Failure Mechanisms in Electronic Products at High Altitudes

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Introduction

Understanding the risks of using commercial off-the-shelf (COTS) electronic components, specifically laptop computers, in a non-commercial environment is critical to designers of military systems. The environment studied in this paper is that of an un-pressurized aircraft cockpit operating at 35,000 feet. During operation in this environment, COTS may be exposed to low atmospheric pressure and may experience low temperatures and humidity.

The Department of Defense Design Criteria Standard for Human Engineering, MIL-STD-1472F, provides guidance as to the required environment in un-pressurized cockpit. At 35,000 feet, the atmospheric pressure in the cockpit is expected to decrease to around 0.28 atmospheres. In addition, the temperature will tend to range between 5°C and 20°C[1] and the relative humidity will be maintained to at least 45%[2]. The assumed environmental parameters used for this study are shown in Table 1.

The typical laptop computer will contain parts that may be sensitive to high altitude failures, including:

1. Hard Drive
2. Batteries
3. Capacitors
4. Liquid Crystal Display
5. Memory
6. CPU

[1] Dependent if the aircraft is used in nominal or Arctic conditions.

[2] To ensure human comfort. This is surprising, considering that cities in the American Southwest typically experience relative humidities in the single digits.

Solid State Electronics (Memory and Microprocessors)

The CPU memory and chipset make up most of the solid state electronics of the laptop. The chipset forms the bridge between the CPU and the various I/O devices of the computer. Modern laptops have almost all functions such as video, sound, and interfaces integrated into the chipset. At the environment specified two conditions can adversely effect the operation of the solid state electronics. These are reduced air density and cosmic rays. The reduction in air density can degrade the thermal management system used to cool the devices. Cosmic rays can cause soft failures to occur in the solid state electronics.

Temperature	Absolute minimum: 5°C Nominal: 20°C
Altitude	35000 feet maximum
Pressure	≈ 0.25 atmospheres
Humidity	≥ 45 % RH

Table 1: Assumed environmental conditions

Soft fails[3] of electronics have been known to occur from nuclear particles. The two primary sources for these particles are 1) decay from radioactive atoms and 2) extraterrestrial cosmic rays. However, the density of cosmic rays changes greatly with altitude and is therefore of great concern to electronics used at high altitudes. Once root-cause is positively identified, flex cracking, and a quantitative description of the influence of stress drivers has been presented, it is possible to make an informed decision on possible corrective actions. Eventual selection of successful

[3] Failure is not permanent. Typical failure mode is data corruption or reboot of the operating system

corrective actions will take into consideration effectiveness, time, cost and outcome on functionality.

Cosmic Rays

IBM has conducted extensive studies detailing cosmic ray intensities and soft error rates (SER) for digital electronics. The diagram in Figure 1 details how cosmic rays cascade through the earth's atmosphere. High energy particles hit the earth's atmosphere shattering atmospheric atoms causing a cascade of atomic particles. The initial particle flux striking the earth's atmosphere contains about 1000 particles/m^2s^1. This increases to 1,000,000 particles/m^2s^{-1} at airplane altitudes (40,000 ft). At lower altitudes more particles are absorbed by the denser air until the particle flux is reduced to 1 particles/cm^2s^{-1} at sea level **[1]**.

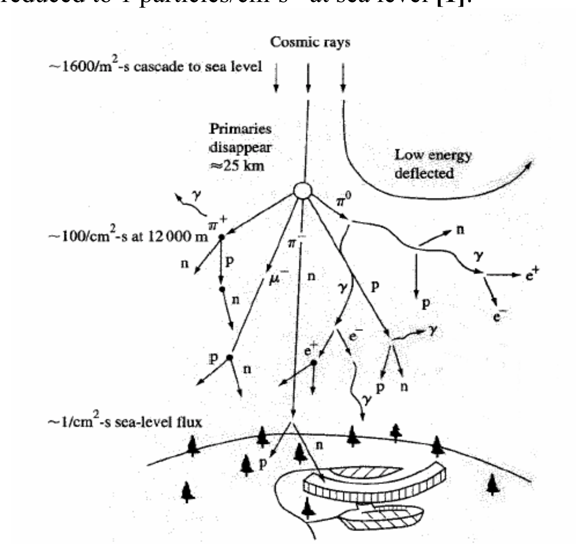

Figure 1: Cosmic rays cascading through the atmosphere, n – neutrons, p – protons, e – electrons (positron pair), μ – muons, γ- gamma ray, π – pion, n – neutrino [1]

Of all the particles present in the cascade, only neutrons and pions can cause significant soft failures in digital devices [1]. However, the mean lifetime of a pion is 26ns and therefore does not exist long enough to impact the electronic device and cause failure. The mean lifetime of a neutron is stable and neutron impacts are known to cause soft failure of electronics. The graph in Figure 2 shows the energy and neutron flux as a function of atmospheric pressure. Atmospheric pressure can be converted to altitude by using the formula in Equation 1. An altitude of 35,000 ft is therefore roughly equivalent to a pressure of 278 g/cm^2.

Experiments conducted by IBM and others have shown that the failure rate due to cosmic rays is about 100 times greater for electronics at airplane altitudes than those at terrestrial altitudes [1]. At space altitudes soft failures have also been documented. For example, IBM ThinkPad computers on the MIR Space station (1,200,000 ft) have shown upsets every nine hours while other laptop computers on the Space Shuttle (600,000 ft), have shown upset rates of one per hour [2].

Using the graph in Figure 2, and taking 0 g/cm2 pressure as space it is easy to see that the neutron flux is higher at 35,000 feet; which means that the likelihood of a soft failure could be higher at airplane altitudes.

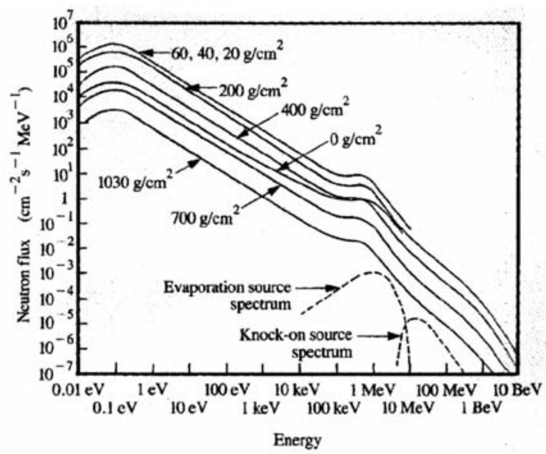

Figure 2: Neutron flux vs. atmospheric pressure [1]

$$A = 1033 - (0.03648H) + (4.26 \times 10^{-7} H^2)$$

Equation 1: Altitude (feet) to pressure (g/cm^2) [1]

Failure Behavior

CPU's and memory chips store information as small packets of electrical charge. A soft failure or single event upset (SEU) occurs when electronic noise causes the electrical charge storing the information to change. This electronic noise comes from various sources such as lightning and noisy power supplies. Manufacturers have tried to design their electronics to be immune from most sources. However, not all sources of electronic noise can economically shielded against. Therefore, cosmic rays are still a significant source of electronic noise at high altitudes.

Mitigation

Most companies that design high altitude electronic systems use redundant designs or radiation hardened components to reduce the occurrences of soft failures or single event upsets (SEU's). Companies then test the devices under neutron bombardment to ensure that occurrences of SEU's are limited to acceptable levels. The use of COT's devices precludes the use of radiation hardened components and custom redundant designs.

There are steps that can mitigate some of the SEU's that will occur at high altitude. The use of error-correction code (ECC) memory in the laptop can identify and repair memory that has been corrupted by a SEU. The ability of the laptop to support the use of ECC memory is dependent on, it's support by the chipset and if the laptop manufacturer has configured the ECC memory support option. The main memory chips are not the only memory that is susceptible to soft failures. There is memory built into the CPU, such as cache that can also be affected. There are no viable mitigation techniques for reducing the chance of soft failures occurring in these memories.

Thermal Management

Thermal management in laptops is primarily through a system of heat-pipes with a fan for forced air cooling as shown in Figure 3.

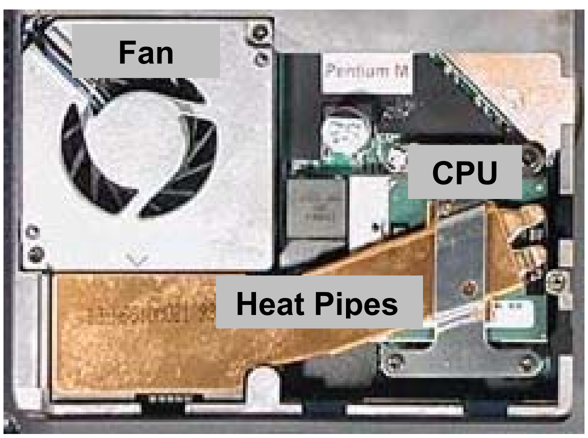

Figure 3: Laptop cooling system

The primary effect of altitude on thermal management is the reduced efficiency of convection based heat-sinking schemes. Because of this reduced cooling efficiency, the operating temperature of the CPU will increase for the same ambient air temperature.

The decrease in air density as the altitude increases is responsible for this reduced cooling efficiency and must be accounted for when doing thermal calculations. The lower air density reduces the mass flow of air over heat sinks, reducing the amount of power that can be dissipated. As shown in the following equation, the mass flow rate of air over the heatsink is directly proportional to the density of the air.

$$m = K_m \rho N D^3$$

K_m : *constant for geometric and dynamic similiar operation*

m : *mass flow rate (kg/m or lb$_m$/m)*

N : *fan speed (RPM)*

D : *fan diameter (m or ft)*

ρ : *air density (kg/m^3 or lb$_m$/ft^3)*

The following example illustrates the effects of reduced air density on convection cooling. Simple CPU temperature rise example[4]:

Altitude	0 feet	35000 feet
Air density (ρ)	1.147 kg/m^3	0.377 kg/m^3
Air temperature (T)	30°C	20°C
Thermal conductivity (k)	0.0265 W/m K	0.020 W/m K
Absolute viscosity (μ)	18.70 x 10^{-6} N s/m^2	14.2 x 10^{-6} N s/m^2

Table 2: Properties of air at altitude

Assumptions for sample calculations:
Power dissipation for a typical mobile CPU: 5 Watts
Size: Length (L) = 51 mm, Height = 3 mm
Surface area = 3.214 x 10^{-3} m^2
Air velocity (U) = 2.5 m/s
The Reynolds number equation:

$$\mathrm{Re}_L = \frac{\rho U L}{\mu}$$

Nusselt number determination:
Using the Jacob correlation for a square shape we have B=0.160 and n=0.699

$$Nu_D = B \, \mathrm{Re}_D^n$$

The heat transfer coefficients from the average Nusselt number are:

$$h_c = \frac{Nu \cdot k}{L}$$

4 Remsburg, Ralph. Advanced Thermal Design of Electronic Equipment. Chapman and Hall 1998

The temperature rise is found by:

$$\Delta T = \frac{q}{h_c A}$$

Altitude	0 feet	35000 feet
Re_L	7820	3385
Nu_D	84.23	46.91
h_c	43.77 W/m^{2}K	18.40 W/m^{2}K
ΔT	**35.5 K**	**84.6 K**

Table 3: Thermal calculation results

The formulas and the assumed environments yield the temperature changes shown in Table 3. This simple example illustrates that the CPU temperature will be 35.5°C above ambient at sea level and 71.5°C above ambient at 35000 feet. The temperature of the ambient air in the aircraft at 35000 feet surrounding the laptop computer will most likely be 20°C or less so the CPU temperature will be around 104.6°C. A nominal outside ground level temperature of 30°C (86°F) yields a CPU temperature of 65.5°C. The 35000 feet temperature value is outside the temperature specifications of 100°C for most mobile CPUs (Intel) as shown in Table 4.

While this simple example doesn't accurately reflect the actual cooling system of a laptop, it does indicate that a potential for inadequate cooling of the CPU could exist.

Failure Behavior

Most mobile CPU's include a thermal diode that monitors the temperature of the die. When the temperature reaches a preset limit, the CPU may invoke schemes to reduce its power dissipation in an attempt to lower the temperature. This could include reducing voltages, frequencies or shutting down. These schemes can adversely effect the operation of the laptop and cause software anomalies or spontaneous rebooting.

CPU	Maximum Specified Die Temperature	Thermal Design Power
Mobile Pentium 4 Processor-M 1.2 GHz	100°C	20.8 Watts
Mobile Pentium 4 Processor-M 2.0 GHz	100°C	32 Watts
Mobile Pentium 4 Processor-M 2.6 GHz	100°C	35 Watts
Mobile Pentium III Processor-M 400 MHz	100°C	3.8 Watts
Mobile Pentium III Processor-M 866 MHz	100°C	10.1 Watts
Mobile Pentium III Processor-M 1.333 GHz	100°C	22.0 Watts
Mobile AMD Duron 1.0 GHz	95°C	25 Watts
Crusoe TM5500-800-1.0	100°C	8.0 Watts

Table 4: Specified maximum temperature and power dissipation for CPUs

Mitigation

The CPU temperature at altitude could be reduced by using a different fan. A replacement fan that is designed to run at higher rotation speeds could be used to compensate for decreased air density. Other thermal solutions include external fans or cooling plates upon which the laptop sits. Figure 4 shows examples of two different cooling plates that utilize passive and active designs.

Figure 4: Passive and active notebook cooling pads. The passive cooling pad utilizes heat pipes, while the active cooling pad utilizes forced convection.

The device shown in Figure 5 provides additional cooling by forcing air into the laptop via the PCMCIA slot. This may not be applicable to all laptops. All these devices can provide additional cooling for less than $50.00 per laptop.

Figure 5: PCMCIA fan for supplemental cooling

Electrolytic Capacitors

Laptops use electrolytic capacitors, but in significantly less numbers when compared to a typical desktop computer. When capacitors are used at high altitudes, the atmospheric pressure is less than the internal pressure of the capacitor and this may cause the capacitor end seal to bulge. However, some manufacturers indicate that there should be no problem when using electrolytic capacitors below 10000 meters (32800 feet) [Nichicon Corporation]. Another manufacture [EPCOS] specifies an altitude limit of 7000 meters (23000 feet) for standard electrolytic capacitors and offers special capacitors rated for altitudes above 7000 meters.

Mitigation through replacement is not necessarily recommended as handling the laptop during rework could result in more failures then it solves. Instead, if PSI is concerned about this failure mode, contact the laptop manufacturer and request information on the electrolytic capacitor manufacturers and contact the manufacturers directly.

Liquid Crystal Display

The liquid crystal display (LCD) is affected by temperature and air pressure changes. As the temperature decreases the liquid crystal becomes less viscous. This leads to an increase in the response time of the display. At 0°C the response time of the Super-Twisted Nematic (STN) LCD could be as long as 4 seconds. Thin film transistor (TFT) LCD display response times are not as greatly affected by low temperatures since each pixel is driven by an individual transistor. Low temperatures can also reduce the display contrast and shorten the life of the backlight. Temperature changes can also lead to coefficient of thermal expansion (CTE) mismatches in the LCD assembly. The temperatures in the cockpit are not expected to be below 20°C, so thermal mismatches and temperature related performance degradation should not be an issue. Using the LCD beyond the manufactures specified altitude limits can cause failure through overstress, low pressure, or wearout, pressure cycling, mechanisms.

Low Pressure

The 32000 feet altitude is well beyond the typical maximum altitude specification of 10000-12000 feet for a LCD. At high altitudes the corresponding low air pressure can cause mechanical stress in the seal. This stress may cause micro cracks in the seal, which become a path for moisture ingress into the cell. Moisture ingress can cause voiding and other failures. Voids appear as black spots on a normally white display or vice versa. This is because there is no optical effect at the place of voids.

Change in the static state of seal: Expansion and elasticity of the seal can create a volumetric change within the display. The seal expands through environmental stressors like pressure, temperature and humidity and its static state changes. Compensation for this volumetric change comes from the formation of vacuum voids in the LC material.

Pressure Cycling

If subjected to repeated flights, the COTS laptop will experience changes in pressure during its lifetime. This pressure cycling may cause chemical breakdown of the LC material. A color shift in the display background is often an indication of such a breakdown. Pressure cycling can also cause breakdown of the LCD seal [3, 5], which is the same mechanisms affected by low pressure.

Mitigation

Liquid crystal displays are sealed and using them beyond their specified limits may damage the LCD. Typical maximum operational altitude for a LCD is between 10000 and 12000 feet. Laptop LCD's rated at the altitudes specified may not be obtainable. The laptop LCD should be cycled to pressures equivalent to the field environment and then inspected to verify operation and seal integrity.

Batteries

The battery type used in most current laptops is lithium ion. The use of lithium ion batteries in consumer electronics on airplanes has led to some incidents and is a serious safety concern. In response to this issue, the United Nations released a Recommendation on the Transport of Dangerous Goods (ST/SG/AC.10/11/Rev.3), which recommended that lithium-ion batteries with a equivalent lithium content of greater than 8 grams be capable of surviving six hours at 42800 feet in unpressurized conditions. This recommendation was by adopted by the International Civil Aviation Organization (ICAO), responsible for all aspects of international civil aviation, and the International Air Transport Association (IATA), a trade association representing airlines, in the form of the A45 special rule.

Eight grams of equivalent lithium content is approximately equivalent to 96 W-hours. This is below the typical content of a lithium-ion battery for commercial laptops, which tend to have a capacity of 20 to 40 W-hours. As a result, there is no guarantee of battery survivability at 35000 feet. Not all manufactures provide altitude operational specifications, but American Power Conversion (APC) specifies a maximum operating altitude of 50000 feet for its IBM ThinkPad replacement batteries.

If the lithium-ion battery is susceptible to high altitudes, the failure mode would most likely be shorting of the cells followed by a potential fire or explosion. While the likelihood of this failure mechanism may be less than that of single event upsets or hard drive failures, the potential consequences are severe enough that PSI may wish only consider those laptops with batteries rated to 35000 feet. The selection of the laptop based on the battery, rather than selecting an appropriate battery, is due to the constraint laptop manufacturers place on the availability of alternative sources of batteries.

Hard Disk Drive

The hard disk drive is a major component of the computer system and is known to be sensitive to atmospheric pressure changes. The major parts of a hard drive are:

- Flying head/magnetic media system
- Servo positioning voice coil actuator
- Read/Write channel electronics
- Spindle and Spindle motor
- Servo control channel electronics
- Contamination control system

Some typical hard drive specifications are:

- Max operating altitude 10000 ft
- Max humidity 95 %
- Min humidity 5 %
- Max change 20%/hr
- Max temp 55 C
- Min temp 5 C
- Max change 20 deg C/hr

Flying Head

Several specific parts of the drive are sensitive to the high altitude environment. Disk drives are designed for environments which are relatively benign compared to the environment found aboard a military aircraft. The un-pressurized airborne environment will exceed the disk drive specification. The concern is that while it takes a significant amount of time for the humidity in the drive to reach the ambient environment the pressure is allowed to reach equilibrium rather quickly. The change in air density can effect the operation of the drive.

The air in the hard drives creates an air bearing as the disk spins on which the magnetic head is supported. The head flying height is determined by this air bearing, and is proportional to the rotational surface speed of the disk and the air temperature and pressure (air density). If the head flies below its design limit for prolonged periods, the head may come into contact with the disk and cause head crashes or excessive head/media wear [2]. Newer head designs fly more consistently (less variation in gap) over a range of pressures than older designs. This is a combination of design improvements in heads, suspensions, and media vibration. Drive crashes (catastrophic head or disc damage) occur less frequently with every new generation. This improvement in fly height control is necessary to meet market demands for increased reliability with lower fly-heights. [Industry Source]

Bearings and Electronics

There are various bearing surfaces in the disk that require lubrication. Low pressure conditions in the disk drive may cause outgassing of these lubricants changing their viscosity. This change can create functional problems and affect the performance of the drive.

Mitigation

In general, some companies design for operation to 10,000 ft and non-op to 40,000 ft and do not generally test a drive beyond the 10K limit. The issue is the head-disc interface. The air bearings can not support the head as the air thins. At higher altitudes, the head may start to contact the disc more frequently. This disrupts the head and causes decreased performance or in the extreme, lead to catastrophic damage of the head or disc surface. There is variability from product-to-product in the air bearing design that will affect the altitude margin. Some products will run at 20K feet, but the overall failure rate may suffer, beyond specification limit failure rate tests are rarely conducted. There may also be an acceleration of some failure mechanisms if the drive were required to continuously operate at that altitude.

The solution to many of the problems with hard disk drives is to employ a sealed disk cartridge design. Replacing the hard drive with a solid state device will eliminate the altitude problem associated with hard disk drives.

Flash memory devices are typically used to replace hard disk drives and can be specified to an operational altitude of 80000 feet. The typical cost per megabyte for a 1.2 gigabyte drive is about 4 dollars compared to 0.20 dollars for a standard notebook hard drive. Flash memory is also known to be resistant to soft failures due to cosmic ray impacts.

Discussion and Conclusion

In conclusion, the failure mechanisms that may be of greatest concern are failure of the liquid crystal display (LCD) seal, battery leakage, and lack of sufficient air cushion for the hard drive. Initial tests by PSI indicate no immediate failure of the LCD at 35,000 feet. This should indicate limited issues during early use. The LCD seal will most likely leak after repeated pressure cycles; however the number of cycles required for failure is unknown and could exceed the expected lifetime.

While the probably of battery leakage is unknown, this should be seriously considered as a design limitation due to the potential for fire and explosion.

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