State of the Union

Michael Fumento

"Fusion will be ready when society needs it."
— **Lev Artsimovich**, 1972.[1]

In the future, there will be an energy source that uses cheap and inexhaustible fuel, does not produce emissions, and has no risk of meltdowns. That energy source, often described as "the sun in a bottle," is controlled nuclear fusion. And, even better, it is *just* thirty years away. Proponents of controlled fusion have been making this claim for the last sixty years.

"Fusion is the energy of the future," as the old joke goes, "and always will be."

In 1980, US President Jimmy Carter signed into law the Magnetic Fusion Energy Engineering Act. Drafted in response to an "impending worldwide shortage of many exhaustible conventional energy resources in the next few decades," the bill sought to "establish as a national goal the operation of a magnetic fusion demonstration plant at the turn of the twenty-first century."[2] A *Newsweek* cover story published in May 1989 once heralded "The Race for Fusion."[3] If there was any sense of urgency surrounding the enterprise, it has ebbed away.

It is no longer a matter of getting there by a particular date, but getting there at all.

Some of the reasons that have been offered for the importance of controlled fusion, such as over-reliance on fossil fuels, nuclear power plant safety, and global warming, were not even discussed until decades after fusion research began. Concerns about dwindling fossil fuel supplies first emerged during the oil embargoes of the 1970s.[4] Most electricity, then as now, was generated from coal. But with mines in the US and elsewhere closing due to declining demand, few seem worried about reserves. The safety of nuclear power plants only became an issue following the incident at Three Mile Island in 1979. These fears were further heightened by the disaster at Chernobyl in 1986. Global warming, currently considered a pressing issue, only began to assume prominence around the turn of the century.[5]

There is no simple explanation why controlled fusion remains elusive. The variety of approaches so far developed speaks to the many scientific and engineering challenges involved. The physics is more difficult than the physics for controlled fission. These problems aside, the question of need remains unanswered.

If necessity is the mother of invention, controlled fusion is an orphan.

On March 24, 1951, Juan Perón announced that Argentina had "completed thermonuclear reactions under conditions of control."[6] The new technology, in the form of a device known as a thermotron, would, he believed, be the solution to the country's energy shortages. At the same press conference, Perón also predicted that energy would be sold in bottled form. A year later, Perón cancelled the research program. The experimental results had been proven fraudulent. Argentinian shopkeepers, one imagines, were only a little less disappointed than *El Presidente*.

Rather than serving as a cautionary tale, the bold predictions and dashed hopes that accompanied Perón's fusion program could almost be considered a template for the many projects that followed. Charles Seife has chronicled the troubled history of fusion research in his *Sun in a Bottle*. The account he provides is far from reassuring.

- 1958: The Zero Energy Thermonuclear Assembly (ZETA) project claimed to have achieved fusion. Sir John Cockcroft, the project's director, expressed ninety percent certainty in ZETA's results.[7] The claims were later retracted.
- 1974: KMS Fusion, an American private sector firm, achieved fusion through the use of lasers, albeit without even remotely approaching a net energy flow. Despite successful tests, the company wilted under sustained pressure and opposition from the US Atomic Energy Commission.[8]
- 1989: One of the most infamous scientific scandals of recent decades ensued following the claim by American researchers Martin Fleischmann and Stanley Pons to have achieved cold fusion—a sustained nuclear reaction at room temperature.[9]
- 1996–98: The JT-60 Tokamak in Japan was claimed to have been producing five watts for every four consumed. "Instead, the JT-60," Seife notes, "had reached temperatures, pressures, and confine-

ment times that, according to calculations, *would* mean breakeven *if* researchers had used a [more energetic] deuterium-tritium mix rather than just deuterium as fuel."[10]

- 2002: Evidence for bubble fusion, or sonofusion, was observed in beakers of acetone, according to researchers at Oak Ridge National Laboratory. Although the claim was greeted with skepticism, *Science* published a paper by the researchers.[11] A series of investigations culminated in two findings of research misconduct. The lead researcher lost his professorship.

"Over and over again," Seife remarks, "the dream of fusion energy has driven scientists to lie, to break their promises and to deceive their peers. Fusion," he concludes, "can bring even the best physicist to the brink of the abyss. Not all of them return."[12]

Most of these projects should not be considered complete failures. Lessons were learned that could be applied in future projects. But they were failures nonetheless.

TWO CONDITIONS MUST be satisfied before controlled fusion can be considered a realistic commercial prospect. The first is a suitable method for the containment of the reaction itself. The second, termed breakeven, is a sustained reaction that produces more energy than it consumes. In the absence of either a sun or a bottle, there is little chance of success.

In the solar core, hydrogen is fused to form helium at a temperature of fourteen million kelvin.[13] Fusion reactors are not quite comparable to the sun. Two light atomic nuclei, deuterium and tritium, have been the focus of recent research. Deuterium can be distilled from seawater. It is for this reason both readily available and pretty much inexhaustible. Tritium, on the other hand, is extremely rare and only trace amounts are found in nature. It can be produced in reactors from the neutron activation of lithium, but lithium is itself a relatively scarce element that must be first extracted from rocks or brine. The temperature required for deuterium and tritium fusion is approximately forty million kelvin.

Controlled fusion requires the creation of plasma, a gas cloud comprised of charged ions and electrons. Plasma has an extremely low density, just a millionth that of air, and by virtue of its charged nature, plasma is strongly reactive to electromagnetic fields. But any contact with material surfaces results in cooling and contamination. For this reason, a scheme for self-containment, or non-solid containment is crucial. Controlled fission is relatively easy to achieve. Splitting the nucleus of an atom produces a tremendous amount of heat, but the reaction is sustained at a low level. Attaining a similar level of control in fusion reactors is considerably more challenging.

The two main branches of controlled fusion research currently being pursued are inertial confinement fusion (ICF) and magnetic confinement fusion (MCF). Inertial electrostatic confinement is also the subject of research, but on a much smaller scale.

UNDER THIS SCHEME, massive blasts of energy, most commonly in the form of high-energy laser beams, are directed at a fuel target, a tiny sphere containing approximately ten milligrams of deuterium and tritium isotopes. Heating the fuel target ablates its exterior, which, in turn, produces an opposing force that implodes the remaining material, forcing the two isotopes to fuse. The objective is to achieve ignition, a self-sustaining reaction.

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, completed in 1989, is capable of delivering 60 times more energy to the fuel target than any previous laser system—1.8 megajoules of power provided by 192 lasers. Originally scheduled to open in 2003 at a projected cost of US$1 billion, the NIF was not only long overdue, but also over budget, with a final cost of at least US$4 billion.[14] The initial objective for the NIF was to achieve ignition in 2010, although this goal was subsequently pushed back to 2012.[15] Writing at the time in the *IEEE Spectrum*, Bill Sweet described the NIF facility as the "fattest white elephant of all time."[16]

A 2013 announcement by the NIF in 2013 describing an "order-of-magnitude improvement in yield performance over past deuterium–tritium implosion experiments," prompted headlines such as "National Ignition Facility Announces Record Amount of Fusion Energy," and "Is Fusion Success in Sight?"[17] But, as *BBC News* noted, this was "a step short of the lab's stated goal of 'ignition.'"[18] Nonetheless, there were reasons to be optimistic.

> [T]he amount of energy released through the fusion reaction exceeded the amount of energy being absorbed by the fuel—the first time this had been achieved at any fusion facility in the world. … [T]he latest achievement has been described as the single most meaningful step for fusion in recent years, and demonstrates NIF is well on its way towards the coveted target of ignition and self-sustaining fusion.[19]

The excitement did not last long. In a follow-up article entitled "Fusion 'Breakthrough' at NIF? Uh, Not Really," Daniel Clery explained:

> NIF's laser input of 1.8 MJ is roughly the same as the kinetic energy of a 2-tonne truck traveling at 160 km/h (100 miles/h). The output of the reaction—14 kJ—is equivalent to the kinetic energy of a baseball traveling at half that speed.[20]

A report by the US Department of Energy released in May 2016 declared: "The question is *if* the NIF will be able to reach ignition in its current configuration and not *when* it will occur."[21]

The NIF has not been without benefits for researchers. Nuclear weapons development is undertaken at the facility, along with experiments on "the properties of various materials at extremely high pressures and temperatures, shock wave creation, hydrodynamics and fuel pellets."[22]

ICF research continues despite these setbacks. In October 2014, the *Commissariat à l'énergie atomique et aux énergies alternatives* (Alternative Energies and Atomic Energy Commission) opened a new facility, the *Laser Mégajoule* (LMJ), near Bordeaux in south western France. When fully operational, the LMJ will have a comparable laser power output to the NIF's ICF project. According to its website, the LMJ will be used to "study, at a very small scale, the behavior of materials under extreme conditions similar to those reached during the operation of nuclear weapons."[23] The website also states that "The LMJ is designed to be able to achieve inertial confinement fusion."

In his critique of the NIF facility, Sweet posed the question: "[W]hen will inertial confinement fusion be delivering commercial electricity? That one," he said, "is easy. Never."[24]

The charged nature of plasma particles is the basis for MCF. Magnetic fields are used to confine the plasma; ions and electrons follow helical paths around magnetic field lines. The plasma is thus kept isolated from the much cooler walls of the surrounding vessel. The most promising magnetic configuration is toroidal shaped, something like a donut. The Tokamak design developed by Andrei Sakharov and Igor Tamm, at the Kurchatov Institute in 1951, remains the basis for most current MCF research. The first Tokamak, the T-1, was operational in 1958.[25] Despite decades of research, progress towards commercialization has been limited.

The Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory was operational between 1982 and 1997. The project's website notes that, "in 1994, TFTR produced a world-record 10.7 million watts of controlled fusion power, enough to meet the needs of more than 3,000 homes."[26] The energy required to produce this yield is conspicuous by its absence.

The Joint European Torus (JET) project, located at the Culham Centre for Fusion Energy, is the largest operational MCF facility. Construction of JET began in 1977, with the first plasma achieved in 1983. JET is funded by the European Commission, with a budget of 283 million euros for the period 2014–2018.[27]

JET is famed for producing, as *Engineering and Technology Magazine* put it, "a hefty 16MW of power."[28] This yield was only achieved using a rather more hefty "total input power of 24MW." A considerable leap in imagination is needed to construe a result that involved net energy loss on this scale as hefty. As Seife noted, "a net loss of 40 percent of energy is not the hallmark of a great power plant."[29] This result was achieved two decades ago.

Interviewed in 2014, Culham Centre director Steve Cowley remained upbeat about the prospects for commercialization: "We're not that far away from being able to produce electricity and once we've produced this, we've then got to grind away at the engineering until it's commercially viable."[30] Net generation of electricity, Cowley admits, is just the first step. After sixty years of research, it is a first step that is yet to be completed.

The International Thermonuclear Experimental Reactor (ITER) project was initiated by Ronald Reagan and Mikhail Gorbachev at the 1985 Geneva Summit. Seven participants—USA, Russia, China, India, Japan, South Korea, and the European Union—entered a formal agreement in November 2006 to fund the development of a fusion reactor. The ITER project has since expanded to include thirty-five participating countries. An experimental Tokamak facility is currently being constructed at the Cadarache research center in southern France not far from Marseille. First plasma was originally scheduled for 2020, followed by full fusion in 2023. First plasma has now been pushed back to 2025, with full fusion not expected until 2035. The current estimated cost of construction is twenty billion euros, a four-fold increase on the original estimate.[31] Even if the 2035 target is achieved, the ITER project will not have delivered a solution for commercialization.

Nor was it ever intended to.

Work has already begun on the successor to ITER, an initiative known as DEMO (Demonstration Power Plant), which is currently in "a pre-conceptual design phase."[32] ITER was designed to produce 500 MW of power from 50 MW of input power for pulses of 400–600 seconds duration.[33] DEMO is intended to yield a four-fold increase, 2 gigawatts of power produced on a continuous basis.[34] A further stage, PROTO, is envisaged for the second half of the century. All of this, of course, depends on the success of ITER, which is by no means guaranteed. In a best-case scenario, a commercial fusion reactor remains decades away.

Writing in 2015, Robert Hirsch, the former head of the US fusion program, concluded that "tokamak fusion power will almost certainly be a commercial failure."[35] He described the situation as "a tragedy in light of the time, funds, and effort so far expended." But Hirsch does not see the failure of tokamaks as a dead end for fusion research, instead suggesting that other technological approaches "can benefit from the lessons learned from the tokamak experience."

In late 2014, Lockheed Martin announced that it was developing a compact fusion reactor (CFR).[36] "Our compact fusion concept combines several alternative magnetic confinement approaches," reported project lead Tom McGuire, "taking the best parts of each, and offers a 90 percent size reduction over previous concepts."[37] Early production models of Lockheed's CFR, it was hoped, would be small enough to fit in a shipping container and produce 100 megawatts of power, enough to power 80,000 homes.[38]

Aside from the dimensions of the device, the most striking aspect of Lockheed's announcement was the projected timeline. A test CFR, it was claimed, would be built within a year, a prototype within five years, and an operational device within the following five years.[39] The project has progressed to a magnetized ion confinement experiment, but little further.

While much of the mainstream media were enthusiastic, publications such as the *MIT Technology Review* were rather more circumspect, pointing out that Lockheed "offers no data."[40] MIT's Ian Hutchinson noted that the confinement method described by Lockheed had long been studied without success.

> Based on [what Lockheed had released], as far as I can tell, they aren't paying attention to the basic physics of magnetic-confinement fusion energy … It seems purely speculative, as if someone has drawn a cartoon and said they are going to fly to Mars with it.[41]

The cost overruns and shifting schedules that have plagued controlled fusion research also occur in large-scale military projects. The F-35 Joint Strike Fighter development program is just one example.[42] In common with fusion research, these programs are primarily funded by the government and can sustain overruns. But unlike fusion, projects such as the F-35 or the troubled *Zumwalt*-class destroyer program eventually produce something of value despite the delays and escalating costs.

Having fallen short of predictions for more than six decades, controlled fusion's many false starts should not be seen as proof that it is unachievable. The first successful manned flight was preceded by a long history of failed attempts, some dating back millennia.[43] Unlike the Manhattan Project, an obvious point of comparison, a technological achievement as complicated as manned flight could not simply be forced into being. This is exactly what we have seen with controlled fusion.

It really does seem that we are just not ready for it yet.

Michael Fumento is best known for his writings about myths and hysterias in science and medicine.

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3. Sharon Begley, "The Race for Fusion – The Scientific Debate – Why the Stakes Are So High," *Newsweek*, May 8, 1989, 48–54.
4. See, for example, US President Jimmy Carter's "Address to the Nation on Energy," on April 18, 1977 in which he announced that the world was running out of both oil and natural gas. A transcript is available online at the *The American President Project*.
5. Spencer Weart, "The Discovery of Global Warming [Excerpt]," *Scientific American*, August 17, 2012.
6. Nathaniel Nash, "Sequel to an Old Fraud: Argentina's Powerful Nuclear Program," *The New York Times*, January 18, 1994. See also Enrico Fantoni, "Nuclear Island: The Secret Post-WWII Mega Lab Investigated," *Wired Magazine*, February 14, 2011; *Wikipedia*, "Huemul Project."
7. Charles Seife, *Sun in a Bottle: The Strange History of Fusion and the Science of Wishful Thinking* (New York: Viking, 2008), 99.
8. Lauren Merriman, "Examination of the United States Domestic Fusion Program Submitted to the Department Of Nuclear Science and Engineering," BSc diss., MIT, February 2015.
9. Douglas Martin, "Martin Fleischmann, Seeker of Cold Fusion, Dies at 85," *The New York Times*, August 11, 2012.
10. Charles Seife, *Sun in a Bottle: The Strange History of Fusion and the Science of Wishful Thinking* (New York: Viking, 2008), 207.
11. Rusi Taleyarkhan et al., "Evidence for Nuclear Emissions During Acoustic Cavitation," *Science* 295, no. 5,561 (2002): 1,868–73.
12. Charles Seife, *Sun in a Bottle: The Strange History of Fusion and the Science of Wishful Thinking* (New York: Viking, 2008), 2.
13. For further details, see *Wikipedia*, "Stellar Nucleosynthesis."
14. Charles Seife, *Sun in a Bottle: The Strange History of Fusion and the Science of Wishful Thinking* (New York: Viking, 2008), 212.
15. "Is Fusion Success In Sight?" *NBC News*, January 28, 2010; Eric Hand, "Laser Fusion Nears Crucial Milestone," *Nature* 483, no. 788 (2012): 133–34.
16. Bill Sweet, "National Ignition Facility: Mother of All Boondoggles?" *IEEE Spectrum*, October 5, 2012.
17. See Francie Diep, "National Ignition Facility Announces Record Amount of Fusion Energy," *Popular Science*, February 12, 2014; Paul Rincon, "Nuclear Fusion Milestone Passed at US Lab," *BBC News*, October 7, 2013; Tia Ghose, "Fusion Leaps Forward: Surpasses Major Break-Even Goal," *LiveScience*, February 12, 2014; "Is Fusion Success In Sight?" *NBC News*, January 28, 2010.
18. Paul Rincon, "Nuclear Fusion Milestone Passed at US Lab," *BBC News*, October 7, 2013.
19. Paul Rincon, "Nuclear Fusion Milestone Passed at US Lab," *BBC News*, October 7, 2013.
20. Daniel Clery, "Fusion 'Breakthrough' at NIF? Uh, Not Really…" *Science*, October 10, 2013. See also Daniel Clery, *A Piece of the Sun: The Quest for Fusion Energy* (New York: The Overlook Press, 2013).
21. US Department of Energy, *2015 Review of the Inertial Confinement Fusion and High Energy Density Science Portfolio*, DOE/NA-0040 (Washington DC, May 2016), 8.

22. Tom Hartsfield, "What to Do with a Failed $5 Billion Experiment?" *RealClearScience*, July 22, 2014. In 2012, the NIF facility was also used as the location for scenes in an upcoming "Star Trek" film. See Angela Hill, "Filming for 'Star Trek' Sequel at Lawrence Livermore Lab," *The Mercury News*, May 1, 2012.
23. *Le Laser Mégajoule*, "Introduction: The Megajoule Laser."
24. Bill Sweet, "National Ignition Facility: Mother of All Boondoggles?" *IEEE Spectrum*, October 5, 2012. Indeed, there was evidence all along it wouldn't work. In a 2014 interview, Stephen Bodner posed the question, "Why did they go forward with something that failed almost immediately?" Bodner has been a persistent critic of the NIF and in 1995 published a paper predicting that ignition would not occur. Bodner is a retired physicist who worked on fusion at Livermore during the 1960s and 1970s. Kenneth Chang, "Machinery of an Energy Dream, The Challenge: How to Keep Fusion Going Long Enough," *New York Times*, March 17, 2014.
25. Valentin Smirnov, "Tokamak Foundation in USSR/Russia 1950–1990," *Nuclear Fusion* 50 (2010), doi:10.1088/0029-5515/50/1/014003.
26. See *Princeton Plasma Physics Laboratory*, "Tokamak Fusion Test Reactor."
27. See *Eurofusion*, "Europe's Largest Fusion Device – Funded and Used in Partnership."
28. Rebecca Pool, "Fusion Energy: Promises and Problems," *Engineering & Technology Magazine*, June 16, 2014.
29. Charles Seife, *Sun in a Bottle: The Strange History of Fusion and the Science of Wishful Thinking* (New York: Viking, 2008), 207.
30. Rebecca Pool, "Fusion Energy: Promises and Problems," *Engineering & Technology Magazine*, June 16, 2014.
31. Daniel Clery, "UPDATED: Panel Backs ITER Fusion Project's New Schedule, But Balks at Cost," *Science*, April 28, 2016. MIT's Dennis Whyte has claimed that the final cost of the ITER will be in the range US$40–50 billion, based on the fact that the US is a 9% partner in the project with a contribution of US$4–5 billion. Lucas Mearian, "MIT Reactor Sets Nuclear Fusion Record on the Day It's Closed Down," *Computerworld*, October 18, 2016.
32. See *Eurofusion*, "DEMO and the Road to Fusion Power," October 19, 2016.
33. See *ITER*, "ITER Goals: What Will ITER Do?"
34. See *Wikipedia*, "DEMOnstration Power Station."
35. Robert Hirsch, "Fusion Research: Time to Set a New Path," *Issues in Science & Technology* XXXI, no. 4 (2015).
36. See *Lockheed Martin*, "Compact Fusion: It's Closer than You Think." This project was being undertaken at Lockheed Martin's famous "Skunk Works," where development took place for such advanced US military projects as the U-2 and SR-71 Blackbird, the F-117 stealth Nighthawk, and the F-22 Raptor. Most recently, however, it includes the trouble-plagued, horrifically overbudget, and behind-schedule F-35 Lightning II. Jeremy Bender, "Why the Pentagon Is Spending So Unbelievably Much on the F-35," *Business Insider*, April 30, 2014.
37. "Lockheed Martin's Skunk Works Builds a Fusion Reactor," *New Energy and Fuel*, October 16, 2014.
38. As described, the device uses deuterium-tritium fuel plasma in evacuated containment, but instead of constraining the plasma within tubular rings, a series of superconducting coils confine the plasma within the reaction chamber. Energy is supplied by radiofrequency heating. Superconducting magnets within the coils generate a magnetic field around the outer border of the chamber. The goal is attaining plasma pressure as great as confining pressure at a high enough temperature for ignition and net energy yield.
39. Andrea Shalal, "Lockheed Says Makes Breakthrough on Fusion Energy Project," *Reuters*, October 15, 2014.
40. David Talbot, "Does Lockheed Martin Really Have a Breakthrough Fusion Machine?" *MIT Technology Review*, October 20, 2014. See also, for example, Jesus Diaz, "Lockheed Martin's New Fusion Reactor Might Change Humanity Forever," *Gizmodo*, October 15, 2014; Guy Norris, "Skunk Works Reveals Compact Fusion Reactor Details," *Aviation Week & Space Technology*, October 15, 2014. *Aviation Week*'s report noted: "The team acknowledges that the project is in its earliest stages, and many key challenges remain before a viable prototype can be built."
41. Quoted in David Talbot, "Does Lockheed Martin Really Have a Breakthrough Fusion Machine?" *MIT Technology Review*, October 20, 2014.
42. Jeremy Bender, "Why the Pentagon Is Spending So Unbelievably Much on the F-35," *Business Insider*, April 30, 2014.
43. See *Wikipedia*, "Early Flying Machines."

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