Transistor Lifetime Optimization in Compliance with Safety and Reliability Standards.

Rubayet Kamal
Advanced Hardware Engineering
Hochschule Hamm-Lippstadt
Lippstadt, Germany
rubayet.kamal@stud.hshl.de

***Abstract*—Modern automotive systems depend heavily on power semiconductor devices such as IGBTs, MOSFETs, and diodes. These components operate under harsh environmental and electrical conditions throughout the lifetime of a vehicle, which is typically expected to exceed 15 years. Ensuring the reliability and safe operation of these devices requires a combination of functional safety standards, analytical lifetime prediction models, and experimental qualification testing. This report discusses how industry standards—particularly ISO 26262-11, SN 29500, MIL-STD-750D, and AQG 324—contribute to assessing and improving the lifetime of power transistors in safety-critical automotive applications. It explains methods of lifetime estimation, degradation mechanisms, reliability tests such as power cycling and vibration testing, and statistical evaluation using Weibull analysis. The goal is to show how analytical models, stress tests, and field data can be balanced to create a realistic and robust lifetime prediction strategy.**

***Index Terms*—ISO26262, AQG324, MIL-STD-750D. SN29500, Weibull analysis**

I. INTRODUCTION

The reliability of electronic circuits plays a crucial role in modern automotive systems. With the rapid electrification and automation of vehicles, components such as traction inverters, on-board chargers, and DC-DC converters have become critical to ensuring safe and efficient power conversion. These systems directly influence the safety, performance, and cost of the vehicle throughout its operational lifetime.

Fig. 1 shows typical components inside an EV [1]. The ones highlighted are DC-AC inverter and DC-DC inverter. Fig. 2 shows a DC-AC composed of two transistors (IGBT). Such transistors are at the heart of power electronic modules — from electric vehicles and renewable energy inverters to industrial drives. A single transistor failure in such systems can lead to costly recalls, downtime, or even unsafe operation. Therefore, it's not enough to design for performance; we must design for long-term reliability under realistic stress conditions.

A vehicle is typically designed to operate reliably for 15 years or more under harsh environmental conditions, including extreme temperature variations, high humidity, and continuous mechanical vibration or shock. Such stresses can cause degradation of electronic components, leading to performance drift or even failure. Therefore, the reliability and robustness of semiconductor devices used in these systems are essential to achieving long-term safety and durability goals.

Fig. 3 shows layer structure of an DC-AC power module [3]. A typical power module, such as an IGBT or MOSFET module, contains multiple layers : semiconductor chips, bond wires, solder joints, and substrates. Each of these layers can degrade differently under thermal, electrical, or mechanical stress. Understanding where and how these failures occur helps us design more robust modules and predict their lifetime more accurately.

To illustrate how serious this can be, here is an example. In July 2024, NASA reported that "similar parts were failing at lower radiation doses than expected" on the Europa Clipper spacecraft [5]. This incident shows that even in high-end, rigorously tested systems, unexpected reliability issues can arise — and when they do, they can threaten mission success. It reminds us that predictive reliability modeling is just as important as physical testing.

Automotive electronics are inherently safety-related, as their malfunction can lead to hazardous events. To address this, the automotive industry follows the ISO 26262 standard — "Road Vehicles – Functional Safety" — which defines a structured approach for managing and validating safety throughout the product lifecycle. ISO 26262 comprises 12 parts, covering everything from terminology and management of functional safety to hardware, software, and production processes. Within this framework, Part 11 (ISO 26262-11) provides "Guidelines on the Application of ISO 26262 to Semiconductors." It offers specific recommendations for semiconductor manufacturers on how to apply functional safety principles to chips, IP blocks, ASICs, and power devices used in safety-critical automotive applications. One key aspect of Part 11 is the qualification and validation of semiconductors, requiring evidence that the component is both functionally safe and robust under real-world stress conditions.

Such evidence is typically generated through reliability and qualification standards, which complement ISO 26262 by focusing on physical durability rather than functional behavior. Reliability tests such ACQ (for automotive), MIL-STD (for US Military) and SN 29500 (industry) provides framework to assess semiconductor robustness and lifetime. By combining functional safety validation (ISO 26262-11) with reliability qualification (AQG 324), manufacturers can ensure that automotive semiconductor devices meet both safety integrity and lifetime performance requirements. This holistic

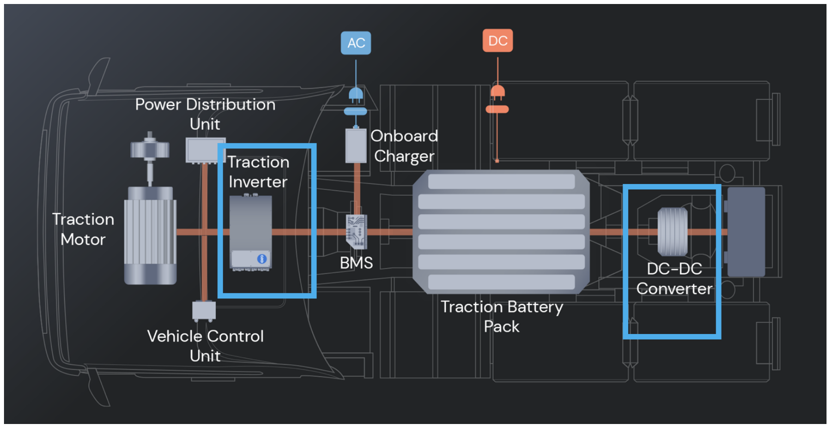


Fig. 1: Components inside an EV [1]

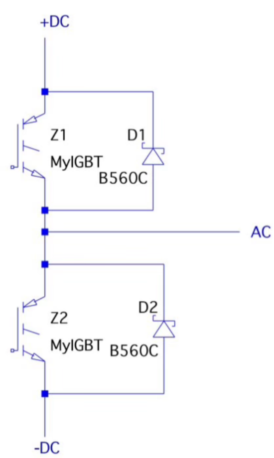


Fig. 2: DC-AC inverter

approach forms the foundation for improving the lifecycle of critical components such as IGBTs and diodes used in automotive power electronics. Fig. 4 shows an overview about the importance of lifetime estimation of semiconductors.

II. Functional Safety and ISO 26262-11

In the automotive industry, the main safety standard is ISO 26262. It defines safety requirements for all electrical and electronic systems installed in vehicles. Within it, ISO 26262-11 gives guidelines specifically for semiconductors. It tells us how to ensure robustness and document safety, but it doesn't define how to prove reliability — that's left to reliability standards and testing methods. So, safety and reliability go hand in hand, but they're treated separately in engineering practice. ISO 26262 defines the functional safety lifecycle for safety-related electrical and electronic systems installed in road vehicles. It covers hazard analysis, system design, hardware and software development, and validation.

ISO 26262-11 provides guidelines for applying functional safety principles to semiconductor devices. It addresses semiconductor development lifecycles, safety mechanisms, diagnostic coverage, and qualification and validation requirements. However, ISO 26262-11 does not specify how to prove physical reliability. Instead, it requires evidence of robustness, which must be obtained from reliability standards and qualification testing.

ISO 26262 is intended to be applied to safety-related systems that include one or more electrical and/or electronic (E/E) systems and that are installed in series production passenger cars with a maximum gross vehicle mass up to 3 500 kg. ISO 26262 does not address unique E/E systems in special purpose vehicles such as vehicles designed for drivers with disabilities.

Many parts can go wrong in a power transistor. Common failure mechanisms include bond-wire lift-off, solder fatigue, cracks in the silicon or metallization, and dendrite growth due to humidity or contamination. Each of these mechanisms corresponds to a specific type of stress : thermal, mechanical, or electrical and each requires a dedicated test to detect or predict.

III. Reliability Evaluation and Lifetime Estimation

Testing components for their entire operational lifetime is impractical. Therefore, reliability evaluation relies on accelerated testing, analytical lifetime models, and field experience.

But the question is how can we measure or estimate reliability? There are three main approaches as also shown in fig. 5:

- Testing : subjecting components to stress and observing failures.
- Field experience – collecting data from real-world operation.
- Calculation or modeling – using mathematical or statistical models based on known failure rates.

Typically, all three are used in combination to create a comprehensive reliability picture.

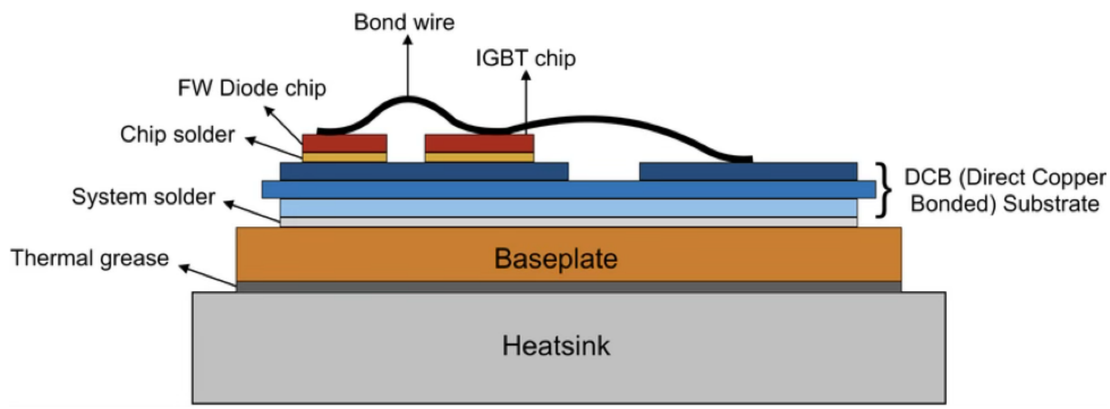


Fig. 3: Layer structure of a power module [3]

Fig. 4: Importance of lifetime estimation.

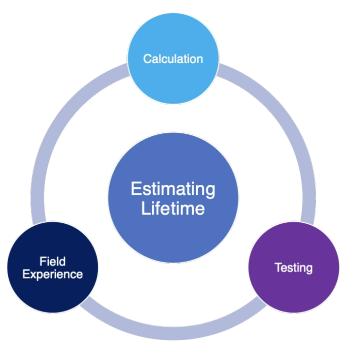


Fig. 5: Ways of estimating lifetime

Lifetime estimation helps engineers determine how long a component will last under normal operating conditions. For instance, the failure rate, denoted as λ, represents the total number of failures per unit time and is typically normalized using FITs (Failures in Time). One FIT equals one failure per billion device hours. Another key metric is MTTF (Mean Time to Failure), which represents the average operational time before failure. These metrics are foundational for predicting product reliability and planning maintenance or replacement intervals.

IV. Reliability Standards

Testing reliability is not straightforward, because waiting for components to fail naturally could take years — sometimes longer than the expected lifetime of the product itself. So, engineers use accelerated lifetime tests. These apply higher stress levels, such as elevated temperatures or voltages, to simulate years of wear within a much shorter time. However, these tests must be carefully designed to ensure that the failure mechanisms remain realistic. Some of the reliability standards are talked about below.

A. Siemens SN 29500

an analytical model developed by Siemens, used widely in industry and automotive applications to predict failure rates. It provides reference failure rates and correction factors for temperature, voltage, current, and environmental stress. Lifetime prediction often uses Arrhenius-type acceleration models to account for temperature effects, allowing early-stage reliability estimation during design.

B. MIL-STD-750D

MIL-STD-750D [12] is a U.S. military standard defining uniform test methods for semiconductor devices. It includes thermal, mechanical, electrical, and environmental stress tests such as temperature cycling, thermal shock, vibration, power cycling, and high-temperature bias testing. While it does not directly improve lifetime, it reveals degradation mechanisms that guide design optimization.

C. AQG 324

AQG 324, developed by ECPE e.V., defines qualification procedures for power modules used in automotive power electronic converter units. It evaluates complete power modules rather than individual chips. The guideline divides testing into environmental tests (thermal shock, vibration, mechanical shock) and lifetime tests (power cycling, HTRB, HTGB, and H3TRB). Results from AQG 324 tests are used to calibrate lifetime models and validate automotive robustness.

The AQG 324 [13] represents an industry guideline based on best practices and cooperative requirement engineering

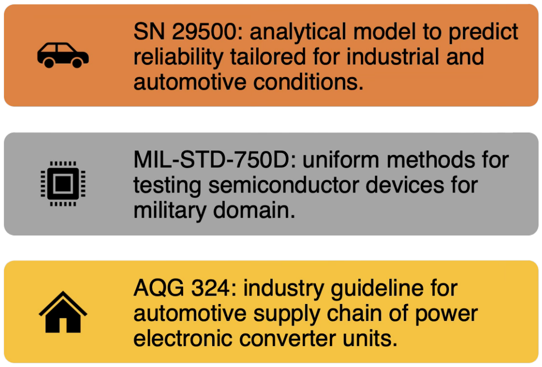


Fig. 6: RELIABILITY STANDARDS SUMMARY

alignment through the automotive supply chain for power electronic converter units. The spirit of the AQG 324 Guideline is based on a fair dialogue between supplier and customer with the aim of supporting these stakeholders along the automotive supply chain. Therefore, it leaves room for individual interpretations and clarifications which is indicated in the document by the statement "to be agreed with the customer". Regarding future technology developments, this guideline is intended to overcome innovation blocking hurdles and to close gaps in product capability and corresponding assurance processes. With the continuously increasing complexity of automotive electronic systems, it is necessary to combine the expertise and to standardize approaches along the whole supply chain – different to outdated approaches where the alignment primarily occurred within a design hierarchical level, rather than from a complete system perspective. Consequently, a core achievement has been and still is to define the same technical language as was only possible through jointly define and tune terms, definitions and processes.

Fig. 6 and table I shows an overview about the standards discussed in brief.

V. Fault models and related tests

Accelerated reliability tests reveal physical degradation mechanisms such as bond-wire fatigue, solder layer cracking, delamination, gate oxide degradation, and corrosion due to humidity. Understanding these fault models allows engineers to link test results to targeted design improvements, including advanced packaging technologies and improved thermal management.

Each failure mechanism is linked to specific tests: Bond-wire lift-off is analyzed through power cycling tests. Solder fatigue and bond connection defects are studied using vibration and thermal shock tests. Surface defects in semiconductors are tested via HTRB. By correlating test outcomes with physical failure models, we can pinpoint weak spots in design and materials. Once we understand the failure mechanisms, we can act on them. For example: Replacing bond wires with copper clips avoids bond-wire fatigue. Using silver sintering instead of solder reduces cracking. Employing SiN substrates helps reduce thermal expansion mismatch. Better cooling systems lower junction temperature. Smart gate control can reduce electrical stress. These material and design improvements directly extend the transistor's lifetime.

VI. Weibull Analysis for Lifetime Assessment

Weibull distribution is a powerful tool for modeling time-to-failure data. It helps us understand whether failures are due to early defects, random events, or wear-out mechanisms. When combined with results from standards like AQG 324 or MIL-STD-750D, Weibull analysis provides deep insight into a device's reliability behavior. The cumulative failure distribution is given by:

$$F(t) = 1 - e^{-(t/\eta)^{\beta}}$$

where η is the characteristic lifetime and β is the shape parameter. Values of $\beta > 1$ typically indicate wear-out failures, which are common in power semiconductor devices subjected to thermal cycling. Fig. 8 shows the work flow for weibull analysis. Weibull analysis enables comparison between analytical predictions, stress test results, and field performance.

The equation above can be linearised as follows:

$$Y = \ln\big(-\ln(1 - F(t))\big), \quad X = \ln(t), \quad C = -\beta \ln(\eta)$$

An example is shown in fig. 9 where for a given β and η, accumulated failures per hours increases with change lifetime. This model helps engineers separate early design issues from end-of-life wear mechanisms. This allows engineers to quantify and compare device reliability across technologies or test conditions.

VII. Conclusion and Takeaways

Insights gained from reliability testing and modeling lead to practical lifetime improvements. These include advanced interconnection technologies such as copper clip bonding and silver sintering, improved substrate materials, optimized thermal management, electrical derating, and active monitoring strategies. Together, these measures enhance both reliability and functional safety compliance.

Ensuring the lifetime of transistors in safety-related automotive applications requires a holistic approach combining functional safety standards, analytical lifetime prediction, accelerated testing, and statistical analysis. ISO 26262-11 defines safety requirements, while SN 29500, MIL-STD-750D, and AQG 324 provide the tools to generate reliability evidence. By integrating these methods, engineers can optimize transistor lifetime and ensure safe, reliable operation throughout the vehicle lifetime.

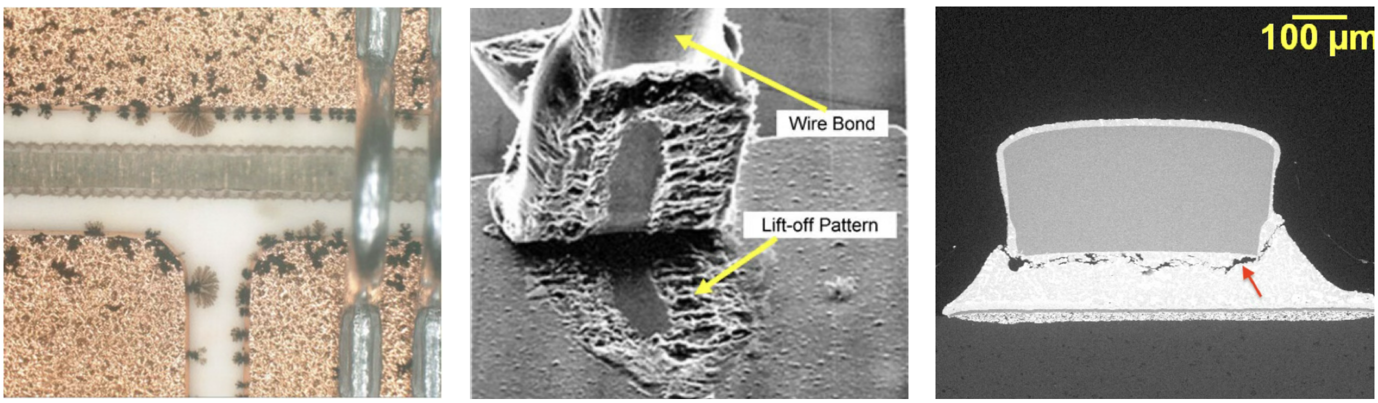
Testing itself doesn't improve lifetime — it reveals what needs to be improved. Analytical results are often too conservative, and field data helps calibrate models. Accelerated tests may overestimate stress, so proper correlation is essential. By combining test results, field data, and Weibull analysis, engineers can obtain the most realistic reliability estimates. Ultimately, these insights enable optimization of transistor design for longer life and higher safety compliance.

TABLE I: Comparison of Functional Safety and Reliability Standards

Standard	Domain	Purpose	Output
ISO 26262-11	Functional Safety	Required reliability evidence	Safety compliance
SN 29500	Analytical	Predicts failure rate	FIT, MTBF
MIL-STD-750D	Experimental	Defines stress test procedures	Physical test results
AQG 324 []	Automotive	Qualifies power modules	Lifetime and degradation data

TABLE II: From Reliability Testing to Lifetime Improvement Measures

Observed Failure Mechanism	Test Revealing the Failure	Lifetime Improvement Measure
Bond wire fatigue	Power Cycling Test	Copper clip bonding, bondless interconnects
Solder joint degradation	Power Cycling, Thermal Cycling	Silver sintering, improved solder alloys
Excessive junction temperature swing	Power Cycling	Enhanced cooling, optimized thermal design
Gate oxide wear-out	HTGB Test	Gate voltage derating, improved oxide quality
Humidity-induced corrosion	H3TRB Test	Protective coatings, improved encapsulation
Mechanical fatigue	Vibration Test	Reinforced package design, optimized mounting



(a) Dendrite growth [7]. (b) Bond wire lift-off [8]. (c) Solder fatigue [9].

Fig. 7: Defects in power electronics modules: (a) dendrite growth, (b) bond wire lift-off, (c) solder fatigue.

TABLE III: Fault Models and Corresponding Reliability Tests

Fault Model / Failure Mechanism	Primary Stress Cause	Related Test
Bond wire lift-off	Repeated thermal expansion mismatch	Power Cycling Test
Solder fatigue / cracking	Temperature swing and CTE mismatch	Power Cycling, Thermal Cycling
Die attach delamination	Thermo-mechanical stress	Power Cycling, Thermal Shock
Gate oxide degradation	High electric field and temperature	HTGB (High Temperature Gate Bias)
Leakage current increase	High temperature reverse voltage	HTRB (High Temperature Reverse Bias)
Corrosion and metallization damage	Humidity and electrical bias	H3TRB (Humidity HTRB)
Package cracking	Mechanical stress	Mechanical Shock, Vibration Test

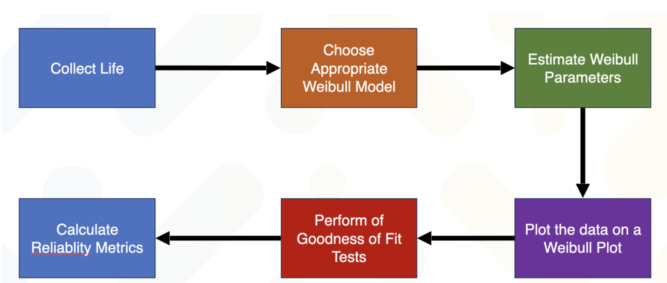


Fig. 8: Work flow of Weibull analysis [14]

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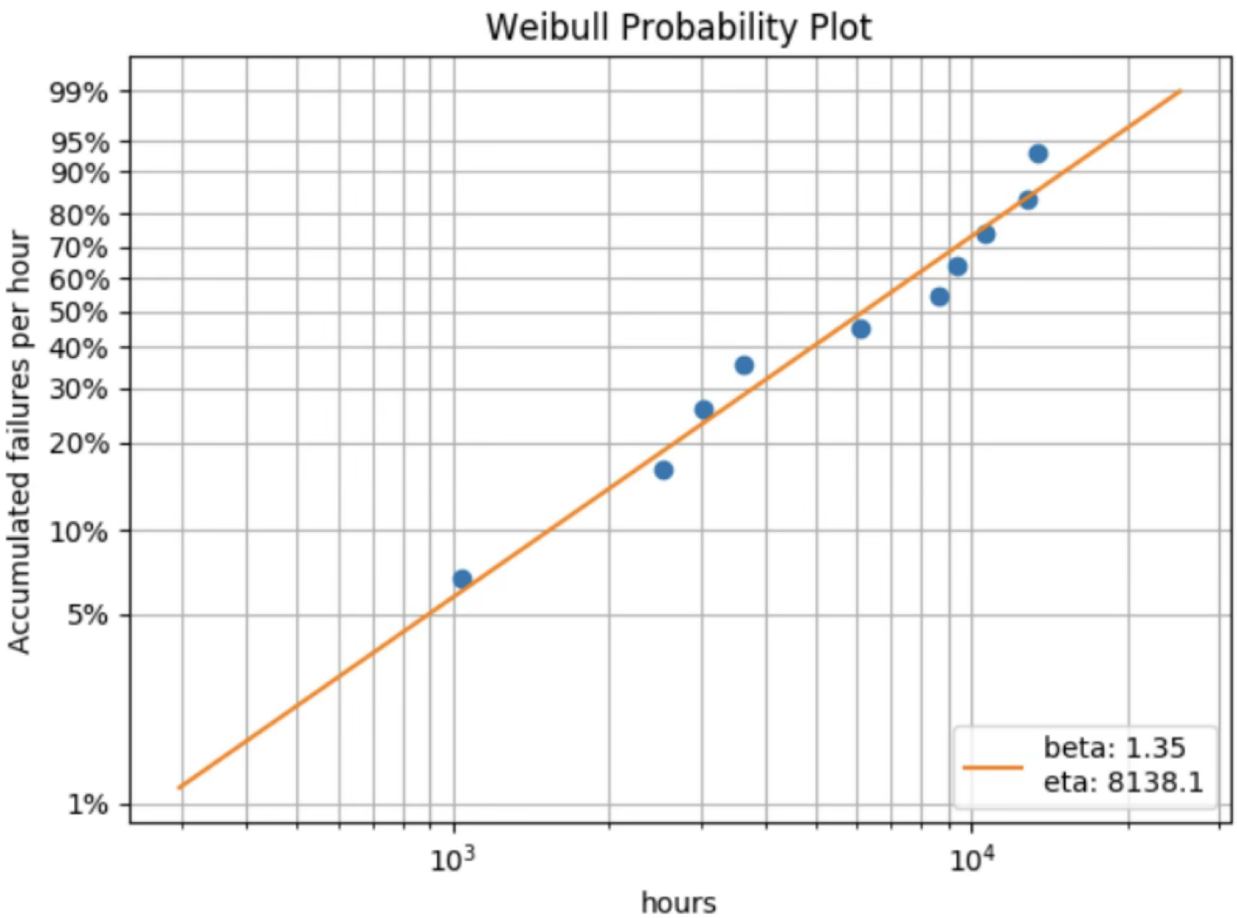

Fig. 9: Example of weibull esimation chart

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