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ESP: Paper #1

Topic: Nuclear Fusion

> *[Tara – You say in your note at the beginning that you wrote this paper "at the last minute." Why? You know (and this applies to* <u>*everyone*</u>*) several weeks in advance when your papers are due. I strongly suggest, especially near the end of the semester when you will be busy preparing for final exams in other courses, that you start early on your papers. It takes time to do the research and to go through several drafts. For most people, good writing requires a lot of re-writing.]*

<u>Nuclear Fusion: The Journey from E=mc2 to ITER</u>

In the 19th century scientists believed that the sun's inferno was caused by the gravitational contractions of a large gas cloud. The heat was a product of the cloud's potential gravitational energy. This explanation, while popular, was highly disputed as it only allowed the sun to be about 20 million years old and did not agree with observations of stars and space (1). In the early 20th century Arthur Stanley Eddington, a scientist, puzzled out the internal structure of stars. This discovery, unlike the previous theories, agreed with astronomical observations. However, Eddington had not worked out how stars produced energy (1). Around the same time, two other scientists, Atkinson and Houtermans collided light particles and after applying Einstein's equation E=mc2 predicted that large amounts of energy could be released by fusing small nuclei together. It was not until 1939 though, when Han Bethe while trying to account for the sun's energy, applied Atkinson and Houtermans' discovery, and established a quantitative theory describing fusion (3). Bethe asserted that the energy of the sun and other stars was from a type of indirect fusion, the four-step "carbon cycle." In this cycle a carbon isotope reacts with three hydrogen nuclei to form a nitrogen isotope. Then this isotope reacts with a fourth hydrogen nucleus, releasing energy, the carbon isotope, and a helium nucleus (2). This was the first real step in the field of nuclear fusion and earned Bethe the 1968 Nobel Prize (3).

Nuclear fusion seems, on the surface, a very simple process. Two nuclei collide and generate energy. (This explanation, however, oversimplifies the process. For the nuclei to fuse, the short-range nuclear attraction must overcome the long range repulsion between like particles also called the Coulomb repulsion (4).) Nuclear fusions can only take place if the nuclei are in close enough proximity and have enough energy to counter the repulsion of the protons. The easiest way to add energy is to add heat. However, while heat does give the needed energy, the higher temperature also causes the particles to expand, increasing the pressure against the plasma fuel's containing force. So the outside force must exude enough pressure to counter and contain the expanding plasma. Natural fusion reaction sites, such as the sun, have an extremely large amount of gravitational pressure holding the plasma. Unfortunately on Earth scientists cannot recreate the same conditions as the sun's core. Therefore to manufacture a fusion reaction on Earth scientists must increase the temperature to compensate for the lack of outside pressure (4). For example, on the sun this process operates at 15 million degrees Celsius while on Earth fusion reactions require 100 million degrees Celsius (5). Since no metal can hold such extreme temperatures, scientists have devised a way to contain the plasma fuel using magnetic fields. Another possible technique, though less used, requires causing compression by means of a laser. Once the environment reaches the necessary conditions, reactions can occur. While nearly any two nuclei can fuse,

> *[Only for nuclei lighter than iron does the fusion process release energy. For heavy nuclei like uranium, the fission process releases energy. This is because medium-weight nuclei in the region of iron are the most stable.]*

scientists prefer to use a D-T reaction. This reaction has a low threshold energy and yields a neutron, which can be used to create more tritium (the T of D-T). Both nuclei are isotopes of hydrogen.

Deuterium has one neutron and tritium has two. While deuterium can be found easily in water, tritium's short half-life makes the nuclei very difficult to find.

> *[Tritium has a half-life of 12.5 years, and is a very hazardous to human health. It's a gas, and when it's inhaled it can exchange with normal hydrogen atoms in water and stay in the body for a long time. So, the tritium in a fusion reactor has to be handled with great care and not allowed to escape.]*

Tritium must either be taken from lithium or created within the reaction by causing the deuterium nuclei to accept a second neutron. The individual nuclei collide and form an unstable nucleon. Unlike fission reactions in which the nucleus has too few neutrons, the fusion nucleon has too many. The nucleon discharges a spare neutron, proton, and/or alpha particle as well as energy (This depends upon the type of fusion reaction being created. If the reaction does not release a neutron the reaction is labeled 'aneutronic.' This sort of reaction can not be easily used within reactors as it does not contribute to the chain effect.) (16). The energy produced by a fusion reaction usually exceeds the amount of energy needed within the reactor to initiate the reaction (4). This exothermic behavior attracts many scientists and others with an interest in energy to the field of nuclear fusion.

Nuclear fusion certainly yields great benefits. While the process does produce a low amount of radiation,

> *[In addition to the tritium problem mentioned above, fusion reactors do become radioactive due to neutron-induced reactions in the reactor components. But this radioactivity is considerably less (by a factor of 10 or more) than that of a nuclear fission reactor. But still, discarded reactor components have to be handled, stored, and disposed of with care.]*

the energy sources will not be depleted anytime soon. Deuterium exists naturally in sea water; one atom in every 6500 hydrogen atoms is this isotope. Tritium comes from the rarer metal, Lithium, which can be found in the Earth's crust (7). The relative abundance

> *[Lithium is not an abundant element. It would be used up on a time scale similar to that for uranium, for comparable development of the industries. So, the D-T fusion process would not be a long-term, or renewable energy source. The D-D fusion process would be long-term because of the high abundance of deuterium in sea water, but this fusion process requires much higher temperatures and is harder to make work. The first generation fusion reactors would use the D-T reaction.]*

of these materials in comparison to current leading energy sources and the fact that a nuclear fusion plant would not emit any greenhouse gas (9) should appeal to many of those who wish to conserve fossil fuels or fear running out of energy resources. Nuclear fusion should also garner positive support from the general public. Unlike nuclear fission, which has incurred a great amount of public backlash for the Three Mile Island and Chernobyl incidents (8), a fusion reactor would never be at risk for a meltdown (6). Also, the potential energy gain draws seekers of alternative fuels. A mere thimbleful of deuterium would produce the same amount of energy as 20 tons of coal (6). And, even though the amount of energy needed to initiate the reaction is very great, scientists have been able to break-even, have the output power and input be equal, since 1997 (9).

However, despite the definite benefits of a nuclear fusion power source, a commercial reactor can not yet be built. Currently nuclear fusion reactions require more electricity and money than they produce (6). While getting energy from a fusion reaction will not occur for at least 30 years (9), scientists hope to reach the next step in solving this problem by reaching a stage in nuclear fusion called the 'burning plasma' point. At this stage the plasma would heat itself and need less external heating to make reactions occur (9). A current international group of nations, including Europe, Japan, Russia, the United States, China, the Republic of Korea (10), until just recently, Canada (11), is trying to achieve this stage through the development of the latest (and largest) tokamak yet, ITER or the International Thermonuclear Experimental Reactor (9). ITER (meaning 'the way' in Latin) will become the largest tokamak to date (10).

The tokamak contains fuel plasma using magnetic fields (12). Invented in the 1950s by Soviet scientists, Igor Yegenyevich Tamm and Andrei Sakharov, the tokamak has remained the dominant machine for holding plasma. This doughnut-shaped machine produces a spiraling magnetic or helical field by "inductively driving a current in the plasma" (13). In 1974, a small-scale research-oriented tokamak named the TOSCA (Tokamak Shaping and Compression Assembly) was built at the Culham Science Centre of Atomic Energy. This machine helped scientists refine the process by which the tokamak contained the plasma in magnetic fields (5). The research gathered from

TOSCA helped with the design of the later JET (Joint European Torus), which is currently the largest tokamak in the world (5) that can handle D-T fusion fuel (14). In 1997 the JET tokamak generated 16 MW of energy, creating a world record.

Scientists hope to break this record with the development of ITER. The concept for ITER originates in 1986 after the project was suggested in the previous year Geneva conference. The official agreement and plans, however, did not occur until 1992 (10). Scientists are building the ITER reactor to have a 6m radius, twice the measurements of the JET. The goal of the ITER project is to generate enough energy to reach the burning plasma stage (9), to create a convincing demonstration for a nuclear fusion power plant (10), and to generate 500 megawatts of power for 500 seconds (15).

> *[Please check the "500 seconds" number. I'm surprised it's this long. For some time the break-even point was sustainable for only milliseconds.]*

The countries involved with the ITER project have yet to choose a site. Currently they are divided between two; one in Cadarache, France, the other in Rokkasho-mura, Japan (11). The United States prefers the Japanese site, while Europe prefers France. The final location will be decided later this month (15). If the ITER project succeeds, then the use of nuclear fusion power for energy on Earth becomes more possible.

> *It's still a big if, it seems to me. But John Sheffield (author of chapter 2 of our text) is an expert in nuclear fusion and was involved in the ITER project at one time. He's optimistic about the success of ITER, but one has to be careful about the objectivity of scientists – like everyone else -- when it comes to their own work. Scientists can be overly optimistic when seeking funding for their work.]*

Nuclear fusion power has traveled from a vague concept and explanation for the sun's inferno to almost very viable energy source for Earth. The once impossible idea of harnessing nuclear fusion is now happening. However, actually gaining electricity from the fusion reactions won't occur for a while still. Scientists predict that, providing ITER does not fail, the first commercial fusion power plant will be built until 2050 (9). Therefore, people and companies still need to find ways of conserving fossil fuels and using them more cleanly. Also, governments should still seek out alternative energy sources such as wind farms. Nuclear fusion is coming though, one discovery at a time.

> *[Your conclusion is sound – that commercial development of nuclear fusion is a long way off and we need an energy policy that doesn't depend on it. It may turn out to never be scientifically or economically feasible]*

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