Fusion Energy: the Agony, the Ecstasy and Alternatives

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Abstract

Most fusion research reactors confine the nuclear fuel using magnetic fields. John Perkins argues that we should not forget alternative methods, and calls for a diversified world fusion program.

Introduction

Fusion — the release of nuclear binding energy from light nuclei and its practical exploitation — has been a major world research discipline for the past four decades. It promises to be an energy resource capable of indefinitely sustaining humanity under all conceivable scenarios of population growth and energy demand. In fact, fusion is the only energy source indigenous to Earth that will last as long as our planet exists.

That's the ecstasy, so what's the agony? The problem is that although we have made enormous progress in our scientific understanding of fusion, we have, as yet, no clearly identified route to an attractive commercial fusion power plant that will sell in the energy marketplace of the 21st century and beyond.

Arguably, this situation has been exacerbated by the fact that the world's fusion community has prematurely concentrated on a single route to fusion power. This route is the conventional tokamak, in which magnetic fields are used to confine the nuclear fuel. Moreover, because we are still at a relatively early stage of fusion development, it is essential to strive for a diversified program that can withstand the physics and technological uncertainties that accompany any single class of fusion-reactor concepts.

People often ask whether we will actually need fusion energy in the next century. Here at least there is an answer. Electrical power generation in the 21st century will be an industry worth tens of trillions of dollars, and there will be an assured and significant growth in demand from the developing world. The question really is whether we will have a fusion-reactor product that will be sufficiently attractive to compete in this marketplace? If we do, then fusion will be "needed."

The future viability of fusion energy therefore comes down to the question of the competition. So what else is out there? In the near term, the answer will continue to be fossil fuels in general, and natural gas in particular. However, once our access to such fossil fuels is foreclosed due to either exhaustion, environmental constraints or sequestering for other, more critical needs, there will remain only two indigenous energy sources that can fully sustain humanity for the foreseeable future. These are fission and fusion. Although renewable energy sources, such as solar power, will undoubtedly play important niche roles in the next century, they will not be able to sustain the central base-load demands of future society.

Fission versus Fusion

So how does our ultimate conception of a fusion reactor compare with fission? Both fission and fusion are forms of nuclear energy, but they can be differentiated by various attributes, including their capital costs, safety, environmental impact, proliferation problems and fuel availability. If the presently known reserves of fission fuels were used to sustain the full electrical energy needs of future populations, these fuels would probably not last for more than about 100 years using conventional thermal reactors with a “once-through” fuel cycle. However, such reserves could be made to last for thousands of years if they were efficiently used in breeder reactors with a reprocessed-fuel cycle. Uranium could also, in principle, be extracted from sea water, although we do not yet have the technology to achieve this.

In contrast, lithium — the primary fuel for “first-generation” deuterium-tritium fusion reactors — is significantly more abundant in the Earth’s crust than either of the primary fission fuels, uranium or thorium. Lithium is also about 50 times more abundant than uranium in sea water. And deuterium, which is arguably the ultimate fusion fuel for “second-generation” deuterium-deuterium fusion, comprises 0.015% of all of the hydrogen on Earth by atomic ratio. Thus, (deuterium) fusion is a fuel reserve that will be available to us for as long as the Earth exists.

What about the relative safety of fusion and fission power? The stored energy in the fuel of a fission core is sufficient for about two years of operation. So although adequately safe fission reactors probably can be designed, this stored energy could trigger severe accidents. In contrast, the amount of fuel in the core of a fusion reactor — of whatever class that we can conceive of today — is sufficient, at most, for only a few seconds of operation. The fuel would also be continually replenished.

The other disadvantage of fission is that spent fuel rods in a fission core contain giga-Curies of radioactivity in the form of fission products and actinides, some with half-lives of hundreds or even millions of years. Such radionuclides therefore have to be disposed of into securely guarded repositories deep underground. In contrast, the main potential for generating radioactive waste from fusion comes from neutron activation of the structural materials that surround the reactor. A judicious choice of these materials can reduce fusion’s potential biological hazard by many orders of magnitude relative to spent fission fuel. Indeed, such materials would not need to be disposed of in a long-term waste repository.

Perhaps most importantly, we must recognize that the exploitation of breeder reactors to extend the fission fuel reserves of uranium and/or thorium beyond the next century will result in significant reprocessing traffic of 239Pu and/or 233U. Although international safeguards and security could no doubt be implemented, the diversion and exploitation of even a few kilograms of these materials would be a severe test of the public’s stamina for this energy source.

Can Tokamaks Work?

To what extent do fusion’s tangible advantages compensate for the present perceived disadvantages of the cost and complexity of the fusion reactor core? I believe that this question has not yet been fully addressed - either by the world fusion community or by its detractors. In fact, it cannot be satisfactorily answered until our physics research programs have matured enough to identify the path to a tangible commercial-reactor product. We have made tremendous scientific progress in the world fusion program over the past 40 years. That is incontrovertible. Our basic understanding of the rich and complex phenomena underlying plasma physics has increased profoundly, as has our ability to control these processes to our ends. In particular, our achievement of the basic “figure of merit” for magnetic-confinement fusion — the product of the plasma density, energy confinement time and plasma temperature, n*T — has increased by around six orders of magnitude over this period. It is now approaching the value required to realize a self-sustaining ignited burn in a mixture of deuterium and tritium fuel, in which no external energy would be required.

To date, most of the world’s fusion research funds have been spent on the tokamak approach. Because of the tokamak’s capacity for holding heat and its effectiveness in achieving the required magnetic-field configuration, it has proved to be the best research tool so far for achieving fusion conditions in the laboratory. For example, the Joint European Torus (JET) tokamak at Culham in the UK should soon approach — and hopefully exceed — "scientific break-even", at which the fusion energy output exceeds the external energy injected to drive the reaction. Despite the pulsed fusion devices that demonstrated (perhaps unfortunately for humanity) extremely high fusion gains in the early 1950s, this will be a unique and exciting achievement for thermonuclear fusion research.

So we have some confidence that the tokamak can conceivably produce a fusion power reactor that works. For these reasons, the International Thermonuclear Experimental Reactor (ITER) project — a multi-billion dollar international engineering design study of a burning fusion plasma experiment — has focused on the tokamak as its vehicle of choice. However, it is not clear that the conventional tokamak approach will lead to a practicable commercial power plant that anyone will be interested in buying. This is a consequence of its projected low power density, high capital cost, high complexity and expensive development path. After all, the acid test for fusion energy is, ultimately, not its scientific achievements but whether it will be adopted by the market. Certainly, the tokamak is a valuable scientific research tool for studying high-temperature plasma physics and it must continue to be supported to that end. However, such support should not — and must not — come at the exclusion of other, potentially viable routes.

Alternative Options

The main alternative to the tokamak in the world fusion energy program is the stellarator, and there are vigorous research programs on this concept in both Europe and Japan. However, I believe that in the future, companies that are looking to build electricity generating plants that are cost-effective and reliable will view a fusion reactor based on the stellarator as being no different to that based on the tokamak. In other words, we must acknowledge that the tokamak and stellarator are two closely related approaches that belong to the same class of fusion concepts. If the tokamak ultimately turns out to be too expensive and complex to engineer — and so fails the commercial reactor test — then so might the stellarator.

These future uncertainties are best addressed by broadening our range of approaches. I believe that at this formative stage of fusion research it is too early - and unnecessary - to put all our eggs in one basket. It is beyond the scope of this article to examine an exhaustive list of alternative fusion concepts but, fortunately, a number do exist at varying stages of maturity. Within magnetic-confinement fusion, the spherical torus, the spheromak and the field-reversed configuration could lead to a much cheaper, more compact fusion-power core. These designs are certainly worth pursuing to the proof-of-principle stage. In particular, there is one class of fusion concepts - inertial fusion energy (IFE) - that can be considered a step change in their manner of realizing fusion energy.

In IFE, a millimeter-sized capsule of fusion fuel is compressed by an energetic pulse of energy from a "driver", which is typically a heavy-ion accelerator or a laser. The drive energy is delivered in a precise way to cause the fuel capsule to implode, creating - during the short inertial time before the target flies apart - the high densities and temperatures necessary for fusion to occur.

Although both magnetic and inertial fusion are at about the same stage of scientific understanding, the scientific and technological criteria by which these two distinct approaches will succeed or fail are very different. In particular, IFE provides a route to a fusion power plant that is a paradigm shift away from that of a tokamak and indeed from that of all other fusion concepts of the magnetic-confinement class. It offers, I believe, the potential for lifetime fusion chambers with renewable liquid coolants facing the targets, instead of solid, vacuumtight walls that would be damaged by heat and radiation.

Protected in this way, all of the reactor structural materials would be lifetime components, and their minimal residual radioactivity would mean that at the end of the fusion plant's life, the materials could be buried on-site and near the surface, rather than deep underground. The use of such thick liquid protection would probably also eliminate the need for an expensive R&D programs on exotic, low-activation materials. Moreover, IFE plants are inherently "modular", in that several, independent fusion chambers could be constructed around a single driver. This provides operational redundancy, in that one chamber could be shut down for maintenance while the others are up and running. This also provides the option that the plant could be expanded in phases to match any growth in demand. These are both important characteristics for future multi-GWe electrical reservations.

Our scientific understanding of inertial-confinement fusion should also be significantly advanced early in the next century by the completion and operation of the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in the US, and the Laser Megajoule (LMJ) facility in France. Indeed, the NIF may be the first laboratory device to realize fusion "ignition". This is the process whereby the energy deposited by energetic alpha particles from the deuterium-tritium fusion reaction promotes a self-sustaining burn in the surrounding fuel, resulting in significant fusion energy gain.

Although the primary missions of both the NIF and the LMJ are defense related, a spin-off benefit of the NIF — and presumably the LMJ — is to show that inertial-fusion energy is feasible. Of course, much parallel work still needs to be done so that these demonstrations can be converted into the technical and economic success of an inertial-fusion power plant. In particular, today's lasers are not suitable for power-production applications, and the development of a suitable and cost-effective driver is the decisive research area.

Heavy-ion accelerators are attractive candidates for IFE because they build on our extensive experience with high-energy and nuclear physics facilities. They also promise efficiency, long life and magnetic final optics — whereby the beam is focused onto the target — that are relatively immune to the effects of the target explosions. Certainly, the high ion currents needed are a new and challenging element. Other candidate drivers include diode-pumped solid-state lasers as well as krypton fluoride lasers. The problem is that the development of IFE as a distinct class of alternative fusion concepts is not being pursued with the funding vigor that it deserves in the world fusion energy program. Because of the long lead time required to bring a new energy technology to market, this situation must change if we are to provide society with the technical information necessary to pursue inertial-fusion energy to its full potential in the next century.

The Future for Fusion?

I believe that advances leading to a clearly economic fusion reactor lie in the parallel investigation of alternative approaches, rather than simply in engineering the nuts and bolts for the present conventional approach. This is particularly important for the US, where fusion research budgets have declined in recent years and where a fresh, vigorous rationale is required. The smartest investment of our world research budgets would be to press for innovation and understanding of the physics of various advanced concepts — this is, after all, where the greatest uncertainties lie, and where the greatest potential exists for improving the economics of the ultimate fusion power plant.

Alternative physics approaches are particularly important if we are ever to exploit the so-called "advanced" fusion fuels, such as d-d, d-^{3}He and p-^{11}B (see table). Such fuels suggest several advantages over "conventional" deuterium-tritium reactions. For example, they produce few or even no neutrons, and they could even directly convert charged fusion products into electricity without the need for a conventional thermal cycle. However, such fuels would require significantly higher plasma densities and temperatures to realize the same fusion power density as deuterium-tritium plasmas.

As in cancer research, the world fusion program has made enormous progress in the fundamental understanding of its field. But, again like cancer research, we have not yet arrived at our ultimate goal. Because of the profound benefit to future humanity of the ultimately successful end-point — a limitless energy source for all time — we must continue with an innovative and, most importantly, diverse fusion research program until that goal is accomplished.

References

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