Aerospace engineering

# Iodine powers low-cost engines for satellites

**Igor Levchenko & Kateryna Bazaka**

Solid iodine transforms directly into gas when heated – a property that has been used to create cheap, compact engines that could make large networks of small satellites commercially viable. **See p.411**

Satellites organized in flexible networks known as constellations are more agile and resilient than are those operating alone. Manoeuvring satellites into such constellations requires inexpensive, reliable and efficient engines. Many networked satellites have electric propulsion thrusters, which generate thrust by using electrical energy to accelerate the ions of a propellant gas. However, the choice of gas presents a problem. Ionizing xenon requires a relatively small amount of energy, but xenon gas is expensive and needs to be compressed in high-pressure tanks to fit on board a satellite. Krypton is cheaper, but still requires a complex and heavy gas-storage and -supply system. On page 411, Rafalskyi *et al.*[1] report a successful demonstration of an iodine-ion thruster in space – offering a cheaper and simpler alternative to xenon or krypton.

Iodine differs from other propellants in that its solid form sublimates (transforms directly into a gas) when heated. This means that the solid iodine used in Rafalskyi and colleagues' system can be placed straight into the thruster (Fig. 1), removing the need for bulky high-pressure tanks and complex gas-feed systems. The iodine crystals can then simply be heated. Because only one watt of power is required to convert the crystals into gas in this thruster, solar energy can be used for this purpose, which is in line with NASA's Solar Electric Propulsion project (see go.nature.com/3pwyeyg).

The iodine gas used in the thruster described by Rafalskyi and co-workers is then fed into a chamber where it is bombarded with electrons to form a gas of ions and electrons known as a plasma. In any neutral gas, there are a small number of 'free' electrons that are not attached to any molecule or atom. These electrons are slow-moving, so when they collide with a gas molecule, they simply bounce off it, and the molecule's electric charge remains neutral. To convert their gas into plasma, the authors used a radio-frequency antenna. This generates an electromagnetic field in the chamber, which speeds the electrons up so that the collisions have sufficient force to knock an electron off the molecule. This produces two free electrons as well as the ion required to form the plasma.

A set of charged grids is then used to extract the iodine ions from the plasma and accelerate them in the direction of the thruster's exhaust[2]. A cathode at the exit produces electrons that are injected into the ion beam to neutralize it without slowing the ions down. This ejected beam of particles propels the satellite forwards. When the thruster is not in use, turning off the heater quickly cools the gas, converting it back into a solid. Gas trapped in the small orifice that connects the tank to the tube through which the gas is fed therefore forms a solid iodine plug, which prevents any further flow without the need for a control valve.

This system is not only remarkably simple, light and inexpensive, but also efficient. Before testing their engine in space, Rafalskyi *et al.* performed a direct comparison with xenon, which was supplied from an external gas tank. They found that the electric current in the beam of ions ejected from the plasma source for iodine was nearly 50% stronger than the current generated using xenon, even though the rate at which the gas flowed and the radio-frequency power were the same in both cases. This is because iodine has a lower ionization energy than xenon, as well as other properties that increase the rate at which iodine ionizes to form a plasma. And because it contains lower-energy electrons than does ionized xenon, the iodine plasma loses less energy through interactions between the plasma and the walls of its containment chamber.

Now that Rafalskyi and colleagues have

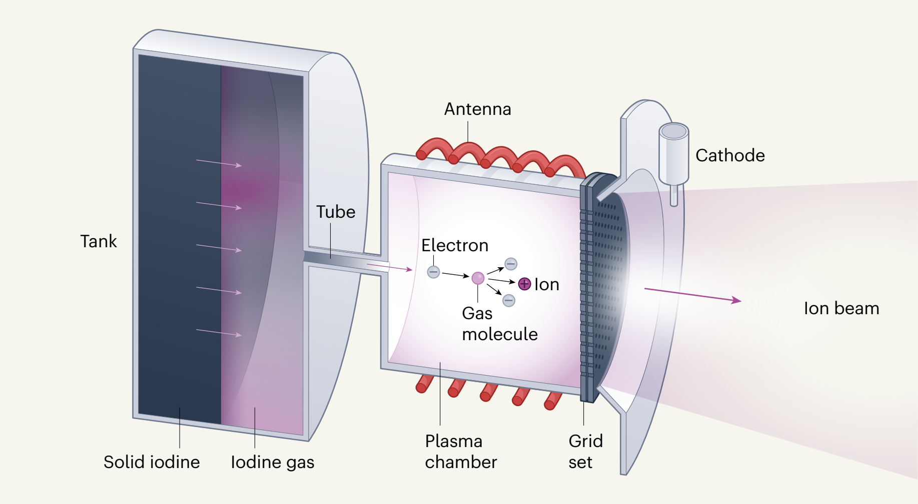

**Figure 1 | An iodine-based electric propulsion system.** Rafalskyi *et al.*[1] have designed an electric propulsion engine that heats solid iodine in a tank until it forms a gas. This gas is then fed into a chamber through a tube. A plasma is generated by ionizing the gas with electrons that are accelerated by an electromagnetic field, which is created by a radio-frequency antenna. When an incoming electron collides with a gas molecule, it produces two electrons and an iodine ion. These ions are then extracted and accelerated towards the exhaust using a set of charged grids. The ion beam is neutralized by electrons from a cathode after being ejected from the engine to create thrust. When the engine is turned off, any gas trapped in the orifice connecting the tank to the tube cools to form a solid iodine plug, which stops the gas flowing. (Adapted from Fig. 1 of ref. 1.)

demonstrated its viability in space, this simple and efficient system could be a game-changer for systems using small satellites[3]. The number of small satellites launched into space increased steadily from 39 in 2011 to 389 in 2019, before jumping to 1,202 in 2020 (see go.nature.com/3ggb3yc). There is therefore much research going on globally into the development of similar engines. Busek, a spacecraft-propulsion company in Natick, Massachusetts, has a line of thrusters with powers ranging from 100 W to 20 kW. All of these engines are capable of operating using xenon or iodine, depending on the requirements of the mission.

The drive to reduce the cost and increase the lifetime of space assets is now stronger than ever – a push designed to capitalize on the lower costs associated with reusable rockets that can launch multiple satellites simultaneously. For large satellite constellations, such as the 42,000-satellite Starlink system planned by aerospace-manufacturer SpaceX in Hawthorne, California, changing the propellant from xenon or krypton to iodine would lead to multi-million-dollar savings. Further savings could come from simplifying the propellant's storage and supply technology, which would also save money by decreasing the mass of the thruster.

Satellite constellations are not the only type of space mission that could benefit from this technology. For example, the research company Varda Space Industries in Torrance, California, is building the world's first commercial zero-gravity industrial park in space. The facility will manufacture products that are difficult to build on the surface of Earth owing to the effects of gravity, such as 3D-printed arteries and hearts, and certain pharmacological drugs. The feasibility of 3D printing tissue constructs in space was demonstrated in 2018 by the Moscow-based biotechnology company 3D Bioprinting Solutions, working at the International Space Station[4]. Cheap iodine-based thrusters might reduce the cost of in-orbit manufacturing and help the factory to manoeuvre the product out of orbit and back to Earth.

However, the use of iodine thrusters is not without its challenges. Iodine is highly corrosive, presenting a potential danger to electronics and other satellite subsystems – Rafalskyi and co-workers had to use ceramics and polymers to protect the metal components of their system. They also needed to strengthen the solid iodine by embedding the crystals in a porous aluminium oxide matrix, which added to the weight and volume of the system. Finally, solid iodine requires a relatively long time (around 10 minutes) to be heated to sublimation temperature, which might not make the thruster responsive enough to avoid collisions while in orbit. These challenges need to be addressed before this technology can be incorporated safely into working satellites. Nevertheless, now that it has been validated in space, the system developed by Rafalskyi and colleagues is an impressive contribution to the rapidly changing landscape of electric propulsion technologies.

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**The authors declare no competing interests.**

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Immunology

# A neurotransmitter limits antitumour responses

## Daniel L. Kaufman

Analysis of immune cells shows that, unexpectedly, B cells secrete GABA, a molecule best known as a neurotransmitter. B-cell-derived GABA can modulate immune responses against tumours, raising the prospect of new therapies. **See p.471**

Efforts to better understand how immune cells function hold the promise of providing information that might lead to improved clinical treatments. On page 471, Zhang *et al.*[1] present results that point the way to the development of new approaches to enhance anticancer therapies.

The authors investigated changes in metabolite molecules that occurred in mouse lymph nodes – a tissue rich in immune cells – after the animals had been exposed to a foreign protein through immunization. Using state-of-the-art technologies, Zhang and colleagues compared the metabolites in lymph nodes near the immunization site with those in lymph nodes on the opposite side of the animal's body. They found that levels of around 200 metabolites were significantly different in lymph nodes near the immunization site, particularly metabolites associated with activation of a system called the glutamate pathway.

Zhang and colleagues repeated this experiment using mice deficient in immune cells called B cells and T cells, and, by comparing these animals with those not lacking immune cells, found that the predominant metabolic changes after immunization occurred in B cells (which are antibody-producing cells). Surprisingly, the major metabolite upregulated in response to immunization was γ-aminobutyric acid (GABA), which was not previously known to be made by B cells. GABA acts as a neurotransmitter in the brain, with key roles in neurodevelopment. It is linked to certain neurological disorders[2], and is produced through the glutamate pathway.

To explore GABA synthesis in immune cells, the authors investigated B cells and T cells from mice and humans. They activated the cells *in vitro* using antibodies that bound to a key defence receptor on the cells. They then exposed the cells to a pulse of an amino acid called glutamine that was labelled with an isotope, and traced its metabolism. As expected, the glutamine was converted into glutamate, a molecule that was then made into GABA by the enzyme glutamic acid decarboxylase (two versions of this enzyme are dubbed GAD65 and GAD67). Levels of labelled GABA in B cells, but not in T cells, increased following activation of the cell, and B cells secreted labelled GABA. The authors report that T cells do not express GAD65 or GAD67, whereas B cells express GAD67. Together, these results demonstrate that immune stimulation induces mouse and human B cells to synthesize and secrete GABA (Fig. 1).

Previous studies investigating autoimmunity found that T cells express type A GABA ($GABA_A$) receptors. Activation of these receptors through GABA binding opens a chloride channel in the receptor. This opening leads to the inhibition of inflammatory types of T cell called helper CD4 T cells and killer CD8 T cells[3–6], and both T-cell types are key contributors to tissue damage in autoimmune disease. Activation of $GABA_A$ receptors also boosts the numbers of a type of T cell called a regulatory T cell, which dampens