Metal: The fuel of the future

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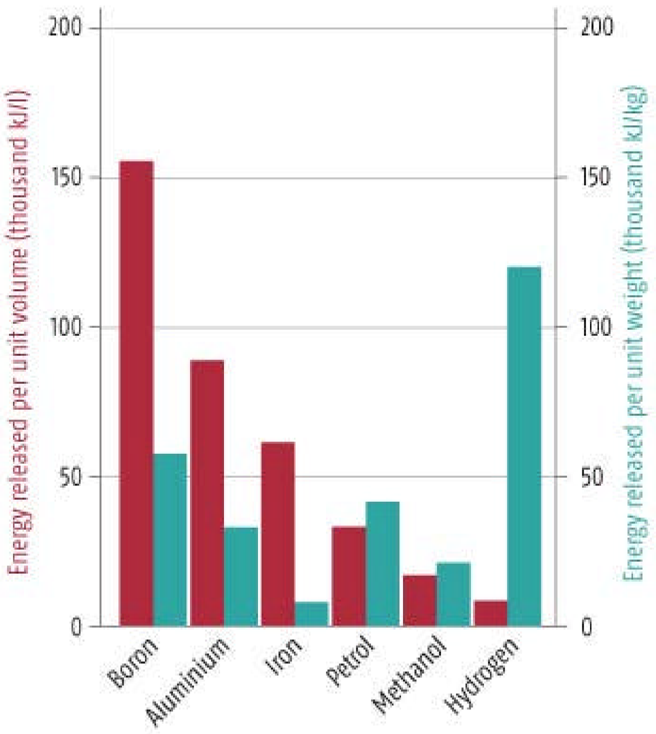
FUELS OF THE FUTURE

How metals and conventional fuels compare

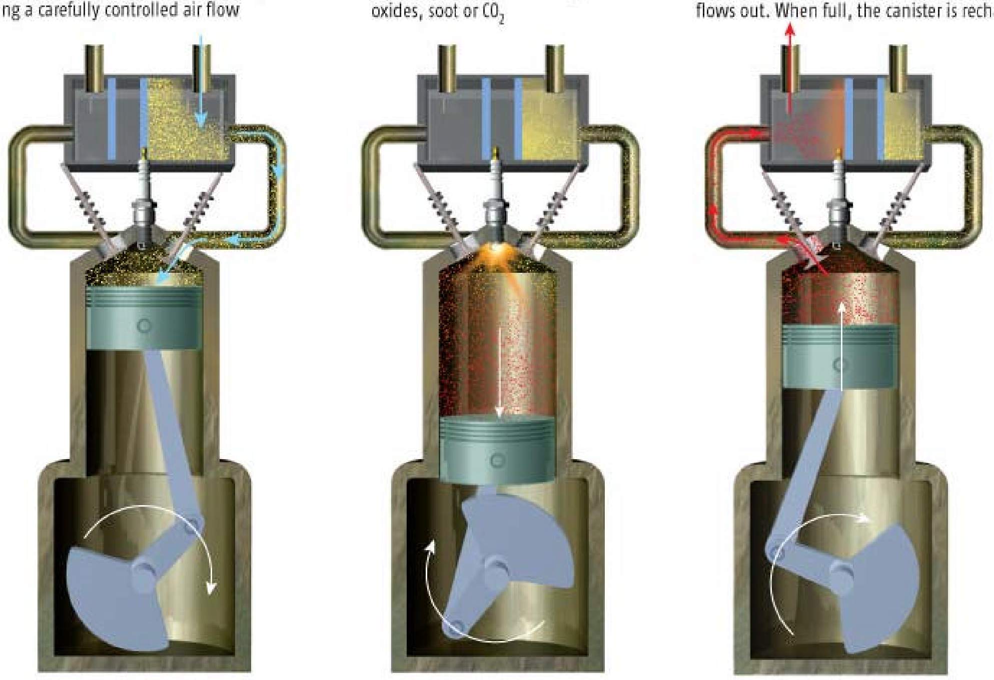


If smog-choked streets test our love for petrol and diesel engines, then rocketing fuel prices and global warming could end that relationship once and for all. But before you start saving for the fuel-cell-powered electric car that industry experts keep promising, there's something you should know. The car of the future will run on metal.

So reckons Dave Beach, a researcher at Oak Ridge National Laboratory in Tennessee, who has come up with a plan to transform the way we fuel our engines. Chunks of metal such as iron, aluminium or boron are the thing, he believes. Turn them into powder with grains just nanometres across and the stuff becomes highly reactive. Ignite it, and it releases copious quantities of energy. With a modified engine and a tankful of metal, Beach calculates that an average saloon car could travel three times as far as the equivalent petrol-powered vehicle. Better still, because of the way that this metal nano-fuel burns, it is almost completely non-polluting. That means no carbon dioxide, no dust, no soot and no nitrogen oxides. What's more, this fuel is fully rechargeable: treat your spent nanoparticles with a little hydrogen and the stuff can be burnt again and again. It could spell the start of a new iron age, and not just for cars. All kinds of engines, from domestic heating units to the turbines in power stations, could be adapted to burn metal.

Topping up your tank with what are essentially iron filings might sound bizarre, but vehicles can run on all sorts of materials, from methane to coal dust or gunpowder. So why not metal too? After all, burning a heap of powdered iron releases almost twice as much energy as the same volume of petrol. And replacing iron with boron gives you five times as much (see Graph).

Rockets already use metal powder as fuel. A dash of aluminium gives extra oomph to the space shuttle's solid rocket boosters, for instance, and metal powder is used in rocket-powered torpedoes.



RUNNING ON IRON

With a few modifications an internal combustion engine could run on metal fuel. Unlike a petrol or diesel engine, this design will produce almost no pollutants

In the removable fuel canister, a movable membrane separates fresh and burnt fuel. Metal fuel is injected into the engine cylinder using a carefully controlled air flow

Metal powder is ignited by a spark and burns at low temperatures. This creates almost no nitrogen oxides, soot or CO_2

Exhaust gas carries oxidised metal particles into the fuel canister. An electromagnetic strip collects the particles, and the exhaust gas flows out. When full, the canister is recharged

However, putting metal inside a rocket engine is a very different proposition from using it in a car engine. When granules of metals such as iron and aluminium come into contact with air, they become coated with a layer of oxide that must be removed before the metal can ignite. To kick off combustion in most metals, you need a heat source with a temperature of at least 2000 °C, which is high enough to vaporise the oxide layer and expose the bare, reactive metal beneath. That might be fine for a rocket, but it's not so simple for a car engine. Another problem is that once the vaporised metal oxide starts to cool, it solidifies and forms ash. While high temperatures and clouds of ash present no problems in a one-shot rocket, they create a serious mess for anyone trying to burn metal powder in an internal combustion engine.

Solomon Labinov, also a researcher at Oak Ridge, is all too familiar with this problem. In the early 1980s, while he was the director of an engineering institute in Kiev, Ukraine, he and his team tried burning micrometre-sized iron particles in an internal combustion engine. They modified the engine to work at high temperatures, but found that the oxide ash deposited on the pistons, cylinder walls and valves, clogging up the engine. They couldn't find a way round the problem and gave up.

Labinov subsequently moved to the US, and went to work at Oak Ridge. In 2003 he suggested to Beach and theorist Bobby Sumpter that they take a fresh look at the problem, this time using nanoscale particles.

In experiments they found that iron nanoparticles measuring about 50 nanometres across ignited far more easily than the larger granules of iron that Labinov had worked with: heating them to around 250 °C, or even just a spark, could do the job.

And the more the researchers looked, the more they realised that the nanoparticles behaved in a very different way to their less finely divided cousins.

Nanoparticles burn much more easily because their surface area to volume ratio is huge. Iron reacts very readily with oxygen, so if a lot of it is exposed to air at the same time, oxidation can generate enough heat to ignite the metal spontaneously. To prevent this, nanoparticles are usually given a protective oxide coating during manufacturing. But even with an oxide layer, the huge surface area of these nanoparticles means that with just a little heat, it is easy for oxygen molecules to diffuse through and trigger combustion.

One consequence of this is that once the nanoparticles are ignited by a spark, say, they burn rapidly and the combustion temperature peaks at around 800 °C - hot enough to do useful work but not so high as to melt an alloy engine. And crucially, unlike the micrometre-sized particles, nanoparticles don't burn hot enough to vaporise or even melt. They just oxidise, leaving a heap of oxide nanoparticles. And that means no sticking to the walls of the cylinder, and no clogged engine.

The tidy heap of iron oxide left over from the combustion process gave Beach an idea: he realised that it would be easy to convert the iron oxide back into usable fuel. He heated the burnt fuel to 425 °C in a flow of hydrogen. The iron oxide particles were reduced to iron, and the hydrogen combined with oxygen to form water. Now the fuel was ready to burn again.

There was one more problem to solve if the particles were to have any real potential as fuel. Individually, nanoparticles burn in a flash, releasing all their heat in a millisecond or so. But to make the metal fuel useful in a wide range of engines, the rate of heat production should not be so fast that an engine cannot deal efficiently with the heat produced. In internal combustion engines, for example, each burst of combustion can last anywhere between 5 and 20 milliseconds. If heat is released any faster, the fuel is used below its maximum efficiency.

So the team attempted to limit how quickly their fuel burnt by pressing the nanoparticles into larger clusters. The idea was to limit both how fast oxygen could diffuse into the nanoparticles and how fast heat could flow out of them, so reducing the rate of heat release.

The plan worked. Beach and his colleagues found they could create nanoparticle clusters weighing anything from 1 to 200 milligrams each, and by adjusting their size, shape and density they could control the burn rate. While single particles would burn in just milliseconds, the largest clusters could take from 500 milliseconds to two seconds.

With the first stage of the research complete, the team now plans to design an engine that can run on the fuel. It would be relatively easy, Beach believes, to convert external combustion engines such as the gas turbines that power jet aircraft and vehicles such as tanks, or even those used to generate electricity in power stations. These engines might operate on metal fuel without too much difficulty, he suspects, though they would certainly need modifications to the fuel-delivery systems, and he would need to find a way to collect the spent fuel.

Another option is to use the fuel to power a Stirling engine, an efficient external combustion engine in which a fluid or gas in a cylinder is alternately cooled and heated to move a piston (*New Scientist*, 11 December 1999, p 30). Stirling engines are used in domestic combined heat and power units, for example, and for cooling satellites.

When it comes to cars, a Stirling engine is a possibility: NASA and a number of car manufacturers, including Ford, have already experimented with Stirling engines designed to power vehicles. But Beach also hopes it will be possible to use his metal fuel in an internal combustion engine. A modified diesel engine might be able to burn nanoparticle powder as a fuel, just as a conventional diesel engine uses a mist of diesel fuel (see Diagram).

Beach suggests that metal powder or clusters could be injected into the engine cylinders from a storage tank, possibly using a jet of air, which could also supply the oxygen for combustion. A spark plug would trigger ignition and burnt fuel would be carried from the cylinder by the exhaust gases.

Beach's team must also find a way to collect that spent fuel. One possibility is to store it in the fuel canister, with a movable membrane dividing the canister into two sections, one for fresh and one for spent fuel. The burnt fuel might be collected using a filter or, since iron oxide powder is ferromagnetic, an electromagnet. When a driver needed a top-up, the entire canister could be unclipped and exchanged for a fresh one at a filling station, and the used fuel would then be recharged.

“Scrapyards full of old cars could become fuel for the vehicles of tomorrow”

The result would be an engine similar to a conventional one, but which emits no carbon dioxide, harmful particulates or even nitrogen oxides. These compounds usually form in combustion at high temperatures, but Beach has shown that he can lower temperatures to about 525 °C by varying the size of the clusters. However, plenty of work is still needed to strike the right balance between temperature, speed of combustion and engine efficiency.

A vehicle running on metal fuel should please both drivers and environmental campaigners. Beach calculates that a fuel tank holding 33 litres of his iron fuel will power a car engine for the same distance as a 50-litre tank of conventional petrol or diesel.

Heavy load

There are still major drawbacks, however, the most significant of which is weight, according to Nathan Glasgow, a consultant at the Rocky Mountain Institute, a think tank in Snowmass, Colorado. Although iron is a compact fuel compared to hydrogen, it is also extremely heavy, and even though its high energy content allows you to almost halve the size of a typical 50-litre fuel tank and still get the same energy out, a tank of fuel would weigh about 100 kilograms - more than twice as heavy as the petrol it replaces. And because the spent fuel is kept on board, unlike the polluting by-products of conventional fuel, this weight won't decrease as you drive - you must always lug the full load around. The weight of fuel will also add to the cost of shipping it back and forth to recycling facilities.

David Keith, a physicist at the University of Calgary in Alberta, Canada, is satisfied that the technology itself is sound, but believes there are fundamental difficulties with iron as a fuel. Even if everything works perfectly, he says, the fuel is simply too heavy to be really useful.

So for the ultimate in clean, green driving, perhaps hydrogen really is the answer. After all, it packs over 12 times as much energy per kilogram as iron.

Beach is unconvinced. Of course hydrogen is important, he says, but you don't want to be filling your tank with it. "What we're saying is that metal fuel is a more convenient, safer, and more practical energy carrier than hydrogen." And it's true that engineers are still struggling to find ways to store hydrogen at densities high enough to make it a practical alternative to petrol. In contrast, metal fuel is stable at room temperature, so it is easy to store and transport. "We've got a solid at ambient pressure. So moving it around on freight cars or storing it for long periods of time isn't a problem," says Beach.

Besides, there's a potentially more serious problem with hydrogen-powered vehicles that the use of metal would sidestep. The water produced by hydrogen fuel cells is usually just allowed to escape into the atmosphere. Some climate scientists are concerned that the huge amounts of water vapour released by millions of hydrogen-powered cars and trucks would accelerate global warming.

Recycling metal oxide fuel with hydrogen also produces water vapour, but it would be generated at large recycling units rather than by vehicles out on the road. This means that it would be simple to collect the water and recycle it - perhaps even using electrolysis to convert it back into hydrogen.

It might even be possible to dispense with hydrogen altogether. If carbon sequestration becomes viable, carbon monoxide could be used to recycle spent metal fuel, creating carbon dioxide. Carbon monoxide is a common by-product of coal gasification - one of the technologies likely to become more important as the coal industry attempts to reduce its contribution to global warming. Use this carbon monoxide directly for recycling fuel and the industry would get more useful energy out of its coal than before.

Beach has even got some solutions to the weight issue. Use aluminium nanoparticles rather than iron, for example, and you get about four times as much energy per kilogram. With boron you'd get almost six times as much. Of course, since these metals cost more than iron, the fuel would be more expensive in the first place. Aluminium, for instance, costs about 15 times as much as iron.

Clearly it is very early days for metal power. The Oak Ridge researchers are still applying for grants to build a prototype engine, and Beach has yet to carry out a full analysis to find out whether his fuel could be cost-effective. The team also plans a series of experiments to optimise the size of its nanoparticles, as well as to investigate the best way to package, inject and collect the stuff in a real engine. And even if their work succeeds, who is going to buy the first metal-powered car when there's nowhere to fuel it, and who is going to build a network of fuel stations until there are cars to fill?

At the very least, metal-burning engines are another entry in the list of alternatives to oil. And whatever happens, Beach's remarkable idea does raise one interesting possibility. In the past, energy magnates have earned billions from coal, oil and gas fields. In the future, they could grow rich from scrapyards full of yesterday's cars, by transforming them into fuel for the vehicles of tomorrow.

Kurt Kleiner is a science writer based in Toronto.

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