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SELECTED PROBLEMS OF ELECTRONIC EQUIPMENT DESIGN IN ROCKETRY

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Abstract

The paper introduces selected problems of electronic equipment design in rocketry. It mainly focuses on most common issues of electronic equipment design in rocketry. Some history of electronic equipment designed in the Institute of Aviation is outlined. Subsequently, basic avionics requirements are presented. In the next part of the article inevitable negative phenomena that occur during a short flight of a rocket such as vibrations, shocks, thermal stability or cosmic radiation are presented and discussed. Moreover, a few solutions and precautions for designing electronic equipment are proposed. Additionally, a concept of the on-board computer for the rocket ILR-33 *Bursztyn*, being which is designed and built in the Institute of Aviation, is presented. The idea of the structure and some components which will create data logger and requirements are outlined.
Keywords: electronic equipment in rocketry, rockets, vibration, shocks, thermal control, cosmic radiation.

1. INTRODUCTION

In the last few years the space department has been evolving in the Institute of Aviation. Numerous works have been carried out like: designing power systems of rocket engines, modelling injection and mixture formation, analyses of combustion processes, a construction optimization due to the thermo-mechanical loads, etc. Quite recently, considerable attention has been paid to electronic equipment. In the past, many electronic devices were designed and built for space programmes in the Institute of Aviation. At present avionic department is preparing an on-board computer for the rocket ILR-33 *Bursztyn.* For this reason, electronic designers not only have to take into account some constraints but also be aware of more difficult work environment of the hardware.

2. HISTORY

In the seventies of the twentieth century, Poland participated in the international programme named *Intercosmos.* Among the research equipment was a Polish Radio Spectograph RS-500K designed for measuring solar radiation on radio frequencies. Moreover, a specialized satellite and ground equipment were developed at the Institute of Aviation such as channel generators BGK-3-J (M), Doppler geodetic receivers and low frequencies spectrum analysers.

Fig. 1. Block of channel generators BGK-3-J (M), designed for *Intercosmos -15, 18, 19* programmes (1976-79), [7]

In the eighties of the twentieth century engineers from the Institute of Aviation built a specialized system to analyse the spectrum of plasma waves within the range of 2-10 Hz. It conducted measurements in the Earth magnetosphere on the board of the satellite *Prognoz-8*.

Furthermore, two identical low frequency spectrum analysers APW-N were launched on board of the twin Vega space probes in the year 1984. They were designed for plasma instability investigations in the vicinity of Halley's comet. In 1988 two similar APW-F analysers were launched towards Mars under the *Phobos* project with the objective to survey the atmosphere around the planet and around one of its satellites – *Phobos*.

Unfortunately, the cosmic specialization disappeared from the Institute of Aviation due to a migration of a part of professionals and engineers to the Space Research Centre of the Polish Academy of Science. However, the Institute of Aviation restored the cosmic technology. [7][9]

3. AVIONIC REQUIREMENTS

The DO-160F standard defines environmental conditions and test procedures for airborne equipment. They cover a wide range of strictly physical conditions including temperature (and condensation) for an altitude, humidity, mechanical shock, vibration, explosion, waterproof, etc. In table 1 standard categories are presented. Groups can be distinguished due to heights, temperature and pressure.

Tab. 1. DO-160 F standard categories, Y – Yes, N – No, P- Partially, PP- Power Plant compartment [8]

Category	**Temperature criteria**	**Pressure criteria**
A up to 4600 m	A1 – Y, A2 – P, A3 – Y/P, A4 – Y	A1 – Y, A2 – Y, A3 – Y, A4 – Y
B up to 7620 m	B1 – Y, B2 – N, B3 – PP, B4 – Y	B1 – N, B2 – N, B3 – PP, B4 – N
C up to 10700 m	C1 – Y, C2 – N, C3 – PP, C4 – Y	C1 – N, C2 – N, C3 – PP, C4 – N
D up to 15200 m	D1 – Y, D2 – N, D3 – PP	D1 – N, D2 – N, D3 – PP
E up to 21300 m	E1 – N, E2 – PP	E1 – N, E2 – PP
F up to 16800 m	F1 – Y, F2 – N, F3 – PP	F1 – N, F2 – N, F3 – PP

In figure 2 a temperature range due to altitude is depicted. Below the Kármán's line it hesitates between -30°C and 70°C. Whereas, in table 2 are presented a few examples of a set of temperature limits for on-board electronic elements. In fact, those numbers are very similar to temperature requirements in the avionic standard. Hence, electronic engineers, when designing a hardware for rocketry, can use electronic elements that are applied in avionic systems.

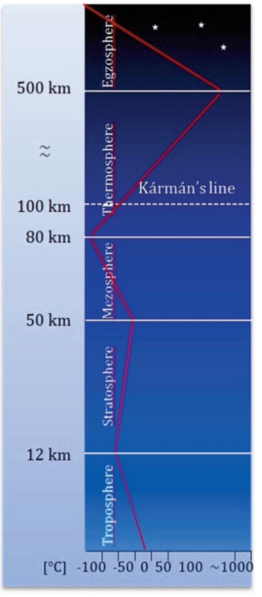

Fig. 2. Temperature range due to heights [Szpakowska-Peas, 2015]

Tab. 2. Exemplified thermal conditions for space hardware [12]

Unit	On-orbit temperature range [°C]			Qualification range [°C]	
	Non-operating	Operating		Operating	
	Min	Min	Max	Min	Max
Electronic equipment					
TWT (travelling wave tubes)	-30	0	75	-10	85
Electronic power conditioner	-30	0	50	-10	60
Input filters	-30	5	50	-10	60
Microwave units (transponders, receivers, etc.)	-30	-10	50	-20	60
Output multiplexers	-30	20	70	10	80
Data processing units	-30	-10	50	-20	60
IR and sun sensors	-45	-30	50	-40	60
Battery Ni-H^2	-20	-5	25	-15	35
Non-electronic equipment					
Tanks	0	0	40	-10	50
Solar generator	-180	-165	70	-175	80
Propellant lines	0	0	50	-10	60
Momentum wheels	-40	-15	45	-25	55

4. VARIABLE STRESS AND HAZARDS TO ELECTRONIC SYSTEMS

During a short flight of a rocket inevitable problems will emerge and precautionary measures should be considered. Electronic equipment units will be exposed to severe vibrations, shocks or cosmic radiation. Furthermore, electronic designers must take into account a heat transfer issue. In this section some remedies for the above mentioned problems are presented.

4.1. Heat exchange/transfer problem

In general, three types of the heat transfer can be distinguished: radiation, conduction, and convection. With a higher altitude pressure drops, hence in vacuum conduction and convection are much less significant and radiation dominates.

Over the years the heat exchange problem has been tackled in the space industry in different ways. For example, in 1938 the gondola of the Polish stratospheric balloon *Gwiazda Polski* was coated with a transparent non-heat conducting varnish in order to avoid overheating the interior of the gondola.

Fig. 3. The gondola of *Gwiazda Polski*, Polish stratospheric balloon, [Narodowe Archiwum Cyfrowe]

During the last decades, NASA has developed various techniques of thermal insulation. Engineers not only had to design heat resistance protection for space shuttles but also this protection had to be reusable, lightweight and low cost. Several types of the Thermal Protection System were used on shuttles. The materials included tiles, advanced flexible reusable surface insulation, reinforced carbon-carbon, etc. Additionally, the external tank required insulation to maintain the fuels as well as to provide additional structural integrity through launch and after the release of the orbiter. The thermal protection system is composed of spray-on foam and hand applied insulation and ablator. [5]

Furthermore, in satellites and probes multilayer insulation is applied. It is composed of multiple layers of thin sheets.

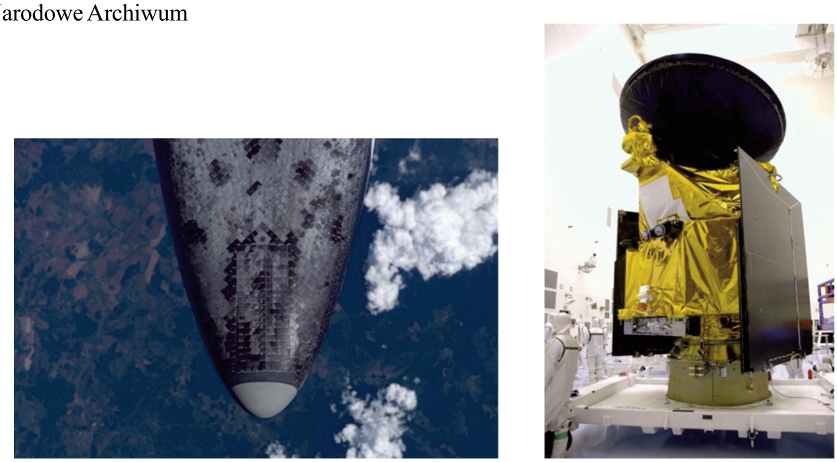

Fig. 4. Heat shield tiles as an advanced flexible reusable Surface insulation and thermal insulation composed of multiple layers of thin sheets [15], [16]

All things considered just an outline of general solutions for the thermal insulation in the spacecrafts. The heat transfer problem also concerns smaller electronic equipment and systems. It is important to ensure the stability of the temperature within the housing of an electronic device. Continued with the heat transfer problem a few solutions are proposed in electronic design.

Firstly, a chassis with a radiator panels can be designed**.** It will support a high dissipating electronic units to moderate heat sources. The structural composition of those panels is generally an aluminium face sheet and a honeycomb core. Secondly, heat pipes in the systems can be applied. The heat pipe is a combined heat conduction and phase change mechanism which has very efficient heat conductivity properties. The phenomena of evaporation of water, ammonia or alcohol/water is applied in the cooling system, hence no energy is required for operation. Furthermore, mechanical systems can be used to augment the heat transfer capability of the heat pipe. Figure 5 illustrates a simplified heat pipe schematic. [9][11]

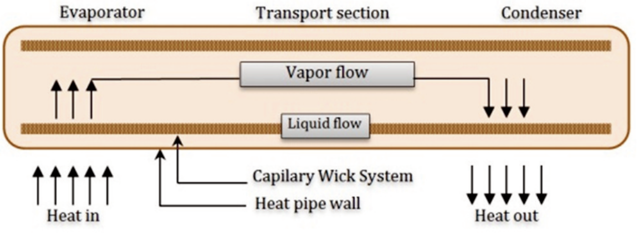

Fig. 5. Simplified heat pipe diagram showing heat transfer process [Szpakowska-Peas, 2015]

Thirdly, a special type of an insulation can be added to electronic system, which is a multilayer insulation blanket. This design consists basically of a number of layers of vapour-deposited aluminium, silver or gold on Kapton or Mylar . Conductive insulation between layers is insured by interleaved fabric netting. As a result, the blanket will reduce the heat flow in both directions. Moreover, it is important to provide efficient protection against Electro Static Discharge (ESD).

However, in some particular cases designers have to control electronic equipment temperature within a narrow range (ambient ±20°C) so that special heaters can be applied. Heating elements are generally thermofoil conductive electrical elements embedded in a thin Kapton substrate. [11]

4.2. Vibrations

A rocket launch consists of a series of events that has several independent sources of load for the launched vehicle components. Sensitive electronic parts could fail when exposed to a shock and vibration excitation during flight. For instance, a crystal oscillator may shatter or a solder joint may fail. The flight environment that generates static and dynamic loads on spaceflight hardware are normally categorized as follows [3]:

- The static acceleration, generated by constant external forces or which change slowly with time so that the dynamic response of the structure is not significant (also called quasi-static acceleration associated to a quasi-static event).
- The low-frequency dynamic response, typically from 0 Hz to 100 Hz, of the launch vehicle/payload system to transient flight events. However, for some small launch vehicles the range of low-frequency dynamic response can be up to 150Hz.
- The high-frequency random vibration environment, which typically has significant energy in the frequency range from 20 Hz to 2000 Hz, transmitted from the launch vehicle to the payload at the launch vehicle/payload interfaces.

- The high frequency acoustic pressure environment, typically from 20 Hz to 8000 Hz, inside the payload compartment. The payload compartment acoustic pressure environment generates dynamic loads on components in two ways: (1) by direct impingement on the surfaces of exposed components and (2) by the acoustic pressure impingement upon the component mounting structures, which induces random vibrations that are mechanically transmitted to the components.
- Shock events. The energy spectrum is usually concentrated at or above 500 Hz and is measured in a frequency range of 100 Hz to 10 KHz.[3]

A designer can apply some measures to ensure that the equipment can endure the mechanical environment during a rocket launch without failures. Unfortunately, the exact determination of the dynamic loads that the equipment will experience can be obtained by using previous flight data for the same launcher. Therefore, some steps are taken to ensure that the PCB is constructed in a manner that provides maximum stability and reliability. Furthermore, a passive insulation can be introduced to electronic hardware housing in order to protect it from vibrations, for example an anti-vibration frame, insulation such as cable isolators, wire rope isolators, cup mounts, plate mounts, ring and bushing mounts. In figures 6 and 7 examples of passive isolators are shown.

Fig. 6. Wire Rope Isolators [13]

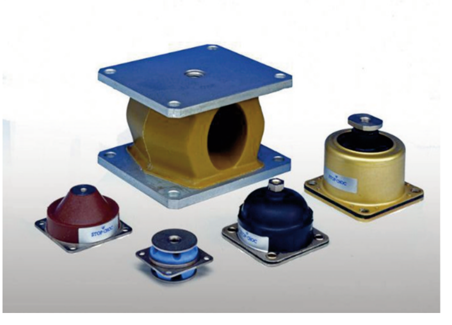

Fig. 7. Passive isolation [14]

4.3. Cosmic radiation

Cosmic rays are extremely high-energy radiation mainly originating outside the Solar System. Cosmic radiation consists predominantly of protons, atomic nuclei (hydrogen) and alfa particles (helium) and the nuclei of heavier elements. Probably, they originate from supernovas and active galactic nuclei.

Unfortunately, the phenomena may affect electronic equipment. Firstly, total ionising dose can create electron-hole pairs within dielectric layers. This can cause a flat band and threshold voltage shifts, surface leakage currents and noise. Secondly, cosmic radiation can create damage in semiconductor materials by displacing atoms in the crystal lattice. As a result, this effect induces thermal dark current in detectors, reduction of minority carrier lifetime and effects in LEDs and laser diodes, resistance in a lightly doped collector in a bipolar transistor can increase.

Furthermore, single event effects arise from the interaction of single particles (e.g. protons, neutrons or heavy ions) with the semiconductor causing either destructive (or potentially destructive) effects or transient effects. Cosmic radiation affects materials like a polymer sand. Effects on the optical material could be :degradation of mechanical and dielectric properties, coloration, and production of gases that can contaminate and corrode nearby materials.

Another important phenomena due to cosmic rays is spacecraft charging. The surface can charge from energetic electrons (MeV) or plasma, which penetrate the spacecraft skin and gather in insulators leading to deep dielectric charging. The subsequent discharges can couple into spacecraft systems leading to some anomalies and damage.

Last but not least, another phenomena is multipaction that occurs in a vacuum. It is an electron resonance effect that occurs when FR fields accelerate electrons in vacuum and force them to impact with a surface, which depends on its energy, releases one or more electrons into vacuum. Hence, the phenomena of multipaction cause loss/distortion of the RF signal (increase of noise figure or bit-error-rate) and damage RF components or subsystems due to excess RF power being reflected back or dissipated. [2]

Electronic designers have a daunting task to prevent integrated circuits from damages caused by cosmic radiation. Units designed to achieve robustness to space conditions are more expensive and less advanced than currently available, commercial components. In table 3 are distinguished three categories of integrated circuits due to endurance to a particular level of cosmic radiation.

Tab. 3. Categorization of integrated circuits (Ics) due to space environment [17]

	Total ionising dose (TID)	Single event latch-up (SEL)	Single event upset (SEU)
Commercial Ics	3-30 krads(Si)	1-120 MeV	1-120 MeV
Radiation-Enhanced Ics (Customised to circumterrestrial orbit conditions)	100 krads(Si)	< 120 MeV	< 120 MeV
Radiation-Hardened Ics	>100krads(Si)	< 120 MeV	< 120 MeV

5. DATA LOGGER

In the Institute of Aviation the rocket ILR-33 *Bursztyn* is being designed. It requires an on-board computer for data logging, a wireless transmission for sending flight parameters and especially for mission control. It will be supplied by its own accumulator. It is recommended to use cadmium-nickel storage cell. The most important advantages of this kind batteries is that they are robust. NiCd batteries withstand vibrations and some crashes. Moreover, low temperatures do not affect cells and they are simple and fast to charge.

The hardware has to fulfil the following preliminary requirements:

- Measurement and logging of on board sensors signals and transmitting them to the ground station;
- Energizing of the FLIGHT CONTROL SYSTEM; 8 channels, current: 5A;
- Operation temperature range: from -40°C to +60°C;
- Pressure range: 0 – 1200 hPa;
- Humidity: up to 100%;
- Vibrations: 10 g / 20 Hz – 20 kHz;
- Linear acceleration: 1000 g;
- Frequency of measurements and data memorising: 500 Hz;
- Time of logging 0.5 h, time of functioning 1 h.

Figure 8 illustrates a concept of the computer. The device will be based on a microcontroller STM32F4. Beside central processing unit several sensors will be applied such as:

- an Inertial Measurement Unit (triaxial digital accelerometers, magnetometers and gyroscopes, digital barometer) (IMU),
- a sensor of a dynamic pressure (p_d),
- an ambient temperature sensor (T_{amb}),
- a GPS module,
- and an additional accelerometer in the x-axis (a_x).

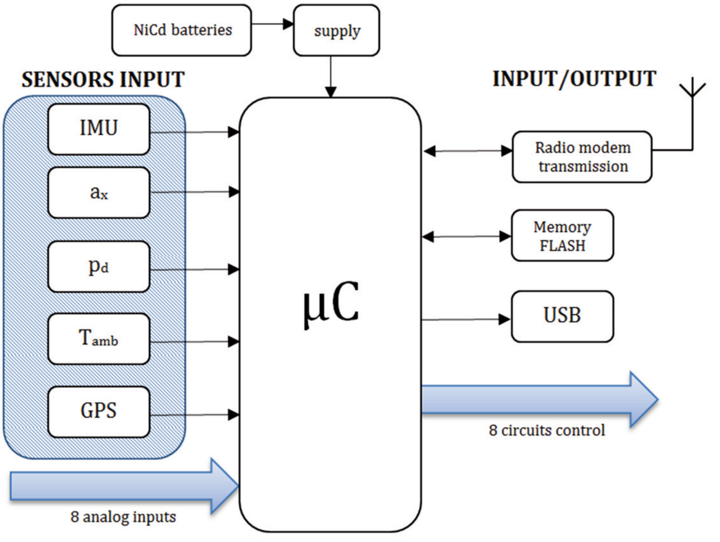

Fig. 8. On-board computer [Szpakowska-Peas, 2015]

Any data will be written into a non-volatile NAND flash memory. For the user's convenience the system will be equipped with a USB interface for coping data from the internal memory for further analysis.

It is suggested not to use electronic elements such as integrated circuits in BGA package because of smaller resistance to shocks and vibrations. The housing of the device should be robust thus it will be made of aluminium. The electronic board will be mounted directly to the chassis. In this particular case dampers will not be used, due to necessity of capturing undisrupted data.

The problem of cosmic radiation is negligible due to very short time of electronic equipment stay in space environment.

When the device is ready, selected environmental tests will be conducted in the Institute of Aviation. The preliminary testing will reveal any defects of the device and it will help to make any further improvements.

6. CONCLUSIONS

In the case of electronic equipment units designed especially for flights lasting for a short time, the main problems of design are focused on the robustness to mechanical vibrations, shocks and cosmic radiation. Problems of temperatures and heat transfer in aforementioned flights can be solved by passive means – a thermal insulation of the appropriate parameters and thickness.

Robustness to vibrations & shocks problem should be divided into two sub-problems:

1) the problem of electronic boards mechanical design and mounting the electronic circuits elements on boards,
2) the problem of protecting the electronic unit as a whole within its housing.

The first sub-problem can be solved by keeping the known standards for assembling electronic circuits. The latter sub problem is planned to be solved by passive mechanical insulation inside and outside the housing. Robustness to cosmic radiation can be achieved by the design of a unit's housing with accordance to the known standards.

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WYBRANE PROBLEMY PROJEKTOWANIA URZĄDZEŃ ELEKTRONICZNYCH W TECHNICE RAKIETOWEJ

Abstrakt

Artykuł omawia wybrane problemy projektowania urządzeń elektronicznych w technice rakietowej. Przede wszystkim skupi się na najczęstszych problemach podczas projektowania takiego rodzaju sprzętu. Na wstępie przedstawiono trochę historii sprzętu elektronicznego zaprojektowanego w Instytucie Lotnictwa. Następnie są zaprezentowane podstawowe wymagania awioniki. W następnej części artykułu są przedstawione i omówione negatywne zjawiska, które występują podczas krótkiego lotu rakiety, takie jak wstrząsy, uderzenia, stabilność termiczna lub promieniowanie kosmiczne. Ponadto, zaproponowano kilka rozwiązań i przedstawiono środki ostrożności podczas projektowania urządzeń elektronicznych. Dodatkowo w artykule została poruszona kwestia koncepcji komputera pokładowego dla rakiety ILR-33 „Bursztyn", który został zaprojektowany i zbudowany w Instytucie Lotnictwa. Krótko omówiono pomysł struktury i niektórych elementów, które będą tworzyć rejestrator danych według wymagań dotyczących sprzętu.

<u>Słowa kluczowe:</u> sprzęt elektroniczny rakiet, rakiety, wibracje, wstrząsy, kontrola termiczna, promieniowanie kosmiczne.