Outgassing Environment of Spacecraft: An Overview

Zilong Jiao\textsuperscript{1,2,*}, Lixiang Jiang\textsuperscript{1,2}, Jipeng Sun\textsuperscript{1,2}, Jianguo Huang\textsuperscript{1,2} and Yunfei Zhu\textsuperscript{1,2}

\textsuperscript{1}Science and Technology on Reliability and Environmental Engineering Laboratory, Beijing, China
\textsuperscript{2}Beijing Institute of Spacecraft Environmental Engineering, Beijing, China

*Corresponding author

Abstract. With the advancements of materials science and technology, organic materials found significant applications in aerospace industry. But under the orbital thermal and vacuum environment, organic materials can outgas and the outgassed products and induced environment often degraded performances of spacecraft or its subsystem. In this article, the typical impacts of outgassing environment on spacecraft are explained briefly. Then the outgassing theory, test method, identification of compounds and control measures were reviewed in detail. The need for transient and long-term outgassing model is discussed. The standard test methods of E595 and E1559 are compared. The promising new techniques such as infrared spectrometry and/or mass-spectrometry with thermogravimetric analysis is proposed for the identification of outgassed compounds. The vacuum bakeout and molecular absorber for outgassing control are reviewed and for the last more research work is needed.

1. Introduction
The space industry has made great achievements, and it is inseparable with aerospace materials technology development and breakthroughs. Developments of materials play a strong supporting role for space technology, in turn, the development of space technology has great demand to lead and promote the development of aerospace materials [1]. Deep space exploration, high-resolution Earth observation, manned space program and other projects are put forward even higher requirements for the aerospace material. NASA in 2012 announced technology roadmap, noting in particular high-performance structural and functional materials is one of the areas in the next 10 years need to focus on the study [2].

With the stringent requirements of long life, high reliability, high resolution on future spacecraft, the application of polymeric materials in spacecraft is increasingly demanded. For example, carbon fibre/epoxy composites widely used in structures of spacecraft [3]; a large number of thermal control coatings, thermal insulation materials and others used in the spacecraft’s structure and thermal control system [4]; the manufacturing processes of spacecraft’s structure also uses adhesives extensively [5].

When in space, the materials used in spacecraft including structural and functional materials must withstand the space environment factors, including high vacuum, rather large temperature variations, ionizing radiation (Earth trapped radiation belts, solar cosmic rays, galactic cosmic rays), solar electromagnetic radiation, micrometeoroids / orbital debris, atomic oxygen, plasma environment and other factors, resulting in chemical, electrical, thermal, optical, mechanical and other performance parameters of materials have been seriously affected, and therefore the need for adaptability of the space environment materials research [6-8].
Polymeric materials can outgas in the space environment, causing mass loss, not only affects the performance of the material itself, the outgassing products and its formed self-atmosphere also have detrimental effects on the spacecraft itself. Therefore, it is important for materials outgassing research. Although research in this area has a lot of achievements, but the lack of systematic summary analysis, and there is still the key issue is not resolved, affect the effective control of the material outgassing. Spacecraft development is mainly concerned with the practice of the total mass loss, compounds of outgassing and control measures in three areas. In this paper, the results of these studies have been carried out systematically summarized in three areas, pointed out the direction of future work.

2. Outgassing Phenomenon and Its Impact

Any materials in a vacuum environment will lose its mass. Material will evaporate; molecules adsorbed on surface will desorb. Also, organic polymer in the production of the polymerization process will contain a large number of low molecular weight additives. The compounds contained within the material will diffuse to the material surface and desorb from the surface. Evaporation of materials is related to its saturated vapour pressure. Polymers used on spacecraft have very low vapour pressure, so in the normal operating temperature, mass loss caused by evaporation are small. Therefore, the main consideration is outgassing caused mass loss.

As can be seen from figure 1, the outgassing results in brown coloured deposits on aluminium panel, which is a clear evidence of exists of outgassing. And there are many lessons learned about outgassing impacts. Outgassing can easily have serious impact for space borne optical system, HV devices, scientific exploration tasks etc.

![Figure 1. Contamination from internal outgassing of spacecraft. The brown coloured outgassing deposits on aluminium panel.](image)

2.1. The Impact on Deep Space Exploration Spacecraft

In the first moon orbital flight by Apollo 8, the silicon rubber seals outgassed severely and contaminated large observation window, so had to temporarily move to less contaminated small view window to take picture and video. On Apollo 14 the sealed motor switch failed during flight, the reason is the room temperature vulcanized (RTV) silicone rubber used during operation outgassed silicone compounds with low molecular weight, and outgassed silicone formed carbon particle with petroleum-based lubricant in the brush arc action, increased brush marks lead to motor failure [9]. European comet probe Rosetta mission used a quadrupole mass spectrometer for detection of comets surrounding gas composition. Analysis showed that material outgassing seriously affect the results of the detection of the gas components [10]. In deep space exploration, as the most important feature of the origin of life, water detection is one of the main tasks, and material outgassing of water is the main component of one of them, so its direct impact on mission success.
2.2. The Impact on Spacecraft Optical System

The image quality of charge-coupled device (CCD) detector inside the navigation sensor of NASA's Stardust probe was degraded due to outgassing. Narrow viewing angle camera on Cassini spacecraft also experienced severe flare in image due to outgassing (figure 2), for removing the contamination, had held a long heating degassing [11].

![Figure 2. Glow in image of planet due to contamination of spacecraft Cassini: Left: no contamination; Right: with contamination](image)

Space telescope and earth observation satellites are equipped with extremely sophisticated optical systems, materials outgassing product in the low-temperature optical system condenses, causing contamination, so that the optical system transmittance and signal-to-noise (SNR) decrease, seriously affect the performance of the optical system. Hubble Space Telescope and the James Webb Space Telescope have made very stringent contamination control requirements, including control measures of outgassing.

2.3. Impact on the Spacecraft High-voltage Devices

As the spacecraft performance improvement, power increases, the high-voltage devices are used more widely, such as ion propulsion system, a photomultiplier tube (PMT), traveling wave tubes amplifier (TWTA), high voltage solar array and scientific exploration instruments. Vacuum insulation are main insulating method for high-voltage devices, local atmosphere from outgassing easily generated discharge breakdown, seriously affecting the performance and reliability of the satellite [12].

![Figure 3. Corona of discharge resulted in high voltage radio frequency system.](image)

A series of satellites in thermal vacuum tests, high-power microwave switch repeatedly appear abnormal temperature rise and along with the output power falling. With dissembling the switch found inside contact ablation. The reason was speculated on outgassing of a large number of non-metallic materials in thermal vacuum environment, formed local atmosphere with higher pressure in the vicinity of high-power microwave switch, in the switch-on process causing the low pressure discharge problems. Besides, outgased contaminants at the same time may condense inside contacts, resulting in a large contact resistance, which may lead to micro-discharge phenomenon, leading to the switch burned [13-14].
3. Materials Outgassing Theory

In order to quantitatively assess the impact of outgassing caused firstly need to determine the amount of outgassing under certain conditions. Bareiss proposed that outgassing rate $\frac{dm}{dt}$ is proportional to the remaining material mass $m$, and the coefficient $k$ related to temperature of materials $T$, then outgassing rate was expressed as [15]:

$$\frac{dm}{dt} = -km$$ (1)

$$k = k_0 e^{-\frac{E_a}{RT}}$$ (2)

$$m = m_0 e^{-\lambda t}$$ (3)

Accordingly, the logarithm of total amount of material outgassing $\ln(\Delta m)$ is linear with temperature. Scialdone proved this law by experiments [16]. However, additional experiments found that this equation can only fit best with initial outgassing process, but not for long-term variation of the material outgassing.

Taking into account the long-term changes in the material outgassing controlled by diffusion process, many researchers modelled outgassing process by diffusion equation[18-20].

![Figure 4. Diffusion model of outgassing](image)

As in figure 4, for one-dimensional diffusion problem, we have:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} + f(x,t)$$ (4)

There, $C$ is concentration of the volatiles in materials, $t$ is time, $x$ is distance, $D$ is diffusion coefficient, $f(x,t)$ is the volatile source in materials.

Then the outgassing rate can be expressed as follows:

$$q = -D \frac{\partial C}{\partial x} \bigg|_{x=\delta}$$ (5)

The outgassing amount at time $t$ is

$$Q(t) = \int_0^t q(\tau) d\tau$$ (6)
Boundary conditions for the above problem:

\[
\begin{align*}
&C |_{x=0} = C |_{x=\delta} = 0 \\
&C |_{t=0} = \phi(x)
\end{align*}
\]  

(7)

The definite solution of the problem is non-homogeneous equations and boundary conditions for the standard homogeneous parabolic equation. Under the given conditions, as long as the initial conditions to ascertain the specific form, it can be solved. Usually suppose that total amount of volatiles isn’t change with time, so \( f(x,t) \) set to zero. And very often the polymers can outgas not only one kind of volatile compound, but tens of them. But we don’t know the initial concentration distribution of them, i.e. the function \( \phi(x) \), and precise value of diffusion coefficient \( D \) for every kind of volatiles, that make the equation unresolvable. Then the analysis with diffusion equation can only be qualitative.

In addition to diffusion of volatiles from inner to surface, Roussel et al. suggested that it should be using surface desorption model and internal diffusion model for materials outgassing [21]. The current work is limited to qualitative discussion, it’s expected to validate the theoretical analysis with more experimental quantitative results.

In conclusion, theoretical analysis of outgassing have unresolved issues in two aspects. First is the transient material outgassing model. Such as satellite internal pressure changes; the optical system internal outgassing, adsorption, desorption, etc., belong to the transient material outgassing problems. In this aspect focus should on the impact of temperature of the material on outgassing. Second is the long-term outgassing model. Currently satellites can live up to 15 years, but there is no relevant test or measurement data in orbit, make the effective application of the material difficult.

4. Materials Outgassing Test Methods

The American Society for Testing Materials (ASTM) has developed two material outgassing test standards, namely ASTM E-595 “Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment” and ASTM E-1559 “Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials”.

In test method of E-595, the vacuum of test chamber need to be better than \( 7 \times 10^{-3} \) Pa, the sample was heated to 125°C, test duration is 24h. Test temperature was selected according to spacecraft surface temperatures at extreme conditions, while the degree of vacuum guarantee for molecular flow. The results obtained from the experiments include: material mass losses (total mass loss, TML), the fraction that can deposit of mass loss (collected volatiles of condensable materials, CVCM), the ratio of water to the mass loss (water vapor recovery, WVR). Due to the need for contamination control, generally require the use of TML <1%, CVCM <0.1% of the material.

For test method of E595 there are several deficiencies: 1) TML and CVCM two parameters does not fully reflect the contamination characteristics of outgassing products, i.e. the different degrees of contamination impacts on sensitive surface; 2) In contamination simulation and analysis, it is required dynamic characteristics of outgassing, the relationship between the outgassing, deposition and temperature, while the test method of E595 uses single sample heating temperature, a single collection plate temperature, single test duration, it cannot give dynamic outgassing data; 3) Test temperature and actual using temperature are different; material sample in test are sheet or block, are different with actual state. All these make the test results may not be the same when materials in the orbit. In short, test method of E595 is more an evaluation criterion, not a test standard for outgassing properties.

Recognizing the deficiencies of E595, Air Force Material Laboratory Non-Metallic Material Group contracted to Lockheed Missiles and Space Company to develop a new test method, and provided to the ASTM, became the test method of E1559. After subsequent improvement of this standard method, and now for the 1559-03 revision.
Figure 5. E1559 test configuration diagram.

Test configuration shown in figure 5. Materials placed in temperature-controlled effusion cell. Quartz crystal microbalances (QCM) are temperature-controlled type. A QCM for low temperature, liquid nitrogen cooling, to collect all of its surface impingest outgassing product. TML total mass loss as a function of time is determined by the quality and geometric relationships deposited thereon. The VCM determined by QCM temperature. Inside the test chamber is shroud, i.e. molecular sink. Three QCM were controlled at different temperatures, such that the in-situ material outgassing TML and CVCM at different surface temperatures can be measured. Standard requires temperature control accuracy of QCM should be better than ± 0.5 °C.

In E-1559 there are two method options: Test Method A and Test Method B. Method A the various test parameters was of the strict rules. 3 QCM operating temperatures are 90K, 160K and 298K. Method B allows the user to select the sample heating temperature, the QCM temperature and other parameters, so as to perform the material outgassing test for specific tasks possible. Two test methods tested samples at three temperatures 398K (125 °C), 348K (75 °C), 323K (50 °C), the duration is 1-5 days.

The test method of E-1559 is characterized in using three different temperatures TQCM, it can provide dynamic data of outgassing in different time and temperature. The use of QCM thermogravimetric analysis (QTGA) also gives composition desorption temperature, the adsorption heat (heat of condensation) and other information about the outgassing component.

5. Identification of Compounds of Materials Outgassing

Materials outgassing products contain complex compounds, and its concentration is extremely low, commonly used analysis methods are mass-spectrometry and infrared spectrometry.

It was found that water is one of the most important product of outgassing, mainly from material processing and storage environment. Relatively loose structure of the polymer material, microscopic pores larger than the diameter of a variety of common gas molecules, therefore polymers can dissolve a variety of gases. Solubility depends on the affinity between the material and the gas molecules.

Water is a polar molecule, the affinity is relatively large, so the solubility is high, and this is the reason why water is one of the main products of outgassing.

Chen P T et al. use low temperature cold finger to collect outgassing product in thermal vacuum test, by using mass spectrometry to identify compounds. Through statistical analysis it is found that the molecular weight of more than 100 of outgassing products mainly siloxane and phthalate esters [22]. Yokozawa H. et al., using infrared spectroscopy for outgassing products analysis [23]. The method further improved can be used for real-time analysis of outgassing compounds.

Identification of compounds of material outgassing products should combine with materials outgassing test described in section 4, aimed at obtaining total amounts of different outgassing products. Possible methods include temperature-controlled QCM in combination with mass spectrometry, temperature-controlled QCM in combination with infrared spectroscopy. Vanhove E et
al. presented an experimental method to obtain compound information by coupling QTGA and mass-spectrometry [24]. By using an automated computer program, the outgassing species are separated and their initial masses and characteristic desorption constants are obtained. This technique is called deconvolution by the authors. It is promising, but as the Roussel J-F et al. stated in another paper, there are still some improvements should be made to the experimental configurations, such as temperature control along movement path of molecules etc. [25]. The identification of compounds is expected for further research works.

6. Control Measures of Outgassing
The control measures of materials outgassing includes vacuum bakeout, molecular adsorber, etc. The vacuum bakeout is based on linear relationship between logarithmic of outgassing amount with material temperature described in section 3. It is heating the material to a higher temperature, and artificially remove volatile components in materials, which can effectively reduce the contamination caused by outgassing [26]. Molecular absorber is based on absorption property of the highly porous material which has large specific surface area. Currently more attention was focused on zeolite absorber. NASA GSFC has developed a zeolite absorber coating technology [27-28]. This technology has broad application prospects; it is worth further study.

7. Concluding Remarks
Outgassing is a unique phenomenon of polymer material in space applications. Outgassing can have a negative impact on spacecraft optical systems, high-voltage devices and for scientific exploration missions. Therefore, outgassing and its control measures must be studied in detail. In this paper, the research on outgassing of polymers for space applications in the thermal vacuum environment were reviewed, including theoretical analysis, test method, identification of compounds and control measures.

On the basis of current researches, the next step should be to establish a long-term and transient physical model for outgassing; combine outgassing test with material outgassing compound analysis to create a new test method, aiming at obtaining outgassing characteristics of different products; study control measures of outgassing contamination based the different requirements of materials and spacecraft systems, in particular the application of zeolites and other porous adsorbent material.

References
[1] Li C G, Fu H Z and Yu Q 2002 Aerospace Materials (Beijing: Defense Industry) pp 7-8
[2] Wang J Q 2012 Space Intl. 7 35
[3] Chen L M 2005 Spacecraft Structures and Mechanisms (Beijing: Science and Technology) pp 63-70
[4] Hou Z Q and Hu J G Spacecraft Thermal Control – Principle and its Application (Beijing: Science and Technology) pp 129-140
[5] Chen S H 2004 Shanghai Aerospace 3 39
[6] Miller S K R, Banks B 2010 MRS Bulletin 35 20
[7] Edwards D L, Tighe A P, Eesbeek M V, Kimoto Y and de Groh K K 2010 MRS Bulletin 35 25
[8] Feng W Q 2010 Spacecraft Envir. Eng. 27 139
[9] Malave V, Burkitt B, Riegler B, Johnson R and Thomaier R 2011 J. of Sp. Roc. 48 235
[10] Schläppi B, Altwegg K, Balsiger H, Calmonte U, Hässig M, Hofer L, Jäckel A, Wurz P, Berthelier J J, De Keyser, et al. 2011 Characterization of the gaseous spacecraft environment of Rosetta by ROSINA Proc. 3rd ALAA Atmospheric Space Environments Conference (Honolulu, US, 27-30 June 2011)
[11] Haemmerle V R and Gerhard J H 2006 Cassini Camera Contamination Anomaly: Experiences and Lessons Learned (Jet Propulsion Laboratory)
[12] Capineri L, Dainelli G, Masterassi M and Dunn B D 2003 IEEE Trans. Elec. Pack. Manuf. 26 294
[13] Liu T X, Luo C, Zhu J T, Yi Z and Yang D S 2014 Spacecraft Eng. 23 47
[14] Zhang H B, Liu T X and Li C J 2011 Spacecraft Eng. 20 125
[15] Bareiss L E 1978 Contamination design analysis approach for spacelab Proc. 10th Space Simulation Conference (Bethesda, US, 16-18 October 1978)
[16] Scialdone J J 1976 An equivalent energy for the outgassing of space materials (NASA)
[17] Tribble A C, Boyadjian B, Davis J, Haffner J and McCullough E 1997 Contamination Control Engineering Design Guidelines for Aerospace Community (NASA)
[18] Salnikov V A 1994 Vacuum mass loss of materials (mathematical model) Proc. 6th International Symposium on Materials in a Space Environment (Noordwijk, Netherlands, 19-23 September 1994) ed T D Guyenne (ESA)
[19] Silver D M 1992 Modeling of spacecraft contamination outgassing as a diffusion-controlled process Proc. Optical System Contamination: Effects, Measurement, Control III (San Diego, US, 18 December 1992), ed A P M Glassford (SPIE) pp 37-45
[20] Girard T J 1993 Algorithm for calculating nonisothermal diffusion-limited outgassing rates Proc. Damage to Space Optics, and Properties and Characteristics of Optical Glass (San Diego, US, 11 January 1993) ed J B Breckinridge, A J Marker III (SPIE) pp 114-118
[21] Roussel J-F, Tondu T, Paulmier T, Faye D, Eesbeek M V and Rampini R 2011 J. of Spacecraft Rockets 48 246
[22] Chen P, Hedgeland R and Montoya A 1997 Statistical Evaluation of Molecular Contamination During Spacecraft Thermal Vacuum Test (Goddard Space Flight Center)
[23] Yokozawa H, Baba S and Miyazaki E 2012 Evaluation of bakeout effectiveness by optical measurement of a contaminated surface Proc. Optical System Contamination: Effects, Measurements, and Control (San Diego, US, 21 July 2012)
[24] Vanhove E, Tondu T, Roussel J-F, Faye D and Guigue P 2016 J. of Spacecraft and Rockets 53 1166
[25] Roussel J-F, Vanhove E, Grosjean E, Faye D, Rioland G, Rampini R and Ergincan O 2018 Progress in a physical approach to contamination in Europe Proc. Systems Contamination: Prediction, Control, and Performance (San Diego, US, 5 November 2018) ed C E Soares, E M Wooldridge, B A Matheson (SPIE) pp 137-145
[26] Dyer J S, Benson R C, Philips T E, Guregian J J 1992 Outgassing analyses performed during vacuum bakeout of components painted with Chemglaze Z306/9922 Proc. Optical System Contamination: Effects, Measurement, Control III (San Diego, US, 18 December 1992) ed A P M Glassford pp 177-181
[27] Abraham N S, Hasegawa M M, Straka S A 2014 Black molecular adsorber coatings for spaceflight applications, Proc. SPIE Optics and Photonics 2014 (San Diego, US, 19-21 August 2014)
[28] Abraham N S, Jallice D E 2018 Preliminary testing of NASA’s Molecular Adsorber Coating technology for future missions to Mars Proc. Systems Contamination: Prediction, Control, and Performance (San Diego, US, 5 November 2018) ed C E Soares, E M Wooldridge, B A Matheson (SPIE) pp 41-46