Artículo de investigación

Electrochemical migration: Stages and prevention

Электрохимическая миграция: этапы и профилактика

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Abstract

The modern trend of miniaturization of electronics has also affected the aviation industry. With each new generation of aviation electronics (avionics), the layout of electronic components becomes smaller and smaller. This led to a significant complication of all electronic components of avionics in general, as well as compaction topology of printed circuit board (PCB) used in avionics, in particular. Any complication of electronic equipment, and especially important facilities, leads to increased requirements for reliability. Given that the aircraft equipment is operated almost constantly in extreme conditions, even the slightest probability of failure is unacceptable. That is why the physical reliability of avionics is so important. One of the factors significantly reducing the physical reliability of aviation electronics is electrochemical migration.

Electrochemical migration can lead to failures in the operation of aviation electronics, to its complete failure, and even to a fire outbreak on the aircraft. Now the electrochemical migration is explored badly. Only the factors causing it and the consequences of electrochemical migration are determined, and the existing way of struggle it is either ineffective or significantly increase the weight and cost of aircraft equipment set, so that their use becomes impractical.

This article presents experimental studies of the kinematics of electrochemical migration, the consequences of its occurrence, as well as, the way of struggle of the occurrence of electrochemical migration with the analysis of experimental data.

Аннотация

Современная тенденция миниатюризации электроники затронула и авиационную промышленность. С каждым новым поколением авиационной электроники (авионики) компоновка электронных узлов становится все меньше и меньше. Это привело к значительному усложнению всех электронных узлов авионики в целом, а также уплотнению топологии печатных плат, использующихся в авионике в частности. Любое усложнение электронной аппаратуры, а особенно аппаратуры ответственного назначения, приводит к повышению требований к надежности. Учитывая, что авиационная аппаратура эксплуатируется практически постоянно, в экстремальных условиях, даже малейшая вероятность возникновения сбоя или отказа недопустима. Именно поэтому физическая надежность авионики настолько важна. Одним из факторов, существенно снижающим физическую надежность авиационной электроники, является возникновение электрохимической миграции.

Электрохимическая миграция способна привести к сбоям в работе авиационной электроники, к ее полному отказу, а также даже к возгоранию на борту летательного аппарата. На сегодняшний день явление электрохимической миграции изучено достаточно плохо. Определены лишь факторы, вызывающие ее, и последствия электрохимической миграции, а существующие способы борьбы с этим явлением либо неэффективны, либо значительно увеличивают вес и стоимость бортовой аппаратуры настолько, что их

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Keywords: Avionics, conformal coating, corrosion, dendrites, electrochemical migration, moisture protection, reliability.

использование становится нецелесообразным.
В данной статье приводятся экспериментальные исследования кинематики явления электрохимической миграции, последствий ее возникновения, а также с учетом проведенного анализа экспериментальных данных предложен способ борьбы с возникновением явления электрохимической миграции.

Ключевые слова: авионика, влагозащита, дендриты, конформное покрытие, коррозия, надежность, электрохимическая миграция.

Introduction

Aircraft operation in countries with humid subtropical climates (e.g., India) showed insufficient protection of avionics from electrocorrosion and electromigration processes in PCB, greatly reducing its physical reliability (Medvedev, Sokolsky, 2015).

Despite the fact that at the final stage of production, the PCB is covered with a layer of insulating material (conformal coatings), it is impossible to achieve absolute moisture protection, and moisture, in one way or another, will penetrate and accumulate on its surface and inside the dielectric (Han, Osterman, 2012). It occurs not only because of poor-quality application of a protective coating (which is quite rare), but also because of the difficult climatic conditions of aircraft operation. As a result of fast and frequent changes in external temperature (from -50°C at an altitude of 10 000 meters to +60°C at the aerodrome), the coating is deformed and covered by microscopic cracks, which increase over time. High humidity promotes liquid condensation on the surface of the PCB. The liquid precipitates in the form of distilled water and reacts with substances on the surface of the board, forming a favorable environment for the electrocorrosion and electrochemical migration (electromigration).

Electromigration is a complex electrochemical process with many possible consequences and causes. However, most of the time there are three necessary conditions for the occurrence of it (Munson, 1998; Sokolsky, Sokolsky, 2016):

- Presence of a pair of electrochemically dissimilar metals (for example, gold/tin metal, silver/nickel, etc.), or creation of a potential difference between homogeneous metals (connector strip);
- Presence of ionized particles (usually haloids, hydrated oxides, etc.);
- Presence of a monolayer of condensed water, which dissolves the salts in atmospheric pollution, electrolyte solution occurs because of it.

Theoretical basis (kinematics of electrochemical migration)

The phenomenon of electrochemical migration exists if there is the conductive medium (electrolyte) and the potential difference between the conductors, a conductor with a high potential dissolves, giving positively charged metal ions through the medium to a conductor with a lower potential. Thus, there is the growth of conductive textile-dendrites in the electrolyte (dendritic, dendroidal), which are subsequently metallized, which leads to a short circuit of electrical circuits.

Dendrites are thin metallic filaments passing from one conductor to another. The growth principle of them is based on the phenomenon of electrolysis. When there is a potential difference between the conductors, a conductor with a high potential is an anode, and a conductor with a lower potential is a cathode. Under the influence of voltage in the electric system, the conductor-anode dissolves, giving positively charged metal ions into the electrolytic medium. These ions are directed to the conductor-cathode, where they are reduced to a metallic state. This leads to the fact that between the vapor of anode-cathode conductors a thin strap is formed as the dendrite-like loose metal structure. This process is the electrochemical migration (Hung, Ning, Tien, Ouyang, 2016).

The result of the electromigration for a few minutes can form crystals with a thickness of 2-20 microns and a length of up to 12-15 mm. After the formation of the straps the crystals gradually thicken up to 0.1 mm. The resistance of such metal filaments can achieve several Ohm. Over time, conductive dendrites reach the conductor-cathode, which causes the short circuit and the failure of the device (Kucharek, 2009; Kopytov, 2012).

One of the ways to prevent the phenomenon of electrochemical migration is a thorough cleaning of PCB and application of conformal coatings.

Conformal coatings protect Infinity cove of solder, conductors, metallized objects, as well as electronic components on PCB from corrosion and external influences during operation in adverse conditions.

Preparation before the conformal coating (for example, cleaning) and compliance with the modes of the process are also important for protection against electrochemical migration (Medvedev, 2005).

If the process of applying a conformal coating is not considered carefully, there may be undercure or overdry of coatings, which ultimately affect the characteristics of the material, such as surface tension, thixotropic properties, time for undercure, etc. For example, if poor-quality or blunt drills are used when drilling mounting or transition holes in the PCB, it is possible to heat the PCB above the glass transition temperature and its subsequent deformation, and the use of blunt drills significantly increases the probability of appearance of flipped side and foil rises at the exit of the hole. These factors significantly reduce the density of the conformal coating to the surface of the PCB, which in turn significantly impairs its properties (Phil, 2015; Vantsov, Vasilyev, Medvedev, Khomutskaya, 2018; Zve, 2018).

Methodology (experimental study of electrochemical migration)

To propose a technique to combat electrochemical migration, it is necessary to study the mechanisms of this phenomenon experimentally.

To study the stages of the process of electrochemical migration the board which includes the fragment "C" of the test coupon E according to State Standard 55693-2013 (Figure 1a) is designed and manufactured and the experimental setup (State Standard 56252-2014), functional diagram of which is shown in the Figure 1b.

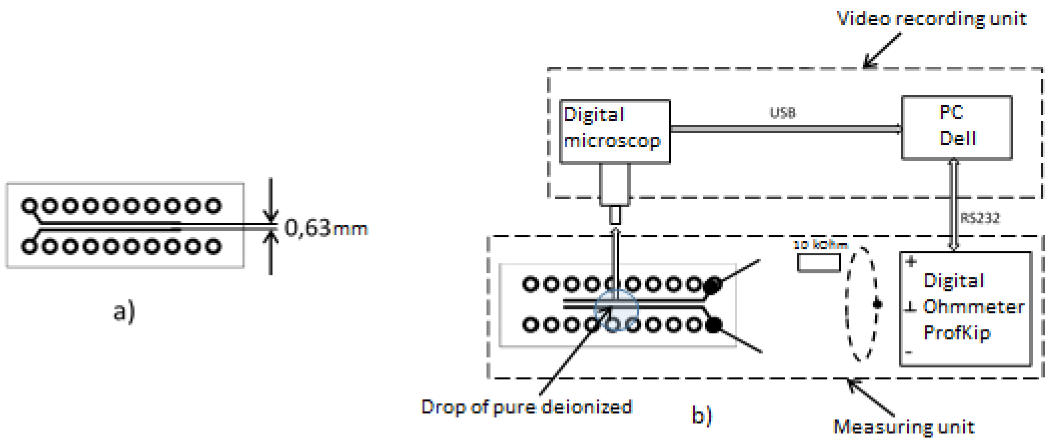


Figure 1. Test board and experimental setup

To monitor the experiment, a DTX 30 digital electron microscope was used. To measure the resistance, a UT61E digital multimeter was used. As a power supply, a direct current source LW PS-305Dm was used. To prevent a short circuit in the formation of dendrites and their metallization, a 10 kOhm resistor is installed in the circuit (Babaahmadi, Tang, Abbas, 2013).

The experiment was carried out at the temperature of 400°C and with a voltage of 5 V. In order to create ideal conditions for the occurrence of electrochemical migration, a drop of deionized water with a volume of 1 ml and with a specific resistance of 18.2 MOhm·cm was applied to the conductors of the test board. The experiment was carried out with the several test boards under the same conditions (Sokolsky, Sokolsky, 2018).

Results

The change in resistance depending on time during the electrochemical migration and metallization of dendrites is shown in the Figure 2.

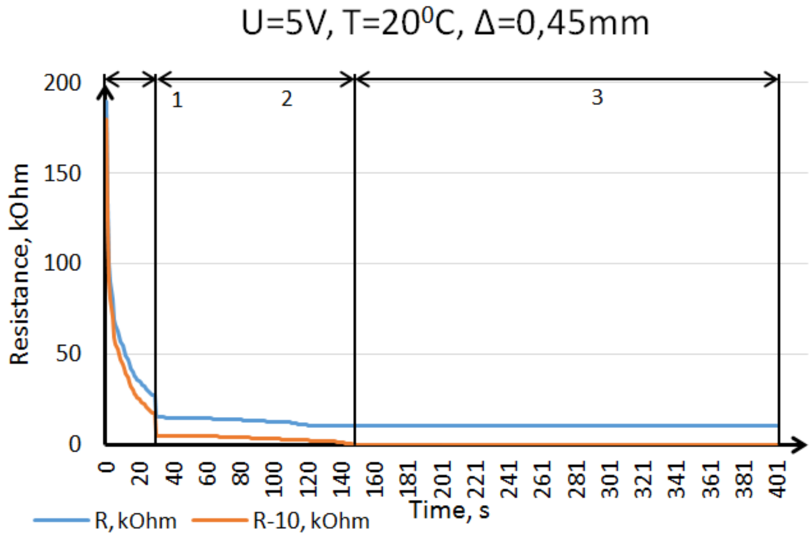


Figure 2. Change in resistance during the growth and metallization of dendrites

After analyzing the results, we can conclude that the process of electrochemical migration will be divided into three stages (Figure 3):

- Formation of copper ions and the release of hydrogen;
- Growth and closure of dendrites;
- Metallization of dendrites with short circuit.

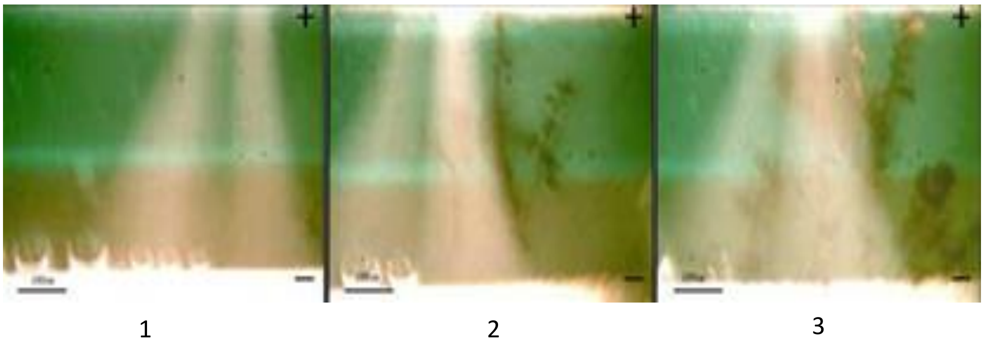
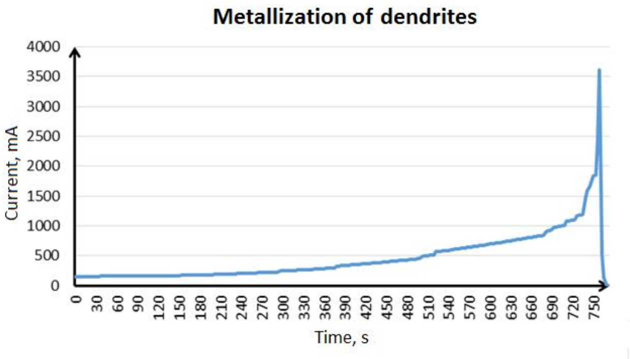


Figure 3. Stages of electrochemical migration

At the first stage (0-29 s), the formation of copper ions and the restoration of hydrogen cations occurs (resistance drops from 180 to 17 kOhm, and at 29th second the resistance falls

sharply to 5 kOhm in 0.3 s due to the beginning of dendrite formation. At the second stage (30-153 s) occurs the formation of dendrites and their closure (resistance drops from 5 kOhm to 30 Ohm). At the third stage (154-378 s), the dendrites are metallized (resistance drops from 30 Ohm to 3 Ohm), i.e. the exothermic metallization process begins, but since the volume of a drop of deionized water is insignificant, it evaporated within 5-15 seconds under the influence of temperature and the metallization process stopped. If the liquid does not have time to dry (378-750 s), the growth of the metal bridge between the conductors continues, which leads to a short circuit and carbonization of the dielectric of the PCB (Figure 4). The third stage ends with short circuit of the conductors.



a)

b)

Figure 4. Metallization of dendrites
a - current change; b - result.

It is obviously, that the failure of avionics occurs at the end of the second stage, because the resistance of the dendrite circuit falls to 30 Ohm, which corresponds to the insulation current of ≈160 mA in the circuit. Then, the process of electrochemical migration leads to catastrophic consequences: by ≈ 750 s, a metal bridge of reduced copper is formed between the conductors, the resistance of which is only a few Ohm, which can lead to a fire outbreak of the PCB.

We can conclude that the failure of avionics occurs after the second stage of electrochemical migration: the growth of dendrites. That is why it is necessary to study and eliminate the possibility of the occurrence of the possibility of electrochemical migration.

Discussion (prevention of electrochemical migration)

As it was mentioned above, two of three necessary conditions (presence of a potential difference and ionized particles (from air pollution)) are always present, and it is impossible to protect from them. But the formation of a condensed layer of water on the surface of the board can be prevented. Moisture condensation requires a certain temperature and humidity. If the temperature of the PCB is lower than the ambient temperature, at a certain humidity, by an amount greater than the dew point, condensation forms on the surface of the PCB and, while maintaining the surface temperature of the PCB at least ambient temperature, moisture condensation can be prevented.

We introduce the concept of $\Delta T_{dew} = T_{PCB} – T_{dew}$, where T_{PCB} is the board temperature. The dependence of ΔT_{dew}, ºC on the ambient temperature at various humidity values is shown in the Figure 5.

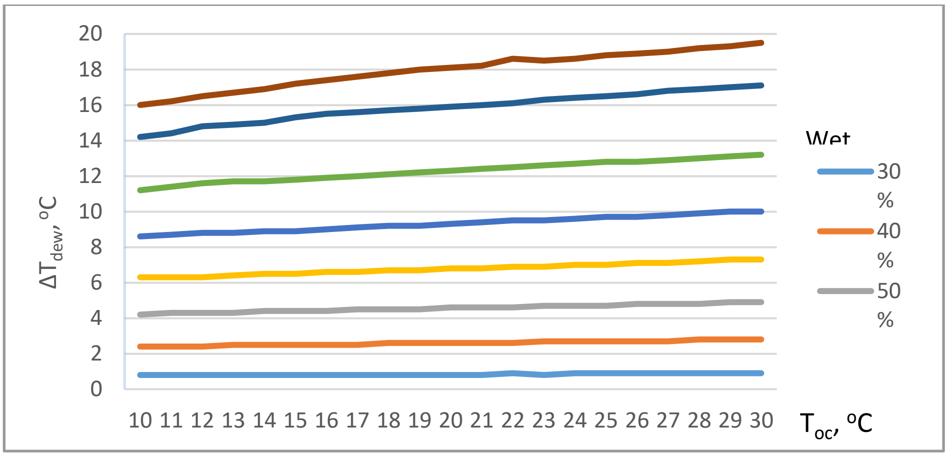


Figure 5. Dependence of ΔT_{dew} on ambient temperature

Obviously, if the difference between the temperature of the PCB and the ambient temperature was minimal, then there was no condensation of moisture on the surface of the board, and there were no created conditions for the deposition of a monolayer of condensed water.

The following experiment was carried out in a constant climate chamber (Votsch vc3 7018). The studied object was kept there at a constant temperature of 20°C for 30 minutes. Then, at a constant value of humidity, the temperature gradually decreased to -50°C, the take-off of the aircraft was simulated. After reaching the minimum temperature inside, the test PCB was cooled to -50°C, which was recorded by a temperature sensor built into the board. Then the temperature gradually increased, the decrease was simulated. In this case, the moments of the appearance of condensate on the surface of the PCB were recorded.

Then, the constant climate chamber was heated with a PCB from 20 to 50°C at a humidity of 95%. In this case, the air temperatures there and the PCB and the formation of condensate were recorded.

During the experiment, it was found that at a certain value of humidity, ambient temperature and the object under study, liquid droplets precipitate on the surface of the investigated PCB, and the board temperature was lower than the ambient temperature (Figure 6). As the temperature of the PCB increased, the condensation stopped.

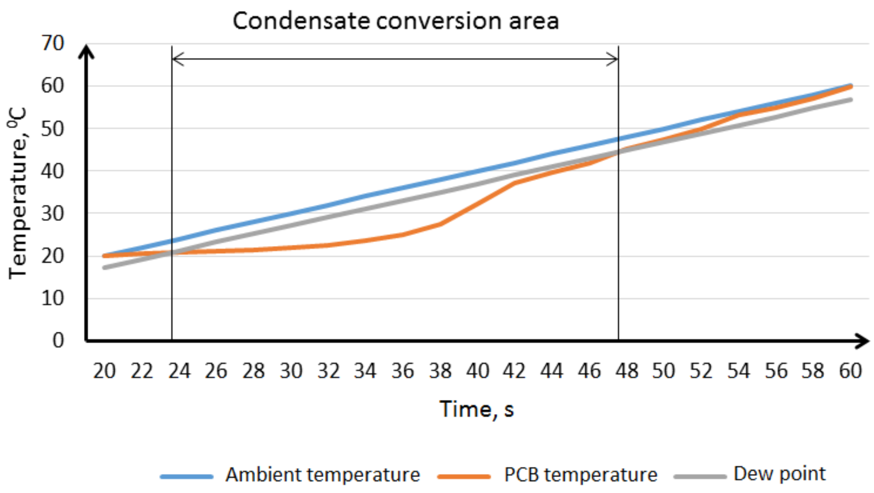


Figure 6. Condensation conditions

To prevent condensation from forming on the surface of the PCB, a control device that, when the ambient temperature rises, begins to heat up the PCB, was developed (Figure 7, 8). A test board with a heating layer and temperature and humidity sensors placed on it was also developed (Figure 9).

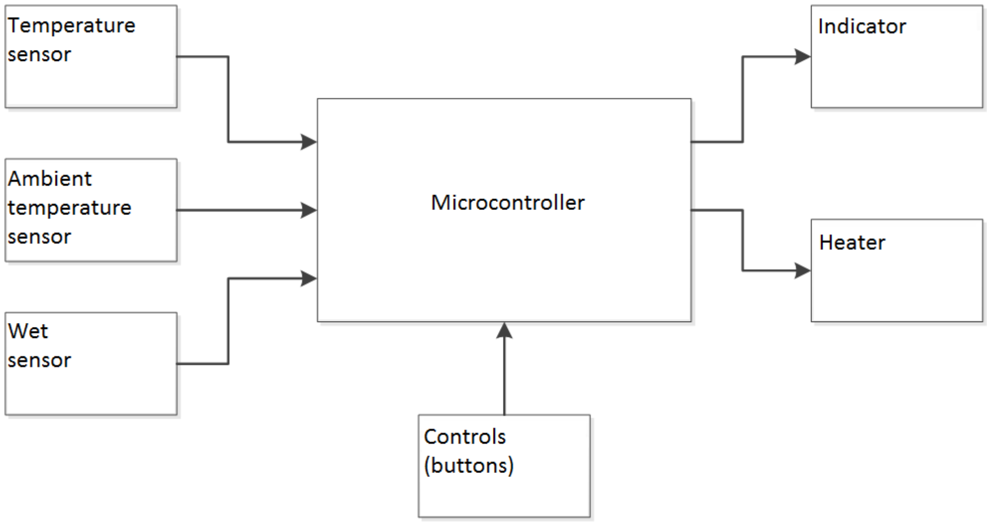


Figure 7. Functional diagram of the system

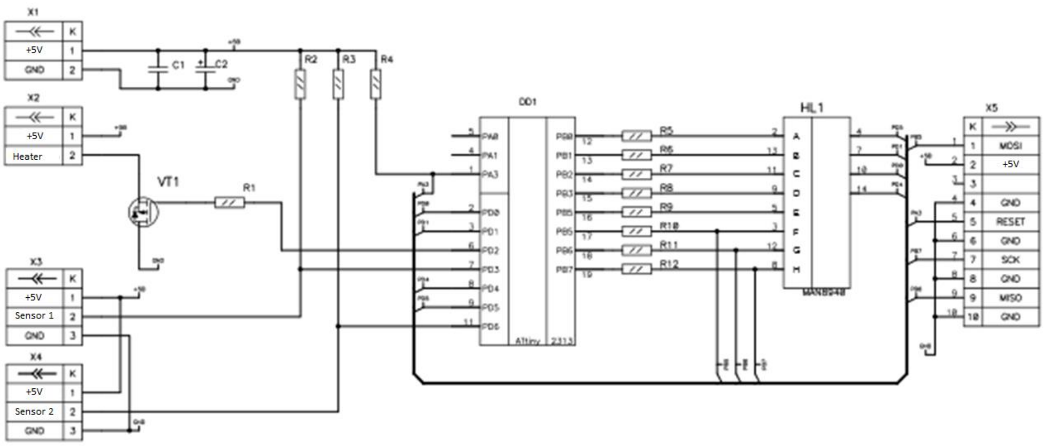
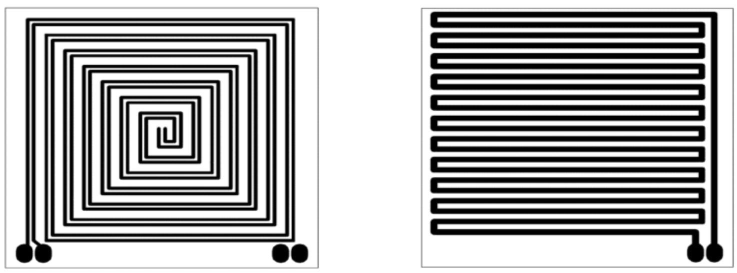


Figure 8. Schematic diagram of the device



Test layer - open conductors Heating layer

Figure 9. Test boar

For the operation of the device, a microcontroller program was written. The device works according to the algorithm from the Figure 10.

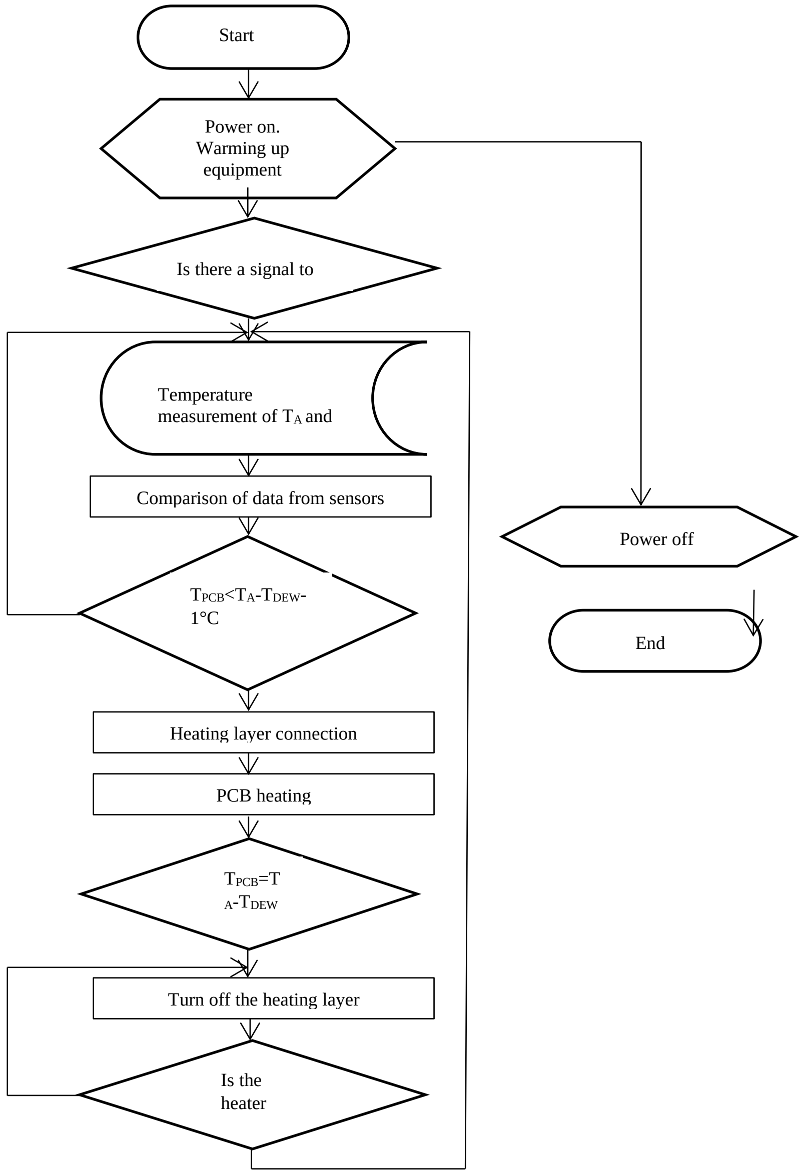


Figure 10. Block diagram of the algorithm of the device

To test the operability of the device for preventing electrochemical migration, the following series of experiments was carried out.

At the first stage, the climate chamber is cooled to a temperature of -10°C (take-off of the aircraft is simulated). Then, the steady-state temperature is maintained for 10 minutes (flight of the aircraft is simulated), during which the temperature of the test board and the ambient temperature come to a steady-state value. At the next stage of the experiment, the temperature inside the climate chamber begins to rise (simulating a decrease in the aircraft), at this time moisture should be deposited on the test board, since the temperature of the test board cannot change simultaneously with the ambient temperature. The difference between the temperature of the test board and the ambient temperature at a certain point in time will reach a value that exceeds the ΔT_{dew} value for a certain value of ambient temperature and humidity, which will cause liquid condensation on the surface of the test board. In turn, this will lead to the formation of dendrites, and the appearance of current in the interconductor gap. An ammeter records the increase of amperage.

At the second stage of the experiment, the heating layer of the PCB, two temperature sensors that are installed on the test board and in the climate chamber, are connected to the control device. The climate chamber heats up, and when ΔT_{dew} becomes higher than the dew point temperature, the control device sends a signal to heat the test board, which should prevent moisture condensation on the surface of the PCB, and, as a result, prevent the formation of electrochemical migration.

During the first stage of the experiment in the climate chamber, condensation was detected on the surface of the test board, while in the second stage of the experiment, condensation did not occur.

Conclusion

There is the hypothesis about that if one of the factors, which is necessary for the occurrence of the phenomenon of electrochemical migration is excluded, the process of the migration will not begin. After the analysis (presence of conductors, potential difference and electrolyte), it was decided to exclude the electrolyte presence factor, because there is no way to eliminate other factors that arise due to the design features and operation of avionics systems.

In order to eliminate this factor, it is necessary to ensure that there is no condition for the formation of condensate on the surface of the PCB during the operation of aircraft equipment. Condensation on the surface of the PCB is not possible if the temperature of the board is greater than the value indicated in the dew point table for a given air humidity, when the ambient temperature rises. To comply with this condition, it was decided to incorporate a heating layer into the inner layer of the multilayer PCB, and to create a control device for this heating layer, in order to prevent the difference between the ambient temperatures and the board one is more than the value indicated in the dew point table for a given humidity. A series of experiments showed the validity of the hypothesis and confirmed the performance of the whole system.

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