The Many Q's of Nuclear Fusion

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1 Introduction

There are ongoing research programs in nuclear fusion funded by consortiums of governments. Periodic advances in these programs generate breathless journalistic enthusiasm tempered with the remark that practical applications are not expected in our lifetime. This research note provides relevant background for understanding the engineering challenges in creating a practical electrical power plant based on nuclear fusion. Our goal is to help the reader to understand the nature of the progress that is being made better than can be gleaned from the bald press releases and journalistic responses.

2 Fuels

The fuel for nuclear fusion is hydrogen. All hydrogen atoms contain a single proton. They may contain 0, 1 or 2 neutrons. These three variants are known as isotopes. The three isotopes of hydrogen are respectively protium (H), deuterium (D) and tritium (T.) Tritium is unstable and transforms by beta decay into helium-3. The decay process is moderately rapid; after 11 years half the original tritium has decayed. Because of its short half-life tritium does not occur in nature. Deuterium, by contrast, is stable and occurs intermixed with protium in nature. In particular natural water (H_2O) contains approximately 0.0014% HDO.

Because the weight of deuterium is about twice that of protium, its physical properties and chemical equilibrium constants are different. This provides the basis of several industrial processes for preparing deuterium gas D_2 from water feedstock. In the GS process (also known as the Girdler sulfide process or as the Gelb-Spevack process) differential equilibrium constants are exploited to enrich the content of heavy water D_2O in natural water via the reactions

$$\begin{aligned} H_2O + HDS &\longrightarrow HDO + H_2S \\ HDO + HDS &\longrightarrow D_2O + H_2S \end{aligned}$$

This process can be run as a cascade producing 1.82 enrichment of D_2O at each stage. Once the concentration of heavy water reaches 20% nearly pure heavy water is seperated out by fractional distillation. The distillation process works because the boiling point of D_2O at 101.4C is slightly above the 100C boiling point of H_2O. Finally electrolysis extracts deuterium gas D_2 from D_2O. An alternate process uses ammonia rather han hydrogen sulfide as the exchange medium in the first stage of the process. Favorable economics result from attaching the process to an ammonia plant. Finally when electric power costs are very low (for instance at a hydroelectric facility) an electrolysis cascade may be set up to purify heavy water directly from regular water. A famous incident of World War Two involved the sabotage of such a plant in Norway. Heavy water plants are typically sized to produce 1000 ton per year quantities. Production costs are controlled by the price of power and a gram of deuterium currently costs about 70 cents.

Whereas deuterium is purified from water, tritium must be manufactured. The process begins by bombarding lithium compounds with neutrons. Currently nuclear power reactors are the usual source of the neutrons. Some lithium is converted to tritium and the tritium is seperated out by physical and chemical processes. At present the only major use of tritium is to build hydrogen bombs and so there has been no need to scale the process up or make it economical. Over the past half century the US has manufactured about 75kg of tritium and the gas currently costs $30,000 per gram. Despite the high cost, it has found minor commercial application as a safer substitute for radium in phosperescent watch dials.

Based on current production processes a gram of DT fusion fuel costs $18,000 per gram. In a completely efficient fusion reactor that gram of material would produce heat equal to 53 barrels of oil with a cost of about $4,7770 currently. As this simple calculation shows, reducing the production cost of tritium to about $7,500 per gram is necessary for an economically competitive process. Producing all of the US's electric energy production from DT fusion would require approximately 1000 tons per year of fuel, so a scale up of tritium production processes would also be required.

Fusion reactors produce considerable neutron fluxes of their own. These fluxes could be applied to breed tritium from a lithium substrate. In principle this could be organized into a self sustaining industrial process such that a minimal amount of tritium would be needed to start the reactor and thereafter it would breed its own tritium supply. No one has yet demonstrated this breeding concept at scale. If we assume success with this process then the only fuel input to a fusion reactor would be deuterium, which as we have noted is readily available at low cost. This remark is used to support the journalistic puffery that fusion promises unlimited electrical power virtually cost free.

Actually the claim of unlimited cost free power ignores substantial operating and capital costs. As a supplier of electrical power fusion will need to compete with solar and wind which of course have no fuel costs. The likely niche of fusion power would be as a base load/seasonal swing load producer. In that role it currently competes against natural gas fired plants and fission reactors. Natural gas produces climate unfriendly emissions and fission is costly and bedeviled by safety issues. Accordingly there may be a role for fusion. Until climate issues became top of mind, however, there was considerable doubt about the ultimate economic viability of fusion reactors. That concern in part explains the chronically underfunded status of government R&D in this field for the past fifty years.

Three reactions are relevant to fusion reactor work

$$\begin{aligned}&\mathrm{D}+\mathrm{D}\longrightarrow \mathrm{He}+\mathrm{n}(3.27)\\&\mathrm{D}+\mathrm{D}\longrightarrow \mathrm{T}+\mathrm{H}(4.03)\\&\mathrm{D}+\mathrm{T}(0.01)\longrightarrow \mathrm{He}(4.3)+\mathrm{n}(17.1)\end{aligned}$$

Here He denotes a helium nucleus, also known as an alpha particle and n denotes a neutron. The numbers in parentheses give the kinetic energies of the different species in units of millions of electron volts (MeV.) Both reactions require some considerable energy to be initiated but produce more energy than the input. The neutron flux produced by the D + T reaction has the unfortunate consequence of rendering the surrrounding apparatus radioactive. As a result, most fusion experiments are done with the D + D fuel mix and the results extrapolated to D + T. Some apparatus is built to run on either mix. In this case the D + D experimental series is completed before the D + T series is begun. In this approach, the hope is that the D + T series will confirm the accuracy of the extrapolation from D + D.

We are interested in the D + T reaction because this is the reaction most likely to result in a useful fusion reactor. It is traditional to use Q to denote the ratio of output power to input power. There is a whole ladder of interesting Qs. The first is the pure reaction ratio. The D + T reaction initiates at a supplied energy of 0.01 MeV (per atom) but yields 17.1 MeV so $Q_{DT} = 1710$. By contrast the first D + D reaction initiates at 0.1 MeV and thus $Q_{DD} = 32.7$. Thus the D + T reaction is both easier to start and much more productive.

3 Fusion Engines

Discussions of fusion use unfamiliar physical units and thus give rise to the belief that the process is very remote from daily experience. Actually D + D fusion can be demonstrated at small scale in a table top apparatus called a fusor. This device is only slightly more complicated than a neon sign. The whole complexity of power generation from fusion is one of scaling up to an industrial scale while maintaining favorable energetics.

However this scale up is attempted, the ultimate use of fusion is simply to supply heat to boil water. Generated steam is then used drive a steam turbine for production of electric power. As noted above, most reactor concepts seek to breed tritum from lithium. Accordingly the designs call for a liquid lithium salt which is circulated into the fusion reactor to extract heat and to convert lithium to tritium. Outside the reactor the salt circulates into a heat exchanger to boil water and then to a purifying station to extract tritium.

There are two basic designs under consideration for fusion reactors: tokamaks and inertial confinement. In a tokamak we construct a large torus shaped vaccuum chamber with a D shaped cross section and surround it with powerful magnets. Field strengths of about 13 teslas are required, so superconducting magnets powered by hundreds of thousands of amps of electrical power are used. The fuel mix is injected in an ionized state and the magnetic field confines it to a toroidial volume within the vaccuum chamber. Ion beams and microwaves are beamed into the fuel mix, heating it to about 100 million degrees, at which point fusion occurs. The alpha particles generated by fusion reactions are captured by the fuel mix and contribute to heating it. The neutrons flow out of the fuel mix and as a result cool it. The neutrons deposit their energy into circulating lithium salt lining the interior surface of the reaction vessel, thus heating it up. In addition the transformation of lithium to tritium generates heat as well. This reaction contributes about 10% of the total extracted heat.

In inertial confinement fusion (ICF) the process is rather different. The DT fuel mix is produced as a frozen droplet and placed in a metal capsule which is positionned at the center of a spherical reaction chamber. The capsule is blasted with ultraviolet rays from high power lasers. The walls of the capsule give off x-rays which compress and heat the internal fuel pellet and generate shock waves which converge at the center of the pellet. The central point is raised to fusion conditions. Alpha particles generated by the fusion then propagate into the shell around the center raising it to the point of fusion. In this way the fuel pellet fuses from the center outwards. The entire process might be considered as a rearrangement and miniturization of some of the the design concepts used in the hydrogen bomb. This is not an accidental similarity. The ICF concept was first proposed by Edward Teller and the US government has funded the research primarily to build detailed physical understanding of how the hydrogen bomb works. However, the idea is not just a simple application of bomb technology. Ten years of engineering refinement has gone into shaping the laser pulse and refining the design of the fuel target. Primarily this work has centered on understanding the hydrodynamics of the bombarded fuel and controlling its instabilities so as to achieve maximum yield from the fuel.

Converting inertial confinement fusion to a power plant is not so different from the tokamak. Neutron flux is captured in the wall of the reaction chamber. Lithium is transformed to tritium and heat is routed to steam generation. Unlike the tokamak, however, the ICF is a rapidly pulsed design. Concepts for a power plant envision 50 fuel pellets per second being processed through the reaction chamber.

4 Tokamak Engineering Analysis

For the tokamak we define $Q_{scientific}$ as the ratio of fusion power produced to heating power applied. A reactor for which $Q_{scientific} = 1$ is said to have achieved scientific break-even. Some of this produced power feeds back into heating the fuel, so reducing the need for applied heating power, some is lost as gamma rays and some is captured as useful heat. In tokamak designs about 79% of raw produed power is available for power generation. This power is then converted to electric power with an efficiency of about 40% in the steam plant. This electrical power is used to power the microwaves which heated the fuel in the first place. The conversion of electrical power to fuel heating proceeds with an efficiency of about 70%. These considerations lead to

$$Q_{engineering} = \frac{\text{electrical power produced}}{\text{electrical power consumed}}$$

Achieving $Q_{engineeering} = 1$ is known as engineering break-even. It is estimated $Q_{scientific}$ must reach 5-8 for engineering break-even to occur. Some of the electrical power produced must be used to power the magnets, process the fuel and run all the other operations of the plant. This leads to

$$Q_{plant} = \frac{\text{electric power produced}}{\text{power used in operations}}$$

Then plant break-even is at $Q_{plant} = 1$ which is the point at which we transform from an experiment in power production to an actual producer of power. Finally we have

$$Q_{economic} = \frac{\text{value of sellable power produced}}{\text{operating and capital costs of plant}}$$

Then $Q_{economic} = 1$ represents economic break-even at which point we have a viable power production business.

To date no tokamak has achieved even scientific break-even. The JT-60 experiment in Japan achieved an estimated $Q_{scientific}$ of 1.35 based on $\mathrm{D} + \mathrm{D}$ experiments, but available data suggests an actual $\mathrm{D} + \mathrm{T}$ experiment would give $Q_{scientific} = 0.65$. The JET experiment at Cambridge has achieved $Q_{scientific} = 0.67$ with a $\mathrm{D} + \mathrm{T}$ burn. The next experiment in the tokamak development program will be the ITER in France. It has been designed as a scale up of the JET experiment. If things scale properly, it should achieve $Q_{scientific} = 10$ and $Q_{engineering} > 1$. The experiment is currently under construction. It should start taking $\mathrm{D} + \mathrm{D}$ data in 2025-2030. After about 10 years of $\mathrm{D} + \mathrm{D}$ burns it will be reconfigured for $\mathrm{D} + \mathrm{T}$ burns, and so enginering break-even could occur in the 2040s. Planning is underway for a follow on DEMO experiment aimed at achieving plant break-even. Construction might start in 2050 and hopefully plant break-even would be demonstrated by 2070.

There are several different reasons why the tokamak development program moves at this leisurely rate. The first problem is that magnetic confinement of the fuel mix is only a quasistable process. Instabilities build up in the circulating fuel which cause it to leak out of the confined region and quench the fusion reactions. In principle we could learn how to attenuate these instabilities by running computer models of the process. The physical equations governing hot fusing magnetically confined plasma are just about the most challenging models known, however. Computer models must be cross checked against reality every step of the way before they can be usefully applied to design problems. Second, the instabilities are mainly ameliorated by scaling up the apparatus. The ITER will be an enormous machine. Its vaccum vessel has an outside diameter of 64 feet, an inner diameter of 21 feet and a heigth of 37 feet. Constructed of steel, it has a weight of 5116 tons. The rest of the plant is to scale and the estimated final construction cost is estimated at between 20 and 65 billion dollars. The uncertainty in cost results from farming components out to the different countries involved in the funding consortium and differences in administration make a unified cost figure correspondingly uncertain. Before allowing this expensive machine to irridated by $\mathrm{D}+\mathrm{T}$ burns, it is first desirable to extract as much knowledge as possible from a long series of $\mathrm{D}+\mathrm{D}$ burns. There are also some outstanding practical engineering problems with the tokamak design:

1. Fuel which leaks out of magnetic confinement needs to be swept from the vaccum chamber.
2. Efficient production of tritium needs to be demonstrated.
3. Optimal construction materials for long exposure to high neutron fluxes need to be determined.
4. Procedures for maintaining the apparatus with the remote handling gear required by the radioactive environment need to be worked out.

These problems are additional to verifying successful scale up of the JET design and the tuning of computer models to the new operating range. The mix of different issues make it unlikely that a breakthrough on a single issue could materially accelerate the entire program.

5 Inertial Confinement Engineering Analysis

For this design we define

$$Q_{scientific} = \frac{\text{power produced}}{\text{laser heating power applied}}.$$

The $Q_{engineering}$ is defined as before as

$$Q_{engineering} = \frac{\text{electrical power produced}}{\text{electrical power used}}$$

Currently conversion of electrical power to laser power is very inefficient with efficiencies of 1-2%. Thus a $Q_{scientific}$ of 50-100 must be achieved to reach engineering break-even. The inertial design does not require the powerful magnets of the tokamak design, so plant break-even is only a small step beyond engineering break-even.

Recently the US Lawrence Livermore National Laboratory announced that it had achieved $Q_{scientific} = 1.53$ in a single pellet experiment. To scale this up to an operating reactor either the $Q_{scientific}$ must be raised to 50-100 or the efficiency of the lasers must be significantly increased so that engineering breakeven is achieved at a lower $Q_{scientific}$. Also the laser cycle time must be cut from minutes to fractions of a second so that the reactor can process about 50 fuel pellets per second. In fact, the laser plant at the laboratory was not optimized for power consumption and even ten fold improvements in efficiency may be possible with alternate lasers now that the needed operating specifications are understood. An encouraging fact is that fusion power output scales as the fourth power of applied heating. Increasing $Q_{scientific}$ to 100 requires an increase in heating power of only about 2.85x. Another good attribute of the ICF approach is that it operates directly with DT fuel rather than the slower experimental process of tokamak experiments. Indeed the engineering obstacles of ICF now appear to be mainly in laser technology rather than in fusion specific engineering.

There is thus the possibility that ICF development can proceed at a faster pace than tokamak development. It is difficult to estimate how quickly this work might proceeed as the experimentation is ongoing at a national laboratory whose primary focus is strategic weapon systems. It seems likely, however, that work on high power lasers will be accelerated and perhaps a ”moonshot” project will be organized to accelerate technological development.

6 Safety Issues

Experience with fission reactors has shown that there are three principal safety concerns with such machines. First, the machines must be operated under tight and complex control conditions. Short excursions outside the design operating band can result in the machine destroying itself. In general, commercial operators are leery of multi-billion dollar investments that can self destruct in moments due to operator error. Second, the machines require continuous pumping of cooling fluids through their interior. Failure of cooling systems can result in meltdowns which not only destroy the machine but also pollute township size areas with long lived nuclear waste. Third, the normal process of the plants creates tons of long lived radioactive waste which must be stored safely for thousands of years. Dealing with these safety issues makes fission power very costly and waste storage remains an outstanding problem.

Currenty it seems fusion reactors would have some safety issues, but not such severe issues as fission plants. From a health perspective it is not recommended that one drink heavy water or breathe tritium, but exposures must be at the macroscopic rather than trace level before there is a significant concern. The magnetic fields of the tokamak design store energy equivalent to twelve tons of TNT. If a superconducting magnet suffers a cooling fault it self destructs and takes its near environs with it. Thus the tokamak design has some of the same brittleness as the fission reactor but it does not imperil surrounding habitations. As the fusion reaction must continuously be fed with fuel and heating power, a run-away fusion reaction is impossible with these machines. The neutron irridation eventually turns the reaction vessel into radioactive waste. Careful selection of construction materials should, however, avoid production of long lived or hard to manage waste products.

7 Advanced Concepts

DT fusion is the approach receiving the greatest reearch and funding because it is the apparently most practical approach. Other concepts, however, receive discussion and funding at the exploratory level. Generally these efforts look to overcome fundamental challenges of the DT process.

A combination of tritium and helium-3 can be used to catalyze a pure deuterium fusion reaction $6\mathrm{D} \longrightarrow 2\mathrm{He} + 2\,\mathrm{H} + 2\,\mathrm{n}$ The power output is 43.2

MeV which is 2.5x the DT reaction for 3x the fuel input. As only deuterium is consumed in the reaction, fuel input cost is negligible. In a tokamak design the conditions for initiating this reaction are daunting. In an ICF design the reaction may be more feasible. Currently the main source of helium-3 is harvesting tritium decay products from hydrogen bombs. This is not exactly a commercial source. However if tritium breeding is successful then helium-3 should be more readily available.

Aneutronic fusion uses fusion reactions which generate minimal neutron fluxes. Instead their primary energetic outputs are alpha particles. Minimizing the neutron flux avoids the problem of induced radioactivity in the surrounding plant. An alpha particle flux can theoretically be transformed into electric power output at much higher efficiency than the steam plant of neutronic fusion designs. The primary reaction considered for aneutronic fusion is $\mathrm{H} + \mathrm{B} \longrightarrow 3\mathrm{He}(8.7)$ Here B represents the boron-11 isotope. This isotope constitutes about 80% of naturally occuring boron and thus is readily available. However bringing this fuel to fusion requires about 10 times more heating than the DT mix. Although the power yield of this reaction is only half that of the DT mix, greater efficiency in electric power generation may compensate for that detriment.

8 Summary

The tokamak research program has high probability of reaching plant break even, but the program is currently planned to take 50 years and multiple technical breakthroughs are likely needed. The ICF program presents different engineering challenges and may require fewer technical break throughs. At least potentially it could move much faster than the tokamak program. These are still engineering research projects and it is entirely unclear if commercial deployment at scale will ever occur. In a decade's time we should be able to form a better estimate of ultimate commercial potential and the time to get there. In particular a well funded power generation oriented ICF program could deliver a positive surprise.