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Nuclear Fusion: Electrical Energy for the Future or Just Another Boondoggle?

In the opening months of 2018, there was a spate of news stories pronouncing a coming victory in the effort to achieve nuclear fusion — an unlimited, pollution-free energy source, the same source of energy that powers the sun.

The U.K. *Guardian* article entitled "Nuclear fusion on brink of being realised, say MIT scientists" was typical of the tone of the stories, with its subtitle reading, "Carbon-free fusion power could be 'on the grid in 15 years.'" The article quickly sums up the benefits of fusion and the biggest hurdles standing in the way of producing it:

Fusion works on the basic concept of forging lighter elements together to form heavier ones. When hydrogen atoms are squeezed hard enough, they fuse together to make helium, liberating vast amounts of energy in the process.

However, this process produces net energy only at extreme temperatures of hundreds of millions of degrees Celsius — hotter than the centre of the sun and far too hot for any solid material to withstand.

To get around this, scientists use powerful magnetic fields to hold in place the hot plasma — a gaseous soup of subatomic particles — to stop it from coming into contact with any part of the doughnut-shaped chamber [used to create a fusion reaction].

Let's unwind the fusion process a little further: As the word implies, fusion is the fusing together of two components to create a new atomic nucleus. Atoms typically repulse each other and do not fuse together except under great pressure and temperature. Under very extreme conditions, hydrogen isotopes "fuse" into a helium atom, at the same time emitting a neutron (more about that later) and a massive amount of energy — equivalent to approximately four times the amount of energy released when a uranium atom undergoes fission.

In the sun's core — since increased mass means increased gravity, and the sun is thought to compose 99.8 percent of all the mass in our solar system — the internal pressures are so great that hydrogen atoms fuse together to become helium at a temperature of about 15 million degrees Celsius (27 million degrees Fahrenheit). On Earth, pressures that equal those in the core of the sun aren't possible, so the temperatures must be greater to induce a fusion reaction. Not just a little greater, but at least 10 times as great as those of the sun: 150 million degrees Celsius or 270 million degrees Fahrenheit.

To contain both the plasma and the fusion reaction, scientists typically employ magnetic fields as containment vessels created in machines called tokamaks.

Of course, these machines do not use the same flexible magnets holding your school pictures or football schedule on your refrigerator door to contain the fusion reaction. Such magnets have a magnetic field of about 50 gauss (abbreviated G), while an iron horseshoe magnet may have a field of 100 G. The gauss, incidentally, is becoming an obsolete unit being replaced by the tesla, abbreviated, as you may suspect, T. The relationship is one T equals 10,000 G, which is the typical strength level for a scrapyard magnet. Other typical, strong magnets include those in industrial motors and transformers, which are made with a special steel alloy and can reach approximately 20,000 G, for moments at a time. We can say these industrial applications operate at a field strength of two T. This level of magnetic field strength is about as high as we will normally see outside of laboratories and hospitals.

The strength of a magnetic field is proportional to the current (amperes) in the coil circuit and the number of turns around the coil. For non-superconducting magnets, the heating effect of the current increases the resistance of the conductors that, in turn, causes a further increase in coil temperature, leading to failure. Moreover, some metals exhibit a saturation point such that increases in their current flow do not further increase their magnetic field strength. Fortunately, as noted below, there is a way around this problem.

Magnetic resonance imaging (MRI) scanners, which operate usually in the range of 1.5 to 3 T, are cooled to the temperature of liquid helium (4 kelvins, or 4 K), a major cost of this diagnostic procedure. As insulation to keep the liquid helium cold, there is a "blanket" of 77 K liquid nitrogen around the inner helium chamber. (Perhaps you're asking: "So what is this kelvin business?" The kelvin scale for temperature has the same divisions in degrees as Celsius but starts at absolute zero, which is minus 273.15 degrees Celsius, or minus 459.67 degrees Fahrenheit. To convert to kelvins subtract 273.15 from the temperature in degrees Celsius, or vice versa. For very high temperatures both are interchangeable, but in the cryogenic range, K is prevalent.)

Superconductivity is a bizarre characteristic of some metals and metal alloys. Few things in physics are absolute, but extensive research has scientists convinced that there is zero resistance in superconducting circuits. Once the current is flowing in a superconducting coil, it will continue forever.

Consequently, the metals that are used in electromagnets are cooled below their *critical temperature*, allowing electrons to flow unimpeded and making it possible to generate the magnetic field necessary to contain the fusion reaction. Without superconductivity, a fusion reactor would be impossible, as the power needed to create the magnetism would exceed any possible output of the reactor.

Until recently the record for a superconducting magnet was 23.5 T, a record made to be broken in the race for fusion-powered electrical generation. Florida-based National MagLab just raised the bar to 32 T using a newly developed material known as YBCO (for yttrium-barium-copper oxide).

The hurdles to achieving fusion are formidable, but now, we are led to believe, these will soon be overcome, and we will have limitless amounts of clean energy. And there are numerous efforts afoot to bring fusion about.

Some of the Contenders

Participating in the quest for the "brass ring" of energy research are diverse groups that encompass a range including country sponsors, universities, and private enterprises.

First let us pause to identify the milestones on the progress to a working fusion reactor. The initial goal is "first plasma," wherein a reactor is able to successfully generate and contain a mass of electrically charged gas — plasma — inside its core. This has been accomplished by numerous reactors, both those that use multiple lasers to heat a pellet of fuel and the magnetically contained tokamaks that are the leading contenders for producing fusion power.

The next point on the path to fusion-energy nirvana is "breakeven," when the amount of energy produced from the fusion reaction is equal to or greater than the energy required from an outside source to sustain the reaction. This point has never been reached.

Finally, the holy grail of fusion is known as "ignition" and is analogous to an automobile when you engage the starter — and varoom! You have a self-sustaining reaction such that as long as you send gasoline to the engine, or the hydrogen-isotope fuels to the tokamak, the reaction continues. No one is even close to this in 2018.

But as was said, there are those making the effort:

ITER: The prima donna of fusion reactors is the International Thermonuclear Energy Reactor under construction in St-Paul-lez-Durance, France. It is difficult to find words to describe the facility — colossal and gargantuan are the best that come to mind. Begun in 2007 with "partners" EU, Japan, China, India, North Korea, Russia, and the United States, the initial cost was supposed to come in at $5.6 billion with a completion date in 2017. The new director-general, Bernard Bigot, now predicts "first plasma" in 2025. A follow-on generating plant is planned to be available in 2045 for actually producing electricity — provided someone is still living who can remember what the project was all about.

The ITER machine will weigh 23,000 tons, the equivalent of three Eiffel Towers. The 18 superconducting magnetic coils are 18 feet high and 10 feet wide, each weighing 310 tons — the weight of a fully loaded Boeing 747.

ITER is rolling some very big dice. If successful, we may have that limitless, clean, reliable energy usually found only in science fiction. But if not, it will take a very large dustbin to accommodate this history.

ARC and SPARC: MIT is collaborating with newly formed Commonwealth Fusion (Cambridge, Massachusetts) in the design of a tokamak reactor using high-temperature superconducting magnets. This is made possible by development of the aforementioned superconducting material YBCO that exhibits superconductivity at temperatures as high as 90 to 100 K, permitting a reduction in the size of the reactor. In addition, it has the valuable property of maintaining its super-magnetism in magnetic fields higher than 25 T.

SPARC, Commonwealth's smaller demonstration reactor, is now under construction. A pilot plant — based on the ARC acronym of "affordable, robust, and compact" — is planned, presumably if the demonstration reactor is successful.

Tokamak Energy: Based in Oxfordshire, U.K., the company has developed its ST40 spherical tokamak reactor, which is claimed to have achieved a temperature of over 15 million degrees Celsius — about the temperature of the solar core. Plans are to continue to the fourth stage in a five-stage plan that, it is claimed, will deliver a plasma temperature of 100 million degrees Celsius — high enough to sustain a fusion reaction on Earth. Hmm, maybe.

The company plans to build an energy-generating reactor by 2025 that will provide an output of several megawatts. (A typical coal or nuclear plant is in the 1,000 to 1,500 megawatt range.)

Lockheed Martin: In 2014, the company's California "Skunk Works," renowned for its aeronautical miracles such as the U-2 and SR-71 spy planes, announced a planned truck-sized fusion plant that could provide 100 MW, enough to power 100,000 homes. The company appears to have had a decimal-point problem, however; they found later that they didn't have enough capacity within the tokamak to produce 100 MW. The reactor would have to be 100 times the size of the original estimate.

One shouldn't rule this innovative company out however, as some of its reactor patents are considered revolutionary.

JET: Located at the Culham Science Centre in Oxfordshire U.K., the Joint European Torus is the largest operating fusion reactor in the world, and prides itself on generating a temperature of 300 million degrees Celsius.

It seems odd that a fusion reactor built in the early 1980s holds the world record for power generation by a nuclear fusion experiment, namely a pulse of 16 MW. The only drawback to the experiment was the necessity to provide 25 MW of power to the plasma for this to occur — not exactly breakeven, but record-setting nonetheless.

EAST: In April 2018, the BBC was allowed a tour of the Experimental Advanced Superconducting Tokamak located in the Dongpu Science Island in Anhui Province, China. Under the direction of the Chinese Academy of Science, the researchers claim to have sustained a single fusion reaction for more than 100 seconds, which, if true, would stand as a world record.

There are other entities in the race, including Germany's Wendelstein 7-X *stellarator* and the now-inactive but still operational Alcator C-Mod tokamak at MIT. And we can't overlook General Fusion, employing *magnetized target fusion* — a project of Jeff Bezos and Amazon.

Given the expense of the complex hardware and the costly scientific know-how involved in creating fusion, it seems unusual that there is so much activity in this highly technical field, but then certain fame and fortune await the successful developer of a working system.

Problems in Fusion Paradise?

Besides the obvious high research and development costs and complexity of fusion, there are fusion hurdles that have not seen the light of media exposure. Let's look at some:

Isotopes: Isotopes are two or more forms of the same element, with equal numbers of protons but different numbers of neutrons. In fusion the isotopes of hydrogen are a major part of the discussion. A hydrogen atom, 1H, is the predominant isotope of the element, comprising 99.98 percent of all hydrogen on Earth. It has one proton and no neutrons. 2H is the isotope normally referred to as deuterium and given the symbol D. (No other element has common names or letter designations for its isotopes.) D has one proton and one neutron. 3H is known as tritium, has the symbol T, and has one proton and two neutrons. While H and D are stable, T is radioactive with a half-life of 12.32 years, which means that virtually none of it will be found naturally occurring — and this is a problem.

The sun can produce its energy by proton-proton fusion, resulting in helium being produced from four hydrogen atoms. In the sun, two deuterium atoms can also be fused into helium, although there is relatively little deuterium in the sun. On Earth — because fusing two deuterium atoms only produces about one-twentieth of the energy compared to a deuterium-tritium reaction and fusing the most prevalent hydrogen atoms is not possible — tokamak-based experiments rely on deuterium and tritium fuels.

And while fusion-power enthusiasts often refer to the fuel for fusion reactors as being available in unlimited supply from seawater, that's not quite true. While there are 33 milligrams of deuterium per cubic meter of water, thus allowing extraction of the isotope, there are only infinitesimal amounts of tritium. Tritium isn't even listed as a trace gas in Earth's atmosphere.

A pretty good estimate of the scarcity of a substance is its cost. Tritium comes in at $30,000 per gram, about the mass of a paper clip. As of the year 2000, the U.S. demand for the isotope was 400 grams per year.

ITER News and Media estimates that every fusion reactor will require 100 to 200 *kilograms* of tritium per year. That's *kilograms*, not *grams*. So with today's pricing, the tritium fuel to run a fusion reactor would cost a tidy $3-6 billion per year. (One kilogram is $30 million, times 100 to 200 kg per reactor.) Not only would this make magnetic containment fusion reactors uneconomical, there likely isn't the capacity to process the necessary amount of tritium, as evidenced by the Department of Energy's 1996 (latest available report) showing only 225 kg was produced in the 40 years prior to the report.

For ITER to be self-sustaining, it would have to create its own tritium through "breeding" the isotope in a nuclear process where the neutron expelled in the fusion reaction is used to transmute the isotope lithium-6 into a helium nucleus and tritium, a "not inconsiderable feat." Plans are to mount experimental blanket lithium modules inside the ITER vacuum vessel to test the breeding concepts. According to ITER News, while "the results of the tritium breeding experiments will be open to all members, each provider will keep manufacturing details a secret due to the high commercial stakes linked to tritium production."

None of this — tests, experiments, secrets — gives your correspondent a warm fuzzy feeling about the assurance that this is going to be a slam dunk.

That Neutron Again: A second serious problem with generating limitless fusion energy is the neutron that is expelled during the deuterium-tritium reaction. While this neutron flux may be used to transmute tritium from lithium-6, it can also make other materials brittle and radioactive, perhaps too radioactive to allow humans in the vicinity of the reactor.

Tungsten, the metal with the highest melting point, 3,683 degrees Celsius, and the highest tensile strength of any metal at temperatures over 1,550 degrees Celsius, along with excellent corrosion resistance, was expected to be a mainstay of reactor materials. But that has recently been found to be doubtful.

Scientists at the University of Huddersfield, in England, with new facilities designed for experiments to aid the development of fusion reactors, have found tungsten is liable to become brittle, leading to structural failure. Researcher Dr. Robert Harrison states, "At this moment in time, even though tungsten is a leading candidate, we don't see how we can use it as a structural material. We can use it as a barrier, but not for anything structurally sound."

Many materials, particularly metals, are made up of a lattice of atoms. When one of these atoms captures a neutron, it is no longer the original material, but transmuted to some other element or elements. A break in the lattice weakens — embrittles — the host material, and the new material in the lattice may cause neutron-induced swelling similar to a blister that degrades surface characteristics and other properties of the metal.

There are other concerns and skepticisms of fusion power, which are explained in an American Physical Society forum paper by Daniel Jassby entitled "Fusion Reactors Share Seven Drawbacks of Fission Reactors." Among them are:

• Nuclear proliferation: A fusion reactor can become a source of weapons-grade plutonium simply by placing natural or depleted uranium inside the reactor vessel, where the high neutron flux will produce plutonium 239.

• Radiation shielding: Even when the reactor is not in operation, the intensely radioactive environment would require remote-handling equipment robots for even minor maintenance.

• Coolant demands: A fusion power plant would need water for cooling — from a river, lake or aquifer — water that will be used once then treated as wastewater. Water needed for "once through" cooling might amount to 30,000 gallons per megawatt-hour and would likely meet competition from agricultural and industrial interests.

• Outsized operating expenses: Current fission power plants require a high degree of training, with typically 500 employees for a 1,000 MW plant. Fusion plants are much more complex and would require at least a doubling of personnel. A natural-gas plant takes only a handful of attendants.

All these items raise the question of how much "unlimited energy" is going to cost us.

Fusion vs. Fission as It Relates to the USA

Presently, the development of fusion energy is following an eerily similar path to "green" power sources, e.g., wind and solar power. Research is largely done on the public dime, and if and when scientists can get the system to operate, it might be so costly and impractical that it would be virtually useless to our country.

If you have read carefully, you will have noted that all of the projects are still "experimental," seeking "breakeven" on the way to "ignition" on the way to functionality on the way (at last) to power generation. Only ITER has plans for producing significant electricity (if everything else works) in 2045, and that planned output of 500 MW is not particularly impressive, being only half or less than that of a typical nuclear fission or coal-fired plant.

If our country is to maintain a competitive position in the international marketplace, it must have cheap, reliable sources of electrical energy. It may come as a surprise to some that "free" sunlight and "free" wind are not the same as free electricity. In fact, the countries with the highest percent of wind and solar — namely Germany and Denmark — have the highest costs per kilowatt-hour of electricity, with Germany, at 36 cents, being three to four times the U.S. rate of 10 to 12 cents.

International competition in the race to provide inexpensive power promises to be stiff. While China, like the United States, is a partner in ITER, it is not sitting around waiting for a fusion miracle. China has 14 new fission power reactors scheduled to be on line by or before 2020. The United States? Zero. The International Atomic Energy Agency projects the U.S. fission nuclear generation capability to be reduced from the current 20 percent to 11 percent, while the rest of the world is predicted to grow by

123 percent.

What has happened to our country? Have we forgotten how to build the fission plants that were the mainstay of the world, or are we tangled up in bureaucratic tape and anti-industrial litigation by the likes of Greenpeace and the Natural Resources Defense Council? Below is a short case history:

In 2005, the Nuclear Regulatory Commission approved the final design certification rule for the Westinghouse AP1000 nuclear power plant. (AP is for Advanced Passive: One of the "Advanced Passive" features is a system reaction, without operator input, to open valves allowing 72 hours of core coolant water to flow — not from pumps, but from the quite reliable force of gravity.) After lots of legal wrangling, the NRC approved the construction of two reactors in Georgia. At this point the generators are expected to come on line in late 2021 and late 2022.

The Chinese, on the other hand, received the final design certification at the same time in 2005 for two nuclear plants. One is already on line, and the other is expected on line later this year. What does this tell us? China, India, Brazil, and others are dedicated to having a competitive infrastructure, while we are allowing an entrenched cadre of leftist bureaucrats to stifle what is our best, most reliable source of clean, abundant, dispatchable electrical energy for at least the next generation: nuclear fission power reactors.

Nuclear Fission Scares

Of course, Americans have worries about the safety of nuclear power plants, having heard horror stories about nuclear meltdowns at Three Mile Island, Chernobyl, and Fukushima Daiichi in Japan.

But facts should overwhelm the fears. At Three Mile Island the only harm to the public was caused by the news media's coverage exaggerating the problem and causing mental stress and anxiety. Chernobyl was caused by a reactor designed for both power and breeding bomb-grade plutonium by the Soviet government. There was no containment structure, and the moderator was carbon, which can and did burn, causing the deaths of 31 responders, but there were no deaths or harm to the public from radiation.

The Fukushima earthquake and tsunami caused the deaths of more than 19,000 people, and the distress of being relocated for no good reason was responsible for an additional 2,500 deaths, yet Fukushima is called a nuclear disaster by the media.

In the United States, radical environmentalists concentrate on the supposed dangers of nuclear wastes and nuclear-waste storage, such as at the Yucca Mountain repository, where, incidentally, despite years of engineering work and the natural safety of being built under a mountain of solid rock, not a gram of "waste" has ever been deposited.

But other countries that have nuclear power reactors, such as France, the U.K., Russia, and Japan, don't suffer from waste problems. They reprocess their "spent" reactor fuel, to use again. It still contains more than 97 percent valuable uranium, in addition to a relatively small amount of plutonium that arises during the fission process. The remaining three percent of high-level wastes are glassified to be tucked away in salt formations that haven't seen water in millions of years. These wastes would have the same radioactivity in 300 to 400 years as did the ore they came from.

Unfortunately, U.S. reprocessing efforts were halted by Presidents Jimmy Carter and Barack Obama both times they were instituted. Why? Nuclear proliferation! Supposedly the presidents feared bandits might hijack trucks of spent fuel and leach the plutonium 239 out of the fuel rods and build a bomb. Ironically, a fusion reactor is so rich in neutrons that terrorists could just put bricks of natural uranium in the tokamak and cook them like a pound cake into weapons-grade plutonium.

It is 27 years until ITER is planned to begin generating fusion power. Between now and then, the United States could continue the engineering charades of so-called renewable energy or build hundreds of safe, modular fission power plants to provide cheap, reliable power to our industries. Sadly, leftist politicians and environmentalist groups would like nothing more than to thwart our country's success and prosperity.

Producers of high-energy-content products are currently flocking to the United States to take advantage of our reliable, relatively inexpensive electricity, such as that produced by the Palo Verde fission plant outside Phoenix, which sells energy to California wholesalers at two cents per kWh. (Of course, it gets marked up and taxed to 16 cents before reaching the residential market.) If we continue financing renewable energy windmills and solar collectors with subsidies and destroy our reliable generators, in 30 years we will be high-priced has-beens, much as Germany, Denmark, Italy, and Spain are becoming today. Even our most loyal energy-intensive industries would leave, or go under.

It is rumored that President Trump is not looking with favor on our participation in the ITER project. Perhaps we can help President Trump understand these problems on the way to Keeping America Great Again.

Photo: iter.org