

## COMPUTER AND STRATOSPHERIC FLIGHT SIMULATION OF SPACE EXPERIMENT ON CURING OF EPOXY COMPOSITE

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**Abstract.** Curing technology of composite materials directly in space environment can be used for creation of large space structures in Earth orbit, on Moon, on Mars and other celestial bodies in future. The curing will be occurred under free space conditions such as high vacuum, temperature variations, cosmic radiation, microgravity and others. The space factors can significantly influence on the curing process and final properties of the composite. A space experiment on curing of the composite is complicate. At first stage, a laboratory experiment, computer modelling and stratospheric flight experiments are used for investigation of curing process. The results show a possibility of the curing and first prepreg of the composite was cured in stratosphere.

### 1. Introduction

Modern space programs of Russian Space Agency, NASA, ESA and other government agencies as well as private companies are focused on future long flight missions to Moon, Mars, asteroids and other planets. Such missions require a large space ship, large space base, large habitat, large storage unit and large green house [1-4]. However, modern technology for creation of a large space structure is based on complicate, risky and expensive way of docking ready-to-use separate blocks launched with a number of space rockets to the orbits. This technology was used for the International Space Station that took 10 years to complete the station and it costed more then 150 billion dollars.

There is another way to create the large space structure: a fabric impregnated with a long shelf-life epoxy matrix (prepreg) is prepared in terrestrial conditions and, after folding into compact envelope, is delivered to orbit or other celestial body with one space ship [5-9]. The prepreg can be kept folded on board of the ship for a long time. In due time the prepreg is taken into free space and unfolded by inflating. Then a reaction of epoxy matrix curing is initiated. After completeness of the curing reaction, the hard structure can be fitted with air under normal condition and used.

However, the space environment is specific for uncured epoxy matrix and the curing reaction is sensitive to space factors such as high vacuum, temperature variations and cosmic radiations [10, 11]. An ignoring of free space environment influence on the curing reaction can cause a fail of the space mission. An investigation of the curing process in free space environment is essential for successful future space missions.

A space experiment on curing of the composite is complicate and expensive. At first stage, laboratory experiments, computer simulations and stratospheric flight experiments are used for investigation of the curing process in a simulated space flight. A comparison of space flight conditions and stratospheric flight conditions related to the curing reaction investigation is an aim of this study.

## 2. Evaporation into vacuum

The altitude of Low Earth Orbit (LEO) is varied from 90 to 1000 km. Usually an orbit for man's flights is varied between 300 and 400 km of altitude. The pressure of residual atmosphere on altitude of 300 km reported in different missions is  $10^{-3}$ - $10^{-5}$  Pa,  $10^{-5}$  Pa or  $10^{-7}$  Pa. The pressure near space ship or space construction depends on time from Earth start. During flights desorbing gases, venting trapped volumes, releasing dust and ice particles can increase the pressure near new space construction. By experimental observation the pressure can vary from  $10^{-5}$  to  $10^{-3}$  Pa depending on the time of flight, sun irradiation, local configuration and materials of space ship and activity of the engine. The virgin atmosphere (without influence of artificial space construction) at 400 km altitude consists of atomic oxygen (AO) (86.6 %), helium (9.6 %), molecular nitrogen (1.5 %), hydrogen (1.3 %), molecular oxygen (0.01 %) and argon (0.00001 %). A Geostationary Earth Orbit (GEO) is varies between 36-42 thousand km from the Earth. The virgin pressure at GEO mission without disturbance from spacecraft is about  $10^{-9}$ - $10^{-11}$  Pa. Near satellite or space ship the pressure can be significantly higher up to 10 and 100 Pa.

The pressure in simulated space environment experiments varies in different systems  $10^{-7}$ - $10^{-8}$  Pa,  $10^{-5}$  Pa,  $7 \times 10^{-5}$  Pa,  $10^{-4}$  Pa,  $2 \times 10^{-4}$  Pa,  $6 \times 10^{-4}$  Pa, 27 Pa, 73 Pa and 200 Pa. The temperature in experiments is usually varied from -150 to +150 and even +800 °C. The combination of high vacuum and high temperature is used for the analysis of outgassing processes in materials for space applications. The test of outgassing process for space materials corresponding to NASA and ESA standards contains a procedure of sample ageing during 24 h at 124 °C and  $10^{-3}$  Pa residual air.

The residual atmospheric pressure in stratospheric flight depends on an altitude of the flight. In some our flights the lowest pressure was observed around 200 Pa, while in other flights the lowest pressure achieved only 2000 Pa.

The main influence of such vacuum is observed as evaporation of low molecular mass fractions. The rate of evaporation into high vacuum following the Langmuire formula depends on molecular mass of vapour, temperature and equilibrium vapour pressure of fraction from Klausius-Klapeyron equation. In high vacuum the stoichiometric of low weight molecular components in matrix can be changed. The changes of active components concentration in oligomers composition are important for creation of plastic with high durability. The vapour pressure of active epoxy components at room temperature is in a range of 500-1000 Pa, that is significantly higher then the pressure in LEO and GEO and higher then the pressure in some stratospheric flights. However, the vapour pressure of some hardeners is very high up to 10000 Pa, that is much higher then the pressure in all flights. Therefore, the evaporation of the active components can be simulated in stratospheric flight under some assumptions.

## 3. Temperature variations

Temperature changes of space ship frame depend on an orientation to Sunlight, absorption and emission indexes of frame surface and internal heat sources. The solar irradiation level depends on season (position of Earth on solar orbit) and it can vary from 1316 W/m<sup>2</sup> at minimal solar energy flux (summer solstice) to 1428 W/m<sup>2</sup> at maximal solar energy flux (winter solstice). The level of de-irradiation of sun light by Earth surface and its atmosphere equals to 240 W/m<sup>2</sup>. The temperature measurements of the satellite surface on LEO showed variations in wide diapason: -100 °C ÷ +200 °C. In far space mission as NGST mission ( $1.5 \times 10^6$  km from Earth) the temperature is observed in - 223 ÷ +122 °C range.

On LEO the surface of space ship is under thermal cycling with period about 90 min due to Sun light and Earth shadow. On GEO the surface temperature of space ship depends only on orientation and rotation of space ship related to Sunlight. In our stratospheric flights, the virgin temperature was observed from -80 to +30 °C. An influence of payload orientation

to the sunlight is essential for the flight. In stratospheric flight the orientation is usually random and disturbed by a wind, while a stabilisation of the orientation is possible with additional sensors and motor. We also used a heater for the sample, which provided a controlled heating up to +120 °C in the stratosphere.

The temperature is a significant factor, which influence on the curing kinetics of composite.

#### 4. Cosmic radiation

The cosmic radiation factor is mostly difficult to be simulated. Cosmic radiation is created by the fluency of galactic and Sun protons, electrons, neutrons and heavy particles with very wide diapason of energy from some eV to hundreds GeV; infrared, visual, ultraviolet and vacuum ultraviolet photons and X-ray photons. On LEO the fluent of atomic oxygen (AO) is added as a most significant factor in comparison with other factors of cosmic radiation on GEO. The main destruction factors of cosmic radiation for hard polymer materials observed in space flights and laboratory experiments are thermal atomic oxygen, high energy electrons and protons flux, VUV irradiation and X-ray irradiation.

**Atomic oxygen.** By experiments on LEO with degradation of polymer materials the AO is the main factor which limits the exploitation time of materials. The average AO flux on LEO (near 300 km altitude) during flight experiments was observed  $2.88 \times 10^{13}$  at/cm<sup>2</sup>/sec,  $3.88 \times 10^{13}$  at/cm<sup>2</sup>/sec in LDEF mission,  $10^{14}$  in MISSE mission,  $5 \times 10^{14}$  at/cm<sup>2</sup>/sec theoretical value and  $4.3 \times 10^{14}$  at/cm<sup>2</sup>/sec on Kapton equivalent for ESEM mission,  $5 \times 10^{13}$  at/cm<sup>2</sup>/sec and  $10^{12}$ - $10^{15}$  at/cm<sup>2</sup>/s for ESEM mission,  $10^{13}$ - $10^{15}$  at/cm<sup>2</sup>/s. In Hubble mission (595 km altitude) the AO flux equals to  $6.86 \times 10^{11}$  at/cm<sup>2</sup>/sec. The flux of AO varies due to Sun activity, season, position, longitude-latitude and altitude of space ship, variations of Earth atmosphere and outgassing processes of space ship materials.

**Vacuum ultraviolet irradiation.** Vacuum ultraviolet (VUV) irradiation is a part of solar spectra of irradiation. The intensity of VUV light is low, but the effect of VUV light on polymers is significantly higher than visual and UV light. At LEO the level of VUV light was estimated of about  $4 \times 10^{11}$  photons/cm<sup>2</sup>/second for 121.6 nm wavelength. The Sun irradiation density corresponds to 0.75 μW/cm<sup>2</sup> in VUV diapason of 100-150 nm wavelength and 11 μW/cm<sup>2</sup> in UV diapason of 200-300 nm wavelength.

A number of gas-discharge sources are used for the simulation of solar VUV light in laboratory experiments. The hydrogen lamp generates a line at 121 nm in VUV diapason. The deuterium lamp generates the continuous spectra in diapason of 115-400 nm. The krypton and argon lamps are used too. Usually, the irradiation intensity of some units of solar VUV activity from lamps is used for quick ageing of polymers. The VUV factor is significant for polymers at LEO and GEO missions.

**X-rays.** The level of X-ray on Earth orbit equals to  $2.3 \times 10^{-9}$  W/cm<sup>2</sup> for 1-8 Å wavelength and  $1.43 \times 10^{-10}$  W/cm<sup>2</sup> for 0.5-4 Å wavelength. The most flux of X-rays is directed from sun and less from stars. The simulation of X-ray irradiation was made with Cu Kλ line source with electron excitation energy lower 60 keV. The intensity of X-ray irradiation was  $1.3 \times 10^{-3}$  W/cm<sup>2</sup>.

**High energy particles.** The energetic spectrum of electron and ion fluxes at LEO and GEO is very wide. The energetic spectrum and flux of charged particles depends on the kind of particle, altitude, longitude-latitude, seasons and Sun activity. The energy of charged particles varies in diapason from 0.1 eV to some GeV. In laboratory experiments some theoretical models are used for the analysis of effects in materials generated by charged particles flows. The density of electrons at LEO altitude of 400 km was measured to  $10^5$  e/cm<sup>3</sup> (night side) and  $10^6$  e/cm<sup>3</sup> (day side) with energy of 0.1 eV. The electrons flux at GEO mission equals to  $10^9$  e/cm<sup>2</sup>/sec for electrons with energy of 0-12 keV. The electron

density on GEO mission of  $1.12 \text{ e/cm}^3$  at average energy of  $1.2 \times 10^4 \text{ eV}$  and the ion density of  $0.236 \text{ ion/cm}^3$  with average energy of  $2.95 \cdot 10^4 \text{ eV}$  are used for simple analysis of plasma on GEO missions. The most frequent ions are hydrogen ions (90 %). Other 10 % of ions consists of all elements.

The laboratory simulation of high energy particles is made on the base of accelerators of electrons and ions. The energy of electrons in Earth laboratory experiments varies from 20 keV to 2 MeV. The energy of ions in experiments varies from 40 keV to 2 MeV. Mostly, the electron and ion beams are used for simulation of GEO space environment on polymers.

In stratospheric experiments above ozone layer the measurements of the high energy particles was done by silicon integral detector, that showed significantly higher level of the cosmic radiation in comparison with Earth conditions. The integral level of the radiation in stratosphere is lower then in the space flight, however the effect of high energy particles on curing prepreg was clear observed in our experiments.

The effects of space plasma action at LEO and GEO on liquid oligomers composition and on polymerisation process are mostly significant and it must be examined in wide diapason of irradiation kind, density and energy.

## 5. Conclusions

The results of the analysis show that the stratospheric flight experiments can partly simulate the space flight environment in the investigation of the curing process in free space flight conditions. Most effects, which can be observed and investigated, are an evaporation of low molecular fractions, chemical reaction kinetics and high-energy processes caused by cosmic radiation. The stratospheric flights can be used as a quick and cheap test of the curable materials before the space flight experiments. This is a good possibility to exclude a fail of future space missions at an absent of specific standards for curable materials used for large space structures.

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