Plastic damping failure	3.3	0.4	2.0	1.6	2.4	2.5	0.4	0.2	0.8	0.9	1.7	0.1	0.4										80.25%

How do we find this?

Test exaggeration or
Relative Damage factors $\frac{t_t}{t}$

Agenda

- ▲ Motivation
- ▲ Introduction: *testing to target life*
using the Non-parametric Binomial distribution
- ▲ Accelerated testing: *testing beyond target life*
using the Parametric Binomial distribution
with a shallow dive into the 1-parameter Weibull distribution
- ▲ Conclusion
- ▲ Q&A



Simple case: testing to target life

The Binomial Mass Function

$$f(n, k, q) = \binom{n}{k} q^k (1 - q)^{n-k}$$

$$= \frac{n!}{k!(n - k)!} q^k (1 - q)^{n-k}$$

n : number of tests

k : number of failures

q : probability of failure (e.g. 5% for 95% reliability)

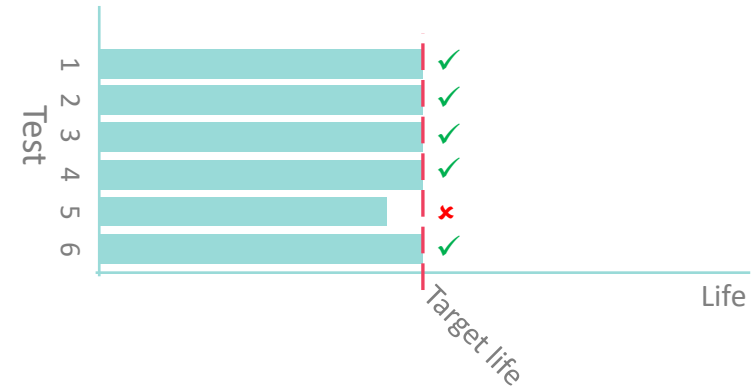
In words:

“What’s the probability of seeing exactly k failures in a sample of n items taken from the production line?”

- Probability of seeing k failures is q^k
- AND probability of seeing $(n - k)$ survivors is $(1 - q)^{n-k}$
- AND there are $\binom{n}{k}$ combinations of these failures

e.g. $n = 4$ and $k = 2$
then $\binom{4}{2} = 6$

1 :	⊗	⊗	⊙	⊙
2 :	⊗	⊙	⊗	⊙
3 :	⊗	⊙	⊙	⊗
4 :	⊙	⊗	⊗	⊙
5 :	⊙	⊗	⊙	⊗
6 :	⊙	⊙	⊗	⊗



- The probability of seeing 1 or fewer failures is:
Probability of 1 failure OR probability of no failures
 $F = f(n, 1, q) + f(n, 0, q)$
- F is known as the ‘Cumulative Distribution’

Define confidence level as: $C_L = 1 - F$

(Also use reliability α instead of probability of failure q):

$$\alpha = 1 - q$$

$$C_L = 1 - \sum_{i=0}^k \binom{n}{i} (1 - \alpha)^i \alpha^{n-i}$$

Simple case: testing to target life

What does this mean?

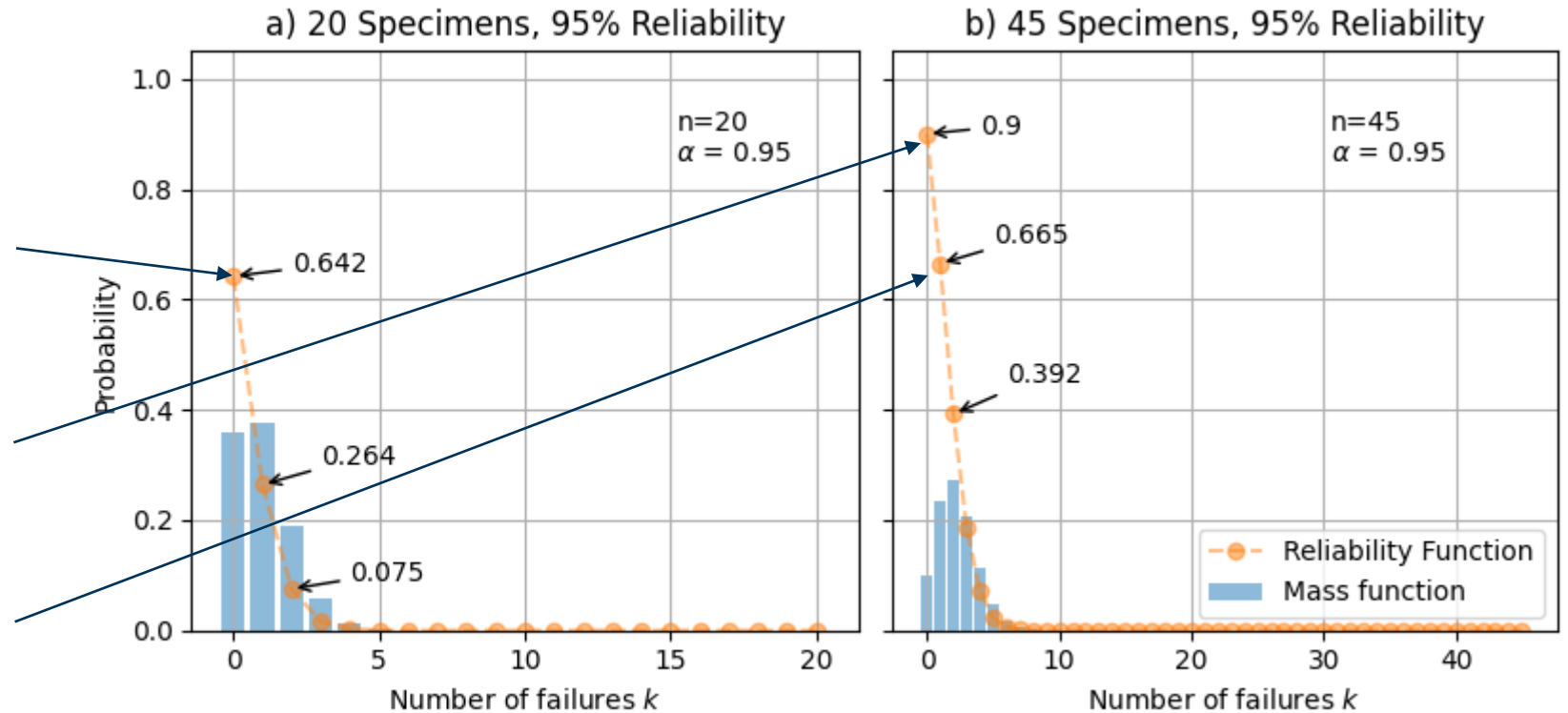
If I test 20 specimens and none fail, my confidence that the population has a 95% reliability is only 64.2%

If I want 90% confidence, then I will need to test 45 specimens and have no failures

If just 1 specimen fails out of 45, my confidence reduces to 66.5%

There is a big difference in confidence between 0, 1 and 2 failures!

$$C_L = 1 - \sum_{i=0}^k \binom{n}{i} (1 - \alpha)^i \alpha^{n-i}$$



Why is zero-failure testing useful?

1. Zero-failures are common in non-critical failure modes ∴ we expect specimens to fail in a different mode first 👍
2. And they're much easier to calculate 😊

Simple case: testing to target life

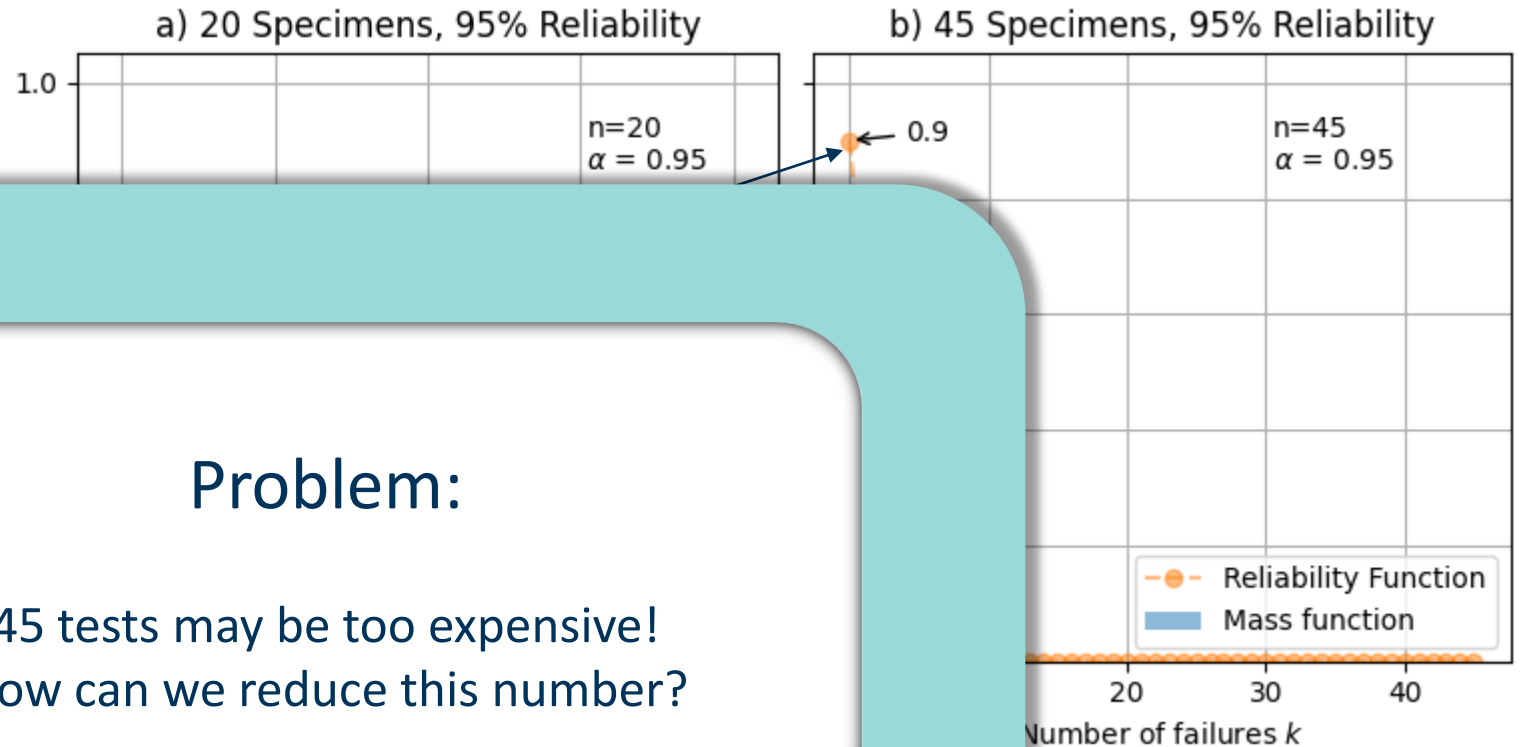
What does this mean?

If I test 20 specimens and none fail, my confidence that the population has 95% reliability is only 64.2%

If I want 90% confidence, then I need to test 45 specimens to avoid failures

If just 1 specimen fails out of 45, my confidence reduces to 64.2%

There is a big difference in confidence between 0, 1 and 2 failures



Problem:

45 tests may be too expensive!
How can we reduce this number?

$$C_L = 1 - \sum_{i=0}^k \binom{n}{k} (1 - \alpha)^i \alpha^{n-i}$$

$$= 1 - \alpha^n$$

specimens to fail in a different mode first 👍

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Agenda

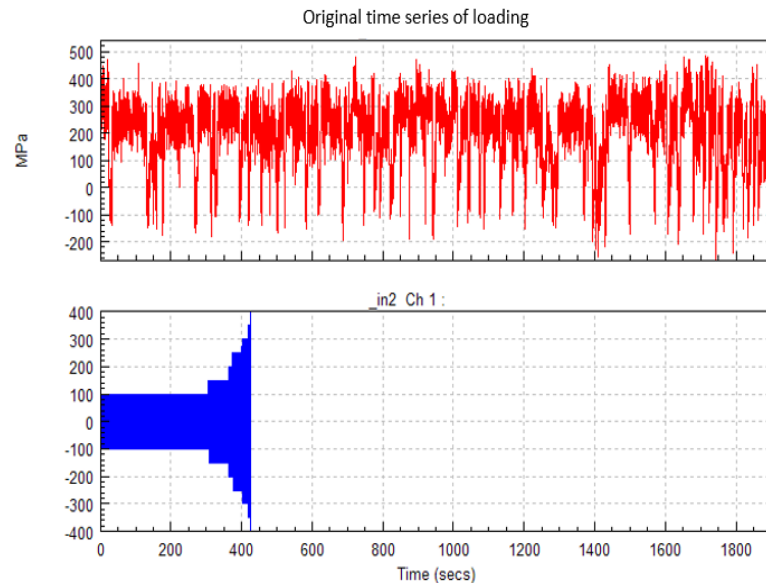
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Accelerated Life Testing

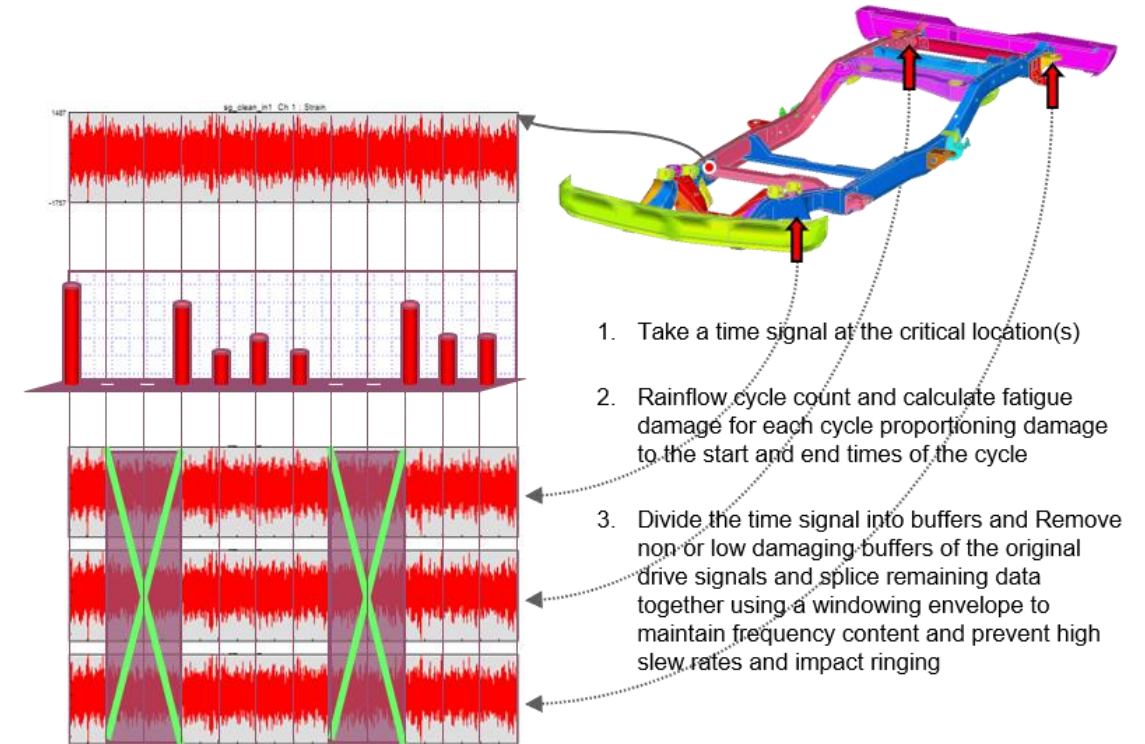
Three approaches:

1. Cycle compression (or compressed time testing)
2. Load amplification
3. Extended life testing (testing beyond target life)



Block Load Reconstruction

Removing non-damaging segments of time

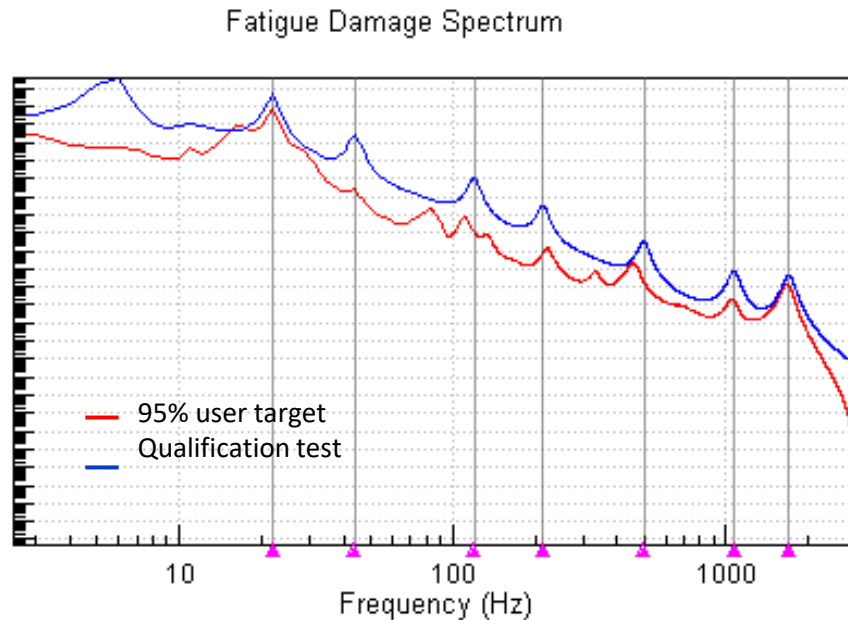


Halfpenny, A., and Thumati, B., 2021, "Accelerating Fatigue Qualification Tests," Annual Symposium on Reliability and Maintainability (RAMS) 2021.

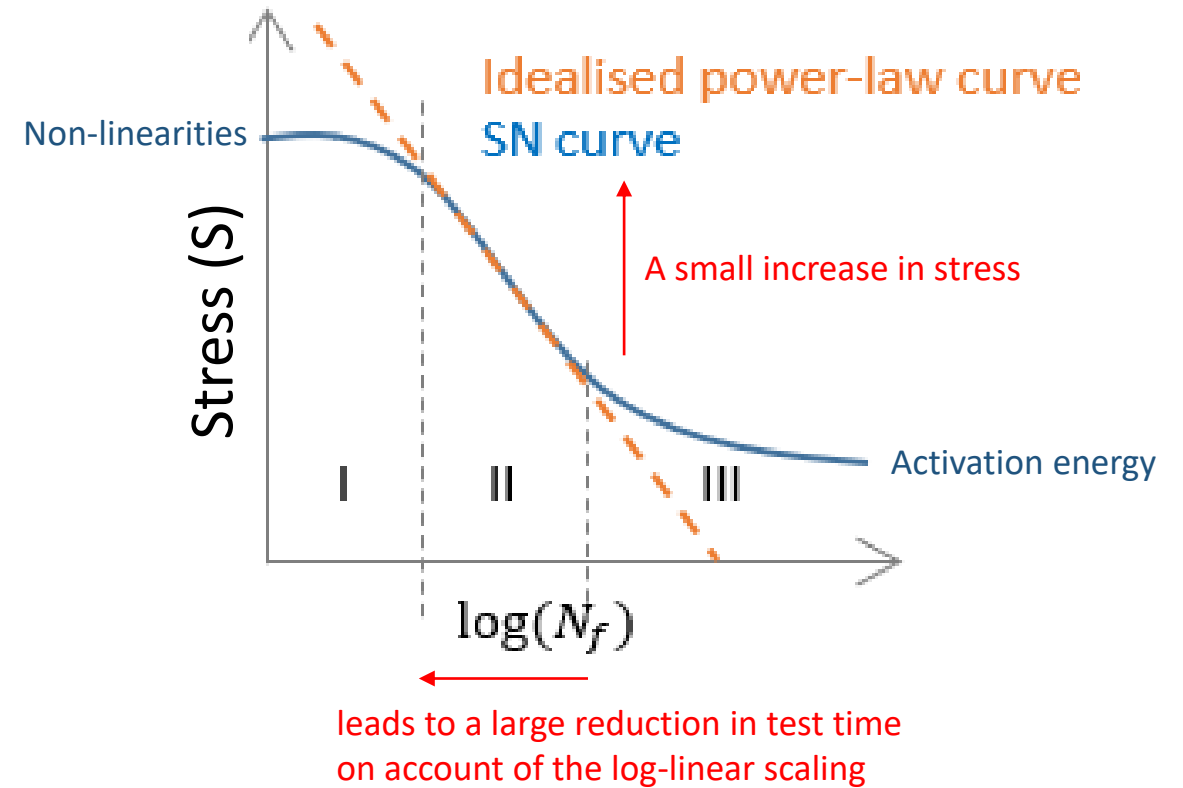
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Accelerated Vibration Testing



But be careful of non-linearities!

Accelerated Life Testing

Three approaches:

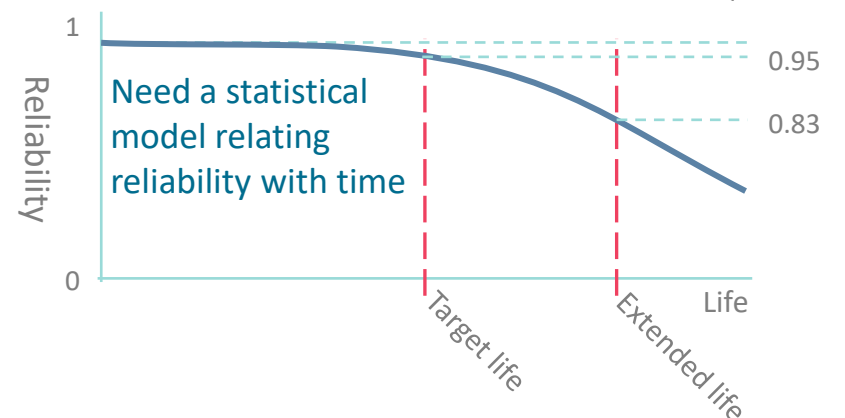
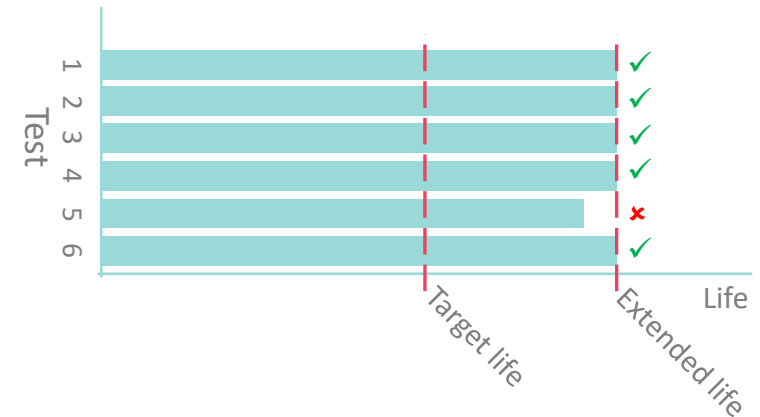
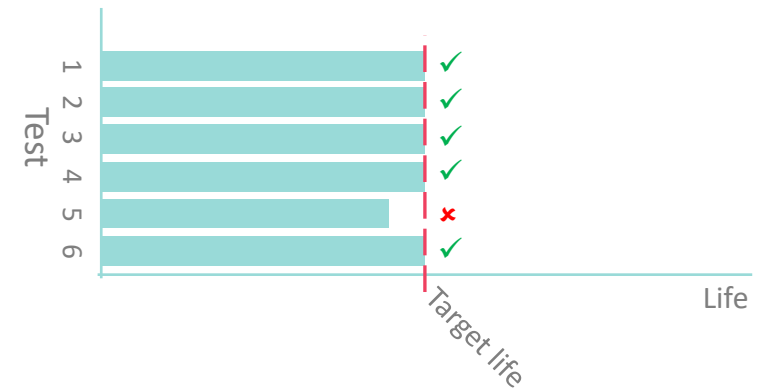
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$$C_L = 1 - \alpha_t^n$$

but target reliability on test α_t is now smaller 😊

The new α , (called α_t), depends on the reliability vs. time model e.g. **Weibull**, log normal, etc.



Shallow-dive on Weibull

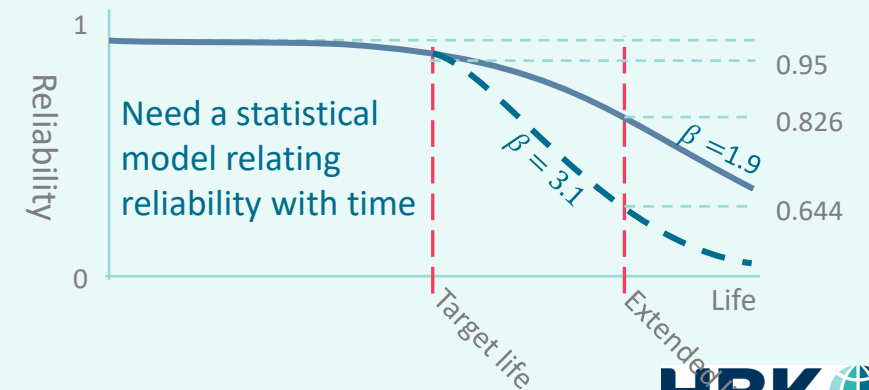
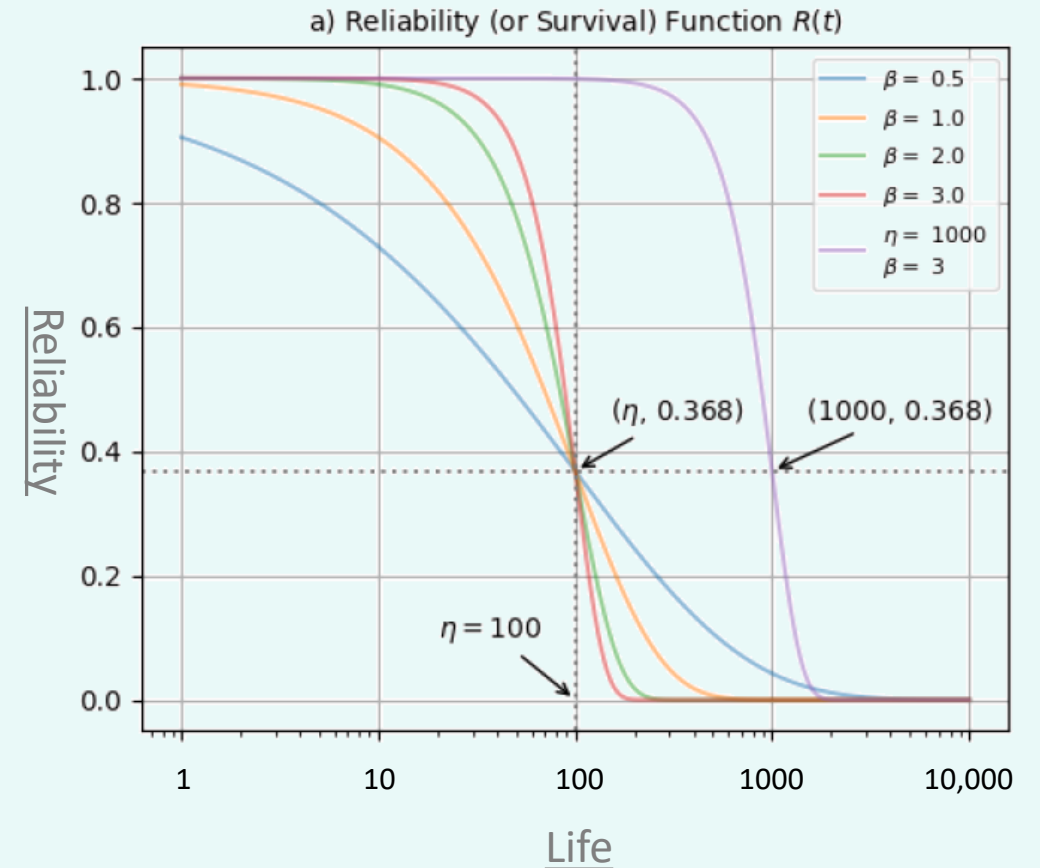
$$R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta}$$

η : Characteristic life – the point where the reliability curves intersect

β : Slope

In words:

- Early in life, when $t \ll \eta$, $R \rightarrow e^{-0}$, $\therefore R \rightarrow 1$
- Late in life, when $t \gg \eta$, $R \rightarrow e^{-\infty}$, $\therefore R \rightarrow 0$
- In between, it tends to a straight line in log space, with negative gradient β , $\therefore e^{-\left(\frac{t}{\eta}\right)^\beta}$
- The reliability at the characteristic life $t = \eta$ is $e^{-1} = 0.368$
- Larger β means steeper gradient, $\therefore$ better confidence with longer test



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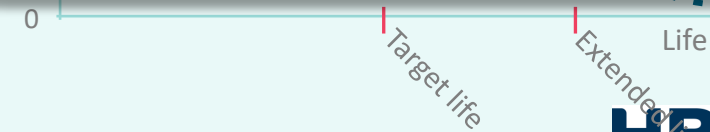
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a) Reliability (or Survival) Function $R(t)$



I remember Weibull being a nasty long equation. But actually, Herr Weibull probably started from a neat and intuitive Reliability function, and then derived his nasty long equation like this:

$$\begin{aligned} f(t) &= \frac{d}{dt} (1 - R(t)) \\ &= \frac{d}{dt} \left(1 - e^{-\left(\frac{t}{\eta}\right)^\beta} \right) \\ &= \beta \frac{t^{\beta-1}}{\eta^\beta} e^{-\left(\frac{t}{\eta}\right)^\beta} \\ &= \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^\beta} \end{aligned}$$



Accelerated Life Testing

Three approaches:

1. Cycle compression (or compressed time testing)
2. Load amplification
3. Extended life testing (testing beyond target life)

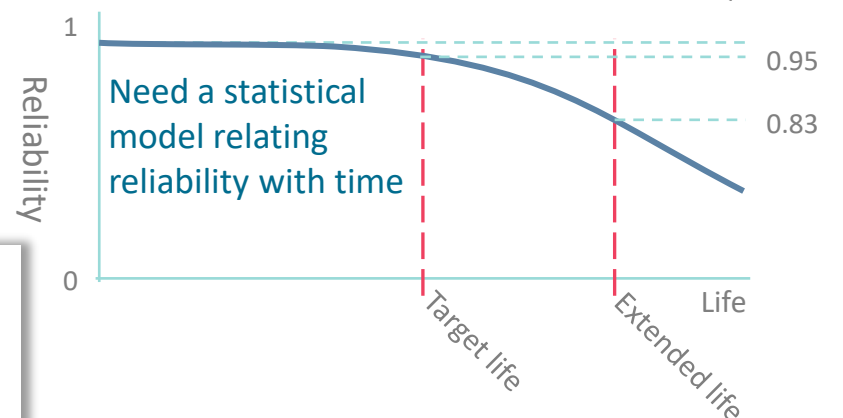
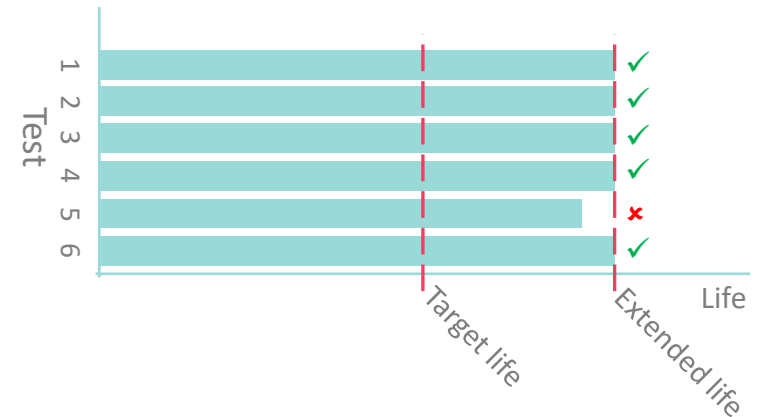
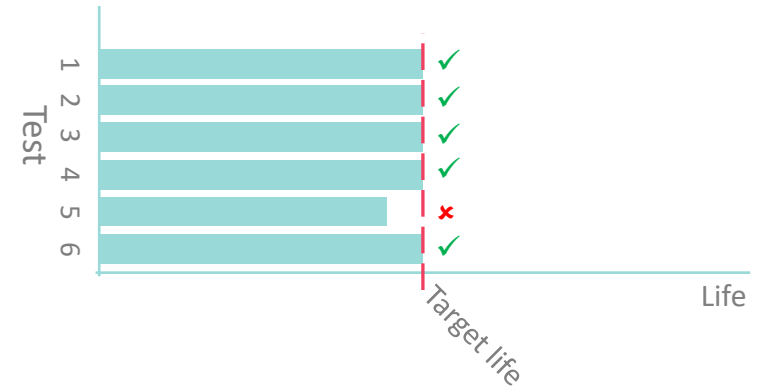
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but target reliability on test α_t is now smaller 😊

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e.g. **Weibull**, log normal, etc.

$$\text{New } \alpha_t = \alpha \left(\frac{t_t}{t} \right)^\beta$$

Test exaggeration or
Relative Damage factor $\frac{t_t}{t}$



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Beyond words:

From Weibull, target reliability α at time t is:

$$\alpha = R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta}$$

Rearrange to find η

$$\eta = \frac{t}{(-\ln(\alpha))^{\frac{1}{\beta}}}$$

Substitute back into the original equation to find
smaller reliability α_t for test time t_t

$$\alpha_t = R(t_t) = e^{-\left(\frac{t_t}{\eta}(-\ln(\alpha))^{\frac{1}{\beta}}\right)^\beta}$$

Simplifying yields:

$$\alpha_t = \alpha \left(\frac{t_t}{t} \right)^\beta$$

Accelerated Life Testing

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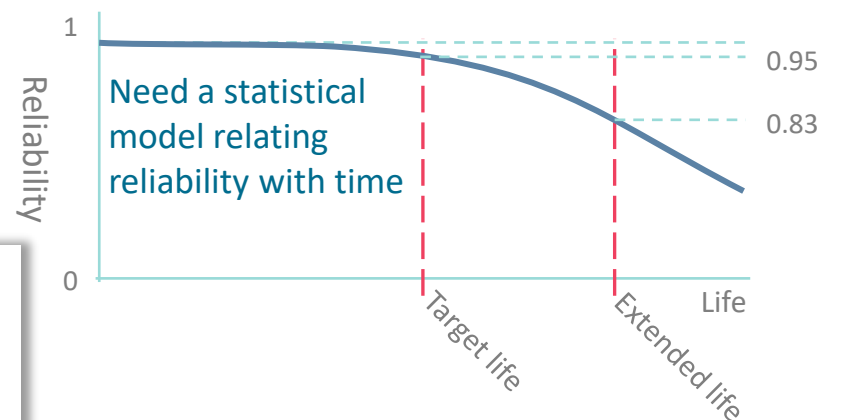
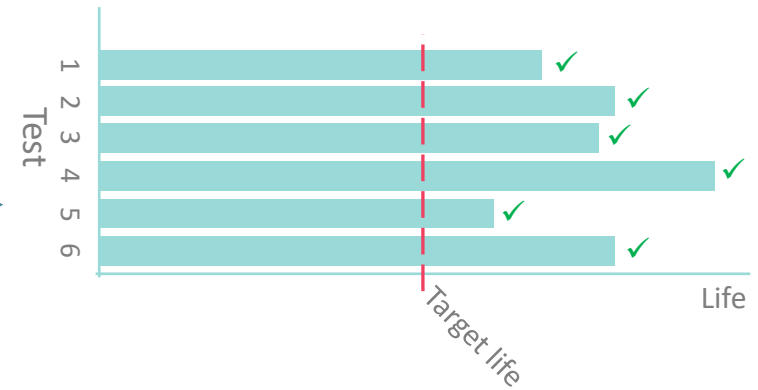
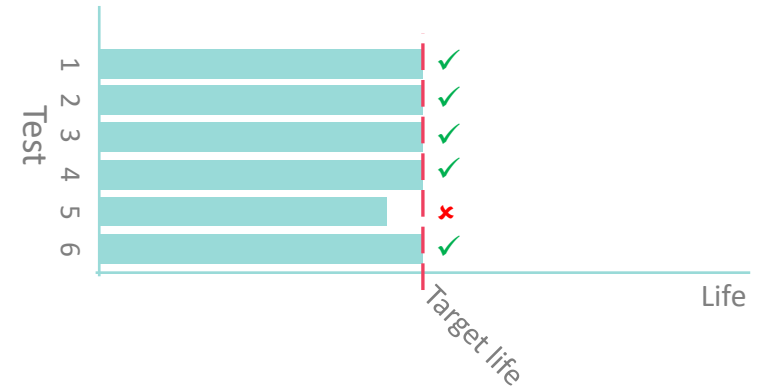
if tests have different exaggeration factors

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Conclusion

Testing to target life using the Binomial distribution

- Confidence level for reliability target α obtained as:

$$C_L = 1 - \sum_{i=0}^k \binom{n}{k} (1 - \alpha)^i \alpha^{n-i}$$

where:

- n = number of specimens
- k = number of observed test failures
- α = required reliability statistic (e.g. 95%)

- Special case for zero-failure testing:

$$C_L = 1 - \alpha^n$$



Why is zero-failure testing useful?

- Zero-failures are common in non-critical failure modes $\therefore$ we expect specimens to fail in a different mode first 👍
- And they're much easier to calculate 😊

Conclusion

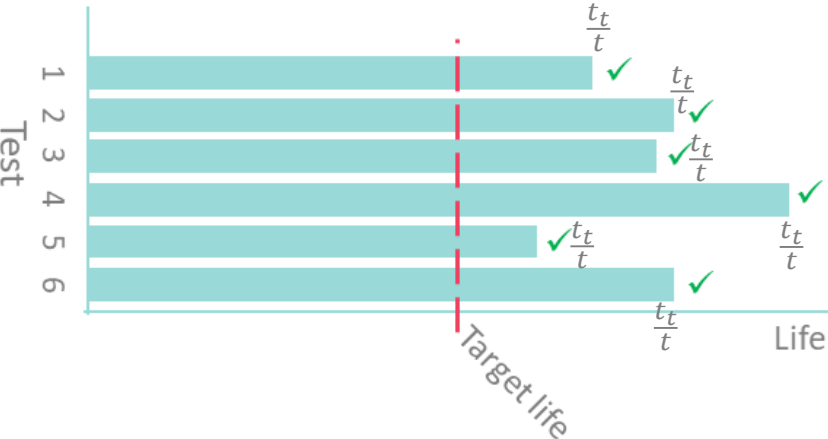
Testing **beyond** target life using the Parametric Binomial distribution

Confidence level for reliability target α obtained as:

$$C_L = 1 - \prod \alpha^{\left(\frac{t_t}{t}\right)^\beta}$$

where:

- α = required reliability statistic (e.g. 95%)
- β = the Weibull shape parameter
- $\frac{t_t}{t}$ = the test exaggeration (or damage ratio) factor for each test (assuming zero-failures)



Confidence levels supplement RPN obtained from FMEA:

- RPN based on initial risk estimate (subjective)
- Confidence levels based on test evidence (measured)

Test type	Full structure										Component			Element				Coupon/Supplier					Confidence Level CL
	Proving Ground 1					Proving Ground 2					T1	T2	T3	T1	T2	T3	T4	T1	T2	T3	T4	T5	
Failure Mode	T1	T2	T3	T4	T1	T2	T3	T4	T5	T6	T1	T2	T3	T1	T2	T3	T4	T1	T2	T3	T4	T5	
Ribbon to cell endcap failure	0.7	2.4	1.0	1.9	2.5	1.6	1.7	1.5	1.5	1.8	0.4	1.2	1.7	1.6	1.5	1.1	0.3	1.2	2.7	0.3	1.7	1.9	92.44%
Ribbon connector failure	3.6	0.6	2.4	0.7	2.4	0.8	2.9	1.0	2.9	2.3	1.7	1.5	0.4	1.7	1.0	0.8	1.6						94.46%
Ribbon to busbar failue	1.6	2.2	3.8	3.4	1.0	0.8	1.5	2.9	2.3	0.1	1.3	0.9	1.3	0.1	0.1	1.8	0.4	2.4	0.3	2.8	2.8	2.0	98.04%
Busbar failure	2.1	3.1	1.0	0.4	2.1	2.9	1.9	0.6	2.7	1.4	1.9	0.0	1.3	0.8	0.5	1.7	0.1	1.5	0.3	3.0	1.6	2.3	96.27%
Busbar to module plug failure	3.6	3.1	0.5	3.9	1.2	0.6	1.4	2.3	2.2	2.7	0.2	0.4	1.9										94.56%
Module plug failure	2.1	2.0	2.5	0.4	0.3	1.0	2.2	2.2	0.9	2.5	0.8	0.5	0.8										80.48%
Busbar fixing screw failure	1.1	1.4	3.5	4.0	2.0	0.2	2.8	0.7	2.7	2.5	0.7	0.4	2.2										94.53%
Plastic damping failure	3.3	0.4	2.0	1.6	2.4	2.5	0.4	0.2	0.8	0.9	1.7	0.1	0.4										80.25%

How do we find this?

Conclusion

Testing beyond target life using the Parametric Binomial distribution

- ▲ Confidence level for reliability target α obtained as:

$$C_L = 1 - \prod \alpha \left(\frac{t_t}{t} \right)^\beta$$

where:

- α = required reliability statistic (e.g. 95%)
- β = the Weibull shape parameter
- $\frac{t_t}{t}$ = the test exaggeration (or damage ratio) factor for each test (assuming zero-failures)

Final question:

How do we calculate the damage ratio $\left(\frac{t_t}{t} \right)$ of the tests?

by **Virtual Testing** – i.e. simulating the tests in nCode DesignLife 😊

Final question + 1:

How do we improve confidence using in-service data?

Weibull++ has methods that support large datasets 😊

Element					Coupon/Supplier					Confidence Level
1	T2	T3	T4	T1	T2	T3	T4	T5		CL
0.6	1.5	1.1	0.3	1.2	2.7	0.3	1.7	0.9		92.44%
0.7	1.0	0.8	1.6							94.46%
0.1	0.1	1.8	0.4	2.4	0.3	2.8	2.8	2.0		98.04%
0.8	0.5	1.7	0.1	1.5	0.3	3.0	1.6	2.3		96.27%
										94.56%
										80.48%
										94.53%
										80.25%

How do we find this?

Conclusion

Testing beyond target life using the Parametric Binomial distribution

- Confidence level for reliability target α obtained as:

$$C_L = 1 - \alpha^{\sum \left(\frac{t_t}{t}\right)^\beta}$$

where:

- α = required reliability statistic (e.g. 95%)
- β = the Weibull shape parameter
- $\frac{t_t}{t}$ = the test exaggeration (or reduction) factor for each test (assuming zero-failures)

In-service data may contain evidence from 1000's of replaced maintenance items 🤖

- but there is often more than one failure 😬
- but there are alternative confidence methods available for large sample sets 😊

- Confidence levels appended to FMEA as supplementary to RPN:

- Confidence based on test evidence (measured)
- RPN based on initial risk estimate (subjective)
- Inservice data provides additional evidence based on maintenance records

	Function	Potential Failure Mode	Potential Effect(s) of Failure	SEV _i	Potential Cause(s) of Failure	OCC _i	Current Design Controls	DET _i	RPN _i	Recommended Action(s)
1	Supply Voltage 1.2v for 85Ah	Thermal runaway	Lost of primary function for a single cell (7,-) Propagation beyond individual cell, catastrophic failure of the entire pack and potential damage to surroundings (9,-)	9	Short circuit due to overcharge or overdischarge	3	Current limiting by fuse	2	54	
2					Internal short circuit due to battery recharging in low temperature	2	Module temperature monitoring	2	36	
3					Electrolyte vaporization due to high storage temperature	3	Pressure detection	4	108	
4					Failure of the separator due to repeated charge-discharge cycling	4	Charge discharge current monitoring	2	72	
5					External short circuit	4		2	72	
6					External mechanical abuse	3		4	108	
7					Aging due to electrochemical cycling	2	SOH monitoring	2	36	
8		Does not supply specified voltage of 1.2v	Sub optimum performance (7,-)	7	Aging due to degradation of electrode properties caused by electrochemical cycling	6	SOH monitoring	2	84	
9					Accelerated degradation due to trace contaminants	2	Quality control	5	70	
10					Residual mechanical stress induced by the packaging the cell	5	Durability test	3	105	

Agenda

- ▲ Motivation
- ▲ Introduction: *testing to target life*
using the Non-parametric Binomial distribution
- ▲ Accelerated testing: *testing beyond target life*
using the Parametric Binomial distribution
with a shallow dive into the 1-parameter Weibull distribution
- ▲ Conclusion

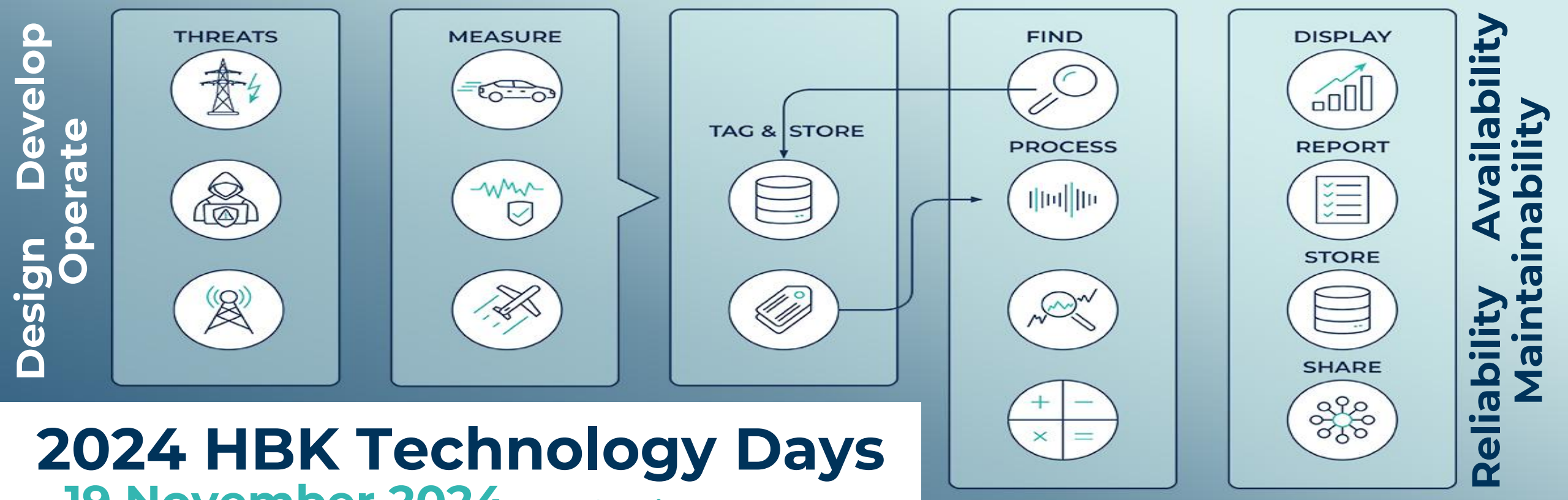
▲ Q&A



Thank You

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2024 HBK Technology Days

19 November 2024

Session 5: Reliability Engineering from Limited Failure Data

Accelerated Life Testing

Three approaches:

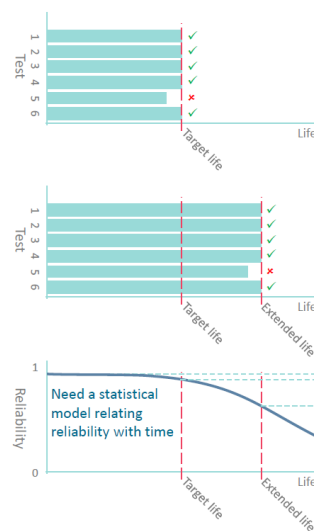
1. Cycle compression (or compressed time testing)
2. Load amplification
3. Extended life testing (testing beyond target life)

If we require 95% reliability at the target life,
we only need to prove a smaller reliability at an extended life.

$$C_L = 1 - \alpha_L^n$$

but target reliability on test α_L is now smaller 😬

The new α_L (called α_L), depends on the reliability vs. time model
e.g. Weibull, log normal, etc.



- Statistical qualification of complex systems based on zero-failure evidence

Dr. Andrew Halfpenny,
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