Fusion–fission hybrids revisited

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With the increasingly urgent need to find solutions to the impending energy crisis, there is growing interest within the fusion community in revisiting the concept of the fusion–fission hybrid reactor. But how soon could such reactors be realized, and could they meet the challenges of the coming century?

The worldwide demand for energy continues to grow at an unprecedented rate. This, combined with the dwindling supply and increasing cost of fossil fuels plus the realization of the threat they pose to the global climate, has led to a renaissance in the nuclear power industry. Yet despite improvements in the design of nuclear-fission reactors, there remain public concerns about their safety and the waste that they produce. Many have suggested that harnessing nuclear fusion could provide a better way to meet the world's energy demands, with greater safety and long-term sustainability, and much smaller quantities of long-lived waste than that produced by nuclear fission. But even the most optimistic of assessments predicts that this technology will not be able to produce electricity on a commercial scale for at least another three decades. Such issues have led to a resurgence of interest in a third nuclear option, which combines aspects of both technologies in the form of the fusion–fission hybrid reactor.

The fusion–fission hybrid

One of the basic properties of nuclear fission is the requirement of a constant flux of thermal neutrons to drive the splitting of heavy nuclei. In a conventional reactor these neutrons are supplied by the fission reaction itself, which requires a certain concentration of the correct fissile isotopes (typically ^{235}U or ^{239}Pu) to be present in the reactor's fuel rods. Each fission reaction releases a huge amount of energy (about 200 MeV) but requires a chain reaction for the reactor to remain self-sustaining.

By comparison, a fusion reactor generates an abundance of neutrons without the need for a chain reaction, but releases less energy per reaction. Each time a deuterium nucleus fuses with a tritium nucleus (the two hydrogen isotopes that are the most promising for use in a fusion reactor), it produces a 3.5-MeV alpha particle and a 14.1-MeV neutron, a total of only 17.6 MeV. For the fusion reaction to be sustained, a constant supply of new fuel must be fed into the reactor.

The fusion–fission hybrid was conceived to capitalize on the advantages and minimize the disadvantages of both processes, neatly encapsulated by Lidsky in his 1975 review of the subject[1]: "Fusion reactors are 'neutron rich' and 'power poor' while fission reactors are 'neutron poor' and 'power rich' ". The idea, then, is to build a hybrid device, the core of which consists of a fusion reactor whose purpose is to supply a steady flux of neutrons to a surrounding blanket of fissile materials (see Fig. 1). Such a reactor could generate electricity, produce fuel for conventional fission reactors or provide a way to transmute the long-lived actinides of nuclear waste into shorter-lived and materials that are more safely disposable. These are not new ideas, with the earliest reference dating back to Sakharov in 1951 (ref. 2). Yet despite the numerous detailed studies of their potential that followed[1,3–9], the conclusions have been the same: further development could not be justified, as the fusion component of such a system was technologically complex, scientifically risky and significantly more expensive than alternatives. So what has happened to change these conclusions? To see why none have ever gone beyond the drawing board — and why some researchers feel that it is time that they should — it is important to understand the pros and cons of each application, and to relate them to their wider context.

Subcritical electricity production

An often cited but not technically significant advantage of a hybrid is that it allows a fission blanket to be operated subcritically. To ensure an adequate supply of neutrons to drive the fission process, a conventional nuclear reactor must operate at a level that is self-sustaining: at least as many neutrons are produced as are consumed in the fission process or non-productively absorbed in other non-fissionable materials. Because the neutrons of a hybrid are supplied externally from the fissile fuel, there is no need to concentrate this fuel to maintain criticality. Thus a criticality accident in a hybrid is physically impossible. But such accidents are also extremely unlikely to occur in a properly designed light water reactor (LWR) with negative temperature coefficients. In such a design, as the temperature goes up, the neutron population goes down, thereby shutting down the reactor. This is in contrast to the Chernobyl reactor design, which did not have this feature. There, the reactor had a positive temperature coefficient, meaning that as the temperature went up so too did the neutron population.

In practice, however, the safety of a conventional nuclear power plant is not primarily determined by criticality accidents but by other accidents and transients resulting in a failure to deliver enough cooling water to the core after a reactor is shut down. Nevertheless, for the past 25 years the safety record of the nuclear power industry in the United States has been nothing less than remarkable. This situation has improved still further with the advent of advanced LWR designs that are substantially simplified in comparison with older reactors, therefore involving fewer components that might fail, and incorporating passive fail-safe features that cause them to shut down safely without manual intervention when something goes wrong. Most scientists and engineers consider the safety issues of conventional reactors to have been more than adequately resolved by these designs.

And so it is difficult to make a compelling case on the basis of safety for the development of more complex and costly hybrid designs, as both technologies will require emergency core-cooling systems to remove decay heat from the fission process should there be a 'loss of coolant' accident. In other words, if producing electricity safely is the goal, then LWRs are the most economical nuclear solution.

Fissile fuel production

A future concern for LWRs is that the fuel supply will eventually run out or become too expensive to mine. However, with a sufficient flux of hybrid-produced neutrons, the desired fissile fuel isotopes can be produced by neutron capture from the much more abundant non-fissile isotopes ^{238}U or ^{232}Th. This generates ^{239}Pu in the case of the former and ^{233}U in the case of the latter, both of which can readily be used to power LWRs or used directly in sodium-cooled fast breeder reactors, which produce more fuel than they consume, owing to the production of ^{239}Pu in the blanket from ^{238}U.

Even so, a recent study[10] has estimated that the accessible reserves of natural uranium are sufficient for the next 50 to 100 years, even assuming a 10-fold increase in the number of nuclear reactors from those that exist today. Consequently, the issue of fuel supply is a long-term issue, and not one that demands the large and immediate investment that would be necessary to develop a hybrid on a short timescale (25–30 years). For the foreseeable future, the most economical way to obtain fuel for LWRs is to dig it out of the ground.

Safe nuclear waste disposal

As has already been noted, demand for CO_2-free electricity is growing. As yet, there is no demonstrated industrial-scale process to sequester the enormous amounts of CO_2 produced by coal. Wind and solar power, because of their intermittent nature, their high cost and the absence of inexpensive large-scale energy storage, are not well suited to replace baseload electricity. Simply put, nuclear fission is the only large-scale option available today for the next generation of CO_2-free, baseload power plants.

There are currently about 100 LWRs in the United States, producing 20% of the nation's electricity. Although there have been no new reactors ordered since the Three Mile Island accident in 1979 — an event that turned majority public opinion in the United States against nuclear power — there have been 26 applications for Construction and Operating Licenses and four new orders for US plants during the past two years, spurred by the growing demand for CO_2-free electricity plus the existence of a long-term stable fuel supply. Internationally, the growth in the number of nuclear power plants is even more rapid.

Despite this demand and the advances made in the safety and design of fission reactors, the issue of waste remains a barrier to the public's willingness to accept (or at least be comfortable with) the re-emergence of nuclear power. This concern has recently focused on the proposed nuclear waste disposal facility at Yucca Mountain in Nevada, and the decision of the Obama administration to terminate consideration of this facility, a decision based on politics and not science. With no clear long-term political solution to the growing problem of what to do with the nuclear waste produced in the United States and throughout the world, this issue represents the most promising near- to mid-term application for a fusion–fission hybrid.

One possible solution is transmutation, which converts long-lived nuclear waste (the minor actinides plus, if desired, plutonium) into short-term non-fissile waste that can be disposed of more efficiently in a geological repository. Transmutation is accomplished by bombarding the long-lived waste with high-energy neutrons and is one way to ultimately increase the storage capacity of a geological repository like that proposed at Yucca Mountain by an order of magnitude. Most recent fusion–fission hybrid studies have recognized this fact and focused on the transmutation of long-lived actinides.

With half-lives of the order of thousands of years, the actinides represent the most important long-term radioactive toxicity hazard. It should, nevertheless, be noted that the total volume of actinides including plutonium produced by a LWR generating 1 GW electrical power for one year is only about a cubic foot — not a very large volume. However, it is not just the actinides that need to be considered. Several of the lighter, long-lived byproducts of fission, such as ^{99}Tc and ^{129}I, are more soluble in moist soil and therefore can more easily be transported to underground water supplies, so they also represent a risk to public safety. Moreover, these lighter elements are inherently more difficult to transmute.

At present, there are two alternative non-fusion approaches that have been proposed for transmuting nuclear waste: non-breeding sodium-cooled fast-spectrum reactors or particle-accelerator-driven spallation hybrids. Both of these options are more developed than the fusion–fission hybrid. Which one will ultimately turn out to be the more desirable from the technological, proliferation, economic and environmental points of view remains to be seen. But from a purely economic point of view it seems that the best approach is not transmutation but disposal of waste in a permanent repository, storage in an interim repository or burial in deep bore holes. In fact the US Department of Energy has already demonstrated long-term disposal for transuranic military wastes quite effectively at the WIPP facility in New Mexico.

The disposal situation for commercial spent fuel is more complicated. Until policy makers decide whether to bury 'once-through' nuclear waste permanently, for instance in a repository such as Yucca Mountain, or instead to reprocess (that is, chemically separate out the actinides and plutonium), the best solution is likely to be an interim storage facility or the continued use of on-site storage at existing nuclear plants. This strategy makes both economic and technological sense. There is no crisis, because commercial waste has already been successfully stored on site in spent

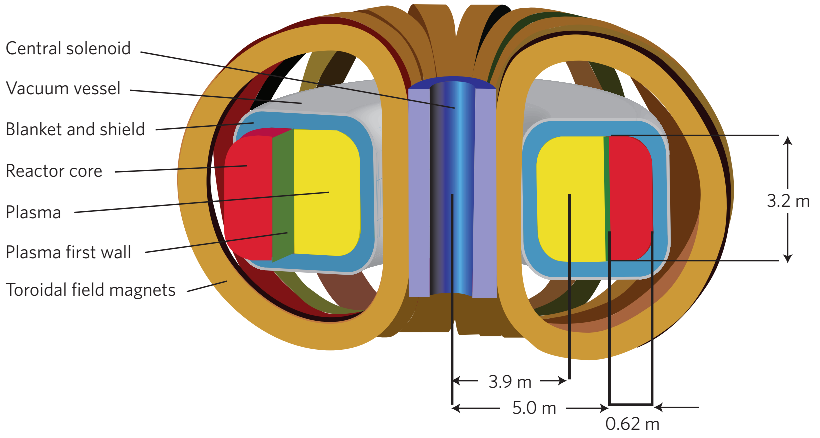

Figure 1 | The most common hybrid design consists of a fusion reactor core surrounded by a blanket of fissile material such as uranium or thorium. The generation of neutrons by the fusion of hydrogen isotopes in the core drives fission reactions in the blanket. These neutrons can be used to generate electricity, produce nuclear fuel for LWRs or transmute waste. Reproduced with permission from ref. 7; © 2008 ANS.

fuel storage pools of water and dry cask storage, as well as in government facilities around the country for almost 50 years. Furthermore, no matter how much waste is transmuted, there will always be some left over so that a long-term geological repository will still be needed, although the storage capacity of a given repository could increase by an order of magnitude compared with the once-through fuel cycle.

What is the bottom line with respect to the nuclear industry? The most useful application of the fusion–fission hybrid is in nuclear waste management. But this does not address the most important immediate problem facing the industry, which is the high capital cost of the plant. The cost of a hybrid further adds to the cost of electricity, as it would be more expensive than either interim or on-site storage because of the complexity and scale of the fusion machine required. The overall implication is that even if the hybrid were available tomorrow, it would not have a game-changing short-term impact on the fission industry because of economics. Stated differently, there may be industrial interest in the use of hybrids for waste management, but only on the mid- to long-term timescale.

The US Department of Energy, on the other hand, has a shorter, more immediate need. The government has the legal responsibility to dispose of nuclear waste and is way behind schedule in doing so. Here the hybrid could help. There might also be an indirect benefit to industry in that if an economically and environmentally credible solution to waste disposal was available that did not require multiple repositories of the type found at Yucca Mountain, the government might be more supportive of the nuclear renaissance. In short, the hybrid could represent a perceived technical solution to an immediate political problem.

At present, then, the transmutation of nuclear waste seems to be the nearest-term application of hybrids, with the government being the primary customer.

Hybrids in fusion research

Fusion research has now been going on for about half a century, with most of the attention focused on understanding the plasma physics required to confine and heat a plasma to thermonuclear temperatures at a high enough density for net power production. Great progress has been made, and it seems that much, although not all, of the scientific uncertainty about fusion associated with early hybrid studies has been greatly reduced.

Still, there are remaining plasma physics issues facing the leading magnetic fusion concept, the tokamak. First, plasma confinement in the presence of a dominating amount of fusion produces alpha-particle heating; second, efficient non-inductive steady-state operation, which is not possible using the tokomak's transformer; and third, plasma disruptions, which are large-scale magnetohydrodynamic instabilities, can quite literally inflict material damage on the first wall and vacuum chamber of the reactor. These issues are expected to be addressed by the ITER project.

There are also engineering and technology problems associated with the hybrid. An important unsolved plasma engineering problem involves interactions between the plasma and the first wall (that is, the first material surface that makes contact with the plasma). The related issues involve heat load, neutron wall loading, refuelling and impurity removal. There are equally important basic fusion technology problems — materials, blanket design, tritium breeding, magnet development, gyrotron and neutral beam source development, remote handling, reliability and maintainability. All of these problems must be solved in an integrated fashion if the hybrid is to achieve an economically satisfactory capacity factor. Overall, the engineering and technology problems are of comparable difficulty to the plasma physics problems, yet there has been only a small and rapidly diminishing basic research effort in the US fusion programme devoted to engineering and technology problems.

From a plasma physics perspective, a key advantage of the hybrid is that the fusion power gain (the ratio of fusion power produced to power required to maintain the plasma) need only be a value of about 2, as compared with over 50 for a reactor that generates electricity from fusion alone. The reduced plasma physics requirements have led many members of the fusion community to conclude that the hybrid is an attractive intermediate goal on the path to pure fusion electricity. There is merit to this position, although not as much as one might think because of the unsolved engineering and technology problems. A hybrid could be developed in perhaps 25–30 years as compared with 35–50 years for pure fusion electricity.

Finally, there is a rarely discussed issue facing the fusion community that further motivates the development of the hybrid. Pure fusion electricity, when developed, will still have to compete with LWRs for market share, assuming that solutions are in hand to the LWR waste problem and, in the longer term, fuel supply problems. This is likely to be a difficult competition because of the inherent high capital cost associated with the fusion core, the result of lower power density and increased technological complexity. Interestingly, the fusion–fission hybrid may offer attractive solutions to the LWR problems of waste and fuel supply, thereby postponing the time when pure fusion electricity will be needed.

The conclusion is that the hybrid could serve as an intermediate stepping stone to pure fusion electricity but it also may serve as an end goal in itself, making fission power a sustainable source of electricity for thousands of years.

Outlook

The hybrid may be attractive as a short- to mid-term fusion goal for the fusion community. But there is not a sufficiently compelling case to demand an urgent, Manhattan-like project for its development. The nearest-term (25–30 years) commercial application is to transmute nuclear waste from spent fuel. The hybrid may indeed be a very good way to process radioactive waste but there are other, more mature options (fast reactors and accelerator hybrids) that will be competitive technologically and economically, with the ultimate winner to be determined. A longer-term (50–100 years) commercial application of the hybrid is the production of fissile fuel, which has the important advantage of enabling the nuclear industry to remain focused on LWR technology rather than the breeder. The weakest link in the design of a hybrid, and other fusion systems in general, comes from the unaddressed engineering and technology problems associated with the fusion component of the reactor. Addressing these problems is an indispensable first step in any fusion application, whether it is for electricity, fuel production or waste management, and an important area for future research. ❐

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