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The Uncertain Future of Fusion Energy

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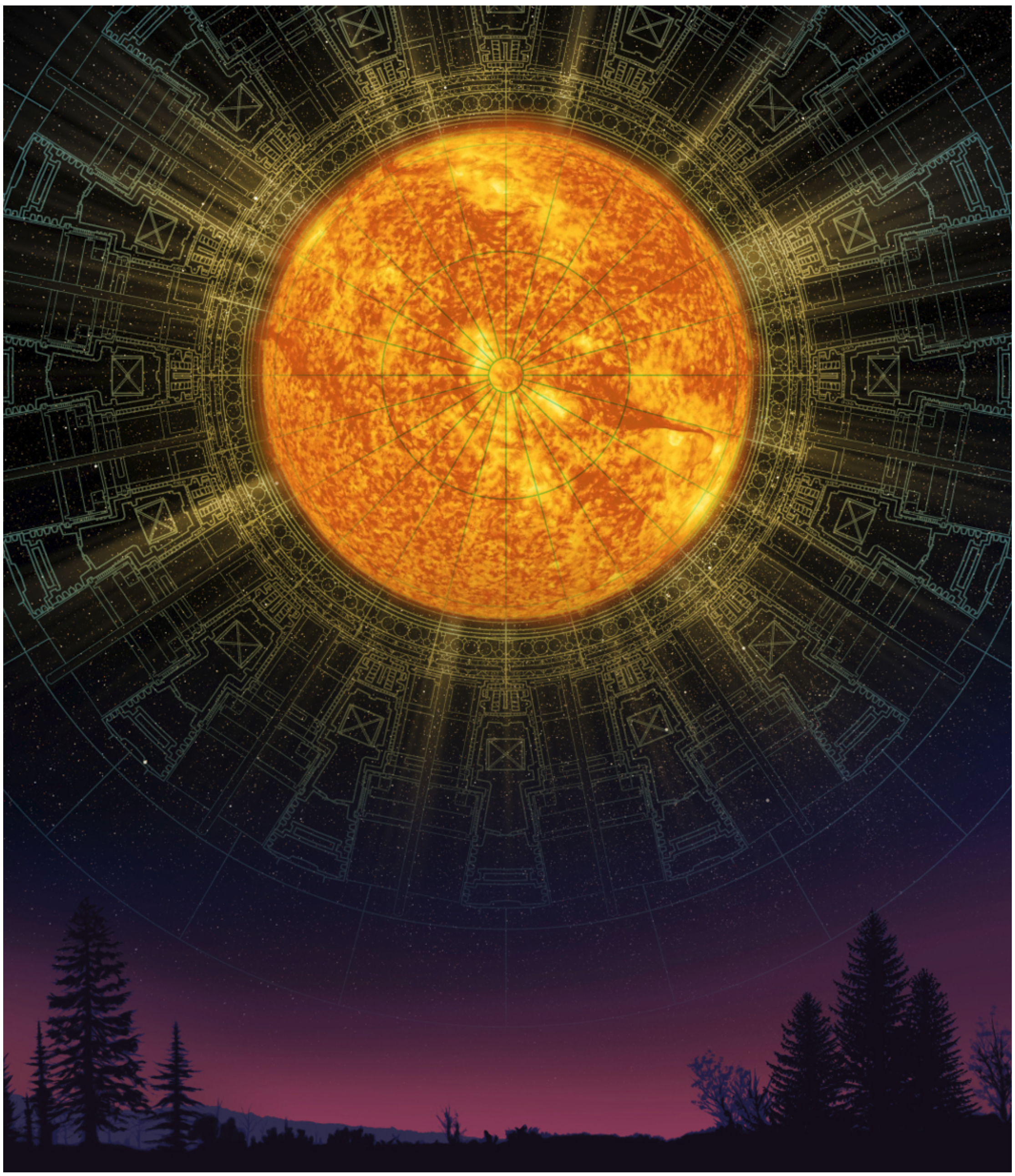

A giant reactor under construction seeks to achieve net energy gain, but some canny start-ups may get there first.

Nuclear fusion has long been hailed as the clean energy source of the future, but has so far failed to live up to this promise. Though it was only three years between the first nuclear fission detonation in 1945 and the first light bulb powered by a nuclear power plant, it has been 65 years and counting since the first fusion detonation in 1952 with no electrons to show for it.

A new documentary called “Let There Be Light” explains the history and promise of fusion, and offers first hand accounts of fusion’s technical, financial and political challenges. “Let There Be Light” recently premiered at the South By South West Film Festival and will be released more widely in the coming weeks. Written, directed and produced by Montreal-based Mila Aung-Thwin, the documentary showcases ongoing efforts to create an artificial star in a box. “I wanted to make a movie about the future of energy, what is even more out there than solar and wind,” says Aung-Thwin.

For future power generation, fusion reactors have unique benefits. Unlike conventional nuclear reactors, fusion reactors cannot melt down and do not produce radioactive material that can be weaponized or that requires special disposal. Safety and environmental concerns with fusion reactors are minimal, and the deuterium and lithium required for fuel can be extracted from seawater. A fusion power plant can, in aspiration, be built at a competitive capital cost and have virtually no input cost beyond operating expenses.

Fusion energy is produced within high-temperature plasma when small atoms, typically starting with hydrogen's heavier isotope of deuterium, are fused together into larger atoms. Funding for fusion, currently around $400 million a year and shrinking in the U.S. Department of Energy budget, peaked in the late 1970's during the energy crisis of the day. At the time fusion reactors had been making significant progress towards achieving the conditions required for net energy gain, in which more energy comes out the fusion reaction than is put in to create and sustain it. By doubling the product of the plasma temperature, density, and confinement time (known as Lawson criterion) every two years or so, fusion research was indeed making progress commensurate with Moore's law. However, to make significant additional progress a fusion reactor would need to be very big.

The Tokamak to End All Tokamaks

A tokamak (a Russian acronym for "toroidal chamber with magnetic coils") was originally a Soviet idea but has since been pursued in many other places including the United States, Europe, and Japan. A tokamak is an empty space in the shape of a hollowed-out bagel, surrounded by magnets. A ring-shaped plasma is contained within the hollow core around its center axis. Planning for a very large tokamak called the International Thermonuclear Experimental Reactor, or ITER, kicked off with a handshake between Reagan and Gorbachev in 1985. ITER is being designed and built to produce, maintain and study the plasmas required for future fusion power generation.

Large enough to essentially guarantee net energy gain fusion, ITER will be packed with enough control systems and sensors to fully characterize almost any conceivable plasma shape that could be used to generate power from fusion. Once the plasma characteristics are well understood, each signatory country can then go and build smaller, simplified practical reactors leveraging the knowledge gained at ITER.

ITER will not only be the largest fusion reactor to date, but also quite possibly the most ambitious engineering project in history and the most complex machine mankind has ever attempted to build. With partners including the European Union, the United States, Russia, China, India, Japan, and South Korea (even Iran wants in), ITER is turning out to be the sort of political and logistical challenge that could be expected of an international collaboration of this magnitude, particularly one of such long duration. Unfortunately, but not surprisingly, budget and schedule overruns reflect this reality. ITER’s current budget is on the order of $18 billion (no one knows for sure), first plasma is expected in 2025, and the intended fusion reaction of deuterium-tritium will not begin until 2035. Obviously this schedule may continue to slide, especially if

ITER remains underfunded.

American funding for ITER is directed toward domestic contributions, such as the central solenoid, a superconducting magnet being provided by General Atomics. Other critical American supplied subsystems include the cooling water system, the vacuum pumping system, and a host of diagnostics. Of the roughly $400 million the U.S. government typically spends annually on fusion research, about half is supposed to go to ITER development. However, the federal fusion budget is being cut to just over $300 million, and the current budget request for ITER is only $63 million; as of now the Senate does not have ITER funding in its budget at all.

Not funding ITER will result either in ITER's incompletion or in ITER's success without American participation. With Canada long since withdrawing, the U.K. considering doing so, and the United States underfunding its commitment, ITER's future is by no means secure. "ITER is a key stepping stone required for commercializing fusion. If we pull it off, we will have a clean, abundant energy source on the grid in probably 30 to 35 years. If we don't fund fusion, we risk blocking this path for generations," says Mark Henderson, a physicist working at ITER.

Fusion Start-ups

Unlike their government-backed brethren, whose fundamental purpose is plasma physics research, fusion start-ups are narrowly focused on building practical reactors for power generation. Burnaby, British Columbia based General Fusion is developing a fusion reactor that uses a toroidal plasma design similar to that in a tokamak. Instead of surrounding the plasma with an array of giant magnets, General Fusion is surrounding the plasma in a swirling vortex of liquid lead-lithium. The metal vessel containing the swirling lead-lithium will then be surrounded by an array of pistons. These pistons will compress the liquid in a coordinated way to subsequently compress the plasma at the center to a density high enough to sustain a fusion reaction.

Whether the plasma will behave as it needs to while being surrounded and pressed against by liquid lead-lithium is yet to be seen. However, if General Fusion manages to figure out how to continuously heat liquid lead-lithium through fusion, the challenges of running this liquid through a heat exchanger to generate power and process heat should be relatively straightforward, and so a practical power plant should follow soon after.

If General Fusion's liquid lead concept sounds audacious, an even more radical idea is being pursued by Foothill Range, CA based Tri Alpha Energy. Like General Fusion, Tri Alpha Energy's idea is based on technology developed in the 1970's, has remained largely under-explored, and is now advancing with the benefit of high-speed computing and precision controls that were not available forty years ago. Instead of a tokamak, Tri Alpha Energy's vessel uses field-reversed configuration (FRC), which is also a magnetic confinement device, but one in which the magnetic field lines are contained in the vessel without the need for a central channel (the "hole" in the tokamak bagel).

If tokamak plasma were shaped like a ring, Tri Alpha Energy's plasma is shaped more like the blanket portion of a pig in a blanket. With $500 million in committed capital claimed and backers such as Goldman Sachs, Paul Allen's Vulcan, Rockefeller's Venrock, and the Government of Russia's Rusnano, Tri Alpha Energy may be the only fusion initiative that could not claim to be underfunded. Their latest machine has been dismantled to provide parts for their next generation machine, which has a forecast price tag on the order of $200 million.

The audacity of Tri Alpha Energy's concept stems in part from the inherent difficulty of the boron-hydrogen fusion that is being pursued. This fusion reaction is an order of magnitude more difficult to achieve than the deuterium-tritium fusion of tokamak plasma designs such as ITER and General Fusion. To put this into perspective, the temperature at the center of the sun is about 27 million ^{O}F (15 million ^{O}C); while ITER's plasma would see temperatures of about 270 million ^{O}F, Tri Alpha Energy is expecting plasma temperatures around 5 billion ^{O}F, over two hundred times that of the solar core. Notwithstanding these mind-bogglingly high temperatures, boron-hydrogen fusion has the distinct advantage of not emitting any troublesome high-energy neutrons. If a suitable energy capture system could be developed, the resulting device could, in theory, be used for direct energy conversion for power generation.

Other fusion start-ups are also pursuing unique reactor designs. Redmond Washington's Helion Energy has raised around $20 million, including from the U.S. Departments of Energy and Defense. Helion Energy is building a fifth prototype and hopefully the first to break-even on energy balance, with plans to subsequently develop a 50-megawatt direct energy conversion device. The UK's Tokamak Energy is taking a more conventional approach, through miniaturizing tokamak technology. Tokamak Energy has recently achieved first plasma in their latest prototype and is aiming to deliver fusion power at commercial scale by 2030. Others such as Lockheed Martin and start-up Focus Fusion are also pursuing their own concepts.

Though each individual fusion initiative has a low probability of success, a diversity of concepts increases the likelihood that one of them will achieve net energy gain. The consequence of under-funding a wide range of fusion research beyond large tokamaks is that a potentially successful route to fusion energy is overlooked or neglected. As Eric Learner of Focus Fusion indicates in "Let There Be Light", although he cannot prove that his approach will work, nobody can prove that it will not, and no one yet knows which approach will best lead to practical and economic fusion.

Ultimately, the competition between ITER, other research initiatives, and the start-ups is a friendly competition. Though they may compete for funding, the fusion research community must by necessity collaborate to advance the science. "Our models tell us that ITER will achieve net energy gain, but I would love for a start-up to get there first. Ultimately I want fusion to be mastered," adds Henderson.

Fusion Investing

Notwithstanding the promise of fusion, investors are understandably concerned about the technological risks as well as the long-term nature of their required commitments. Even optimists would admit that within twenty years we will not see any grid connected fusion power, with the possible exception being a demonstration facility or two. In light of this reality, investors are still looking closely at fusion start-ups. If the plasma physics challenges of fusion can be solved, then the remaining engineering and economic challenges should be fairly straightforward, particularly for a technology such as General Fusion's, which lends itself well to existing grid connectivity and process heat applications.

Once a fusion technology demonstrates net energy gain and commercial viability, a second wave of investment would then enter. The financial risk for this second-wave investment depends more on engineering and commercialization than on technological viability, and so early investors may see an exit at this point. "Fusion right now is somewhat like airplanes right before the Wright Brothers flew for the first time," says General Fusion Founder and Chief Scientist Michel Laberge. "Once someone shows how it can be done, excitement will go up and then investment will pour in, but right now there is not much excitement in fusion," adds Laberge.

Those involved with "Let There Be Light" are hoping that the movie will raise awareness for fusion to help ensure that it remains in our long-term plan. Ultimately fusion's emergence for practical power generation relies on our collective interest in and commitment to fusion research. If the most dire climate models do in fact turn out to be right, the long-term future of our species might depend on it. Putting more chips on the fusion table today seems like a sensible hedge.

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