Episode 8

The Fusion Marathon

Clay Dumas

Progress in fusion over the last three to four decades has actually outstripped Moore's law. The main measure for advances in fusion is something called triple product, which measures plasma density, temperature, and the time it can be sustained. Since the 1970s, we've seen orders of magnitude improvement in the triple product for fusion. In some cases, we're only a single order of magnitude away from the types of output needed to support commercial fusion. That's really exciting, and I think it's been easy for people to discount because of how long it's taken.

But if you look around us, we are surrounded by vertical curves. If the last two years have told us anything about the advances of technology and what we've seen in AI, it's that the pace is not going to let up anytime soon. I think fusion is one of those areas that is going to catch people by surprise at how fast the milestones are hit and how quickly we're able to get past not just this one critical milestone of Q>1, but as Ben Conway, the CEO of Zap likes to say, we're going to turn that into base camp.

Packy

There's this joke that fusion energy is always 30 years away. 50 years ago, it was 30 years away. 20 years ago it was still 30 years away. Today, though, we might be within a decade.

You just heard from Clay Dumas, a general partner at Lower Carbon Capital, one of the world's leading climate funds and the only one to launch a dedicated fusion fund, which they named "Q>1" after the key milestone in fusion, the point at which a fusion reactor generates more energy than it consumes. They're betting the fund on the belief that that remarkable triple product curve will continue.

Julia

And that curve is truly a thing of beauty. Nearly 80 years worth of work on fusion from governments, academics, researchers, physicists, engineers and entrepreneurs across the globe captured in one chart. Beyond simply trusting the curve, there's evidence that we're going vertical in the rush of activity from entrepreneurs in the last few years alone.

After spending most of its life in government and academic labs, startups have taken the fusion baton in the last sprint towards commercial fusion.

Packy

Earlier this year, I wrote a piece in Not Boring with Rahul Rana called "The Fusion Race." We compared what's happening in fusion to a relay marathon. We wrote, "a bizarro relay marathon in which one runner carries the baton for the first 26.0 miles, opens up a backpack full of batons and hands them out liberally to a waiting horde of sprinters to dash all out for the final 0.2 miles." That's the best analogy we can come up with for this moment in the fusion race. Global governments are the marathon runner.

From the race to develop thermonuclear weapons after World War Two to the $22 billion, 50-plus year cooperative ITER reactor currently being built in France, to the National Ignition Facility's ignition achievement in December 2022, governments have led fusion research efforts for the better part of eight decades. Companies like Helion, Commonwealth Fusion Systems, TAE Technologies, General Fusion, and Zap Energy are the sprinters. Armed with $5 billion in funding, most of which has come in the past couple of years alone, and decades worth of research made feasible by new tools, fusion startups are locked in a mad dash to the finish line in what might be called Fusion Race 2.0.

When Rahul and I wrote that piece, we put together a list of about 30 funded fusion startups, which we'll link to in the resources guide. Today, according to Clay, there are somewhere around 80 or 90 companies working on fusion. The race is on.

Julia

Over the next two episodes, we'll get you warmed up and ready for the race so you can watch it play out with a fan's understanding of what's happening and who the key players are. Today, we'll cover the basics of fusion: what it is, how it works, why it matters, how progress is measured, and what the main approaches are. On the next episode, we'll talk to founders building fusion companies, taking different approaches that physicists have long imagined but are only becoming possible now, as well as some of the investors backing them.

We spent the first half of the season on nuclear fission and the last episode on other energy sources that will play a role in meeting humanity's growing energy demands and building an age of miracles. All of them will be critical. But there's a growing chorus of people who believe that if we're going to meet the demand for three to five times the amount of energy we use today with clean energy, we're going to need fusion.

And as we climb the Kardashev scale, the framework for measuring a civilization's technological advancement based on energy use, fusion is going to be our ladder.

Packy

The Kardashev scale, proposed by Soviet astronomer Nikolai Kardashev in 1964, lays out three stages of civilization. A Type I civilization can use and store all the energy available on its planet, including sources we've talked about and some we haven't, like earthquakes and volcanoes. Type II civilizations can harness the total energy of their star, not just the solar energy that lands on the planet. You need something like a Dyson sphere for this. A Type III civilization can control energy at the scale of the entire galaxy, including its billions of stars.

Types IV, V, and even VI get more speculative, talking about capturing energy from the universe, alternate universes, and dimensions, but we're a ways away from that. We're not even Type I yet. In his 1973 book "Cosmic Connection," astrophysicist Carl Sagan came up with a formula measuring humanity at 0.7 on the scale. Today, using the same formula, we're at about 0.731.

One way to climb the Kardashev scale is to capture as much energy from the stars as possible. The other is to make that energy ourselves the same way stars do: fusion. Take a second to appreciate how lucky we are to be alive right now, to see that happen.

Julia

In that context, it's easy to see why people are so excited about fusion. But how does it work?

Andrew Cote is a fusion engineer and one of our favorite follows on X. He breaks down complex ideas in deep tech physics and energy in a way that's easy to understand. So we asked him to explain fusion to us.

Andrew Cote

Well, the easiest way to understand fusion is to look at the sun. The sun shines by fusion energy, and that's a great place to start. The sun is very big, so it has a huge amount of gravitational pressure at its center. It's very hot and dense, and at very high temperatures and densities, you can take individual atoms and fuse their nuclei together. When they come together, they fall downhill in energy. As they fall downhill in terms of energy, they gain a lot of kinetic energy, like a ball rolling down a hill. That kinetic energy comes out as something we observe as heat.

Many different types of atoms and elements can fuse. Stars are mostly powered by hydrogen fusion. That's the main sequence, or the main lifetime of a star. Towards its later life stages, it'll run through its hydrogen fuel and start to burn heavier elements, but those don't release as much energy. So that's how you get the end of a star's lifetime.

For us humans, most fusion energy companies are trying to burn hydrogen isotopes, specifically deuterium and tritium. There's different isotopes, which is when you have a different number of neutrons. Each type of fusion fuel has different characteristics. But fusion is a broad physical phenomenon that is the opposite of fission. Fission is when large heavy atoms split apart. Fusion is small light atoms coming together.

Julia

It all comes back to Einstein's formula, $E = mc^2$. In nuclear fission, a neutron strikes the nucleus of a heavy atom, typically uranium-235 or plutonium-239, which absorbs the neutron, becomes unstable and splits into two or more lighter nuclei, releasing energy along with additional neutrons, which can trigger more fission reactions.

Fusion is almost a mirror image of that. In fusion, two light nuclei, typically the hydrogen isotopes deuterium and tritium, merge to form a single heavier nucleus. The process releases energy because the total mass of the resulting single nucleus is less than the mass of the two original nuclei. The leftover mass becomes energy. $E = mc^2$. Simple, right?

Sehila Gonzalez, the global director of fusion energy at our sponsor Clean Air Task Force and former senior expert in fusion as a fusion physicist at the International Atomic Energy Agency, said the principle behind fusion actually is pretty simple.

Sehila Gonzalez

The principle is simple. You have two light nuclei, usually isotopes of hydrogen. In fusion, you fuse the two nuclei. The problem is the nuclei are positive, so when you try to join two positive charges, they repel each other. You need to overcome these forces by putting more energy into the system to make them fuse or collide. The whole trick is how to make that happen to overcome these Coulomb forces.

Lawson found a criteria which says, if you want to have this fusion reaction, to put these nuclei as close as possible to fuse and overcome these repulsion forces, you need to go beyond a threshold. This is defined by three parameters: density, temperature, and the time you keep things together. The multiplication of these three factors is called the Lawson criterion. If it goes higher than a certain number, you have fusion reactions.

So if you can imagine a machine that can put hydrogen isotopes inside and reach this threshold, you have fusion. The challenge is having a machine where you put the nuclei, heat them up high enough for long enough, and have a high enough density for fusion to happen. This is really complicated because these temperatures are hundreds of millions of degrees, densities are very high, and even if the time scale is seconds or less, it's really difficult to achieve.

This is why you have magnetic coils, because you want to confine your plasma. But the principle is simple. You only need to reach that condition.

Packy

The principles may be simple, but creating the conditions to make them happen here on Earth is anything but. Some of the smartest people in the world have been working on this problem since World War II, and we're just now getting close to pulling it off. But a ton of progress has been made. As Clay highlighted at the start of this episode, fusion is progressing faster than Moore's Law.

There are two main metrics to keep in mind when thinking about fusion: the triple product, which we'll cover in depth later, and $Q>1$. One is roughly the inputs (the triple product), and the other ($Q>1$) is the goal. $Q>1$ has been the goal of the fusion industry since the early days. Simply put, it means that a fusion reactor generates more energy than it consumes. That's critical for a power plant - it needs to add more usable energy to the grid than it takes in.

How close we are to getting there is measured by the triple product: the multiplication of density, temperature, and energy confinement time. The Lawson criterion states that the triple product must exceed a certain value to achieve Q>1. The plasma needs to be dense enough, hot enough, and confined for a long enough period for the fusion reaction to occur.

Andrew Cote

I put this chart on Twitter recently, a scatter plot of different shapes going up and to the right. We love plots that go up and to the right. This plot showed what we call triple product, or really, the product of density, temperature, and confinement time. These three numbers tell you whether a fusion reaction is energy profitable, meaning would it release more energy than you put in, and importantly, would it become self-sustaining? Density and temperature determine how fast particles hit each other to fuse. Confinement time is how long it takes for energy to leak out.

The longer it's trapped by the plasma, the more efficient the heating, and the easier it is to get to ignition. Ignition is when the reaction becomes self-sustaining. It's like burning wet wood versus dry wood. Wet wood just smokes and slowly gets singed, constantly needing energy input. Dry wood ignites and the reaction is self-sustaining.

This concept of triple product has seen steady progress over decades across different reactor designs. The plot shows stars, circles, and squares, representing different reactor designs, slowly getting closer to conditions where you start to get break-even energy release, and then a self-sustaining reaction, which is like Q infinity.

Julia

We're going to hammer this point home because everything we're going to talk about from here on out is essentially a function of increasing the triple product by using technology, engineering, and physics to increase density, temperature, and confinement time. Here's what each is and why it matters.

First, density: the number of fuel particles in a given volume of plasma. Plasma is a hot ionized gas where electrons are separate from their nuclei. More particles mean a higher chance of collision and fusion.

Second is temperature. Fusion requires extremely high temperatures, often hotter than the core of the sun itself, north of 100 million degrees Celsius. At such high temperatures, particles move really fast, and the faster they move, the more likely they are to overcome electrostatic repulsion and collide with enough energy to fuse.

Third, energy confinement time: the average time the energy remains in the plasma before it's lost. Fusion reactors need to contain and maintain the plasma at high enough temperatures long enough for fusion to occur efficiently. More time in the plasma means more time for collisions and fusions.

In other words, a higher triple product increases the likelihood of achieving Q>1 and eventually of Q infinity, or self-sustaining reactions.

Packy

So how do you increase the triple product and eventually achieve Q>1 and Q infinity? There are different types of fusion reactor designs that emphasize various components of the triple product. The two main categories are magnetic confinement and inertial confinement. Magnetic confinement fusion uses magnets to confine plasma within the reactor. These reactors typically optimize for high temperatures of 100 to 150 million degrees Celsius and longer confinement times on the order of seconds.

Inertial confinement fusion works by rapidly compressing and heating a small fusion fuel pellet by bombarding it with high-energy beams like lasers or ion beams. It also relies on high temperatures above 100 million degrees Celsius but optimizes for density instead of confinement time. The fusion event in inertial confinement fusion (ICF) is measured in nanoseconds, or billionths of a second. To date, inertial confinement fusion is the only approach to achieve Q>1.

In December 2022, the National Ignition Facility at Lawrence Livermore National Lab shot 192 lasers at a deuterium-tritium fuel pellet and generated slightly more energy from the fusion reaction than the lasers put into it. It was a huge milestone, confirming that Q>1 is possible in a reactor. But as Andrew told us, publicly funded laser inertial confinement has never been part of an energy development program. NIF has always been used for weapons testing, using lasers to tune the yield in the hydrogen secondary stage of nuclear weapons.

Given the super-short fusion event, capturing the energy and converting it into useful power in a controlled and sustained way remains a huge challenge. Thanks for listening, we'll be right back after a quick word from our sponsors.

Julia

That said, there are private companies developing inertial confinement fusion for energy production, along with several approaches within magnetic confinement, including tokamaks and stellarators. There are even startups like the Sam Altman-backed Helion pursuing hybrid magneto-inertial reactors or magnetic target fusion that combine elements of each approach. These aim for higher densities than typical magnetic confinement systems, but lower than ICF, while also seeking longer confinement times than ICF but shorter than typical MCF approaches.

Amazingly, many of these approaches are based on old ideas that are only now becoming feasible. Now that we've given you some basics, we can go back to the beginning and ride the triple product curve back up to the present day. The history of fusion is one of scientific discovery, military application, and a mix of global competition and cooperation.

Once humans discovered how the sun makes its energy, the bizarro marathon began. Since then, it's been about figuring out how to increase the triple product using the best available technology and engineering at any given time.

Packy

To start our journey into the history of fusion energy, we need to go back to right before World War II. Until 1939, physicists' best understanding of what happens inside stars was based on Lord Kelvin's 19th-century theory of gravitational contraction. Stars are balls of gas, and as gravity pulls the gas in, it heats up, causing the star to emit light and heat. Pretty good.

But in 1939, building on the previous year's work by George Gamow and Edward Teller, who theorized, partially correctly, that stars produce energy through fusion as protons tunneled through the strong nuclear force, two physicists, Hans Bethe and Carl Friedrich von Weizsäcker, independently arrived at the proper explanation. They proposed that stars produce energy through a series of nuclear fusion reactions known as the CNO cycle (for carbon, nitrogen, oxygen), by which stars convert hydrogen to helium. Bethe and Weizsäcker's theory was timely, coming as it did on the eve of World War II.

On episode two, Rod Adams told us that we actually tried to use fission for energy before using it for the bomb. For fusion, the bomb came first, as Andrew explains.

Andrew Cote

We had fission reactors before we had fission bombs. The first one was Chicago Pile-1, underneath what's now a dorm at the University of Chicago, run by Fermi and Szilard. So we had fission power very early on.

After we had developed the fission bomb, people started working on what's called the super, which is a hydrogen bomb. So they started to understand those reactions more.

Julia

What the bomb makers figured out at Los Alamos was a clever and destructive trick. The Teller-Ulam configuration, named after the physicists who devised it, uses the energy from the fission bomb to compress and heat the fusion fuel to such an extent that the atomic nuclei begin to fuse together, releasing a huge amount of energy. The resulting hydrogen bomb, Ivy Mike, yielded 10.4 megatons of energy, over 450 times the power of the bomb dropped at Nagasaki.

It obliterated the island on which the test was performed, leaving an underwater crater 6,240 ft wide and 164 ft deep where the island had once been. Hydrogen bombs are not a practical way to create fusion energy. You don't want to turn your power plants into smoking craters. But Ivy Mike was the first man-made fusion reactor to achieve Q>1.

Fortunately, the bomb has never been deployed in combat, but with fusion proven possible, governments around the world sprung into action to harness it.

Packy

In the US, President Truman signed the Atomic Energy Act and established the United States Atomic Energy Commission as a successor to the Manhattan Engineer District, better known as the Manhattan Project. Given the relative maturities of the two technologies, the AEC focused most of its effort on nuclear fission, becoming both the champion and regulator of the nascent industry. As we discussed on episode two, this came with all of the problems and benefits that entailed, but the AEC also laid the groundwork for research into fusion energy.

Then in 1951, Argentinian president Juan Perón dropped a bomb of his own, announcing that a scientist named Ronald Richter, who had moved to the country from Germany after World War II, had achieved controlled nuclear fusion. The claim turned out to be false, but it did accelerate the race worldwide.

Julia

If our history of nuclear fission was about understanding what slowed nuclear down in order to take those lessons into the nuclear renaissance, what's most salient in the history of fusion?

Packy

To me, it's really the bizarro relay marathon we talked about. The race went from various countries competing with a bunch of designs to a big cooperative international effort focused on mainly one design. This was cool in a Kumbaya sense, but bad in that it slowed down fusion development like any large international project and lack of competition does.

But governments and academia did make real progress, and today's entrepreneurs get to piggyback on their work.

Julia

The early days of fusion remind me a lot of the early days of fission, with so much experimentation going on with different designs. Starting in 1951 with fusion, after the Argentinian announcement, three separate projects pursuing different approaches to plasma confinement sprung up and would form the basis for Project Sherwood, a classified US program in controlled nuclear fusion.

First was the Stellarator designed by Lyman Spitzer at the Princeton Plasma Physics Laboratory. Stellarators are devices designed to confine hot plasma within magnetic fields in a twisted torus-shaped configuration to sustain nuclear fusion reactions. Next is the toroidal pinch. Designed by James Tuck at Los Alamos, toroidal pinch devices work by confining a high-temperature plasma into a doughnut-shaped chamber using magnetic fields. The fields are generated to pinch the plasma, increasing its pressure and temperature to the point where nuclear fusion can occur. Tuck named the device the Perhapsatron, because perhaps it might be able to achieve a fusion reaction.

Packy

The Perhapsatron, I think, is my favorite product name of all time, not just in fusion. It sounds like a nuclear fusion device straight out of Dr. Seuss.

Julia

Totally. And finally, there was the magnetic mirror. The names are great here. This one was designed by Richard Post at the Livermore National Laboratory.

Magnetic mirror devices contain plasma within a chamber using magnetic fields that are stronger at the ends, reflecting the charged particles back to the center, creating a magnetic mirror.

Packy

Instead of me trying to explain the physics of these crazy devices, let's turn it back over to Andrew.

Andrew Cote

In the early '50s, you had this flourishing of different approaches for fusion reactors, which evolved as we learned more about the field. Plasma is an interesting substance - a gas of separated electrons and ions that responds to magnetic and electric fields, with currents generating magnetic fields. There's lots of interesting dynamics. One of the first devices was called Z-pinch, where you drive a current through plasma in a tube, generating a magnetic field that constricts the plasma. Hypothetically, this could heat the ions enough to fuse and release energy. It didn't work for many reasons, like plasma instabilities and magnetic confinement issues. The early history of fusion development was about beating scaling laws for capturing heat energy versus magnetic field strength. Other devices like magnetic mirrors came along, where ions bounce between magnetic "bottles" along field paths. This design had limitations, constantly leaking fuel or heat energy through a "loss cone". There were lots of other machines like the Z machine. The stellarator is a kind of magnetic confinement fusion device where people thought, "The magnetic mirror doesn't work because particles lose energy when bouncing back and forth. What if we wrapped that bottle into a circle?" Now particles never reach the bottle's end and can keep circulating indefinitely. You'd think you could build up more energy, putting it into particle speed, and they'd remain trapped along magnetic field lines. Lyman Spitzer at Princeton developed the stellarator concept around 1952 or 1956. At first, it looked like a super figure-eight thing. He realized, though, that it performed worse than expected. There were scaling laws about how easy it is to trap energy versus magnetic field strength. It's expensive to get very strong fields and reproduce them accurately, so it didn't work quite well. At the same time, around '56, the Soviets published their data on the tokamak, their version of a magnetic confinement fusion reactor, which just blew everything out of the water.

Packy

As Andrew points out, physicists devised ingenious designs back in the 1950s, but they didn't work given the materials and technologies of the era. Then there was the tokamak, the dominant design for the past half century. There's a fascinating bit of history that led to its development. In 1952, the UK began work on its own Zero Energy Thermonuclear Assembly (ZETA) project, which attempted to use the Z-pinch method. In this method, an electric current is shot through the plasma in a straight line along the z-axis, generating a magnetic field around it, which compresses the plasma.

ZETA is perhaps most famous for a series of false positive results. In 1958, the ZETA team announced they had observed neutrons indicative of fusion reactions. However, subsequent analysis revealed that the neutrons were likely produced by plasma instabilities, not fusion reactions. Once again, a strong idea faced technological limitations of its era. While Western democracies were experimenting with various approaches, the reigning heavyweight champion would be developed a few years later in communist USSR. In 1956, Soviet Premier Nikita Khrushchev actually visited ZETA. There's a great picture, which we'll flash up on the screen, that shows a bald man in the middle looking at ZETA. That's Khrushchev, a sign of the open international cooperation on fusion development.

Two years later, the Soviets would crack open the problem and reveal the approach that remains the leader to this day: the tokamak.

Julia

To the extent that you think about fusion reactors, the image that springs to mind is probably one of a tokamak. The tokamak uses magnetic fields to confine plasma into a doughnut-shaped configuration. This plasma is heated to extreme temperatures, causing atomic nuclei to collide and fuse together, releasing energy in the process. The magnetic field helps keep the hot plasma away from the machine's walls, which is crucial for maintaining the conditions necessary for fusion to occur.

Compared to early stellarator and pinch designs, tokamaks were more efficient, stable, and scalable. In 1958, the Soviets unveiled the first tokamak. A decade later, in 1968, they announced that the T-3 tokamak had achieved significantly higher plasma temperatures and densities than their Western counterparts, around 1000 eV, or 10 million degrees Celsius. The numbers beggared belief.

So in a decision that would set the stage for ongoing international cooperation in fusion research, they invited a team of British physicists behind the Iron Curtain in 1969 to confirm the results, which they did. The tokamak was the real deal.

Packy

Starting with that confirmation in 1969, the same year we landed on the moon, the tokamak has attracted most of the international funding dollars and research efforts. That's not necessarily because it was the best platonic ideal design, the easiest to operate, or the most stable.

Ian Hogarth, an investor at Plural Platform, told us that the world essentially made a trade-off.

Ian Hogarth

Reading the history of the field, it felt to me that the stellarator is like the platonic ideal of magnetic confinement. In 1951, this would be the perfect way to confine plasma in three dimensions using external magnetic fields. But when you tried to design that in 1951, it was too challenging due to the incredibly complex coil shapes.

A tokamak represents reducing the design complexity to build something, but losing that steady state. You could think of it as almost 70 years of accepting a harder-to-operate machine that was easier to design. We're now moving into the era of using new high-complexity simulation techniques to accept hard design for easy operation.

Packy

Ian makes a crucial point. Tokamaks, shaped like big donuts, were easier to design and build than more creative designs. That's why the world converged on them, not because they were the highest potential reactor ever designed. The result of the Soviet experiment was like an inertial confinement fusion reaction in its own right.

Quickly, all the different experiments fused into a concentrated international effort to work on the tokamak. Only recently has there been vision. New reactor designs that are harder to build but easier to operate once built are being given another look.

Julia

This period, right after the confirmation in the early 1970s, is almost the mirror opposite of what happened in fission. As nuclear reactor orders cooled off, fusion research took off. The conditions on the supply side (early tokamak progress) and demand side (high energy prices) formed the perfect storm for fusion excitement.

The 1973 oil crisis sparked interest in energy sources that would free the United States from OPEC dependence, inspiring a 6x annual government funding increase. As the energy crisis abated, US funding for fusion research leveled off at about one-third of its 1970s peak in inflation-adjusted dollars.

Packy

While US funding for fusion slowed, fusion research became an international and increasingly cooperative affair. Across the pond, the European Atomic Energy Community (Euratom) announced the Joint European

Torus (JET) in 1977. They began construction in 1978 and achieved plasma by 1983.

JET, a tokamak reactor, had many firsts. It was the first to use tritium, produced 16 MW fusion power from 24 MW input heating power (Q of 0.67) in 1997, and importantly, furthered confidence in the tokamak design, setting the stage for the largest tokamak ever built, the International Thermonuclear Experimental Reactor (ITER).

Julia

ITER was born of compromise. In 1985, as the Cold War neared its end, American President Ronald Reagan and Soviet Premier Mikhail Gorbachev met in Geneva to establish a personal rapport and negotiate, among other things, a reduction in nuclear arms. While they couldn't reach an arms control agreement, they included in their joint statement an item emphasizing the potential importance of controlled thermonuclear fusion for peaceful purposes, advocating for international cooperation in obtaining this essentially inexhaustible energy source.

By the next year, in Reykjavik, the initiative was confirmed and a quadripartite committee was formed with Euratom and Japan. In 1987 in Vienna, the committee agreed upon the name ITER.

Packy

ITER, the largest tokamak reactor ever designed, has been at the center of fusion research since its inception. A collaboration among 35 countries, including Russia, the United States, China, India, South Korea, Japan, and the European Union across five decades, the project has five goals: 1) Achieve a deuterium-tritium plasma in which fusion conditions are sustained mostly by internal fusion heating. 2) Generate 500MW fusion power in its plasma on 50MW input (Q > 10).

3) Contribute to demonstrating the integrated operation of technologies for a fusion power plant. 4) Test tritium breeding. 5) Demonstrate the safety characteristics of a fusion device.

The facility is still under construction in Saint-Paul-lès-Durance, France, and plans to generate its 500MW fusion power sometime between 2035 and 2040.

Julia

Achieving Q>10, whenever that happens, will be an incredible feat. At the same time, you have to wonder what the state of the fusion industry would be today if so many eggs hadn't been placed in one huge, slow, expensive basket, at least to start. The United States, one of the largest potential drivers of fusion progress, essentially outsourced much of its work to an international coalition with all the benefits and challenges that entails.

A 1976 report by the US Energy Research and Development Administration (the R&D; successor to the AEC, while the regulatory arm was split off into the Nuclear Regulatory Commission) proposed 40-year funding scenarios ranging from "maximum effective effort" to "fusion never." When Jeffrey Olenek analyzed the actual fusion funding 40 years later, he found that funding tracked below the "fusion never" scenario since the mid-1980s, right around the time the US decided to participate in ITER.

Packy

"Fusion never" was probably a bit overdramatic. Thankfully, a lot of progress has been made. The triple product continues to outpace Moore's law. Innovation on other approaches did continue, if more slowly and with less funding.

Earlier, Andrew referenced a chart he posted on Twitter with different symbols representing various reactor designs and their triple products. There are many circles on that graph representing tokamaks, but also green stars for stellarators, black X's for laser inertial confinement, and maroon triangles for magnetized target fusion, all near the top of the achieved triple product range.

While the world waits for ITER, progress is still being made across several approaches worldwide. The world's largest stellarator, for example, is the Wendelstein 7-X at the Max Planck Institute in Germany. It began construction in 1995 and operation in 2015 - pretty fast, at least relative to ITER. It was the first to be tested in silico before construction, meaning they used simulation software to test it before they actually had to build it.

As mentioned, NIF achieved Q>1 with laser inertial confinement fusion. And several other approaches like spheromaks and field-reversed configurations lived on in labs around the world.

Julia

But until 2010, novel approaches were few and far between. According to Commonwealth Fusion Systems co-founder and MIT professor Dennis Whyte in his interview with Lex Fridman, ITER sucked a lot of air out of the room.

Dennis Whyte

I worked most of my career on ITER because when I came into the field in the early 1990s, when I completed my PhD and started to work, this was one of the most exciting things - we're going to change the world with this project. We poured an entire generation's imagination and creativity into making this thing work very well.

But at some point, when it got to being another five years or decade of delay, you start asking yourself, "Is this what I want to do? Am I going to wait?" I just want fusion energy because I think it's so important to the world.

If that's the case, then why do we have only one attempt at it on the entire planet, which was ITER? That makes no sense to me. We should have multiple attempts at this.

Julia

Whyte praises the contributions of ITER and the importance of government-funded research in pushing the space forward. He's right. It's near miraculous that in less than a century since unraveling the stellar secret of nearly limitless energy production, we stand at the cusp of harnessing that power for our own use.

But he's also right to say that we should have multiple attempts at this; we can't afford to wait just for ITER.

Packy

Fortunately, we're not waiting. Entrepreneurs across the globe are taking what they learned at ITER, at school, and in other government-funded labs, combining their knowledge with modern materials, software, and a little bit of VC funding, and taking the baton into the final sprint of the fusion race.

We'll talk to some of them, including folks from Helion, Zap, Fuse, and Proxima on the next episode.

Julia

Before we get there, let's recap where we've been with fusion and where we're headed next. It's remarkable and almost a little scary that we started with the hydrogen bomb as the first instance of Q>1.

But it's cool to see that we've captured that, taken a step back and said, this is really important for society. We've seen governments all over the world, even from competing great powers, working and coming together on this.

Packy

I would love to be in one of the committee meetings at ITER, where people from Russia, China, and the US are all sitting in a room working on this together. It reminds me of 'For All Mankind' last season, when Russian and American astronauts, even in the middle of the Cold War, are working together because they care about the science and making these missions to the moon and Mars happen. Hopefully, there's a similar vibe there, but it's a big government project, so it is a little slow.

Coming into the space from the outside, I had believed that joke that fusion was always 30 years away, that it was this nearly impossible thing. But looking at this, despite all these ups and downs and dips in funding, that curve just continues to go up. The triple product continues to increase, and now there are all these different companies taking the learnings from labs around the world and adding a little startup secret sauce. It's wild to me how that stuff works out.

It's also right at the time that we need a bunch of clean energy and a lot more electricity. It's kind of wild that the world works that way.

Julia

I love that you framed our fusion discussion here as this bizarro marathon. You have all these companies with different approaches, and I'm genuinely excited and curious to see who's going to win. We know who's made what types of progress, but I'm super excited for the next episode where we dive into each of the different approaches that various startups are taking.

There's not one right way to do this, but there might be one that moves us forward the fastest. And that's what I think everyone's super excited to follow along with.

Dennis Whyte

Right.

Packy

You'll get to hear this on the next episode. Maybe I'm just easily convinced by really smart people working on big things, but each conversation I had, I thought, "That actually sounds like the right approach." I'm really interested to see how it plays out. Each person had a different answer, but we'll have to see it play out in the real world. Is it a winner-take-all market? Does the first one that gets there just get all the funding, sign the big government contracts?

I'm sure there's going to be a race once this is possible among countries to be the first to put a fusion reactor in their country, among states in the US to be the first to have one in their state. Does everything coalesce again around one design? Or do we see a bunch of different things work for different reasons? Maybe for the military there might be one thing, for municipalities, another approach might work better. I think all of that is TBD, and we'll dig into that a little bit on the next episode, at least how these companies are thinking about it.

But is it a race to untold trillions of dollars in revenue for one of these companies? Or are there just going to be a bunch of hundred billion to trillion dollar companies that come out of the fusion race?

Julia

I think it's a fantastic question and I don't want to undervalue the labs, governments, and academics working in this field too. They're sometimes the people who keep the really obscure ideas going. Sometimes the commercial markets decide they all want to stick towards one proven approach, but you never know when progress is also made in other funny little corners that just come back again.

It's like some of the molten salt reactors that are largely academic and national lab driven, but are now coming back again decades later with a commercial approach. You never know if we might see something like that happen in fusion, too.

Packy

Even Aalo is going through university reactors and research reactors as their sales channel. I think nuance gets lost on Twitter or in these big conversations about whether it's entrepreneurs, governments, or academics who move the world forward. This is one of those examples, kind of like the space race, where it's just very clearly all three of them. Would you like ITER to be moving faster? Sure. Would you like there to have been more progress and we already have fusion on the map? Sure. But I think it takes each leg of that bizarro marathon to get where you are on a problem this hard.

And it is just cool. To me, the reason I wrote the piece in the first place is that it's cool that we got to the point where at least 80 smart people and a bunch of investors think that now is the time when it makes sense to start building fusion companies because we are that close.

Julia

I think it's super heartening that there are 80 plus companies now working on fusion because you know that means there's going to be this talent pool developing of people who are going to develop know-how over the years, that will further help us move towards unlocking commercial fusion. So that's exciting. It'll also mean there's going to be an industry that gets to stand up around this. It's like the picks and shovels of the world and supply chains that are needed.

We'll talk about this on the next episode. But there has been a 'why now' for fusion in some of the capabilities, like technology breakers that allow certain things to exist today to support fusion energy right now. And so those will also further continue to compound on themselves and strengthen the entire industry.

Packy

Even if you believe Peter Thiel's view that we've had a 50-year period where we haven't built anything in the world of atoms, software is playing a big role in the "why now" for fusion. This is one of my big beliefs: none of that was a waste. First, we're doing this over Zoom and people get to listen to it because of everything that's happened over the past 50 years. But more importantly, we're now able to combine bits and atoms in really interesting ways that we couldn't have 50 years ago. This is a prime example of that.

It's not like people didn't have the ideas. The designs were there on paper, but you just couldn't quite optimize them without everything that's happened in software over the past 50 years. Not everything - without cat pictures, we'd be fine, but certainly not without the simulation software. And all of that is an amalgamation of different things that went into creating the simulation software.

So I'm obviously a big fan of progress generally, but I think fusion is a great example of how this works. Before we wrap up this episode, because we have a jam-packed one next, I want to make sure we get this in. We asked a few people we talked to why fusion matters when we have fission, solar, and fossil fuels. I think that's a good place to leave this one. So we're going to turn it over to a few of them.

Sehila Gonzalez

The demand for energy from population growth is increasing, and we cannot afford to burn coal and gas forever. You need energy because populations are demanding higher living standards, particularly people from less developed countries. They are now having access to many other facilities and needs, which is great. But you simply cannot afford to keep burning fossil fuels.

So you need to find new sources of energy that are clean by definition. On top of that, you want to have security and geopolitical independence. Fusion provides those characteristics that you're looking for. It's clear that mankind needs to find this new source of energy, which is much more sophisticated and complicated than burning coal. But it needs to be developed.

Packy

And here's Ryan from Zap Energy.

Ryan Umstattd

This really comes down to a thrive versus survive kind of thing for me. Yes, it is possible that renewables plus storage can help decarbonize. But all the models I've seen show that as you try to fully decarbonize with renewables plus storage, costs for electricity start to skyrocket when renewables plus storage get to about 80-90% of the target.

So yes, we could get there, and there are ways. But if we want to thrive as a species versus survive, we need to start harnessing the power source of the universe, and that is fusion energy.

Julia

And here's Clay from Lower Carbon Capital.

Clay Dumas

So much of the conversation around climate change today is about giving up things you love: living in smaller homes, driving smaller and less powerful cars, flying less, changing your diet. While some of these can be impactful, it's not a future that most people are inspired by. At Lower Carbon Capital, we believe there are maybe a couple hundred million people around the world who will go out of their way, pay more, or be inconvenienced to do the right thing for the planet. The question is, how do we turn the other 7.8 billion unwittingly into hippies? That is the task for all of us.

With fusion, we can imagine a path to a world where we can promise people access to more energy at lower prices, to live a much higher quality of life. It's hard to see doing that with just the technologies we have today. Solar and wind have been transformative and will continue to reshape the global energy landscape. We'll see geothermal energy unlocked in unexpected places. In certain parts of the world, we'll see more investment in fission. But to get where we need to be, for everyone to have an abundant life without turning the planet into an open pit mine, we're going to need fusion.

Packy

This stuff matters. We're going to need at least 5x the amount of electricity we use today in the next few decades. Within most of our lifetimes, we're going to need a lot more electricity.

Yes to fission, yes to solar, but hopefully also fusion. On the next episode, we'll talk to the companies racing to make that happen.

Julia

I can't wait. See you then.

Packy

Thank you for listening and watching to this episode of Age of Miracles. If you like what you hear, please rate, subscribe and share. And if you're feeling really generous, tell us what you think in the comments.

Plus, we have a ton of resources and references in our resource hub. If you want to go deeper. And we've linked them all in the show notes below. See you next week.