Fusion: The Energy of the Future?

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Overview

This seminar is dedicated to renewable energy and the consequences of our energy intensive society including global warming. This unit will explore the nature of energy sources and generation. In my AP Physics II B class and Gifted Physics I classes, I will explore the viability of fusion as an energy source. I will also make the case that we need to have a monumental effort much like the Apollo Missions on a global scale to be able to solve the scientific issues of fusion. Money and lots of effort would drastically reduce the time to realize a commercial fusion reactor. In my physics classes, we spend a lot of time on energy and electricity. I will explore the need for carbonless fuel sources, primarily fusion, as well the relative amounts of energy we get and use from different sources, including fossil fuels and renewables. I will make the case that we should be pursuing controlled fusion. The unit will culminate in a Creative Design Project to design parts of a fusion power plant.

Rationale

Our modern civilization is extremely energy dependent. Higher GDP is strongly correlated with individual energy use. Since the Industrial Revolution, we, humans, have relied ever more intensely on burning fossil fuels for our energy. Fossil fuels are the result of biomass being trapped under the earth for long enough periods of time at high enough temperatures and pressures to convert them into concentrated energy sources. However, as the population and energy use increase dramatically our use of fossil fuels is going up exponentially. Within the past few decades, the case has been substantiated by scientists that the release of CO_2 as a consequence of burning fossil fuels has resulted in global warming, which consequently will result in climate change. This global warming is the result of the phenomenon of our atmosphere known as the greenhouse gas effect. In effect, our atmosphere allows visible light in from the sun, which is a source of energy. The light energy is absorbed by the Earth, warming it, and the energy is reemitted as infrared (EM waves). If our atmosphere was transparent to infrared radiation, then the energy that came in would simply leave in this other form. That would be most unfortunate, because our average temperature without our atmosphere would be approximately -10 ºC which would make Earth uninhabitable. However, our atmosphere is not transparent to infrared radiation (heat) and the greenhouse gases trap in some of the energy maintaining an average global temperature around 20 ºC which enables us to be here. It is important to discuss the greenhouse gases and why they are called as such. The reason is that the atmosphere works just like a greenhouse, letting light in but trapping some of the heat energy from leaving. The problem with burning fossil fuels is that it is reversing the process that captured the CO_2. Photosynthesis in plants on Earth turns light energy into stored sugar. O_2, oxygen is released. The formula is $6\,CO_2 + 6\,H_2O$ + light —> $C_6H_{12}O_6 + 6\,O_2$. When the sugar, $C_6H_{12}O_6$, is burned in respiration, the CO_2 is released in a perfect balance. The earth has maintained a remarkable balance that has enabled life to thrive on earth over billions of years. Over that time, photosynthesis released enough oxygen to produce 20.95% in the atmosphere and an equivalent amount of buried biomass that is the source of fossil fuels. Since the Industrial Revolution, only around 100 years ago, the CO_2 level has been rising dramatically due to the burning of fossil fuels and will double within the next 20 years or so, beyond any point in human history. This will result in many devastating impacts some of which climatologists believe are likely to be catastrophic.(1)

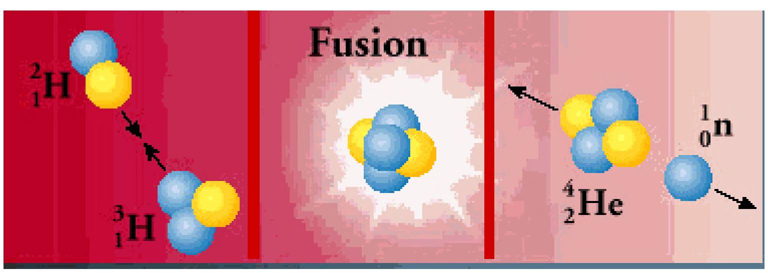
Sources of Energy

So, we need to do something now to mitigate climate change. Some have suggested that the concern is that we will run out of fossil fuels… this however, is not the case. The evidence for this is that, although we have burned a tremendous amount of fossil fuels, the oxygen content in the atmosphere has remained steady at about 21%. This is a clear indication that there is a tremendous amount of fossil fuels still buried within the earth because burning all of the fossil fuels will entirely deplete the oxygen in the atmosphere. This is based on the chemical equation listed above. So, we will not run out of fossil fuels, but we still need to proactively deal with this crisis. Some of the reasons are the geopolitical uncertainty of our energy supply, disruptions of our energy supply, regional conflicts, cost, etc.(2) Many have proposed the development of renewable energy sources. However, only 9% of our current energy use is produced by renewable energy. Much of the renewable energy is subsidized to make it cost effective, but even so the sources of solar, wind and biomass are currently cost prohibitive. While these efforts to increase the use of renewable energy and decrease the production of CO_2 are laudable, when I look at the future energy demand of China and other developing countries, I cannot imagine that renewables are a viable comprehensive solution…. But, I believe there is one source of energy… one that not many people talk about, that if it could be adequately developed would be able to supply a tremendous amount of virtually clean energy… and that is the focus of this unit….FUSION… controlled fusion… capturing the energy of the sun!

Fusion

The benefits of controlled fusion are that a tremendous amount of energy is produced based on the conversion of mass into energy ($E=mc^2$) by combining heavy hydrogen (protons with extra neutrons) together to create helium! Nuclear energy releases nearly inconceivable amounts of energy. Compared to chemical bond energy, the creation of one helium nucleus from four hydrogen nuclei releases 10 million times the energy of the burning of 2 hydrogen molecules with oxygen to form water! Ideally this process produces no radioactivity (unlike nuclear fission- which is the breaking apart of large atoms, such as uranium-235, into isotopes that are radioactive for tens or hundreds of thousands of years).(3) Ideally, water, using thermonuclear fusion, could power the world! The sun combines four protons in the form first of deuterium atoms; deuterium (D) is a hydrogen isotope with one neutron. In this reaction, one of the protons releases a positron, thus becoming a neutron and conserving charge. Then the deuteron collides with a proton forming helium-3... this entire reaction occurs twice. The two helium-3 atoms collide, releasing two protons and forming helium-4. The collisions occur at solar temperatures around 14 million degrees within the sun's core resulting from the Sun's gravitational Force. The 4 hydrogen atoms form a helium atom with less mass and based on the famous equation $E=mc^2$, millions of electron volts are released in each reaction, with no resultant radioactivity. However the reaction takes a million years. This is good for us, otherwise the sun would have burned up by now!(4)

On earth there are some additional challenges, in addition to the fact that we cannot wait a million years! The gravitational force of the sun is immense and cannot be replicated here, so instead of 10 million degrees, the reaction requires several hundred million degrees! Currently, the process that is used combines two isotopes of hydrogen. The first is a deuterium isotope of hydrogen, a proton with one neutron, which can be found readily within salt water at the rate of approximately 1 deuterium per 6500 hydrogen on earth.(5) The second isotope is tritium (T), which is a heavier isotope of hydrogen with 1 proton and two neutrons. Tritium can be produced by bombarding a lithium atom, which is prevalent on earth, with a high-energy neutron, splitting the lithium atom into a helium nucleus (known as an alpha particle) and a tritium isotope, in a reaction that requires 2.5 MeV. This can be written as: $^{7}Li+n \rightarrow {}^{4}He+T+n-2.5MeV$. So, if neutrons are desirable for a breeder reaction, then ^{7}Li can be used and, as long as energy is supplied, more tritium can be produced. Finally, the overall fusion reaction involving deuterium and tritium can be written as: $D+T \rightarrow n\ (14.1\ MeV) + {}^{4}He\ (3.5\ MeV)$.



http://www.lbl.gov/abc/wallchart/chapters/14/2.html

It should be mentioned, however, that fusion results in 1/10 th the energy per reaction that splitting a U^{235} atom does, as a result of the difference in mass conversion. The benefit is that there is virtually no radiation (except the radiation that results from the high-energy neutrons hitting the inside of the reactor and the lithium breeder reactor of the tritium, which has a half-life of 12.3 years.) For all practical purposes, there is an unlimited supply of fuel for fusion. An additional advantage to fusion is that there isn't the possibility of an accident that would result in massive radioactive contamination as in fission. The failure of a fusion reactor at worst would result in an explosion of the reactor because of the uncontrolled release of the high-temperature plasma, but the dissipation of the plasma cannot result in a further reaction. It is even suggested that in the current designs of ITER (International Thermonuclear Experimental Reactor) that such an explosive event is not possible.

Fusion Is Always 30 Years Away?

There are many critics of fusion who indicate that the reality is different! The most common saying about fusion is that controlled fusion is twenty-five years away… and some say… AND ALWAYS WILL BE!!! In Charles Seife's book, *Sun in a Bottle, The Strange History of Fusion and the Science of Wishful Thinking*, he makes just such a contention. The book was written in 2008. He argues that JET the Joint European Torus, which others claimed reached breakeven and even exceeded it in pulses of 13 MW, although impressive actually lost 10% of the energy input. He also indicates that

fusion isn't clean and it probably never will be."(6) In terms of ITER's success (International Thermonuclear Experimental Reactor), which is the largest and seemingly most promising test fusion project being undertaken, Seife says,(7) "It is a glorious vision. Unlimited energy- a tiny star bottled in a magnetic jar- would liberate mankind from the fear of global warming and from the impending energy crisis… And if ITER works as planned when scientists turn it on, it will light the way to a fusion reactor. If, miraculously, no more instabilities crop up that prevent scientists from bottling their plasma, fusion energy will be within reach. Scientists would then build a demonstration fusion power plant that would begin operations in 2035 or 2040. After five decades of broken promises, lies, delusions, and self-deception, it will finally be true. Fusion energy will be thirty years away." Already a fusion reactor is anticipated to be ready no sooner than 2050.

All of this indicates the promise of nuclear fusion, the driving hope and Seife's own frustration with the process, but he fails to illuminate all of the progress that has been made and the plasma physics that has had to be learned, applied and difficulties that have had to be overcome. The task is truly monumental! Seife closes his dismissal of fusion as an energy source with the supposition that "the fusion community clings to the hope that fusion energy is just thirty years away- and that it will solve *all* our energy problems. Despite the failures of the past, despite the enormous hurdles ahead, despite the tremendous cost, despite the easier alternatives, scientists still insist that fusion energy is the path forward. It is just another case of wishful thinking."(8) Charles Seife's frustration is palpable and he makes many good points, but ITER is being built by 7 countries that encompass more than half the world's population… it is moving forward and as pessimistic as Seife can be, the plasma physicist Francis F. Chen is equally unperturbedly optimistic.

History of Fusion

Alchemists were the first to seek nuclear transmutation. The process actually became possible with nuclear fission, which is the splitting apart of larger atoms into smaller ones. Fusion is the combination of elements into larger ones.(9) Scientists realized that nuclear fusion was the process that fuelled the sun and nuclear fission was only understood after Einstein's equation $E = mc^2$, Francis Aston's accurate measurements of the elements and with the introduction of quantum mechanics!

Uncontrolled Fusion

The hydrogen bomb is an example of uncontrolled fusion. In most cases, hydrogen bombs are atomic (fission) bombs, containing fusion fuel. The atomic bomb is detonated on the inside of a strong vessel, forcing the fusion material into itself, imploding. The fusion fuel, D and T are compressed at high enough temperatures that they undergo fusion and release multitudes more energy.

History of the Tokamak

An early invention by the Russians at the Kurchatov Institute was the development of the tokamak, which "is an acronym of the Russian word for toroidalnaya kamera, for "toroidal chamber," and magnitnaya katushka, for "magnetic coil."(10) This design for magnetic confinement of a plasma was first shared when the international community declassified knowledge about fusion and the United Nations held a conference in Geneva called Atoms for Peace in 1958.

Fusion Progress

So let's look at the physics and engineering behind making fusion a viable energy source and see where we actually are! Francis Chen wrote a book titled, "An Indispensable Truth: How Fusion Power Can Save the Planet." Chen starts his book with a reference to Al Gore's book about climate change, "An Inconvenient Truth" and it seems more than coincidental that his title is so reminiscent! Chen highlights the tremendous challenges faced and overcome in developing plasma physics, many of which were unforeseen. However, he believes fervently that the majority of the physics is established at this point and many of the issues, albeit substantial, are engineering concerns. Chen acknowledges that "Fusion has suffered from the reputation that it is always promised to be available in 25 years. This was because the difficulties were not initially known. They have been overcome, but it took time and funding to build the necessarily large research machines, to train a generation of plasma physicists, and to develop the diagnostic tools to be able to see what we are doing. The underlying physics is now understood well enough that more accurate estimates of what it takes to make magnetic fusion work can be made. Thousands of dedicated physicists and engineers labored for decades to bring fusion within the foreseeable future. There are still a few physics problems to be solved. Engineering is another matter. What has to be done to make fusion reactors practical is the subject of [chapter 9]."(11) He goes on to indicate that "With the information they have gathered from the public media, most people who have heard of fusion consider fusion energy to be a pipedream. Their information is out of date. As we have shown in the last two chapters, great advances have been made in fusion physics, and our knowledge of plasma behavior in a toroidal magnetic bottle is good enough for us to push on to the next step. This does not mean, however, that fusion is *not* a pipedream. There is a large chasm between the understanding of the physics and the engineering of a working reactor. There are problems in the technology of fusion so serious that we do not know if they can be solved. But the payoff is so great we have to try."(12) So in the end, Chen does not end up that far from Seife except that he is more knowledgeable and specific and he makes a far more compelling case.

For fusion to occur and a net energy output, meaning more energy is produced than goes in to creating the reaction, the conditions must be just right. John Lawson first showed these criteria. The three primary factors, called the triple point, that must be considered are temperature, T_i, of the ions, n, the density of the ions or the electrons and time of interaction, T_E (tau), the energy confinement time. These factors must be multiplied to produce a sufficient product for fusion to occur. According to Chen, this measure of success has increased over 100,000 times in the last forty years and doubling every two years recently.(13) This certainly bodes well for the future progress that fusion research and development of a reactor is likely to make. These parameters allow for the nuclei to overcome the coulomb repulsion and predominantly the potential energy associated with the strong nuclear force. It also turns out that quantum tunneling is necessary for the reaction to occur.

The nuclei must be accelerated to 100,000 Volts. But none of this is possible unless the potential energy of the triple point is achieved so that the required potential energy for the reaction to occur can be achieved.Magnetic Confinement Fusion

The most prevalent current method for creating the conditions for fusion is called magnetic confinement fusion. The majority of the work over the past fifty years has been on Magnetic Confinement Fusion (MCF). One of the most challenging problems about creating a controlled fusion reaction is that the fusion material must attain at least 100 million degrees! Consequently, the fusion reaction must occur without touching any boundary materials because they would melt. So, the ingenious way that this has been solved is to suspend the fusion material in a field. At such extreme temperatures, atoms dissociate, or ionize, from their constituent parts and become a plasma. A plasma is the fourth state of matter, besides the familiar solids, liquids and gases, and it exists when atoms are stripped apart. The protons and their electrons are separated. The fusion material before it is heated is neutral, meaning that it has the same number of protons and electrons. Therefore, after being heated, the plasma, as a result of the conservation of charge, must still have the same number of positive and negative charges and still be neutral. This is very important in the ability to create magnetic confinement.

Magnetic confinement works because a magnetic field interacts with an electric field and vice versa. So, it is conceivable to create a strong enough magnetic field to contain the plasma, which is made up of charged particles. Natural magnets by themselves are not strong enough to contain 100 million degree plasma; however, electromagnets are strong enough if supplied with enough current. There are a couple of challenging aspects to contain a plasma, however. The first is that the electromagnetic fields do not act parallel to each other but instead act perpendicular to one another by the formula $F=q(v \times B)$ by the "right-hand rule." What this means is that the charged particle with charge q which must be in motion with velocity v, experiences a force (F) perpendicular to the magnetic field(B), in a right-hand orientation for a positively charged particle. Since the particles of the plasma must be in motion, the only way to contain them is to have them go in a circle. The shape of the "doughnut" is called a torus. But it gets even more fun, because the forces on the oppositely charged particles experience opposite directions. The ingenious solution is to twist the torus shape into a slight helix, so the resultant form of the predominant magnetic confinement vessel is known as a helical toroidal tokamak.

The Difficulty of Fusion

There are many reasons that the development of fusion has been slow… IT'S HARD! According to the plasma physicist, Stewart Prager, in the preface of *Fusion: The Energy of the Universe*, "A reader of this book will be rewarded by an understanding of why fusion is one of the most challenging scientific endeavors undertaken, how plasmas are rich with fascinating phenomena, how scientists across the world have met the challenges of fusion, and the road that lies ahead."(14) Like many of the scientists who work on fusion, I want to believe that we can solve the issues to make it viable. I think that if it were to become a national and international priority, along with the commitment of the requisite resources, that like the Apollo missions were in the 50's and 60's we would undoubtedly be able to harness fusion's potential. Although fusion was much more challenging than expected, I am hopeful that, as the great Russian physicist Lev Andreevich Artsimovich wrote in the 1970's, "nevertheless, 'thermonuclear [fusion] energy will be ready when mankind needs it.'"(15) I sure hope that he is right!

Problems and Successes with Fusion Reaction

One of the questions asked is why it is so difficult to achieve fusion. After all, CERN is able to accelerate protons and antiprotons to energies of 7 TeV. Isn't this enough energy? It turns out that it is not just an issue of energy there is also the issue of what enables a fusion event. Only 1 collision in 100 million results in fusion. So why is this? It has to do with the very small cross-section of the 'fusion hole' and the very steep 'hill.' Most of the accelerated nuclei bounce off the 'hill' and never get close enough to the target nucleus to fuse. The energy that has been invested in accelerating them is lost… the problem is not so much the number of lost balls but the amount of energy that is lost with them."(16) The analogy is made with the golf course with the hole at the top of a very steep hill. The chances of making it are 1 in 100,000,000… not good… so we have to consider another method. Another method is to put the "balls" on the analogy of a billiard table. Now once confined, they can continue to bounce around without losing energy. The likelihood of a successful collision is still 1 in 100,000,000 but energy is not lost. This is an analogy for magnetic confinement.

As indicated, fusion requires incredibly high temperatures that even exceed those of the sun. There are no materials that can contain this hot fuel. However, there are at least two distinct approaches to the problem. The first is called Magnetic Confinement Fusion (MCF), which we have already discussed, and the second is Inertial Confinement Fusion (ICF).

Inertial Confinement Fusion

Inertial Confinement Fusion solves the problem in a completely different way. Although the triple point conditions, $T_i x n x T_E$, must still be met, the method is to attempt to compress and heat the fusion fuel so quickly that there is no need to have a containment vessel. The fusion reaction will occur before the fuel even has a chance to expand. The amount of energy is tremendous, and the energy is supplied by hundreds of powerful lasers on a small, hollow, millimeter sized ball of fusion fuel, made of deuterium and tritium. The lasers must be incredibly precisely aimed and symmetrical as well as pulsed for optimal effect. Currently the approach is to attempt a single event. In order to provide the energy for a reactor, the process would have to occur approximately 10 times per second or 100,000 times per day. Significant progress is being made on ICF, but the lasers have to be amazingly powerful and precise.

The Current State of Fusion

Summing up the state of Fusion, both MCF and ICF, McCracken and Stott, state that "After many years, the scientific feasibility of thermonuclear fusion via the magnetic-confinement route has been demonstrated, and inertial-confinement experiments are expected to reach a similar position soon. Developing the technology and translating these scientific achievements into power plants that are economically viable will be a major step that will require much additional time and effort."(17)

Breaking Even and Ignition

The state of magnetic confinement fusion called breakeven has been achieved. This is the situation in which the same amount of energy that is put into the reaction is gotten back out. In 1997, JET (Joint European Torus) produced an excess of 16 MW for a few seconds with a 50% T and D mixture! This is not easy to calculate because of all of the sources of energy, but it was a momentous occasion for the development of fusion! The goal with ITER is to reach ignition, which is the situation where the reaction is self-sustaining and energy could be drawn off of the reaction. ITER hopes to achieve the state that 50 MW are supplied and ten times the power is produced, 500 MW! This would result in the final stage of the process which would be to produce a full scale fusion reactor. The triple point is now within a factor of five for ignition for both MCF and ICF! And on occasion, individual experiments have exceeded the conditions for ignition. Now the goal is to sustain the reaction.

Creating a Fusion Reactor

The three next steps toward creating a commercial fusion power plant based on the tokamak MCF are to demonstrate the feasibility, which has been achieved with JET, TFTR and JT-60U. The second step will most likely be achieved by ITER which will test most of the technical aspects of a power plant, including the tritium breeder reactor. It must demonstrate that fusion is technically feasible. The third step is to build DEMO, a full scale operational reactor to prove that fusion is commercially feasible. It is unlikely that DEMO will be operational before 2050! So in fact, the fusion scientists and their critics are both too optimistic!!! Fusion is not just 25 years off, most likely it is 50 years away!!! This is taking into account the political and economic issues as well as the scientific challenges. Fusion and plasma science has come a tremendous way, but there is a tremendous way to go… If I had to bet, I would suggest that we are half way there! So if we want to get there faster, we must commit resources, money and a lot of determination. I'm of the inclination to believe that we MUST solve this issue to address the problems we have with global warming.

Strategies

This entire unit will be taught to Gifted Physics I students for 6 weeks during the material on energy, static electricity, current electricity and magnetism. First, the students will learn about the various forms of energy. I will introduce them to the idea that mass can also be converted into energy, although we don't usually think of it in our conservation laws. We will delve into potential and kinetic energy as well as heat as energy. This is more comprehensive than I usually teach my Physics I classes but it is within their grasp and we will complete supplemental readings to reinforce the concepts. Then when we get to electricity, we will explore the conception in depth of how an electric field results in a magnetic field and vice versa. We will cursorily touch on the perpendicularity of the fields and the right-hand rule. This will enable us to understand the MCF model of the tokamak. With the EM fields, we will also discuss lasers so that we can explore the feasibility of the Inertial Confinement Fusion. These concepts will provide the background for the culminating project.

I will teach all of this more in depth to my AP Physics II B students at the end of the year when we are discussing nuclear fission, quantum mechanics and reviewing electricity and magnetism. My AP B students will have a 4 week culminating activity to integrate all of these concepts.

To both groups, the unit will be a Creative Design Unit, which is an approach that I have adapted from an engineering model. It is an exploratory process based on an engineering model that stresses iterations, hands-on learning and physically creating models. The students will experience a prolonged laboratory experience designed to create cognitive dissonance in a process that they build, construct, imagine and explore multiple solutions about fusion.

Classroom activities

Lesson Plan 1: Fusion Simulations

The Fusion Simulations are activities designed to demonstrate the key aspects of developing fusion for commercial use. The first simulation is to give the students jello, which represents the plasma, and have them try to contain "the plasma" with rubber bands!!! This demonstrates how hard it is to get magnetic confinement fusion to work.

The second simulation is an activity to demonstrate how difficult it actually is to get fusion reactions to occur. This entails a roll of duct tape in the center of a 2 1/2'x5' aluminum "drip" pan. The students are given a bulbous ball and told that they get 13.7 million student bucks if they can get the ball into the duct tape roll. The students must keep their hands on the outer edge of the long side of the pan. (The key to this simulation is that the bulbous ball needs more potential (or kinetic) energy than it can be given.) Consequently, it's 1/100 million but the payoff is 13.7 MW!!!

The last simulation is of Inertial Confinement Fusion. To simulate many lasers, the students will surround the "drip pan" with duct tape roll. Only this time the ball will be a Velcro ball and each student will be given a small dart gun with Velcro darts. The students are instructed that they must launch their darts simultaneously, symmetrically and within 10 cm to insure that the darts have sufficient energy to result in a fusion reaction. The ICF reaction is only successful if all darts stick and they are symmetrical. (These are the extremely demanding requirements of laser ICF.)

Lesson Plan 2: Magnetism and Electromagnets and Generators

This will involve a demonstration of circular and bar magnets as well as an introduction to electromagnets. The students will explore (safely) the parameters and versatility of magnets and the challenge of perpendicular fields. The students will also explore generators so that they understand not only the production of energy but how it is converted in a power plant into a usable form, usually in the form of electricity, whether it is a coal plant, a fission plant or the design we are working on the fusion plant.

Lesson Plan 3: Culminating Project (Creative Design)

The students will be divided into engineering groups. Their task will be to design a nuclear fusion plant. Each group will either design the power generation plant converting heat into electricity or they will work on ideas of how to develop a fusion power plant.

The unit will be a Creative Design Unit, which is an approach that I have adapted from an engineering model. It is an exploratory process based on an engineering model that stresses iterations, hands-on learning and physically creating models. The students will experience a prolonged laboratory experience designed to create cognitive dissonance in a process that they build, construct, imagine and explore multiple solutions about fusion. The process is meant to challenge the students and to encourage them to construct a product that exceeds their expectations. Hopefully, the students come away with a passion for problem solving and an increased knowledge of fusion.

Resources

Chen, Francis F. *An Indispensable Truth: How Fusion Power Can Save the Planet*. Springer. New York. 2011.

Fowler, T Kenneth. *The Fusion Quest*. John Hopkins University Press. Baltimore. 1997.

Herman, Robin. *Fusion: The Search for endless Energy*. Cambridge University Press. New York. 1990.

Martin, Richard. *Super Fuel: Thorium, the Green energy Source for the Future*. MacMillan. New York. 2012.

McCracken, Garry and Peter Stott. *Fusion: The Energy of the Universe*. Academic Press. New York. 2013.

Seife, Charles *Sun in a Bottle: The Strange History of Fusion and the Science of Wishful Thinking*. Penguin Books. New York. 2008.

Sheffield, John. *Fun in Fusion Research*. Elselvier. New York. 2013.

Stacey, Weston M. *The Quest for a Fusion Energy Reactor: An Insider's account of the Intor Workshop*. Oxford University. New York. 2010.

Yergin, Daniel. *The Quest: Energy, Security, and the Remaking of the Modern World*. Penguin Books. London. 2012.

Notes

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1. Chen, 3

2. Yergin ,221

3. Chen, 179

4. McCracken, 37

5. Sheffield, 4

6. Seife, 169

7. Ibid, 169

8. Ibid 226

9. McCracken, 1

10. ibid, 58

11. Chen, 270

12. Ibid, 311

13. Ibid, 273

14. McCracken, xiv

15. Ibid,xv

16. Ibid, 36

17. Ibid,5

APENDIX

COMMON CORE STANDARDS

English Language Arts Standards in Grade 11-12 number 1 will be utilized in reading the texts about fusion. Students will cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account. This will involve the argument about whether fusion is likely to be a reality in their life time.

English Language Arts Standards in Grade 11-12 number 2 will determine the central ideas or conclusions of a text; summarize complex concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms. This is essential to decipher the complex fusion texts.

English Language Arts Standards in Grade 11-12 number 3 will be utilized in the experiment of Creative Design. The students will follow precisely a complex multistep procedure when carrying out experiments, taking measurements, or performing technical tasks; analyze the specific results based on explanations in the text.