Space propulsion goes green

A European Space Agency-led consortium has successfully test-fired the first large space propulsion engine developed in the UK for almost 20 years. Dr Adam Baker, Senior Lecturer in space engineering at Kingston University, UK, reveals the materials and engineering behind the ambitious project.

British engineers have been involved in building satellites since the early days of the space age. However, much of the knowledge developed, particularly in the area of space propulsion, has slowly been lost through retirement, consolidation of companies into Europe and limited Government support for the R&D required to develop new products. In fact, no new large chemical spacecraft propulsion system has been developed in the UK since the mid-1990s. But all that is set to change. Increasing Government and commercial interest in space services, from communications relay and navigation broadcasting to weather and climate forecasts, has seen a resurgence of support for underpinning technologies such as rocket propulsion.

In June 2013, following a two-year programme, a small team of British engineers successfully test-fired the first high-thrust apogee rocket engine (HTAE). Thanks to investments in space technology funding from the UK and European Space Agencies (ESA), the TSB and the Satellite Applications Catapult, the team from aviation engineering company Moog ISP Westcott Ltd, based near Aylesbury, Buckinghamshire, developed the first-high thrust bipropellant rocket engine designed to deliver future exploration missions into orbit around Mars. It is hoped that HTAE will lead the way to a new generation of large and small space propulsion engines for commercial missions that may also use non-toxic rocket propellants. This Government backing has gained momentum through a European drive to join American and Russian probes in exploring our solar system. This starts with missions to Mars and to a comet, with the first landing scheduled for late 2014. But to explore our solar system calls for another kind of exploration – for new materials that will stand up to the extreme operating conditions created by this new generation of rocket engine.

Opposite: Hotbird 10 telecommunications satellite, built by Airbus Defence and Space.
Left: The European Space Agency's ExoMar Rover.

Permission to launch

All spacecraft require a launch vehicle (called a launcher) about the size of an aeroplane to deliver them into an orbit above Earth's atmosphere. Weight is a key driver in the design of launchers, which has seen extensive use of aluminium alloys and increasing use of composites. Titanium, despite its excellent strength- and stiffness-to-weight ratios, is used only sparingly due to its high cost.

Launchers are the ultimate in throwaway vehicles, with a life of only a few minutes or tens of minutes in most cases. While missions carrying astronauts and cosmonauts are mostly restricted to the low space station orbit a few hundred kilometres above Earth, robotic missions usually require an ascent to higher orbits and sometimes a push beyond Earth's gravity altogether. The latter requires on-board spacecraft propulsion, which raises the satellite's orbital energy after it departs from the launch vehicle. State-of-the-art apogee rocket propulsion systems are currently used, such as the UK-made Leros, which takes large communications satellites weighing several tonnes (or example, Airbus Defence and Space's EuroStar) from a transfer orbit into geostationary orbit.

Geostationary orbits at 36,000km altitude above the equator effectively allow satellites to remain stationary with respect to the area on the ground below, which is useful for persistent communications links or broadcasts to fixed regions. Reaching geostationary orbit or going beyond that, for example to Mars or to other bodies in the solar system, requires a huge quantity of rocket propellant. The practicalities of keeping a large and often delicate satellite with solar panels and antennas deployed mean that rocket thrust is limited. As a result, the manoeuvre can take several hours, sometimes days, over several orbits. For telecommunications satellites and exploration missions where there may be only one chance to rendezvous with a target, a high thrust may make the difference between mission feasibility and impossibility.

Apogee propulsion currently uses a bipropellant liquid rocket engine that delivers around 400N of thrust – about half the weight of an average adult on the ground. The rocket engine operates for long periods at the beginning of the mission, but possibly never again over the subsequent years of the operation. The European Mars Express mission, which started orbit around Mars in late 2003, required the main rocket engine to operate continuously for 33 minutes to slow the spacecraft enough to be captured by the planet's gravity. In 2018, the much larger ExoMars mission will place a European rover on to the surface of Mars to search for life and will require an orbit insertion burn of two-and-a-half hours to do the same job. ExoMars also faces stringent constraints on materials, partly because the great cost of placing it on the planet's surface means that every gramme saved is important. As such, lightweight titanium and aluminium alloys do most of the structural work. However, unlike launchers, structurally efficient composites are largely excluded due to their carbon content. ExoMars will be searching for carbon-based life, so any contamination from materials containing large amounts of carbon must be avoided.

Future communications satellites, large space science spacecraft (such as Mars Sample Return) and even astronaut missions to other planets will place increasing demands on the rocket propulsion system. Requirements for these future engines include:

- high thrust – greater than the current 400N and ideally approaching 1,100N
- improved performance, defined in terms of the exhaust velocity – think of this as a rocket engine's miles per gallon
- components sourced, where possible, from European suppliers – many space technologies are classified as dual use or have military applications and so are export controlled, especially if sourced from the USA. Although this can be managed, an all-European sourced engine can be sold to a wide range of international customers and will be more commercially attractive to develop
- the ability to use the next generation of non-toxic rocket propellants

All this will have to be done within mass and volume constraints imposed by a limited range of rockets that start the spacecraft on their lengthy journeys.

Space-suited materials

What do these space propulsion requirements demand of the materials used for the job? Principally, an ability to maintain mechanical strength and stiffness at extremes of temperature. The temperatures reached by many combusting rocket bi-propellants can approach 3,000°C, which immediately reduces the range of potential materials. Structurally, all polymer composites, most metals and many ceramics are ruled out at such high temperatures, leaving a few costly refractory metals such as iridium and tungsten, typically brittle ceramics such as alumina, and carbon- or graphite-based materials that have low tolerance to oxidation. Thermal shock considerations eliminate ceramics, leaving actively cooled metals or carbon composites as the material of choice for many short-lifetime launcher engines.

Spacecraft in orbit frequently use mono-methyl hydrazine fuel and nitrogen tetroxide oxidisers. If combusted in the right proportions with some in-built fuel cooling, the temperature of the rocket wall can be reduced to 1,400°C without sacrificing too much performance. Unfortunately, these propellants are highly toxic and so pose many health and safety challenges for research and use in operating missions, as well as generating a highly aggressive combustion product. On the face of it, this environment is similar to that in a gas turbine or jet engine where thermal barrier-coated nickel alloys operate routinely in this temperature range. Specific solutions for rocket propulsion have also been found, including coated niobium-based alloys developed in the USA and platinum alloys from Europe. While these have potential for the new rocket engines, they still have limitations.

New design, new materials

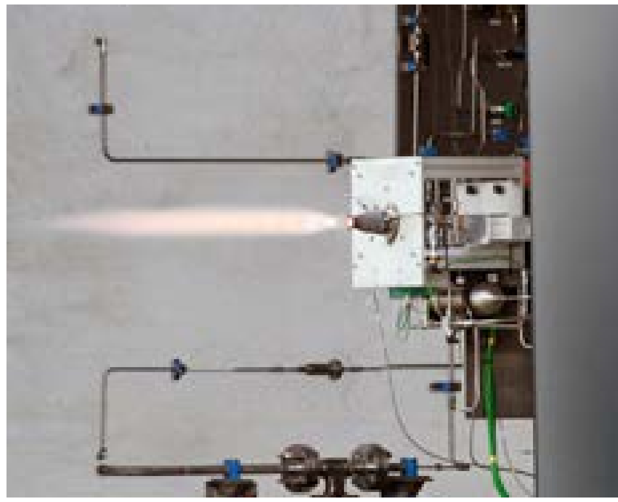
The particular goals of the HTAE, agreed between the ESA and its main industrial partner, Moog ISP Westcott, require both a new design and research into new materials. The engine is substantially larger than those currently in use, requiring almost double the mass to generate the required thrust of 1,100N. A new combustion chamber and injector design as well as new valves will be needed alongside new fluid dynamic models of the flow and combustion process to try to predict performance.

Critically, a challenge for materials scientists is to find a suitable material that can allow extended operation without oxidation at well above the current temperature – ideally up to 1,600°C for a period of several hours. This will allow a performance increase sufficient to extend the life of many commercial spacecraft. Material selection must also take account of the need to:

- thermally cycle between deep space temperatures (potentially as low as a few Kelvin) and the high operating temperatures
- be joined to conventional alloys such as Nimonic (nickel/chromium, for the nozzle) and Ti-6Al-4V (propellant injector)
- be available in Europe and at the right price to make an affordable engine, particularly for the commercial satellite market

Most recently, a series of short hot firings have been carried out on a test engine to verify the basic design and to establish whether combustion performance is adequate. The challenge now is to find and test a material that can withstand the required engine conditions for the several hours needed for future commercial and exploration spacecraft.

Left: **The European Space Agency's Mars Express.**
Below: **Test-firing the High Thrust Apogee (HTAE) rcket engine.**



The C103 niobium alloy (niobium/hafnium/titanium) and its proprietary, US export-controlled R512E (iron/chromium/silicon) oxidation protective coating, are known to be increasingly less effective as the temperature rises above 1,400°C. Although this alloy and coating form the basis of the current engine testing, new, higher temperature materials will be needed to allow HTAE to reach its potential performance and be commercially attractive. Options under consideration include:

Niobium alloy – either C103 from the USA, or a European equivalent. This material is strong and stiff enough at 1,600°C, but would need coating with more oxidation-resistant layer. One option based on tungsten and iridium is being explored by UK company Archer Technicoat Ltd.

Highly oxidation-resistant platinum and iridium-based alloys are attractive as no coating is needed, but these are extremely expensive, dense, difficult to join and suffer from poor mechanical properties at the required operating temperatures. An engine that visibly distorts during firing would not be acceptable.

A toughened monolithic ceramic based on silicon nitride is lightweight, stiff and strong, and has already flown on a smaller rocket engine for a Venus mission. However, scaling of this ceramic to the required size has yet to be demonstrated. The larger the ceramic part, the more likely that a strength-limiting critical flaw exists. It is also unclear whether the ceramic will oxidise, embrittle or even decompose at 1,600°C.

Carbon – silicon carbide-based composites have high temperature and oxidation resistance, low density and are more robust than pure ceramics, although joining these to metallic parts such as propellant injectors is a challenge and they are also porous to gases. Only three suppliers are known in Europe and the best and most affordable material has yet to be evaluated.

All of the potential materials evaluated so far have different advantages and drawbacks, but the first stage of the development, building and testing of a new bi-propellant spacecraft rocket engine has already proven successful with known materials. The carrot of being able to develop this prototype into a range of large and small engines that are attractive to the global space industry is a strong driver to continue in the exploration for new materials.

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