

# Modelling of Spacecraft Operating Conditions During Off-Nominal Situations in Orbit and Analysis of Acoustic Emission Monitoring Parameters for Their Optimisation

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**Abstract:** The subject of the article is the planning and comprehensive preparation of an experiment for monitoring the condition of a satellite's structure under vacuum conditions modelled using a space environment simulator. Simulating the space environment is essential for verifying the performance of materials, structural components and equipment prior to their actual launch. Such testing makes it possible to confirm the correctness of material selection, the accuracy of engineering calculations and the validity of technical decisions made during the design phase. The behaviour of materials under vacuum, extreme temperatures, sharp thermal fluctuations, and exposure to cosmic radiation may differ significantly from their performance under standard operating conditions on Earth.

**KEYWORDS:** ACOUSTIC EMISSION, AE SYSTEMS, ARTIFICIAL SATELLITES, SPACE ENVIRONMENT SIMULATOR, VACUUM CONDITIONS, STRUCTURAL COMPONENTS, DURALUMIN, COMPOSITE.

## Introduction

Acoustic emission (hereinafter AE) is one of the promising methods of non-destructive testing, particularly relevant for assessing the strength and reliability of structures under space conditions. In the context of spacecraft, such as artificial satellites, the application of AE enables the detection of hidden damage and defects that occur under the influence of extreme factors of the space environment [1,2].

The aim of the study is to plan and comprehensively prepare an experiment for monitoring the condition of a satellite's structure under vacuum conditions simulated using a space environment simulator. Particular emphasis is placed on the development of a methodology for modelling the operating conditions of spacecraft during off-nominal situations and the analysis of AE monitoring parameters, including sensor type, frequency range and equipment placement schemes for their subsequent optimisation.

Simulating the space environment is essential for verifying the performance of materials, structural components, and equipment prior to their actual launch. Such verification makes it possible to confirm the correctness of material selection, the accuracy of engineering calculations, and the validity of the technical decisions made during the design phase.

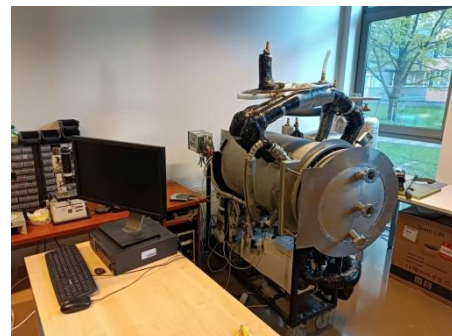
The behaviour of materials under vacuum conditions, extreme temperatures, sharp thermal fluctuations, and exposure to cosmic radiation may differ significantly from their performance under standard operating conditions on Earth. Conducting tests that simulate these factors makes it possible to identify potential weak points, verify airtightness, resistance to deformation and degradation and assess the reliability of defect detection systems. This approach enables the evaluation of the structural material's behaviour under various types of loading and lays the groundwork for identifying potentially hazardous areas susceptible to structural degradation [3,4,5].

The results obtained may be used to enhance the reliability of spacecraft and reduce the risks associated with off-nominal situations in orbit. Furthermore, they will demonstrate the applicability of the acoustic emission method for monitoring under space conditions and may potentially pave the way for further research and innovation in this field.

## Space environment simulator

The simulation of the space environment on Earth is carried out using specialised equipment, i.e. thermal vacuum chambers, which enable the reproduction of key parameters characteristic of orbital

conditions: high vacuum, extreme temperature fluctuations, and intense radiation. These chambers are used for testing materials, electronic components, and entire structures to assess their performance and functionality under conditions closely resembling those in space. This makes it possible to identify potential weak points and improve equipment reliability at the ground testing stage. For the present study, a space environment simulator developed at a research laboratory was used (see Fig.1).



**Fig.1.** Space environment simulator

The unit is capable of creating a vacuum chamber pressure of up to  $3 \cdot 10^{-3}$  mBar using a fore-vacuum pump during the initial evacuation phase, and down to  $3 \cdot 10^{-6}$  mBar when a turbomolecular pump is integrated into the system. The chamber is also equipped with a specialised and unique cryo-shield, which enables the simulation of temperature conditions close to those in space. When liquid nitrogen is circulated through the cryo-shield system, the temperature in the chamber drops to  $-196$  °C. Conversely, an internal xenon lamp increases the temperature through infrared radiation. This configuration makes it possible to achieve thermal fluctuations comparable to those encountered in space - where one part of the test specimen is heated by sunlight (in this case, by the lamp), while another is maintained at a significantly lower temperature, resembling that of the cosmic vacuum.

## Test specimens

An essential stage in the preparation for acoustic emission testing under vacuum conditions is the selection and preparation of test specimens. The specimens represent simplified or fragmentary structural elements made from the same or similar materials as the satellite body and are subjected to simulated loads that replicate space environment conditions [6].

The objective of the testing was to assess the behaviour of the material under the following conditions:

- exposure to vacuum;
- thermal gradients and potential mechanical stresses;
- evaluation of the AE system's functionality in a non-standard environment (in this case, limited to testing AE performance under vacuum conditions).

In addition, such tests make it possible to determine the optimal parameters for the placement and configuration of AE equipment, as well as to verify the reliability of connections under low-pressure conditions.

For the experiment, two test specimens were selected: a segment of duralumin plate of grade D16, shown in Fig. 2, and a composite plate made of carbon fibre, shown in Fig. 3. The composite plate is square-shaped, measuring 15.24×15.24 mm (6×6 inches), with a thickness of 3 mm, and consists of six layers of carbon fibre arranged in a 0°/90° weave. Each layer is rotated by 45° relative to the previous one. The plate was manufactured by DragonPlate.



*Fig.2. Duralumin plate*



*Fig. 3. Composite plate*

#### Applied AE equipment

Two AE monitoring systems were used in the study. The stationary AE system Vallen AMSY-6 (see Fig. 4) is a fully digital, multi-channel acoustic emission measurement system. It consists of eight parallel measurement channels and system interface software that operates on an external personal computer

Portable System Pocket AE-2 (Fig. 5). The Pocket AE-2 is a high-performance, computerised, two-channel acoustic emission system housed in a robust, portable handheld unit. The main differences between the two systems lie in the number of available channels and, in the case of Pocket AE-2, a more limited functionality. Accordingly, for the purposes of this study, two channels were used on both systems, and sensors with identical specifications were employed.



*Fig. 4. Vallen System AMSY-6*



*Fig. 5. Pocket AE-2*

#### Experiment procedure

During the experiment, the sensors of both AE systems were positioned on the test specimens, taking into account the material properties and geometry. The sensors of the two AE systems were installed at a distance of 430 mm from each other during testing of the duralumin plate, and 170 mm during testing of the carbon fibre plate.

The difference in sensor spacing on metal and carbon fibre is due to the significantly higher wave propagation speed and lower attenuation in metals, whereas composites exhibit much higher attenuation levels. Reducing the distance between sensors on the composite specimen improved detection sensitivity and helped prevent loss of information.

Both sensors were mounted using a silicone coupling agent and secured in place with clamps to ensure stable contact and eliminate the possibility of displacement during the experiment. The test specimens themselves were placed on a silicone pad to minimise the influence of parasitic signals, such as external vibrations and mechanical interference, on the experiment. This setup ensured the reproducibility of results and the reliability of subsequent data analysis. The test specimens inside the space environment simulator are shown in Fig. 6.



*Fig.6. Test specimens (duralumin - left, composite - right) with mounted sensors inside the space environment simulator*

A frequency filter provides frequency selectivity and improves the signal-to-noise ratio. Its primary function is to suppress unwanted frequency components typical of background noise, equipment vibrations or electromagnetic interference that may hinder the accurate detection of AE signals. The passband of the filter is selected according to the characteristics of the object under inspection and the sensors used - typically within the range of 30 kHz to 1 MHz, although it may be adjusted depending on the material of the structure and the experimental conditions.

In addition, filtering aligns the measurement chain with the specific application requirements, ensuring optimal sensitivity and reliability of the results. In this case, when using the Vallen System AMSY-6 equipment, the filter automatically adapts to the test environment and suppresses irrelevant signals.

Pocket AE-2, in turn, does not feature automatic adjustment and requires manual configuration. After the sensors are connected and mounted on the test specimen, signal recording is initiated. Real-time data are displayed on the screen (see Figs. 7-10), where each tick represents a registered event. Since the test specimen is not subjected to any load, all detected events can be considered noise and subsequently filtered out based on signal amplitude. During filter setup, a threshold was selected such that all signals below 45 dB were excluded.

Figures 7-10 show the signal measurement results obtained from the specimens.

### Results of AE signal measurements on the duralumin plate using AE systems

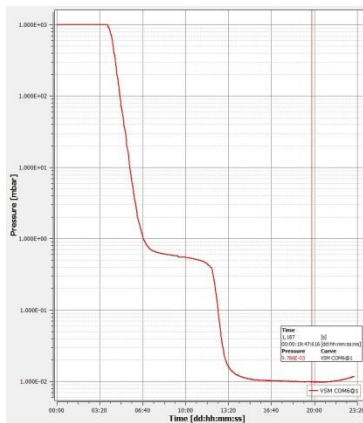


Fig.7. Pressure-time graph in the vacuum chamber during pump-down for the duralumin plate experiment and AE equipment verification using the Vallen System AMSY-6

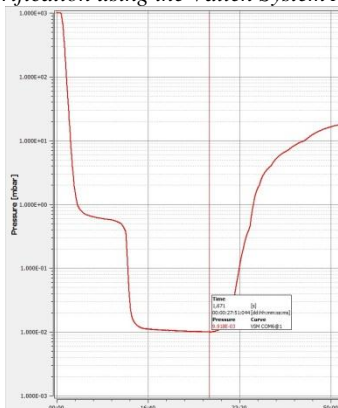


Fig.8. Pressure-time graph in the vacuum chamber during pump-down for the duralumin plate experiment and AE system verification using the Pocket AE-2

### Research results

During the experiment, the feasibility of applying the acoustic emission (AE) method for non-destructive testing using different AE systems under space-like conditions was examined, confirming the relevance and significance of the study. The experiment also explored the specific features and limitations of the AE method, particularly its sensitivity to noise contamination, allowing for the development of approaches to minimise interference and improve the reliability of monitoring results.

A work plan and procedural algorithm were developed for conducting the experiment to verify the feasibility of detecting AE signals in a vacuum environment. The procedure primarily involves calibrating the system prior to the experiment to ensure correct operation of the equipment and transmitting test pulses that simulate acoustic emission signals through one of the sensors. One sensor in the system functions as the signal source, while the other acts as the receiver. Signal verification was carried out under both atmospheric conditions and vacuum conditions. All experiments were conducted

in the space environment simulator. The verification of acoustic signal transmission under vacuum conditions was carried out on two specimens simulating the materials of a potential spacecraft. The first material selected was duralumin of grade D16, and the second - a carbon fibre-based composite. Contact between the sensor and the material was established using a silicone-based coupling agent and secured with clamps. After calibration and verification of sensor functionality, simulated signal generation was performed under both atmospheric and vacuum conditions. In both cases, the vacuum level was approximately the same. The collected data show the presence of detectable signals in both environments on the test specimens when using two different AE systems, confirming the applicability of the acoustic emission monitoring method under vacuum conditions and, potentially, in space environments.

Furthermore, analysis of the experimental results revealed differences in the characteristics of the transmitted signals, highlighting both the possibility and the necessity for further investigation and experimentation in this area.

### Results of AE signal measurements on the composite plate using AE systems

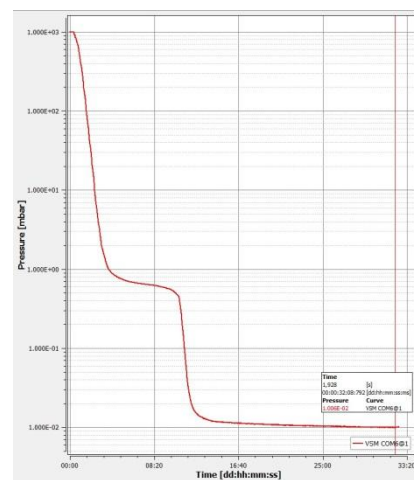


Fig.9. Pressure-time graph in the vacuum chamber during pump-down for the composite plate experiment and AE equipment verification using the Vallen System AMSY-6

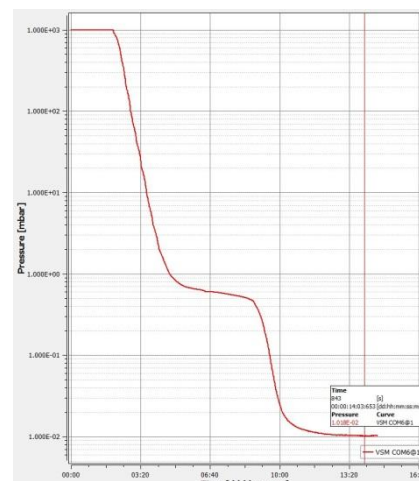


Fig.10. Pressure-time graph in the vacuum chamber during pump-down for the composite plate experiment and AE system verification using the Pocket AE-2

## CONCLUSIONS

While reviewing theoretical sources, it was observed that, throughout the existence of acoustic emission as a non-destructive testing method, there remains a relatively limited amount of information available in various fields. Research on this topic is rather scarce and does not provide sufficient data to draw definitive conclusions regarding the application of the method for studying or synthesising specific materials. Furthermore, only a small number of studies and publications were found concerning the use of the AE method in space-related applications. All identified studies were conducted either under terrestrial conditions or within artificially simulated Earth atmospheres. In most cases, AE signal interpretation must effectively be developed from the ground up. The impact of the space environment on AE signal detection remains an open topic and will be explored further through dedicated research.

A methodology was developed for conducting an experiment to verify the detection of AE signals under vacuum conditions. Two AE systems were used in the experiment: Vallen System AMSY-6 and Pocket AE-2. The first system is stationary and offers greater functionality and capabilities compared to the second, which is portable. However, the sensors used in both systems were identical, and the comparison of results showed a high degree of consistency in the data obtained. The experiment was carried out in a space environment simulator, which generated the required vacuum in the chamber, comparable to the pressure at an altitude of 80 km above sea level. The experiment was conducted on two specimens made of different materials - duralumin and a carbon fibre-based composite. The selection of these materials was based on their similarity to those used in the structure of spacecraft. The experiment did not include irradiation of the specimens or simulation of the temperature fluctuations typical for spacecraft operating in open space. These factors will be addressed in future studies on this topic.

The results obtained confirmed the feasibility of detecting AE signals under vacuum conditions.

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