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The Upcoming Energy Crisis

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Abstract

This project analyzed current energy policy and energy production dilemmas. We evaluated other technologies that are developing, which are designed to resolve those issues. Technologies mainly discussed include fuel cells, nuclear fission and fusion, and coal gasification. New policies were proposed based upon the merits of emerging technologies and addressing the most urgent shortcomings of current ones.

Executive Summary

The project team divided the project into three different segments. The first segment focused on gathering information on fossil fuels, emerging technologies, and researching current projects and facilities. The second segment of the project was dedicated to using the gathered information from the previous segment and drawing a model and making predictions. The final segment was allotted for investigating current policies, and formulating new policies and courses of action.

The fossil fuels research centered around the properties of the three fossil fuels, how clean energy generation is using each fossil fuel, foreign and domestic dependence on each individual fossil fuel. Points of interest were U.S. dependence on foreign oil imports, high emission level from coal-fired power plants, and the limited supplies of oil and natural gas.

The emerging technologies investigated include fuel cells, nuclear fission and fusion, and coal gasification. The fuel cell is a new spatially and thermally efficient method of generating energy. Nuclear fission and fusion are two methods of harnessing nuclear energy in a clean, efficient, and powerful process to generate electricity. Nuclear power has been researched for over fifty years and still has not reached a stage where it can be used for widespread or broad scope electricity generation. Coal gasification is one of several new concepts being investigated by the CleanCoal initiative. Coal gasification seeks to change the phase of the fuel from solid to gas and channel it through a gas turbine, divesting it of pollutants while enroute.

All of this information was gathered and molded into a model. What happens ten years from now? Twenty? Thirty? How does it affect the world? How will emerging technologies affect the future picture of the world? A good portion of the model building went towards answering these questions and other ones like it.

Models are good and well, but the important question is what do that powers that be intend to do about the coming energy crisis? We decided to find out. We looked at their current policy on the energy industry and their projects in progress. We made our own energy policies. We considered our models and data and we decided what would be best; what would be the most appropriate course of action given the current and projected circumstances.

Introduction

The world as we know it today requires energy to operate. Anything and everything that could be considered useful requires some sort of energy to function properly. Our society is a product of a countless number of dynamic parts, and in order to maintain them a lot of energy is required.

There are growing concerns in the United States and around the World about the coming energy crisis. Why are we on the verge of an energy crisis if there are so many sources of energy and many of them renewable? Because we are most reliant on fossil fuels and the world shall deplete them within the next thirty years. What can we do about this? We have two options. We can find either alternative fuel sources or more efficient ways of expending fossil fuels. If we found a more efficient way of expending fossil fuel, we would still be taxing a limited supply of fuel, though we will have delayed the onset of an energy crisis so that we have more time to find other, plentiful, renewable fuel sources.

Energy is everywhere, and in many different forms. However, only a fraction of these is of practical use. Originally, the decision for how energy was obtained was based on how economic it was. In general, the more abundant and the easier the fuel was to process, the cheaper it was. As planners start looking into the future, many other considerations start to develop. Based on experience considerations such as the environment are also starting to play a role in our decision on how energy can be obtained. As the current fuel source is being depleted, the demand for the development of future fuel sources is growing.

Our intent is to find methods to alleviate the energy crisis by finding more efficient ways to expend our current fuel stocks and also to find cleaner, efficient, renewable sources of energy to diminish or destroy the threat of a major energy crisis. Naturally, there are questions to be answered with each of these sources of energy. Such questions are as follows. How much does it cost? How efficient is it? Can it provide energy on a large scale? If so, how large? Can it be miniaturized? If so, can it be used to power vehicles? Can it be made into a form comparable to a power generator? We intend to research several things. Among these are current standards for safety, efficiency, etc.; future standards of the same; plans for conversion, crossover, or implementation; and current research. Why is this a relevant topic of research? Energy and energy crises has a major effect on international politics, international relations, world-wide business, and the life-style of people around the world.

There are currently many competitors for the fuel source of the future. In the long run, there may be more than one type of standard fuel. This could lead to more effective energy solutions for different applications. What needs to be done is to properly understand the current progress of the developments for future fuel technologies, and the potential strengths and limitations.

The fuel of the future will have to support a new era in the development of society. This source of energy has not yet been determined yet, however it has many requirements and expectations to fulfill. The fuel source should not only be able to completely replace the current one, but also have additional benefits. This fuel should have greater capabilities, and efficiencies. The goal in that the costs saved in the future would help pay for the reorganizing of the previous infrastructure, and a society with a more effective use of energy.

The choice that will be made to determine the future source of energy will also have a profound affect on humanity as a whole. The production and consumption of energy plays a vital role in modern human society. By making changes to such a fundamental part of our society it is inevitable that there will be many and large consequences. These consequences must be taken into consideration when deciding on the future source of fuel. It is important to understand the role energy plays in society. Engineers as well as politicians must deal with the development and implementation of technologies. These technologies, based on the conclusions of scientific research, affect society in numerous ways.

As engineers, we are the mediators between science and society. We feel strongly about the interactions between these aspects of humanity. Although we share a mutual interests in this topic, our emphasis on these technologies' applications are different.

Michael would like to attain a deeper understanding behind the operation and technologies of these future energies. A lot of research will be done to develop effective use of these energies. The utilization of these energies will involve many new technologies. There may be many new sources of fuel, and many methods for extracting them. These fuels may be processed in different ways. Building a new infrastructure to accommodate these new fuels may also be necessary. He would like to get a better understanding of the underlying principles behind how these technologies function.

Morgan would like to explore the affects of these energy technologies on military infrastructures and methods for applying these technologies. A new source of energy will have a new set of attributes. He feels strongly about understanding effective ways of utilizing these energy sources, as well as the global implications of new sources of energy.

Robert would like to analyze the current developers and their developments in alternate energy sources. Societies affect on the choice of energy in the future will be just as great as that energies affect on society. Economics will still play a large part in determining the source of energy for the future. Since energy does play such a large role in society, the people who control this source of energy will hold a great deal of power. As a result, the cooperation, and/or competition of these developers will also affect our futures a great deal.

Mike's Introduction

Personal Motivations

Studying energy systems and alternate fuel sources will prepare me to dealing with other technologies in the future. This project will give me first hand experience in researching and understanding the evaluation process of technologies. Fuels and energy systems in particular are a critical part of all technologies. By researching possible future energy sources, I hope to also understand the evolutionary processes of technologies.

Besides the aforementioned general interests, investigating different fuels and energy systems is also a critical concern. Since all technologies have some dependence on energy, their designs will be affected by the fuel and energy system they use. As most people know, the current energy systems have many large drawbacks. Potentially the most dangerous long-term drawback is the environmentally damaging affects. I feel strongly that in order for technology to progress any further, it is critical that it can coexist with the rest of the world.

Relations to Personal Goals

I am fascinated by modern technologies. I feel that the knowledge I gain from studying science and technologies will empower me and allow me to accomplish great things in the future. I feel that future technologies should be more mobile and automated. I would really like to be part of these developments in technology.

History has demonstrated the revolutionary affects of machines. Machines allowed humans to evolve and develop into a civilization. History is often categorized by the types of machines and technologies they had at the time. Each new development in technology was accompanied by a significant change in human society. As time progresses, new technologies will push the realm of possibilities even further. The advent of computers, advanced space-age materials, and manufacturing technologies, coupled with increased levels of miniaturization and demand for mobile products will be leading to new developments. I predict that it is only a matter of time before highly mobile, automated robots are developed to augment certain functions in society. In my opinion, this development will be the start of a wonderful new era for mankind. I feel that participating in such a development will be a great honor, and will be a very meaningful accomplishment.

Energy is the foundation on which technologies are built. Mobile technology designs are especially affected by the limitations of their energy sources. In order for new technologies to be more mobile, their energy systems must be redesigned first. Even without actually designing a fuel cell, I am interested in the various aspects of energy systems and their influences on the design of mobile technologies.

What Qualifies this topic as an IQP

Studying alternate fuels and energy systems involves the understanding of the societies that use them. The researching and evaluating of these fuels and systems reflect the concerns and priorities of those that use them. Raising awareness about the interactions between technology and society is the primary purpose of the IQP. I feel my accomplishments in this project will prepare me to be constructive, and contribute to my future profession.

Morgan's Introduction

Personal Motivation

The personal motivation in this project for me was to answer some of my own questions regarding the future of energy. My personal feelings regarding the energy situation coming into this project was: given that fossil fuels are not a renewable resource, and many key systems depend on these fuels, it only stands to reason that it is only a matter of time until many fossil fuel based systems need to be replaced by an alternate source of power. I did not have much of an idea what these sources would be, much less what the transition would look like. The research in this project will help me understand what upcoming fuel technologies will help replace fossil fuels, and how the transition will be made.

Another personal interest of this project is a curiosity in the technical underpinnings of upcoming alternate energy sources. This project should help with the understanding of how some alternate energy sources function, and how they have evolved to the point where they are.

Relation to Career Goals

Research is an important part of understanding new technologies, or learning existing ones. At work, I often spend more time attempting to understand a technology than actually spending time using it. Learning to research and understand unfamiliar technologies in this project will help in my career, at times when I need to study different technologies without guidance.

Why This Project is an IQP

Research done in this project regarding different fuel technologies will also help in understanding what the future plans of societies are regarding the research and plans for deploying these fuel technologies. In this way, the upcoming alternate fuel source can be seen in the context of how societies plan to deal with the upcoming energy crisis.

Chapter 1

Data, Properties, and Flaws of Current Energy Systems and Fuels

The United States (as well as most of the world) heavily relies on fossil fuels for energy. The fossil fuels that see the most use are oil, coal, and natural gas. Oil is not only heavily depended on for electricity, but also transportation, machinery maintenance, war materiel, personal needs, and so forth. Coal power was the earliest discovered from the powerful but highly inefficient steam locomotives powered by coal-fired furnaces. Coal is the dirtiest fossil fuel, but also the most plentiful (especially in the United States). Natural gas is the cleanest fossil fuel of the three. Unfortunately, natural gas is the least abundant fossil fuel in the world, based on known reserves and deposits.

Currently, the world is highly dependent on fossil fuel-based energy. The United States, alone, accounts for two thirds of the world's energy consumption. 40% of all in the U.S. electricity is generated at oil-based power plants. 30% of U.S. power is based on coal-fired power plants, 28% from natural gas-fired plants, and 2% of U.S. electricity is generated by other means (hydroelectric dams, wind-powered generators, etc.). There are simply not enough fossil fuels to adequately power the world for more than thirty years at our current rate of consumption. Judging by the rate of increase in power consumption, world fossil fuel supplies (both strategic reserves and untapped deposits) will not hold for even that long.

Current Environmental Problems: Supply problems aside, there are other issues that plague our current energy production systems and fuels. For example, coal is the dirtiest of all fossil fuels and is employed in coal-fired power plants, which are common in the U.S. and the world. There are over 1000 coal-fired power plants and 89 more proposed for building in the U.S. alone. At our current rate of consumption, we have a 200 year supply of coal, but coal is simply too dirty in coal-fired plants. Coal-fired plants have the highest emission level of any other type of energy plant. The other fossil fuel-based power plants also rely on oxidation (burning) of these fuels. These processes emit high levels of nitrogen oxides, carbon dioxide, carbon monoxide, sulfur dioxide (sulfuric acid), and mercury (in the case of coal-fired plants). The carbon dioxide alone generates growing concern for global warming. This century alone, we can reach a level of 550 parts per million (ppm) of carbon dioxide in the atmosphere. This is compared to the normal of 275 ppm. If left at 550 ppm over time, the heat trapping effect of greenhouse gases, like carbon dioxide, can produce a rise in temperature whose magnitude is comparable to that of the temperature drop for the last Ice Age.

Other than the greenhouse effect, there are other environmental issues to deal with as a result of fossil fuel power generation. The release of the other emission gases into the atmosphere causes a small variety of problems. The release of sulfuric acid into the atmosphere seeds the clouds. The next time it rains, there will be a small concentration of sulfuric acid in the raindrops. This is called acid rain, although acid fog, hail, sleet, and snow are just as common. This means that over time, concentrations of sulfuric acid build up in our drinking water. Naturally this causes health problems. It also endangers natural wildlife. Acid rain has been known to kill fish in bodies of fresh water. Any animals that drink from said bodies of water can also fall victim to the small amounts of sulfuric acid in the water. Acid precipitation also has detrimental effects on the vegetation, especially at high elevations. The raindrops strike trees and foliage and the acid eats away at the leaves, bark, buds, blossoms, etc. Not only does this damage the tree or plant, but it also hinders the organism's abilities to heal and reproduce.

Releasing amounts of carbon dioxide, carbon monoxide, and mercury can also be incredibly detrimental to communal health in the area around the given power plant. Take the example of the coal-fired power plant in Salem, Massachusetts. Not only is there a demand for a $36 million clean up operation of the Salem Harbor area, but also there is a rise in frequency of diseases and afflictions linked to power plant emissions. Such afflictions are as follows: asthma, permanent structural damage to lungs, chronic bronchitis, acute respiratory ailments, heart disease, various forms of cancer, and premature death.

1.1 Oil

Oil, as stated before, is relied on most heavily of the three fossil fuels. Everything from power plants to weapon lubricant to gasoline and beyond is synthesized from oil. Despite a strong oil mining industry in the United States, there was and is still a gap between the needs of the government and industry and what can be made available each year.

Table #1: Oil Production by Year (thousands of barrels per year)

Year	Oil Prod.	Year	Oil Prod.	Year	Oil Prod.	Year	Oil Prod.
1973	75072	1980	82908	1989	96732	1996	113736
1974	73344	1981	71952	1990	96216	1997	121944
1975	72672	1982	61356	1991	91524	1998	128496
1976	87756	1983	60612	1992	94656	1999	130224
1977	105684	1986	74688	1993	103440	2000	137508
1978	100356	1987	80136	1994	107952	2001	142452

1979	101472	1988	88824	1995	106020	2002	136440

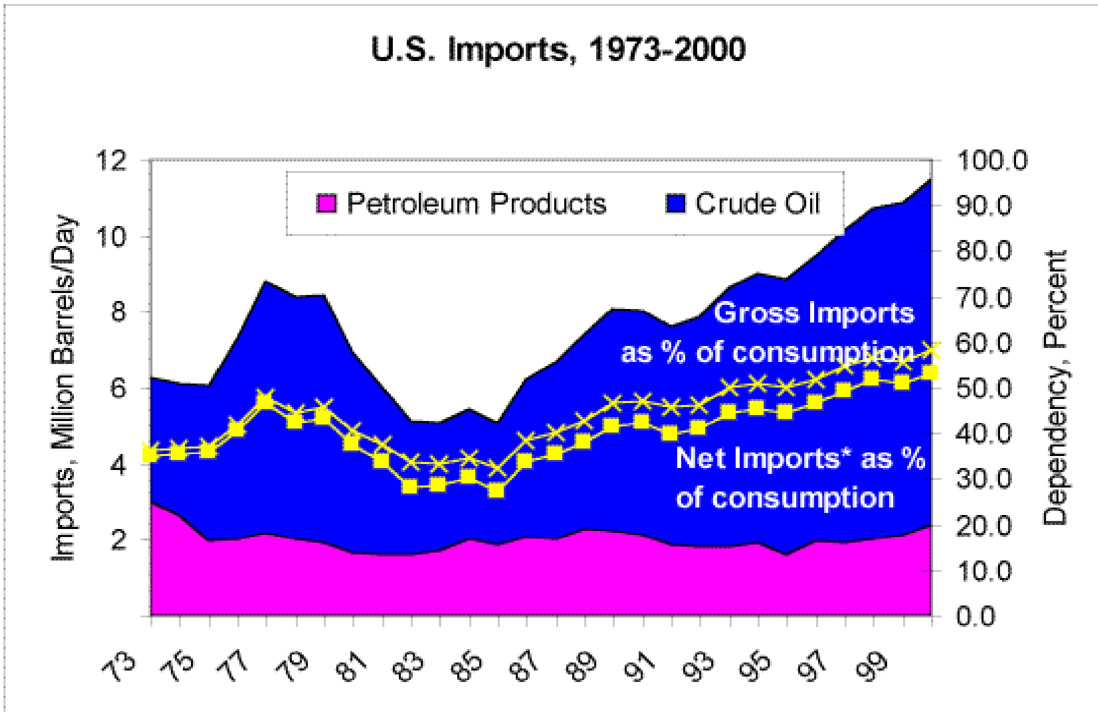
This forces the U.S. to import oil from around the world. As we all know, the United States has not necessarily been on the best terms with the rest of the world (we can all recall the Cold War). This can force us into awkward political positions and forces us to protect foreign national oil-related interests. In the year 2001, the United States imported from thirty-four different countries:

Table #2: U.S. Oil Imports, 2001

	Country of Origin	Thousand Barrels		Country of Origin	Thousand Barrels
1	Saudi Arabia	588,075	21	Brunei	8,174
2	Mexico	508,715	22	United Arab Emirates	7,802
3	Canada	494,796	23	Oman	7,138
4	Venezuela	471,243	24	Guatemala	6,485
5	Nigeria	307,173	25	Malaysia	5,643
6	Iraq	289,998	26	China, People's Republic of	4,684
7	Angola	117,254	27	Brazil	4,667
8	Norway	102,724	28	Algeria	3,966
9	Colombia	94,844	29	Peru	2,524
10	United Kingdom	89,142	30	Thailand	1,751
11	Kuwait	86,535	31	Ivory Coast	1,517
12	Gabon	51,065	32	Cameroon	1,255
13	Ecuador	41,403	33	Congo (Kinshasa) *	345
14	Argentina	21,013	34	Qatar	69
15	Trinidad and Tobago	18,562	33	Congo (Kinshasa) *	345
16	Other	15,874	34	Qatar	69
17	Indonesia	14,759		**Total**	**3,404,894**
18	Congo (Brazzaville)	14,430		Non OPEC	1,635,274
19	Australia	12,567		Arab OPEC	976,445
20	Yemen	8,702		Other OPEC	793,175

At our current rate of consumption, there is a thirty-year supply of oil (approximately). U.S. Department of Energy research indicates a growing dependence on oil and also indicates that most of the oil which we depend on is imported.

Graph #1: U.S. Oil Imports



As our and the world's (especially the developing third world nations that are establishing power grids) dependence on oil increases, our supply of oil will decrease from the thirty years' worth that we have. Decades ago, our projections indicated that we had centuries of oil left untapped. However, as you can see, our oil consumption has significantly increased over the years.

Table #3: Total Petroleum Products Supplied, 1949-2001 (thousand barrels per day)

Year	Oil Supplied	Year	Oil Supplied	Year	Oil Supplied	Year	Oil Supplied	Year	Oil Supplied	Year	Oil Supplied
1949	3,585,820	1958	5,159,930	1967	4,584,526	1976	6,390,750	1985	5,740,143	1994	6,467,128
1950	3,641,280	1959	5,364,473	1968	4,901,789	1977	6,727,468	1986	5,942,429	1995	6,469,475
1951	3,796,029	1960	3,585,820	1969	5,159,930	1978	6,879,017	1987	6,082,742	1996	6,701,059
1952	3,921,364	1961	3,641,280	1970	5,364,473	1979	6,757,077	1988	6,325,692	1997	6,796,411
1953	4,034,236	1962	3,796,029	1971	5,552,560	1980	6,242,445	1989	6,323,681	1998	6,904,756
1954	4,202,039	1963	3,921,364	1972	5,990,316	1981	5,861,058	1990	6,200,801	1999	7,124,558
1955	4,410,796	1964	4,034,236	1973	6,317,303	1982	5,582,938	1991	6,100,550	2000	7,210,594
1956	4,584,526	1965	4,202,039	1974	6,078,239	1983	5,559,364	1992	6,234,025	2001	7,151,577
1957	4,901,789	1966	4,410,796	1975	5,957,515	1984	5,755,575	1993	6,291,407		

As you can see, our oil consumption has more than doubled since 1949. At the rate of increase of our oil consumption, there will more likely be a 20- to 25-year supply of oil/petroleum.

Oil supply problems aside, most power plants based on oil-fired boilers top off at approximately 35% thermal efficiency. This means that 65% of the energy we put into generating electricity at oil-fired plants is wasted. Keep in mind that we are not using electricity to make electricity, but rather burning a fossil fuel to heat the boiler to create water vapor. And so, 65% of the energy released from burning of oil is wasted. Another important issue is the strong emissions that are involved in oil-fired power plants. 40% of the electricity in the U.S. is generated in oil-based power plants.

Chapter 2

Fuel Cells

System Information

Fuel Cell Introduction

The advent of the Fuel cell heralded a new era in energy. It created a new choice for energy with many desirable attributes, as well as opportunities to explore new possibilities with energy. Fuel cells are one of the most notable candidates for alternate energy generation because they promise a clean and practical energy solution. Their designs can also utilized other new technologies, such as renewable fuel, which will probably make them a popular replacement for the current energy generation systems.

Versatility and performance benefits of fuel cells make them a favorable choice for an energy system. The developed fuel cell designs have already surpassed their currently established counterparts in numerous aspects. While there are a number of competing alternative energy solutions proposed for the future, fuel cells are one of the few that can be operated completely independent of fossil fuels. Most of the major types of fuel cell designs that are being researched function primarily on only hydrogen and oxygen. That means when fossil fuels are inaccessible these designs will still be able to operate. Both oxygen and hydrogen are harmless in their preprocessed forms, unlike fossil fuels. They also do not create any toxic byproducts when they are processed to generate energy as current power plants do.

Fuel Cell Advantages over Fossil Fuel Systems

Fuel cells energy systems are a great improvement over fossil fuel ones, but their advantages are not only theoretical, they have been demonstrated with a significant level of success. Instead of combustion, fuel cells utilize a newer and more direct technique to process their fuel. With it, modern fuel cells are already capable of performing more efficiently than their competing fossil fuel solutions. The most efficient cells operate at efficiencies up to seventy percent. This means that seventy percent of the energy obtained by processing the fuel will be electricity, and the rest as heat.

Another great feature that fuel cells have over fossil fuel systems is that the heat waste product given off is a lot easier to use. In certain fuel cell energy system designs this heat can also be used in a cogeneration process to produce more electrical energy. Utilizing this technique is currently being researched and developed. With it, electrical efficiencies of beyond eighty percent are possible.

Fuel cells are better suited for mobility than fossil fuel energy systems, because they can be scaled without efficiency loss. The same type of fuel cell will operate just as efficiently powering an industrial complex as a digital personal organizer. They have no geographic requirements and minimal environmental effects so they can be installed anywhere. Those features create new energy solutions that were not previously possible with other energy systems. Current commercially available fuel cells demonstrate these potential applications by operating office buildings and hospitals. These examples are a sign of things to come. Unlike the current electrical energy solutions fuel cell power does not need to be centralized. Power distribution is costly and inefficient. A lot of money can be saved by not having to build an electrical utility infrastructure, and energy lost in transforming and transmitting electricity will also be reduced.

One of the greatest strength of the fuel cell is its potential to be effectively optimized for specific tasks. The emphasis on efficiency and environmentalism in an energy system is growing by the day. It is already apparent that as time progresses the demands and design requirements of energy systems is increasing, varying, and becoming more specific. Fortunately, many fuel cells technologies have already been developed in anticipation for them.

Fuel Cell Advantages over Batteries

When the market increases, fuel cells could potentially replace portable batteries, and even power large industrial facilities. The physical attributes of a fuel cell closely resemble those of common batteries; also know as an electric cell. Their functions are also based on the same electrochemical reaction principles. However, fuel cells and batteries have a fundamental difference.

The main difference between batteries and fuel cells is their source of fuel. Batteries store their own fuels. The reacting chemicals and the device that collects the energy from them are built as a single unit, needlessly relating cell performance with operational capacity. A battery's characteristic flaw is that its life span is limited based on storage capability. Certain designs can be recharged, but that process is time consuming and often impractical. Since they will inevitably deplete their fuel supply and cease to function, batteries are restricted from being used as a primary source of power.

Having to store fuel is not a constructive design parameter when it comes to an energy generating system. Very often fuel storage and fuel-processing requirements will conflict. Fuels can be stored more effectively separately. Not having to worry about fuel storage requirements allows fuel cells to explore new possibilities. The design for the energy system can be more focused on meeting performance requirements and raising efficiency in the energy production processes. The energy stored per kilogram, or per liter of volume, of a fuel cell is greater than that of a battery. They can operate indefinitely, at a range of pressures and temperatures that are not possible with batteries. New combinations of fuels will be possible. Sets of electrochemically reactive fuels that have different storage requirements, or are too reactive to be used in batteries can be processed by a fuel cell. Overall, the new design possibilities allow fuel cells to practically accomplish tasks that would not be suitable for batteries.

Since fuel cells only process fuel, they can operate indefinitely as long as a constant source of fuel is supplied.   Fuel cells are designed only for providing an environment for the chemical reaction/reactions and collecting the energy released from them. The chemicals to be processed and their byproduct are stored separately. An analogy to demonstrate how significant this difference can be made. Imagine replacing the engine of a car every time the internal fuel source was exhausted instead of just refilling a gas tank.

Fuel cell technologies are more diverse, and can be adapted to a wide range of tasks unsuitable to batteries. Its limited life span and its lack of flexibility have always hindered the role of batteries. Batteries were ideal only for limited and relatively small-scale tasks. Fuel cells have a few flaws of their own, however many of their features address the shortcomings of batteries. Current goals in research and development are addressing these performance issues to allow fuel cells to become a practical and competitive energy solution.

<u>Current Energy Systems Roles</u>

Three types of markets exist for energy systems that are differentiated based on scale. They are categorized as stationary, automotive, and portable. Fuel cells are capable of addressing all of them.

Portable

Modern technologies are decreasing in size and becoming increasingly mobile. These technologies are also becoming more sophisticated and affordable. As more people adopt these technologies, it is clear that a complementary energy solution must be available as well. The power requirements for these technologies are exceeding the performance of available portable energy devices. The popularity of the portable technologies also demands that the energy system used be affordable.

Analysts consider this a growing market worth noting for fuel cell development. Providing energy for portable electronics is a large market, which requires a relatively smaller investment than the other two types of markets. With current technologies failing to meet performance requirements, a new and exclusive energy market will become available. This makes it a good place for developing energy products to be established.

Automotive

One of the greatest prospective markets for fuel cells is the automotive industry. There is currently great demand and testing for these systems. Transportation is a critical part of social infrastructure. Trade, production and development are heavily dependant on it. Not only is it a desirable market, but it will also respond to urgent problems surrounding fossil fuels, especially petroleum. Introducing fuel cells into this market will help establish their presence, and encourage further development of its technologies.

Transportation in general is one of the largest contributors to energy consumption. Implementing fuel cells to compensate for these energy demands will be a practical way to introduce them to the general masses. The fossil fuel energy systems in an automobile are far less efficient than the ones found in a dedicated power plant. Since fuel cell efficiency does not decrease with scale their use will be preferable and also conserve a lot of fuel. This increases the practicality of implementing fuel cells for transportation use.

New developments in automobiles are implemented yearly. New car designs are introduced into the market every year. Car companies compete with themselves and each other to produce competitive products. They are major investors in fuel cell technologies. The introduction of fuel cells into the automotive industry could guarantee them a steady source for funding and development.

Stationary

Stationary fuel cell plants are currently being used and tested around the world. They are being designed to provide large quantities of energy to local facilities that demand them. Fuel cell plants are already being tested around the world in Europe, Asia, and America. Since pollution can be eliminated from operation, fuel cells can be located almost anywhere. This convenience is an attractive advantage over previous energy systems that many people would like to adopt.

The inconsequential placement of fuel cell plants can render power grids obsolete. However that transition will take time. During the meanwhile fuel cells can be used to augment the power grid system and aiding in their own development. Power grids do not provide a flexible response to varying energy demands. Often times power plants are producing more energy than required, resulting in waste. On the other hand, energy demands may exceed energy production which my have catastrophic affects. A regenerative fuel cell may be used to store excess energy in times of low demand, and return it when there is an increase in demand. This can also encourage the development of smaller, more localized energy grids that are more efficient.

Fuel Cell Function

Fuel cells produce energy in two ways. Unlike fossil fuel systems, fuel cells produce electricity directly from the fuel, however heat is also produce. In certain fuel cell designs, heat based energy systems can be used to cogenerate electricity. These systems most commonly use the heat from the fuel cells to operate steam turbines.

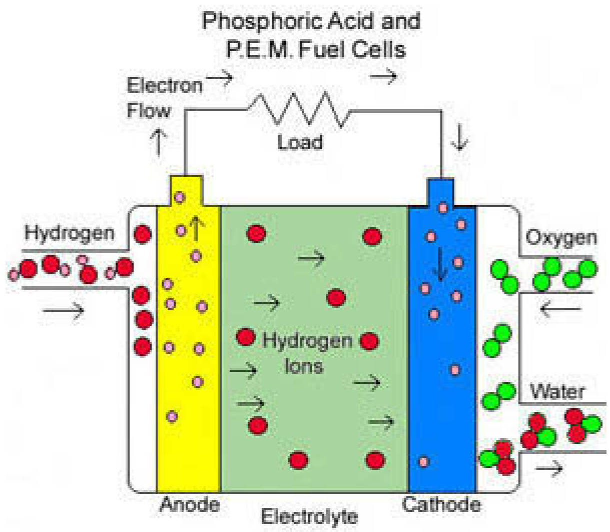
The principle behind how current fuel cells work is similar to those of batteries. Both of these devices share the same key components, two electrodes, a cathode and an anode, and an electrolyte. Both are based on combinations of chemicals that give off energy when they are reacted. In contrast, to fossil fuel systems, fuel cells utilize the energy naturally released in this reaction and convert it directly into electricity, rather than harnessing the heat byproduct of a combustion process. Several types of chemical reactions can occur in a fuel cell. The combination of chemicals used by most fuel cell designs to produce electricity is oxygen, and hydrogen.

Combinations of fuels used by a fuel cell are selected based on their ability to go through an electrochemical oxidation-reduction reaction. It is by harnessing the reaction that fuel cells generate electricity. An oxidation-reduction reaction is a type of chemical reaction that involves the atoms of the reacting fuels to gain or lose electrons. The atom of the one reactant that gains an electron is said to be reduced since the electron has a negative charge while the other atom that looses the electron is said to be oxidized. That is because oxygen can easily strip electron off other atoms, and therefore a very common reactant in this type of chemical reaction.

Fuel cells are designed to facilitate this reaction. Two fuels, chemicals that are to be processed, are directed into the fuel cell separately. Each of the fuels is introduced from a different electrode. The fuels react with the electrolyte inside of the cell. The electrolyte catalyzes, and assists the reaction between the two fuels. During the reaction, electrons are separated from the atoms of the fuel. These electrons are forced through an external circuit via the electrodes creating a useful electric current. The electrode through which the electrons leave becomes the anode. The electrode through which the electrons reenter the cell is the cathode.

Fuel Cell Types

Though fuel cells can be designed to use a variety of different fuels, the most prevalent chemicals used are oxygen and hydrogen. The aspects of hydrogen fuel will be discussed later. Suffice to say it is not commonly found in its pure form and is usually extracted from other sources. Fuel cells can be designed to either directly extract the hydrogen through internal chemical reactions, or use the energy that they generate to run a fuel processor externally. There are currently five main, well-established classifications of fuel cells, though some other variations and experimental types exist. The different types of fuel cells are classified based on their electrolyte. Each electrolyte will have their own unique set properties that dictate the fuel cell designs' performance and demand specifications. This will allow fuel cells to adapt and excel in a variety of specialized fields.



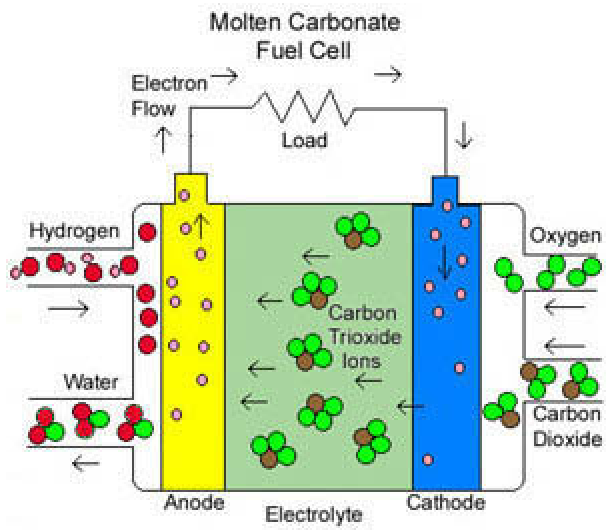
Phosphoric Acid fuel cells (PAFC) are some of the oldest and therefore most well established fuel cells design. They are have been commercially available for about a decade and have been implemented in several facilities around the world. They are well suited for small to medium scale stationary energy production such as office buildings. Although their designs are rather bulky and require a period of time to start up, they have also been tested for automotive transportation such as busses.

As the name suggests these types of fuel cells use 100% concentrated phosphoric acid (H3PO4) electrolyte that is retained on a silicon carbide matrix. These cells operate in temperatures between 180 and 220 degrees Celsius, which is considered a medium range for fuel cells. Many other designs operate at higher temperatures. Phosphoric acid is not a very good ionic conductor, but is more stable at these high temperatures than most other acids. Another advantage to operating at such high temperatures is that these cells are more resistant to carbon monoxide. Carbon monoxide is generally known to "poison" fuel cells by corrupting the electro catalyst coating on the anode. Phosphoric acid can tolerate a CO concentration of 1.5 percent and still operate normally, but only at these high temperatures. The efficiencies of this type of fuel cell is around 40%, however since they operate at high temperatures, they can be used with a cogeneration device that can raise this efficiency to above 80%.

Proton Exchange Membrane fuel cells (PEMFC) function similarly to PAFCs. They are a relatively recent fuel cell technology, but their design holds a lot of potential. This makes them very popular and many groups are researching and developing its technology. PEMFCs have adopted other names such as Solid Polymer fuel cells, and Polymer Electrolyte fuel cells, but they are all the same type of technology.

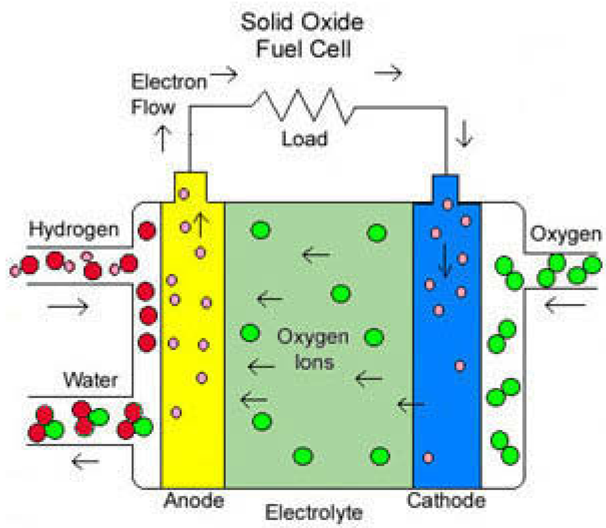
PEMFCs use thin permeable sheets of plastic as the electrolyte. These sheets of plastic only allow certain ions, such as the protons of hydrogen, to pass through it. The electrodes are both coated with a layer of highly dispersed metal alloy particles (mostly platinum). The metal alloy coating acts as a catalyst. Hydrogen is introduced to the cell from the anode. The catalyst coating causes the hydrogen to disassociate with its electron and ionize. The hydrogen ions travel through the membrane, while the stripped electrons travel through an external circuit where they provide electrical power. Oxygen is introduced at the cathode side of the cell where the hydrogen ions and electrons end up after reacting with the catalyst and forms water.

PEMFCs have a lot of potential as a general fuel cell energy system, and are planning to be used in all three previously mentioned markets. They operate with 40-50 percent efficiency at the relatively low temperature of around 80 degrees Celsius, which is safe for wide scale general use. They react quickly to changes in energy demand, and provide high power density. PEMFC designs are unique because they are particularly well suited for small-scale applications and are the primary candidate for providing portable and automotive power. A current specialized version of this type of fuel cell is the Direct Methanol fuel cell. It is essentially a PEMFC that is capable of processing methanol directly without a reformer, rather than requiring pure hydrogen to operate.

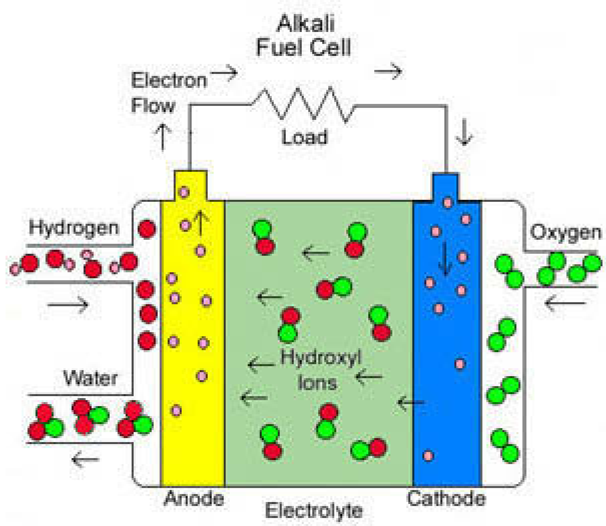


Molten Carbonate fuel cells (MCFC) offer another option to stationary power generation. Partially developed as a technology to compete with or replace PAFCs, their design is rather complex and recent but provide unique possibilities that are undergoing testing by countries around the world. A unique property of this type of fuel cell is that it uses CO2 to operate. They can use nickel-based catalysts instead of platinum, which dramatically reduces the price of the cell. The main disadvantage of this design is the complexity of using a liquid electrolyte, which is harder to manage than a solid, at such a high temperature.

This type of cell uses an alkali carbonate (sodium, potassium, or lithium salts, i.e., Na2CO3, K2CO2, or Li2CO3) or a combination of alkali carbonates that is retained in a ceramic matrix of lithium aluminum oxide (LiAlO2) as its electrolyte. They operate at temperatures between 600 and 700 degrees Celsius. At these temperatures, carbonate salts melt and are in liquid form. These cells are capable of reaching efficiencies of 60 percent without cogeneration. High operational temperatures allow the fuel cell to use cogeneration to raise its efficiency. High temperatures also give the fuel cell additional benefits such as the capability of reforming fossil fuels.



Solid Oxide Fuel Cells (SOFC) are yet another type of stationary power fuel cell competing with PAFCs. This type of fuel cell is capable of producing more energy than others do. The operational benefits of this type of fuel cell address the MCFCs' main disadvantage. A liquid electrolyte is not used, so special monitoring and regulating equipment is not required. Hydrocarbon fuels can be directly reformed inside of these cells. They operated at an extremely high temperature compared to the other cell designs, 1000 degrees Celsius. The solid electrolyte used contains vacancies that allow oxygen ions to diffuse through it. High temperatures are required to allow oxygen to pass through the electrolyte but these temperatures were unnecessary and uselessly high. They wear down the cell components and force the cell to use costly and difficult to manufacture ceramic materials instead of metal alloys to resist these temperatures. Much effort was successfully invested to lower the operating temperature of these cells and have helped in reducing the cost of these cells by eliminating the need for special materials.



Alkaline fuel Cells (AFC) are considered best suited for space flight. The design uses hydrogen and oxygen as fuel, and potassium hydroxide in water is generally the electrolyte used. They operate at temperatures below 200 degrees Celsius, and have a high efficiency of 70% without the aid of cogeneration. Unfortunately, certain factors of their design outweigh advantages of its high performance. A significant amount of platinum is required in these designs for use as a catalyst. They are also very intolerant to impurities and easily poisoned by even small amounts of CO and CO2. Since most hydrogen extraction techniques are not always free from these compounds, AFCs will probably not be a popular mainstream fuel cell choice in the near future.

<u>Fuel Cell Evaluations</u>

Two fundamental factors in designing and evaluating fuel cells are efficiency and cell voltage. These factors are used to compare the performances of different fuel cell designs as well as those of currently established energy systems. When compared with non-fuel cell energy systems efficiency is the most common measure used. This type of comparison is based on measuring the overall amount of energy released by the fuel, with the overall energy that is captured by the system.

There are two different types of efficiencies, thermodynamic and electrical, used to measure the fuel cells performance. Thermodynamic efficiency is based on the energy that is released by the chemical reactions and the amount that is available to the energy system. This figure is determined by the Gibbs free energy equation under normal temperature and pressure conditions.

Gibbs free energy equation: $\Delta G = \Delta H - T \Delta S$

Where ΔG is the amount of energy, ΔH is the standard enthalpy of formation, T is the absolute temperature in Kelvin, and ΔS is the entropy change for the reaction.

Electrical efficiency is often used to evaluate the fuel cells performance. This type of performance is the one generally used when comparing with other systems. It compares the maximum electrical work done on a load at a measured terminal voltage to the standard enthalpy of formation. Unfortunately, this figure is quite lower than the thermal efficiency due to the internal resistance of the cells.

$$(\text{Electrical Efficiency}) / (\Delta H * 100)$$

Cell voltage is the potential difference between the two electrodes of the cell. Electrons from the site of oxidation (the anode) are pushed toward the cathode by an electromotive force, EMF. This force is due in part to the charge of the electron from the reaction inside of the cell. The quantity of work that can be done by a cell is the product of these on these two factors.

Work = (Charge of an electron) * (Potential Difference of the two electrodes)

Fuel Cell Developments

A great prospect of fuel cells over modern day energy systems will be its wide scale application. Though like any other energy solution, its benefits must outweigh its deficiencies. Many design considerations are taken into account in the development of a fuel cell. Although there are certain limitations, fuel cells feature many attributes that can be modified without undermining its performance. A variety of fuel cell configurations have been created specifically to fulfill common sets of design and performance specifications.

Cost Performance Emissions Fuel processor Specifications & Requirements Balance of system H2O/thermal management	Cell/stack geometry Manufacturing Start-up/transients Temperature Pressure Materials Lifespan

Many parties have power requirements that can not tolerate the drawbacks associated with current energy solutions. Several of these organizations and governments around the world are already investing in the research and development of fuel cells and its supporting technologies. Other groups are also investing in an attempt to exploit its many benefits. This demand has already made certain fuel cell technologies commercially available, however there are many obstacles that need to be overcome before mainstream use is possible.

The possibilities for applying fuel cells are great. All the different types of materials, chemical fuels, and energy extraction techniques give fuel cells a wide range of operational conditions. Though current flexibility in fuel cell design is quite impressive, there are still developments that need to be tested before a range of fuel cell application can become practical. Standards for fuels, performance, and equipment are just a few examples. Testing the reliability of these technologies takes a very long period of time. All aspects of prototype systems need to be operated continuously, under various operating conditions, for thousands of hours to gather performance data. Supporting subsystems are still being refined to enhance performance, and methods to reduce the impact of switching energy systems also need to be tested.

Implementing fuel cell systems will set the groundwork for independence from fossil fuels, but the market is currently not very familiar with the technology. Other competing types of energy systems are being developed. Many of these systems are still based on fossil fuels, but are designed to address at least one of their shortcomings. These rivaling technologies decrease the significance of some fuel cell benefits. People are more familiar with fossil fuel technologies. Technicians are more familiar with the operating concepts. This lack of familiarity to fuel cell systems puts it as a disadvantage.

Keeping technological developments and manufacturing capabilities in mind, the materials used in the production, construction and operation of the fuel cell need to have their lifespans, and full product cycles evaluated. The unique design of the fuel cell incorporates a variety of special materials. Careful considerations for the environment will be taken as well. These materials not only have to provide fuel cells' with outstanding performance, but also need to be easily manufactured and processed after being disposed of.

By far the greatest obstacle that stands in the way of the establishment of fuel cells as the new standard of energy is cost. Fuel cell technologies are currently commercially available but very expensive. Only in specific circumstances are they worth the large initial investment. This limits fuel cells to a small market. Theoretically, the cost of operating a fuel cell is lower than that of current fossil fuel technologies due to increased efficiency. Many other aspects of cost must also be considered when comparing the cost of energy delivery systems though. Cost for the system itself and its maintenance are some examples of issues that are very important. These costs have a large impact on a consumer's final decision.

Currently the benefits that fuel cells deliver are heavily outweighed by the difference in cost compared to a fossil fuel system. It is not surprising to find the price ranges on current fuel cell energy systems to be around 3000 dollars per kilowatt. Fossil fuel energy systems can cost as low as 400 dollars per kilowatt. Analysts estimate that as demand increases, the scale of the market will cause the cost of the technology to decrease. Studies predict that in order for fuel cells to establish themselves in a larger more mainstream market, prices have to drop to at least 1500 dollars per kilowatt. Ultimately in order for Fuel cells to successfully replace and phase out fossil fuel systems, their cost must be lowered to a comparable figure.

About one third of the cost of a fuel cell energy system comes from the actual stack of fuel cells. The rest of the costs come from external support systems. There are different types of fuel cells but the stated ratio is generally true. Even though one of the advantages of having a variety of fuel cell designs are meant to allow them to be as cost effective as possible, the small size of the market produces the opposite effect. The reason why fuel cell technologies are so expensive is mainly its level of complexity. Fuel cell systems, and the technologies that support them, incorporate many different and relatively new technologies. Each of the technologies must be monitored, controlled, and optimized for use in a fuel cell energy system. These technologies not only add to the overall cost of the system, but also affect its level of performance since some may require energy to operate.

Despite the fact that the support systems contribute more to the overall cost of the energy system, the key to lowering the cost of the fuel cell energy systems naturally lies in the fuel cells. Lowering fuel cell design costs can be done by material selection. Many different systems and components support the operation of fuel cells, however certain parts can be eliminated if better designs are achieved. Different materials can affect numerous fuel cell attributes. The material selection for each component must be done carefully since there is usually more than one factor to take into consideration. Often times there are relatively large trade-offs between different materials, and the choice of one material can affect the material selection options for other components as well. Unfortunately the materials needed to accomplish these cost saving measures still need to be developed.

Different materials in the fuel cell give it different operational requirements. The efficiency of the chemical reactions, the pressure required to operate, the temperature required to operate, and the purity of the fuel source are just some of the many aspects that can be affected by the choice of materials used in a fuel cell. Often times, support systems in the energy system are needed to achieve those requirements. Some of these systems require energy, such as sensors, regulators, and fuel purifiers, while other' s help generate more energy, such as steam turbines connected to the fuel cell. The materials in the components as well as the fuel cell also have to be able to withstand the operating conditions. Of course, many of these components are necessary, but in many cases, the extreme requirements and operating conditions of the fuel cell call for extra systems or costly modifications to standard systems.

The size and cost of many fuel cell materials and components are proportional to the fuel cells themselves. Construction requirements for fuel cell technologies are unique. Both physical and chemical properties of the materials need to be considered since they can influence, be influenced by manufacturing capabilities and operation. Knowledge from both these areas of science are required to design a fuel cell. First, since the energy production of fuel cells is based on the oxidation-reduction chemical reaction, the chemical properties of the components must be considered. Secondly, even though fuel cells don't have any moving parts, they do go through certain physical extremes that must be taken into account by designers. There are only a few known suitable materials. Besides being rarer and more expensive, newer, and less popular materials used in modern fuel cells, such as ceramics, have different physical properties that affect the manufacturing process. This will also contribute to the cost of the fuel cell since the cost of processing, machining, and manufacturing with these materials will also be higher.

The heat byproduct of fuel cell energy systems is a unique design consideration. Though it is very useful for cogeneration purposes, depending on the type of chemical process and design of the fuel cell, there are circumstances where temperatures of 1000 degrees Celsius are achieved. These operating conditions are quite extreme and do require specialized material. However, even with specialized materials, the fuel cell still goes through tremendous thermal stresses. This wears out the components of fuel cell very quickly. This emphasizes the importance of maintenance for a fuel cell. Considering the current cost of the specialized materials used in fuel cells, it is essential that fuel cells have as long, reliable, and consistent a lifespan as possible. It is imperative that the cost for maintenance must be no more than the savings acquired through using it compared to a fossil fuel energy solution.

Fuel Information

Fuel cells might be an ideal choice of energy generation for the future, but its incredible capabilities are not achieved alone. High efficiency is a very desirable aspect for any energy system. Fuel Cells attain this benefit by using a more direct way of processing its fuel. However, there are other critical concerns as well. These include environmentally safe operation and energy security. The fuel cell is capable of this, but the credit for it falls on the fuel it is designed to use.

Hydrogen

Hydrogen is the primary choice for most fuel cell designs. It could be called a "perfect" fuel. It is very versatile, clean, nontoxic, and available from an abundant number of sources. These properties make hydrogen very desirable as a fuel. Its highly reactive property also makes it relatively easy to harness, and allows it to be effectively used in different ways. To many people the potential of Hydrogen as a fuel is very clear to see. Hydrogen is the fuel of stars. It is used in rocket propellants. Other areas of research in alternate fuel sources, such as fusion, are looking at hydrogen as their choice fuel.

Hydrogen is the simplest element on the periodic table. Despite that, it has the highest heating value per kilogram of any fuel. Hydrogen has a low ignition temperature, which means that it requires very little energy to start a reaction. Therefore, it is very combustible, and burns very quickly and completely. If hydrogen reacts with oxygen, in a combustion process, the only byproduct is water. Since the carbon and/or sulfur found in fossil fuels are not present in the reaction harmful byproducts based on these chemicals will also be absent. This allows Hydrogen to perform many of the same tasks as other fossil fuels that are processed through combustion. Hydrogen' s sensitivity also means it can be burned at lower concentrations. This allows hydrogen to be consumed more efficiently (in terms of combustion at least 20-25% more than gasoline).

With all the advantages that hydrogen provides, why is it not already taking over the energy market? The fact of the matter is that despite its clear advantages over current energy solutions, it still needs to establish itself and grow to surpass the current fossil fuel market. There is currently little to no hydrogen distribution system that is anywhere close to having the capability of serving as a staple fuel economy. A new hydrogen based fuel infrastructure needs to be developed. Even though some aspects of modern infrastructure can be adapted, modifications and incorporation will take time and money.

One of the biggest selling points of a fuel cell system is its ability to operate without producing any pollutants. Unfortunately, hydrogen is not a primary fuel source. As mentioned earlier, large quantities of pure hydrogen are not naturally found on earth. It is usually already reacted, and a part of another chemical compound. Fortunately, hydrogen can be extracted from large and abundant natural resources.

There are a few ways of acquiring hydrogen from different sources, however none are ready for mainstream use. Current methods of extracting hydrogen from other compounds require more energy to attain than the resulting fuel provides. This is a somewhat ineffective solution to the production of hydrogen. Under those terms, it can only be a secondary fuel source. This may not be as undesirable as one might imagine though.

Most hydrogen is produced primarily from energy produced by fossil fuels. Though these methods can not be depended on to support a full-scale hydrogen economy, they can aid in the transition from fossil fuels. For example even if manufacturing hydrogen is less than 100% efficient. If the fuel cell's efficiency is significantly higher than scaled down fossil fuel systems, such as car engines, it is possible to conserve fossil fuels, and reduce pollution. Hydrogen fuel visionaries have much higher aspirations than that. Energy solutions such as solar, wind and water are very desirable. Their main drawback is that they are not very practical on small scales. They also have unique geographical requirements. Transmitting electricity over power lines over long distances can be inefficient and costly. Hydrogen would be a great intermediary for transporting these energies.

The model source to extract hydrogen is water. At temperatures below a hundred degrees Celsius, hydrogen can be extracted from water via electrolysis. This process can currently be done to the efficiency of about eighty percent. That means that eighty percent of the energy that was used to attain the hydrogen can be reacquired when the hydrogen is used. At higher temperatures it becomes even easier to disassociate/split the water molecules. At above two thousand degrees the disassociation/splitting is almost spontaneous. Such high temperatures are not practical though.

Fossil fuels are the most commonly used source to extract hydrogen. The process to extract hydrogen from fossil fuels is called reforming. Any fuel cell system that is introduced into the consumer market will probably acquire their hydrogen through reforming. Reforming separates hydrogen from fossil fuels, however the other byproducts of this process are the same as combustion. This often defeats the environmental benefits of using a fuel cell. The process to extract hydrogen from fossil fuels is slightly more complex, but under current circumstances, it is a more practical and economical solution. Hydrocarbons are reacted at high temperatures with water vapor. Like with water, high temperatures split the bonds in hydrocarbons to create a hydrogen rich gas byproduct, syngas. Syngas can be further processed, and purified to produce hydrogen.

The unique properties of hydrogen require specific conditions for transportation that are difficult to meet. Hydrogen is a very thin and sparse gas. Its volumetric energy density is low. This makes the amount of space required to hold a volume of hydrogen for practical purposes very large, so hydrogen must be kept pressurized. Being pressurized is a challenge, and potentially hazardous. Certain properties of hydrogen also add to the difficulty of storing and transportation. The error of margin for storing Hydrogen is very small. It has corrosive properties and is more likely to leak than most other fuels. Hydrogen also diffuses very quickly, which makes even the smallest leaks a big problem.

Methanol

Another attractive possible fuel is methanol (CH3OH). Methanol is the simplest alcohol. Each of its molecules contains a single carbon atom bonded to three hydrogen atoms and a hydroxy (OH) group. Methanol lacks many of the benefits of Hydrogen, but provide some characteristics that make it a good choice for use in fuel cells. Methanol as an alternative fuel has been consideration for a long time now. Since the Clean Air Act program was introduced in 1989, methanol was a candidate for a cleaner fuel.

Unlike hydrogen, Methanol has some disadvantages as a fuel, however, its practicality, especially for use as a new fuel make it a noteworthy consideration. The greatest concern for methanol is that it can be extremely toxic. Small quantities/low concentrations of methanol are not dangerous. In fact many food products contain trace amounts of methanol, and it is even produced at certain stages of digestion. Larger/higher concentrations of methanol can do serious damage to people. Just a few milliliters of it can cause blindness, and a little more than that can be fatal.

Methanol's greatest advantage over many other fuels is its safety. This safety refers to it being less flammable than gasoline. Since fuel cells do not utilize a direct combustion process or derive energy directly from heat, using highly combustible fuels such as gasoline or even hydrogen might be seen as an unnecessary risk, especially in portable personal devices. Methanol only burns 25 percent as fast, and releases heat at $1/8^{th}$ the rate of gasoline. Methanol also needs concentrations four times higher than gasoline in order to burn. Unlike gasoline, which has vapor 2-5 times denser than air, methanol is more buoyant in the air, which allow it to disperses away from ignition sources close to the ground, and into non-flammable concentrations more quickly. Since methanol is less volatile than gasoline, it fires do not spread as fast. Lower flammability does not compromise methanol's performance as a fuel though. It has demonstrated high performance capabilities in properly equipped vehicles. In fact Indianapolis-type racecars only use methanol because of its safety features and exceptional abilities.

Another great advantage methanol has over current fuels is low pollution and versatility. Methanol does contain carbon, so it is not free of harmful emissions, but even though it is closely related to hydrocarbons, like gasoline, tests done on combustion emissions from cars show much lower levels of toxic compounds, particulate matter, and nitrogen oxides. Methanol is compatible with certain existing fuel technologies, such as diesel. It has even been mixed with gasoline as an additive to reduce pollution. As a fuel, methanol typically comes in two forms, M85, a mixture of 85 percent methanol, and 15 percent unleaded gasoline, and M100, which is pure methanol. M85, which is used in most methanol based vehicles burns with 30-40 percent less hydrocarbon emissions than pure gasoline. M100 pushes this figure up to 80 percent. When used with fuel cells this figure is expected to increase even more, since there is no combustion in a fuel cell.

There are many known sources from which methanol can be obtained. Biomass such as wood can be used to produce methanol, which classifies it as a renewable fuel source. Unfortunately, like hydrogen, not enough methanol is available to have it be considered a primary fuel. It is predominately obtained through a steam reforming process. A number of different feedstock can be used to produce methanol; however, today's e conomy most favors natural gas.

Both hydrogen and methanol fuels need to be obtained through reforming, but methanol is clearly a better choice in many cases. The storage advantage that methanol has over hydrogen is literally overwhelming. While hydrogen storage requires new and expensive materials, or energy leeching cooling systems, methanol is an easily contained liquid at room temperature and ambient pressure. Even if it were to be coupled with a hydrogen based fuel cell methanol could be used as a hydrogen-carrying compound. Methanol contains no sulfur, which can contaminant and corrupt a fuel cell. There are no hard to break carbon-to-carbon bonds, and a very high hydrogen-to-carbon ratio in methanol, which makes it a great source to for hydrogen to be reformed from. A small but noteworthy characteristic of methanol is that it can be ignited in small enclosures, such as the gas tank. Since combustible fossil fuels are usually kept away from ignition sources anyway, this probably will not be any great concern in many cases. In any case, a few modifications could be done to allow methanol storage to be even cheaper. Lastly, a potential concern for motorists, methanol carries about half the energy per volume than gasoline, so twice the amount of fuel will be required to travel the same distance.

An infrastructure that distributes methanol to the public is already present. Methanol has many uses other than fuel and has been in commerce for over 350 years. It is used in many consumer products such paints. It is already used as a fuel in a number of vehicle fleets. Around 14000 passenger vehicles, and 400 busses that run on methanol are in service today. Methanol is also cheap to produce, and estimates predict that it can be produced at a price that is competitive with gasoline.

Fuel Cell Conclusion

The days of the fossil fuel energy systems are ending. For at least the last decade, their use has been a controversial issue. Consequences of using fossil fuels are becoming increasingly difficult to bear as time progresses. It is imperative that a new energy system is developed as fast as possible. Without an alternate energy source that is as practical and affordable, fossil fuel energy systems stood unchallenged. The fuel cell is one of the most promising solutions to this dilemma. Their potential has been recognized, and growing demand for a non-fossil fuel based energy system is increasing.

In most of these cases, fuel cells cover a great range of options. Being such a new technology with an ambition as large being the new staple of energy is quite difficult. Add to that the fact there is close to no infrastructure to support them; fuel cells will require every bit of advantage they can muster. Lowering costs will increase the practicality and popularity of fuel cells. To that end, new methods are being researched and implemented to reduce the financial commitments required by fuel cells.

Fuel cells have to be able to meet the standards, and fulfill the new energy requirements of the modern world. They must all provide a reasonable range of energy output, and must do it reliably. More importantly though, they need to surpass those specifications and set new standards. These factors are critical for practicality and transitional reasons. New environmental issues suggest that consumption of fuel be more efficient, but more importantly to produce less environmentally damaging byproducts.

Certain types of fuel cells have specific properties suited for particular tasks. Certain tasks are in more demand than others are. It would be ineffective to simultaneously, and evenly allocate resources, and focus on developing for all these technologies. While there are many parties contributing to the research of certain fuel cell design, their main objectives remain relatively similar; to increase performance and decrease overall system cost.

Emphasis on research for fuel cell technologies is shifting from specialization, to performance. There is an unnecessarily large potential for developing multiple types of fuel cells. An abundance of specialized designs for fuel cells has already been discovered. Each of these designs can be improved in many ways. Besides their performance, fuel cells also have many design restrictions that deserve attention.

Many auto companies are developing fuel cells, most notably PEMFCs. The large resources of these companies have boosted fuel cell developments. Many conceptual designs have already appeared at many exhibitions. These designs have also been submitted for government evaluation, and support. The benefits of fuel cells will undoubtedly make them very desirable and competitive. Fuel cell vehicles can be expected to appear on the market within this decade. The only obstacle left is fuel distribution. With the government involved, a solution to this dilemma can be expected shortly.

Direct Methanol fuel cells are new, but have demonstrated a competitive quality of performance. There are also many applications that would benefit from their application. Methanol is an easier fuel to handle, and distribution issues can be resolved much easier and faster than hydrogen. These fuel cells will also be available toward the end of, or early on in the next decade. They will most likely be used in cars first, but will be adapted to be used with portable electronics

With such a huge contrast to fossil fuel energy infrastructure establishments it is unlikely fuel cells will penetrate this market in the near future. Even though large stationary fuel cell designs are already in operation, their high cost still prohibits them from becoming more popular. Fuel cell designs used for such large-scale applications not only cost more, but are also more complex. Their many components go through more extremes and require higher standards. Stricter standards, and prolonged testing add to the difficulty of widespread use.

There are many current developments in the field of fuel cells that hold a lot of promise. Advancements in technology allow fuel cells to operate with greater capability, and fewer demands. Regenerative fuel cell systems work in tandem with other energy sources, but can also be used as backup, or modified to replace them as well. Zinc Air fuel cells act like rechargeable batteries. Their operational performance and endurance can let them operate vehicles on only oxygen. Current versions can be rechared as quickly as five minutes. Protonic Ceramic fuel cells are the most recent development for fuel cells. They are highly efficient (60%) because they operate at high temperatures (700 degrees centigrade, like MCFC), and can automatically reform fossil fuels internally, but are not as extreme as in SOFCs. They do not have a liquid electrolyte that can leak(PAFCs) , or an electrolyte that can dry out(PEMFCs).

Chapter 3

Coal Gasification

System Information

There are two special coal gasification plants in the United States, one in Indiana and one in Ohio. These power plants use the combined power cycle. The combined power cycle is a new, experimental method of coal power being tested. These two plants of grants from the EPA and are being closely watched for economic feasibility. Power consumption is expected to rise from 2.7 trillion kilowatt-hours (1990) to 4 trillion kilowatt-hours (2010 estimate) to over 5.3 trillion kilowatt-hours (2030 estimate). The United States and the world must be ready to cope with this level of energy consumption. This new innovation in coal power technology is a key method to be used to deal with this demand for electrical power.

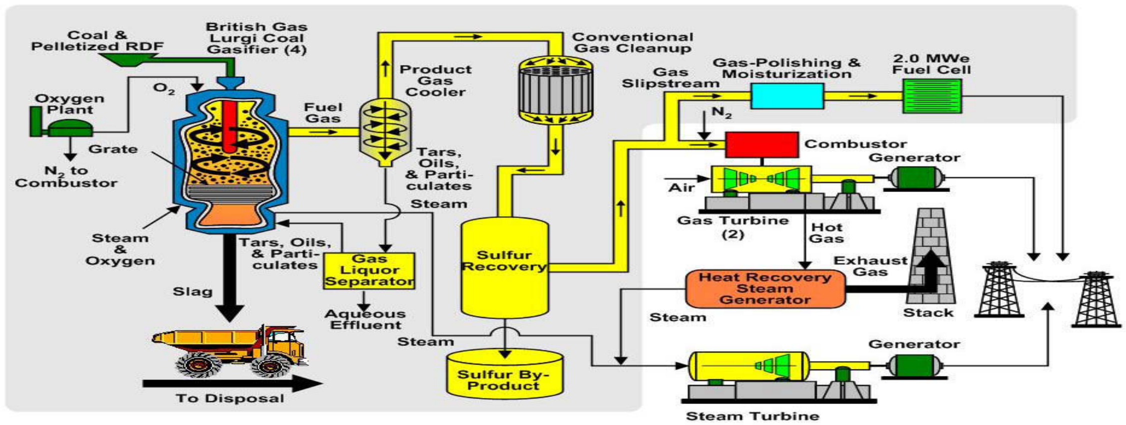
There are four basic steps in the combined cycle: (1) partial oxidation with steam/air or steam/oxygen mixture under substoichiometric conditions to create a combustible gas, (2) gases are cleaned and divested of pollutants (i.e. sulfur, sulfuric acid, etc.), (3) the gases are combusted and passed through a gas turbine to generate electricity, (4) The hot exhaust is channeled through a heat recovery system to change liquid water to steam for a conventional steam turbine. (Office of Fossil Energy, US Department of Energy). The Combined Cycle can reach efficiencies as high as 55% and can produce as much as 25% more electricity per amount of coal than standard coal-fired plants.

New facilities can be built to house the equipment for the Combined Power Cycle or existing power plants can be refitted to house the necessary equipment. In refitting an existing coal-fired plant, the following are added: gas turbine, coal gas clean-up system, and waste heat recovery unit. This replaces the old coal burner. The electrical generator and steam turbine, among other equipment, are left. This nearly doubles the life of the plant. In addition, the plant's efficiency is increased from the ideal 35% of conventional coal-fired plants to 50-55%. The net output of the plant is increased by 50-150%. The Combined Cycle meets and surpasses federal standards for emissions and outperforms conventional coal-fired plants. Combined cycle plants output less than 21% of the Sulfur dioxide, 20% of the nitrogen oxides, and less than 79% of the carbon dioxide emitted by standard coal-fired plants. Refitting facilities with limited space is not a problem because the new system takes marginal amounts of additional space.

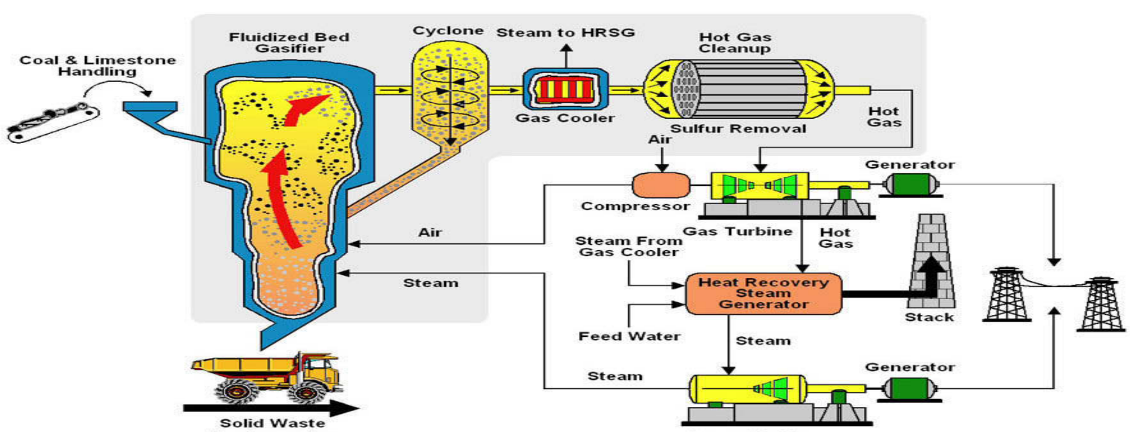
There are four power plant projects testing the Integrated Gasification Combined Cycle (IGCC) for coal power: the Kentucky Pioneer IGCC Demonstration Project in Trapp, KY; the Pinon Pine IGCC Power Project in Reno, NV; the Tampa Electric Integrated Gasification Combined-Cycle Project in Tampa, FL; and the Wabash River Coal Gasification Repowering Project in West Terre Haute, IN. The main difference between the four projects is the gasifier used. A British Gas Lurgi Coal Gasifier (or Fixed bed gasifier) is used in Kentucky; a Fluidized-bed Gasifier is used in Nevada; a Single-stage Entrained Flow Gasifier is used in Florida; and a Two-stage Entrained Flow Gasifier is used in Indiana.

The project in Trapp, Kentucky uses high sulfur bituminous coal mined in Kentucky and palletized refuse-derived fuel. The capacity/production of the plant is 580 MWe (gross), 540 MWe (net), and 2.0 MWe MCFC (molten carbonate fuel cell). 18% of the $431,932,714 was financed by the Department of Energy. The remaining

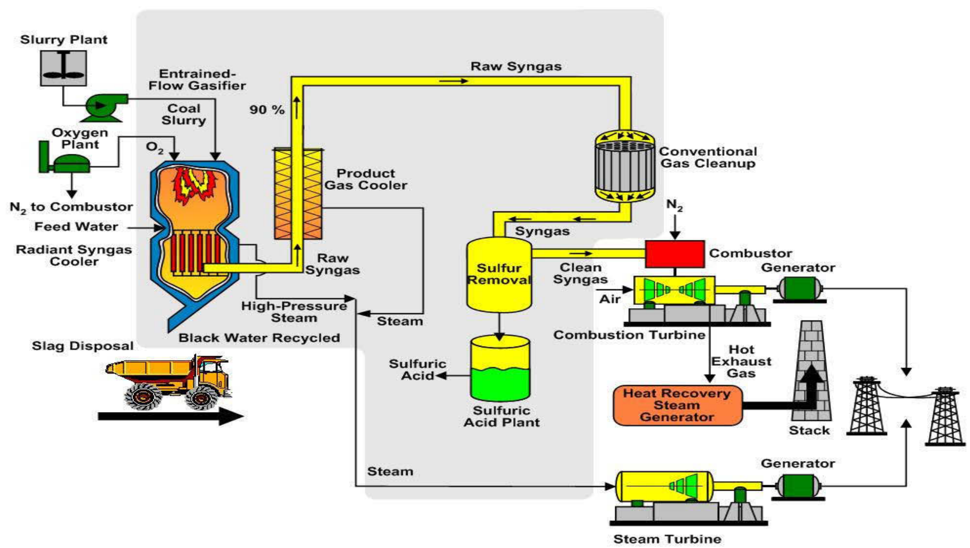
$353,846,225 was paid for by Kentucky Pioneer Energy, L.L.C. A diagram of the power cycle for the Kentucky Pioneer Project is given here:



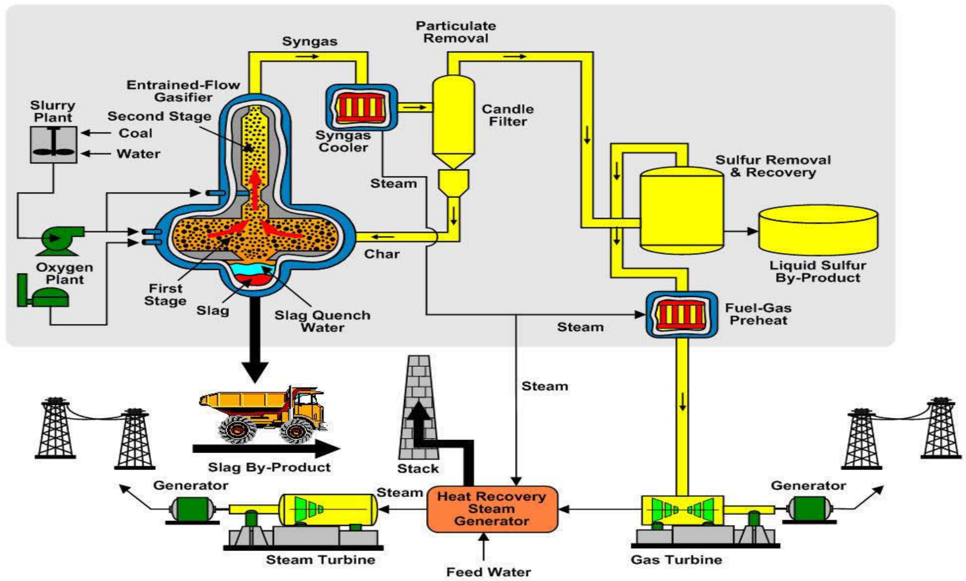
The project in Reno, NV with the Fluidized bed gasifier (as opposed to the fixed bed gasifier in Kentucky) uses Southern Utah bituminous, 0.5%-0.9% sulfur (design coal); eastern bituminous, 2%-3% sulfur (planned test). The capacity/production of this plant is 107 MWe (gross), 99 MWe (net). That is, the plant outputs 107 Megawatts electric, but requires 8 Megawatts to run leaving 99 MWe overall. The project cost $335,913,000, which was split evenly between the Department of Energy and the Sierra Pacific Power Company. A diagram of the Pinon Pine Project in Reno is given here:



The project in Tampa, FL with the Single-Stage Entrained Flow Gasifier uses Illinois #6, Pittsburgh #8, Kentucky #11, and Kentucky #9; 2.5%-3.5% sulfur coal. The capacity/production of this plant is 316 MWe (gross), 250 MWe (net). The project cost $303,288,446. The Department of Energy split the cost with the Tampa Electric Company 51% and 49%, respectively. A diagram of the power cycle for the Tampa Electric IGCC project is given here:



The Wabash River Project using a Two-Stage Entrained Flow Gasifier operates on Illinois Basin bituminous coal (Petroleum coke was also used). The capacity/production of this plant is 296-MWe (gross), 262-MWe (net). The project accrued a cost of $438,200,000, which was evenly split between the Department of Energy and the Wabash River Coal Gasification Repowering Project Joint Venture (a joint venture of Dynegy and PSI Energy, Inc.). A diagram of the Wabash River Project Power Cycle is given below:



The project with the highest net power output is the Kentucky Pioneer Project at 540 MWe. The cheapest project was the Tampa IGCC project costing $303,288,446. The most efficient project (when considering cost versus net power output) is the Kentucky Pioneer Project with the cheapest Megawatt: $799875.39/MWe.

The coal is fed into a vertical standing gasifier through the top. These gasifiers operate between one and two atmospheres of pressure with a compressor built in for delivery gas turbine. There are two sections in a gasifier. The upper section is where the volatile components of coal are gasified. The lower section is where the remaining ash and residue gasifies. The coal that is gasified in the upper section comprises approximately 40% of the raw and while the other 60% of the gas comes from the ash and residue from the coal which is gasified in the lower section of the gasifier. The actual gasification of the coal is performed by a reaction with steam-oxygen mixture that is fed through a vent in the bottom of the gasifier. The coal moves through the two sections of the gasifier. The carbon, hydrogen, and sulfur in the coal react with the steam and oxygen to produce oxides of carbon, hydrogen, methane, ethane, ethylene, and hydrogen sulfide are produced. The volatile matters in the coal (tar, tar oil, naphtha) are released in the upper section of the gasifier and pass into the upper gas stream. The steam-oxygen mixture that is needed for the gasification reaction are supplied a vent in the bottom of the gasifier. The left over ash and by products are swept through a grate close to the steam-oxygen vent by revolving blades that sweep the bottom of the gasifier. The upper and lower gas streams pass through separate cyclones to remove large solid particles in the gas stream. The upper gas stream is directed through and electrostatic precipitator to remove more tar and tar-like substances. The lower gas stream is passed through a heat recovery system. Once the gases pass through these devices, they are mixed together and strained one last time for tar-like substances. The gas that is passed out of the final tar precipitator is the raw gas, which is to be combusted. After the cleanup process, the combustible gas is passed through what is called the combined power cycle coal gasification system. There are two power plants in the United States that use this process and are being tested, currently. These power plants can have efficiencies as high as 55%.

High levels of sulfur dioxide and nitrogen oxides are produced from electrical power generation through burning fossil fuels, such as coal. Approximately 66% of all sulfur dioxide and 25% of all nitrogen oxides in the United States are produced by said power generation. These high levels of pollutants in the air cause a phenomenon called “acid rain,” though a better name would be acid deposition. The acid is produced when the pollutants from the coal power plants react with water, air, or other gases in the atmosphere. This can cause mild concentrations of sulfuric and nitric acid. Approximately 50% of these acids will fall back to the earth in particles or pockets of gas. The other 50% falls back to earth in the liquid state, hence the term acid rain.

Though acid rain is the common term for when acid falls out of the atmosphere, there is also acid fog and acid snow. The acid precipitation causes a number of problems for the environment and society. Acid precipitation acidifies lakes and steams which feed a vast number of plant- and wildlife. The plant-life will degrade and/or die off. What wildlife that doesn't move to another area for cleaner water will die off from acid poisoning. Acid precipitation eats away at our buildings, statues, and national monuments and undermines the materials that they are built out of. Acid precipitation can also cause direct damage to trees at higher elevations (i.e. Spruce trees above 2000 ft.) and can directly degrade public health. One good thing that comes from coal burning is that it puts more dust into the atmosphere, which slows the greenhouse effect.

There is a new method of burning coal, the Integrated Gasification Combined Cycle (IGCC) which greatly reduces the output of pollutants. Although the supply of fossil fuels is beginning to wan, the US still has a vast quantity of coal. The IGCC process will allow us to much more cleanly and efficiently use this supply of coal and allow us to make a gradual change over to a clean and renewable power supply.

There are four types of Coal Gasification Systems: air blow pressurized, fluidized-bed gasifier (Nevada); two-stage, pressurized, oxygen-blown, entrained-flow (Indiana); oxygen-blown, fixed-bed, slagging gasifier (Kentucky); and entrained-flow, oxygen-blown gasifier (Florida). Although each of these systems is similar in principle, there are technical differences between each of the four systems.

At the Nevada project, the gas turbine, heat recovery steam generator (HRSG), and steam turbine (the power island) demonstrated good performance (94% of the time, the plant was available for operation) during the demonstration period. The first-of-a-kind

GE MS6001FA Gas turbine designed to operate at 2350 degrees Fahrenheit was able to pull 140 Btu per standard cubic foot of synthetic coal gas. There were a number of technical problems, however.

> “The unit experienced accelerated temperature ramps during startup (once the bed is ignited), which induced spalling of the gasifier refractory and threatened the integrity of the ceramic candle filters in the hot gas particulate filtration system…Early operations uncovered some quality control problems in the HRSG and an undersized gas turbine/generator coupling, which were easily resolved. Also identified was a shortcoming in the 2nd stage bucket shroud design, which caused a premature failure. The shroud on the periphery of the 2nd stage bucket in the hot gas path distorted radially and contacted and damaged the honeycomb seal blocks.” (Los Alamos National Laboratory)

In addition, 18 individual, failed attempts were made to start up the power island. Every failed attempt ended in an ignition malfunction, which facilitated the need for system modification. Once the ignition was properly working, the change of temperature with respect to time was too high and caused radial spalling in the gasifier refractory and endangered the ceramic candle filters in the hot gas particulate system. Based on these problems, the air blow pressurized, fluidized-bed gasifier is not economically feasible because it is not yet even safe. Although this technology demonstrates great potential, the technological community of the United States is not yet prepared to handle the engineering problems encountered at the Nevada project. Perhaps with another year or two of testing and research this gasifier may be a more desirable option. In fairness, the plant efficiency (while it was running) was 43.7% thermal efficiency. This is a marked improvement over the 35% best-case thermal efficiency of most other types of power plants and even out-performed some other types of gasification plants during the demonstration period.

The two-stage, pressurized, oxygen-blown, entrained-flow gasifier in Indiana did not perform as well as the Nevada project. The plant was capable having zero heat loss while cleaning the syngas with its hot/dry particulate removal system. The dual power cycle greatly increased system efficiency so that the waste heat from the coal gas turbine was used to power a standard steam turbine for more power out with the same power in. The syngas was cleaned (slagged) to remove several pollutants including SO2, NOx, and CO2. The facility was able to separate 99.99% of the sulfur out of the pollutants to make the commercially valuable product of pure sulfur. 95% pure oxygen was used in the actual gasification process to reduce the required of the gas injection system, which in turn raises system efficiency. Finally, NOx control was made easier by syngas moisturization. This plant had its problems, as well. Within the first year of the demonstration period, three major problems were encountered with different components of the system. Said components are the ash deposition on the second stage gasifier walls and downstream piping, the particulate breakthrough in the hot gas filter system, and the chloride and metals poisoning of the COS catalyst. The problems with these systems were eliminated by 1998, 1996, and 1997, respectively. However, those problems were encountered only in the first year. The second year was not clear sailing either. Second year problems included cracks in the combustion liners of the gas turbine and leaks in various gas and fluid tubes. By the third year, all major issues had been resolved and the downtime for the system was limited to routine maintenance and the occasional minor system problem, such as equipment or part replacement. During the fourth year, however, the plant gas turbine suffered damage to rows 14 through 17 causing a three-month halt to plant operations. The plant was available for numbers approaching and including a high of 79.1% of the time in 1999. This is compared to the 94% of the Nevada project. Though both of these project demonstrate great potential, the Indiana project was less available than the Nevada project and had more system problems that would have generated a variety of health and environmental issues if left to be. Therefore, the two-stage, pressurized, oxygen-blown, entrained-flow gasifier is not yet within our grasp either, judging by the project conclusion. However, Ideally, the plant efficiency should be above 45% thermal efficiency. In fairness, the plant's thermal efficiency was 40.2% which is considerably better than the 35% thermal efficiency that is achieved by other power plants which are combustion-based.

The oxygen-blown, fixed-bed, slagging gasifier project of Kentucky is still underway and so a full analysis on its economic feasibility cannot be done at this time. The final report shall be issued in December of 2006, according to the project timeline provided by Los Alamos National Laboratory.

The oxygen-blown, fixed-bed, slagging gasifier also featuring full heat recovery, conventional cold-gas cleanup, and an advanced gas turbine with nitrogen injection for power augmentation and NO_x control of the Florida Project's demonstration period had less major maintenance issues than the Nevada and Indiana projects. Nitrogen was mixed with the oxygen at gasification. This increased the mass flow through the gas turbine, which increases power output and also raises system efficiency. Mixing nitrogen with the oxygen for gasification also lowered NOx emissions and eliminated the need for steam/water injections for further emission control. Soon after the initial start up, chunks of ash clogged the system causing a failure in the exchangers in the high-temperature heat recovery system and seriously damaged the combustion turbine. The exchangers were removed in 1997. Another problem with ash clogs in the heat recovery system were resolved via design modifications in 1999. There were several brief, forced power outages in 1997 and 1998 to replace valves and piping that began to corrode. Though design modifications were implemented to fix problems, mainly, the plant engineers were proactive in amending the design. For example, designers came up with and implemented a hot start-up procedure to restart the plant after it had been shut down. This took 18 hours less time than the previous cold-start procedure took. Overall, the plants performance was 9350 Btu/kW-hr. The availability of the gasifier during the fourth and fifth years was 88.7% and 84.2% respectively. The availability of the power block during the fourth and fifth year was 86.6% and 93.9%, respectively. The availability of the air separation unit was 93.9% and 90.5%, respectively. The gasifier capacity during the fourth and fifth year was 75% and 66%. Although, the plant did not have as many major maintenance issues as the Nevada and Indiana projects, the plant efficiency was 36.5%, which is not much better than standard coal-fired plants. The oxygen-blown, fixed-bed slagging gasifier is more economically feasible than the Indiana and Nevada Projects because it had less major issues. Note that the Nevada and Indiana projects outperformed the Florida project in terms of capacity and efficiency. The thermal efficiency of the Florida project was 36.5% thermal efficiency. Although, there are improvements within out grasp to raise this efficiency to 38%, the other gasification plants still out-perform this type of gasification, as the systems are configured.

Coal gasification power is unreliable at times. Theory says that gasification plants should be getting phenomenal efficiencies and power outputs, provided that there are no major maintenance problems or design flaws. Practice, however, has introduced said maintenance issues and design flaws. Judging from the Nevada, Indiana, and Florida projects, coal gasification is a very clean method of power generation, but its efficiency and economic performance is very comparable to standard coal-fired, oil-based, or natural gas-fired power plants. We currently lack the resources and the technology to make the numbers of theory become a reality. The last hope for the Clean Coal Initiative that is in sight is the Kentucky because the project is incomplete to date. Hopefully, by the time that the Kentucky Project Report is issued, the U.S. Department of Energy will have a better idea of how to execute and make these numbers come out of the power plants and flow across the power grid.

Fuel Information

The process used in coal-based power plants is a set of chemical reactions and state changes which coal transforms lumps partially or completely into a gas. After they are transformed into the gas state, they are combusted to produce electricity. A Scottish engineer named William Murdock pioneered coal power techniques in 1792. Murdock's process involved heating the coal inside a retort without any oxygen at temperatures ranging from 450 degrees Celsius to 1300 degrees Celsius. Murdock licensed his process to Gas Light and Coke Company and Baltimore Gas Company in 1813 and 1816, respectively. This crude method had a low energy yield (100-150 Btu/ft^3). In 1873, the innovation of a steam-air process allowed energy outputs in the range of 300-350 Btu/ft^3. The air is a mixture of carbon monoxide and hydrogen, commonly referred to as water gas in the gas industry. Later on, oil was added to the reactor and the thermal energy output was raised to 500-500 Btu/ft^3. This became the standard energy output for plants powering residences and industries. In the 1940s water gas was replaced with a nearly equivalent gas mixture of steam and almost pure oxygen as the reactant. Another, more recent development, has been the use of a steam-pure oxygen mixture as the reactant at elevated pressures of 450 psi or 3.09 Newtons/meter^2. The elevated pressure process converts the coal to synthetic natural gas.

Coal is by far one of the most plentiful sources of energy from of fossil fuel, second only to oil. Oil reserves will be exhausted in 30 years. Natural gas reserves will be exhausted in 20 years. At this rate of consumption (1063.5 million short tons in 2001), coal reserves will run out in 200 years. 1121.3 million short tons of coal were produced in the year 2001; that is 4% higher than coal production in 2000. The increase in coal production is due to an increase in coal stocks, which are mined. Though coal mining and production was up in 2001, there were some problems. Some mining companies had sandstone deposits in their mines or they delayed regular equipment maintenance to produce more coal in times of high demand, which led to equipment failure later on. This coupled with the insurance companies that insured the coal mining companies having financial and being declared insolvent threatened to close some mines. Another set of problems were caused by the delay in permit issuing by the Army Corps of Engineers. This caused administrative problems, which delayed the production of coal that could have made it to the market. These and other issues, including legal problems, hindered what could have been an even larger coal production level in 2001.

1063.5 million short tons of coal were consumed in 2001, which are 17.4 million short tons less than coal consumption in 2000. In the year 2001, coal consumption was down by 2%, overall. The coal that was not used helped to replenish coal stockpiles that were stretched thin due to high consumption and low production of coal over the past two years. The lower coal consumption is an effect due to milder-than-normal weather and the decline in the national economy. Coal importation was up in the year 2000 by over than 58% for a record high of 19.8 million short tons because many utility plants had to import low-sulfur coal in order to comply with phase two of the 1990 Clean Air Act Amendments. 90% of the coal produced is consumed by electrical power plants. 25% of all electricity in the US is coal-generated.

Not all coals are the same. Unlike other fossil fuels, there are some rather significant differences between the different types of coal.

ANTHRACITE: Hard coal, found deep in the earth. It burns very hot, with little flame. It usually has a heating value of 12,000-15,000 British thermal units (Btu) per pound.

BITUMINOUS: Soft coal containing large amounts of carbon. It has a luminous flame and produces a great deal of smoke. Bituminous coal is the most abundant coal in active U.S. mining regions. The heat content of bituminous coal consumed in the United States averages 24 million Btu per ton.

COKE: A porous solid left over after the incomplete burning of coal or of crude oil.

LIGNITE: The lowest rank of coal, often referred to as brown coal, used almost exclusively as fuel for steam-electric power generation. It is brownish-black and has a high inherent moisture content, sometimes as high as 45. The heat content of lignite consumed in the United States averages 13 million Btu per ton. The texture of the original wood often is visible in lignite.

SUBBITUMINOUS: Ranking below bituminous is subbituminous coal with 35-45 percent carbon content and a heat value between 8,300 and 13,000 BTUs-per-pound. Reserves are located mainly in a half-dozen Western states and Alaska. Although its heat value is lower, this coal generally has a lower sulfur content than other types, which makes it attractive for use because it is cleaner burning.

Coal prices have been on the rise for the past two years due to the relatively tight supply of coal. Coal cost $24.77 per short ton on annual average or $1.235 per million BTU. If and when the sources of oil and natural gas are depleted it will put a higher strain the coal supply. As a result, the coal supply will not last for the projected 200 years. Also, the price of coal will increase, especially as third world nations continue to modernize, the coal supply decreases, more coal power plants are built, and as the other energy sources are depleted.

The annual average Coal prices per short ton for 2001, 2000, 1999, 1998, and 1997 were $24.77, $15.68, $16.63, $17.67, and $18.14, respectively. The annual average coal prices per short ton for the five-year interval of 1996, 1995, 1994, 1993, and 1992 were $18.50, $18.83, $19.41, $21.11, and $22.90, respectively. The average coal prices per short ton over the years 1991, 1990, 1989, 1988, and 1987 were $23.97, $25.15, $26.20, $27.52, and $29.74, respectively. The annual average coal prices over the five-year interval of 1986, 1985, 1984, 1983, and 1982 per short ton were $31.59, $34.20, $35.85, $37.72, and $41.13, respectively. Note that these are the averages of prices of all coal.

The average prices of Anthracite over the five-year interval of 2000, 1999, 1998, 1997, and 1996 per short ton were $38.21, $33.57, $41.58, $34.45, and $36.78, respectively. The average prices per short ton of Anthracite over the five-year interval of 1995, 1994, 1993, 1992, and 1991 were $40.55, $37.57, $35.02, $37.28, and $40.53, respectively. The average prices per short ton of Anthracite over the five-year interval of 1990, 1989, 1988, 1987, and 1986 were $45.54, $51.56, $55.06, $56.26, and $58.58, respectively. The average prices per short ton of Anthracite over the five-year interval of 1985, 1984, 1983, 1982, and 1981 were $62.15, $67.50, $75.91, $75.25, and 71.00, respectively.

The average prices of Lignite over the five-year interval of 2000, 1999, 1998, 1997, and 1996 per short ton were $10.43, $10.53, $10.91, $10.70 and $10.92, respectively. The average prices per short ton of Lignite over the five-year interval of 1995, 1994, 1993, 1992, and 1991 were $11.04, $11.22, $11.81, $11.77, and $12.15, respectively. The average prices per short ton of Lignite over the five-year interval of 1990, 1989, 1988, 1987, and 1986 were $11.71, $11.90, $12.54, $13.99, and $14.13, respectively. The average prices per short ton of Lignite over the five-year interval of 1985 and 1984 were $14.49, and $14.63, respectively. The data on the prices of Lignite for the years 1983, 1982, and 1981 have been withheld from record in the Department of Energy.

The average prices of Bituminous over the five-year interval of 2000, 1999, 1998, 1997, and 1996 per short ton were $22.66, $22.82, $23.92, $24.17 and $25.17, respectively. The average prices per short ton of Bituminous over the five-year interval of 1995, 1994, 1993, 1992, and 1991 were $26.06, $26.75, $27.80, $29.16, and $30.66, respectively. The average prices per short ton of Butiminous over the five-year interval of 1990, 1989, 1988, 1987, and 1986 were $31.71, $32.91, $34.48, $36.34, and $38.30, respectively. The average prices per short ton of Butiminous over the five-year interval of 1985, 1984, 1983, 1982, and 1981 were $41.77, $42.88, $45.17, $48.53, and $50.52, respectively.

The average prices of subbituminous over the five-year interval of 2000, 1999, 1998, 1997, and 1996 per short ton were $6.66, $6.59, $6.79, $7.28 and $7.87, respectively. The average prices per short ton of subbituminous over the five-year interval of 1995, 1994, 1993, 1992, and 1991 were $8.26, $8.72, $9.92, $10.54, and $10.80, respectively. The average prices per short ton of subbutiminous over the five-year interval of 1990, 1989, 1988, 1987, and 1986 were $11.21, $12.20, $13.03, $14.59, and $16.28, respectively. The average prices per short ton of subbutiminous over the five-year interval of 1985, 1984, 1983, 1982, and 1981 were $17.06, $17.37, $18.92, $20.18, and $19.53, respectively.

The U.S. Coal mining industry is much stronger than the domestic oil industry. Considering that the U.S. is 60% more dependent on oil than it is coal magnifies this fact. Below is data about how much coal has been mined over the past 52 years and how much coal has been consumed. As you can see from these numbers below (courtesy of the U.S. Department of Energy), the U.S. produces more coal than it consumes per year. This allows us to, both, build a strategic coal reserve and to export coal. Currently, the only fossil fuel that the U.S. hoards as a strategic reserve is oil (the Strategic Petroleum Reserve or SPR).

Table #4: Coal Production and Consumption, 1949-2001 (short tons)

Year	Bitomous Coal Produced	Subbitomous Coal Produced	Lignite Produced	Anthracite Produced	Coal Consumed
1949	437,868,000	*	*	42,702,000	483,237,420
1950	516,311,000	*	*	44,077,000	494,101,770
1951	533,665,000	*	*	42,670,000	505,904,006
1952	466,841,000	*	*	40,583,000	454,057,241
1953	457,290,000	*	*	30,949,000	454,798,204
1954	391,706,000	*	*	29,083,000	389,943,671
1955	464,633,000	*	*	26,205,000	447,012,195
1956	500,874,000	*	*	28,900,000	456,857,996
1957	492,704,000	*	*	25,338,000	434,476,232
1958	410,446,000	*	*	21,171,000	385,713,170
1959	412,028,000	*	*	20,649,000	385,062,221
1960	415,512,000	*	*	18,817,000	398,081,359
1961	402,977,000	*	*	17,446,000	390,352,128
1962	422,149,000	*	*	16,894,000	402,259,869
1963	458,928,000	*	*	18,267,000	423,480,494
1964	486,998,000	*	*	17,184,000	445,670,457
1965	512,088,000	*	*	14,866,000	471,965,119
1966	533,881,000	*	*	12,941,000	497,748,823
1967	552,626,000	*	*	12,256,000	491,430,533
1968	545,245,000	*	*	11,461,000	509,827,069
1969	547,172,000	8,321,000	5,012,000	10,473,000	516,413,917
1970	578,469,000	16,423,000	8,040,000	9,729,000	523,230,708
1971	521,344,000	22,151,000	8,697,000	8,727,000	501,574,619
1972	556,842,000	27,547,000	10,997,000	7,106,000	524,262,778
1973	543,532,000	33,933,000	14,273,000	6,830,000	562,583,603
1974	545,689,000	42,240,000	15,477,000	6,617,000	558,401,800
1975	577,522,000	51,099,000	19,817,000	6,203,000	562,640,432
1976	588,364,000	64,841,000	25,480,000	6,228,000	603,789,974
1977	580,991,000	82,115,000	28,238,000	5,861,000	625,290,963
1978	534,020,000	96,757,000	34,350,000	5,037,000	625,224,827
1979	612,279,000	121,475,000	42,545,000	4,835,000	680,524,248
1980	628,769,000	147,715,000	47,160,000	6,056,000	702,729,735
1981	607,986,000	159,693,000	50,673,000	5,423,000	732,626,833
1982	620,166,000	160,946,000	52,411,000	4,589,000	706,910,644
1983	568,609,000	151,044,000	58,349,000	4,089,000	736,672,312
1984	649,489,000	179,200,000	63,070,000	4,161,735	791,295,693
1985	613,851,000	192,657,000	72,422,000	4,708,375	818,048,659
1986	620,059,000	189,610,000	76,354,000	4,291,951	804,230,968
1987	636,609,000	200,165,000	78,427,000	3,560,459	836,940,592
1988	638,105,000	223,504,000	85,101,000	3,554,509	883,641,806
1989	659,771,000	231,171,000	86,439,000	3,347,996	894,999,882
1990	693,206,000	244,274,000	88,090,000	3,506,247	902,917,828
1991	650,700,000	255,325,000	86,514,000	3,445,080	899,226,805
1992	651,842,000	252,158,000	90,062,000	3,482,861	907,654,798
1993	576,652,000	274,901,000	89,549,000	4,322,263	944,081,285
1994	640,260,000	300,517,000	88,081,000	4,646,032	951,285,899
1995	613,764,679	327,997,855	86,499,740	4,711,498	962,103,774
1996	630,741,292	340,290,580	88,055,815	4,767,826	1,006,320,771
1997	653,827,506	345,071,099	86,341,244	4,691,939	1,029,544,456
1998	640,586,262	385,930,397	85,766,784	5,251,724	1,037,102,819
1999	601,731,551	406,714,233	87,217,912	4,767,752	1,038,646,541
2000	574,275,630	409,203,124	85,560,584	4,572,223	1,084,094,875
2001	620,226,274	413,329,498	83,914,674	3,857,095	1,060,302,680

Chapter 4

Nuclear Fusion

Introduction to Nuclear Fusion

Nuclear fusion is an experimental concept that allows for massive amounts of energy to be released from a relatively small amount of fuel. This is done by the collision of two atoms in a superheated mixture called a plasma, and converting the energy released into power using conventional methods, such as steam turbines. Fusion is still not a commercially viable source of power, as it is not yet able to produce more energy than it consumes, nor scale to the demands of a conventional power plant.

Plans for Fusion as an Energy Source

Although fusion is not currently a viable commercial source of power, it is still being considered by the U.S. Government when taking stock of possible future power sources. The National Energy Policy Development Group (NEPD) of the U.S. Government published the National Energy Policy in May 16, 2001 that, among many other topics, discusses fusion power.

The NEPD, in its energy policy report, noted that "both hydrogen and fusion must make significant progress before they can be considered viable sources of energy. However, the technological advances experienced over the last decade and the advances yet to come will hopefully transform the energy sources of the distant future." The NEPD's recommendation was:

- "…that the President direct the Secretary of Energy to develop next-generation technology- including hydrogen and fusion."
- "Develop an education campaign that communicates the benefits of alternative forms of energy, including hydrogen and fusion."

One of the focuses of the NEPD's report was on the concern that the U.S. does not have a diverse enough usage of fuels ("…an increased dependence, not on foreign oil, but on a narrow range of energy options," in their words). This would be done in the interests of increased reliability and affordability of power, and also in the interests of national security. This is one of the reasons why research into fusion power is being done. The NEPD recommended, along with nuclear power, that clean coal technologies and more efficient oil and natural gas usage be researched. It also recommended making more use of nuclear fusion and hydro power sources.

Along with a national energy plan, the U.S. Government has published numerous papers regarding the development of fusion energy. The energy plan that was published above did not go into depth about the current state of the fusion program nor specific recommendations for progress. In August 9, 1999, the Dept. of Energy (DOE) published a paper on these issues.

The task force that published said paper's take on fusion power was that "the threshold scientific question – namely, whether a fusion system producing sufficient net energy gain to be attractive as a commercial power source can be sustained and controlled – can and will be solved." It goes on to note that, in their view, it is simply a function of funding and effort. The task force also recommended "[i]t is [their] view that [the U.S.] should pursue fusion energy aggressively." Magnetic Fusion Energy, or MFE, is currently the most promising method of fusion power. The task force recommended that the U.S. collaborate with other nations to develop fusion power, as this would allow the U.S. to partake in programs with much more funding and resources than current research efforts within the U.S. It also recommended "engaging the Congress at an early stage", to attempt to obtain and sustain the long term funding necessary for researching fusion, as well as explain the necessity of collaborating with other countries on fusion research.

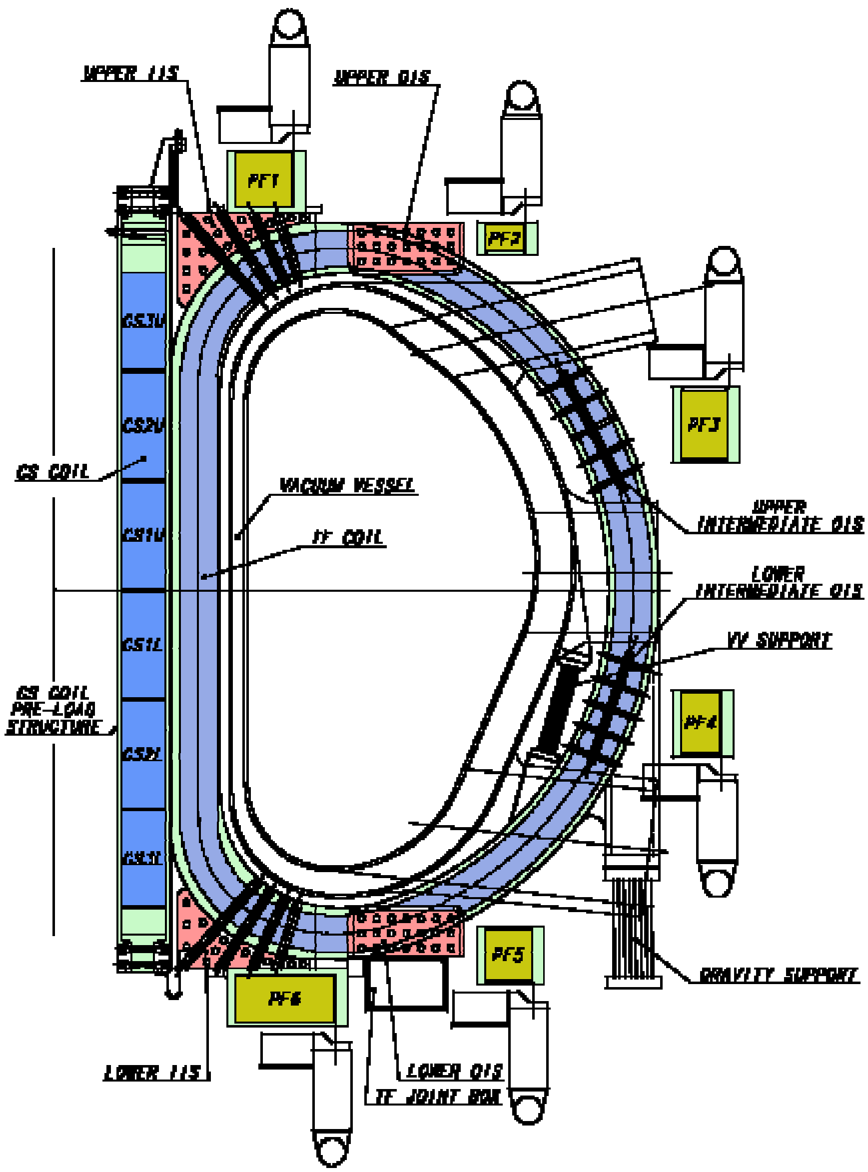
Concepts Behind Fusion & Implementations

Nuclear fusion works by taking deuterium (1 proton, 1 neutron) and tritium (1 proton, 2 neutrons) and heating them until they collide. When they collide, they may combine to form Helium-4 (2 protons, 2 neutrons) and a neutron. A small amount of mass is lost in this reaction, which is converted to energy according to $E=mc^2$. Thus far, the only viable known way to create fusion is to heat the mixture of deuterium and tritium to a temperature of around 100 million degrees Celsius. Since the cores of the nuclei so strongly repel each other, the mixture needs to be heated to a temperature that allows the cures to move fast enough to overcome this repulsion, so that they collide and fuse. This is known as a DT reaction.

Magnetic Confinement

There are two primary methods to achieve this: magnetic confinement, and internal confinement. Of these two methods, magnetic confinement has yielded the most promise so far. Using physical means to contain this reaction is not viable, as the temperature and pressures needed to contain said reaction would cause any conventional container to explode. As the reaction turns out to conduct electricity, and magnets and electricity are inextricably linked, magnets currently hold the most promise for containing fusion reactions.

However, magnets pose some unique problems, the main one being that magnetic fields are two dimensional, and only act on the perpendiculars to the current. Currently, the most successful design for containing a nuclear reaction is the tokamak.



(from http://www.iter.org/ITERPublic/ITER/gifs/magnet.gif)

The tokamak is an elliptical torus-shaped container for the fusion reaction. It consists primarily of three parts: the torus shaped vacuum chamber, the field coils that are wrapped around the chamber, and transformers around the field coils and vacuum chamber. The vacuum chamber provides a place for the reaction to take place. The field coils provide the field that contains the reaction. Since the field coils go in a loop around the vacuum chamber, you cannot directly apply voltage to them to create the field. Instead, the transformer is used to provide the coils with the voltage needed to produce the field that contains the reaction.

One very important concept in nuclear fusion is the containment of the plasma. This can be tricky to do, as weaknesses in the field can lead to loss of plasma containment. This is done by using electromagnetic fields surrounding a tokamak. A magnetic field is most easily described using field lines. In reality, there are no magnetic field lines, just a field. However, it is an easy way to imagine field lines. Where the field lines are condensed, the magnetic field is strongest, and where they are spread apart, the magnetic field is weakest. The field lines inside the tokamak are arranged in such a way that the plasma inside the tokamak will not escape, since the plasma will follow those field lines. These lines inside the tokamak spiral around and around the toroidal shape of the tokamak, never crossing. This can be imagined as a ring shaped surface with spring--like spirals, known as the flux surface. Similar surfaces run concentric, inside and outside of this surface. The plasma follows this spiral, and thus stays inside the tokamak.

The magnetic field inside the tokamak, and is the result of the combination of two fields: the field generated by the toroidal field coil (known as the toroidal field), and the plasma itself (known as the poloidal field). The toroidal lines can be imagined as vertical rings surrounding the torus of the tokamak. The poloidal field lines can be imagined as 'donut'-like lines running horizontally around the tokamak. The combination of these two produces the spiral-shaped field lines around the tokamak.

Due to the shape of the flux surface, the field lines are denser on the inside of the toroid than on the outside. Thus, the magnetic field is weaker outside, and this is where a loss of plasma containment occurs. To calculate the possibility of a loss of plasma containment, a concept known as Troyon's pressure rule is used. As described in The Fusion Quest, by T. Kenneth Fowler:

$$2nt \leq [(I * B) / a] * 4.4 * 10^{26}$$

The first part of the formula is calculated by adding the ion pressure (nT) and the electron pressure (nT), to get the total pressure ($2nT$). n is the ions per cubic meter, and T is the temperature in Celsius. I is the current, given in megamperes. B is the field strength, in tesla. a is the minimum minor radius (the radius of the inner wall of the torus). This gives the conditions needed for plasma containment. For the ITER reactor, $T = 10^8$ degrees Celsius, $I = 21$ megamperes, $B = 5.7$ tesla, and $a = 2.8$m. This gives us a necessary fuel density (n) in ITER of $0.94 * 10^{20}$ $1/m^3$.

Inside the plasma, there are vast differences in temperature. At the core of the plasma, the temperature is approximately 100 times what it is at the outer edges. This creates an outward force. In order for the magnetic field to contain this plasma, the plasma must have a current, since magnetic fields only apply force on currents. The pressure in the plasma itself must supply this current, which is known as the diamagnetic current. Without the diamagnetic current, plasma would not be contained by magnetic fields. However, these magnetic fields need to be arranged in such a way as to not allow the plasma to escape.

The combination of the above concepts is known as magnetohydrodynamics, or MHD. MHD is the study of how electrically conducting fluids interact with a magnetic field. This was a concept that came from astrophysics. Later on, a concept known as the energy principle was derived in part from MHD. The energy principle is important to containment of plasma because it offers a way to calculate the stability of the system. Before this principle, most of the obvious arrangements for containing plasma had been found to be unstable. The concept behind the energy principle is fairly simple. It is described in The Fusion Quest using the analogy of a marble and cup. The idea is to find whether a system is stable or unstable. If one drops a marble into a cup, the marble reaches the bottom. No matter where the marble is pushed, it will return to the bottom of the cup. The system in this case is stable. However, if the cup is then turned over, the marble escapes the cup and falls. No matter where the marble is placed in the cup, it will fall, and the system is unstable.

Inertial Confinement

Inertial confinement is an alternative method to magnetic confinement as a way to achieve nuclear fusion. In inertial confinement, large energy beams, known as drivers, strike small fuel pellets known as targets. When the pellet is struck with energy, it vaporizes the surface of the pellet. This causes the pellet to experience massive pressure from all sides, compressing it. This compression causes the pellet to heat to the point of creating fusion. Electricity could then be produced from this reaction in the same manner as it is produced for magnetic fusion.

One issue that has not yet been solved with inertial confinement fusion is that of developing a driver which can provide enough energy to sustain fusion reactions large enough to reach breakeven. In order to reach this point, the driver must be efficient enough to provide energy to the reactor without consuming too much electricity. Thus far, the highest ratio of energy yielded to energy consumed by the driver is approximately 1 to 100. In order to produce a commercially feasible reactor, this ratio must be 20 to 1.

There are several different types of drivers in research to solve this problem, including glass lasers and carbon dioxide gas lasers. A glass laser works by taking a laser beam and shooting it through what are known as glass amplifiers. Inside these glass amplifiers is an element (such as neodymium) that is charged by outside forces. When the laser beam passes through this glass amplifier, it picks up the energy that was fed into the glass amplifier. Typically, the laser will pass through multiple glass amplifiers. Glass lasers are being researched in order to try to achieve breakeven in scientific research, while carbon dioxide gas lasers are being studied for use in commercial fusion reactors. Glass lasers are acceptable for scientific research, but whether they can be adapted for use in a commercial power plant remains to be seen. The reason for this is that the laser heats the glass to the point where the glass must be cooled before the laser can be fired again. In a commercial setting, glass lasers would be too slow (Glass lasers fire at about the rate of once per hour, while a rate of around 10 times a second would be needed in a commercial setting). Gas lasers use the same concept as a glass laser, but the beam passes through an energized gas instead of the energized glass. The end result is the same, though- a higher power laser beam. Carbon dioxide gas lasers have the advantages of being more efficient and having a higher firing rate than glass lasers. The disadvantage currently is that they require special equipment to operate, and the lenses are difficult to make properly.

A possible alternative to using lasers for drivers would be to use particle beam systems, such as electron beam drivers. These work by using pulse power accelerators to create bursts of very high energy, which are then focused to create particle beams. The pulse power accelerators are fed electricity to create these particle beams. The efficiency of the drivers is still around 50% currently, whereas the best laser system can only achieve around 15%. These drivers are still experimental, however. It is unknown how well they would work in an inertial confinement fusion system. It has yet to be seen how well these drivers would scale to a production sized reactor, and there is a possibility that they would not be able to provide the power needed to drive larger reactors. Another issue is possible radiation damage.

Fuel pellets are the second part to the equation in inertial confinement fusion reactors. These pellets are spherical, and are made from a mixture of deuterium and tritium. Currently, however, it is difficult to manufacture these pellets to the specifications needed. If the pellet surface differs more than 10 to 100 nanometers from a perfect sphere, the reaction may not work correctly. Currently, approximately 1% of pellets created are suitable for use in reactions. It is expected to see improvements in this number as production techniques mature.

Fuel Production

Deuterium and tritium are the two substances that will almost certainly be used to power commercial fusion reactors, due to the low ignition point compared to other possible fuels. Deuterium can be found in abundant supply in the earth’s water supply, but tritium is not, due to its relatively short half life of 4500 ± 8 days (around 12.3 years, or 5.5% per year). Due to this fact, tritium must be artificially produced.

Though tritium is needed to produce reactions in a typical fusion reactor, a fusion reactor could actually produce tritium as one of its byproducts. The tricky part is that producing tritium in a fusion reactor is done at a tradeoff of producing electricity. When a fusion (or fission) reaction takes place, excess neutrons are produced. These neutrons can be used in nuclear reactions that produce tritium. By placing helium or lithium atoms so they are struck by these neutrons, tritium will be produced.

The Department of Energy (DOE) currently has a Tritium Production Program that is developing methods of using fusion reactors to replace the supply of decreasing tritium. This program is not intended to produce tritium for fusion reactors, though. Its main goal is finding a viable method of producing tritium for use in nuclear weapons. This means that a fusion reactor used in this program could actually consume more electricity than it produced, as long as it produced excess tritium. In this case, tritium is the main goal, not electricity. It is possible to have a fusion reactor produce its own tritium, but it has yet to be seen if this will be viable for a fusion reactor that's goal is to produce electricity.

Another way to produce tritium would be to use a particle accelerator. One particle accelerator that currently does this is the Accelerator Production of Tritium Project (APT). In this particle accelerator, a 170MW proton beam is projected onto tungsten which is surrounded by lead. Beside the tungsten, and inside the lead, there are tubes of helium gas. When the proton beam strikes the tungsten, neutrons from the tungsten are then absorbed by the helium, converting it into tritium. The tritium is constantly filtered from the tubes of helium, replaced with more helium.

Public Safety Concerns

With conventional nuclear power (fission), there are many safety and environmental risks that must be considered, such as nuclear waste and meltdowns. Nuclear fusion is fairly safe and has low environmental impact in comparison to fission. However, there are still hazards to be considered. The two substances that will pose the most threat in a nuclear fusion plant are tritium, activated dust and the components of the reactor itself.

The primary fuel source of current fusion reactors is a mixture of deuterium and tritium. Tritium is a radioactive isotope of hydrogen, with a half-life of 12.5 years. When it decays, it emits a weak beta particle, and becomes helium-3, which is stable. Tritium by itself has a low impact on health; however, it does pose some health risks when it combines with other substances. When tritium combines with water, for instance, it forms a radioactive water vapor which can easily be absorbed through the skin or through inhalation. This water is treated by your body in the same way as ordinary water, so it will spread through the human body in similar fashion. A relatively large amount of tritium would need to be absorbed to pose a health risk, however. The human body ordinarily replaces half of its water over a period of a week to a week and a half, depending on the amount of fluid ingested. If needed, this period can be reduced to around three days under medical care, so tritium can be expelled from the body rapidly. Most of the tritium supply for a fusion reactor will be produced on site. The only times that substantial amounts of tritium will need to be shipped around outside the plant are the amounts needed to start the fusion reaction, and the amount left over when the plant is decommissioned (For ITER, this will be approximately 16kg over the life of the plant. ITER will also use weekly shipments of tritium fuel, however.).

Activated dust is another radioactive substance to be considered in nuclear fusion plants. This radioactive dust is the byproduct of corrosion of the machine containing the fusion reaction. When combined with steam, this activated dust will combust, so the amount of activated dust in the system must be kept to a minimum. ITER uses a cooling system that only allows air to flow in from the environment, and filters all outgoing air as to remove this dust before it is released back into the environment.

The third radioactive component of the system is the reactor itself. This only poses an environmental threat when the reactor is decommissioned, or when parts of the reactor need to be replaced. The system becomes radioactive when neutrons released from the fusion reaction strike the reactor. This causes the metals in the reactor to become radioactive. When a plant is decommissioned, approximately 30,000 tons of the material will be radioactive and must be dealt with appropriately. Within 100 years, however, 80% of this material will have a low enough radioactivity level to be released from regulatory control and recycled.

Fusion reactors, unlike fission reactors, pose no risk of "runaway" nuclear reactions. In the event that a reactor begins to function improperly, it can be shut down automatically. Unlike fission, fusion power is not the result of a chain reaction. When the plant is shut down, all plasma reactions stop, and the residual energy is low enough that evacuation of the surrounding area will never be needed. Fusion reactions require a constant fuel source – without this, reactions will stop within a few seconds (In ITER, the fusion reactor requires ~0.5g/s of fuel). Failure of exhaust systems will also halt the fusion reactor, since impurities in the plasma will quickly extinguish any reaction.

One possible concern the public could have about the safety of fusion reactors is the assumed possibility of nuclear meltdown. Due to the method in which fusion reactors operate, this is not possible.

At any point when the fusion reactor is operating, the plasma only holds enough energy to burn in the tens of seconds. In the event of the plasma reactor losing containment, the plasma will cool due to expansion and collision with the walls of the reactor. The plasma must be kept in a very specific range of conditions (temperature, pressure) to sustain any reactions. When the plasma cools, the reaction is brought to a halt. Another possible concern is what happens if too much fuel is injected into the plasma. If this occurs, the plasma density would become too high. When the plasma density is too high, it cannot sustain a reaction, and will disrupt (terminate).

Costs

Even if fusion plants can produce amounts of energy comparable to existing alternatives using cheaper, more abundant fuel and using less waste, they will still need to compete with existing plants in terms of cost to build a commercial fusion plant. They will also need to have a lifetime comparable to that of current power plants. As a commercial fusion plant has yet to be built, it is unknown what the cost will be. Fusion plants such as ITER and JET have been built, but these are experimental reactors, and are not as large as a commercial reactor would be. ITER currently is funded by $188 M per year, over the course of 20 years. Decommissioning ITER is projected to cost an additional $335 M. Though unknown, fusion reactors are estimated to have a lifetime of 30 years, compared to the 30 to 35 years expected for a coal plant. As commercial fusion matures, the costs of getting a fusion plant online will most likely decrease as well. While the cost for a commercial fusion reactor is not known, since no commercial fusion reactors exist, some insight into what costs will be required can be seen by examining current fusion reactors. The ITER project, which is an experimental fusion reactor, has published a breakdown of their costs. Costs are given in units of IUA (1 IUA is equivalent to the worth of $1,000 in January 1989). The costs of ITER (totaling ~2,755kIUA) can be broken down into three parts: construction costs, operational costs, and decommissioning costs. The following table summarizes the costs of ITER.

	Cost (kIUA)
Construction Costs	
Direct capital cost	2755
Management and support	477
R&D during construction	60-80
Operational Costs (average/year)	
Permanent personnel	60
Energy	~30
Fuel	~8
Maintenance/improvements	~90
Total	188
Decommissioning Cost	335

Summary of ITER Cost Estimates
(Source: ITER Technical Basis – Plant Description Document)

The construction costs of ITER can be broken down as follows:

	Direct Capital Cost (kIUA)	**Percentage of Total**	**Deferred Investment (kIUA)**
Magnet Systems	762.1	28%	40.2
Vacuum Vessel	230.0	8%	0.0
Blanket System	165.2	6%	8.6
Divertor	76.0	3%	6.9
Machine Assembly	92.7	3%	0.0
Cryostat	75.8	3%	0.0

Thermal Shields	28.8	1%	0.0
Vacuum Pumping & Fueling System	34.2	1%	6.8
Machine Core, subtotal	**1464.8**	**53%**	**62.5**
R/H Equipment	61.1	2%	52.3
Cooling Water Systems	131.5	5%	16.8
Tritium Plant	36.6	1%	45.2
Cryoplant & Distribution	88.9	3%	7.9
Power Supplies & Distribution	214.7	8%	3.5
Buildings	380.3	14%	12.0
Waste Treatment and Storage	2.1	0%	7.0
Radiological Protection	1.0	0%	3.2
Auxiliaries, subtotal	**916.2**	**33%**	**147.9**
IC H&CD	32.2	1%	2.0
EC H&CD	77.5	3%	3.0
NB H&CD	96.0	3%	0.2
Heating and CD, subtotal	**205.7**	**7%**	**5.2**
Diagnostics	118.0	4%	42.3
CODAC	50.0	2%	0.0
Grand Total	**2754.7**	**100%**	**257.9**

Summary ITER Direct Capital Cost
(Source: ITER Technical Basis – Plant Description Document)

The following paragraphs attempt to describe the components that make up for the costs of ITER.

The magnet system and vacuum vessel are parts of a fusion reactor that work together to contain the plasma.

The blanket system in ITER is intended to provide shielding against the plasma. The blanket modules surround the plasma, and absorb heat and radiation. Due to the conditions these modules will face, they will need to be replaced or maintained if damaged from heat. The modules consist of two parts: back and front. The back consists of steel and water, and has a radial thickness of approximately 30cm. The front consists of 1cm of beryllium armor on the outside, then 1cm of copper to act as a heat sink, then 10cm of steel.

The divertor in ITER is a series of 54 cassettes located at the bottom of the vacuum vessel. As part of the fusion reaction, helium is created. The job of the divertor is to remove this helium exhaust from the plasma, to help maintain the fusion reaction.

The machine assembly cost refers to the cost of assembling the different components of ITER, such as the building housing the tokamak. The cassettes consist of tungsten and carbon facing the plasma, and a copper heat sink, with a SS 316 LN (stainless steel) structure.

The cryostat is a cylinder made from SS 304L (stainless steel), and measures 24m high and 28m wide. The cryostat encloses the tokamak vessel in a vacuum, and helps to maintain temperature.

The thermal shields are placed to shield the magnet system from heat, as the magnets lose effectiveness at higher temperatures (over 4.5K).

The fueling system is comprised of a gas supply that is capable of storing multiple gases and multiple systems to distribute these gases. This allows injections of gases into the plasma (such as deuterium, tritium, argon, etc.), as well as providing gases for wall conditioning (wall conditioning is the process that removes impurities from the walls facing the plasma, prior to the reaction). The vacuum pumping systems provide vacuums for all major systems that require it (e.g. leak detection systems, torus pumping systems, etc.).

R/H Equipment refers to remote handling equipment. This equipment allows for the repair and replacement of components in the fusion reactor. Since many of these components are highly radioactive, they must be replaced with remote equipment.

The cooling water system provides cooling to the tokamak and other components of the fusion reactor. It must be able to regulate the temperature, pressure and rate of flow of the water.

The tritium plant is responsible for processing incoming gas streams to produce the gases for fueling, as well as confining tritium and removing tritium from waste gas streams, air and water.

The cryoplant and cryodistribution refer to two components of ITER responsible for regulating temperatures in the fusion reactor, such as plasma temperature and magnet temperature.

Power supply and distribution costs refer to the systems that exist to provide the large pulses of power required to supply both the superconducting coils as well as the heating and current drive (described below).

The 30 buildings in ITER are comprised of two groups: conventional buildings and radiologically controlled buildings. The radiologically controlled buildings differ from the conventional buildings in that they provide shielding from radiation, ventilation systems and drainage systems. These buildings are used to house the portions of ITER that will be dealing with radioactive substances. Building costs also include the fences surrounding ITER to provide security.

Radiological protection costs refer to any costs incurred from systems to protect against radioactivity, such as protection of workers from radiation.

H&CD refers to heating and current drive. H&CD systems have multiple functions. One function is to heat plasmas that will not be used in a fusion reaction. This can be used to commission different modules of the plant. These systems also help with wall conditioning, plasma rotation, assisted startup and other functions. The H&CD systems in ITER are made up of three parts: Ion Cyclotron (IC H&CD), Electron Cyclotron (EC H&CD) and Neutral Beam (NB H&CD).

Diagnostics and CODAC make up for the remaining cost of the construction of the ITER system. Diagnostics exist to monitor both the equipment in ITER and the state of the plasma reaction. CODAC stands for "command, control, data acquisition, and communication". It provides control over all different aspects of ITER (fuelling, cooling, vacuum, waste, etc.). This system also exists to protect the facility and personnel if there are any system failures. It also helps keep the plasma within operating conditions.

Energy Production

Until commercial fusion plants are produced, it is unknown how much energy they will produce. However, current estimates place the amount of energy generated by fusion reactors at 1-2 GW. In comparison, the output of the average fission plant is 1GW. The current 1,024 coal plants in the US could potentially be replaced by 139-278 fusion plants, if those fusion plants produced 1-2 GW as predicted. The current 3,007 petroleum plants could be replaced by 23-46 fusion plants, theoretically. The current total energy consumption of the US is 639,429 MW, provided by 9,351 power plants of various types. Theoretically, these could be replaced by only 320-640 fusion plants.

Commercial Feasibility

Fusion power currently has many obstacles to overcome before it can become a feasible source of power. The main problems that currently impede fusion power include issues with magnetic confinement, inertial confinement, commercial feasibility and other yet to be explored issues.

One problem that has not yet been solved is the problem of breakeven. Breakeven is the point at which a fusion reactor generates equal power to that it is consuming. The problem of how to achieve breakeven spreads across different parts of a fusion generator.

One issue that must be dealt with is the problem of scaling. Scaling refers to being able to calculate how to take a smaller fusion reactor, and extrapolate data from it that will allow larger generators to be designed successfully. Heating is another issue. Until the plasma reaches a heat level of approximately 100 million degrees C, there will not be enough energy to force the particles in the plasma to collide and generate the fusion reaction. Foreign matter in the plasma is another problem needing to be solved. Foreign matter in the plasma can make the plasma cool off faster than expected, or can cause instability in the plasma. Plasma stability is also an issue. Finding a shape for the plasma that uses less energy to contain means smaller, cheaper reactors can be built.

Even if breakeven is achieved, there are still engineering problems that must be overcome before fusion power can be used economically. For example, there are concerns of how to take a tokamak and scale it to the level that would be needed to produce a viable commercial power plant. Currently, scaling a tokamak to such a level would be a complex task, and would possibly make the power plant too uneconomical to build. Research as to how to more simply scale tokamaks is currently being researched.

One issue that is being worked on is that of magnetic confinement. Current magnets are large and require a high amount of electricity to contain the plasma. Superconducting magnets, of developed to operate at high temperatures, would allow the same amount of magnetic confinement using less space and electricity. Another issue is that of having neutral beams powerful and efficient enough to raise the plasma temperature as needed. This area is currently under research. Refueling is another issue that has not been solved. So far, fuel has only been introduced in small amounts at a time, so refueling has not yet become an issue that needs to be dealt with. In a commercial fusion reactor, however, methods for constantly refueling the fusion reactor must be developed. There are many different techniques currently under research to do this, including rotating centrifuges and pellet injectors. The issue as to what materials to build a fusion reactor out of is also an issue. Currently, the damage from radiation would cause a fusion reactor to become unstable after 10 years. Alternative building materials and modular replacements are currently under research. The issue of waste disposal is also an issue. Although the fusion reaction itself produces no pollution, the material that houses the fusion reaction will slowly grow radioactive over time and disposal would be required. However, the radioactive waste from fusion reactors is approximately a tenth of that of fission reactors.

Commercial feasibility must also be reached before fusion reactors are available as a viable option for power. In addition to all the issues above, a fusion reactor must also be able to compete economically with existing sources of power, and gain public acceptance as a viable, safe alternative to existing power sources. The issue of commercial feasibility is secondary to that of the technical feasibility currently, as there is no reason to worry about commercial feasibility if the technical issues have not been solved.

Chapter 5

Energy Policy

Proposed Energy Policy

The Department of Energy is engaged in a variety of projects to solve our upcoming energy crisis and the growing concern for global warming, as well as other environmental issues. One such initiative is the Clean Coal projects. The main focus of Clean Coal is to develop a new system for coal power. This is called the Integrated Gasification Combined Cycle (IGCC). The main objective of the IGCC is to greatly reduce the emissions of coal plants. The secondary objective is to increase power plant efficiency so that our coal supply will last longer. The US DOE is also looking at nuclear fission and fusion. Nuclear power theoretically has near zero emission power production. The main objective of Nuclear power is to safely provide large quantities of clean power. Another notable project that the DOE is researching, as well as the automotive industry, are fuel cells. Most likely, the fuel cells shall be powered by methanol, at least at first. Fuel cells have the promise of providing large sums of efficient and portable energy, which is safe for the environment.

Unfortunately, many aspects of these technologies is still on the drawing board for one reason or another. The IGCC cannot achieve the thermal efficiencies that research indicates are feasible. There is not enough Uranium 238 to power nuclear fission plants (and it takes too long to harvest for feasibility) and despite the large sums of energy that go into and come out of fusion reactors, the energy output almost breaks even with the energy input. Therefore, nuclear fusion has not reached the operational efficiency that is required for it to be relied upon for significant commercial power generation. Fuel cells are also still in the developmental stages, although their commercial implementation is closer at hand than the other two (ten years for fuel cells as opposed to the fifteen to twenty years before the IGCC system can operate at the level its supporting theory and research boast.

There are two threats generated by currently implemented methods of energy production. One threat is that we shall expend our supply of fuel and plunge ourselves back into a low level of technology, out of necessity. The other threat is that we shall make our world unlivable for generations to come because of the lack of environmental friendliness of our methods of energy production. In both cases, the fuels are the source of the problem. Current fuels are in limited supply and produce high levels of emissions. What can be done about this? Clearly, we should change the fuel that we use and, thus, our systems as well. This will be a long and arduous task and so it must be gradual.

The first step to gain more time is by replacing inefficient and/or dirty power plants with clearer, more efficient ones. That is, replace the oil-fired and coal-fired plants with coal gasification plants. Since both coal- and oil-fired plants use a steam turbine, the changeover will be slightly cheaper since the steam turbine is also used for part of the combined cycle in coal gasification plants. This will allow us to lower the increasing rate that emissions are pumped into the air.

We must also redouble our efforts in other aspects. Devising methods to conserve current fuels, finding alternative fuels that do not depend on rapidly depleting fossil fuels such as methanol and water based hydrogen fuel, and adapting them for multiple roles are just a few of the larger issues. Hydrogen can be used by fuel cells and nuclear fission/fusion to operate. Methanol can only be used with certain types of fuel cells but is easier to manage. Transportation is a field that could really benefit from these new technologies. The automotive industry is one of the firsts to incorporate fuel cells, though adaptations could later be made for the aircraft industry and the military, which are still using petroleum-based fuels.

Although natural gas-fired plants are much cleaner than coal- or oil-fired plants, they have roughly the same thermal efficiency. Another significant point about natural gas is that it is the most limited fossil fuel, in terms of supply. At our current rate of consumption, there is a 20-year supply of natural gas. Some critics suggest that the energy industry should convert to 100% natural gas. Natural gas accounts for, approximately one quarter of the power in the United States. If we changeover to natural gas, the supply will last one fourth as long as it would at our current rate of consumption. That means that we have a five-year supply of natural gas after we convert all of our power plants to natural gas (which will also take about five years). Natural gas is very critical to energy policy, but only in the short term. It is clean and not incredibly inefficient, but due to its limited supply it can only be used to transition from coal and oil power to an energy source that is cleaner and more efficient.

Table #5: Natural Gas Prod., Im-/Ex-ports, & Consump., 1949-2001 (10^6 ft^3)

Year	Dry Gas Production	Imports	Exports	Consumption
1949	5,195,404	0	20,054	4,971,152
1950	6,022,198	0	25,727	5,766,542
1951	7,164,959	0	24,163	6,810,162
1952	7,694,299	7,807	27,456	7,294,320
1953	8,056,848	9,225	28,322	7,639,270
1954	8,388,198	6,847	28,726	8,048,504
1955	9,028,665	10,888	31,029	8,693,657
1956	9,663,910	10,380	35,963	9,288,865
1957	10,246,622	37,941	41,655	9,846,139
1958	10,572,208	135,797	38,719	10,302,608
1959	11,547,658	133,990	18,413	11,321,181
1960	12,228,148	155,646	11,332	11,966,537
1961	12,661,579	218,860	10,747	12,489,268
1962	13,253,006	401,534	15,814	13,266,513
1963	14,076,412	406,204	16,957	13,970,229
1964	14,824,027	443,326	19,603	14,813,808
1965	15,286,280	456,394	26,132	15,279,716
1966	16,467,320	479,780	24,639	16,452,403
1967	17,386,791	564,226	81,614	17,388,360
1968	18,494,523	651,885	93,745	18,632,062
1969	19,831,680	726,951	51,304	20,056,240
1970	21,014,229	820,780	69,813	21,139,386
1971	21,609,885	934,548	80,212	21,793,454
1972	21,623,705	1,019,496	78,013	22,101,451
1973	21,730,998	1,032,901	77,169	22,049,363
1974	20,713,032	959,284	76,789	21,223,133
1975	19,236,379	953,008	72,675	19,537,593
1976	19,098,352	963,768	64,711	19,946,496
1977	19,162,900	1,011,001	55,626	19,520,581
1978	19,121,903	965,545	52,532	19,627,478
1979	19,663,415	1,253,383	55,673	20,240,761
1980	19,403,119	984,767	48,731	19,877,293
1981	19,181,261	903,949	59,372	19,403,858
1982	17,820,063	933,336	51,728	18,001,055
1983	16,094,461	918,407	54,638	16,834,912
1984	17,466,472	843,060	54,753	17,950,527
1985	16,453,857	949,715	55,268	17,280,943
1986	16,059,030	750,449	61,271	16,221,296
1987	16,620,581	992,532	54,020	17,210,809
1988	17,102,621	1,293,812	73,638	18,029,585
1989	17,310,645	1,381,520	106,871	19,118,997
1990	17,809,674	1,532,259	85,565	19,162,713
1991	17,697,802	1,773,313	129,244	19,562,067
1992	17,839,903	2,137,504	216,282	20,228,084
1993	18,095,460	2,350,115	140,183	20,789,509
1994	18,821,025	2,623,839	161,738	21,246,717
1995	18,598,679	2,841,048	154,119	22,206,417
1996	18,854,063	2,937,413	153,393	22,608,502
1997	18,902,334	2,994,173	157,006	22,736,203
1998	19,023,550	3,152,058	159,007	22,244,539
1999	18,832,234	3,585,505	163,415	22,403,380
2000	18,986,745	3,781,603	243,716	23,455,305
2001[P]	19,355,370	4,028,904	394,248	22,635,322

Of all fossil fuels, we rely on natural gas the least. Natural gas is the cleanest fossil fuel and is also in the shortest supply. Currently, natural gas-based power and heat plants account for 23% of the energy in the U.S. As we can see from the table to the left, we have a strong natural gas industry, domestically. Despite the fact that we imported over four trillion cubic feet of natural gas (under standard temperature and pressure) in the year 2001, we produced almost five times that amount of dry gas that year. Despite a strong natural gas industry and an abundance of importing, the world's supply of natural gas is limited (between twenty and thirty years, at our current rate of consumption). The efficiency of natural gas-based power plants is comparable to those of oil- and coal-fired power plants (30% to 35% thermal efficiency), but the emissions from natural gas-fired power plants are significantly lower. Some suggest that the energy industry should generate all electricity and heat from natural gas. This is unwise for two main reasons. We will exhaust our supply of natural gas in less than one quarter of the time that it would take us at our current rate of consumption. That is, if we convert to 100% natural gas-derived energy, we will exhaust our supply of natural gas between five and seven years. This is not to mention the five years that it will take to convert the other power plants to accept natural gas as a fuel instead of coal or oil.

Once the coal- and oil-fired plants have been converted to coal gasification plants, the natural gas plants should be converted, as well. Even though gasification plants are not as thermally efficient as theory indicates, they can be at least 15% more efficient than any of the fossil fuel-fired plants. Furthermore, natural gas is not as plentiful as coal. Once coal gasification plants are dominant in power generation, large scale power plants based on fuel cells may be feasible and should be investigated. Also, methods for time efficient methods of harvesting Uranium 238 for nuclear fission and/or Thorium for nuclear fusion should be investigated and implemented. There will not be very many nuclear power plants in the U.S. compared the number of coal gasification plants because of the lack of fuel and the problems with radioactive waste disposal, but nuclear power is near zero emissions. This way, we have decreased our dependence on foreign fossil fuel imports. We have placed greater reliance on a fossil fuel that can be mined and refined in great quantity, domestically and we have devised a new, cleaner, more efficient method of generating power with this fuel. We will also have made major breakthroughs in currently emerging technologies and implemented them to our advantage. At the least, we have bought ourselves one hundred to one hundred and fifty years before we have need to worry again. This is not an excuse to be lax, however. There must be clean up operations for the atmosphere and new methods of power generation should be designed for current fuels, as well as discoveries of new fuels be made.

Aside from the deficiencies and complications of fossil fuel use, there is still much drive into the development of alternate energy solutions. Technologically advanced nations are especially dependant on energy. As technologies continue to advance and more countries around the world develop and adopt these technologies, the demand for energy is constant and continuously growing. Finding alternate fuel sources and energy systems can be quite profitable. However, the longer it takes for new technologies to become available, the less of an impact they will make, and more effort will be required to implement them.

If fuel cells are to ever overcome all the deficiencies of fossil fuels, they must operate on primarily water-based hydrogen. Other technologies such as pebble bed nuclear reactor, coal gasification based power plants, and natural energy sources can be developed to aid in energy supply and hydrogen fuel production. Those technologies are also in need of development though. Hydrogen storage is especially in need of attention. Methanol would be just as suitable for a solution.

The transition process and its funding both need to be carefully planned out. Securing funding will be the most important step since "it makes the world go around". Funding can probably be raised through slightly increasing taxes on fuels and energy systems that operate on or with the flaws that are trying to be eliminated. Raising tax prices will promote alternative energy solutions. Larger organizations should be charged more with since they have more funds, need more encouragement, and can do more to change energy infrastructures. A new energy standard should be set, and the extra cost they pay will be based on how far they exceed the standards. These include pollution and efficiency levels, as well as whether they are produced domestically or not. This funding must be dedicated only to the promotion of the energy solutions that address problems or aid the transition from current energy systems. Since funding will be directed to lowering prices of new alternative energy systems, consumers can cut more of their losses by switching over.

Time is something money can not purchase. Transition periods and goals must be set as well. Spending the money taxed from one or two energy systems to fund tens to potentially hundreds of competing energy proposals and variations of their technologies would most likely end in failure. Many of the most promising technologies will still take a lot more time to develop. Instead of pursuing the best know solution, funding should be used primarily on the easiest system to implement that has the most benefits. A smaller amount of money can be reserved for development. Transition periods should be long enough to allow the parties who adopted new technologies to recover from losses and make their investments worthwhile. On the other hand they need to be short enough so development does not stall.

Due to the urgency and political controversies of depleting petroleum fuels, the first transition should probably be to coal gasification systems. Not only is coal abundant in the United States, the new gassification technologies make them a lot cleaner to use. They are also more efficient, so they will last longer than and delay the exhaustion of supplies. For non stationary energy requirements, burning petroleum should no longer be considered. Fuel cells must be encouraged regardless of the fuel they operate on. Their scalability, higher efficiency and non burning energy generation process might still need minor development, but their benefits are too promising to ignore.

Conclusion

The deficiencies of modern fuels and energy systems have already inspired the research and development of a variety of energy technologies. Large organizations and governments have already invested in these technologies. Some technologies are already capable of starting to be implemented. Companies and investors have spent a great deal of time and effort developing these technologies. Before they start spending more on promoting their product, they must make sure there is a demand for it.

It is an unavoidable fact that fossil fuel deposits will one day be depleted. When that day comes, it is imperative that society has not become entirely dependant on a nonrenewable resource. Currently utilized nuclear energy technology is considered too hazardous and risky to depend on entirely. These factors guarantee the demand for a new source of energy.

Research and development of such technologies are based on three main driving aspects. Geopolitical, economic, and most importantly environmental situations would all benefit from the transition to fuel cells as the staple energy system. Many issues will be solved when new energy system and fuel sources are discovered and utilized. Several of those issues are in dire need of attention, however their solution needs to be practical. Considering the interests of investors, the main objective behind research is to profit. Exposure and market size are two of the most critical factors in determining the success of a product.

Once new energy technologies are applied mainstream, they will not only benefit the environment, but the economy as well. The wide range of applications that they can be used for makes them very competitive. Coal gasification can be used to provide large quantities of energy, and be sustained by currently existing infrastructure. They are a cleaner technology, and can be used to manufacture hydrogen. The innate versatility and flexibility of the fuel cell concept will create many new and large-scale markets. Entirely new industries can be developed based on fuel cells and their supporting technologies.

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