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THERMAL MANAGEMENT FOR MISSION CRITICAL AIRCRAFT EQUIPMENT

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Abstract: *The operation of modern electronics under extremely low thermal conditions (below -50 °C) encounters a multitude of difficulties. The age of chip shortage limited available selection of state-of-the-art electronic components to only a fraction of previous offer. Automotive industry has gobbled most of the yet available stock while the aerospace-grade components are not available at all. In this paper we evaluate application of positive temperature coefficient heating strips as a means to keep the under-specified electronic devices in reasonable operational range while minimizing impact on the electronics design process. Our experimental results of PTC heaters testing suggest significant benefits compared to standard heaters used in the aerospace industry, but also some challenges, which are discussed in this paper.*

Keywords: Thermal management, heating strip, positive temperature coefficient, aviation, electronics.

1. Introduction

Integrated circuits (ICs) are fundamental to modern electronics, with their operation relying heavily on temperature. These circuits generate heat during operation due to energy losses manifested as heat in components, connections, wiring, or the printed circuit board (PCB). The greater the loss, the greater the excess heat generated. As the trend in electronic designs leans towards more compact devices with a greater concentration of components, IC packaging is becoming smaller but with poorer thermal properties. This is further compounded by the fact that component gates in semiconductor devices have been shrunk down to nanometer sizes, leading to a single die containing millions of gates formed from billions of transistors. Despite advancements in technology that allow for more compact and efficient devices, these new generations may face thermal-related problems in certain situations.

The operation of integrated circuits (ICs) at ultra-low temperatures, specifically below -50 °C, encounters a multitude of difficulties. A paramount issue originates from the differential coefficient of thermal expansion (CTE) between the components soldered to the circuit board and the circuit board itself. This discrepancy can engender considerable stress, especially upon the activation of the equipment. When hot components modify their shape due to this phenomenon, they might shatter brittle plastics, akin to what occurs when dry ice is introduced into a container constructed from brittle material such as an ice chest. An additional problem emerges when the equipment is transferred from extremely cold conditions to a warmer environment which may cause humidity condensation problems. Although these can be solved by application of protective varnish, there are even more serious problems.

Silicon dyes face several challenges when operated at extremely low temperatures. One of the main issues is the increase in resistance of semiconductors at lower temperatures as stated in Thompson (1961) and Jones (2003). Once the temperature drops below certain levels, the types of IC devices that can be used and their performance are significantly limited. Another problem is the decrease in electron mobility (quantized

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vibrations of the atomic lattice) at lower temperatures. This problem occurs in most silicon dyes, leading to potential performance degradation - see Clark (1992) and Gurrum (2005).

Operating ICs at such low temperatures requires specialized packaging and treatment. However, even nowadays after the chip shortage is supposed to be over it is not possible to obtain certain specific components from any source. The manufacturers have simply quit production of ICs on ceramic substrates or even never encountered a requirement of a specific component to be used under extreme conditions.

Printed circuit boards (PCBs) made from FR4 face challenges when exposed to extreme temperatures. The glass transition temperature (Tg) of FR4, typically ranging from 130 °C to 140 °C, causes the material to lose its mechanical properties and soften at this threshold, especially under rapid temperature increase. High temperatures also lead to moisture absorption by FR4, causing swelling and distortion of the board and potentially damaging the components and causing connectivity issues described by Shreyas (2023). Additionally, the adhesive used to bond the FR4 layers can weaken and fail at high temperatures, leading to delamination. Potential solutions include using high Tg FR4, polyimide, PTFE (Teflon), metal-core PCBs (MCPCBs), and ceramic substrates, each with their own advantages and disadvantages depending on the application requirements. For instance, aluminum-core PCBs can aid excessive heat dissipation and external heat distribution, but require unconventional methods due to their reactivity - LaBar (2022). However, our main trouble is the lower end of the extreme temperatures.

The feasible solution to the all above described problems is to maintain the device temperature in the reasonable temperature range given by the components and other material specification requirements. Cooling or heating the device unevenly can cause additional issues, either electric or mechanical, therefore an exact and even heat delivery and distribution across the entire surface of the device under examination is of highest importance. The further text describes one such approach applicable in the aerospace industry.

2. Proposed method

Safety is still a major priority in the aviation industry. We use traditional heaters broadly throughout industries despite the numerous problems that have afflicted them. However, a possible solution to these problems exists: A Positive Temperature Coefficient (PTC).

2.1. Positive Temperature Coefficient Heating elements

PTC heaters are self-regulating heaters that work as open loop elements without outside regulation or/and control. Flexible PTC heaters use conductive inks layers printed on a flexible polymer-based matrix with at least two different conductive particles with different properties, for example carbon black with silica filler on siloxane elastomer-based polymer as element which we used for reference and testing as described in patent by Wachenfeldt (2008).

In addition, PTC elements are characterized by high reliability and durability, where partial function is maintained even after several damages as demonstrated in our previous study by Kostial (2019). PTC heaters are an excellent alternative for applicable in the aerospace industry. Their use ranges from the heating of critical electronics components that cannot be installed into a controlled environment (actuators, lights, etc.) to advanced self-regulating anti-icing systems, which we had already tested but the results are still under evaluation. Testing shows significant benefits compared to standard heaters used in the aviation industry, but also some challenges, which are discussed in the next section.

2.2. Application

In general, electronic components are manufactured at several grades. Consumer grade components are supposed to withstand temperatures ranging from 0 to +70 °C, automotive grade specifies range between -40 to +80 °C whereas aerospace requirements stretch from -55 °C up to +70 °C according to RTCA DO-160G specification (2010). The difficulties here can be seen in general availability and attainability of such components even for applications where the cost could be ignored. Hence, the goal of our sub-project is to keep an electronic PCB at reasonable levels to ensure temperature comfort for the components and also the entire PCB board itself. To ensure spatially-even heating effect for the electronic board two distinct heating strips were evaluated (Fig. 1).

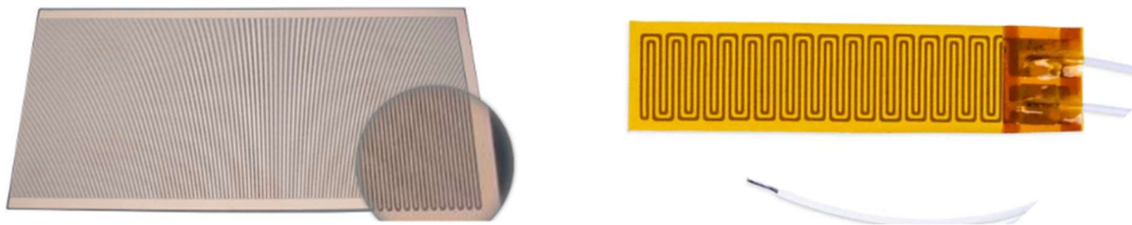

Fig. 1: Evaluated heating elements: A12WM Heating Foil (left), generic polyimide flexible heater (right).

Common method of heating (mainly smaller areas of) PCBs is to populate the board with passive or active components which in combination of analog or digital thermometer ICs and appropriate control ensure local temperature conditions. Use of the heating strips introduces the possibility for global thermal management across the entire area of interest. Compared to other methods of heating, the strips also have their own up and down sides but in general, the advantages and disadvantages of pre-assembled heating strips can be summarized as follows:

Pros	Cons
• Simplifies design process. • Optimal energy use and distribution. • High peak power. • Unaffected by voltage variations. • "Built-in" temperature control without any external components resulting in higher reliability.	• Fixed temperature setpoint given by the material composition. • Availability of custom geometries and temperature thresholds. • Cost of custom solutions. • PE/PET enclosure is not suitable for all scenarios.

Tab. 1: Heating strip advantages & disadvantages.

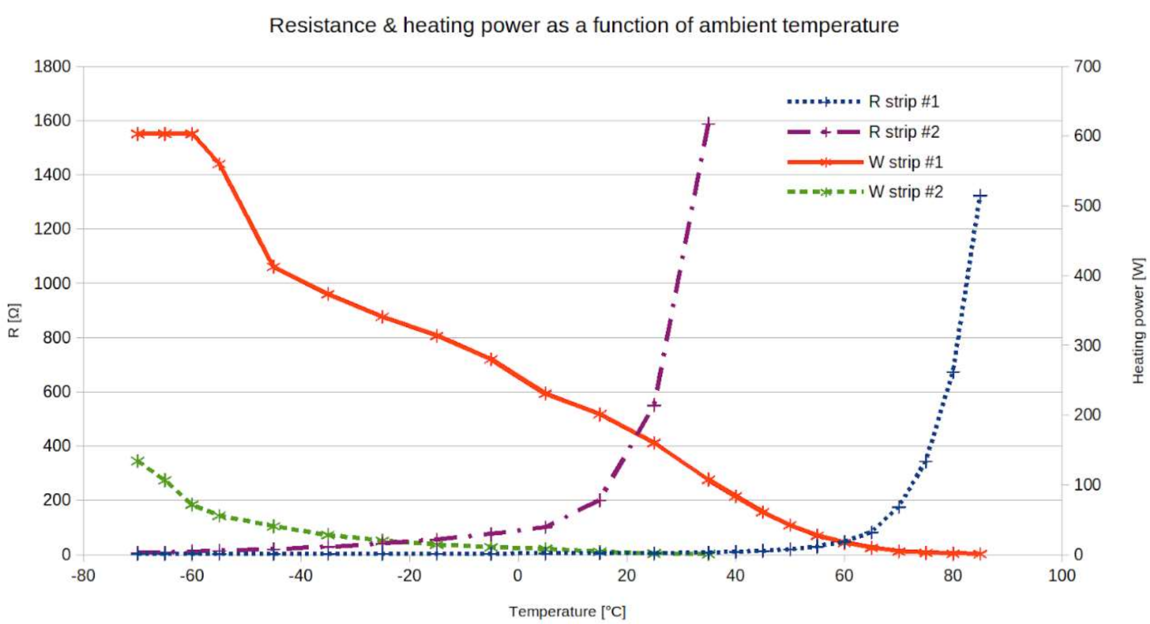

Fig. 1: Comparison of the reference strips in terms of resistance and heating power at Vcc = 28 V. The application would require the threshold temperature to be even lower than the strip #2; slightly negative values of the threshold would also be fully acceptable. The heating performance of strip #1 is too high whereas power output of strip #2 would be completely sufficient.

The evaluated PTC strip A12WM is manufactured to a specific fixed temperature setpoint which limits the heating temperature approximately to 70 °C as specified by the datasheet and also validated by a measurement in climatic/environmental chamber (see strip#1 in Fig. 2). (Over)heating the electronic components to such high temperatures is very undesirable. All such available heating strips are designed to have the breaking temperature around this range which makes this behavior rather undesired. What we are currently looking for is a PTC strip whose characteristic is shown in Fig. 2 as suggested strip characteristic #2 Meaning with significantly limited power output (in tens of watts) and the breaking temperature at around 20 °C or even below threshold. Such a strip is manufacturable, but currently such an option is not offered for sale on the open market.

The most advantageous feature of the A12WM heating strip in comparison to the generic flexible heaters can be seen the fact that the area in which the temperature is already close or above the threshold (e.g. zones below and in vicinity of components like motor drivers and power mosfet transistors) is not heated by the strip. Material of the strip in that particular zone is already in a state of high-impedance and no excessive power is radiated in that area.

3. Conclusions

The aim of the paper was to briefly outline the problems we face today in the development of increasingly complex and sensitive electronics in aviation. Due to flight-levels of commercial traffic we are mainly dealing with very low temperatures of critical elements outside of environmentally controlled areas of the aircrafts. The solution proposed in this paper is to maintain electrical components and PCBs in an ideal temperature range using flexible PTC heaters. These are proving to be very suitable heating instruments due to their self-regulating material-based capabilities and long-term stability.

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