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Reliability in education – a hands-on university experimental course on accelerated life testing

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An experimental lab course on accelerated life testing is conducted at the Ruhr West University of Applied Sciences in cooperation with the University of Defence in Brno. The course is offered to students in the fifth semester as part of the bachelor degree program of functional safety and is held in English. The paper discusses didactical aspects and learning outcomes as well as the structure and the workload of the course. The roles, activities, and responsibilities of the students are described in terms of data analysis and validation, and report writing. Moreover, a liquid-based climate chamber has been designed and built, nicknamed the Fearsum Endjinn, to increase significantly the dynamic of the hot and cold phases compared to conventional air climate chambers.

Keywords: education, experiment, life testing, climate chamber, semiconductor, LED.

1 Introduction

Since 2014, the Ruhr West University of Applied Sciences offers a bachelor degree programme in functional safety. The programme provides a comprehensive education in functional safety, reliability engineering, quality management, and human-technology interaction. The fifth semester forms the bridge between learning the foundations and applying this knowledge. Six different elective lab courses are offered. One of them is the *Critical Component Lab* applying accelerated life testing, refer to IEC 62506 (2023). The course is conducted in cooperation with the University of Defence in Brno, Czech Republic.

The objective of the lab course is to introduce students to the foundations of reliability engineering through a practical scenario, focusing on the lifetime assessment of LED. The mean lifetime of these components is predicted under typical application conditions. Since specific statements about component performance can be gained by testing and empirical evaluation, the students need to implement an experimental setup capable of monitoring and controlling a sample of LED. The students conduct an accelerated life test, collecting and analysing data, formulating conclusions in terms of the LED reliability.

The participants learn to understand component degradation and predicting the mean lifetime by a combination of theoretical lecture and practical application. The course encourages the development of practical engineering competences and provides a hands-on opportunity for participants to consolidate the knowledge. Moreover, the lab course addresses the growing need for efficient and cost-effective testing methods.

2 Course overview

The objective of the course is to provide fundamental knowledge of

- component degradation,
- accelerated life testing,
- and the concept of lifetime prediction

in order to extend and consolidate the competences in reliability engineering of the students. The new knowledge is directly applied to semiconductors, namely LED. as a practical example.

Since the scope of the course includes both lecture-based learning and hands-on experiments, the students will engage in a series of structured activities:

- Initial hypothesis formation
- Data collection
- Data analysis
- Interpretation of results
- Data validation

2.1 *Brief course description*

The course is assigned to the fifth semester (third year) of the bachelor degree programme. The course includes five consecutive days of attendance time starting with a three hours lecture given in English, refer to Vališ (2024a, b, d). Then the students spend their time with hands-on experimental works, refer to Sehic (2024) in the laboratory.

The attendance phase is offered during the lecture-free *Project Week* in the summer semester followed by the homework phase including data analysis, report writing and revisioning.

2.2 *Didactical aspects*

The course is designed around a hands-on approach that connects the theoretical foundations of reliability engineering with real-world applications. The understanding of the students is reinforced by separating the content of the course into (i) the basic concepts of reliability engineering and (ii) the application of these concepts in an experiment. This ensures that the students apply the methods learned to real data in a solid and confident way.

In addition to knowledge of reliability engineering, the course also teaches technical skills and critical thinking in connection with real data.

2.3 *Learning outcomes*

The learning outcomes are focused on the methodology for analysing, predicting, and improving system reliability in terms of accelerated life testing. The following aspects are addressed.

2.3.1 *Applying the knowledge of reliability engineering foundations*

- Discussing failures observed during test runs
- Applying sample size reduction methods
- Discuss lifetime distributions
- Evaluating the calculated reliability data
- Evaluating the components under consideration, here semiconductors (LED).

2.3.2 *Applying probability and statistical methods to assess component reliability properties*

- Assessing reliability factors
- Exploring methods to calculate measures, especially the *MTTF* of a given type of component
- Understanding the significance of the *MTTF* in reliability modelling

2.3.3 *Performing hypothesis testing*

- Conducting hypothesis tests to evaluate the statistical significance of observed trends in data.
- Validating predictions regarding the expected correlation between the stress factors on the one hand and the *MTTF* of the LED on the other hand.

2.3.4 *Further statistical aspects*

- Identifying, collecting, organising, analysing, and managing data
- Detecting and minimising errors
- Assessing the optimal sample size
- Applying regression analysis
- Predicting component reliability
- Calculating and interpreting tolerance limits and confidence intervals
- Enhancing the handling of uncertainty
- Proposing performance improvements

2.4 *Structure and workload*

The course is structured in seven phases.

- Phase 1 – Lecture on the foundations of reliability and testing theory
- Phase 2 – Setting up the experiment
- Phase 3 – Conducting the experiment
- Phase 4 – Hypothesis formation
- Phase 5 – Data collection, elaboration, and analysis
- Phase 6 – Validation of the results
- Phase 7 – Writing, review, and revision of the report

The workload is three credits in terms of the European Credit Transfer System.

3 Design of the experiment

3.1 *The Feersum Endjinn*

We named our experimental system conducting accelerated life testing the *Feersum Endjinn* (FE) after a novel written by Iain M. Banks (1994), where an engine enables a process of relocating the complete solar system out of reach of an impending danger. However, the name of our machine is more influenced by its appearance than by its function.

The objective of our FE is to expose operating LED to dynamically alternating external temperatures, refer to Mammitzsch (2015, 2017), Schenk (2020). These significant temperature differences accelerate the degradation of the LED. Previously, the experiment was conducted with a conventional air climate chamber; however, a liquid-based climate chamber offers a clear advantage. Compared to air, water has a significant higher heat capacity and heat conduction. Therefore, water allows significantly shorter cycle times – in terms of minutes instead of hours – to be achieved. This was the motivation for developing the FE.

The FE is operating by circulating temperature-controlled water through a tempered tank. The water of the tank alternates between hot (ca. 80°C) and cold (ca. 7°C), supplied by a heating or a cooling unit, respectively, see functional block diagram in Figure 1. Inside the tank the LED are shielded by a thin plastic foil to ensure a dry environment. The LED are exposed to rapid thermal stress without any direct water contact.

The water circulation is facilitated by two independent loops supplying hot and cold water. Both loops end up in the tank. Each loop consists of:

- A water heating or a cooling unit, respectively
- Input valves regulating the water inflow using the internal pumps of both temperature control units mounted above the tank
- Output valves preventing unintended outflow.
- Pumps for pumping water from the tank to the heater or cooling unit, respectively, and back.

The tank is alternately filled with hot or cold water. The actuators (pumps and valves) are controlled accordingly to the required water level and temperature in the tank.

The design ensures precise control of temperature changes in the tank while minimizing interference between the hot and cold loop. As applied for four semesters now, the *Feersum Endjinn* provides a platform for accelerated life testing of components, e.g., LED.

3.2 *System hardware*

The latest version of the FE consists of the following hardware components and modules:

- Tank where the LED are exposed to thermal stress
- Water heating unit
- Water cooling unit
- Four valves for controlling the water in- and output to the tank
- Water pumps
- Two water level capacity sensors at the tank
- Control unit Arduino Mega 2560
- Relays on a board controlling the FE actuators
- Power supply AC 230 V
- Power supply DC 24 V
- Power supply DC 12 V

3.3 *System software*

The flowchart in Figure 2 illustrates the software loop running on the Atmega 2560 microcontroller, which is accessed through an Arduino board. The loop is responsible for the alternating hot- and cold-water filling and emptying process. Since the process for hot and cold water is identical, we focus on describing the hot water process in detail, including the initial setup.

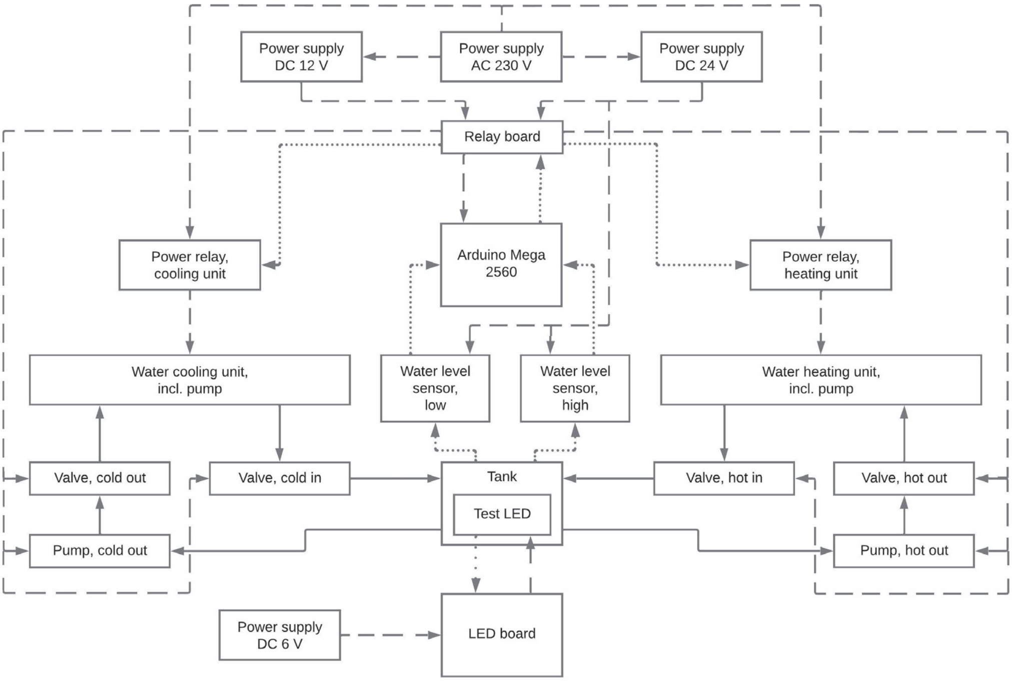

Fig. 1. Functional block diagram of the *Feersum Endjinn* hardware. Solid line: waterflow, dashed line: power supply, dotted line: control signal.

When the Feersum Endjinn is started, the relevant microcontroller pins are defined and set to a safe initial state. This ensures the process always begins under defined conditions. The relays controlling the power supply for the water heating and cooling units, as well as the water level sensors, are set to low preparing these components for operation.

Then the hot in valve is opened filling the tank with hot water by activating the unit-internal pump. The tank continues to fill until the upper water level sensor sends a high signal to the microcontroller, indicating that the tank is filled. At this point, the hot in valve closes.

During an interval of 40 seconds the LED are exposed to the high temperature of the surrounding water beyond the thin plastic foil. This represents the thermal stress during operation. The hot out valve and pump are activated after 40 seconds until the lower water level sensor indicates that the tank is empty by switching to a low signal, which is send the microcontroller. The hot out valve is closed and pump is deactivated. The total time for a water cycle (filling, temperature exposure, and emptying) takes 60 seconds. The same sequence of operations is then repeated for the cold-water process.

The loop is the basis for the consistent and reliable temperature cycling, enabling precise controlling over the environmental conditions to which the LED are exposed.

3.4 *LED board hardware*

The LED board consists of the following hardware components:

- Circuit board as foundation, especially for the current mirror components
- In total 15 LED per board as unit under test
- Bipolar transistors and resistors mirroring the current in one branch of the circuit to others, ensuring consistent LED operation
- Arduino Mega 2560 microcontroller serving as control unit for controlling the LED current and managing data acquisition.
- SD card data storage ensuring that all measurements and timestamps are logged.

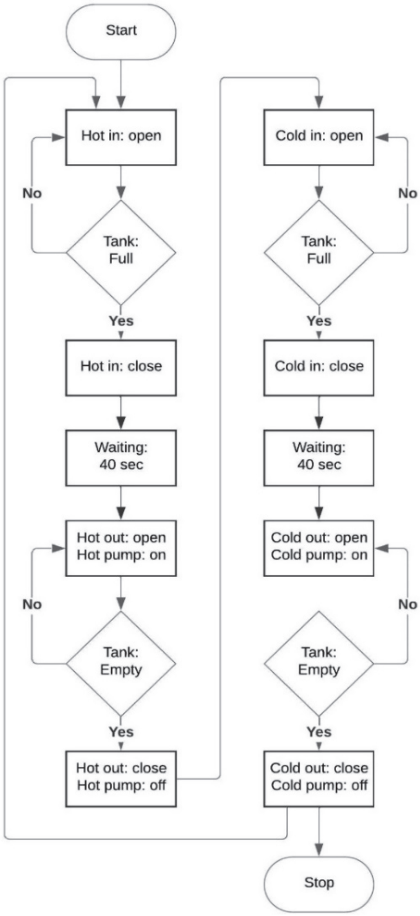

Fig. 2. Flowchart illustrating the actuator activities.

- RTC DS 3231 real-time clock ensuring precise timestamping of all collected data
- MAX31865 amplifier with PT1000 sensor temperature measuring with high precision to monitor the thermal conditions

3.5 *LED board software*

The software developed by the students must fulfil the following requirements:

1) Recording following data from a measurement point: the voltage across the LED, the tank temperature, and the time, when the tank temperature is at 80°C.
2) Switching the LED on or off if the ambient temperature is above or below 70°C, respectively.
3) Enabling safe removal of the memory card without corrupting the data.

To achieve these requirements, the software begins with the initialisation of the necessary libraries for the memory card, the PT1000 measuring transducer, and the real-time clock. Based on this, essential variables are declared, such as:

- The file on the SD card for storing the recorded data
- Parameters for calculating the temperature from the PT1000 resistance
- The threshold temperature for switching the LED on or off

This completes the header section of the software. Next, the setup routine is executed once at the start of the experiment. In this step:

- The serial bus is initialized.
- The pin controlling the LED is defined.
- The RTC and SD card are activated. Their connections are checked to ensure proper functionality.
- The header of the .txt file is written to simplify later data analysis by assigning recorded values to specific events.
- Finally, the serial bus is deactivated to allow other components accessing the bus when required.

Everything described below in the loop is located within an if-condition. The condition checks that the Stop button was not pressed and the corresponding variable is low. This fulfils the third software requirement as the SD card is not removed while it is being written to. Within the loop:

1) The serial bus is reactivated to record the temperature via the PT1000 measuring transducer. Then the bus is deactivated to allow communication with other components.
2) An if-condition checks whether the temperature is greater than 70°C. If true, the LED are switched on via a transistor on the LED board; otherwise, the LED remain off.
3) Another if-condition ensures that measurement points are recorded only under specific circumstances
    - The temperature must have reached at least 80°C.
    - The temperature must have previously dropped below 50°C since the last measurement.

If both conditions are met, the time, temperature, and the voltage drop across each LED (which is measured via the analogue inputs of the microcontroller) are saved to the SD card. This fulfills the first software requirement.

Before the loop restarts, two final checks are performed:

1) Is the temperature below 50°C? If so, reset the cycle for detecting new high-temperature peaks.
2) Has the Stop button been pressed? If pressed, the corresponding variable is set to high, which is the condition of the very first if condition in the loop.

4 Conducting the experiment

4.1 *Roles, activities, and responsibilities of the students*

The students gather in groups of three. Their task is to develop the voltage monitoring circuit and the related software. Typically, two students work together on the circuit; one student sets up the Arduino components and develops the LED controlling and monitoring software. The workloads of both roles are balanced. There is no requirement that every student has to take on every role in the course. Students find and choose their role in the group independently.

To simplify the start, the students are provided with a wiring diagram of the LED-logger, which they first plug on a breadboard with the circuit components. After the circuit has been correctly understood and tested, the students transfer it to a stripboard and solder the components.

Before the software is developed, the students familiarize themselves with the components by controlling them individually on the breadboard. Then the concept of the experiment-related software libraries is explained. After the successful integration of the libraries, a flow chart is created which serves as a template for all subsequent steps that still need to be developed.

The students learn to apply their fundamental knowledge of electrical engineering and microcontroller programming in a practice-oriented way. The course offers a safe and relaxed working framework to the students; however, the group forms a consortium that is jointly responsible for the success of their project, especially for the documentation, the evaluation of the collected data, and the final report.

4.2 *Hypothesis formation*

The formulation of hypotheses is the scientific core of the experiment and of the course. It is an essential part of learning the principles of systematic research. In terms of the experiment, the students develop a hypothesis based on the theoretical principles as learned in the course.

The hypothesis shall reflect the relationship between the increased load on the LED due to thermal cycling and the increased current on the mean lifetime of the LED. The hypothesis is based on the Arrhenius Equation and the Palmgren–Miner Rule predicting the mean lifetime reductions under accelerated stress conditions, refer to Arrhenius (1889), Palmgren (1924), Miner (1945). An example is given here:

> "*Under the given test conditions of thermal cycles and increased operating current, the mean lifetime of the LED decreases predictably.*"

4.3 *Data collection*

After the students have soldered the components onto the board and verified the functionality in conjunction with the software, a final functional test is conducted. On the last day of the lab, the LED are operating under real conditions in the tank of the FE. The recorded data is checked for validity.

As the boards are verified successfully, the practical part of the lab course is completed. Now the long-term testing begins. Over a period of eight weeks, the LED are operated daily on working days to maximise the stress on the LED. (Unfortunately, our *Feersum Endjinn* is not certified to be left alone, which is a lesson learnt from Iain Banks' novel.) At the end of the phase, the students receive the recorded data from their LED.

5 Data Analysis and Validation

The validation and prior analysis of the recorded data is the next part of the lab course. Students shall apply their theoretical knowledge of reliability engineering to this practical scenario in order to systematically analyse the data and calculate the mean lifetime of the LED.

This also includes conducting hypothesis tests to verify the statistical significance of the previously formulated hypothesis. The Arrhenius (1889) equation and the Palmgren–Miner rule (1924, 1945) are applied to analyse the cumulative load during the accelerated life test.

The data are checked for completeness, then cleaned and organised to eliminate measurement errors and outliers. The LED are operated using constant current control. Therefore, the current is logged and if it falls below 80% of the nominal value for the first time, the LED is defined as faulty.

Since the whole testing period is usually too short to get an LED failure, the students perform a regression analysis, based on the recorded voltage data, to predict the residual useful life. This means when the voltage drops below 80% nominally and therefore when the LED is likely to experience soft failure or to fail. Confidence intervals are calculated in order to quantify the uncertainties in the analysis and to assess the robustness of the conclusion.

Thereafter, the experimental data and the results of the mentioned analyses are compared with values from data collections and, ideally, validated.

6 Reporting and review process

Finally, a report is edited in English and submitted to the lecturer. The report shall meet scientific standards and reflect the analytical and methodological competences of the students.

6.1 Writing guidelines

The report authored by the students is a documentation of the experiment and summarises all relevant aspects of the accelerated life testing and the results. With this report, the students demonstrate their ability to explain complex technical concepts in a clear and structured way. The following instructions are given to the students, refer to Vališ (2024c).

Section 1 –Introduction
- Motivation: Explain the significance of reliability testing for semiconductors, especially LED.
- Context: Highlight the relevance of accelerated testing in optimising development time and costs.

Section 2 – Foundations
- Provide the theoretical foundations of reliability engineering and accelerated testing methods.
- Explain relevant models, such as the Arrhenius equation and the Palmgren–Miner rule.

Section 3 – The test setup
- Describe the components under test and the soldered experiment setup.
- Explain the code written for the Arduino, including LED controlling and data recording.
- Refer specific environmental conditions, e.g., average temperature in the lab.

Section 4 – Experimental procedure
- Provide a graphical and textual description of the testing scheme.
- Include an example of recorded data to illustrate the measurements.

Section 5 – Data analysis
- Discuss the recorded data and methods for data elaboration, assessment, and modelling.
- Apply suitable models for trend analysis and predictions of the mean lifetime

Section 6 – Results
- Summarise the generalised test results and interpret their significance.
- Compare the findings with values from data collections and other studies.

Section 7 – Conclusion
- Provide a summary of the key insights gained from the experiment and their implications for reliability testing.
- Offer an outlook on potential improvements and future developments of the experiment.

Section 8 –References
- Include all citations according to ISO 690:2021.

6.2 Review and revision

Students are required to complete and submit their report by a specified date. Once submitted, the report undergoes a review process and – if necessary – is returned to the students for a revision. This iterative process enhances the understanding of the subject and also provides a valuable experience in academic practices. Additionally, the process fosters competences such as critical evaluation and effective communication.

7 Further work

As current is not permanently recorded, we don't get a hint if regeneration effects occur during the cold phases.

To improve the progression of the lab course, it is essential to implement safety functions detecting critical failures of the *Feersum Endjinn* transferring the experiment into a safe state. Once these safety measures are implemented, continuous 24/7 testing can be conducted providing more realistic data. Practicing what we preach, a hazard analysis has been conducted; now a Failure Modes, Effects, and Criticality Analysis follows.

This opens up opportunities for new student projects as implementing the following safety measures based on a V-model:

- Temperature monitoring of the tank
- Monitoring the water levels of the tank and of the water heating and cooling units
- Implementing a leakage detection

8 Conclusion

The lab course introduces students to accelerated life testing and brings an opportunity to apply and deepen their knowhow in concepts of reliability engineering and statistical analysis.

By a combination of theoretical foundations and practical application, students gained an opportunity to develop skills in applied electric engineering and developed essential competences in experimental design, testing, and data analysis. They learned to elaborate real-life data and formulate statements about LED reliability. The students are bridging the gap between academic learning and professional engineering during the lab course.

In addition to achieving the course objectives, the implementation of the *Feersum Endjinn* revealed opportunities for further development as the integration of safety measures, which bring new opportunities for student projects, enabling them to engage with further hands-on aspects of safety engineering.

Overall, the students develop technical and analytical competences as well as they experience real-world challenges in reliability engineering.

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