Materials in space

Dr Barrie Dunn looks at how materials science is pushing the boundaries in space engineering.

Astronaut performing ISS extravehicular activity – installation of a tray supporting material samples for exposure to the space environment.

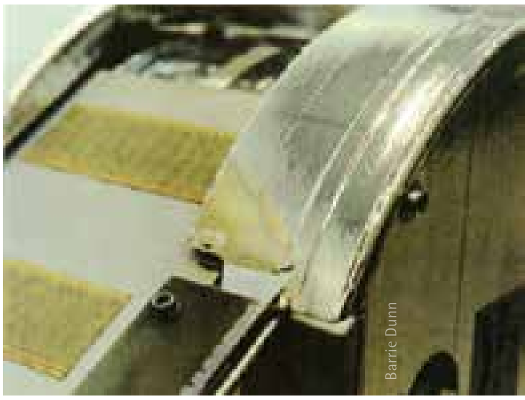
MISSE-8 project, NASA

The materials and processes (M&P) associated with space industries are highly demanding and a continuous challenge to the engineers involved in reducing the risk of failure. Teams involving metallurgists, chemists and electrical and structural engineers work to avoid conventional hardware failures that may cause the loss of function of a spacecraft system, or designs that are so costly to build that the project fails on economic grounds.

The space industry is a key sector in driving economic growth. According to the UK Space Agency, the industry adds £7bln to the economy, supports 70,000 jobs and is growing four times faster than the rest of the economy. The UK presently enjoys 7% of the global space market, predicted to be worth £543bln by 2020. Highly trained engineers and scientists will need to fill this rapidly growing industry. However, it is apparent that there are insufficient materials engineers with adequate knowledge to support the industry – metallurgists are in particularly short supply. Experienced engineers may perform the testing or evaluate the results of mandatory space material tests. Initial screening test methods have been well defined in standards issued by NASA, American Society for Testing and Materials International (ASTM) and the European Cooperation for Space Standardisation (ECSS). The most frequently applied test is related to the outgassing-under-vacuum of non-metallic materials to avoid mass loss and condensation of matter onto sensitive optical or reflective surfaces.

There is no leeway for failure in manned spacecraft projects. M&P requirements are set at different levels depending on performance, safety and reliability goals determined by spacecraft project managers. The materials and manufacturing processes in space system designs are cost drivers. Each system is managed by a different entity applying various M&P requirements. A basic overview of space systems includes:

- The space segment – the particular design of the spacecraft such as its weight, type of payload, amount of software, quantity of fuel and beginning of life power. The sub-systems will include those for structure to support and maintain the craft's configuration on the ground during launch and in orbit. Altitude control and on-board propulsion to provide thrust for orbit changes, station-keeping and deorbiting. Environmental control will maintain specified temperatures, and radiation levels. Electrical power supply and distribution from sub-systems and the communications will relay information (data and commands) between Earth, other spacecraft and itself. Life-support systems will be associated with manned spacecraft and the vessel can be considered similar to a submarine, where internal construction materials must be tested and controlled for flammability, toxicity, microbial resistance and off-gassing (avoidance of nauseating odours). Spacecraft designed for reaching and landing on other planets often contain modules that perform entry, descent and landing and will be equipped with thermal protection systems including heatshields.
- The launch segments – the launch vehicle and its design, weight, payload (satellite, probe, or laboratory), lift capability and propulsion systems.
- The launch sites – these are best located on the east coast of continents to take advantage of the Earth's west-to-east spin, and as close to the equator as possible where the Earth's spin is at its maximum 465m/s.
- The ground segment – consists of tracking and data relay stations sited around the globe. They may be located at mission control centres, but also include very remote sites where spacecraft are tracked by antennas from poorly accessible locations. They provide real-time reporting and communications data when a satellite is visible from the ground station.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Above: Thermal cover returned from a space mission showing fringe pattern of condensed contaminant that altered its thermal properties.

Methodical and well-defined steps are taken to approve these materials for space applications. It is usual that every flight material is listed in a table called the declared materials list (DML), which records the material group. These include aluminium alloys, filler metals, optical materials, paints, lubricant, potting compound, ceramics and wires/cables. The DML records each material processing parameter, its use and location on the spacecraft, and the operational environment. The vernacular used by the space community is that materials are validated, mechanical parts are qualified and manufacturing processes – such as painting, welding and soldering – are verified. Critical materials such as those never tested or those that have given problems during previous use, may be tested for outgassing-under-vacuum, stress corrosion and flammability. But, it is the operational environment that will determine which tests are applicable. Skilled materials engineers and their associates are needed to manage and control such lists.

Surviving in space

As well as ground based testing, NASA, with some support from the European Space Agency (ESA), has conducted a series of space experiments to determine the best materials to survive in the space environment. One experiment involved placing a bus-sized payload into orbit, supporting 10,000 samples ranging from spacecraft polymers, alloys, paints and electronic materials to advanced solar cells. This payload was called the Long Duration Exposure Facility (LDEF), a free-flyer, and after six years in low Earth orbit was collected by the space shuttle and returned so the exposed material

Above: Short circuiting tin whisker operation under vacuum caused whiskers to spark discharge from tip (corona discharge) and fuse, causing a plasma and current surge responsible for the failure of at least three communications satellites.

Below: Lift-off of Ariane flight VA233, carrying four Galileo satellites from Europe's Spaceport in Kourou, French Guiana.

Above: Returned silver mesh solar cell interconnector – atomic oxygen corrodes silver, causing spalling of silver oxide.

samples could be evaluated by numerous companies and universities. The most significant findings have been published and found that ageing and degradation of materials during the six-year exposure period were influenced by:

- Atomic oxygen (10,000 oxygen atoms per cm^{-1}) silver, copper and osmium are mostly affected by oxidation and a Teflon sheet showed 25µm erosion.
- Solar and cosmic radiation caused paints to discolour and many surfaces to darken during the 5,000–14,000 hours exposure to sunlight (depending on the orientation of samples in their trays).
- Thermal cycling (34,200 cycles day/night) caused thermal fatigue, delamination and peeling of certain coatings.
- Impacts (15,000 were recorded on LDEF), 30% from man-made objects and 70% from micrometeoroids.
- Condensation (contamination) from outgassed surrounding materials composed of silicones and hydrocarbons.

Those results were instrumental in the design of later spacecraft including the International Space Station (ISS). New, novel and surface-modified materials continue to be tested in orbit as, for instance by the materials on international space station experiments (MISSE) project. Damage caused by impacts from small particles and micrometeoroids can be reduced by means of protective shutters. Occasionally, space hardware is returned to Earth, as was the case of the Hubble Telescope's solar array, when useful information was obtained from the laboratory examination of the material parts that have come to the end of their service life in orbit. Returned shuttle materials were also often examined in the laboratory.

Launcher propellants

Ariane flight VA233 from Europe's Spaceport in Kourou, French Guiana, was launched on 17 November 2016 on a mission performed on behalf of the European Commission under a contract with the ESA. Ariane 5's main stage cryogenic engine is fed with liquid hydrogen and liquid oxygen from a two-compartmentalised

Above: The ISS dome shaped Cupula was made from forged, then heat-treated (Al 2219-T851) alloy and the windows are fused silica and borosilicate glass panes. The panels include temperature sensitive elements and window heaters.

30.5-metre-high tank. The two solid motor boosters are fuelled with a mix of ammonium perchlorate, aluminium powder and polybutadiene.

The second stage is capable of multiple ignitions and fuelled by monomethyl hydrazine and nitrogen tetroxide. It costs €30,000 to launch 1kg of payload into space, so new launchers, such as Ariane 6, are being developed to incorporate light-weight composite materials and metallic structural parts will use advanced friction stir welded Al-Li alloys. Solid rocket motor propellants emit chloride- and aluminium-containing particulate consisting of aluminium fuel and ammonium perchlorate (NH_4ClO_4) oxidiser. The emissions from past rocket launches can accelerate the corrosion of launch-site fixtures, as seen with the ELA-2.

Chemicals and materials

The EU's Restriction of Hazardous Substances (RoHS), Waste Electrical and Electronic Equipment (WEEE) and Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) are all major directives that need to be met before a material is applied to industry. The RoHS directive prohibits the sale of electronic equipment containing certain hazardous substances including lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyls and polybrominated diphenylethers in the EU. Although this directive does not presently apply to material intended for specifically military purposes or equipment designed to be sent into space, it does pose enormous problems. There is no information available concerning when such exemptions will cease – studies are required to find alternatives.

As the space market is relatively small, commercial products are frequently purchased either intentionally (off the shelf) or by error. Lead-free solder alloys appear less reliable than tin-lead alloys, owing to their reduced compliance during thermal cycling. Pure tin as a solderable coating is now a standard finish for electronic component terminations and printed circuit boards despite the known risk of tin whisker growths. Around 95% of pure lead continues to be used for car batteries and as sheet in the building trade, but hardware designed for sending into space that contains a few grammes of lead in solder alloy or 2% lead in free-machining brass or steel, may be forbidden. Similarly, despite extensive testing, there seem to be no products able to match or replace chemical conversion coatings based on hexavalent chromium for the corrosion protection and low electrical resistance of spacecraft aluminium alloys. However, vehicles manufactured in the EU now use chromium trioxide coatings as a base for corrosion protective paints.

The WEEE objectives centre on improving the management of the rapidly growing waste of electrical and electronic equipment. This has little effect on the space industry, as waste management and recycling has been a predominant factor within most companies with some complexes disassembled for recycling. The REACH directive aims to improve the protection of human health and the environment by providing information and regulation of chemicals produced or imported in the EU. This impacts the space sector to a great extent because of the small production runs and prolonged materials development cycles necessary for niche, space-resilient piece-parts. The supply chains are complex, usually involving international material manufacturers. The low volumes of substances and mixtures used by space industries are very small and can often be overlooked by other industries. This is a major materials challenge when viable alternative chemicals and materials are required to substitute for existing materials with a long heritage, but which now fall foul of REACH. Important examples for the continued use of these substances in spacecraft hardware include:

- Beryllium – used for high-resolution X-ray windows for which there is no substitute material, a component of high-strength-to-weight Al-Li alloys, beryllium oxide for spacecraft cooling devices and heat shields.
- Boric acid – used for high-quality printed circuit board manufacture and plating processes.
- Gallium arsenide – used in power amplifiers and high-performance semiconductors with improved properties compared with silicon technology.
- Hydrazine – needed for liquid propulsion systems and lead used in solid lubricant for bearings and solder alloys.

The UK's space industry is pushing the boundaries of material science and leading the drive in new technologies. It has the physical infrastructure in place to support an evolving and exciting space programme and is growing four times faster than the rest of the economy – there is no better time to be entering the industry.

Pictured: Emission gasses and particulates from a multitude of launches, plus the aggressive sea-coast environment, caused extensive corrosion of Kourou's launch complex ELA-2. It was brought down by a controlled explosion, dismantled, compressed and returned to Europe for recycling.

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