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Radiant cooktop reliability study – accelerated life test

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This paper presents the results and a *quantitative* reliability analysis of an Accelerated Life Test (ALT) with supply voltage as stress factor. The component under study is a radiant heater used in an electric cooktop. In order to check the limits of the component and to have hints for designing the ALT, a *qualitative* reliability analysis of a High Accelerated Life Test (HALT) has been executed as first. The analysis is focused on the most frequent failure mode for the radian heater of electric cooktop: the burning of the ribbon wire. The authors assess the stress over operation of the component under study. Intensity, frequency and duration have been analysed with innovative solutions collecting data from test campaign, connected home appliances and electric grid field variation report of German government. A stress versus strength analysis was fulfilled and the probability of failure has been calculated after 10 years of component usage in home appliance cooktop.

Keywords: Accelerated Life Test; High Accelerated Life Test, electrical radiant heater; electric cooktop reliability

1. Introduction

Using electricity to cook food is a very old concept that have been refined over the year. Since the beginning of 20th century radiant heating was selected as a very interesting alternative to gas and coal, as reported by W. A. Gillot (1914). Many of the concerns raised at that time are still relevant in modern kitchen appliance design – as energy efficiency, element reliability and consumer adoption. In the paper by Gillot (1914), the heating element were identified as the most vital part of an electric cooker, and their reliability was major concerns. In these terms, the author was suggesting the nichrome wire as preferred material for heating element because of its durability, and he warns against poor wiring and insulation, which could lead to failure.

Similar conclusions can be cathead from the design optimization of radiant heaters presented in the paper of Yun Ji Kang et al. (2023). The authors were able to create a numerical model to predict temperature distribution in a radiant heater for cooking appliances starting from some experimental results. They observed temperature drop over time and heat loss of the radiant heaters due to possible thermal inefficiencies and potential mechanical degradation of insulation.

Another compressive study on radiant heaters is produced by F. Odoi-Yorke (2024). The author describes the evolution of the electrical cooking appliances via a bibliometric analysis to identify trends and research contributions on the topic from 1993 to 2023. The author found a growing interest in electric cooking with increasing contributions to research topics as optimising electric cookers with artificial intelligence (AI), Internet of Things (IoT), and integration with smart grids. In the paper, the author describes that the future research outlooks should focus also on cooking habits in order to encourage large-scale adoption.

In the study under disclosure, it is presented a reliability analysis based on one of the most critical components of the radiant hob: the ribbon wire.

2. Function analysis radiant hob

The function of a radiant heater is the energy conversion from electrical to thermal. Heat radiation over the air through the glass ceramic is causing the pot or pan to heat up. The function is a combination of the heat conductivity of the penetrated materials and the radiation between the heater and the glass. In Figure 1 the described components can be found as follows:

(i) Radiant Heater
(ii) Glass ceramic
(iii) Pot / Pan - Bottom

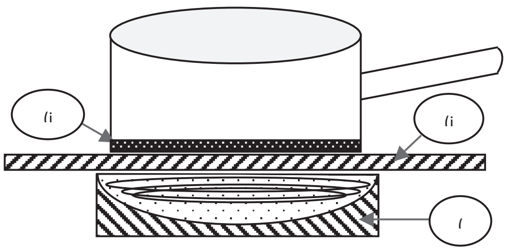

Figure 1 – System Components

2.1.Function analysis radiant heater

A radiant heater consists of five major components:

(i) Connection terminal
(ii) Thermal limiter
(iii) Ribbon wire
(iv) Insulation material
(v) Metal box

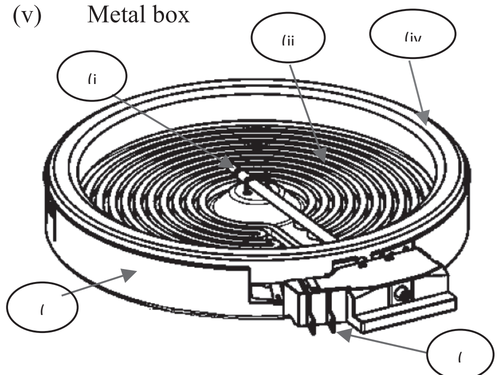

Figure 2 – *Drawing radiant heater*

Each of the components has its own task to guarantee the heater assembly function and cause different failure modes. The electro mechanic bi-metallic switch in the thermal limiter can get stuck or the insulation material can cause increased leakage current to the earth, resulting in RCD to release. According to internal reports the ribbon wire is the component failing earliest.

2.1.1.Critical component – Ribbon wire

During the investigation a heater with 140mm ribbon loop at a nominal power of 1200W (230VAC / 5,22A) was evaluated. The ribbon wire is a resistive load, following ohm´s law.

$$R_{ribbon} = \frac{U_{mains}}{I} \quad (1)$$

According to Joule´s law the amount of generated thermal energy (Q) is proportional to the Resistance of the wire, the current and the time:

$$Q_{Heater} = I^2 \cdot R_{Ribbon} \cdot t_{on} = U_{mains} \cdot I \cdot t_{on} \quad (2)$$

The Eq. 1 and Eq. 2 will be later referenced in this paper to explain stress factor selected for accelerated the failure effect.

The most common failure of the radiant heater assembly is the burning of the ribbon wire. In the left-hand side of Figure 3 the failure can be seen, while in the right-hand side a properly functionating ribbon wire is visible.

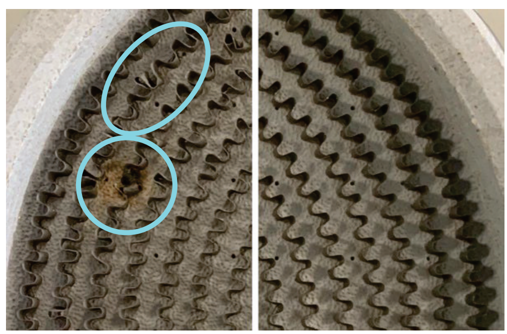

Figure *3* – Ribbon wire failed vs. functionating

An evenly geometrically shaped and homogeneously alloyed ribbon has a constant current flowing and a linear voltage drop over the total length. This results in an even watt density distribution (W/mm²). Looking in Figure 3, in the oval shape a deformation can be seen, while in the circular shape the evolved failure is visible. This is resulting from locally overstressing the ribbon, due to local bottlenecks, caused by the alloy or cross section.

3. Analysis of the Stress

A composition of operating time (frequency and duration) and intensity defines the mission profile for the device under test (DUT). An electric cooktop frequently has four cooking zones that are composed by four different radiant heaters. Every cooking zones is adjusted by a control unit, e.g. an user interface or rotary power selector, with eleven different power levels from zero “0” (Hob zone off) to “P” (full / nominal power). This means that the combination of all cooking cases is huge: the complete hob has 11^4 and the two heater sizes each 11^2 possibilities.

3.1. Stress frequency and duration

The operating time was derived from the usage information available from connected induction hobs, as E. Belmonte et al. 2024 described, assuming that the user cases for induction hob are like radiant hob. The plausibility of this assumption was verified with data coming from an internal survey. Based on this data we can consider that the operating time of an electric cooktop with radiant heaters is 2500 hours for 10 years of appliance life.

3.2. Stress Intensity

The parameter of intensity for the case under study is the electrical power, as a product of the supply voltage and supply current during cooktop operations. Since the heater follows ohm´s law (Eq.1), and the electrical resistance of the cable is steady, the variations of the voltage mains supply (V_{mains}) can produce a variation in the power and electrical current absorbed. The radiant heater has a rated power of 1200W at the nominal voltage of 230VAC.

Table *1 - Electrical parameters*

Voltage (V)	Current (A)	Power (P)	Resistance (Ω)
215	4,88	1049,11	44,06
220	4,99	1098,47	44,06
230	5,22	1200,00	44,06
240	5,45	1307,27	44,06
245	5,56	1362,31	44,06

According to ohm´s law the absorbed electrical current is following the variation of the voltage. Looking at Eq. 2 the power and thermal energy will vary quadratic. According to EN 50160 for the European Union, a ±10% of variation of the voltage mains supply, it is allowed

3.2.1. Voltage variation distribution

The voltage variation is dependent on the local circumstances like:

- Distance to transformer
- Load in the circuit
- Cross section of the supply lines
- Symmetry of the phase load distribution (star point shift)

Therefore, a voltage drop in the lunch time or at the evening is foreseeable, while in the night the voltage usually increases above the nominal rating. According to A. Haber et al. (2024), the measured supply voltage can vary +9,35% and -9,49% around the average value in over 389 measurement spots. The error-bar-plot in the report by A. Haber et al. (2024) is used as reference for creating the mission profile creation. Another report on the same topic based in Germany, Bundesnetzagentur (2020), includes data from a survey deployed in 69 Companies with 101 factories. Power-failures are not considered in both reports. To fit the information gained from the reports, a normal distribution with a mean value of 229,96VAC and a standard deviation of 3,65 is assumed as representative of supply voltage variation.

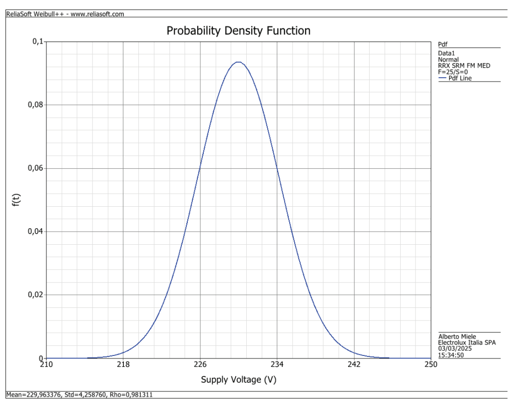

Figure *4 - PDF Voltage distribution assumption*

3.3.Mission Profile

Probability density function can be transformed including the operating time of the electric cooktop, that is 2500 hours in 10 years, as shown in Figure 5.

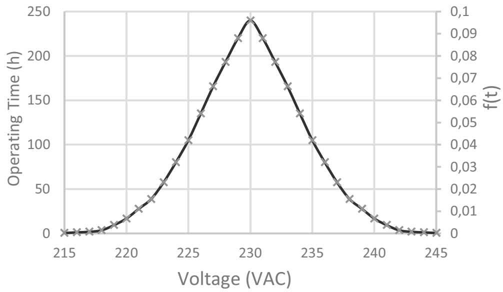

Figure 5 - *Mission Profile Radiant Heater 2500h*

To calculate the reliability with a stress-strength analysis, both the stress and the strength must be normalized at the nominal use stress level (230VAC). Reliasoft 2022© is used for calculating the PDF in a life (hours) - stress (Voltage) folio. The Inverse Power Law (IPL) with a Weibull distribution was chosen because of the electrical, non-thermal relationship. In Figure 6 the PDF for the Life-Stress evaluation can be found. This will refer as "Stress" for the remaining chapters.

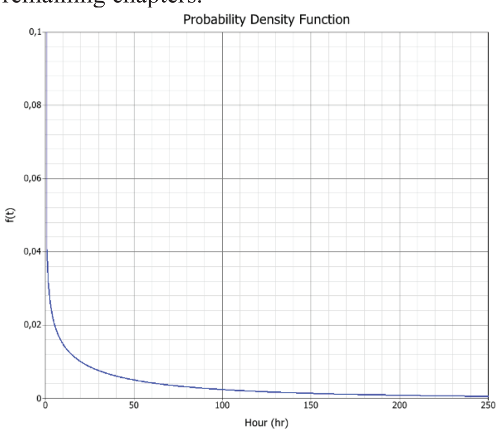

Figure 6 – Stress-PDF (Life (Hours) Stress (Voltage))

4. Analysis of the strength

The fundament of the strength derivation is a test to failure from the Supplier 1 at nominal and three increased stresses with two failures each level. The evaluation was done with the same model (Inverse Power Law) and distribution (Weibull) using Reliasoft 2022 © by HBK.

4.1. HALT – highly accelerated life test

The following testing method to acquire the stress limits of the radiant heater, was first performed within the implementation of the 2 suppliers. In this case a new supplier (2.) as second source was under evaluation and benchmarked with the capabilities of the current supplier (1.) at two DUTs, each. The voltage was increased every 30 Minutes until the ribbon wire burned, starting from the nominal voltage of the heater. The results can be seen in Figure 7.

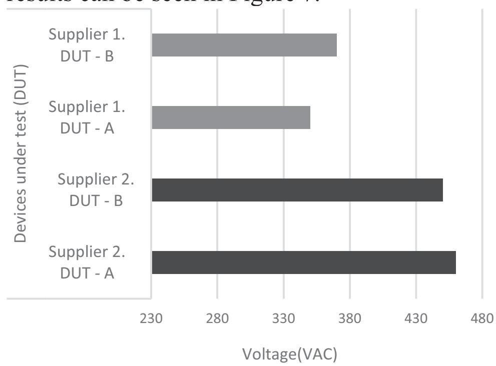

Figure 7 - Limit verification benchmark results

Considering Eq. 1 – Ohm´s Law, the current shall theoretically increase linearly by the voltage. In Figure 8 the real behaviour caused by the specific resistance of the alloy with a temperature coefficient of resistance (TCR (α)) as a function of the voltage can be seen. Without knowing the exact alloy of the ribbon wire some general statements can be derived. The alloy or geometry must be different, because the current - slope is flattening earlier and more than the Supplier 2. At the Beginning both suppliers are increasing linearly, until the resistance is increasing leading to bottleneck the electron flow, resulting in current flattening.

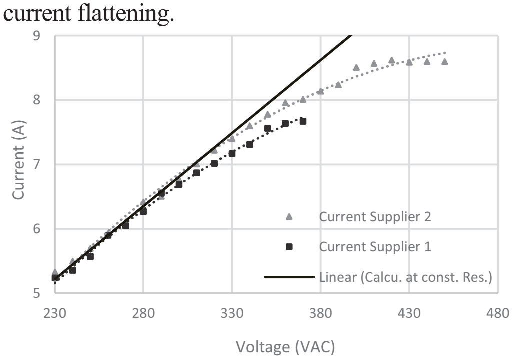

Figure 8 - Current investigation in HALT

This phenomena is represented by the formula for the variation of electrical resistance with temperature:

$$R = R_{20} \cdot (1 + \alpha \cdot \Delta T) \qquad (3)$$

Where:

- R is the resistance at time T
- R20 is the resistance at 20°C (reference temperature)
- α is the temperature coefficient of resistance, specific for the material
- ΔT is the temperature change relative to 20°C

As supplier 2. follows the same damage mechanism with a higher stress, the possibility to accelerate the test with increased voltage is possible. The stress level can be even increased more, since the electron flow is flattening at higher voltage. The highest tested and proven voltage was 264,5VAC for supplier 1. This was within the tolerance of the nominal parameters at the linear field. A current deviation of more than 2% to the nominal values is assumed to be the upper limit of the acceleration bounds, remaining to trigger the same damage mechanism. This would result in 300VAC for supplier 1. and 350VAC for supplier 2.

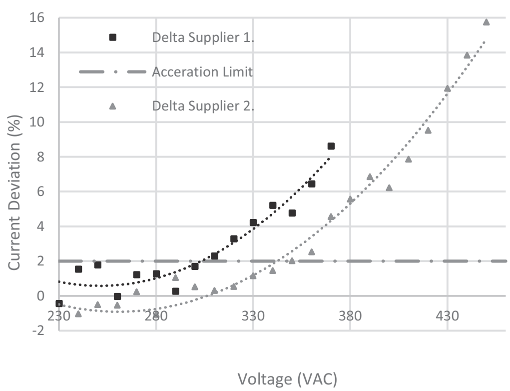

Figure 9 - Acceleration limits

This approach helps to increase the confidence of the test planning in avoiding overstress and new failures not occurring in normal use in the field. It is also useful to initially compare two suppliers as in this case the alloy and geometrical properties are confidential information.

4.2.ALT – Accelerated life test

The evaluation of the radiant heaters strength was carried out with a test to failure on component level at different stress levels (Voltage). At each voltage levels two heaters were tested until failure, with the current supplier in production.

The load capability of approx. 10.000 hours at nominal stress conditions (230VAC) proofed the feedback from the field. Three additional increased stress levels (241,5; 253; 264,5 VAC) were tested to calculate the Eta-Line, illustrating in Figure 10 the relationship of operation hours and voltage. The Eta-Line is created by estimating when 63,2% of the population in the distribution failed at one stress level.

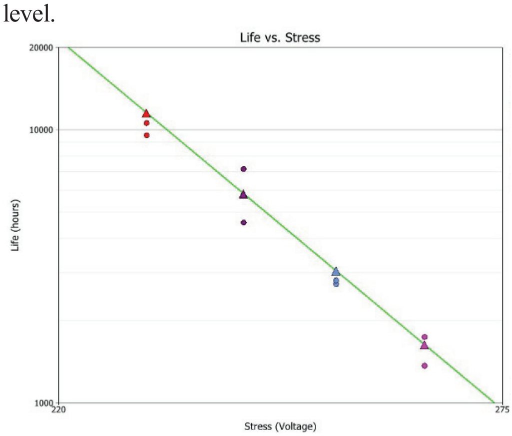

Figure 10 - Life vs. Stress à S/N-Curve

Within this voltage range the DUT could achieve an acceleration of almost 7-times, potentially the voltage and thereby the acceleration factor (AF) could be increased even more. Figure 11. shows the extrapolation until 275VAC with AF~12. The acceleration can be pushed, within the range of the same damage mechanism triggering the failure of the ribbon wire as showed in Figure 3.

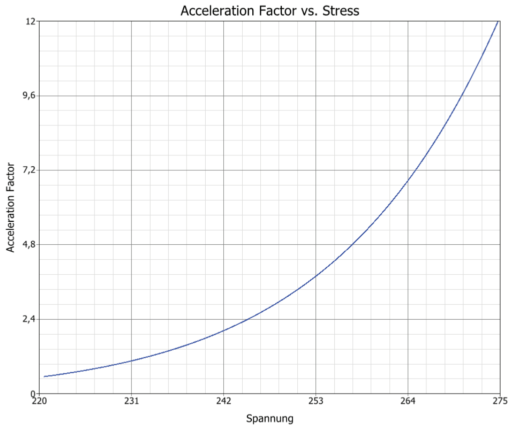

Figure 11 - Acceleration Factor vs. Stress

The PDF with a mean life of 10.700 hours at nominal stress (230VAC) can be seen in Figure 12. It will refer in the following chapter as strength.

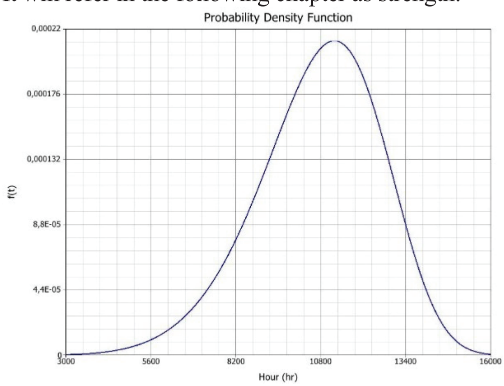

Figure 12 - PDF Strength

5. Reliability quantification

To conclude the reliability in a quantitative manner the stress versus strength approach with Reliasoft © was applied.

The target reliability was specified during a system breakdown, starting on appliance level through the assembly layers. The components needed to provide the function were allocated with a reliability, considering the importance, safety criticality or complexity of each individual part. The radiant heater resulted in R95 (at 2000h) to guarantee a sufficient reliability of the system.

In the evaluation approach comparing the probability density function of the stress in the left-hand side with the one from the strength in the right-hand side of Figure 13. The overlapping area in the middle represents the area where failures can occur. Within the intersection the probability of failures (PoF) is distributed and calculated. With the given data the radiant heater showed a reliability of 99,75%.

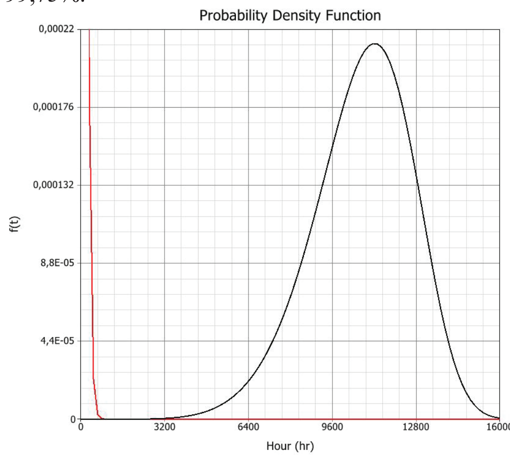

Figure 13 - Stress vs Strength

In Figure 14 a close-up of the probability of failures can be seen.

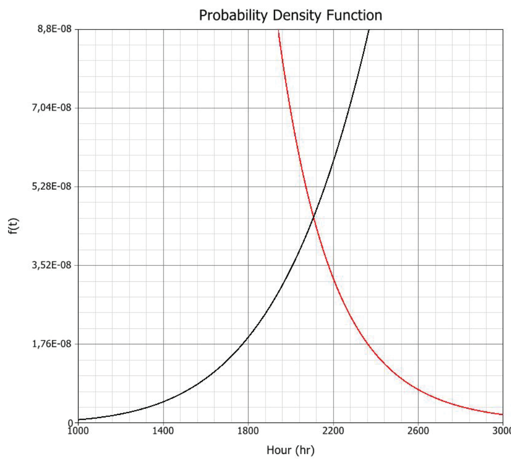

Figure 14 - Stress vs Strength PoF close up

6. Conclusions

The reliability of the heater exceeds the target set for the appliance range, by far. This allows actions to increase the mission profile and decrease the strength of the radiant heater. Further, the initial HALT is acquiring valuable information in short period with very less samples. The ALT with voltage as increased stress factor for radiant heaters is a sufficient approach. Increasing the voltage until the current deviation assumption of 2% is reached needs to be furtherly proven.

7. References

W. A. Gillot (1914), Electric cooking and heating in private houses

F. Odoi-Yorke (2024), A systematic review and bibliometric analysis of electric cooking: evolution, emerging trends, and future research directions for sustainable development

Yun Ji Kang, Sudhanshu Pandey, Su Il Park, Young Soo Kim, Jea Hyuk Wie, Doo Hyun Kim, Man Yeong Ha (2023), Comprehensive analysis and design optimization of temperature distribution in radiant heaters for cooking applications

A. Haber; Urbanrschitsch W. (2024), Statistik über die Spannungsqualität in Österreich 2024 Berichtsjahr 2023. © E-Control 2024

Bundesnetzagentur (2020), Bericht zur Spannungsqualität

Hottinger Bruel & Kjaer Inc. (2022), Reliasoft Weibull ++ 2022©

E. Belmonte, F. Gackstatter and M. Neuman (2024). DfR of the Grill Oven Relay. ICSRS 2024 Proceedings, pp 120 - 122