Lauren Kate Gibson

George Washington University
Elliott School of International Affairs
Center for International Science and Technology Policy
1957 E Street, NW
Washington DC, 20052

Developing Fusion as an Energy Source

Developing fusion as an alternative energy source is currently Big Science—expensive, long-term, and occurring internationally. This paper will examine the effort to develop this technology from several different angles. First, I will provide the background beginning with the argument for developing fusion and then continue with the physics involved. This section will culminate in a brief history of the pursuits from the 1940s to the mid-nineties. Next, I will examine the eight most influential or promising machines in our current era of research, placing them in context with each other and the scientific requirements of a commercial plant. Lastly, I will explore the public policy challenges that will be encountered before the technology transfer to industry can occur. This paper will provide an overview of all that is involved in producing fusion energy.

1. Background

In order to comprehend the current research efforts and political challenges, it is necessary to become familiar with the context of this struggle. I will begin by explaining why fusion is worth pursing and then continue with a brief description of the relevant physics. This section will then conclude with a history of fusion development until the modern era.

1.1 The Benefits of Fusion

Fusion would be a near Utopian means of providing the world with electricity. Using cheap and abundant fuel from the sea, it would create electricity without negatively impacting the environment. It would be much better than our current nuclear energy option, fission reactors, whose radioactive waste and potential for accidents has given nuclear energy a bad name.

> The fusion reaction itself produces no radioactive waste products (although the interior of the machine does eventually become radioactive). A fusion reactor cannot “melt down” –there is so little fuel in the reacting plasma that it quickly runs out of energy if left alone. Second, the fusion reaction is intrinsically so difficult to sustain that any upset of the process in an accident would instantly end it. In fact, if the reaction gets too hot, the probability of particles hitting and fusing actually goes down. And if the plasma touches the “cool” walls of the reactor vessel, it is quenched instantly.[1]

Furthermore, fusion energy would render the United States independent in energy and would be transferable to developing nations without simultaneously giving them the technology to make nuclear weapons. (The hydrogen bomb does use fusion, but it must be ignited by fission, and therefore cannot be developed independently.) As one historian has surmised, “whether the issue is détente, energy security or the environment, fusion has rightly been able to sell itself to policy makers as part of the solution.”[2]

---

[1] Herman, Robin, *Fusion: The Search for Endless Energy* (New York: Cambridge University Press, 1990), 109

[2] Nutall, WJ, *Nuclear Renaissance: Technologies and Policies for the Future of Nuclear Power* (IoP Publishing Ltd, 2005), 254

1.2 The Physics of Fusion, Fusion Reactors, and Research Machines

The process of fusion is what powers the sun. This thermonuclear reaction occurs when two light nuclei are forced together. They fuse and form a new nuclei whose mass is less than the sum of the original two masses. Since energy is equivalent to mass times the speed of light squared, this reaction emits energy. In order to force them together, you have to overcome their natural electrostatic repulsion[3]. This can be done either by kinetically forcing them together or by heating them up enough that they collide at fast enough speeds to fuse. The first occurs in inertial confinement fusion and the latter in magnetic confinement fusion. Deuterium and Tritium are the most favorable nuclei for practically generating this energy. They are both isotopes of hydrogen, and deuterium can be found directly in seawater. Tritium must be created from Lithium. Although it is possible to fuse deuterium with deuterium, it takes about 1/10 of the energy to achieve fusion with deuterium and tritium instead, thus making it a more practical goal for developing fusion energy. When deuterium and tritium fuse, they create a helium nucleus, also know as an alpha particle, and a neutron, both of which move at a certain velocity. This velocity is its energy and both together are the energy released through fusion. (The helium is harmless as a byproduct and even useful in amplifying the energy, but the neutron released will eventually make the containment vessel radioactive.) Through a few more interactions with the materials already present, including the alpha particles contributing their heat (energy) back into the plasma, this energy can be amplified. “If the rate of alpha particle heating equals the rate at which energy leaks from

---

[3] Murray, Raymond L., *Nuclear Energy: An introduction to the concepts, systems, and applications of nuclear processes, 3rd ed.* (New York: Pergamon Press, 1988), 65

the plasma, then ignition has been achieved and a self-sustaining fusion burn occurs."[4] The self-sustaining fusion burn will be the key to a fusion reactor plant. As with many conventional power plants, the heat would heat water into steam and turn turbines, therefore creating electricity.

Before developing a plant, there are three scientific conditions that must be met simultaneously. First, the method must achieve an ideal temperature of 4.4 keV (approximately 52 million degrees Celsius) for the deuterium-tritium reaction. It must also have a certain density for a certain amount of time which, when multiplied together, must be greater than or equal to 1014 sec/cm^3 for magnetic confinement fusion. This is called the Lawson criterion.[5] It is expressed differently for inertial confinement fusion because that method depends less on time and more on the radius of the fuel pellet. The Lawson criterion for inertial confinement fusion is the equation density times radius is greater than 3 g/cm^2. Either of these two conditions has been met independently but has not yet occurred simultaneously. The third condition is a general description of how the energy produced from the reaction relates to the energy put into the system (which, if traced back through its incarnations is pulled from the power grid) in order to start and sustain the fusion reaction. This is called the Q-value. A Q-value less than one means that it is taking more energy to start the reaction than the reaction produces.[6] Q=1 is called the breakeven point. Thus far, the best Q-value obtained is 1.25 at a machine in Japan. This means the energy produced was 1.25 times the original energy input. Ultimately, a commercial plant would need Q=10 in order to for the technology to be competitive with

---

[4] "D-T Fusion: What is it?" 16 March 2007, http://www.nuc.berkeley.edu/thyd/icf/DT_fusion.html

[5] Murray, Raymond L., *Nuclear Energy: An introduction to the concepts, systems, and applications of nuclear processes, 3rd ed.* (New York: Pergamon Press, 1988), 151

[6] "ITER Students and Educators Page" 16 March 16, 2007, http://www.iter.org/a/index_use_1.htm

other means of producing electricity. When discussing different methods of developing fusion energy, they are compared against each other using these three criteria.

The three major designs are the tokamak, inertial confinement fusion, and the z-pinch. The tokamak is a doughnut shaped machine in which plasma is held by creating a current within it from the strong magnetic fields of the machine.[7] While the plasma is being held magnetically, it can be heated, usually through a neutral beam injection. If the fuel is dense enough and hot enough, it will fuse. Inertial confinement fusion is a much more direct method. In it, lasers implode a pellet of fuel, causing it to undergo fusion. The z-pinch machine uses a combination of these methods. It is a metal cone consisting of tungsten wires and fuel pellets. When a current is run through the cone, the tungsten wires become plasma and, as a result of the electric current, emit x-rays, which compress the fuel pellets, and cause fusion.[8] Strong experiments exist in each of these methods and will be discussed further when I examine, case by case, the current efforts in fusion research.

1.3 History of Developing Fusion as an Energy Source

Fusion energy research is not a new arena. It began in the early 1950s and has been characterized by unusual international collaboration, widely publicized failures, and minimal success achieved slowly. This section will consider its scientific history prior to the modern efforts in order to provide a context for today's machines that will be explored later.

---

[7] Nutall, WJ, *Nuclear Renaissance: Technologies and Policies for the Future of Nuclear Power* (IoP Publishing Ltd, 2005), 261

[8] Chang, Michael. "Methods of Fusion." UC Davis COSMOS, 3 August 2006 http://cosmos.ucdavis.edu/2006/cluster2_final_projects/MichaelChangEnergy.pdf

Fusion research began in earnest in 1951 when Juan Peron, President of Argentina, erroneously announced that his country had a working fusion plant. While some experiments in England and the Soviet Union were already underway at this point, this announcement sparked both public and scientific excitement over the technology and lead to the United States launching their Stellerator a year later.[9] For the first seven years, the work on this new branch of physics was classified, and therefore the scientists could not share their progress with the necessary basic research across national delineations. When it was finally declassified at the second Atoms for Peace Conference in Geneva in 1958, it marked "a sacrosanct kind of cooperative endeavor for both the scientists and their government backers."[10] This arrangement is all the more remarkable for persisting through the Cold War.

The first major success in fusion research occurred in 1968 when the Russians announced that their tokomak had defied a theory of the time that stated that "plasma would never remain stable long enough at high temperatures to produce surplus energy."[11] It did not produce excess energy, but it did remain stable longer than the theory predicted.

In 1983, MIT reached another milestone by achieving two of the three criteria necessary that were discussed earlier, namely density and confinement time. Achievements in fusion were slow to come, but significant.

There were failures along the way as well. Britain announced as early as 1958 that they had produced the world's first controlled fusion reaction, but it turned out that the

---

[9] Herman, Robin, *Fusion: The Search for Endless Energy* (New York: Cambridge University Press, 1990), 16-17

[10] ibid. 61

[11] ibid 84

lack of diagnostic tools had led them to misinterpret a byproduct.[12] Of course, there was also the fiasco of cold fusion. Two chemists announced through a press conference—not the customary academic journal—that they had produced table top fusion at room temperature. Politicians and the public became excited, but when other scientists were unable to reproduce their work, their claim fizzled.

In summary, the first fifty years of fusion research were characterized by international collaboration, incremental advances, and widely publicized failures.

2. Current and Recent Efforts

In this section, I will examine the eight most influential or promising research machines from our current era. This will be a general overview of the current state of declassified fusion research.

2.1 ITER

Much of the hope for developing fusion energy currently lies in ITER, a tokamak machine that is currently between planning and construction. The ITER organization, which will administer the construction and operation of the machine, was formally created on November 21, 2006.[13] The seven partners currently include the European Union, China, India, Japan, South Korea, the Russian Federation, and the United States. Scientifically, ITER, which simply means *to go* in Latin, has the goal of reaching Q=10 or Q=5 if the pulses approach a steady state. This means a ten-fold or five-fold increase

---

[12] Herman, Robin, *Fusion: The Search for Endless Energy* (New York: Cambridge University Press, 1990), 50

[13] Duncan Hollis, *"Show me the ITER*," Opinio Juris, 8 March 2007, http://www.opiniojuris.org/posts/1173381771.shtml

in energy from the input to the output (Q=1 is the breakeven point when the energy input equals the energy output.) It will also be used to experiment with creating tritium, a key fuel, from a lithium blanket within the machine. Doing so would lessen the impact of one of fusion's limitations- the availability of tritium.[14] In addition, ITER is intended to test technologies and processes that would be used in a commercial fusion power plant. Among these are superconducting magnets and remote handling.[15]

The future for ITER has begun with the creation of the ITER organization. From here, the proper licenses will hopefully be obtained and the physical construction will commence in 2008. The first plasma is expected to be created by 2016. Once that milestone has been reached, then the machine is expected to be used for experimenting and striving for the scientific goals outlined above for a twenty year period. If all goes as planned, the ITER will be the closest we have yet to come to a commercial tokamak reactor.

2.2 JET

A precursor to the ITER machine was the Joint European Torus (JET). This tokamak in Culham, UK, has been operational since 1983 and is a collaboration of all the European fusion organizations. While JET is too small to supercede the breakeven point, it has been a highly respected endeavor with several technical firsts. It achieved the world record of released fusion energy in 1997 with 16 MW.[16] The design of JET has directly led to the design of ITER, which will be two to three times larger. With the future of fusion no longer at JET, its operations have since been dedicated to studies that would be

---

[14] "ITER Students and Educators Page" 16 March 2007, http://www.iter.org/a/index_use_1.htm

[15] Ibid.

[16] JET homepage, 16 March 2007, http://www.jet.efda.org/

beneficial to ITER. To this end, it has recently been outfitted with new and upgraded diagnostics.[17] Its political situation can also be applied to the ITER. As a regional collaboration, it was first run by the "JET joint undertaking" legal entity. As of 2000, it has been operating under contract by UKAEA (United Kingdom Atomic Energy Authority) with the scientific aspects under the control of the EFDA (European Fusion Development Agreement). Should ITER ever need to change its organizational structure then the transitioning at JET will be a guide.

2.3 JT-60

Another illustrious tokamak is Japan's JT-60. The world leader in fusion research, it holds world records for the Q-value (1.25[18]), the ion temperature, and the triple fusion product. It has been operational since 1985, about the same time as JET and the exact year that ITER was proposed. Its current goals are to contribute to the science of ITER and eventually to the development of the DEMO reactor, the demonstration reactor that is supposed to be able to persuade commercial interests to develop a fusion power plant. Work is currently being done to transform the JT-60 into a superconducting tokamak under the "National Centralized Tokamak (NCT) facility program."[19] This would lead to more research in high, steady state physics which would contribute to the further development of fusion.

2.4 T-15

---

[17] JET homepage, 16 March 2007, http://www.jet.efda.org/

[18] Japan Atomic Energy Agency, Naka Fusion Institute, "Fusion Plasma Research," 16 March 2007 http://www-jt60.naka.jaea.go.jp/

[19] Ibid.

The last of the three major international tokamaks to become operational in 1988 was the T-15 in Russia which was also the first to be silenced. Although not officially shut down, there have been no new experiments since 1995[20] due to “insufficient funding and high prices on energy carriers.” [21] A second modernization project has been planned to begin in 2008 with the goal of becoming more like ITER. (The first occurred from 1996-1998 and focused on secondary systems.) Specifically, the technical goals that the most recent modernization will theoretically allow the machine to achieve include “the production of 10 keV plasma, . . .the increase of the plasma discharge duration up to 1000 s[econds] and the total heating power to 20 MW.”[22] Previously, T-15 had been able to obtain temperatures of 1-1.4 MeV (and densities of (1-3) $10^{13}/cm^3$. The modernization is specifically being done in order to increase “participation of [the Russian Federation] in the experimental collaborative investigations on the tokamak.”[23] If the research center Kurchatov Institute, which administers the program, is able to run experiments again, then the T-15 would once again be an important tokamak. It is a shame that those who invented the tokamak do not have the funding to continue experimenting on their own project.

2.5 Laser MegaJoule

Another major European effort that is being planned is the Laser MegaJoule (LMJ) Project which will be at the Center of Scientific and Technical Studies of

---

[20] Institute of Nuclear Fusion, Russian Centre Kurchatov Institute, 16 March 2007. http://www.kiae.ru/eng/str/inf/o11nsi.htm

[21] Ibid.

[22] G.S. Kirnev, et al. “Superconducting Tokamak T-15 Upgrade”, D. V. Efremov Scientific Research Institute of Electrophysical Apparatus, Metallostroy, 196641, St. Petersburg, Russia, 16 March 2007, http://www-pub.iaea.org/MTCD/Meetings/FEC2006/ft_p7-3.pdf

[23] Ibid.

Aquitaine (CESTA) in France. As the name suggests, this machine will use laser induced inertial confinement fusion. It is currently under development. The Laser Integration Line (LIL), an eight laser beam system intended to prove the technology of the larger project, has been operational since 2003. However, the full use of the facility, which will have 240 lasers, is not expected to be able to occur until 2010, at which point the lasers will deploy 1.8 megajoules. It is intended to be able to reach Q=10 using a deuterium-tritium target. Like all inertial confinement setups, the LMJ will also be used for weapons research since it will be able to simulate thermonuclear explosions. In fact, its management agency, CESTA, is primarily a weapons organization and has been called the "industrial architect of nuclear warheads."[24] This association will likely make the funding for the program more consistent and thus minimize this usual political challenge that has affected other fusion efforts. It appears that LMJ will primarily be part of France's weapons simulation program[25] and only afterward participate in developing fusion as an energy source. These goals, however, are not mutually exclusive and may be done simultaneously.

2.6 US National Ignition Facility

The US has a program similar to France's Laser MegaJoule. In fact, they are estimated to be able to achieve the same fusion triple product, a combination of the factors discussed earlier. The laser at the National Ignition Facility, however, will be the world's largest once it is completed by 2010. Currently, it is 87% complete.[26] This

---

[24] Mary Byrd Davis, "Nuclear France: materials and sites," 16 March 2007, http://www.francenuc.org/en_sites/aquit_cesta_e.htm

[25] Laser MegaJoule homepage, 16 March 2007, http://www-lmj.cea.fr/html/cea.htm

[26] NIF homepage, 16 March 2007, http://www.llnl.gov/nif/

impressive machine is located at Lawrence Livermore National Laboratory in Livermore, California. It has numerous official partners: National Nuclear Security Administration, Department of Energy, Sandia National Laboratory, Los Alamos National Laboratory, University of Rochester Laboratory for Laser Energetics, Naval Research Laboratory, General Atomics, Department of Defense, US Army, US Air Force, and the Defense Threat Reduction Agency.[27] As can be inferred from the list of partners, NIF has a significant role in stockpile stewardship of our nuclear weapons.

> NIF is crucial to the Stockpile Stewardship Program because it is the only facility that can create the conditions of extreme temperature and pressure – conditions that exist only in stars or in exploding nuclear weapons – that are relevant to understanding the operation of our modern nuclear weapons.[28]

Through combining actual experiments with powerful computer simulation, we can access the reliability and behavior of our weapons without actually having to test them. Unlike LMJ, the primary purpose of NIF will be to develop inertial confinement fusion rather than its weapons applications. To this end, it, along with the LMJ, is second only in promise with the ITER machine. Inertial confinement fusion has a vastly different approach from the magnetic confinement of the tokamaks and therefore should be simultaneously pursued, especially since it has the additional application of supporting nuclear test bans and nonproliferation goals. This particular project, however, has suffered from budget fluctuations in the past, though hopefully this will not be the case now that construction of the facility is complete.

---

[27] NIF homepage, 16 March 2007, http://www.llnl.gov/nif/

[28] Ibid.

2.7 Z-Pinch

Another US lab, Sandia National Laboratory, has an inertial confinement machine that does not rely on lasers. The Z Pinch Inertial Fusion Energy Program is currently operational, though it is not one of the current or planned high performers (yet its modest success should not be discounted, especially since it is a unique approach). Its principle mission is not developing fusion as a source of energy but to maintain our stockpile. Specifically, it has been charged with validating the computer codes upon which we rely for information about the weapons. Recently, it has encountered a rather interesting scientific challenge. On March 2, 2006 it was announced that the machine had produced temperature in excess of two billion degrees Kelvin, which is hotter than the interiors of stars. Although these temperatures had been achieved in discrete tests over fourteen months, the researchers are unsure of their cause. Determining exactly why and how these incredible temperatures were produced would be a significant contribution to fusion research since temperature is one of the main criteria to be optimized in a commercial reactor.[29]

2.8 Tokamak Fusion Test Reactor

It would be remiss not to mention the Tokamak Fusion Test Reactor in a survey of relevant fusion machines. This legendary machine operated at Princeton from 1982 to 1997 under its Plasma Physics Laboratory with funding from the Department of Energy. It achieved several records, including being the first to reach 100 million degrees Celsius in 1985 and later, in 1995, achieving 510 million degrees, which was the world record at the time. It also discovered several behaviors of the plasmas, such as the "bootstrap

---

[29] Sandia National Laboratories homepage, 16 March 2007, http://www.sandia.gov

current," an unevenness of pressure that would help sustain the reaction with less external energy. In addition, TFTR was the first magnetic confinement machine to use deuterium-tritium fuel in 1993. It was, in fact, able to achieve all of its research objectives,[30] a feat which contributed to its closing down. The Department of Energy could no longer afford to operate it[31] and it was successfully disassembled and removed in 2002.[32]

2.9 Machine Conclusions

These eight machines represent the current state of fusion research. The two that have been retired were the revered transition from the historical era to the modern, new machines that are being planned. As such, they are still very much a part of the conversation today. The currently operational machines, the JT-60, the JET, NIF, and Z-Pinch, range from providing supporting science for the development of ITER to being a significant and promising machine in their own right, as NIF is. The National Ignition Facility is the best hope for inertial confinement proving itself as a method for a commercial reactor. The Laser MegaJoule has similar technical aspirations, but is behind NIF in terms of physical development of the facility. The best hope overall for fusion as an energy source is ITER, the international tokamak about to enter its construction phase. The next step after ITER completes its expected experimental phase of twenty years in 2036 is to develop a prototype plant.

---

[30] Princeton Plasma Physics Laboratory, Tokamak Fusion Test Reactor homepage, 16 March 2007 http://www.pppl.gov/projects/pages/tftr.html

[31] Richard M. Jones and Audrey T Leath, "Important Hearings for DOE Science Programs," FYI: The AIP Bullentin, 17 March 2000 http://www.aip.org/fyi/2000/fyi00.032.htm

[32] PPPL News release, "Tokamak Fusion Test Reactor Removal Successfully Completed," 21 October 2002, http://www.pppl.gov/news/pages/tftr_removal.html

3. Policy Challenges

There are several policy challenges that stand in the way of achieving the ultimate goal of commercially run fusion power plants. First and foremost is inadequate funding. Fusion research has suffered from the ebbs of flows of public and political opinion that affect its funding level, especially in the United States. All countries must consider how international collaboration now is affecting their future stance in the market. This is assuming, of course, that there will be a market. Technology transfer is yet another political concern. At some point commercial entities need to take over to make the public good of fusion generated electricity available and thus validate the massive investments that several governments have made. Policy makers must act to address these three major policy challenges.

Fusion is now at a critical point where funding is increasingly necessary. As the machines that will take us past our current modest energy gain to a high energy gain are being constructed, this sector is being transformed from basic science with a vague end goal into applied science with the end of a demonstration prototype. The predicted level of funding necessary for the United States to create their DEMO plant, the demonstration prototype that is intended to persuade industry to take over the reins, is $24 billion 2002 dollars. While it is highly unlikely that all funding would be cut off, it is critical that funding levels remain constant so that the research can be productive.

> fusion stands at a critical point. . . The decisions that have to be taken will determine if fusion is to progress as an energy technology or to take a slower course as a basic scientific research program. For fusion to pass from the research stage into reactor development undoubtedly requires a

> substantial increase in funding and this will certainly not become available without strong pressure from within societies.[33]

In the past, the level of funding has fluctuated in the United States. When energy independence or availability is an acute political issue, then fusion becomes significantly funded. When it is not, however, funding falls and the timeline for completion stretches further into the future.

With an eye on eventual returns on government investment, the decades-long tradition of international collaboration that has been a hallmark of fusion research may need to be reevaluated in light of the approaching commercial market. As usual, the United States would like to be a leader in international collaboration in order to secure its future place in the market. However, Europe and Japan are more advanced than we in fusion research, so if this is a legitimate goal rather than a standard policy line, we will have to step up our domestic programs significantly.[34] However, the United States should remain committed to international collaboration because it is the greatest hope for the technology to actually be developed. All involved nations must strike a balance between collaborating internationally and protecting and developing their own technologies in preparation for the global market. This is a particularly poignant situation for the United States since it is used to being the natural leader and is not currently so in fusion research and development.

Of course, whether the United States is in a leadership position will be purely academic unless technology transfer occurs. The obstacles are both economic and social. Energy consumption is predicted to double by 2050, which is also when fusion electricity

---

[33] Braams, CM and Stott, PE. *Nuclear Fusion: Half a Century of Magnetic Confinement Fusion Research* (Bristol, England: Institute of Physics Publishing, 2002) 267-8

[34] A Plan for the Development of Fusion Energy, Final Report to FESAC, March 5, 2003 http://www.ofes.fusion.doe.gov/More_HTML/ FESAC/DevReport.pdf, page 9

is predicted to be commercially available.[35] Industry, however, is not yet ready to discuss the possibility. It is simply too far into the future. [36] Industry would perhaps be more interested in the future if the stigma of nuclear energy is removed. The Chernobyl disaster and the issue of nuclear waste taint the public opinion even though neither would be issues with a nuclear fusion plant. It simply cannot melt down because there is not enough fuel present at any given time and the reaction requires constant tending, not to control, but to sustain. Several studies have concluded that fusion plants would be inherently safe.[37] The public needs to be educated about the differences between fission and fusion power before they would be comfortable with a plant being operated near them. For the most effectiveness, this campaign should be begun immediately. Contrary to public opinion, environmentalism would, in fact, support fusion if traditional means of producing electricity continue to pollute and policies are created to combat that. The spectacle of cold fusion taught us that despite seeming unpopularity the public would be behind fusion if researchers can ever get it to work and industry ever adapts it. While the future of technology transfer is generally positive, it is by no means assured. Policy makers can improve this outlook through certain steps.

The policy challenges now facing the development of fusion are not insurmountable. Obtaining funding consistently will be a matter of lobbying politicians on one hand and producing scientific results on the other. Maintaining a proper balance between international collaboration and cooperation will be harder, especially for the United States, who likes to approach this problem from a leadership position rather than a

---

[35] Braams, CM and Stott, PE. *Nuclear Fusion: Half a Century of Magnetic Confinement Fusion Research* (Bristol, England: Institute of Physics Publishing, 2002) 245

[36] ibid., page 272

[37] Braams, CM and Stott, PE. *Nuclear Fusion: Half a Century of Magnetic Confinement Fusion Research* (Bristol, England: Institute of Physics Publishing, 2002) 246

significant, but secondary position. Technology transfer depends on the economy at the time of the development, specifically the need for environmentally friendly electricity sources. Public opinion will also be a major factor. Beginning to influence public opinion now would go a long way to smoothing the technology transfer later. It is important that policy makers confront these issues as the researchers wrestle with the plasma in order for fusion produced electricity to arrive on time.

4. Conclusions

Fusion research is at a critical and exciting juncture. New machines are being built that will achieve the scientific parameters necessary to making fusion a commercially viable means of generating electricity. This is being done collaboratively at the ITER, a massive tokamak that is our best hope for actually reaching our goals. On the domestic level, the NIF (National Ignition Facility) and the LMJ (Laser MegaJoule) in France are using an alternative method, inertial confinement fusion. While they are not predicted to be as powerful as ITER, they should be fostered as an alternative means to a very noble goal. Fusion is noble because it uses an abundant fuel from seawater and does not harm the environment. On the other hand, it does produce mild radiation whose effects, however, are far from those of the radioactive waste of fusion power plants. The work towards achieving this goal is not confined to scientists and engineers, though there are very real scientific and technological obstacles. Policy makers will also play a critical role as they prepare society for technology transfer while maintaining funding and ensuring a balance between international cooperation and competition. Although developing fusion as an alternative energy source has been scientifically difficult and decades long in both its history and outlook, the rewards will be enormous. Mankind will have imitated the power production of the sun.