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Nuclear Fusion: A Primer

Abstract

Fusion energy has seemingly been ‘right around the corner’ for almost sixty years now. Many have lost faith that a viable fusion reactor design will ever be developed. However, a surge of private funding has sparked renewed public interest in the potentially unlimited energy source. While the emergence of a private fusion energy industry may be bringing a long-overdue wave of fresh ideas and new perspectives, it has only increased the opacity of the industry from an outsider's perspective. With multiple ventures claiming breakthroughs and milestones, it is difficult to gain an accurate understanding of the development without a detailed understanding of the requirements for fusion. This thesis is an attempt to demystify a complex science and undercover some of these requirements. With a better understanding of the physics behind fusion energy development, time and resources might be directed towards the ventures that have the highest potential for success.

Introduction

Nuclear fusion is defined as a nuclear reaction in which atomic nuclei of low atomic number fuse to form a heavier nucleus with the release of energy. Fusion reactions power every star in the universe including our sun, and therefore are the source of all other forms of energy on earth. Doing fusion here on earth is both deceptively easy and exceptionally difficult. Just making a fusion reaction happen is relatively simple. Famously, 14-year old Taylor Wilson did so in his home in 2008 (Clynes). Creating a fusion power plant, however, is exceptionally difficult. The gap between Taylor Wilson and a commercially viable fusion facility can be summarized simply as *efficiency*.

The Fundamentals: Motivation

A meaningful analysis of fusion energy must be firmly grounded in fundamental physics. Other forms of energy have much more intuitive fundamental science. The underlying science to the entire fossil fuel industry, from coal to oil to natural gas, can be understood by simply observing a burning match. Hydropower and wind are perhaps even simpler in their purely mechanical nature. Solar power, while the energy conversion mechanism from photons to electrons might not be readily familiar, is ubiquitous enough that it feels familiar. And the orders of magnitude associated with the conversion feel *natural*. The way all these sources of energy feel intuitive, I would argue, is because the fundamental forces they deal with are the electrostatic and gravitational forces; chemical bonds, gravitational potential and kinetic energy. While these forces are not ‘simple’ to understand on a fundamental level, they are familiar, and their associated orders of magnitude feel intuitive. And because of this, meaningful discussions can be had about their use without a rigorous understanding of their physics.

What makes nuclear energy less intuitive and more opaque is that it involves a fundamental force we aren’t as familiar with: the strong nuclear force. This force is orders of magnitude larger than any of the other fundamental forces, and its everyday manifestations are either light-minutes away (the sun), unfathomably terrible (nuclear weapons), or notoriously misunderstood (fission nuclear power plants). This is all to say that to understand nuclear fusion, it is important to understand the underlying physics.

The Fundamentals: Proton-Proton Fusion Example

To understand how fusion reactions use the strong nuclear force to release energy, it is perhaps best to start with an example. The simplest of all fusion reactions is the reaction between two protons fusing to form deuterium. Deuterium is a stable isotope of hydrogen with the atomic number two. This is a fusion reaction that happens readily within our sun and other similarly sized stars.

To understand this reaction, we will examine the forces present between these two protons as they approach each other from some distance. (With nuclear reactions, unlike chemical reactions, we are only concerned with the interactions of nuclei; electrons do not play a major role.) Two forces are involved in the interaction: (a) the Coulomb (electrostatic) force, and (b) the nuclear force, which is a manifestation of the strong nuclear force. The Coulomb force acts between any charged particles. This is the same force that keeps a statically charged balloon sticking to the ceiling. In our example, because both protons have the same (positive) charge, this force is repulsive at all distances, becoming stronger as distance decreases. The other force considered is the nuclear force. This is the force that keeps nuclei bound together, despite the Coulomb repulsion of their like charges. Without this nuclear force, nucleons would never hold together and none of the elements on the periodic table would exist. At large distances, the nuclear force is attractive but vanishingly small. However, as the distance decreases, the strong nuclear force becomes very large. It has a maximum attractiveness at about 1 femtometer (10^{-15} m) (Kikuchi, Mitsuru, et al). At distances even closer than this maximum, the nuclear force becomes less and less attractive, until a point that it becomes repulsive.

Both forces work in opposition as the protons approach each other. At distances greater than a few femtometers, the Coulomb force dominates the interaction, and the net force on the protons is repulsive. However, if they have enough momentum to overcome this repulsion, they *may* get close enough that the attractive nuclear force pulls them together to fuse. (Note: the quantum physics detailing these interactions is beyond the scope of this discussion. However, it is important to note that interactions are probabilistic by nature, and fusion between nuclei is never guaranteed. Only a likelihood of a reaction occurring can be calculated).

A simplified formula of the fusion reaction between these two protons is given (Kikuchi, Mitsuru, et al):

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + \mathrm{e}^{+} + \nu$$

This reaction releases 1.442 MeV (1 MeV = one million electron-volts) of energy (Kikuchi, Mitsuru, et al). When the two protons fuse, they create a new atom with an atomic number of two. This is unstable, and one of the two protons will undergo decay and become a neutron. The other two products (a positron and a neutrino), are converted into electromagnetic radiation (gamma rays). The energy released from this reaction is carried in the kinetic energy of the deuterium atom, and the electromagnetic radiation.

To understand why this reaction is exothermic, the concept of nuclear binding energy must first be understood. Nuclear binding energy is simply the sum of the nuclear forces holding each nucleon together in the nucleus of an atom. Binding two protons together can be thought of as an energy ‘sink’, where potential energy is low. Potential energy is highest when the protons are infinitely far apart, and smallest when they are bound together. This is exactly analogous to the simple example of a ball rolling from the top of a hill down into a valley. As the ball rolls, its potential energy is converted to kinetic energy and the ball accelerates. The ball settles at the bottom of the valley once all the kinetic energy has been converted into thermal energy from friction with the ground and air. The amount of energy released from this process depends on how deep the valley is. The nuclear force (binding energy) is an energy sink. Just like the ball rolling into the valley, as two protons fuse to form deuterium, an equal amount of energy must be released to balance the binding energy now holding the two nucleons together. In exothermic nuclear reactions, this energy can be released in a few forms: commonly as kinetic energy of the products and electromagnetic radiation.

Nuclear reactions can happen in both directions. In the proton - proton example, the massive amount of energy released by fusion would have to be injected back in to the deuterium nucleus for it to break apart.

Nuclear reactions release or require so much energy because the energy ‘sink’ of a bound nucleus is enormous relative to the very small mass and size of the particles involved. So much so that mass-energy conversion in nuclear reactions becomes measurable. Nuclear reactions differ from chemical reactions in this way. In exothermic chemical reactions, the amount of mass converted to energy, while non-zero, is vanishingly small compared to the masses involved with the reaction. Nuclear reactions are different. The mass of two separated protons is measurably larger than the mass of them bounded together in a deuterium nucleus. Using ($E = mc^2$), we can determine the binding energy of a nucleus by measuring this difference in mass, known as the mass defect. Atoms with larger binding energies will have lighter nucleons. This is because during their formation more mass was converted into energy and released.

The Fundamentals: Expanding the Scope

These essential principles form the foundation of all nuclear reactions. The only factor that determines whether a given nuclear reaction will release energy is if the binding energies of the products are larger than those of the reactants. Using our rolling ball analogy: the ball needs to start at higher point than it ends so it can release energy as it rolls downhill. In our first example, the binding energy of deuterium was obviously larger than that of two single protons, because the binding energy of a single nucleon must be zero (there is nothing for it to bind to).

The same principle applies to reactions with nuclei bigger than hydrogen. **Figure 1** is a graph of the average nuclear binding energy *per nucleon* as a function of mass number of an atom (Encyclopedia Britannica).

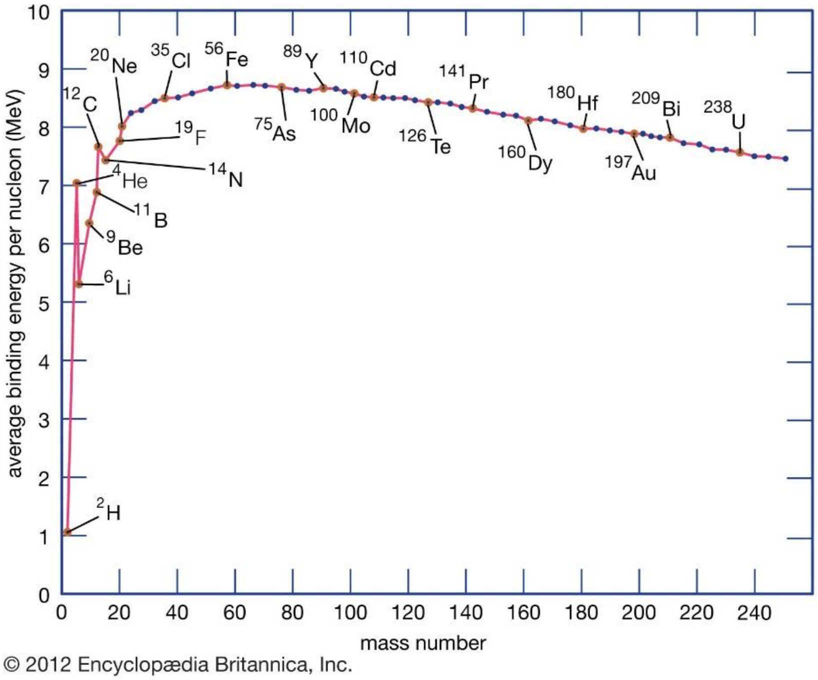

Figure 1 (Encyclopedia Britannica)

Any nuclear reaction with binding energies higher in the products than in the reactants will release energy. If this reaction involves atoms combining to form heavier nuclei, we call it fusion. If it involves an atom splitting to form lighter nuclei, we call it fission. Fission nuclear reactions can be exothermic because the binding energies get smaller in nuclei heavier than Iron-

56 (see Figure 1). Therefore, if a heavy nucleus such as Uranium-235 undergoes fission, if the products have larger binding energies per nucleon, the reaction will be exothermic.

When Fusion Happens: Introduction

After understanding how fusion reactions work, it is essential to understand when they occur; what conditions must be met before atoms can fuse. What do the sun, thermonuclear weapons and the device in Taylor Wilson’s bedroom all have in common?

For this discussion, it is helpful to use a different example fusion reaction. Instead of proton-proton fusion, we will consider the reaction is between deuterium and tritium, both isotopes of hydrogen. This reaction is highly relevant to fusion research, as it happens the most readily. It is written in its entirety below (Kikuchi, Mitsuru, et al).

$$ {}^{2}_{1}\mathrm{D} \; + \; {}^{3}_{1}\mathrm{T} \; \rightarrow \; {}^{4}_{2}\mathrm{He} \quad (\; 3.52\ \mathrm{MeV}\;) \; + \; \mathrm{n}^{0} \quad (\; 14.06\ \mathrm{MeV}\;) $$

In this reaction, deuterium and tritium fuse to make a helium atom (also known as an alpha particle), and a neutron. Because the binding energy per nucleon in helium is so high (see Figure 1), this reaction is extremely exothermic. Practically all the energy released in this reaction takes the form of kinetic energy of the products: about 80% in the neutron, 20% in the alpha particle. Deuterium is a common isotope of hydrogen that is abundant in sea water. Tritium, however, is radioactive and much rarer. This reaction will be discussed in greater detail later.

For now, this reaction is used to discuss the conditions necessary to make fusion occur. As mentioned before, for these two hydrogen isotopes to fuse, they must first overcome the Coulomb force which repels the like charges of their nuclei. Only with enough energy to overcome this repulsion can the nuclei approach each other close enough for the nuclear force to dominate and for them to fuse. This Coulomb force barrier to a successful fusion reaction is like activation energy in chemical reactions. Nuclei without enough energy to get past this barrier can never fuse. This is why fusion does not happen all of the time. Nuclei with more protons, and therefore more positive charge, are more difficult to fuse because this repulsion is greater. This is one of the reasons why fusing isotopes of hydrogen is favorable for a fusion power plant; the single proton in both nuclei minimizes the energy the reactants need to have in order to fuse.

When Fusion Happens: Cross Sections

Nuclear reactions, because they are governed by quantum mechanics, are probabilistic by nature. Just because reactants collide with enough kinetic energy to fuse does not guarantee that they will. The probability of a nuclear reaction occurring under certain conditions can be calculated and is given by a quantity called the cross section. Nuclear cross sections have units of area and are denoted with the symbol σ. For the purposes of this paper, a rigorous mathematical description of cross sections is not necessary. Rather, it is enough to use the cross section as a proxy for reaction rate. The nuclear cross section is a function of: (a) the fusion reaction, and (b) the kinetic energies of the reactants. **Figure 2** shows the cross section of a few fusion reactions that are being considered for a terrestrial reactor (Paris).

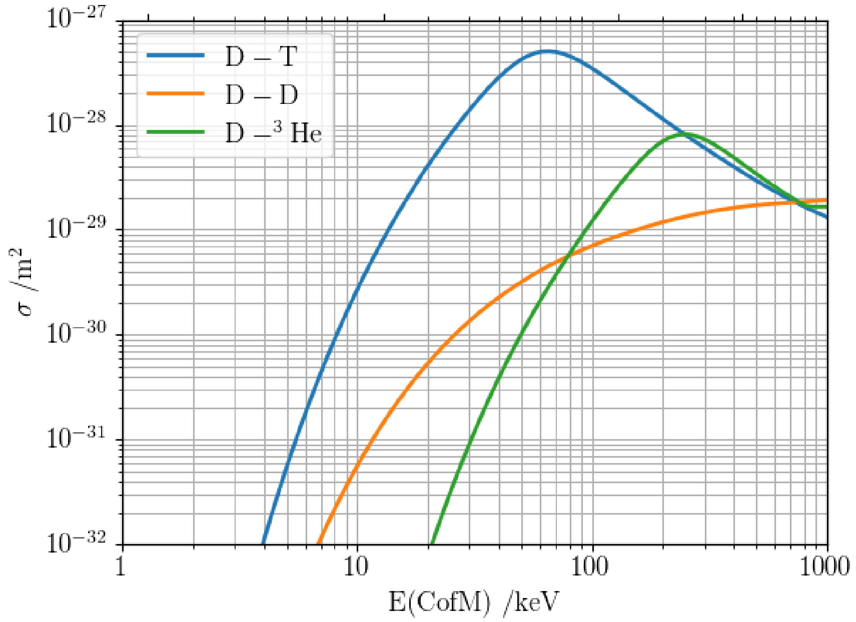

Figure 2 (Paris)

The nuclear cross section for each reaction is on the y-axis. The larger the cross section, the higher the reaction rate. The x-axis is the combined kinetic energy of the two reactants. One keV is one thousand electron volts, which is equivalent to the kinetic energy of one electron after it is accelerated through an electrode of one thousand volts. It is important to note that these cross sections have a maximum. Due to quantum effects, increasing kinetic energy of reactants raises the nuclear cross section only to a certain point. Past that, the reaction rate decreases.

This graph illustrates the most important reason for why deuterium-tritium is such a favorable reaction. It has the largest cross section across all kinetic energies that are relevant for terrestrial power generation. Simply put, for two fusion reactors operating under the same conditions, the D-T reaction will happen more readily by a large factor.

When Fusion Happens: Cold Fusion

A common misconception about nuclear fusion is that simply creating the conditions for fusion reactions to occur is immensely difficult. The reality is that getting two atoms to fuse is, while not simple, not something for a multi-million-dollar company to brag about.

As shown in Figure 2, at kinetic energies of 100 keV, the D-T fusion cross section is already past its peak. These energies can be imparted on an atom relatively easily. To give a nucleus this amount of kinetic energy, a hydrogen atom can be ionized (stripped of its electron) and accelerated through a voltage of 100 kV. Using an electrode, a hydrogen nucleus may be accelerated to fusion-relevant energies and directed towards a target of deuterium or tritium atoms. With enough kinetic energy, fusion reactions will invariably take place and can be detected. This is known as beam target fusion. This is the kind of fusion experiment that Taylor Wilson set up in his home at 14 years old, but he used what is known as a fuser (Clynes). A fuser is essentially a spherical electrode, where ions are accelerated towards the center from all directions. Wilson introduced deuterium fuel into the reactor and detected the presence of neutrons; a product of deuterium - deuterium fusion reactions (Clynes).

Fusers and beam target fusion are both technologies that fall under the umbrella of ‘cold fusion’. Cold fusion has a long history of promising more than it could ever deliver (US DOE). The fundamental problem with pursuing fusion in this way (if your goal is generating electricity) is that the reaction has fundamental inefficiencies. For every accelerated nucleus that successfully undergoes fusion, thousands more will simply deflect off each other. This phenomenon is known as Rutherford Scatting, and is intimately related to the Coulomb force discussed earlier. Even when nuclei have enough kinetic energy to fuse, the majority of colliding nuclei will scatter due to the repulsion of their like charges. These collisions slow both nuclei down and make them even less likely to fuse.

Just as we used cross sections for measuring the probability of a fusion reaction occurring, we too can use the cross section to measure the probability of Rutherford Scatting occurring. At fusion-relevant kinetic energies, the cross section for Rutherford Scattering is more than a thousand times larger than any fusion cross section (US DOE). From here, a simple order-of-magnitude analysis can illustrate why cold fusion will necessarily fail:

A deuterium - tritium fuser accelerates nuclei to 100 keV. Using the D-T reaction equation given before, a successful fusion reaction will release (3.52 + 14.06 = 17.58 MeV = 17580 keV) of energy. Accelerating one of the reactant nuclei with a 100 keV electrode gives a yield of (17580 / 100 = 175.8x). However, Rutherford Scattering has a cross section more than 1000x larger than any fusion cross section. So, for every 1000 nuclei accelerated by the electrode, on average only one will undergo fusion. This knocks down the yield by a factor of 1000: (175.8 / 1000 = 0.1758). Many schemes have been devised to work around this fundamental inefficiency, but none have been successful and reproducible (US DOE). Making fusion happen isn’t the hard part. Making it happen efficiently is exceptionally difficult.

Thermonuclear Fusion: Introduction

As things stand today, a reactor designed around cold fusion will never function because the cross section for Rutherford scattering is too high. To work around this, a fusion reactor must use thermonuclear, or ‘hot’ fusion. The ‘cold’ in cold fusion refers to the fact that accelerated nuclei are *not* in thermodynamic equilibrium with their surroundings. Nuclei that do not fuse bounce around loosing energy until they equilibrate with the ambient temperature of the reactor.

In cold fusion experiments, by definition, this ambient temperature is low. For the nuclei to have a chance at fusing again, they must be accelerated from these low kinetic energies all the way to fusion-relevant energies once again.

In thermonuclear or ‘hot’ fusion, nuclei *are* in thermodynamic equilibrium with their surroundings. Essentially, the fusion fuel is heated to enormous temperatures so that some particles *already* have enough kinetic energy to fuse during a collision. This way, instead of accelerating particles from near-zero kinetic energies all the way to fusion-relevant energies, all a thermonuclear reactor must do is maintain temperatures high enough that some nuclei have enough kinetic energy already to undergo fusion. When Rutherford scattering invariably occurs, the nuclei will stay in thermodynamic equilibrium with the rest of the fuel, minimizing the loss from each failed collision. These are the conditions in which fusion occurs in stars and thermonuclear weapons (hence the name). At these enormous temperatures, gas turns into plasma as electrons are stripped from their atoms in a process called ionization. Both nuclei and electrons flow freely in a plasma. It is important to recall that temperature is a measure of the *average* kinetic energy of particles. Reactant nuclei in a plasma at fusion-relevant temperatures do not all have enough kinetic energy to fuse. Rather, only a small portion of them do: the particles at the high-end of the Maxwell-Boltzmann distribution.

It is a relatively simple exercise to convert the cross section graph (figure 2) to an analogous graph for a thermonuclear plasma. **Figure 3** has cross section again on the y-axis, but this time the random distribution of kinetic energy is included (as v) (Ongena). Once again, it serves as a measure of the fusion reaction rate. Plasma temperature is on the x-axis. The axes are both exponential.

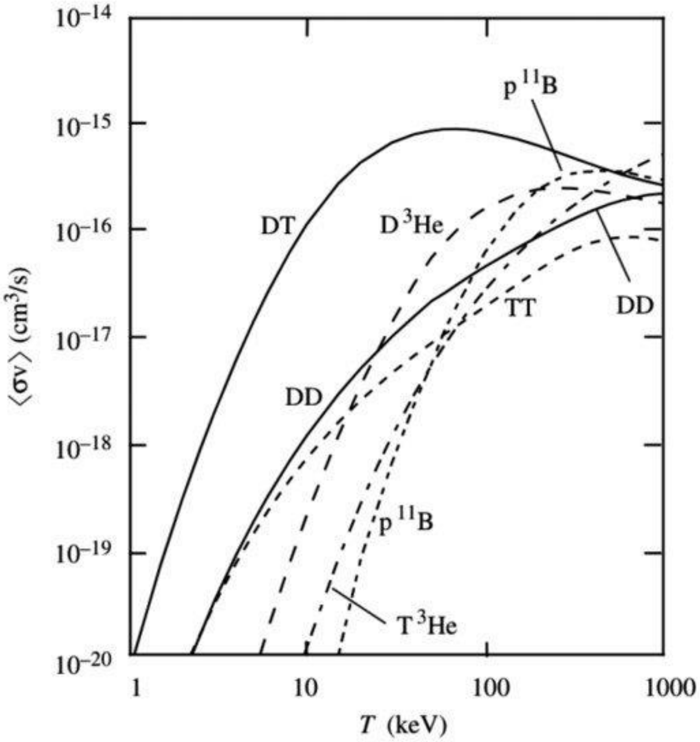

Figure 3 (Ongena)

With 'hot' fusion, the deuterium-tritium reaction remains by far the most favorable. Not only is it the first reaction available at lower plasma temperatures, but it remains the most reactive as temperatures increase. Most of the other reactions plotted will be discussed later.

However, even the favorable D-T reaction is not easy. For reference, the center of the sun is ~1.3 keV (15 million degrees Kelvin) (Kikuchi, Mitsuru, et al). A thermonuclear weapon can reach temperatures of 8.6 keV (100 million degrees Kelvin) (Kikuchi, Mitsuru, et al). The Joint European Torus, a record-holding fusion reactor in the UK has reached temperatures of 12.926 keV (150 million degrees Kelvin) (Banks). The hottest temperature ever recorded on earth was in an experiment at CERN with "quark–gluon plasma" at 5.5 trillion degrees kelvin (Kahle). However, CERN would be a terrible fusion reactor. As it turns out, temperature isn't everything. Being a measure of the average kinetic energy of particles, achieving a high temperature becomes easier with low particle densities held for very brief intervals of time.

These conditions are suitable for a particle accelerator, but not for a fusion reactor. The ‘quality’ of a fusion plasma depends on these variables, too. They can be quantified using a parameter called the triple product

Thermonuclear Fusion: The Triple Product

The Fusion Triple Product: $nT\tau_E$

The fusion triple product is figure of merit for plasma which accounts for density (n), temperature (T), and confinement time (τ_E). As previously discussed, temperature is a measure of the average kinetic energy of particles. Raising the temperature of a plasma increases the likelihood of a collision between nuclei resulting in a fusion reaction (see figure 3). Density is a measure of the number of particles per unit volume. Raising the density of a plasma increases the rate at which these collisions occur. The confinement time is the average time it takes for a unit of energy to leave a plasma. As confinement time increases, input energy needed to heat the plasma decreases. Density and temperature are essential to understanding the quality of the plasma. Confinement time speaks to the quality of the plasma containment. Both are essential in determining the power output of a fusion reactor.

At this juncture, it is necessary to introduce plasma containment techniques. These techniques fall into two categories: inertial and magnetic confinement. These will both be discussed in greater detail later, but a brief introduction here is warranted. Since the atoms in a plasma are ionized, electrons and protons can flow freely and can be manipulated by electric and magnetic fields. Magnetic confinement uses multiple magnetic fields to create a force opposing the plasmas natural tendency to disassemble. With inertial confinement, the idea is to keep a plasma contained for a very short period of time simply by its own inertia and the inertia of its surrounding material. The goal is for enough fusion to occur before the plasma dissipates for a net gain to be achieved.

The triple product may be meaningfully applied to both confinement techniques. The key difference is that, theoretically, a magnetically confined plasma may be maintained indefinitely. With inertial fusion, the plasma will necessarily quickly dissipate, and so triple product values must be much higher to achieve a similar net gain. This will be discussed in more detail later.

Achieving a triple product high enough for a viable fusion reactor has yet to be done. It turns out that generating, and even more so containing, plasmas at fusion conditions is extremely difficult. **Figure 4** is a graph of triple product vs year, with notable plasma achievements plotted (Wurzel).

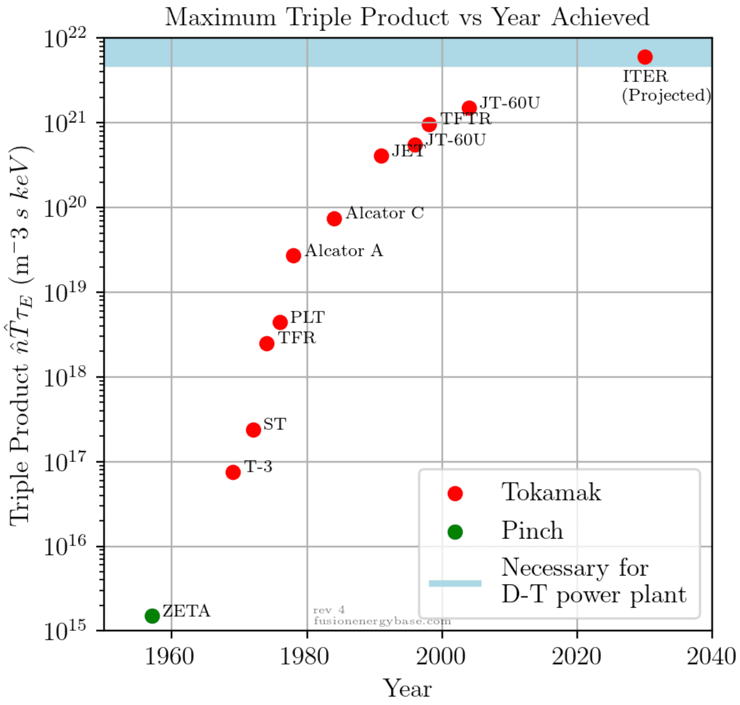

Figure 4 (Wurzel)

Only magnetic confinement experiments are plotted, as triple products between magnetic and inertial confinement schemes are not directly comparable. Tokomak and Pinch are magnetic confinement designs and will be discussed later.

On top of the graph is a blue area labeled ‘necessary for D-T power plant’. This area brings up an important point. How high does the triple product need to be? When is a plasma ‘good enough’? To answer these questions, we need to set some goalposts. We need to introduce another parameter: Q.

Thermonuclear Fusion: Q

It has become common practice to use Q as a figure of merit for a fusion reactor prototype. However, it is important to be careful in defining the parameter, as it can mean different things in different contexts. Generally, Q is defined as the total energy output of a system divided by the total energy input. Rather than a complicated value like the triple product, Q values are simple ratios. A system that has a Q greater than one is producing energy. Systems with a Q less than one are consuming energy. Obviously for a power plant, the electrical Q of the entire system must be greater than one. In fusion research, this Q is referred to as Q_{total}.

However, since fusion power is still in the early stages of development, perhaps a more useful Q value is for the energy input/output to the plasma rather than the entire machine. This Q is referred to as Q_{plasma}. Q_{plasma} focuses attention on the quality of the plasma and its confinement, rather than the efficiency of the reactor’s other systems. It would make sense to optimize these other systems only after a sufficiently large Q_{plasma} has been demonstrated. For an eventual fusion power plant, Q_{plasma} must be much greater than one for Q_{total} to be greater than one: ($Q_{plasma} >> Q_{total} > 1$). This is because: (a) a fusion reactor will have many power-hungry systems to maintain a hot plasma, and (b) the efficiency of the energy conversion from thermal energy of a hot plasma to electricity is necessarily less than 100%, and for D-T reactors will likely be around 50% (Menard et al). The current Q_{plasma} record is 0.7 at the National Ignition Facility in Livermore, California (Clery). As fusion research has been conducted for more than half a century now, this low of a value might seem discouraging. However, while it is reasonable to have some level of skepticism about an industry that has notoriously promised breakthroughs sooner than they occur, there is good reason to suspect that a leap in Q_{plasma} values might be right around the corner. This optimism is a result of the non-linear relationship between Q_{plasma} and the fusion triple product. **Figure 5** illustrates this relationship (Willis).

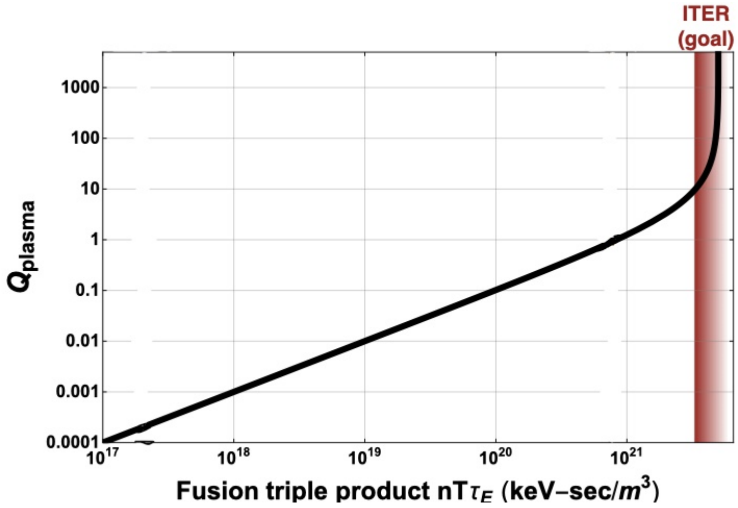

Figure 5 (Willis)

Up till a certain point, the relationship between Q_{plasma} and the fusion triple product is roughly linear. However, when the triple product nears a value where $Q_{plasma} = 10$, the relationship becomes exponential. This critical change is due to an important concept: plasma self-heating.

Thermonuclear Fusion: Ignited Plasma

If a plasma is hot enough, dense enough, and well enough contained, the charged particles that are products from fusion reactions can contribute to heating the plasma. This is known as plasma self-heating. If triple product values keep increasing, ignition may be achieved. An ignited plasma is one that is completely self-sustaining; where no external heating needs to be added. The only requirement of a fusion reactor with an ignited plasma is confinement. The power supply can be turned off. This is the same condition that occurs within stars. The energy released from fusion reactions within a star’s core maintains the high temperatures needed for fusion. The gravitational confinement passively maintains high densities and confinement times. Ignition, while not technically necessary for a fusion power plant, is the holy grail of fusion research.

Getting Nearer: Reaction Candidates

Before discussing confinement techniques and reactor design, it is important to discuss the different fusion reaction candidates in more detail. While we have seen that deuterium - tritium fusion has the most favorable reaction rate, it is less favorable in other regards. A thorough understanding of reactants, products, and necessary conditions for the more important fusion reactions is essential when analyzing fusion reactor designs.

For a nuclear fusion reaction to be considered for powering a terrestrial reactor, it much at least satisfy certain baseline criteria.

1. *Be Exothermic*
2. *Have two reactants*: The unlikelihood of a three-way collision makes cross sections extremely low.

3. *Have two or more massive products*: Some fusion reactions, such as proton - proton fusion, only have one massive product. Necessarily, because of conservation of momentum, another product must be produced which would take the form of electromagnetic radiation, specifically gamma rays. This would make the fusion reactor dangerously radioactive and inefficient.

Using these criteria, a list of 10 viable fusion reactions can be generated. From these, a few more can be eliminated as having no advantage relative to another reaction. The remaining reactions are listed here (Kikuchi, Mitsuru, et al):

Deuterium - Tritium:

$${}^{2}_{1}\mathrm{D} + {}^{3}_{1}\mathrm{T} \rightarrow {}^{4}_{2}\mathrm{He} \ (3.52\ \mathrm{MeV}) + n^{0} \ (14.06\ \mathrm{MeV})$$

Deuterium - Deuterium:

$${}^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} \rightarrow {}^{3}_{1}\mathrm{T} \ (1.01\ \mathrm{MeV}) + p^{+} \ (3.02\ \mathrm{MeV}) \qquad 50\%$$

$$\rightarrow {}^{3}_{2}\mathrm{He} \ (0.82\ \mathrm{MeV}) + n^{0} \ (2.45\ \mathrm{MeV}) \qquad 50\%$$

Deuterium - Helium-3:

$${}^{2}_{1}\mathrm{D} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} \ (3.6\ \mathrm{MeV}) + p^{+} \ (14.7\ \mathrm{MeV})$$

Proton - Boron:

$$p^{+} + {}^{11}_{5}\mathrm{B} \rightarrow 3\,{}^{4}_{2}\mathrm{He} \qquad + \ 8.7\ \mathrm{MeV}$$

These are the four main fusion reactions being considered for use in fusion power plants. To begin to assess their advantages and disadvantages, it is first important to analyze their products, as seen in **Figure 6** (Kikuchi, Mitsuru, et al).

Reaction	**E_{fus} [MeV]**	**E_{ch} [MeV]**	**Neutronicity**	**$\langle \sigma v \rangle / T^2$**	**T [Kev]**	**Inverse Reactivity**	**P_{fus}**
D-T	17.6	3.5	0.80	1.24×10^{-24}	13.6	1	1
D-D	12.5	4.2	0.66	1.28×10^{-26}	15	48	30
D-He3	18.3	18.3	~0.05	2.24×10^{-26}	58	83	16
P-B	8.7	8.7	~0.001	3.01×10^{-27}	123	1240	500

Figure 6 (Kikuchi, Mitsuru, et al)

E_{fus} is the total energy released by a single fusion reaction. E_{ch} is the amount of that energy in the form of kinetic energy of a charged product. This is important, as this is the only form of energy that can contribute to plasma self-heating. Neutronicity is the portion of E_{fus} that is released as kinetic energy of neutrons. Deuterium - helium-3 and proton - boron fusion are ‘aneutronic’ reactions; their stoichiometries do not directly produce neutrons. However, side reactions with the reactants and products within the plasma will invariably produce some neutrons, and therefore the neutronicity is non-zero.

Also in Figure 5 is the maximum reaction cross section, which is the same as was discussed earlier. The value listed is a maximum, which occurs at the plasma temperature listed in column T. Again, D-T is clearly favorable by these metrics, as the optimal temperature is lowest, and cross section is highest. The next column, inverse reactivity, offers a cleaner view of the reaction rate by dividing each maximum cross section by the cross section of D-T. Additionally, this value also considers a ‘penalty’ in reactions with reactants that have higher atomic numbers. This ‘penalty’ is a result of more electrons per reactant not participating in the reaction, but still taking up volume in the plasma. This penalty is a significant hit to the feasibility of the proton - boron reaction. Finally, the last column is P_{fus}. This value takes the reactivity value and adjusts it for the proportion of products that can contribute to self-heating, that is the E_{ch} value.

Understanding these metrics for each reaction is vital in analyzing different approaches to achieving a fusion power plant. For instance, if a company hopes to use proton - boron fusion because it is favorably aneutronic, it is important to understand: (a) the higher temperatures their plasma must achieve to burn efficiently, and (b) the decreased reactivity relative to D-T fuel, especially because of the large reactivity ‘penalty’ due to the abundance of electrons.

Difficulties: D-T Fusion, Tritium, and Neutrons

While D-T fusion takes a bit of a hit in the last column, P_{fus}, it is still the most favorable reaction for a reactor whose goal is to achieve ignition. However, the high neutronicity and the scarcity of tritium introduce some problems.

Tritium is a radioactive isotope of hydrogen with a short half-life of 12 years. Supply of tritium is severely limited worldwide, and it is likely that any nuclear reactor wishing to use tritium as a reactant will have to synthesize their own supply. Luckily, there is a helpful fission reaction with neutrons and lithium that can be used to breed tritium in a fusion reactor (Menard et al).

$$n^0 + {}^{6}_{3}\mathrm{Li} \rightarrow {}^{3}_{1}\mathrm{T} + {}^{4}_{2}\mathrm{He} + 4.784\ \mathrm{MeV}$$

Neutrons produced in a D-T plasma will necessarily escape confinement at a high velocity, as they carry large amounts of kinetic energy from the reaction and are electrically neutral. (Thus, even in magnetic confinement techniques, they will be unaffected by the magnetic fields containing the plasma). In order to contain these neutral particles, enough material must be put in their way so that they are physically brought to a halt. Current approaches boil down to surrounding reactor cores with a blanket up to a meter thick. A blanket made of lithium would serve well in the purpose of shielding the outside of the reactor from neutron radiation, while serving a double purpose as a tritium-breeding method.

Cross sections for the neutron - lithium-6 reaction are high. However, necessarily, a small portion of the neutrons won't participate in a fission reaction. Stoichiometrically, to break even on tritium, every neutron would need to react with a lithium atom to avoid a net loss of tritium from the reaction chamber. To compensate for this loss, beryllium might be used. When a neutron strikes a beryllium atom, a fission reaction may occur where two neutrons are released. Using a breeding blanket with Lithium-6 and beryllium for extra neutrons, a D-T fusion reactor might be able to synthesize its own fuel.

While possible in theory, tritium breeding remains an underdeveloped area of research. Before a D-T reactor can be commercially viable, these breeding techniques must be worked out. While a lack of tritium fuel is not a death sentence for a fusion enterprise using D-T reactions, it must be planned for. Additionally, any reactor that uses a fusion reaction that has neutrons as a product must deal with them in some way. Neutrons can degrade equipment and irradiate cooling water, not to mention surrounding environments. Any fusion reactor that produces neutrons *must* have physical barriers built into the reactor design to contain neutron radiation.

Difficulties: Bremsstrahlung

Another important difficulty that lowers condiment times in plasmas is Bremsstrahlung Radiation. German for "braking", Bremsstrahlung radiation is emitted every time two particles collide. In a plasma, these collisions occur constantly.

When two charged particles collide, they undergo acceleration and emit a photon. In a fusion plasma where kinetic energies are so large, this radiation can be a significant source of energy loss. The equation for Bremsstrahlung radiation is given here (Kikuchi, Mitsuru, et al):

$$P_{\mathrm{Br}}\left[\mathrm{W/m^3}\right] = \frac{Z_i^2 n_i n_e}{\left[7.69 \times 10^{18}\,\mathrm{m^{-3}}\right]^2} T_e\left[\mathrm{eV}\right]^{\frac{1}{2}}$$

Radiation losses go as particle density, and the square root of plasma temperature. Of course, these two parameters are also present in the fusion triple product. It follows that there is a tradeoff between the quality of a fusion plasma (temperature, density) and the confinement time (energy loss). Also, it is important to note that Bremsstrahlung losses go as the square of the charge of the ions. This is another major barrier for fusion reactions between heavier reactants, such as proton - boron fusion.

Difficulties: Plasma Instabilities

Perhaps the most challenging aspect of creating a viable fusion reactor is resolving the myriad instabilities of plasma. The details of these are beyond the scope of this paper, but it is important to note how these instabilities can affect the quality of a fusion plasma.

The same super-high energy densities needed to ignite fusion reactions also makes for an unpredictable, unstable and chaotic fuel. Plasma instabilities create turbulence, which radiate away energy from the plasma. These energy losses are quantified in the confinement time parameter of the triple product. Minimizing these losses is difficult and imperative to driving up triple products and, in turn, Q values.

Plasma instabilities can also disrupt the uniformity of temperature and density profiles within a plasma. These irregularities can affect the efficiency of the burn, and in turn the fusion power output.

Confinement: Introduction

The key to a successful fusion power plant is in the plasma. As introduced by the fusion triple product, the key to a successful plasma is one that has high temperatures and densities, and that minimizes energy loss. The biggest challenge to achieving a high triple product is the tradeoff between the quality of the plasma (temperature, density) and the quality of the containment (confinement time). In a plasma, pressure is proportional to temperature and density. This is a familiar concept, as the same relationship applies to an ideal gas.

Without proper containment, any material at fusion-relevant temperatures will exert so much outward pressure that it will quickly dissipate, and densities will become too low to continue undergoing fusion. Because fusion conditions are so extreme, familiar methods of pressure containment are impossible. In a metal pressure chamber, for example, the heat of the plasma will quickly be conducted away by the walls or will melt them. Practically, there are three forces able to counter the enormous pressures of hot plasma: Gravitational, inertial, and magnetic.

Confinement: Gravitational

Gravitational confinement is, of course, the force used to confine plasma in stars. The quality of its confinement is due to its unique triple product: (a) the density of the plasma is very high, (b) The temperature of the plasma is low, (c) the confinement time is extremely long. The long confinement times are due to the opacity and size of the sun. Any fusion products from the core have approximately 700,000 km of dense plasma to get through before they can escape the reactor. However, the fusion reactions taking place within the sun (such as proton-proton fusion) have much smaller cross-sections than the reactions being considered for terrestrial power generation. Because of the low temperatures and low cross-sections of reactions, fusion occurs much more slowly in the sun than it would in a reactor here on earth. The sun compensates for this slow reaction rate by being, literally, astronomical in size. It is also this low reaction rate that gives it such a long life.

Gravitational confinement, however, is impossible on earth. There simply is not enough mass to generate gravitational forces of relevant magnitudes.

Confinement: Inertial

Inertial confinement is the only technique by which humans have ever released practical amounts of fusion energy; it is the method of plasma confinement in thermonuclear weapons. The idea behind inertial confinement is simple. The fuel is compressed and heated to densities and temperatures where fusion can occur. The inertia of the reactants themselves (and surrounding material) is large enough to resist the building pressure long enough for the reaction to release energy before the plasma dissipates. Triple products for this type of confinement involve very high temperatures and densities and very short confinement times.

In thermonuclear weapons, the input energy needed to compress the fusion fuel is provided by a primary fission reaction within the bomb. The fusion fuel is a mixture of lithium and deuterium surrounded by a dense encasement of uranium. In the reaction, lithium breeds tritium when bombarded with neutrons, and the tritium reacts with the deuterium to release energy. To ignite the fusion component of the weapon, intense radiation from the detonated fission component causes the uranium around the fusion fuel to expand, compressing and heating the fusion fuel to fusion-relevant temperatures. While, like in all inertial confinement techniques, the confinement time is low; the density of the lithium deuteride is so high that the triple product of the fusion reaction is enormous; as is the Q_{plasma}. This is what allows thermonuclear weapons to release so much energy.

There are a few key differences in attempts to harness fusion energy by inertial confinement in a power plant. First, the initial fission reaction is eliminated. This is necessary because fission produces unwanted long-lived radioactive isotopes and is difficult to control. The initial energy must be delivered to fusion fuel using another method. Additionally, the fusion reaction must be scaled down so that it can be contained, and energy can be practically extracted. Also, the desired approach in most inertial confinement reactors is to run multiple (relatively) small, confined reactions in quick succession. Practically, this necessitates a clean reaction that minimizes residue and byproducts. Instead of a uranium-coated lithium deuteride solid, the fuel for most proposed fusion reactors would be closer to pure-form.

There are a variety of approaches being considered to deliver the required input energy to compress the fusion fuel in a reactor. Experiments have been conducted using ion beams and electric currents to supply this energy. So far, the most successful approaches have involved high-powered lasers. This is the approach that the National Ignition Facility uses (Clery).

Confinement: Magnetic

Magnetic confinement is the most well-researched confinement technique for fusion. As discussed previously, plasma ionizes atoms so that the electrons and nuclei may move about freely. This gives the plasma electrical conductivity and allows the matter to be manipulated and contained by magnetic fields. Magnetic confinement attempts to balance the pressure of the plasma with magnetic pressure.

To gain a bit more detail in how magnetic confinement works, the most common design, known as a tokamak, will be quickly analyzed. **Figure 7** is a diagram of the Joint European Torus; a particularly successful tokomak fusion reactor in England (UK Atomic Energy Authority).

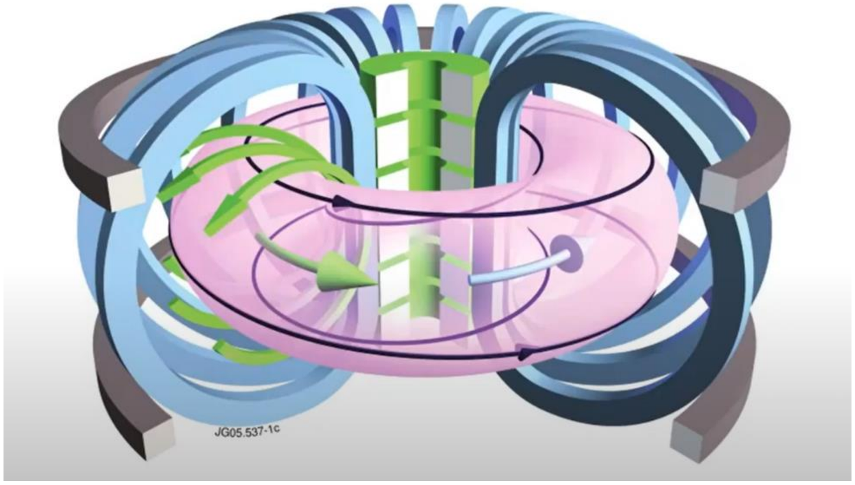

Figure 7 (UK Atomic Energy Authority)

The large blue D-shaped coils looping around the torus are electromagnets. They create magnetic field lines following the torus's shape, depicted in black. Charged particles move along magnetic field lines in spirals. These magnetic fields are not meant to increase of kinetic energy of particles, rather they give them a direction of motion. A torus-shaped reactor is the simplest way of closing magnetic field lines so that particles may be contained indefinitely England (UK Atomic Energy Authority).

The primary method of heating the plasma is through ohmic heating. An electrical current is run through the green coil at the center of the torus. Just like in a transformer, this current imparts a secondary current on the plasma in the torus, as plasma is electrically conductible. The current is depicted as the green and blue arrows within the torus running parallel to the black magnetic field lines. This current in turn heats the plasma by electrical resistance in a process called ohmic heating. Finally, an important secondary containment magnetic field is generated in loops around the plasma by plasma's current. This secondary magnetic field is represented by the green arrows surrounding the torus on the left side of the diagram England (UK Atomic Energy Authority).

Fusion triple products for magnetic confinement devices generally have very high temperatures and low densities. The main area of research and development has been in maintaining a stable plasma with high confinement times as density increases. Instabilities and inefficiencies abound in magnetically confined plasmas and have been the most significant barrier to progress. However, progress has been made. ITER (International Thermonuclear Experimental Reactor) is set to set records for both fusion triple products and Q_{plasma} values when it comes online in 2025 (On the Road to ITER).

Tokomak's aren't the only type of magnetic confinement fusion device, although certainly they are the most well researched. Other designs are being researched but are further behind than tokamak development. For example, Stellarators confine plasma in a twisted torus shape that may allow for less injected power and is actively being researched.

Wrapping up:

The Joint European Torus and the National Ignition Facility are both research devices, and do not have the capability to generate electrical energy. ITER, set to have its first plasma in 2025 and be fully operational in 2035, is also still solely a research facility (On the Road to ITER). Originally planned to reach ignition with a D-T fuel, expectations have been scaled back to $Q_{plasma} = 10$ (What will ITER do?). After ITER, a second project is planned with a stated goal of building upon ITER and finally producing usable electricity. However, operation of this reactor is not planned to start until after 2050 (EUROfusion).

While these publicly funded international projects have power-to-grid timelines still far in the future, there has been a recent surge of funding for smaller, private fusion ventures that are promising commercial fusion power much sooner.

Fantastical development timelines, reliance on unproven technologies, and cases of deliberately misleading reporting have brought skepticism upon the industry. However, the surge of private capital has already enabled research and prototyping for innovative and exciting approaches to fusion. So, while skepticism of commercial-power generation dates within half a decade is warranted, it would perhaps be a mistake to dismiss these ventures completely.

Tracking the progress of companies in this new private sector has been difficult. Press releases sometimes highlight irrelevant information or ignore important context. A general lack of understanding of the basic requirements for a fusion reactor continue to be a source of misunderstanding and perhaps even deception.

Nuclear fusion is not simple. However, important concepts can be meaningfully understood by anyone interested. This thesis is an attempt to provide that context, so that a more informed discussion may be had on all levels.

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