COCKPIT AVIONICS THERMAL COOLING IN DEGRADED CONDITIONS

Ph. Tatry, Ph. Mairet
EADS – Airbus, Toulouse, France

The design of space systems and aircraft is developing in a common manner with respect to the highly increasing use of avionics systems. Although modern avionics presents a lot of design and operational advantages, this development has to be very closely monitored mainly because the reliability of avionics equipment is strongly affected by the thermal environment in nominal as well in off-nominal conditions.

This paper is focused on the close links between avionics functioning and thermal environment in space systems or aircraft (e.g cockpit).

Space vehicles / aircraft: same concern vs thermal environment on avionics

During the last decades, either in space vehicles (e.g launcher, satellite) or in aircraft, the part of the avionics systems has been increasing continuously because of the interest of such systems in terms of weight saving, mission flexibility, control & monitoring, reliability & availability requirements (e.g around 50000 parts of Electrical Electronic Electromechanical concern a launcher).

Indeed, avionics systems are involved in all the main functions of space vehicle or aircraft: Flight Management, Flight Control, Guidance & Navigation, Displays & controls, Communication & Tracking.

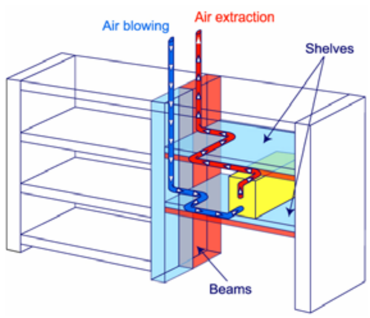
Whatever the aerospace systems (space vehicles or aircraft), the avionics systems capabilities are a major means to contribute to fulfill the Safety, Reliability, Availability and Maintainability requirements such as:

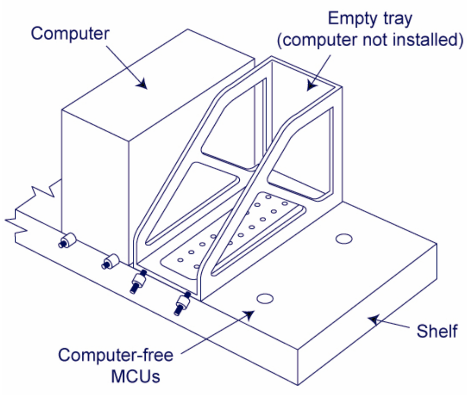
- Redundancies management.
- Fail Operational / Fail Safe requirements (i.e capability to perform the operational mission after any single failure and to return safely to a runway landing after any two failures).
- Built-In Test Equipment (BITE) as a means of component failure detection.
- Fault Detection, Isolation, Reconfiguration (FDIR).

Therefore, a major malfunction could occur in case of failure on avionics systems related to space vehicles or aircraft: wrong thermal environment is one significant root-cause of failure on avionics systems.

Past experience acquired on Aircraft

Aircraft avionics computers are generally installed on fixed brackets or on racks in avionics bays as shown below:



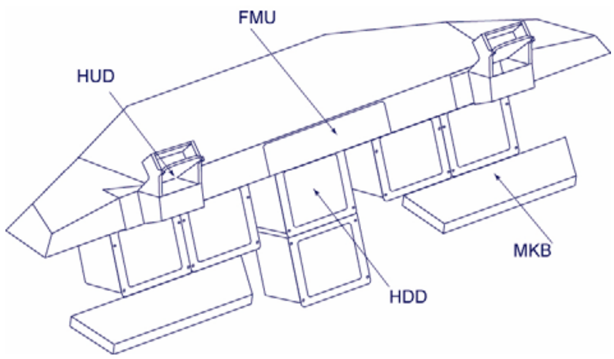


Air blowing and/or air extraction help for dissipating computer heat. Nevertheless, in case of ventilation failure, the equipment is working under the natural air convection. Additionally, for power supply, the use of power bus-bar contributes to the heat internal dissipation in the vehicle.

Past experience from Hermes vehicle

On manned space vehicles, the problematic is quite different than on aircraft due to the available time to recover the favorable temperature/pressure conditions via a Safe Return on Earth. Consequently, to prevent an overheating of the avionics, a cooling system is generally required to provide a path of low thermal resistance from hot avionics items to an ultimate heat sink.

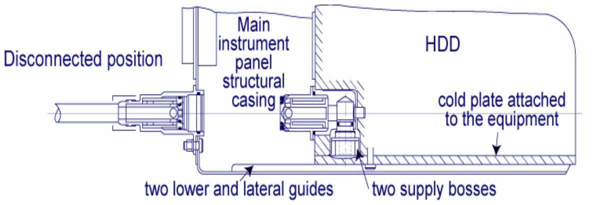
Avionics cooling in a cockpit in degraded conditions (cabin accidental depressurization in orbit) was deeply investigated for Hermes space project by focusing on cooling the 6 “Head-Down Displays” (HDDs) which provided pilots with visual flight data.



Because of HDDs internal components reached high temperatures leading to a degradation of their performance to provide the vital information required by pilots for a safe return to Earth (in emergency conditions) within 3 hours, two thermal controls were investigated:

- HDDs cooling with forced ventilation: With all HDDs running, after 50 mn operation, HDDs were no longer in working order: Even with 2 HDDs running (i.e successive operation), all HDDs on the instrument panel were out-of-service after 2 hours instead of the 3 hours requested. The HDD cooling solution using forced ventilation was not viable (with avionics technologies available at this time) for “Emergency” conditions.
- HDDs cooling by using cold plates thermal efficient with the following constraints:
  - cold plates in direct contact with HDD.
  - HDD specifically re-designed to enable the dissipated flows to be evacuated to the cold plates.
  - coolant temperatures inside the cold plates compliant with the specified limits.

- appropriate design integration of HDD / cold plate / fluid connector as shown by the investigated solution below:



These thermal investigations performed are more and more essential for the space vehicles and aircraft because of the huge development of new technologies on avionics systems.

Examples of significant new technologies on avionics systems.

The new avionics technologies available on-the-shelf or in laboratory are covering a large scope going from power supply (e.g Lithium-ion battery, nanotube packaging) to wirings (e.g high speed bus, polymer conductors, optical interconnections), sensors (e.g piezo-electrics, optical captors, ceramics), components (e.g ASIC, DSP, SRAM, DRAM, microprocessors, FPGA, MEMS), actuators, switches (Solid State Power Controllers), ...

This enhanced field of new technologies can be illustrated by considering some main key-technologies in terms of:

- Power supply, for instance, the Zinc/air generator has a life duration about 20 hours in continuous mode and 10 days in standby mode, its specific energy is high (400 Wh/kg) compared with other values of power supply types such as 130 Wh/kg (for alkaline/Mn, Li-ion) or 220 Wh/kg (for Li/MnO_2 , Li/sulfur , Li/Mn).

  Additionally, two other fields are promising:

  – Fuel cells with ongoing improvements:

    - increasing of life duration of materials by using methyl silicate as basic material on Mg-Ni alloys.
    - new alloy (Cr + Ti + Va condensed inside a crystal with cubic structure and centered faces) doubling the hydrogen absorption capability versus materials with lanthanides.

  – Nanotube based products are also used for power supply with nanotubes that are manufactured by catalytic process (instead of by arcing) leading to high specific areas (about 250 m^2/g) and high power storage quite equal to 10 kW/kg.

  Nevertheless, even if a lot of progresses have been performed on low consumption linked to phone and nomad computers (CMOS conductor using, …), at high frequencies, the cooling is still a remaining problem.

- Space wires because of constraints on data (rate greater than 100 Mbaud), distance (greater than 10 m), power consumption, error rate (lower than 10^{-12} bit error rate), weight and size, susceptibility & emissivity EMC, ESD, immunity, isolation galvanic insulation, …, some technologies are under development / using such as:

  – high rate data bus (4,5 Gb/s) with hyper frequency technology functioning in asynchronous and oriented “word”; composed with modules HB-MUX.

  – using of polymer conductor of electricity (e.g Polyacethylene, Sulfur Polynitride) with a low weight and a conductivity depending on added doping.

- Fibers with technology developments:

  – optical fibers working at 150°C by using a “transparent” resin instead of silica.

  – helicoids carbon fibers presenting a high absorption of EMC.

  – bending measurements via Optical Time Domain Reflectometer.

  – piezo-electrical fibers used for Non Destructive Inspection (NDI): their filament narrow size (15–25 μm) and their random layout allow to increase the resolution by using high frequency.

- Sensors where huge new opportunities are available at Lab or off-the-shelf levels:
  - small accelerometer with piezo-electric sensor in Li Niobate presenting high resistance to vibrations and resolution.
  - piezo-electric ceramic RAINBOW (i.e Reduced And INternally Biased Oxide Wafer) very sensitive and able to sustain displacement of 1% (non useful for ceramics) with potential using on space vehicles to eliminate the noise and vibration environment.
  - ultra-high sensibility magnetometer (10pT/√Hz) for NDI.
  - flexion and bending sensor with optical fiber non-sensitive to EMC with double optical loop to eliminate the effects of ageing, temperature, …

Associated to the above avionics technologies, an important use of items is developed on space vehicles / aircraft such as:

- SSPC (Solid State Power Controller) that are used to replace both relays and fuses to switch for the power line and to protect against over-load or short circuit. The block diagram of the SSPC takes into account the timing & latching unit, sensing circuit, OV protection, auxiliary power supply, Tele-Command and Tele-Monitoring interface. Nevertheless, the SSPC present weaknesses in terms of management of the temperature of the transistor: with respect to the overload duration (some 100 ms), the temperature could raise to about 200°C i.e greater than 180°C that is the function temperature (example of a 100 W power MOSFET on a 22–37 V bus).
- Filters to filter the voltage noise coming from the main bus (e.g ripple, transients such as voltage steps, bus interrupt, overshoots) and rejected current (e.g inrush current, immunity to bus transients, damping with a constant power load).
- Components such as connectors, oscillators, filters, analog (e.g operational amplifier), converters (e.g AD/DA, sample & hold), power supply (e.g voltage reference & regulator), programmable logic Integrated Circuit (e.g FPGA, PLD), ASIC (for gate array, special functions), logic Integrated Circuit, memories (e.g DRAM, PROM, flash EEPROM, SRAM), microprocessors (e.g controller, DSP), opto-electronics (e.g opto-coupler, infrared emitter, phototransistor).

Impact of thermal environment on the failure rate of the avionics systems

In avionics systems, the electronic devices are quite always subject to thermal loads as a result of environmental exposure (i.e “external” heat due to engine firing, propellant/fuel pumps functioning, pressurized fluids cycling, aero-thermal fluxes, …) and/or electrical power cycling (i.e “internal” heat by Joule effect, …). Consequently, temperature cycling or levels can cause the device to fail.

Correct reliability predictions are a fundamental tool for highlighting design trade-off decisions, estimating avionics system reliability and at the end for predicting the global mission reliability. Indeed, inaccurate predictions can lead to either overly conservative design, excessive spare parts procurement resulting in added Life Cycle Cost, weight or neglecting the root-causes of failure with potentially occurrence of Single Failure Points.

Today, two main approaches are used to perform prediction of the avionics reliability:

1) Approach based on standard handbook:

   The useful standard handbook is the MIL-HDBK-217 that includes a series of empirically based failure rate models covering virtually all electrical/electronic parts, covering operational environments, such as ground fixed, airborne inhabited, ... Typical factors used in determining a part's failure rate include a temperature factor (π_T), a power factor (π_P), a power stress factor (π_S), a quality factor (π_Q) and an environmental factor (π_E) in addition to the base failure rate (λ_b).The estimated failure rate is: $\lambda_{estimated} = \lambda_b \,.\, \pi_T \,.\, \pi_P \,.\, \pi_S \,.\, \pi_Q \,.\, \pi_E$

The Parts Count technique has to be applied early in the design phase to determine if the predicted reliability is in line with reliability requirements. When detailed design information is available (e.g detailed circuit schematics, …), the predictions should be refined to reflect actual applied component stress levels. For this topic, the more detailed methodology for the Part Stress reliability prediction is used and leads to the MTBF (Mean-Time-Between-Failure) estimation.

2)`Approach based on the Physics-of-Failure :

The traditional reliability prediction methods (e.g MIL-HDBK-217) present weaknesses:

– Difficulties to update the reliability data mainly when manufacturing improvements have been recently performed.
– Assembly failures not often component related but due to an error in calibration, an improper interconnection of components during a higher level assembly process, an error in socketing, ... Consequently, rather than manufacturing or design defect in the device, the reliability limiting items are much more likely to be in the avionics design (e.g misapplication of a component, stress-margin oversight, inadequate timing analysis, lack of transient control).
– Avionics component failures not always due to a component-intrinsic mechanism but sometimes caused by an inadvertent over-stress event after installation, a latent damage during storage, an improper assembly into a system or a choice of the wrong component for use in the system. Additionally, stress environment (thermal, vibration, …) can also make a model inadequate in predicting field failures.

Consequently, an alternative approach based on the Physics-of-Failure (PoF) is ongoing preferred by space and aeronautics vehicles designers.

The PoF approach to avionics devices is based on the fact that failure mechanisms are mainly driven by fundamental mechanical, electrical, thermal, and chemical processes: By understanding all the possible failure mechanisms, potential problems can be identified and then solved before they occur.

The PoF can be split into:

– Definition of the product requirements by the designer (e.g product's functional, physical, testability, safety features).
– Identification of the environment (e.g temperature, humidity, vibration, shock).
– Stress analysis combined with stress response of the chosen materials and structures to identify the failure sites (i.e failure location), the failure modes and mechanisms (caused by stresses types such as mechanical, electrical, thermal). When potential failure mechanisms are identified, specific failure mechanism models could be employed: The reliability assessment consists of calculating the time to failure for each potential failure mechanism.

Thermal environment is a potential “Single Failure Point” for avionics systems

To fulfill the high level of safety and reliability requirements requested for space and aeronautics vehicles, the avionics systems are implementing various principles such as redundancy architectures, Hi-Rel components, under/over voltage protections, watch-dogs, Circular Redundancy Checksum, qualification methods, ...Nevertheless, in spite of these driver principles, environmental factors could remain a Single Failure Point by "domino effect" (e.g thermal exchanges perturbed by low pressure due to depressurization).

Among the environment factors, the temperature is a key-driver in the failure rate of avionics items : Indeed, high temperatures impose severe stresses on most electronic items with potentially melting of solder joints, burnout of solid-state devices, chemical degradation effects, …

The failure rate is issued by the Arrhenius Model giving $\lambda_T = \lambda_0 \cdot \exp(-\Delta E/kT)$ w.r.t a constant of proportionality (λ_0), the activation energy of failure mechanism (ΔE), the Boltzmann's constant ($k = 8{,}61.10^{-5}$ eV/K) and the Temperature (T). For instance, with $\Delta E = 0{,}157$ eV, an increase of temperature from 25°C to 50°C leads to increase the failure rate λ_T with a factor of 1,6 … and the temperature could be a hidden Single Failure Point.

Risk Mitigation means w.r.t qualification methods of avionics systems

The Environmental Stress Screening (ESS) is a powerful process that allows to expose product weaknesses and to make corrections in the avionics systems design. Benefits are expected from ESS such as help to plan for spare parts, fault detection / correction during the product development cycle, improvement of the process / product quality, early identification of the infant-mortality failures. The effectiveness of an ESS program depends on the effectiveness of the failure analysis and on the implementation of corrective-action procedures after the ESS tests.

ESS tests include methods such as HALT (Highly Accelerated Life Testing) and HASS (Highly Accelerated Stress Screening). The stresses applied "classically" in these testing procedures are temperature (e.g levels, cycling), vibration (e.g sinus, random), humidity, shocks and various electrical stimuli (e.g inrush current, voltage cycling, over voltage, …). To be test-efficient, the levels of applied stress are much greater than those found during the normal running of the avionics systems: consequently, they precipitate the failures occurrence and reduce the test time. Additionally, ESS techniques precipitate latent failures that cannot be detected with electrical testing or visual inspections: so, infant-mortality cases can be eliminated and the avionics items can enter directly in the useful-life phase of the bath-tub curve at the end of the ESS testing:

- The HALT method is used during the design phase of an avionics product by increasing the applied stress in steps and by fixing the faults to improve the design. This step-stress sequence exposes the product's weaknesses, and the process of increasing the stress level continues until the destruction limits of the material is reached. Because of HALT sets the design limits of the avionics product for successful operation, it is a destructive test that identifies the design flaws and safe-operating regions for products.
- The HASS is used after the knowledge of the stress versus destruction limits from HALT to identify the weak products. The screens in HASS testing are high levels of stress that reduce test time. So, this HASS method is a non destructive test.

For various failure mechanisms, the Arrhenius model allows to calculate the Acceleration Factors (AF) given by:

$AF = t_{use}/t_{stress} = \exp[(-\Delta E/k)\ (1/T_U - 1/T_S)]$ w.r.t the temperature during use (T_U) and the elevated stress temperature (T_S generally equal to 85°C , 105°C , 125°C , 150°C or 175°C).

By applying this model, we can note that:

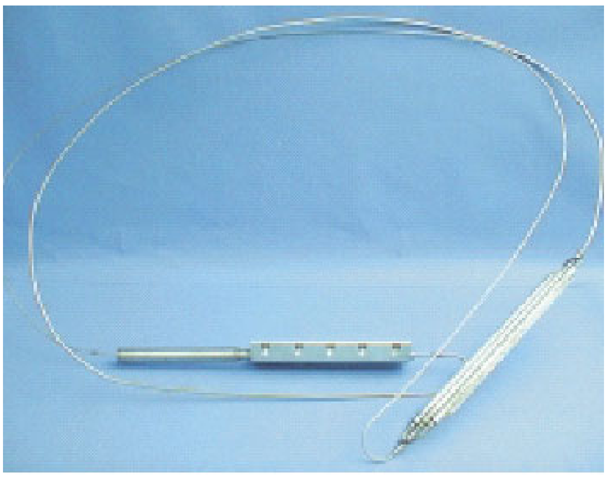
- With E_A=0,5 eV, one hour of MTTF at 105°C is equivalent to 62 hours at 25°C …
- Failure mechanisms with low E_A require a shorter period of accelerated testing to fail than those with high E_A.

Risk Mitigation means based on Thermal Control System

The Thermal Control System (TCS) for space vehicles or aircraft shall conform to the performance requirements related to the temperature gradients, temperature stability, temperature uniformity, heat flux, heat storage, heat lift, ...

Various type of TCS are applicable on avionics systems such as:

– Peltier devices that avoid the moving parts (e.g pumps, fans) and the coolants, are based on the temperature variation, which occurs in junctions of different materials under a voltage difference. This is a mature technology with design efforts concentrated on realizing high-efficiency power sources (Peltier Current Source) coupled with high resolution control of the set-point, efficient immunity to noise, thermal protection, protection against shorts / open circuits, optimal response in frequency and ability to accept a variable load. For instance, Peltier control units have been implemented for different payloads (e.g Biobox, Momo, Fluidpac) and have been flown on SpaceLab.
– Two-Phase Loops such as Capillary Driven Cooling Loop (CDCL): Instead of the conventional cooling loops that use electrical pumps, the CDCL features a two-phase (liquid/vapor) fluid circulation which is driven by a capillary pump, thus avoiding the high mass, electrical power and induced vibrations of a conventional liquid pump. The loop is able to transport up to 1 kW over a distance of several meters. Due to the extremely small size of the capillary pump, the heat transport against gravity is possible and efficient.



The CDCL – as shown above – presents significant advantages such as:

- independency (no external energy supply required).
- passivity (with long service life due to the absence of moving parts, around 25 years).
- low weight (e.g no mechanical pump), small tubing diameter and fluid quantity, low temperature difference evaporator - condenser (10°C).
- easy implementation in the vehicle (i.e because of the loop flexibility, it can be used even if low accessibility).
- capability of miniaturization allowing to used it to cool electronic & computer units.
- interesting heat transfer around 900 Watt over 2 m against gravity.
- large operating temperature range: –75°C to +90°C (overall).

– Phase Change Materials (PCM) can be produced in various chemical formulations that are designed to melt and freeze at a selected temperature. Paraffin wax that consists of a mixture of mostly straight-chain (normal) n-alkanes, CH_3–(CH_2) n–CH_3 is well-characterized chemical. The $(CH_2)_n$ chain crystallization releases a large amount of latent heat. Both the melting point and the heat of fusion increase with increasing chain length. Furthermore, paraffin is non-toxic, non-corrosive, and chemically inert and without unpleasant odor.
– Other solutions such as thermal blankets type Multi Layer Insulation (MLI), washers for increased bearing surface under the head bolt, deployable radiators, …

To select the adapted capabilities, the TCS shall take into account the overall spacecraft configuration and layout versus the requirements and constraints in terms of:

- thermal control performances expected.
- dimension and mass acceptable.
- materials and heat capacities.
- fixation, mounting techniques and contact area for fixation available.
- surface characteristics (e.g. treatment, planarity, roughness), alignment required.
- forbidden zones (e.g. Field Of View and operational range of mechanism).
- connector locations, spacecraft harness.

To summarize

As shown by this paper, to ensure a high level of RAMS (i.e Reliability Availability Maintainability Safety), a particular attention has to be paid to the thermal environment of the avionics items used on space systems and aircraft. Several risks mitigations have to be developed by using new qualification methods and thermal control systems: suggestion in this regard has been presented.

More generally, the end-to-end design of the avionics systems is entailing to consider the thermal environment as a key-driver: consequently, in a space or aircraft project, the thermal architect – and not only a thermal analyst – has to be associated to the avionics design since the feasibility phase of the development.