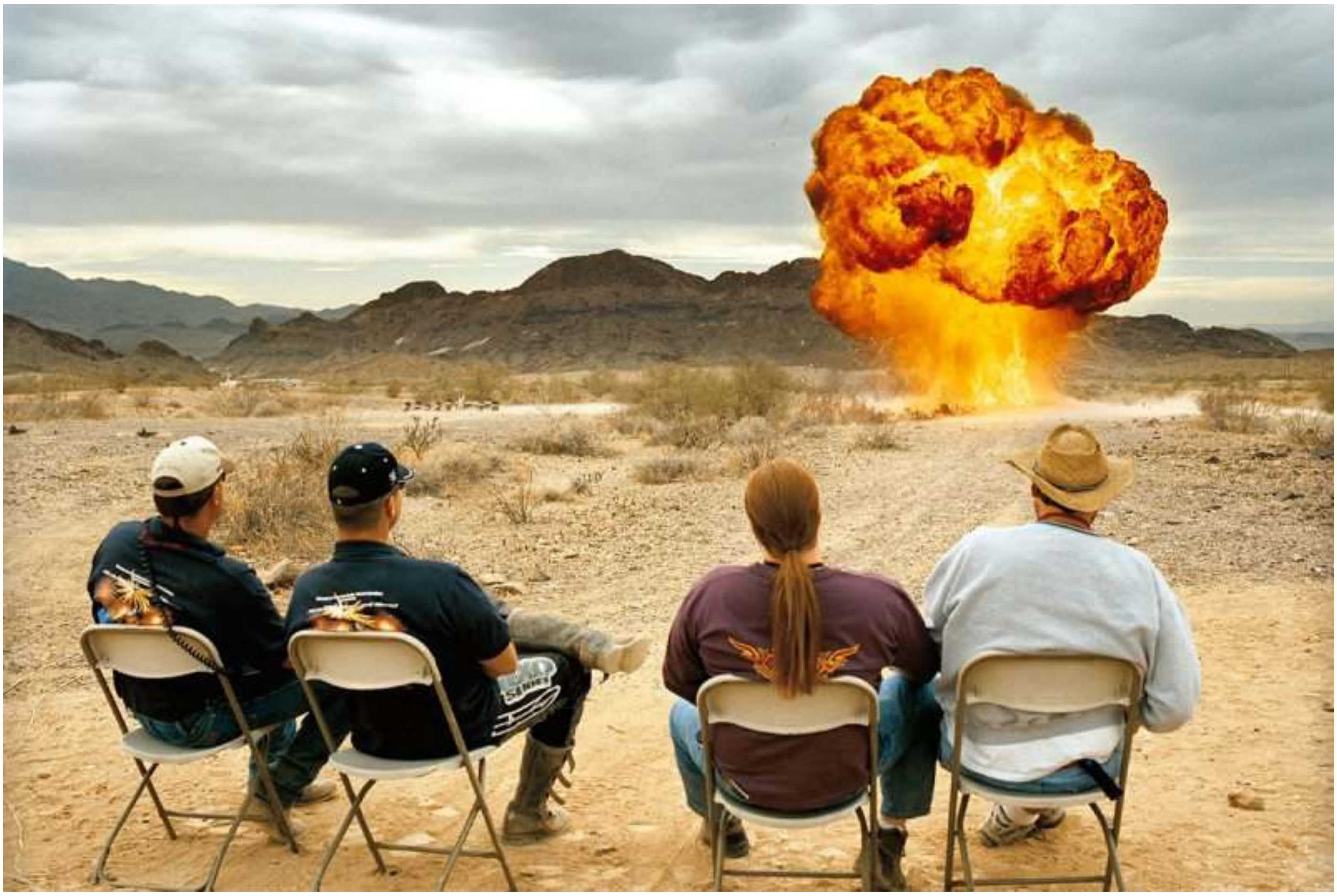
FEATURE 26 July 2017

Bigger bang theory: teach atoms new tricks to beef up explosives

Mastering materials that have never been made before could deliver blasts big enough to shoot rockets to Mars



Simon Roberts/Gallery Stock

By **David Hambling**

BLEARY-EYED, you acknowledge the coffee machine announcing the arrival of the morning brew. You apologise to the fridge door as you fumble for the milk. Narrowly avoiding the salt, you locate the sugar on the counter. Energy required. One spoonful or two?

BOOM! The whole lot goes up.

It’s easy to forget that sugar can be an explosive. In fact, it’s four times more powerful weight for weight than TNT. Forgetfulness here can have tragic consequences. In 2008, finely powdered sugar ignited at a refinery in Savannah, Georgia, causing a blast that claimed 14 lives.

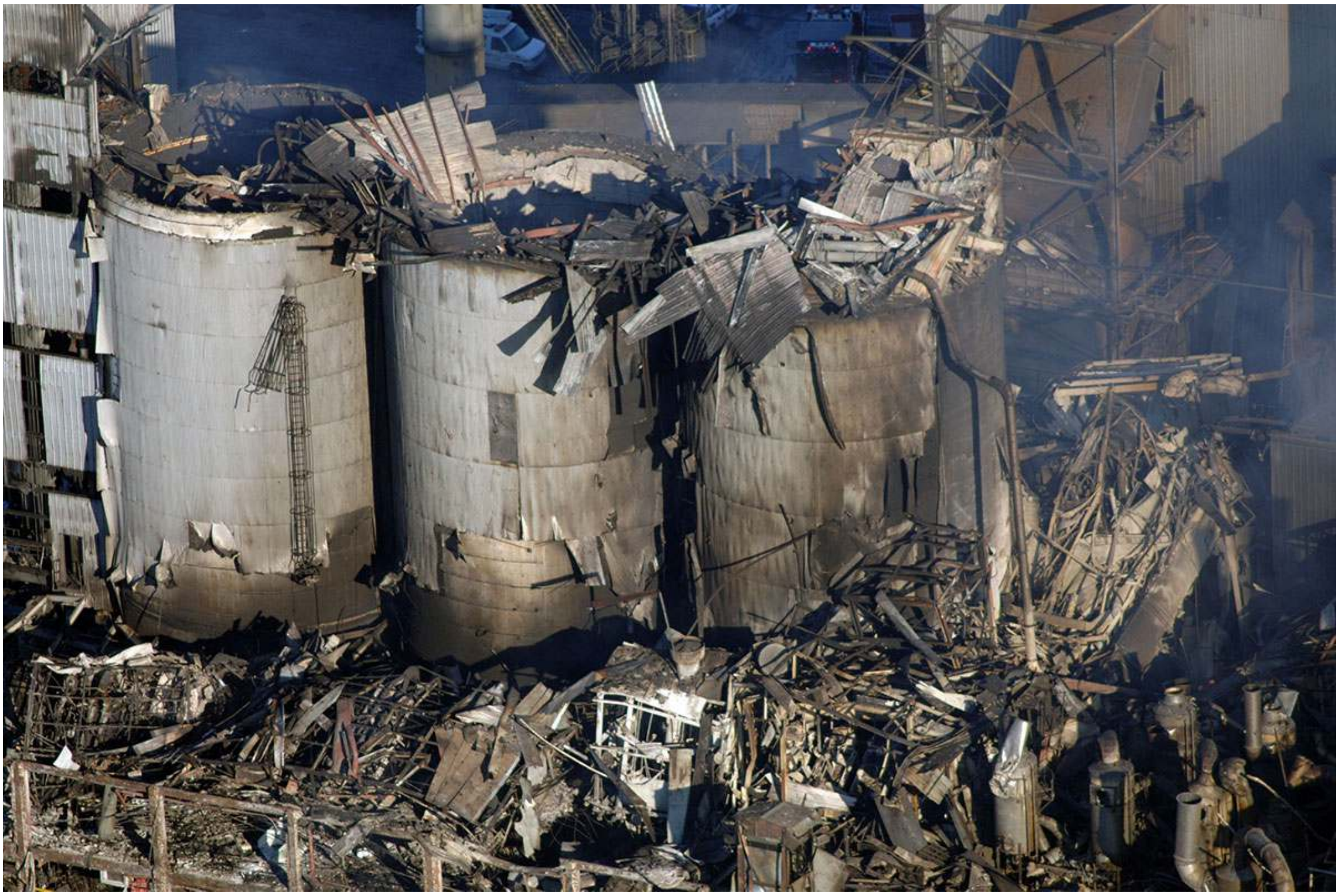
Fortunately, under normal circumstances it takes a lot to make sugar explode. Not so nitroglycerin, the explosive favoured by early safe-crackers: it is notoriously unstable, going sky-high at the slightest shock. An ideal explosive – one with power, but that can also be easily controlled – lies somewhere in the middle. It would store a lot of energy in its chemical bonds, releasing it easily, but not too easily. Therein lies a problem. With everyone from miners to the military to missions to Mars seeking more bang for their buck, conventional chemistry has more or less delivered the best explosives it can.

So step forward unconventional chemistry. A few labs across the world are probing a new generation of “disruptive energetic materials” that promise more explosive power than ever before. Some of them might even leave sugar in the dust – and allow us to reach for the stars.

Finding better explosives has always tended to be a rather haphazard process. No one knows who first discovered the explosive properties of potassium nitrate aka saltpetre, the active ingredient of gunpowder. It was being used in China around a millennium ago, but it wasn’t until the late 17th century that some of the first experiments dedicated to finding out how it worked were conducted at London’s fledgling Royal Society. Only after Alfred Nobel’s nitroglycerin factory blew up in 1864, killing his younger brother, did he discover that by combining nitroglycerin with ground rock you could make a drier, slightly less powerful version that was much safer to handle. Dynamite was soon put to work blasting mines, tunnels, railway cuttings and canals, making Nobel a very rich man.

Construction still remains a prime customer for explosives, as does the military. The most destructive explosions, of course, come from ripping apart the atomic nucleus, but nuclear bombs are made not to be used. The difficulty of controlling and containing nuclear reactions, and the hazardous waste they produce, mean they are unlikely ever to find use as peaceable explosives. Military interest in better chemical explosives is led by a desire for more potent versions of conventional weaponry like MOAB, the “mother of all bombs” containing over 8 tonnes of explosive, that the US dropped on jihadists in Afghanistan earlier this year, or to make small drones equipped with mini-bombs as effective as full-sized munitions.

For the better part of a century, however, those seeking more explosive power have had another,



The 2008 Savannah refinery blast was lethal proof of sugar's explosive power
MORTON/AP/REX/Shutterstock

loftier ambition: space exploration. Escaping Earth's gravity requires a lot of thrust. In 1903, the Russian scientist Konstantin Tsiolkovsky derived the rocket equations that have ever since governed our efforts to do that. The essence of rocket science consists of ejecting hot, explosively expanding gas downwards, generating a reactive force that propels the rocket upwards.

There's a big sting in the rocket tail, however. The more thrust you want to generate, the more fuel you need; but the more fuel you carry, the more thrust you need to get airborne. This catch-22 means gunpowder cannot generate enough impulse to get into space, however much you use. State-of-the-art rockets use a mix of liquid hydrogen and liquid oxygen, which has a much higher energy density. Even so, a mere 2 per cent of the launch weight is payload and more than 80 per cent is propellant, and a rocket can still only reach orbit by ditching weight as it goes. That's why we need multistage rockets that shed empty fuel tanks as they climb.

With better fuels you might get 10 or 15 times the payload for the same size of rocket, says consultant Ian Johnston of Rocket Workshops in Droitwich, UK. That would make satellite launches far more economical, opening up new possibilities for bulky projects like crewed Mars exploration and lunar bases. "With better fuel, you could have single-stage-to-orbit spacecraft," says Johnston. " 'Game changer' is too small an expression for it."

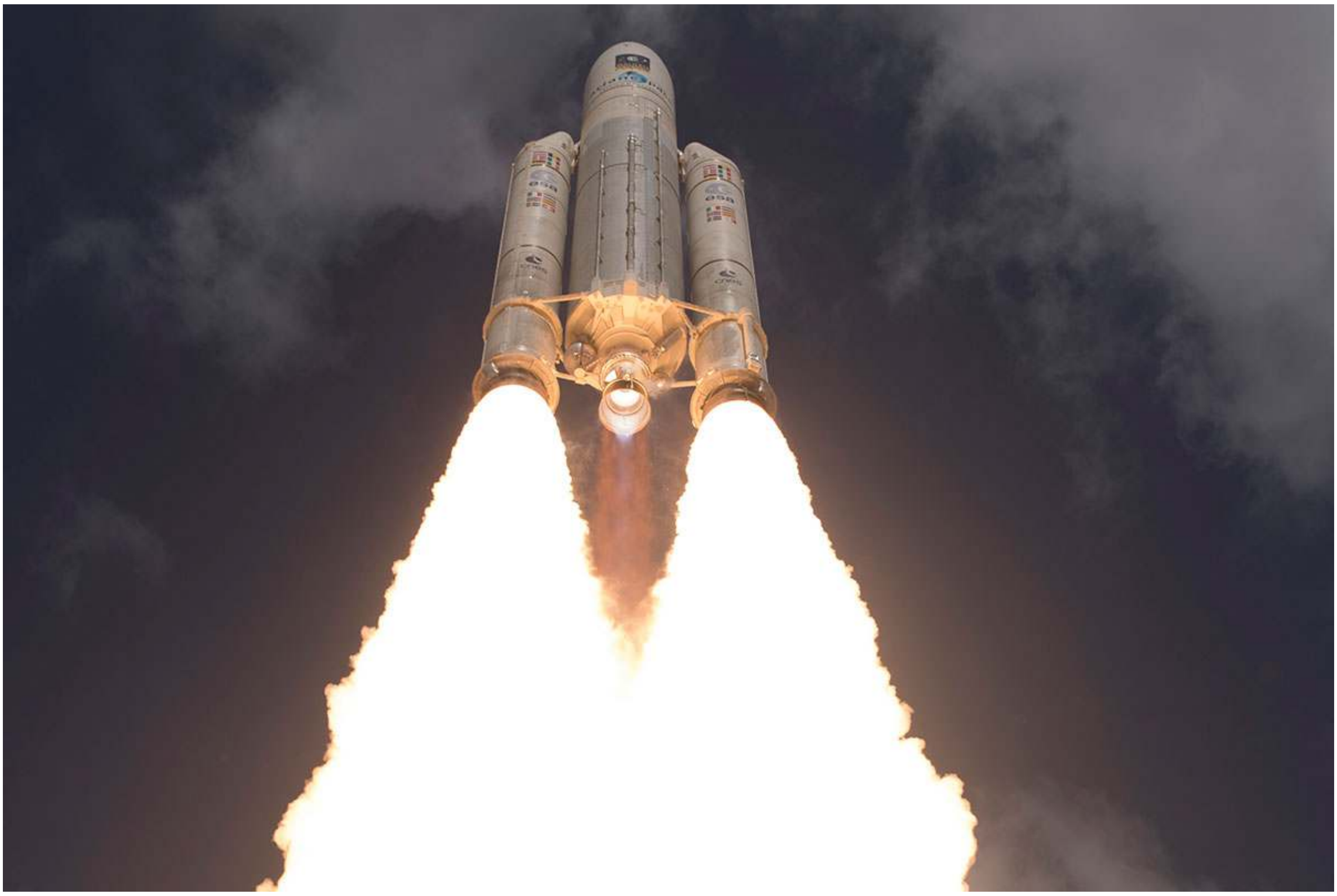
Diamonds and popcorn

A good way to change a game is to change its rules. One line of research to do just that builds on a curiosity that was exercising the Royal Society back in the 1660s just when gunpowder was: Prince Rupert's drops. These tadpole-shaped trinkets are formed by molten glass cooling rapidly, and are named after Prince Rupert of the Rhine, a cousin of King Charles II who first brought them to

England. The way the drops form leaves them under tremendous internal strain. A hammer will bounce off the drop's body and not break it, but if you snap the tail the strain is suddenly released, sending a wave through the drop, shattering it into powder.

This explosivity is based on the release of not chemical energy, but mechanical strain. At the US Army Research Laboratory (ARL) in Maryland, Jennifer Ciezak-Jenkins and her colleagues have been experimenting with the same principle using nanoscopic diamonds. Diamond forms only at high temperatures and pressures, such as those found deep in Earth's mantle, and is a "metastable" form of carbon. It is stable in ambient conditions, only crumbling over cosmic timescales back to graphite.

The energy release comes more easily if the diamonds are very small. Medical researchers have already made nanodiamonds cling to tumours and then irradiated them with ultraviolet light, causing them to expand rapidly, killing the cancer cells.



Rockets' payloads are tiny relative to the sheer mass of fuel needed to reach orbit
Stephane Corvaja/ESA

The ARL experiments keep nanodiamonds under huge strain by surrounding them with a cage of hexagonally bound carbon rather like a buckyball. Burst the ball and the strain is released explosively. "The nanodiamonds pop like popcorn," says Ciezak-Jenkins. Simulations suggest that this could be done by smashing the nanodiamonds together, producing a burst of high-speed, high-temperature carbon particles. These would burn rapidly in atmospheric oxygen, making them ideal candidates for a rocket propellant.

In practice, it isn't that easy. Getting the particles to accelerate is tricky, and high-power lasers are needed to trigger an explosive reaction. We'd need an impractically huge laser if it is to work on a large scale.

Munawar Chaudhri, a materials scientist at the University of Cambridge who has worked extensively with Prince Rupert's drops, is sceptical whether using materials under strain will add much to their explosive capabilities. He points out that the strain energy stored in Prince Rupert's drops is only about a thousandth of the chemical energy in the same weight of explosive, and something similar is likely to be true of nanodiamonds, too. "I do not think that releasing a large amount of stored energy during the collision of nanodiamonds is feasible," says Chaudhri.

If the nanodiamonds fail to make waves, it might be back to chemistry – just not as we know it. Almost all industrial explosives, from gunpowder through dynamite to the ammonium nitrate-based explosives that dominate the market today, have a hefty pinch of nitrogen in them. In molecular nitrogen, two atoms are connected by a triple bond that releases a load of energy when broken. Polynitrogen takes that idea to its logical extreme. Take a load of nitrogen atoms, connect them together in one mega-molecule, then break their bonds and… boom! "Polynitrogens are excellent candidates for disruptive energetic materials," says chemist Karl Christe of the University of Southern California at Los Angeles. Theory suggests, in fact, that they should be five times as powerful as TNT.

Flash in the pan

The practical challenges start with the fact that polynitrogens don't obviously exist. Theory suggests they form like diamonds under extreme conditions of temperature or pressure, but nature seems not to have tried this experiment, at least not in our immediate neighbourhood. Gaseous nitrogen becomes solid at a pressure of about 60,000 atmospheres; models suggest it takes almost two million atmospheres to make polynitrogen. And there's no guarantee that polynitrogen will be a metastable state like diamond once the pressure is reduced again.

Christe led a research campaign at the US Defense Advanced Research Projects Agency in the 1990s to make polynitrogen compounds, and successfully isolated pentanitrogen, an ion with five nitrogen atoms, in 2002. But they could never synthesise it in large quantities – and pure, electrically neutral polynitrogen molecules will be even harder. "It is a long shot because of probable low thermal stability, high sensitivity and great difficulty of preparation," says Christe.

Earlier this year, however, researchers at the Nanjing University of Science and Technology in China reported developing large quantities of ring-shaped, negatively charged pentanitrogen ions within a larger stable molecule – a first step towards useful polynitrogen chemistry. Meanwhile, Ciezak-Jenkins and her colleagues have gone for the direct approach. Following work on the polymerisation of nitrogen at the Max Planck Institute for Chemistry in Mainz, Germany, they have developed a technique for making neutral polynitrogen in a diamond anvil cell, which produces huge pressures. The result is a blue liquid with a density three times that of water and about 50 times as dense as liquid hydrogen, allowing more energy to be packed into a small volume – in theory.

In practice, the liquid is unstable at room temperature and reacts explosively on contact with air, for reasons the researchers don't yet understand. Ciezak-Jenkins jokes that she is sitting on the "world stockpile" of polynitrogen – a total of 3 grams stored at a cryogenic 77 kelvin. At least 10 grams will be needed to test its explosive power, and that test will need to be repeated several times. There's still a good chance it might just be a modern nitroglycerin – powerful, but too prone to blowing up in your face to be useful.

"Metallic hydrogen could store 50 times as much energy per gram

as TNT, but can we make enough of it?”

Perhaps polynitrogen is not the final word anyway. As long ago as 1935, hydrogen was predicted to have a metallic phase that, like diamond and polynitrogen, forms only under tremendous temperatures and pressures. It might occur naturally at the heart of gas giants like Jupiter. It might even be metastable, remaining metallic once formed, even at room temperature and pressure. Above all, it is predicted to store a huge amount of energy – about 50 times as much per gram as TNT.

That might make it even more unruly than polynitrogen. Earlier this year, a team led by Isaac Silvera at Harvard University apparently produced a speck of the stuff using a powerful diamond anvil cell to compress solid hydrogen. Unfortunately, the cell failed just after they had made it, and the tiny sample, 15 micrometres across and a few micrometres thick, vanished.

Other researchers have been sceptical about the claim, and will continue to be until the team can repeat the experiment. Until we can measure the material’s properties, we don’t even know if it is solid or liquid, let alone whether it is metastable and able to release its stored energy rapidly. “You may be able to form it at 5 million atmospheres,” says Eugene Gregoryanz, a condensed matter physicist at the University of Edinburgh, UK, “but we just don’t know whether it will be unstable or metastable at one atmosphere.” He also doubts whether it can be produced in the quantities necessary to make it useful. “That metallic hydrogen exists is beyond reasonable doubt,” he says. “But it’s a bit far-fetched as rocket fuel.”

Ciezak-Jenkins still thinks it is worth a punt. She says her team is carrying out experiments in collaboration with several groups, believing metallic hydrogen might well trump polynitrogen. Silvera points out that if metallic hydrogen turns out to be metastable, you might not need large quantities initially, either: it should be possible to grow a small sample by allowing a gas of hydrogen atoms to condense on its surface. “If a sample exists at room temperature, you have a seed of metallic hydrogen, and you just spray atomic hydrogen gas on it,” says Silvera.

There’s another reason to favour the new materials as rocket fuels: they are potentially cleaner. Common rocket fuels such as ammonium perchlorate produce toxic and corrosive hydrochloric acid as a by-product, so the area around a launch pad has to be decontaminated after every launch. Nanodiamonds burn to carbon dioxide, which although a greenhouse gas is non-toxic; polynitrogen turns into nitrogen gas and metallic hydrogen produces only steam.

So Mars, here we come? Perhaps. With conventional chemistry at a dead end, if we want to aim high with space exploration then unconventional chemistry seems like our best bet. Assuming, of course, people aren’t too busy on Earth blowing each other up with the new explosives – or that the sugar doesn’t get us, one way or another.

This article appeared in print under the headline “Boom or bust”

David Hambling is a freelance writer based in London

Magazine issue 3136, published 29 July 2017