A STAR IS BORN

by Lev Grossman

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THE MACHINE lives in a white building in an Orange County office park so uninteresting-looking that not even the person who's supposed to be taking me there can find it. We literally drive right past it and have to double back.

Though there are a few clues if you look closely. A towering silo of liquid nitrogen out back. A shed that turns out to be full of giant flywheels-for storing energy. The machine, which is the size of a small house, draws so much juice that when they turn it on they have to disconnect from the public grid and run off their own power to keep from shorting out the whole county. If you had X-ray vision you might notice that all the iron rebar in the building's foundations has been pulled out and replaced with stainless- steel rebar, because iron is too magnetic.

The machine is a prototype fusion reactor. It is the sole product of a small, secretive company called Tri Alpha Energy, and when it or one like it is up and running, it'will transform the world as completely as any technology in the past century. This will happen sooner than you think.

It's not the world's only fusion reactor. There are several dozen scattered around the globe in various stages of completion. Most of them are being built by universities and large corporations and national governments, with all the blinding speed, sober parsimony and nimble risk taking that that implies. The biggest one, the International Thermonuclear Experimental Reactor , or ITER, is under construction by a massive international consortium in the south of France, with a price tag of $20 billion and a projected due date of 2027. Fusion research has a reputation for consuming time, money and careers in huge quantities while producing a lot of hype and not much in the way of actual fusion. It has earned that reputation many times over.

But over the past 10 years, a new front has opened up. The same engine of raging innovation that's been powering the rest of the high-tech economy, the startup, has taken on the problem of fusion. There is now a stealth scene of virtually unknown companies working on it, doing the kind of highly practical rapid-iteration development you can do only in the private sector. They're not funded by cumbersome grants; the money comes from heavy-hitting investors with an appetite for risk. These are companies most people have never heard of, like General Fusion, located outside Vancouver, and Helion Energy in Redmond, Wash. Tri Alpha is so low profile, it didn't even have a website until a few months ago. But you've probably heard of the people who invest in them: Bezos Expeditions, Mithril Capital Management (a.k.a. PayPal co-founder Peter Thiel), Vulcan (a.k.a. Microsoft co-founder Paul Allen), Goldman Sachs.

The endgame for these companies isn't acquisition by Google followed by a round of appletinis. It's an energy source so cheap and clean and plentiful that it would create an inflection point in human history, an energy singularity that would leave no industry untouched. Fusion would mean the end of fossil fuels. It would be the greatest antidote to climate change that the human race could reasonably ask for. Saving the world: that is the endgame.

MICHL (YOU SAY IT LIKE MICHAEL) Binderbauer is one of the co-founders of Tri Alpha and its current chief technology officer. He has a Ph.D. in physics from U.C. Irvine. At 46, Binderbauer is charismatic and ultra-focused: he can talk about plasma physics, lucidly and without notes, apparently indefinitely. (We took a break after two hours.) The logical force of his arguments is enhanced by his radiant self-confidence, a trait that the fusion industry seems to select for, and by his Austrian accent – he grew up there – which inevitably reminds one of the Terminator.

Binderbauer's confidence is infectious. Tri Alpha is probably the best-funded of the private fusion companies – to date it has raised hundreds of millions, according to a source close to the company, which is a lot of money but a tiny fraction of what's being spent on the big government-funded projects.

One of the challenges for anybody working on fusion is that people have been talking about it way too much for way too long. The theoretical underpinnings go back to the 1920s, and serious attempts to produce fusion energy on Earth have been going on since the 1940s. Fusion was already supposed to save the world 50 years ago. "All of us fantasize about such things," Binderbauer says. "It seems like it is the answer, so when someone says anything in that field, it usually very quickly

exponentiates to a message of, Progress is already almost done. It gets hyped to a level I think is very dangerous." (That's one reason fusion scientists don't love talking to journalists.)

Fusion also gets mixed up, for obvious reasons, with nuclear fission, which is the kind of nuclear power we have now, though in fact they're very different animals. Nuclear fission involves splitting atoms, big ones like uranium-235, into smaller atoms. This releases a lot of energy, but it has a lot of drawbacks too. Uranium is a scarce and finite resource, and nuclear plants are expensive and hazardous – Three Mile Island, Chernobyl, Fukushima – and produce huge quantities of toxic waste that stays hazardously radioactive for centuries.

Nuclear fusion is the reverse of nuclear fission: instead of splitting atoms, you're squashing small ones together to form bigger ones. This releases a huge burst of power too, as a fraction of the mass of the particles involved gets converted into energy (in obedience to Einstein's famous $E=mc^2$). Fusion has a vaguely science-fictional reputation, but in fact we watch it happen all day every day: it's what makes the sun shine. The sun is a titanic fusion reactor, constantly smooshing hydrogen nuclei together into heavier elements and sending us the by-product in the form of sunlight.

As an energy source, fusion is so perfect, it could have been made up by a child. It produces three to four times as much power as nuclear fission. Its fuel isn't toxic, or fossil, or even particularly rare: fusion runs on common elements like hydrogen, which is in fact the most plentiful element in the universe. If something goes wrong, fusion reactors don't melt down; they just stop. They produce little to no radioactive waste. They also produce no pollution: the byproduct of fusion is helium, which we can use to inflate the balloons for the massive party we're going to have if it ever works.

Daniel Clery puts the contrast with conventional power starkly in his excellent history of fusion, *A Piece of the Sun:* "A 1-GW coal- fired power station requires 10,000 tonnes of coal – 100 rail wagon loads – every day. By contrast... the lithium from a single laptop battery and the deuterium from 45 liters of water could generate enough electricity using fusion to supply an average U.K. consumer's energy needs for 30 years."

THE RUNNING JOKE about fusion energy is that it's 30 years away and always will be. It's not a very funny joke, but historically it's always been true.

What makes fusion hard is that atomic nuclei don't particularly want to fuse. Atomic nuclei are composed of protons (and usually neutrons), so they're positively charged, and as we know from magnets, things with the same charge repel each other. You have to force the atoms together, and to do that you have to heat them up to the point where they're moving so fast that they shake off their electrons and become a weird cloud of free-range electrons and naked nuclei called a plasma. If you get the plasma really hot, and/or smoosh it hard enough, some of the nuclei bang into each other hard enough to fuse.

The heat and pressure necessary are extreme. Essentially you're trying to replicate conditions in the heart of the sun, where its colossal mass – 330,000 times that of Earth – creates crushing pressure, and where the temperature is 17 million degrees Celsius. In fact, because the amounts of fuel are so much smaller, the temperature at which fusion is feasible on Earth starts at around 100 million degrees Celsius.

That's the first problem. The second problem is that your fuel is in the form of a plasma, and plasma, as mentioned above, is weird. It's a fourth state of matter, neither liquid nor solid nor gas. When you torture plasma with temperatures and pressures like these, it becomes wildly unstable and writhes like a cat in a sack. So not only do you have to confine and control it, and heat it and squeeze it; you have to do all that without touching it, because at 100 million degrees, this is a cat that will instantly vaporize solid matter.

You see the difficulty. Essentially you're trying to birth a tiny star on Earth. "It comes down to two challenges," Binderbauer says. "Long enough and hot enough." In other words: Can you keep your plasma stable while you're getting it up to these crazy temperatures? The severity of the challenge has given rise to some of the most complex, most extreme technology humans have ever created.

Take for example the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, outside San Francisco. A 10-story building with a footprint the size of three football fields, the NIF houses one of the most powerful laser systems in the world: 192 beams of ultraviolet light capable of delivering 500 trillion watts, which is about 1,000 times as much power as the entire U.S. is using at any given moment. All that energy is delivered in a single shot lasting 20 billionths of a second

focused on a tiny gold cylinder full of hydrogen. The cylinder, understandably, simultaneously explodes and implodes, and,the hydrogen inside it fuses. This technique is called inertial confinement fusion.

A more common method for creating fusion is by controlling the plasma magnetically. One of the few breaks physicists catch in the quest for fusion is that plasmas are extremely sensitive to electromagnetism, to the point where electromagnetic fields can actually be used to contain and compress them without physically touching them. It's a feat most often performed using a device called a tokamak. (The word is a Russian acronym.) A tokamak is a big hollow metal doughnut wrapped in massively powerful electromagnetic coils. The coils create a magnetic field that contains and compresses the plasma inside the doughnut.

Since they were developed in the Soviet Union in the 1950s, tokamaks have come to dominate fusion research: in the 1980s enormous tokamaks were built at Princeton and in Japan and England, at a cost of hundreds of millions of dollars. Their successor, the colossus of all tokamaks, is being built in a small town in France outside Marseilles. ITER, the International Thermonuclear Experimental Reactor, will be 30 meters tall and weigh 23,000 tons. Its staff numbers in the thousands. It will hold 840 cubic meters of plasma. Its magnets alone will require 100,000 kilometers of niobium-tin wire. Its stupendous cost is being paid by a global consortium that includes the U.S., Russia, the European Union, China, Japan, South Korea and India.

Because of their extreme size and complexity, and the political vagaries associated with their funding, fusion projects are bedeviled by cost overruns and missed deadlines. The NIF was finished seven years late for $5 billion, almost double the original budget. ITER'S estimated date for full power operation has slipped from 2016 to 2027, and even that date is under re-evaluation. Its price tag has gone from $5 billion to $20 billion; for purposes of comparison, the Large Hadron Collider cost $4.75 billion.

The goal for all these machines is to pass the break-even point, where the reactor puts out more energy than it takes to run it. The big tokamaks came close in the 1990s, but nobody has quite done it yet, and some scientists find the pace frustrating. "Academics aren't necessarily good at adhering to a schedule, promising something and delivering it, on budget and on time," Binderbauer says. "The federal process doesn't condition you to live in that mind-set." And even when it does get up and running, ITER will never supply a watt of power to the grid. It's a science experiment, not a power plant. Proof of concept only.

Fusion research is too slow, too cautious, too focused on lavishing too much money on too few solutions and too many tokamaks. "In a university lab the name of the game, the end product, is a paper," says Michel Laberge, founder of General Fusion in Vancouver, who has a Ph.D. in physics. "You want to get to making energy, but it's not the primary goal. The primary goal is to publish a lot of papers, to go to conferences and understand very thoroughly all the little details of what is going on." Understanding is all well and good, in an ideal world, but the real world is getting less ideal all the time. The real world needs clean power and lots of it.

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Источник: *Time, November 2, 2015. – P. 26-29*