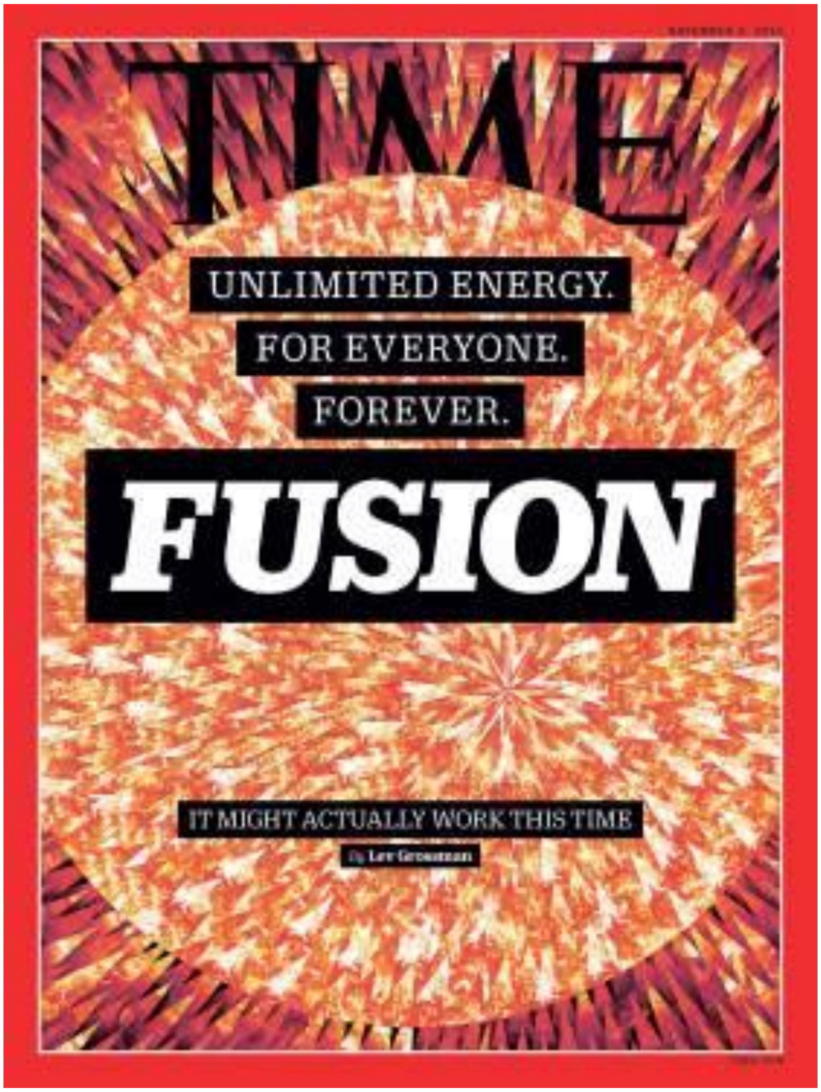
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Illustration by Lola Dupré for TIME

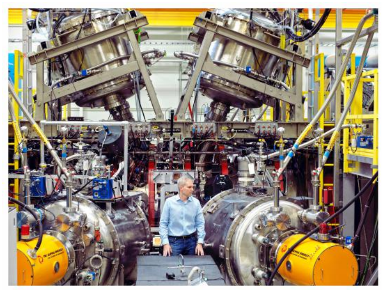
SCIENCE ENERGY

# Inside the Quest for Fusion, Clean Energy's Holy Grail

Lev Grossman @leverus | 5:35 AM ET

**Start-ups are behind the new push**

Hydrogen, the universe's most abundant element, is the fuel for any potential fusion reactor



Vincent Fournier for TIME

Dr. Michl Binderbauer, Tri-Alpha Energy's CTO, near the core of his firm's fusion reactor in Foothill Ranch, Calif.

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[superscript 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 by-product 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.

The driving force behind the founding of Tri Alpha was a physicist at U.C. Irvine named Norman Rostoker. Rostoker, who died in 2014, was a plasma physicist with both a deep understanding of mathematics and a flair for practical applications. He also had an indomitable will and a pronounced independent streak–anybody who talks about him ends up using the word maverick sooner or later. Binderbauer was one of his protégés.

Even in the early 1990s, Rostoker was skeptical of the tokamak hegemony. In a tokamak, the particles in the plasma move in tight spiral orbits around lines of electric current. But it’s hard to keep those particles from being bumped out of their little orbits by electromagnetic turbulence, and when that happens the plasma becomes unstable and loses precious heat. One way scientists fight this instability is by building bigger and bigger tokamaks, but bigger means more complex, and more power-hungry, and more expensive. Rostoker thought there had to be a better way.

He found one in particle accelerators, those colossal rings, like the Large Hadron Collider, that crash subatomic particles into each other. In accelerators, particles travel on wide, conspicuously stable orbits. Rostoker and Binderbauer wondered if you could do something similar in a fusion reactor. They spent a couple of years thinking about it and decided, short answer, probably. “If you can bring accelerator physics into the realm of fusion, you can actually make a better-behaved plasma, one that can give you long timescales,” Binderbauer says. “Then you can invest energy and heat it.”

Rostoker’s other key insight had to do with the flow of people and money around the reactor: he thought the private sector would be a better place to get things done than a university lab. Essentially he recategorized fusion power from an object of lengthy, lofty scientific inquiry to just another product to be shipped. “Fusion is in the end an application, right?” Binderbauer says. “The problem with fusion typically is that it’s driven by science, which means you take the small steps. The most predictable next step, the one you’re comfortable with. So it doesn’t necessarily connect with what you want. Norm said, You’ve got to look at the end in mind. You’ve got to unravel it, reverse-engineer it. What would a utility want? What would make sense? And design something from there, and be agnostic as to how hard the physics might be.”

Raising money was a challenge: tokamaks were eating up all the grant money, and energy startups are expensive, risky long-term bets, especially to Silicon Valley investors spoiled from flipping web startups for quick paydays. Recruiting was tough too: building a fusion device requires a blended culture of physicists and engineers, two groups who don’t historically mix well. For the first few years, the company ran on the brink of insolvency. “You have money for a year or two to develop something, deliver, and go get the next chunk,” Binderbauer says. “It’s not the academic risk profile.”

To keep the pace up they freed themselves from the baggage of theory: as long as something worked, they didn’t analyze to death why. The idea was to stay pragmatic and iterate rapidly, spend as little as possible and not fear failure. “This is one of the failures of the governmental way of running it," Binderbauer says. "It didn't create enough diversity of ideas, and let those freely be pursued to failure. Say, this is where we ultimately want to go, what are the critical steps to get there, what are the risk elements of the path to get there, and can I test for some of these risks without spending a hundred million bucks?"

Some academics would disagree, but no one can deny that Tri Alpha has managed to build a prototype fusion reactor quickly on a tiny budget. The company has a panel of advisers–including Burton Richter, who won the Nobel Prize for Physics in 1976, and Ronald Davidson, past director of fusion labs at both MIT and Princeton–and Binderbauer has fond memories of unveiling his first prototype to them in 2008. "There were like jaws dropping. It was like, holy sh-t, these guys actually did this? On this time frame? This is not possible. Then we had world-record data by August. That was a year basically from seeing dust to seeing physics data taken that's better than anyone else ever did."

Davidson confirms that impression, though in less colorful language. "In the framework of a Department of Energy laboratory, and also in some universities, the level of regulations and restrictions you have on how you do things is somewhat different than in the industry," he says. "The industry can be quite nimble, relatively speaking, in exploring ideas and testing them for the first time."

Tri Alpha's reactor is very different from the towering tokamaks that dominate the fusion skyline, or the supervillain lasers of the NIF. You could think of it as a massive cannon for firing smoke rings, except that the smoke rings are actually hot plasma rings, and the gunpowder is a sequence of 400 electric circuits, timed down to 10 billionths of a second, that accelerate that plasma ring to just under a million kilometers an hour.

And there are actually two cannons, arranged nose to nose, firing two plasmas straight at each other. The plasmas smash into each other and merge in a central chamber, and the violence of the collision further heats the combined plasma up to 10 million degrees Celsius and combines them into a single plasma 70 to 80 centimeters across, shaped more or less like a football with a hole through it the long way, quietly spinning in place.

But a fusion reactor's work is never done. Positioned around that central chamber are six massive neutral beam injectors firing hydrogen atoms into the edges of the spinning cloud to stabilize it and keep it hot. Two more things about this cloud: one, the particles in it are moving in a much wider orbit than is typical in, say, a tokamak, and hence are much more stable in the face of turbulence. Two, the cloud is generating a magnetic field. Instead of applying a field from outside, Tri Alpha uses a phenomenon called a field-reversed configuration, or FRC, whereby the plasma itself generates the magnetic field that confines it. It's an elegant piece of plasma-physics bootstrappery. "What you get within forty millionths of a second from the time you unleash your first little bit of gas," Binderbauer says proudly, "is this FRC sitting in here, fully stagnant, no more moving axially, and rotating."

The machine that orchestrates this plasma-on-plasma violence is something of a monster, 23 meters long and 11 meters wide, studded with dials and gauges and overgrown with steel piping and thick loose hanks of black spaghetti cable. Officially known as C-2U, it's almost farcically complicated–it looks less like a fusion reactor than it does like a Hollywood fantasy of a fusion reactor. It sits inside a gigantic warehouse section of Tri Alpha's Orange County office building surrounded by racks of computers that control it and more racks of computers that process the vast amounts of information that pour out of it–it has over 10,000 engineer control points that monitor the health of the machine, plus over 1,000 physics diagnostic channels pumping out experimental data. For every five millionths of a second it operates it generates about a gigabyte of data.

In August, Tri Alpha announced that its machine had generated some very interesting data. So far the company's primary focus has been on the long-enough problem, rather than the hot-enough part; stabilizing the plasma is generally considered the tougher piece in this two-piece puzzle. Now Binderbauer believes that they've done it: in June the reactor proved able to hold its plasma stable for 5 milliseconds.

That's not a very long time, but it's an eternity in fusion time, long enough that if things were going to go pear-shaped, they would have. The reactor shut down only because it ran out of power–at lower power, and hence with slightly less stability, they've gone as long as 12 milliseconds. "We have totally mastered this topology," Binderbauer says. "I can now hold this at will, 100% stable. This thing does not veer at all." He didn't live to see it, but Rostoker was right. The cat is in the sack. Tri Alpha has tamed the plasma.

Some other people may be right too. Where fusion is concerned, the private sector supports a robustly diverse range of methodologies. In 2002, Laberge, an intense redhead with a thick French-Canadian accent and a droll sense of humor, realized he'd spent enough of his life designing laser printers. "I decided to start a fusion company," he says. "Which is pretty insane, but that's what I went for. I guess, go big in life."

Laberge too was skeptical of the monoculture that dominated fusion science. "The thing in fusion is, when they started they tried many different approaches, and then there's one or two that had a bit of success and whatnot, and then everybody jumped on those approaches," he says. "So it is a good hunting ground for new startup companies, to go and see those abandoned efforts." The approach he hit on is called magnetized target fusion: crudely put, you create a spinning vortex of liquid metal, inject some plasma into its empty center, then squeeze the vortex, thereby squeezing the plasma inside it and causing it to heat up and fuse.

Laberge couldn't get enough grant funding, so he took the idea to investors instead and founded General Fusion. Now General Fusion has 65 employees and is one of a small handful of companies racing Tri Alpha to the break-even point. To date it has raised $94 million and built prototypes of the reactor's major subsystems, including a spherical chamber for the liquid metal vortex with 14 huge spikes projecting out at all angles–the spikes are massive hammers that do the squeezing. It looks, if possible, even more like Hollywood's idea of a fusion reactor than Tri Alpha's. "The tokamak people have a very long timeline, which I don't like," Laberge says, "so we'd like to speed that up, and we think we can move faster." Predictions, like comparisons, are invidious, but when coerced he says, "About a decade to producing energy would be a good timeline to have."

Helion Energy, another venture in Redmond, is already on its fourth-generation prototype. Its approach also has two plasmas colliding in a central chamber, but it will work in rapid pulses rather than sustaining a single static plasma. Helion is focused on developing a smaller-scale, truck-size reactor, and doing it as fast as possible. The company's website states in no uncertain terms that it will have a commercial reactor operational within six years. (Helion told us it was too busy building fusion reactors right now to participate in this article.)

And there are others. Industrial Heat in Raleigh, N.C.; Lawrenceville Plasma Physics in New Jersey; Tokamak Energy outside Oxford, England. Lockheed Martin's Skunk Works division is developing what it calls a compact fusion reactor, which it says will fit on the back of a truck. It also says it'll have a working prototype within five years. (And it said that last year, so four to go.)

There's a kind of cheeky underdog defiance in the attitude of the private sector to the public, but the attitude the other way is a bit more collegial. "They're very interesting," says Professor Stewart Prager, director of the Princeton Plasma Physics Laboratory. "Some more than others. There's a range. It's definitely good to see private investment in fusion.” Dennis Whyte, director of the Plasma Science and Fusion Center at MIT, understands the impatience that drives the startups. “Their argument is that if the science breaks go their way, they will be able to accelerate the pace of getting fusion energy on the grid, and I overall agree with that philosophy,” he says. “I’m part of the quote unquote Establishment that they’re railing against, but you can sense my frustration, because I’m not happy about the delays and so forth.” (He might well be frustrated: Congress has cut funding for MIT’s fusion reactor, which will cease operations next year. He’s currently focused on designing a smaller, modular reactor that takes advantage of recent advances in superconducting technology.)

Within the private sector, there’s a good deal of genial trash talk. The trash talk about Tri Alpha tends to focus on the question of fuel: When you’re doing fusion, which atomic nuclei do you fuse? By far the most popular answer is deuterium and tritium, two isotopes of hydrogen. This is fusion’s low-hanging fruit, because deuterium and tritium fuse at a lower temperature than any other option, a comparatively mild 100 million degrees Celsius. ITER uses D-T fusion (as it’s known), as do the NIF, the National Spherical Torus Experiment at Princeton, Lockheed Martin, General Fusion and almost everybody else.

But there are catches. One is that tritium is rare, so you have to make it. The other is that the reaction emits, along with an isotope of helium, a neutron, which is a problem because when you throw a lot of free neutrons at something it eventually becomes radioactive. That means you’re stuck regularly replacing parts of your reactor as they become too hot to handle. Binderbauer is scathing on the subject of D-T fusion. “Let’s say you have success on ITER,” he says. “You’ve still got another many decades of materials research to try to make something that lasts more than six to nine months, in the hellish bombardment of neutrons it is going to have to live in.”

But there are engineering solutions to the problem: that vortex of liquid metal in General Fusion’s reactor will be a mixture of lead and lithium, which will catch the neutrons. As a bonus, when you hit lithium with neutrons, you get tritium. So two birds, one stone.

Helion’s reactor will fuse deuterium and helium-3, which produces fewer neutrons, though it requires more heat and raises the problem of finding enough helium-3, which is also rare. Tri Alpha plans to fuse protons (otherwise known as hydrogen nuclei) with boron-11. This reaction produces no neutrons at all, and both elements are plentiful and naturally occurring. “We’re always saying, if you want to buy our plant,” Binderbauer says, “we’ll give you a lifetime supply of fuel for free.” The reason hardly anybody else is pursuing it is that proton-boron-11 fusion requires much higher temperatures, insanely much higher: 3 billion degrees Celsius.

No one really knows how plasma will behave at that temperature, and virtually everybody I talked to was skeptical about Tri Alpha’s making it work, and considered the engineering challenges of D-T fusion to be vastly preferable. “Fusion is hard already, even when it’s D-T, and you have to realize how much harder this is than D-T,” says Whyte. “It’s O.K. to take a physics leap, but you also don’t want it to be so big that you worry about its viability.” Laberge felt the same way: “It’s like learning to run before you can walk. Or somebody told me it’s like learning to fly before you can walk. You can argue that General Fusion is outrageously ambitious trying to do fusion, but Tri Alpha is outrageously outrageously ambitious.”

Binderbauer, who is not intimidated by anything, is not intimidated by this either. His next move will be to tear down Tri Alpha’s current reactor and build a new one that will scale up to the necessary temperatures. He points out that particle accelerators can create temperatures in the trillions. “Going to higher temperatures is not that hard,” he says. “It sounds terrible, because it’s billions of degrees, but it’s not. You use techniques much like what you use in a microwave. They’re very similar principles.” You have to imagine the Austrian accent to get the full effect.

Everybody in the fusion industry shares a worldview in which the transformation of the globe by fusion power is imminent. I asked Binderbauer how confident he was that he would see a practical fusion reactor in his lifetime, and his answer was “Very. Scientifically I’m very confident. Now that we have this, this is the foundation.” He thinks he understands theoretically what will happen as his machine claws its way up to 3 billion degrees, and the theory tells him it’s possible. “There should be no physics that says it won’t be. But you gotta test it. This is the field where nature’s the ultimate arbiter, so there's some risk there."

Binderbauer's Austrian rigor restrains him, barely, from making brash predictions about when all this is going to happen. "People tell you they'll have a reactor in five years–I know it's impossible. And it's not because I'm negative. I want this too, and we work as fast as we can, but I know it's more than five years. It just is." Try to pin him down on a specific timeline for Tri Alpha and he writhes like a superheated plasma. "It's not true that it takes 30 years and will always take 30 years. It doesn't. I'm not prepared to tell you, X is the number of years till we have a commercial reactor here. But I will tell you, we are truly about three to four years from the point where the risk changes from a science risk to an engineering risk. And I can certainly see that within a decade such things can mature to the point where you can have the first commercial steps."

There may be a lot of those steps. The utilities will be the ones making the actual transition, and for fusion to be of any earthly use to anybody it will have to make business and engineering sense to them, because fusion plants will be expensive. Unlike solar or wind, fusion would provide energy constantly, not intermittently, but there would have to be enough of it. The gain (the ratio of energy-out to energy-in) of a commercial fusion plant would have to be in the 15-to-20 range; right now ITER's target gain is 10; to date no fusion reactor has yet reached a ratio of 1, the break-even point. Then there's the question of how exactly to extract that energy from the reactor in the form of heat, so that it can plug into the existing infrastructure.

But those steps would be giant leaps for mankind. Bill Gates is currently on a global campaign trying to raise awareness about how badly our addiction to energy is destroying the environment. He's putting $2 billion of his foundation's money into it. "We need innovation that gives us energy that's cheaper than today's hydrocarbon energy, that has zero CO[subscript 2] emissions, and that's as reliable as today's overall energy system," he says in the November issue of the Atlantic. "We need an energy miracle." (He personally has invested in TerraPower, a maker of next-generation fission plants.)

To assess the precise probability that fusion will or won't be that miracle is beyond the remit of a journalist without a Ph.D. in plasma physics, but as miracles go, it's looking a lot more plausible than most. Even Prager, head of the Princeton Lab, who considers the claims of the private sector to be overconfident, still believes it's a question of when not if. "I think it's inevitable. And I don't think I'm alone in that. You can't get commercial fusion in 10 years, but I think we'll have commercial fusion, fusion on the grid, in the 2040s. It may sound like a long way away, but in terms of mitigating climate change, fusion will play a very critical role."

Fusion may just turn out to belong to that category of human achievement, like powered flight and moon landings, that appeared categorically impossible right up until the moment somebody did it. At the very least, a lot of very smart people are betting their money and their careers on it. As for the rest of us, we may already have bet the planet.

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