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# TECHNOLOGY ASSESSMENT – FUSION

An Interactive Qualifying Project Report

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# Abstract

The goal of this project is to assess a methodology used in evaluating the results of a series of breakthrough surveys in the field of technology assessment. The objective of these surveys was to gather subjective information on future technologies. This was accomplished by analyzing data from past surveys on a series of topics, specifically for this project, fusion power. Survey data comparing our research, which we titled "Short Term Immersion", were statistically analyzed for correspondence. We will look for a connection between these sets of data, and ultimately attempt to validate the Breakthrough survey's methodological protocol which reports subjective analysis. By analyzing these relationships we hope to demonstrate the degree to which similar conclusions can be reached using Delphi oriented methods. In addition, we will propose several suggestions for improving the Breakthrough survey and ideas for future project groups interested in this subject.

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# 1. Introduction

Worcester Polytechnic Institute's Social Science and Policy Studies department has had a long-standing interest in the sociology of science and technology, and specifically in social implications research, sometimes called "technology assessment." Many IQP teams have done work on the topic of technology assessment, either in the technology forecasting or social implications part of such studies, and several recent projects have focused on a tool known as the Breakthrough survey to study the forecasting stage of a technology assessment directly. There are several methodological issues present in administering a Delphi study and analyzing its results. The primary focus of these projects is on assessment, and their collective goal is to evaluate assessment methodologies. This project is an extension of previous work which studied the validity of assessment methodologies through the use of the Breakthrough survey and the underlying Delphi technique. The survey includes topics related to the future of technological advancement; examples include the possibilities of breakthroughs in space drives, life support systems, and fusion power. The focus of this project is to analyze the assessment methodology present in a specific section of the Breakthrough survey, which discusses the possibility of fusion power as a future energy source.

It is a common goal among many in the scientific community to consider the possibilities of newer and better sources of energy. Most of the world's energy production currently relies on sources such as fossil fuels and nuclear fission which are, arguably, economically and environmentally unsound, or on sources such as solar and wind energy which are clean but produce comparatively little energy. Because of these problems and their social impacts, it is always important to search for, in some sense, a “better” source of energy. Nuclear fusion power theoretically has strong advantages and few disadvantages; it has the potential to produce a comparatively large amount of energy while being significantly cleaner and safer than current nuclear fission reactors. Additionally, when considering the future of space travel it becomes necessary to envision a relatively safe and effective energy source such as fusion power. For these reasons, it is important to have a method of judging the feasibility and significance of scientific breakthroughs such as fusion power, as well as estimating the time frame in which they might become available. It is also important that the method be effective in comparing this possibility to other related breakthroughs necessary to produce a new energy system or economy.

WPI’s “Breakthrough” surveys use a modified Delphi method to poll experts on the possibilities of scientific breakthroughs. The Delphi method attempts to produce a consensus from a group of people on a certain topic or problem by surveying those individuals, or by having them meet as a group. The concept was created by the RAND Corporation in the 1950s as a way for the military to forecast Soviet strategies in the Cold War. The process has changed over the years, with the most common form being the conventional Delphi survey. In this form, a small monitoring team creates a questionnaire which is sent to a correspondent team who answers it. The monitoring team first compiles the data collected from the correspondent team, and then sends out a follow-up questionnaire to the correspondent team in an attempt to reach a consensus on the topic or problem under consideration. Normally, at least one follow-up questionnaire is presented to the respondents.

There are four distinct phases in the conventional Delphi method. The first involves the correspondent team viewing the questions, and contributing information that may be pertinent to the topic. In the second phase, the data collected is compiled to see if consensus was reached. If the results have a large deviation, a third phase involves the monitor team examining reasons why that happened, and trying to factor those reasons into the follow-up. In the last phase, the questionnaires are sent back with all previously collected data, and the process repeats.

There are some positive aspects of the Delphi method that make it popular, and easy to deploy. The small amount of time it takes to complete the whole process is one such benefit to using the Delphi method, since one only needs to write a survey, collect data from the results, and administer it again. Also, the Delphi method is completely subjective, and as such, does not require resources to run tests or a great deal of money spent on empirical research. The Breakthrough survey modifies the Delphi method but operates on the same general principle; the current survey contains a section on fusion power whose responses we will consider, along with data from our own research.

For the past few years, WPI has been surveying panels using the Breakthrough survey as a part of projects, the goals of which include technology assessment. The Breakthrough survey has been given to several different groups. The most notable of these groups was a panel of Fellows from the NASA Institute of Advanced Concepts (NIAC). This group consists of individuals who are considered experts in the field of aerospace breakthroughs. The assumption is that, since the Fellows are knowledgeable about space technologies, their opinions should be relevant and helpful. Other groups taking the survey included WPI alumni interested in the topics, and current WPI students who had some connection with the aerospace program through their Interactive Qualifying Project (IQP) or major.

In this investigation of fusion power, one of the subjects undergoing assessment through the Breakthrough survey, we intend to review literature on the subject and to rate articles based on the same scale as the breakthrough survey; i.e. for each article we review, we will attempt to infer what the author may have responded if he had been given the Breakthrough survey. In addition, we also think it will be important to take into account the bias and knowledge of the author of each article. Our ultimate goal is to compare the raw data from the fusion portion of the Breakthrough study with the data we collect from the literature and attempt to draw a mathematical connection as well as a subjective connection between these two sets of data. We have also added a third level of comparison that represents views by individuals we designate as futurists and popular press. The ultimate goal of this project, as well as of other related projects, is to study and assess the methodology used in the Breakthrough surveys. We are hopeful that our research will contribute to the improvement of a portion of the Breakthrough survey for future studies.

# 2. Literature Review

The following review represents our documentation of representative literature relevant to this project in the areas of fusion, problems with fusion, environmental aspects of fusion and current energy sources. In addition, opinions from futurists and popular press as well as a chronology are included highlighting key events in the history of the development of fusion.

## *2.1 What is Fusion?*

A fusion reaction is the combining, or fusing, of two hydrogen atoms together to form a helium atom, and in this fusion process some of the hydrogen mass is converted into usable energy. (U.S. Department of Energy)

Fusion reactions are possible on the sun because hydrogen has the ability to change from gas to plasma under extremely high temperatures. Normally, positively charged hydrogen nuclei simply repel each other, but as temperature is increased, the nuclei move faster and collide, overcoming their normal repulsion. When the nuclei fuse, energy is released. In the sun, the fusion process is self sustaining and can be partially attributed to the massive gravitational forces that act on the sun. (World Nuclear Association, June 2005)

Since we cannot emulate all of the conditions found on the sun, we need to go about the process in a different way. The first is finding suitable materials to make the fusion reaction with. The easiest and most promising fusion reaction to make involves combining deuterium and tritium together. These two hydrogen isotopes are also easy to find, as deuterium is plentiful in water, and tritium can be created by combining a fusion neutron with the common metal lithium. By using these two hydrogen isotopes, it is hoped that fusion will be an energy source that never runs dry. (U.S. Department of Energy)

There are two major problems with creating fusion reactions here on Earth: A fusion reactor must heat the deuterium and tritium to temperatures of 100 million degrees Celsius and confine the reaction long enough so that the energy output is greater than the original input. To combat these problems, the magnetic confinement approach was developed. (World Nuclear Association, June 2005) Since this is the most promising and most technologically feasible method of creating fusion power, any mention of fusion power in this IQP will refer to the magnetic confinement approach.

In the magnetic confinement approach, hundreds of cubic meters of deuterium-tritium plasma are confined in a magnetic field (normally, a toroidal-shaped reactor called a tokamak), at a few atmospheres of pressure and heated to the point where a fusion reaction can occur. (World Nuclear Association, June 2005) Due to the fact that energy can be lost in magnetic confinement due to conduction and radiation, the plasma must be continually refueled and heated to make up for the loss of energy. In the right conditions, a steady state should be achieved. (ITER, October 2004) The reason magnetic fields are used in this time of configuration is so the plasma can be freely suspended, as the electrical charges in the plasma will guide it through the magnetic field lines in the reactor. If plasma was to touch the reactor's wall, the plasma's heat would dissipate extremely quickly and slow down or suspend the reaction. The magnetic fields attempt to prevent this contact from ever happening. (World Nuclear Association, June 2005)

### *2.2 Major Problems with Fusion as a Feasible Power Source*

There are several problems that need to be solved before fusion power can become a viable energy source. Plasma heating is one issue that is essential to the realization of fusion power, as different types of heating will influence the plasma's state and how it reacts inside a tokamak. It is theorized that injecting neutral particle beams into a fusion reactor will heat the system, and doing so will cause the heat to drive the plasma in a toroidal current, minimizing energy loss and making a steady state. This problem is something that will be investigated on the International Thermonuclear Experimental Reactor (ITER) project. (ITER, January 2005)

Fuel leakage is another problem. Despite the best efforts so far to contain it, tritium has the ability to leak out of a tokamak. To prevent leakage into the environment around the reactor, systems are needed to confine tritium leakage and extract it should a cleanup be necessary. While this technology is significantly advanced, nothing has been created to deal with the amount of tritium that could possibly leak out of a fusion reactor. Again, this is something that will be looked into on the ITER project. (ITER, January 2005)

The superconducting magnets needed for a fusion reactor to function properly lead to yet another major hurdle in making fusion power feasible. Superconducting magnets are extremely expensive instruments, and need to work at extremely cold temperatures. Since a fusion reaction is an extremely hot process, it can ruin the magnets with little effort. Heavy insulation needs to be put into place to protect the magnets from the heat of a fusion reaction and from plasma radiation. Currently, the ITER Large Project R&D team is working on two ways of improving the magnets, but it is unclear whether or not the projects will work, or when they will be implemented. (ITER, January 2005)

### *2.3 Environmental Issues Regarding Fusion and Current Energy Sources*

#### 2.3.1. Fusion

Fusion has proven potential to be valuable in the search towards more cost effective and environmentally safe energy sources. Major research has been done to look into the environmental safety of fusion reactors. In 1995 a Safe and Environmental Assessment of Fusion Power (SEAFP) team reached the conclusion that fusion has inherent safety qualities. A fusion reactor has no chain reactions occurring. This allows the operators to constantly maintain control over the reaction. The absence of a chain reaction in the fusion process greatly decreases the chance of a meltdown occurring in the reaction chamber. Fusion also produces no radioactive byproducts with excessively long half lives. According to the SEAFP conclusions, the worst possible accident that could occur at a fusion power station would not breach the confinement barrier around the plant. Any radioactive releases from this accident also could not approach levels that would require the evacuation of the local communities (European Commission, 2).

The waste materials of a fusion power station have a very low radio-toxicity and thus will decay very rapidly. The residual activity of the waste will be equivalent to that of the coal ash created by a coal burning plant in under a hundred years. The waste generated by fusion plants will not be enough to burden future generations. Unlike fission waste products, fusion waste products would not need to be isolated from the rest of the environment for long periods of time. The radioactive fuel component used in fusion reactions, Tritium, is both created and consumed on-site; eliminating transportation of a dangerous and radioactive fuel. Fusion reactions also do not produce $CO_2$ or any other climate altering byproducts (European Commission, 2). The absence of fusion reactions adding to global climate change is a major improvement over other modern energy sources.

### 2.3.2. Fission

One of the currently used sources of energy production is fission power. Fission power, like fusion, is a nuclear reaction. Fission shares many of the benefits of fusion but it has disadvantages that fusion does not share. Fission reactions, like fusion, do not produce $CO_2$ or any other climate altering byproducts (Energy Information Administration). The absence of $CO_2$ production means that fission reactions do not contribute to global climate change. Fission reactors produce multiple waste products including solid waste, spent fuel, and process chemical, steam and heated cooling water (Energy Information Administration). All of these waste products must be disposed of in a controlled manner as they all have a high value of radio-toxicity.

Coolant water discharge is heavily regulated by the United States government. Coolant water may affect the temperature conditions of any body of water it is released into which could have a drastic effect on the ecology of that body of water. During a fission reaction nothing is burned in the same manner of fossil fuel plants, and because of this the volume of the fuel used is only changed a minute amount. This spent fuel must be disposed, but because of the reaction it is highly radioactive. This disposition of the spent fuel usually results in burial of the radioactive materials (Energy Information Administration). Spent nuclear fuel rods contain uranium and plutonium, and remain dangerously radioactive for tens of thousands of years. Other waste produced by fission plants is highly radioactive and remains dangerous for tens of thousands of years as well. This waste requires isolation from the environment for the entire duration of the period of radioactivity. The processing of uranium ore for use in a fission reactor creates a sand-like residue known as uranium mill tailings. These tailings have a low amount of radio-toxicity, but large volumes of them pose a hazard through radon emissions or groundwater contamination (National Council for Science and the Environment, July 2001). Unlike fusion reactors, fission reactors require a large amount of fuel to be in the reaction chamber at any given period of time. In the plant operators lose control of the reaction, they would not be able to easily extinguish it and a meltdown would occur. It was a reactor meltdown that caused the destruction of the Chernobyl Plant in the Ukraine. The meltdown in the fourth reactor at the Chernobyl Plant caused a massive explosion and much of the surrounding area from Italy to Sweden became contaminated with vast amounts of radioactive fallout.

### 2.3.3. Fossil Fuels

The burning of fossil fuels, such as coal and natural gas, is the primary source of energy at this point in time. The burning of fossil fuels has many adverse impacts on the environment. When a fossil fuel is burned it releases $CO_2$ into the atmosphere. This $CO_2$ is the major factor in global climate change. The amount of $CO_2$ released into the atmosphere by the burning of fossil fuels creates an incremental climate change risk that is potentially catastrophic (Makhijani, February 1997). Fossil fuel power plant emissions include several other pollutants that are linked to environmental problems. Sulfur dioxide is one of the pollutants emitted by fossil fuel burning plants. The sulfur dioxide reacts with water vapor in the air to form sulfuric acid. This sulfuric acid increases the acidity of precipitation and becomes, what is commonly referred to as, acid rain (Carlin, September 2002). The burning of coal creates coal ash. Coal ash is made up of heavy metals such as arsenic, boron and lead. Coal ash is released through smoke stacks during the burning of coal, and enters into the atmosphere. Due to the make up of coal ash it can be highly dangerous to both the environment and human population. Coal ash is so minute in size that it can easily enter the deepest part of the human lung. Once inside the human lungs it can cause cancer because of presence of the heavy metals (American Coal Ash Association). Smog is also generated through the emissions of fossil fuels and reactions with sunlight.

### 2.3.4. Hydroelectric Power

Hydroelectric power, though generally considered a clean source of energy, also has it impacts on the environment. Hydroelectric plants are created by building a dam on a river. The water at the highest point will flow through the dam and turn a turbine to generate electricity. Hydroelectric power generators emit a very miniscule level of greenhouse gasses when compared to the amount a fossil fuel plant emits. The largest environmental impacts of hydroelectric power are due to the creation of the dams. Dams can also block the passage of fish moving to spawning grounds or to the ocean. The degradation of aquatic and streamside habitats can occur from river channels drying out, because of the water flow being diverted. The amount of dissolved oxygen in a body of water can be lowered because of the presence of a hydroelectric power plant, impacting the quality of the water. The lack of flowing water can cause the water to become stagnant, and create a situation for undesirable growth of insects, aquatic weeds and algae. Reservoirs can also trap large amounts of sediment and nutrients (Environmental Literacy Council, April 2007).

### 2.3.5. Wind Power

Wind power is by far the cleanest of the alternative sources of energy, but it too has a small number of environmental issues. Wind power produces no air or water pollution and poses no threats to the public. In certain areas it may be necessary to cut down trees and create new roads to put wind turbines in place. This can be seen as a negative impact on the environment by some, but wind turbines can just as easily be placed in open fields. Wind turbines also use little land, and farmers can even plant or allow grazing right up to the base of the turbines.

The largest environmental impact that wind turbines have is bird deaths. If turbines are placed in migratory paths this may cause large numbers of deaths in migrating bird populations. Certain studies have shown that reducing the number of perches on and around the turbines will decrease the amount of accidental bird deaths. Techniques for reducing the number of bird deaths are currently in development. A Danish company has decided to replace 750 smaller turbines with 100 larger ones in hopes to reduce the number of injuries (Union of Concerned Scientists, January 1999). Bat populations are also in danger from wind turbines. A study at the Mountaineer, West Virginia turbine site has shown that as an extremely conservative estimate of 48 bats per turbine per year, that the completion of all proposed turbines in this area could kill 29,000 bats annually in this one small area alone. Bat populations are essential to the balance of nature and the continued destruction of bat populations could have drastic effects on the surrounding area (Bat Conservation International, January 2005).

### *2.4 Fusion Chronology*

1932 - "Sir Mark Oliphant discovers He3+, T and D–D reaction." (Australian Academy of Science, 2007)

1939 - "Hans Bethe described a quantitative theory explaining the fusion generation of energy in the stars (including our sun). The results of his calculations presented in a paper entitled 'Energy Production in Stars.'" (European Commission, 1)

1940s – 1950s - "The original large-scale experimental fusion device on which British physicists worked during the 1940s and 50s was housed in a hangar at Harwell. The device called ZETA - Zero Energy Toroidal Assembly was at first shrouded in secrecy but with the temporary thaw in the Cold War created in the late 1950s." (EURATOM/UKAEA Fusion Association)

1951 - "Scientists in Argentina claimed to have controlled the release of nuclear fusion energy. These claims proved to be false but they acted as a spur to many other research groups." (European Commission, 1)

1958 - "The undeniable potential benefits of practical fusion energy led to an increasing call for international cooperation. American, British, and Soviet fusion programs were strictly classified until 1958, when most of their research programs were made public at the Second Geneva Conference on the Peaceful Uses of Atomic Energy." (Britannica, May 2007)

Early 1960s - "Work on the other major approach to fusion energy, inertial confinement fusion (ICF), was begun." (Britannica, May 2007)

1968 - "Results from the Russians Tamm and Sakharov using a new type of magnetic confinement device called a tokamak caused a major stir. Their experiment ran at temperatures ten times higher (10 million degrees centigrade) than anywhere else in the world with excellent confinement results." (European Commission, 1)

1983 - JET (Joint European Torus) fusion experiment construction completed on time and on budget, and the JET's first plasma (19 kA) achieved. (EFDA-JET)

1985 - "The idea for ITER originated from the Geneva superpower summit in November 1985 where Premier Gorbachov, following discussions with President Mitterand of France, proposed to President Reagan that an international project be set up to develop fusion energy for peaceful purposes. The ITER-project subsequently began as a collaboration between the former Soviet Union, the USA, the European Union (via Euratom) and Japan." (ITER, 1)

1989 - Chemists B. Stanley Pons and Martin Fleischmann announce to the world that they had built a table-top fusion percolator made up of two electrodes and a slug of heavy water. However, Pons and Fleischmann were vague about how their cold fusion reactor worked, and other scientists failed to duplicate the pair's results. (TIME, 1999)

1991 - "JET produced for the first time in the world, a significant amount of power (1.7MW or 1.7 million watts) from controlled nuclear fusion reactions." (European Commission, 1)

1993 - "The Tokamak Fusion Test Reactor (TFTR) device in Princeton produced 10 MW of power with a plasma fuelled by a 50/50 mix of deuterium and tritium." (European Commission, 1)

1997 - "JET established the current world record for fusion power producing 16 MW of power." (European Commission, 1)

2001 - “The ITER engineering design activities were successfully completed, and the final design report was made available to the ITER Parties.” (ITER, 1)

2006 - China's EAST test reactor is completed and achieves first plasma. The project is the first to use a new type of poloidial, superconducting magnet to sustain a fusion reaction. (PPPL, 2007)

## *2.5 Futurist and Popular Press Opinions on Fusion as an Energy Source*

### 2.5.1. Dr. Michio Kaku

In 1997, Dr. Michio Kaku, a theoretical physicist who has appeared on countless radio and popular television programs, wrote a book called *Visions: How Science will Revolutionize the 21st Century*. The book delves into theoretical science technologies (such as fusion power, gene manipulation, and computers that can think and learn), and predicts when the technology will come to fruition, as well as how feasible it is. In order to write the book, Kaku interviewed and spoke with over 80 scientists considered to be experts in their fields, ranging from Nobel Laureates in physics to professors of artificial intelligence and computer science at MIT and Yale. (Kaku, x)

On the topic of fusion as a viable energy source, Kaku believes that while fusion power has been “overhyped for years,” the fact that oil reserves are running out and energy demand is rising rapidly will lead to some form of inexhaustible power supply being created. (Kaku, 278) At the time the book was written, Kaku mentioned that physicists at the Princeton Physics Laboratory had created a rough estimate regarding future fusion breakthroughs. It stated

“By 2010: the creation of a 1000-megawatt fusion ITER plant

By 2025: demonstration of a fusion power plant

By 2035: the first commercial fusion power plant

By 2050: widespread use of commercial fusion plants"  (Kaku, 281)

Since the book was written, the ITER plant has run into delays and will not be completed until 2016.  This lead Kaku to later state in an email that "I think fusion is inevitable, but we can not be optimistic about its time table." (Stevens Institute of Technology, 2006)

### 2.5.2. Marvin Cetron and Owen Davies

The authors of Probable Tomorrows, Marvin Cetron and Owen Davies, are optimistic about the possibility of fusion power. In their article, "The Other Atomic Power," (Cetron, 168) they discuss the nature of fusion and its significance as an energy source. In addition to covering the principles needed to understand the reaction, the article discusses the potential for fusion to be much cleaner than current nuclear fission; while the waste products of fission are radioactive, the products of fusion are stable. The authors admit that radioactive waste materials are produced in a fusion reaction, but in much smaller quantities and only after the reactor has been worn out (Cetron, 169). The authors go on to discuss the possible methods for creating a laboratory-controlled fusion reaction, either through the use of a tokamak or inertial confinement of a small capsule.

The article also includes a discussion on the possibility of cold fusion. The original experiment by Dr. Stanley Pons and Martin Fleischmann in 1989 involved a pair of electrodes placed in a glass chamber filled with heavy water. After running a current between the electrodes, they found evidence of tritium and neutrons, suggestive of a fusion reaction, and speculated that deuterium atoms were undergoing fusion. Most scientists were not convinced, and subsequent attempts to recreate the results of the experiment were met with varying degrees of success; however, no experiment seemed to consistently show solid evidence of fusion. Since then, little research has been done in the field of cold fusion. Cetron and Davies are of the belief that even if cold fusion is a feasible chemical reaction, it does not carry much significance as a source of energy: "The chances that it would prove to be a practical new source of energy seem remote." (Cetron, 172)

In any case, the authors do remain positive about the prospect of "hot" nuclear fusion, discussing the American laser facility (which may contribute to research in inertial confinement fusion) and the ITER program. As the article was published in 1997, their predictions now seem a bit overly optimistic: "… by 2010, we will know far more about the practical use of fusion power. ITER will be up and running, and it will produce enough energy to form the heart of a proof-of-principle fusion power plant." (Cetron, 173) Current predictions estimate the ITER project to begin running around 2016. The authors also predict, "It will take several more decades to bring the first fusion power station on-line." In this sense, while they are optimistic about the technology and certain of its significance, the authors recognize that the technology may still be decades away.

### *2.6 Conclusion*

The information gathered in this literature review is intended to represent a background on fusion from the sources. It is this information that will be used in developing the quantification for Short-Term Immersion analysis in Chapter 5, which, in turn, informs the comparisons and conclusions in Chapters 6 and 7.

# 3. Methodology

### 3.1 Introduction

At least seven different IQP groups relating to the Breakthrough survey precede our work. The IQP titled "The Future of Space Exploration" by Berirmen, Zolek, Cakkol, Elko, and Saunders attempted to determine the future of space exploration, including whether there would be a second space race (Berirmen 2004). They focused on incremental advances, which led Professor Makarov, a professor from the Electrical and Computer Engineering department of Worcester Polytechnic Institute, to question why the possibilities of breakthroughs were not considered. In response, two groups were formed to use a Delphi study of experts and alumni to attempt to predict the possibilities of breakthroughs (Climis 2005).

Originally, one group was to focus on manned missions, and one group on unmanned missions, but they soon decided to pool their resources into one project. The ideas for the survey were taken from a number of sources, including a concurrent IQP investigating science fiction. There were two versions of the survey, a paper version and an on-line version. The original paper version lacked an option for "never"; this was subsequently included in the on-line version after finding survey takers often wrote "never" in for the time frame even though that was not one of the options.

After the original survey, outliers (people who had responded inconsistently with most of the group) were questioned, and three comments were recorded as a result. This step is an important step in the Delphi method, as described under the Delphi section in this chapter.

The first continuation group consisted of Patrone and Wilfong (Patrone 2005). They added to the alumni group and tied other loose ends in the original breakthroughs survey.

Later, DelSignore (DelSignore 2006) felt that the original premise of the breakthroughs survey would be better served by including a panel of the general science-educated public, especially science teachers. The reason for this was largely based on history; the Derek Price study of the telephone suggested that around the time of the invention of the telephone, the general public had a better idea of where this technology would lead than the experts.

At the same time, another team (Gillis 2006) consisting of Gillis, Stawasz, and Wu, added a panel of fellows from the NASA Institute for Advanced Concepts (NIAC). The most recently completed IQP involving the breakthroughs survey, written by Flaherty, Luca, and Monfreda, delivered additional surveys to more students and NIAC fellows, and carried out an analysis (Flaherty 2007).

These studies were carried out in order to determine what, if any, technologies pertaining to space related travel were perceived as viable by a notable group of experts in this field. These technologies were discussed to determine how a breakthrough in any of these fields would affect the aerospace industry as a whole. If any of these technologies were proven to be viable then it would have a great impact on the future of space travel, life support systems, and off planet colonization. Delphi studies help determine where the next breakthrough will be so that they can ensure technological growth and adequate future development.

The focus of the questionnaire was to gather the opinions of panelists on certain topics related to technological advancement. In addition, Flaherty et al. had the task of analyzing the panelists' cognitive preferences through what is known as the Myers-Briggs Type Indicators, or MBTI. They then attempted to draw a connection between these cognitive results and the optimism of the responses given to the questionnaire.

In terms of the MBTI, Flaherty et al. decided that among the four factors classified by the type indicator, the two that would be most useful in gauging optimism were Sensing/Intuition and Judging/Perceiving. The MBTI thereby grouped respondents into four categories: NP, NJ, SP, SJ - all four of the possible combinations. They conclude that of the four pairs, those people whose type was determined as NP would tend to be the most optimistic, and people labeled SJ would be least optimistic.

The group was unable to gather MBTI responses from most of the NIAC panel, and instead decided to consolidate the MBTI data from the alumni and students surveyed and compare to their collective responses. Under each of the four types, they tabulated the percentage of respondents who gave what they deemed an "optimistic" response to each of the questions.

Overall, the survey was given to three different groups. The major group, as mentioned above, was given to fellows of the NASA Institute of Advanced Concepts. This group contained individuals who were considered experts in the field of aerospace breakthroughs. It is assumed that since this group's job is to be knowledgeable of upcoming technologies by studying them extensively, their results would be extremely valid. The remaining two groups consisted of WPI alumni who were interested in the topic, and current WPI students who had some connection with the space IQP program through their project or major.

The survey was split into two sections. The first section consists of 21 questions relating to possible aerospace breakthroughs that may be completed in the next 25 to 50 years. Topics ranged from possible drives for space travel to technologies that would make space colonization a reality. When the survey was presented to the three groups, a paragraph of background information was presented, as well as mentioning the name of an author who may be recognized for their work on that topic of research. Below that was a place where they could rate (1 – 6) how significant it would be to make this technology a reality, and how likely it would be for the technology to become a feasible reality. There was also a section that asks when the person being surveyed what time frame they thought the technology would be achieved, be it early (Present-2020), middle (2020-2035), late (2035-2050), or never. A section was included in case any member had comments they would like to make in regards to their conclusions.

The second section proposed scenarios in which technologies found feasible by the first section were presented to the groups in the form of a timeline. The groups were then asked what the likelihood was of the timeline being realistic, and a comment section was included. The IQP group that created the scenarios determined that there may have been some problems with the descriptions, as the timelines were very unrealistic, and the technologies presented did not seem to connect to each other very well. It is also important to note that no WPI alumni responded to this portion of the survey.

### *3.2 Delphi Method*

The Delphi method consists of polling experts by mail or computer rather than interviewing a single expert or polling experts gathered together in the same place, followed by additional polling in an attempt to create a consensus. Polling individuals has the disadvantage of individual bias, and polling groups of people who are close enough to communicate instantaneously with each other may have disadvantageous "follow the leader" tendencies that make it difficult for an expert to change one's mind without losing respect from other experts (Dalkey 1969). The Delphi method aims to use the advantages of the collective knowledge of experts without the disadvantages listed above ("The Delphi Method"). The earliest uses of the Delphi method involved simulation gaming and forecasting, but since then topics "as wide ranging as the future of religion and the family to space exploration" have been investigated (Gordon 1994). Forecasting has had mixed (though impressive) results; a Delphi study undertaken in 1964 predicted accurately advances such as oral contraceptives and artificial organs, but it also predicted man would land on Mars by 2000 and that the population then would be less than 6 billion.

The basic rationale for the Delphi is that "two heads are better than one." (Dalkey 1969). Theoretically, if one collects all of the correct information from a certain number of people, one would get a sum of knowledge greater than or equal to the knowledge of any individual expert in the group. Unfortunately, one could say the same about a group's misinformation, demonstrating that a good method for pooling knowledge must minimize the collection of misinformation, and that some group methods are better than others. A series of experiments conducted at the RAND Corporation during 1968 (involving factual information such as asking for the number of telephones in Africa in 1965) suggest that the Delphi method is more accurate than face-to-face discussion that various correspondences can be made between variables such as round one's average error versus the dispersion of answers, and that combining individual self-ratings of competence yields a meaningful estimate of group accuracy. Thus the Delphi study has been shown in some cases (specifically, concerning almanac-type questions) to be reliable.

The Delphi method can be seen as an attempt to make the best use of "opinion", a type of information Dalkey suggests lies in a continuum between the highly verifiable "knowledge" and the evidence-lacking "speculation". Specifically, "opinion" can be seen as information with partial backing. With "opinion", many analysts decide to work with "knowledge" first and defer the analysis either to the "interpretation of results" step, or to the decision-maker.

The Delphi study has three features, the statistical group response, the iteration and controlled feedback, and the anonymity of response. Statistical group response refers to the ability to take averages of a spread of values to obtain values more likely to be correct. Dalkey shows that if there is a continuous field of possible answers in one dimension (say, the answers to the question, "how tall is the Eiffel Tower?"), then the median of the range is at least closer to the correct answer than half of the responses, and often significantly better. Being able to take statistics from groups sets the Delphi study apart from non-group methods such as polling individuals or conducting a literature review, but it is the controlled feedback and anonymity properties that set the Delphi method apart from other group methods. As stated above, ensuring anonymity has been shown to make answers more reliable. The iteration and controlled feedback process is used to ensure stability in the results. Ideally, the spreads of responses should converge to a consensus with each successive polling.

### *3.3 Project Goals*

The Delphi method has been assumed to be valid for the work of the previous breakthrough groups; the aim of this IQP is to compare the survey results for fusion reactor with an analysis based on the literature. For purposes of comparison, we have titled this review The Short Term Immersion method. This “method” (or more appropriately, this variable) was created by the authors in conjunction with Professor Campisano, Professor Wilkes, and the Space Drives IQP group consisting of Schneeloch and Cummings. The method was created to serve as a data point for comparing Delphi results to information gathered from comprehensive literature review.

The main technique behind the method is to have a small group conduct a short term intensive research into a topic. The group will read papers and articles about a specific topic to learn as much about it as possible. This immersion should last about 4 to 6 months. At the end of the immersion period the group should take the survey given to the Delphi respondents. With the information gathered from the immersion period the immersion group should be sufficiently knowledgeable to answer the survey.

To determine the effectiveness of the short term immersion method it is first necessary to have a group undergoing short term immersion answer the survey as well as to have surveys retrieved from the traditional breakthrough survey panel. Next, the data must be gathered from both groups and compared. If the data from the short term immersion group is similar to the data from the Delphi survey panels then it can be seen that the use of a short term immersion group instead of surveying a large panel of respondents may be a viable option. Of course it cannot be determined whether this is true from just one or two tests of the method, but it is the authors' hopes that more projects will follow after this one to determine the validity of the Short Term Immersion method.

There are a number of ways one could compare the knowledge of the literature obtained in Short Term Immersion with the survey data. First, one could perform an analysis by comparing a summary of the survey data with the literature information in a qualitative way. Second, one could come up with a more objective variable that can be compared with the survey data values themselves. The authors have decided on the more quantitative approach, which can be expanded into four steps:

1. Investigate the research.
2. Determine an objective, but qualitative, answer to the survey questions, using our research and logic as a basis.
3. Match the qualitative answer to some quantitative value, such as the scores resulting from taking the survey.
4. Compare our score with the survey data.

For example, let's consider the question, "Rate the significance of the development of the fusion reactor: highly significant, moderately significant, little significance." One would first research fusion reactors to come up with the knowledge necessary to answer the question. Then a qualitative assessment would be made, one that could, in theory, be proved or disproved. Let's say the assessment is "The development of the fusion reactor would be an enormous breakthrough that could provide environmentally safe and inexpensive power with low risk to people living in a community containing a fusion plant." (Terms such as "low risk" would need to be defined for more objectivity.) This statement would be supported by research, such as data stating showing the amount of energy produced by D-T fusion reactions.

Next, one must come up with a quantitative value that corresponds to the qualitative assessment. The easiest way to do this, and the one the authors have chosen, is to simply answer the survey questions. Finally, once a score is reached, one would then compare that score with the Delphi panel data. To match a small number of scores to an array of values, statistical means exist, which are described below under "Statistics".

There are at least three reasons why one should expect a spread in the survey results. First, a source for uncertainty lies in deciding whether the expansion of trade or of the use of space probes by the magnitude suggested is "highly significant", "moderately significant", or "of little significance". This can be called the "Fuzzy Definition Uncertainty". Unfortunately, one does not know whether previous survey-takers shared the meaning of terms such as "moderately significant." Even if two survey takers happened to share the same assessment, say "solar sails would do nothing more than allow easier communication throughout the solar system", one might judge that "of little significance" and another "moderately significant", due to the inherently fuzzy nature of these terms. However, while there is some uncertainty, among a group of people there will be many whose terms correspond to each other's, and the best the authors can do is to make sure their use of terms like "significant" corresponds to the group average and is stable.

A second source of uncertainty is due to the discrete nature of surveys. If it were possible to rate opinion on a continuous scale, and if a survey-taker were to decide "3.5" best fit his or her opinion, then he or she would be forced to decide on either "4" or "3", resulting in a discrepancy of 0.5. However, this source of uncertainty should not affect the average, and it would probably be masked by the Fuzzy Definition Uncertainty mentioned earlier.

Third, as mentioned above in the Delphi section, each person taking the survey has incomplete knowledge, so it is only by considering the whole of the responses that one should expect a more highly knowledgeable answer. One should expect a spread in opinion scores whenever the knowledge of the survey takers is incomplete.

### *3.4 Discussion of Statistical Methods*

There are two kinds of statistics needed: descriptive statistics, and correlative statistics. For our project measuring the correlation between the spread of data and our scores depends mostly on the descriptive statistics of the data because we have few scores.

To properly describe the results of surveying opinion on a scale from 1-6, it is important to remember there are four scales of measurement: nominal, ordinal, interval, and ratio (Stevens 1946). Nominal measurements are like football numbers; they have no meaning other than existing as a name. Ordinal measurements describe a definite order, but not a definite value, of the thing being measured. Interval scales are scales like the Fahrenheit and Celsius temperature scales; we can measure differences in temperature consistently, but we cannot add them or multiply them. Something 100 degrees Fahrenheit is not ten times hotter than something 10 degrees Fahrenheit. However, we can do such mathematical operations with measurements on the ratio scale. An example of the ratio scale would be degrees Kelvin, where 0 K = absolute zero. We can say that 100 K is ten times hotter than 10 K with certainty.

The survey data, which consist of the opinions of people matched up to numbers 1 through 6, is at least on an ordinal scale. For example, we can say (to the extent that the Fuzzy Definition Uncertainty is small) that a rating of 5 on the significance scale means the survey taker believes the technology is more significant than it would be for a 4. It is not clear whether the survey is on an interval scale. It is possible that for each score on the survey, there exists a corresponding opinion on some sort of "opinion number line" which is fairly definite.

In any case, there is no reason to believe that the difference between, say, 4 and 3 is equal to the difference between 2 and 1, where each number represents an opinion according to the survey key, even though clearly 4 – 3 = 2 – 1 for numbers on the number line. Thus, it is uncertain whether taking the mean, standard deviation, skewness, or any other statistical measure that depends on doing arithmetic on opinion scores is meaningful. (This idea is illustrated in the satirical paper, "On The Statistical Treatment of Football Numbers" (Lord 1953).)

However, some statisticians say that parametric tests (such as the mean, standard deviation, and skewness) do have a use on ordinal data. For example, Boneau states that "…parametric tests are useful whenever a measurement operation exists such that one of several possible numbers (scores) can be assigned unambiguously to an item of behavior without considering the relation of that item of behavior to other similar items, i.e., without ranking." (Boneau 1961). He states that if one compares two populations, one of which has some variable changed, then when one compares the results of an appropriate parametric test (i.e., mean, std. dev., etc.), there should be a difference, assuming that the changed variable had an effect on the population (assuming that one can “reject the null hypothesis”.) The existence of a change should be true even if the opinion scale is not isomorphic to addition. Thus, if one can at least somewhat unambiguously label a technology as “moderately significant”, then conducting averages and standard deviations can be useful in determining if the distribution changes if, for example, we replace experts with the technically literate public.

It should be noted that DelSignore, of a previous IQP, presented alternate arguments against taking the mean of the data (DelSignore 2006). He argued that describing the data solely by averages ignored other aspects of the data, implying similarity even if the distributions were of different shapes. He introduced cross-tables that grouped data into a grid with significance-likelihood pairs on the horizontal axis and the survey groups arranged in the vertical directions. The authors of this IQP have attempted to mitigate this problem in a different way by taking a number of statistical measures, described in the Data chapter. The authors discussed using methods more appropriate for ordinal data, and altering the cross-tables by creating a three dimensional chart of significance vs. likelihood vs. number of respondents, but at the time this was discussed there was too little time left to pursue these methods.

For our scores to be accurate, it is important that they are stable. Each author will attempt to answer the survey fully so that a measure of stability can be achieved. It should be recognized, though, that having three IQP partners who have communicated with each other on this technology extensively for most of a school year is not the best test of stability. Nevertheless, it is the authors' goals to present an argument whose logic and research will make their scores more stable.

# 4. Data Summary

### *4.1 Introduction*

In this chapter, we will present the data taken from all the surveys we have compiled to date. Survey data and the relationship to detailed facts from the literature will be in the next chapter. Comparative analysis of the two will be in Chapter Six. The full data set used to create charts and tables are listed in Appendix B.

The data includes all the survey results from the previous IQPs. It lists the significance, likelihood, and timeframe, with a short space for comments (which are included in Appendix C). The data ranges included are summarized in the chart below taken from the online web survey. For timeframe data, a value of one is “Early” and four is “Never”, with two and three as “Middle” and “Late”, respectively.

| **Significance** | **Likelihood** | **Time Period** |
|---|---|---|
| 1 - trivial | 1 - impossible | Early - Present-2020 |
| 2 - marginal significance | 2 - improbable | Middle - 2020-2035 |
| 3 - small significance | 3 - unlikely | Late - 2035-2050 |
| 4 - moderate significance | 4 - likely | Never – Never |
| 5 - major significance | 5 - probable | |
| 6 - revolutionary | 6 - expected | |

The data is partially incomplete in its original form as well as in the Appendix. Some of the data contains zeros for otherwise complete data points. The majority of this is localized in some of the oldest survey data for timeframe, though there are data inconsistencies throughout. The majority of these zeroes are in the timeframe section from some of the oldest survey data; the reason these exist is because at that time the web survey utilized did not record the timeframe data. To give accurate data numbers, all the zeroes in the data were excluded as they are simply data points that don't exist. This leads to some inconsistencies in group size amongst the categories, and therefore the group sizes by section of the question are listed in the data.

The purely original data was initially grouped by the survey in which it was given, with the data included for all the questions we had thus far. We made some basic modifications by introducing new columns of data, such as a basic numbering system, while removing old data that was unnecessary such as names, contact information, etc. This gave us a large sheet of data with all the survey answers.

We then modified the group data to form three 'major' groups based upon the smaller groups. The NIAC and Expert group were combined as the Expert panel; this panel were the most technically proficient and had the most overall knowledge of fusion. The Student and Alumni group were combined into a 'Technically Literate' category; these groups probably had some idea of the concepts and ideas, but no real experience with them or in-depth study. The final group was the 'General Public' grouped, formed from the schoolteachers group from DelSignore's survey and the space enthusiasts. This group probably had little technical familiarity with fusion, but was still important to help verify our conclusions.

### *4.2 Statistical Background*

The data presented in this chapter is a summary of the raw survey data from past projects that used the Breakthrough survey, representing a total of 189 respondents. The data from each cohort (Technically Literate, General Public, and Experts), as well as the combined data, are separated into their own sheets in Microsoft Excel. At the bottom of each sheet is a summarized form of the data showing the frequency of each response, as well as the calculations of a few descriptive statistics. These are followed by graphs illustrating the data frequency. Abbreviated version of these tables and charts appear in this section. A brief explanation of these calculations will be helpful for those without a background in statistics or probability.

The mean of each data set is the average value of all the responses in the set. The mean measures the central tendency, and gives an idea of what values to expect from the set (for example, if the mean is 5, we expect values in the data set to be near 5). In Excel, the statistical mean is calculated using the following formula (where $x_i$ are the data points, and $n$ is the number of data points):

$$\bar{x} = \frac{\sum x_i}{n}$$

The standard deviation (abbreviated std. dev. in the Excel sheet) of a set of data is a measure of the dispersion of values from the mean. A high standard deviation means that many values are far from the mean, and a low standard deviation indicated that many values are close to the mean. In Excel, the sample standard deviation is calculated with the following formula (where $\bar{x}$ is the sample mean):

$$s = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}$$

The skewness of a data set is a measure of its degree of asymmetry about the mean. A negative skewness indicates that the distribution has a large tail extending to the left, and positive skewness indicates a large tail extending to the right. Excel calculates the sample skewness using the following formula (where $s$ is the sample standard deviation as calculated in the previous formula):

$$\frac{n}{(n-1)(n-2)}\sqrt{\sum\left(\frac{x_i-\bar{x}}{s}\right)^3}$$

Finally, the kurtosis of a data set is a measure of how sharp or how flat its "peak" is. A positive kurtosis indicates a high peak, and a negative kurtosis indicates a flat peak. In Excel, the kurtosis of a sample is calculated using the following formula:

$$\left[\frac{n(n+1)}{(n-1)(n-2)(n-3)}\sum\left(\frac{x_i-\bar{x}}{s}\right)^4\right]-\frac{3(n-1)^2}{(n-2)(n-3)}$$

One other measure of association that will be used is the average absolute deviation. This will be used as a measure of how much the respondent panels' data differ from the short-term immersion group's data. This and the other statistics mentioned will be used in the analysis of the data as means of comparing the survey data sets with the data from the short-term immersion survey results.

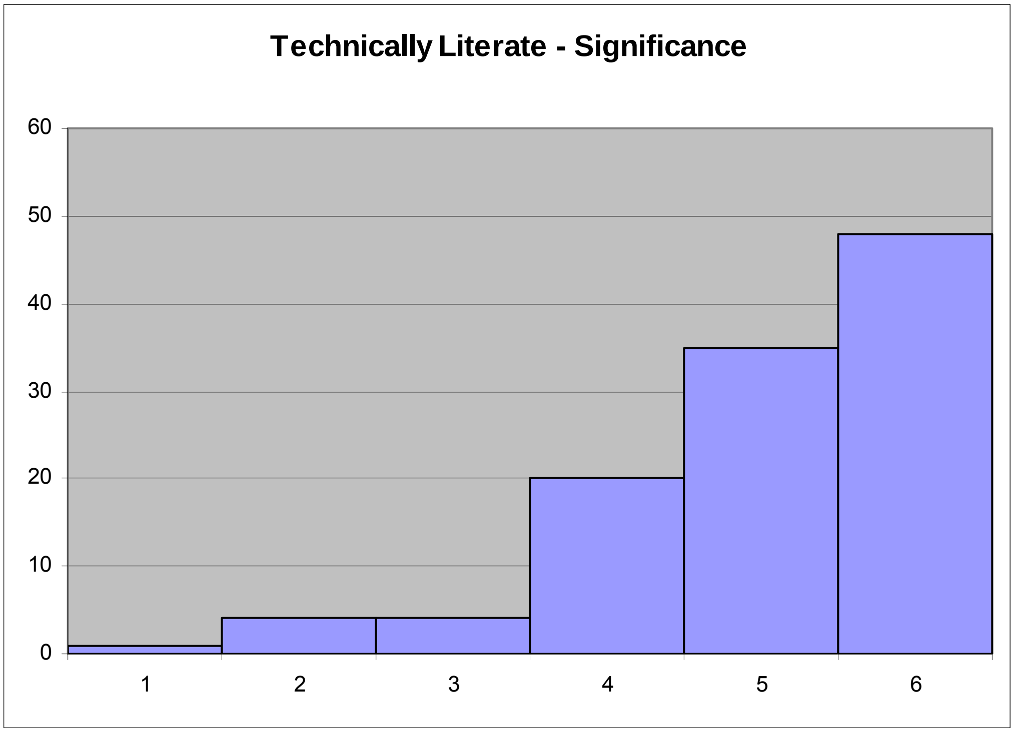
In the following chapter, we present our second major variable, which are the survey responses from the Short-Term Immersion group. This variable represents the project team's responses to the Breakthrough survey. Ultimately, we will attempt to statistically associate the responses by the various cohorts included in the study.

### *4.3 Data Summary*

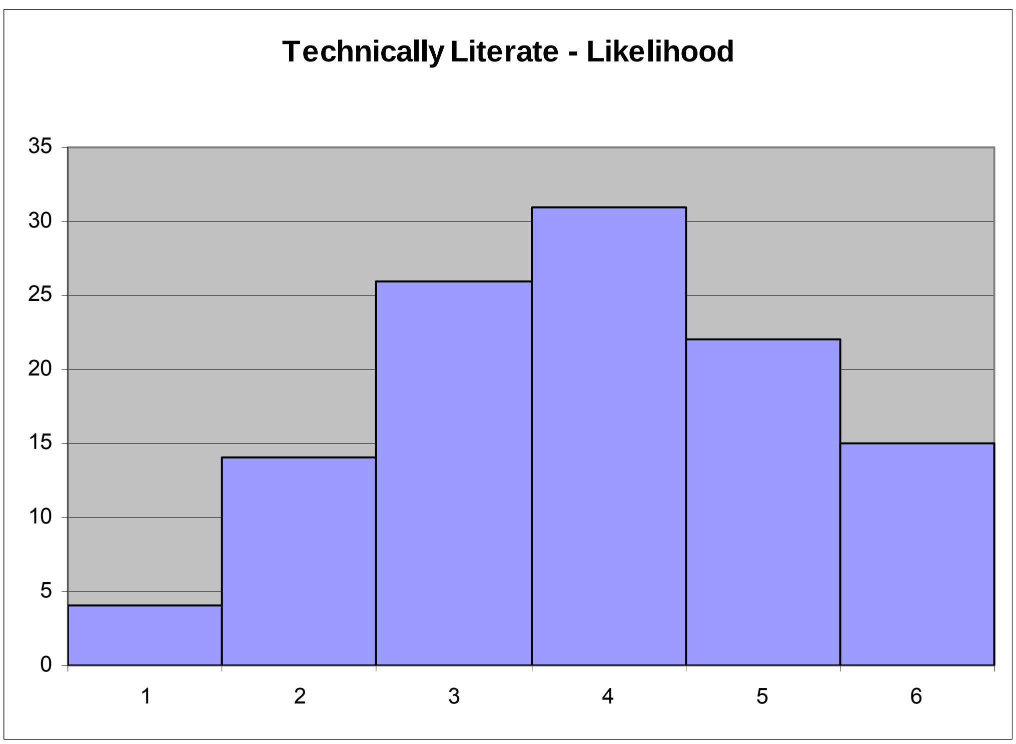
| Technically Literate: | (alumni, students) | | |
|---|---|---|---|
| Data Frequency | Significance | Likelihood | Timeframe |
| 1 | 1 | 4 | 3 |
| 2 | 4 | 14 | 24 |
| 3 | 4 | 26 | 40 |
| 4 | 20 | 31 | 3 |
| 5 | 35 | 22 | 0 |
| 6 | 48 | 15 | 0 |
| Totals | 112 | 112 | 70 |
| mean | 5.03571 | 3.87500 | 2.61429 |
| std. dev. | 1.10632 | 1.33643 | 0.64365 |
| skewness | -1.29091 | -0.11313 | -0.44229 |
| kurtosis | 1.60315 | -0.69000 | 0.15685 |

| General Public | (teachers, enthusiasts) | | |
|---|---|---|---|
| Data Frequency | Significance | Likelihood | Timeframe |
| 1 | 2 | 3 | 2 |
| 2 | 3 | 9 | 11 |
| 3 | 8 | 8 | 22 |
| 4 | 6 | 9 | 3 |
| 5 | 8 | 7 | 0 |
| 6 | 11 | 2 | 0 |
| Totals | 38 | 38 | 38 |
| mean | 4.26316 | 3.36842 | 2.68421 |
| std. dev. | 1.53666 | 1.38371 | 0.70155 |
| skewness | -0.46913 | 0.06246 | -0.45866 |
| kurtosis | -0.81755 | -0.89169 | 0.37739 |

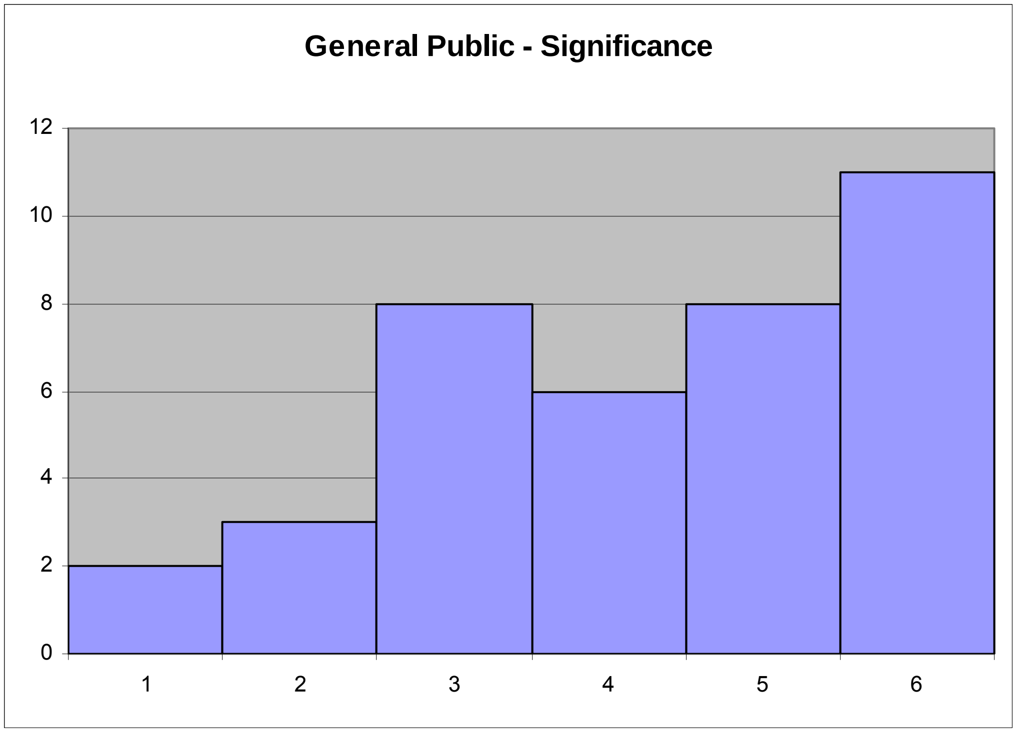
| Experts: | (experts, NIAC) | | |
|---|---|---|---|
| Data Frequency | Significance | Likelihood | Timeframe |
| 1 | 2 | 1 | 2 |
| 2 | 0 | 8 | 8 |
| 3 | 1 | 8 | 22 |
| 4 | 4 | 15 | 1 |
| 5 | 9 | 3 | 0 |
| 6 | 21 | 2 | 0 |
| Totals | 37 | 37 | 33 |
| mean | 5.18919 | 3.45946 | 2.66667 |
| std. dev. | 1.28750 | 1.16892 | 0.64550 |
| skewness | -2.10680 | 0.10314 | -1.04446 |
| kurtosis | 4.56811 | -0.19547 | 1.13652 |



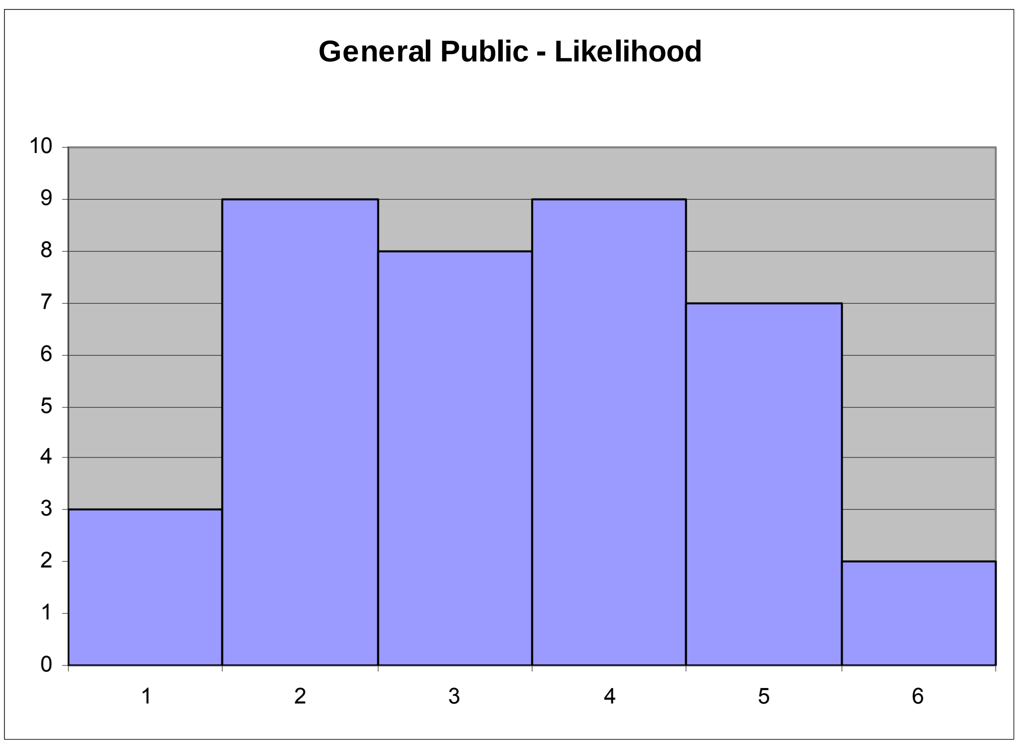

| mean | std. dev. | skewness | kurtosis |
|---|---|---|---|
| 5.03571 | 1.10632 | -1.29091 | 1.60315 |



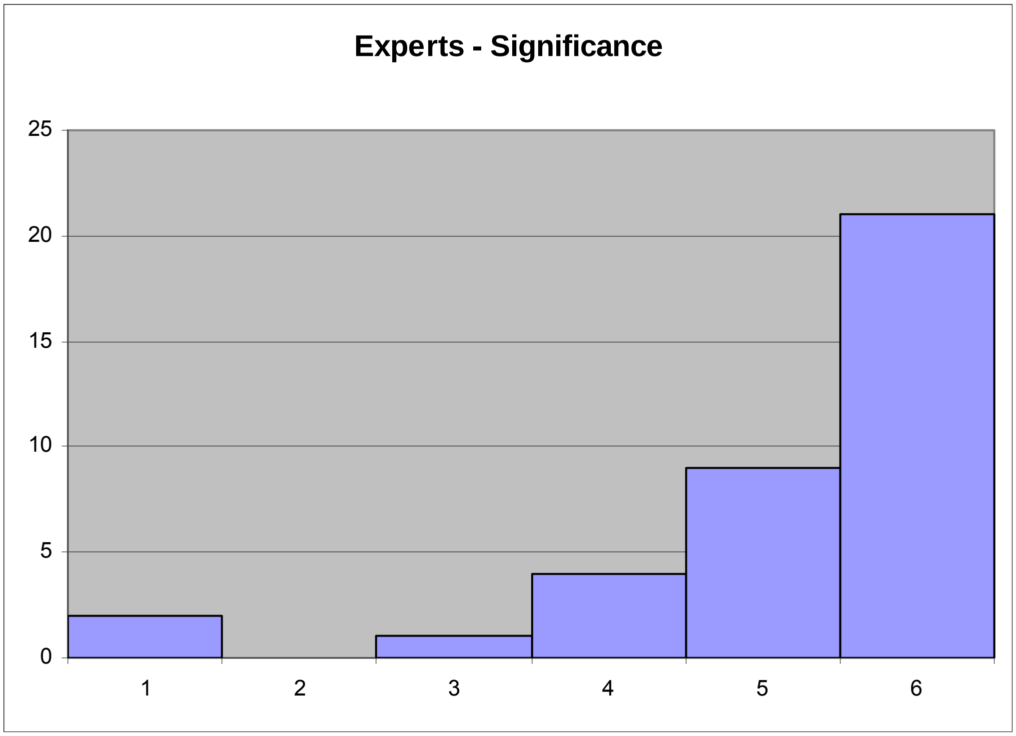

| mean | std. dev. | skewness | kurtosis |
|---|---|---|---|
| 3.87500 | 1.33643 | -0.11313 | -0.69000 |



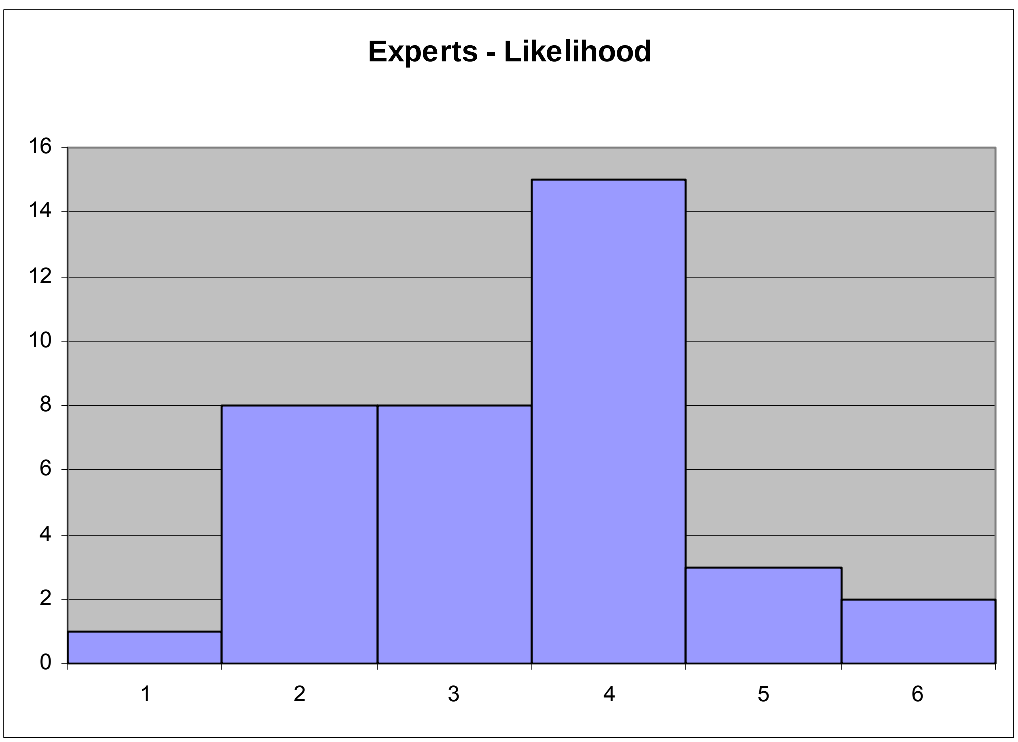

| mean | std. dev. | skewness | kurtosis |
|---|---|---|---|
| 4.26316 | 1.53666 | -0.46913 | -0.81755 |




| mean | std. dev. | skewness | kurtosis |
|---|---|---|---|
| 3.36842 | 1.38371 | 0.06246 | -0.89169 |




| mean | std. dev. | skewness | kurtosis |
|---|---|---|---|
| 5.18919 | 1.28750 | -2.10680 | 4.56811 |




| mean | std. dev. | skewness | kurtosis |
|---|---|---|---|
| 3.45946 | 1.16892 | 0.10314 | -0.19547 |

# 5. Survey Responses from the Short-Term Immersion Team

### *5.1 Introduction*

In order to determine the validity of the Delphi method through the use of short term immersion each member of this IQP group has taken the Fusion Reactor portion of the survey. Using the information acquired through literature research we have answered the pertinent question on the survey and explained the reasoning behind our answers. This section contains our answers to the survey, which in the following sections will be compared to the data retrieved from the other panels in previous IQP groups. Each member of our group has taken the survey so that we will have more data points to compare to the surveys retrieved by previous IQP groups.

### *5.2 Fusion Question*

Fusion Reactors

To make a future moon base profitable, something on the Moon will have to be profitable. Currently, the only identified resource so compact and rare on Earth that it would be worth importing from the Moon is helium-3, a potential fuel for nuclear fusion. However, at the moment, fusion energy is impractical since to get a reaction, one must generally put in more energy than comes out of the reaction. (There are few reports of breakeven experiments.) Hydrogen fusion is easier to achieve than helium since it takes less energy to get the smaller nuclei to fuse. Unfortunately, helium fusion is even more difficult to get started (takes more energy) than fusing hydrogen. In order to use the more challenging, but potentially higher yield helium-3 as a fusion reactor fuel, a major breakthrough is needed in the field of nuclear energy.

### *5.3 Responses from Garon Clements*

*Space Breakthrough Questionnaire: Fusion Reactors*

*Significance:* 6

*Likelihood:* 5

*Timeframe:* Middle

*Comments:*

Fusion power has the capability of becoming one of the most important breakthroughs in science and technology in the future. Any breakthrough in fusion technology could radically change the future of power sources as we know it. Fusion power is a relatively clean energy source when compared to current power sources. It uses materials that are rather easy to obtain in the reaction, and produces minimal amounts of waste that are no problem to dispose of. When this is compared to current power sources, it is a huge improvement. With cheaper, almost limitless fuel, the cost of energy will greatly decrease.

Fusion also is a very safe energy source for both the environment and humanity. It produces minimal amounts of green house gasses, which will help slow down the current global climate change, brought on by the burning of fossil fuels. Fusion plants are also safe for the workers in the plant, and the surrounding communities. Unlike fission plants, a meltdown in a fusion plant is highly unlikely. The amount of fuel present in a fusion reactor at any point in time is so miniscule that if there was a breach in the reactor, the reaction could easily be stopped.

I feel that fusion power is a very likely possibility. There are now multiple groups of scientists, funded by numerous governments, working on making fusion technology a possibility. Numerous scientists in the past have had results with small scale fusion experiments. With the rapid increase of technology, I see no reason why, in the future, fusion power would not be a possibility. Currently groups are doing fusion research using deuterium and tritium. This reaction is much easier to get going than a reaction using Helium-3. Fusion power may be a possibility in the near future but the use of Helium-3 fusion power, especially on the moon may be a little further off. For it to be profitable to build a plant on the moon to process Helium-3 reactions, much more research will be required, and much more time and research. I think that in the next 10-15 years we will have D-T fusion power working on earth as a profitable reaction, and maybe even used as a power source in certain locations on earth, but a Helium-3 processing plant on the moon is a little further off. We should probably consider a few more trips to the moon before even considering the possibility of building a lunar plant.

### *5.4 Responses from Jaime Barriga*

*Space Breakthrough Questionnaire: Fusion Reactors*

*Significance:* 6

*Likelihood:* 4

*Time Period:* Late

*Comments:*

Fusion power becoming feasible would be one of the most significant human accomplishments since landing a man on the moon. The day we achieve steady state fusion power is the day when we no longer need to worry about energy consumption.

Fusion power will be incredibly safe, incredibly reliable, and produce an inexhaustible supply of power.

Unfortunately, we still have a long way to go. While fusion looks theoretically good on paper, we have only made marginal progress so far, and we will not see much more progress made until the International Thermonuclear Experimental Reactor (ITER) project is completed in 2016. Fusion reactors are still not at the point where they can consistently output more energy than is input, and this issue coupled with a variety of other problems lead me to rate the likelihood lower than I would hope. That being said, the ITER project will hopefully fix a lot of the problems facing fusion, and once the ITER experiments are done, we should be a lot closer to making fusion power a reality. 10 years ago, it was unthinkable that we could have personal computers with dual-core 3 GHz CPUs and gigs of RAM, but here we are living that dream. Humankind has consistently made incredible advancements in technology, and with enough money, we will find a way to make fusion work.

As for the time period, there's no doubt in my mind that fusion is 50 years away or later. The most ambitious and well-planned fusion experiment is the ITER project, and even if all goes well and it stays on track, it will end in 2036. I would almost expect unforeseen problems to arise and problems to occur in the construction of the fusion experiments. Fusion reactors deal with technology that is extremely advanced and not everything goes right on the first try.

However, we need fusion to work. Currently, power consumption is rising quickly and we will need a better way to make power. Even if we improve existing technologies, they power output will not be able to catch up to demand in time unless something as effective as fusion is created.

### *5.5 Responses from Tyler Chase*

*Space Breakthrough Questionnaire: Fusion Reactors*

*Significance:* 5

*Likelihood:* 5

*Timeframe:* Late

*Comments:*

The introduction of energy produced from fusion power would certainly be a radical and important change. A fusion reaction has the potential to create a great deal of energy if the reaction can be economically controlled and sustained. Additionally, fusion power would potentially be more clean and safe than any current energy source. As I see it, feasible fusion power is very likely to become a reality at some point in the future, unless other future research efforts in energy production come up with something better. Barring that, fusion seems like it fits in with the natural progression of energy sources.

That said, there is still a long road ahead before feasible fusion power can be realized. It is more likely that we will have to bridge the gap between the present and our hopes for the future by improving energy sources we already have access to, such as nuclear fission. Despite some of the fear and negative connotations associated with them, nuclear power plants are safe, effective and reliable. While we are pursuing the road to fusion power, we should also be looking to make our current fission plants safer and more efficient.

When considering the impact of new energy sources, it is natural to become optimistic. However, there are implications that still must be considered. For instance, if fusion power becomes a reality, cheap energy would essentially put other companies devoted to energy distribution out of business. We can already see what happens when an energy source begins to compete with the oil industry, with the introduction of hydrogen fuel cells. The new technology has to be introduced gradually since the economic and social impacts of suddenly overthrowing the entire oil industry would be undesirable. If and when fusion power becomes a feasible energy source, efforts will have to be taken to make sure its introduction into the economy is smooth.

Another social obstacle that must be overcome is the negative public connotation of the word "nuclear." While it may not seem like a major concern, it was for this reason that ITER's acronym meaning was eventually dropped: It originally stood for *International Thermonuclear Experimental Reactor*, but that meaning was dropped due to negative connotations among the general public.

Though there will be some risks and significant difficulties along the way, the benefits of feasible fusion power should outweigh the potential troubles and disadvantages. The implementation is still a long time away, but fusion power will certainly be an important breakthrough when that point is reached.

# 6. Data Analysis

## *6.1 Introduction*

The analysis offered here pertains to data presented in Chapters 4 and 5 relating to the fusion power portion of the Breakthrough survey. Each cohort (General Public, Technically Literate, and Experts) will be discussed separately and compared to the others, as well as to the Short-Term Immersion group's data through the use of the average absolute deviation measure. Significance and Likelihood data will be discussed in detail, but Timeframe data may only be briefly mentioned, since the methods of collecting these data and our methods of analysis may not necessarily be accurate or effective.

## *6.2 General Public*

The General Public cohort, consisting of teachers and enthusiasts who took the survey, is the one in which we have the least confidence when it comes to drawing conclusions. These individuals are not experts on the level of the NIAC panel, nor do they necessarily have the continual exposure to the topics of the Breakthrough survey that the students and alumni of the Technically Literate group might have. For those reasons, the analysis of these data might be less useful than the analysis of the data from the Technically Literate or Expert cohorts.

*Significance*

The mean of the data from this group is 4.26316, with a standard deviation of 1.53666. Among the three cohorts, the General Public's data in the significance section had the lowest mean but the highest standard deviation. This suggests that members of the group were, on the whole, less certain about the technology's significance, since responses varied more widely than in the other groups. As with the other groups, the General Public's significance responses had a negative skewness (-0.46913), indicating that responses were skewed toward the higher values. Notably, the skewness here has smaller magnitude than in the other groups, indicating that the tail is not as pronounced as in the other groups. This can be seen by looking at the graph, and noting that responses are not as heavily distributed to the right of the graph, as they are in the significance graphs of the other groups.

*Likelihood*

The General Public was fairly evenly split on the subject of likelihood, the mean being 3.36842 with a standard deviation of 1.38371. Again, these suggest that this group may not have been certain about the technology's likelihood. Interestingly, the skewness (0.06246) for this data is small, indicating that the data is almost equally split around the mean. Not many conclusions can be drawn from this, since the distribution of data here is fairly random.

*Timeframe*

22 members of the group responded "late," while 11 responded "middle." This is consistent with the data from the other groups, as well as the combined data from all three groups, in which we see a pattern: About twice as many panelists respond "late" than "middle," and only a few outliers respond "early" or "never."

*Comparison*

The average absolute deviation of this data from the Short-Term Immersion group's average data is fairly large compared to the other groups. In Significance, the average absolute deviation is about 1.59649, and in Likelihood, about 1.56140. This means, on average, the responses differed by those amounts in those areas.

### *6.3 Technically Literate*

The Technically Literate group consists of WPI students and alumni who have taken the Breakthrough survey. We are more confident about the responses from this group, as we have more reasons to believe that they will be helpful. Nevertheless, this group still does not represent the level of knowledge and insight we have in the Expert group.

*Significance*

The mean of this data set is 5.03571, with standard deviation 1.10632. This standard deviation is notably smaller than that of the General Public's Significance data set. These statistics suggest that not only were the Technically Literate very confident about the significance of fusion power, they were consistently confident. The large negative skewness (-1.29091) is suggestive of the long leftward tail which can be seen in the graph. That is, most of the responses are skewed toward the higher values.

*Likelihood*

The likelihood data for the Technically Literate is more naturally distributed than for the General Public. The mean is 3.87500, and the standard deviation is 1.33643. This is about the same level of agreement that the General Public had in this area.

*Timeframe*

40 individuals responded "late," and 24 responded "middle." Again, we see only a few outliers responding with "early" or "never." This is consistent with the data from the other two groups.

*Comparison*

In Significance, the average absolute deviation is about 0.91667, and in Likelihood, about 1.27976. These values indicate that the data from the Technically Literate group agrees fairly well with the data from the Short-Term Immersion group. Particularly, the Significance values on average varied by no more than one point (that is, many of the data points were within one point of the Short-Term Immersion's average score).

### 6.4 Experts

The Expert group is composed of the NIAC panel, and those respondents listed as "experts" in old survey data; these consist of physics professors and individuals at NASA and in the aerospace industry. We are most optimistic about this group giving meaningful data and results (which is the reason they were surveyed in the first place). We hope to find a level of association between the results from this group and the Short-Term Immersion data.

*Significance*

The Expert group was most optimistic about the significance of the technology, with the data set having a mean of 5.18919 and standard deviation of 1.28750. A significant number of the respondents gave a 6 on this section, and only a few outliers responded near the low end of the scale. If not for the outliers (the two panelists who gave a 1), the standard deviation would be only 0.81478, so the data are very close to the mean aside from the few outliers. The large negative skewness (-2.10680) indicates a long leftward tail, and the kurtosis (4.56811) is high, indicative of the large spike in the distribution.

*Likelihood*

The likelihood data for this group is interesting; 15 panelists gave a response of 4, and 8 each responded with 2 and 3, making the distribution strangely spiked. The mean is 3.45946 and the standard deviation is 1.16892, so these individuals agreed with each other slightly better on the subject of likelihood than the other cohorts did. The skewness (0.10314) is again small, which indicates that the data is fairly equally distributed about the mean.

*Timeframe*

Again, most of the individuals in this group expect the technology in a late time period; 22 responded with “late” and 8 responded with “middle,” with only a few outliers responding with “early” or “never.”

*Comparison*

The average absolute deviation of the Expert cohort from the Short-Term Immersion group’s results is about 0.85586 in Significance and 1.40541 in Likelihood. This indicates that the Expert data tends to agree quite well with the Short-Term Immersion data in Significance, though not quite as well in Likelihood. In addition, the timeframe expectation of the Expert group is comparable to the expectations of the Short-Term Immersion group. It seems safe to conclude that although there are discrepancies and disagreements among members of the Expert cohort, the data from the research of the Short-Term Immersion group is still a fairly accurate approximation.

# 7. Conclusion and Suggestions

## *7.1 Conclusion*

+ We conclude that there is a strong association between experts (comprised of the NIAC panel) and the Short-Term Immersion (STI) group which **strongly suggests that the modified Delphi method used in the space breakthrough survey has a significant degree of validity**.
+ This level of validity extends to the correspondence measures relating to significance and likelihood.
+ Attempts to measure timeframe did not achieve the same level of conclusion, however, even in the face of incompatible data, analysis suggests some correspondence.
+ A strong association also exists between the STI group and the futurists (Kaku, Cetron, and Davies) in the areas of significance and likelihood, as all parties agree that fusion will be accomplished and will have a huge impact on society.
+ However, in terms of timeframe, Kaku believed that a timeframe could not be constructed reliably. Cetron and Davies' opinion on timeframe was written over 10 years ago, and since then events have transpired to prove them incorrect in this regard.
+ As such, we can not conclude that there is any correlation between the STI group, experts, and the futurists and popular press in terms of timeframe.

### *7.2 Suggestions and Improvements*

- Improvements could be achieved if the expert cohort could be identified by their sub field expertise. If a person taking the survey was someone whose career was in fusion research or engineering, they would obviously have very credible knowledge in the subject. However, due to the nature of the current survey, and the broadness of topics, it is possible that some cohorts will be experts in some fields, but not as knowledgeable in others. This may negatively impact the outcome of the survey by giving equal credibility to all cohorts in all topics.
- While we are unsure how, if the time frame question could be improved so that the data could be easier to decipher and analyze, it would make finding correspondence among cohorts easier.
- Questions that presented choices representing levels on a scale with no historical predicate may be generating responses beyond any speculative nature that can be supported by any level of current research. A helium-3 fusion reaction would be an ideal source of energy, but since a steady state deuterium-tritium reaction has yet to be achieved, the question is a bit too far fetched to prompt completely accurate responses.
- In future attempts to repeat this validation method, two separate groups should be used: One dedicated to the STI process, without access to any previously completed questionnaire results, and one dedicated to analyzing and comparing the STI group's results. Expanding the STI group would also be an improvement, as it would make it simpler to measure inter-rater reliability and cognitive style data within the STI group.

- A content analysis of the NIAC group's comments may reveal some interesting information; however it would be difficult to receive and aggregate comments from every participant in the space breakthrough survey.
- The survey itself would benefit from critical editing, especially in the areas of grammar and spelling as these problems can cause confusion.

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# Appendix A

This appendix contains the original Breakthrough survey question on fusion reactors, which was presented under the category of life support.

**Life Support**

(Part 5 / 5)

As Freeman Dyson so eloquently puts it, the movement of mankind into space will have as much to do with the bio-technology advances as space technology per se. Our plants have to be able to come with us, we ourselves will have to adjust to a radically changed environment and the whole thing has to make sense economically. People have to be able to make a living in any place that is colonized. Your assessment of the implied trade relationship between Earth and the Moon would be appreciated.

**Fusion Reactors**

To make a future moon base profitable, something on the Moon will have to be profitable. Currently, the only identified resource so compact and rare on Earth that it would be worth importing from the Moon is helium-3, a potential fuel for nuclear fusion. However, at the moment, fusion energy is impractical since to get a reaction, one must generally put in more energy than comes out of the reaction. (There are few reports of breakeven experiments.)

Hydrogen fusion is easier to achieve than helium since it takes less energy to get the smaller nuclei to fuse. Unfortunately, helium fusion is even more difficult to get started (takes more energy) than fusing hydrogen. In order to use the more challenging, but potentially higher yield helium-3 as a fusion reactor fuel, a major breakthrough is needed in the field of nuclear energy.

# Appendix B

This appendix contains the raw data from the fusion portion of past Breakthrough surveys. The data is arranged by the group of respondents.

| Number | Group | Significance | Likelihood | Timeframe |
|---|---|---|---|---|
| 1 | alumni | 6 | 5 | 0 |
| 2 | alumni | 5 | 5 | 0 |
| 3 | alumni | 6 | 4 | 0 |
| 4 | alumni | 1 | 1 | 0 |
| 5 | alumni | 5 | 5 | 0 |
| 6 | alumni | 5 | 3 | 0 |
| 7 | alumni | 3 | 3 | 0 |
| 8 | alumni | 3 | 2 | 0 |
| 9 | alumni | 4 | 2 | 0 |
| 10 | alumni | 6 | 4 | 0 |
| 11 | alumni | 6 | 3 | 0 |
| 12 | alumni | 5 | 4 | 0 |
| 13 | alumni | 5 | 3 | 0 |
| 14 | alumni | 4 | 4 | 3 |
| 15 | alumni | 5 | 3 | 3 |
| 16 | alumni | 4 | 1 | 3 |
| 17 | alumni | 4 | 4 | 3 |
| 18 | alumni | 6 | 4 | 3 |
| 19 | alumni | 6 | 2 | 0 |
| 20 | alumni | 4 | 5 | 2 |
| 21 | alumni | 4 | 4 | 2 |
| 22 | alumni | 4 | 2 | 3 |
| 23 | alumni | 6 | 6 | 0 |
| 24 | alumni | 6 | 4 | 2 |
| 25 | alumni | 3 | 3 | 3 |
| 26 | alumni | 5 | 3 | 3 |
| 27 | alumni | 4 | 4 | 2 |
| 28 | alumni | 5 | 3 | 3 |
| 29 | alumni | 6 | 4 | 2 |
| 30 | alumni | 6 | 4 | 0 |
| 31 | alumni | 5 | 2 | 3 |
| 32 | alumni | 5 | 3 | 3 |
| 33 | enthusiasts | 4 | 4 | 1 |
| 34 | enthusiasts | 5 | 2 | 3 |
| 35 | enthusiasts | 1 | 1 | 3 |
| 36 | enthusiasts | 3 | 3 | 3 |
| 37 | enthusiasts | 6 | 6 | 2 |
| 38 | enthusiasts | 2 | 3 | 3 |
| 39 | enthusiasts | 6 | 4 | 2 |
| 40 | enthusiasts | 6 | 1 | 4 |
| 41 | enthusiasts | 1 | 1 | 4 |
| 42 | enthusiasts | 5 | 5 | 3 |

| | | | | |
|---|---|---|---|---|
| 43 | enthusiasts | 4 | 3 | 3 |
| 44 | enthusiasts | 5 | 4 | 2 |
| 45 | enthusiasts | 6 | 5 | 2 |
| 46 | enthusiasts | 5 | 3 | 3 |
| 47 | enthusiasts | 5 | 2 | 3 |
| 48 | enthusiasts | 6 | 5 | 3 |
| 49 | enthusiasts | 0 | 0 | 0 |
| 50 | enthusiasts | 3 | 2 | 3 |
| 51 | enthusiasts | 6 | 5 | 3 |
| 52 | enthusiasts | 5 | 5 | 2 |
| 53 | enthusiasts | 5 | 4 | 2 |
| 54 | enthusiasts | 6 | 6 | 3 |
| 55 | enthusiasts | 6 | 2 | 4 |
| 56 | enthusiasts | 6 | 5 | 2 |
| 57 | enthusiasts | 3 | 4 | 3 |
| 58 | experts | 5 | 3 | 3 |
| 59 | experts | 5 | 3 | 2 |
| 60 | experts | 6 | 6 | 3 |
| 61 | experts | 5 | 2 | 3 |
| 62 | experts | 6 | 6 | 3 |
| 63 | experts | 6 | 5 | 3 |
| 64 | experts | 1 | 1 | 0 |
| 65 | experts | 4 | 4 | 3 |
| 66 | experts | 5 | 2 | 3 |
| 67 | experts | 4 | 4 | 1 |
| 68 | experts | 4 | 3 | 2 |
| 69 | experts | 6 | 4 | 3 |
| 70 | experts | 6 | 2 | 0 |
| 71 | experts | 6 | 4 | 2 |
| 72 | experts | 5 | 4 | 3 |
| 73 | experts | 5 | 2 | 0 |
| 74 | NIAC | 6 | 5 | 3 |
| 75 | NIAC | 6 | 3 | 3 |
| 76 | NIAC | 6 | 4 | 3 |
| 77 | NIAC | 6 | 4 | 2 |
| 78 | NIAC | 5 | 4 | 1 |
| 79 | NIAC | 6 | 2 | 3 |
| 80 | NIAC | 6 | 3 | 3 |
| 81 | NIAC | 6 | 5 | 2 |
| 82 | NIAC | 1 | 3 | 4 |
| 83 | NIAC | 4 | 4 | 2 |
| 84 | NIAC | 0 | 0 | 0 |
| 85 | NIAC | 6 | 2 | 3 |
| 86 | NIAC | 6 | 4 | 3 |
| 87 | NIAC | 6 | 4 | 2 |
| 88 | NIAC | 3 | 2 | 2 |
| 89 | NIAC | 6 | 4 | 3 |
| 90 | NIAC | 6 | 4 | 3 |
| 91 | NIAC | 6 | 4 | 3 |
| 92 | NIAC | 5 | 2 | 3 |

| | | | | |
|---|---|---|---|---|
| 93 | NIAC | 6 | 3 | 3 |
| 94 | NIAC | 6 | 4 | 3 |
| 95 | NIAC | 5 | 3 | 0 |
| 96 | students | 6 | 5 | 3 |
| 97 | students | 2 | 2 | 3 |
| 98 | students | 6 | 6 | 2 |
| 99 | students | 5 | 4 | 0 |
| 100 | students | 6 | 4 | 0 |
| 101 | students | 5 | 3 | 0 |
| 102 | students | 6 | 4 | 0 |
| 103 | students | 5 | 2 | 0 |
| 104 | students | 6 | 6 | 0 |
| 105 | students | 6 | 5 | 0 |
| 106 | students | 5 | 4 | 0 |
| 107 | students | 5 | 5 | 0 |
| 108 | students | 5 | 4 | 0 |
| 109 | students | 5 | 5 | 0 |
| 110 | students | 6 | 6 | 0 |
| 111 | students | 5 | 5 | 0 |
| 112 | students | 4 | 3 | 0 |
| 113 | students | 5 | 3 | 0 |
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| 115 | students | 5 | 5 | 0 |
| 116 | students | 5 | 3 | 0 |
| 117 | students | 6 | 3 | 0 |
| 118 | students | 5 | 4 | 0 |
| 119 | students | 6 | 5 | 0 |
| 120 | students | 6 | 5 | 0 |
| 121 | students | 4 | 4 | 0 |
| 122 | students | 6 | 6 | 0 |
| 123 | students | 6 | 5 | 0 |
| 124 | students | 6 | 4 | 0 |
| 125 | students | 6 | 1 | 4 |
| 126 | students | 2 | 3 | 3 |
| 127 | students | 6 | 6 | 2 |
| 128 | students | 5 | 2 | 3 |
| 129 | students | 6 | 6 | 2 |
| 130 | students | 5 | 5 | 2 |
| 131 | students | 4 | 4 | 2 |
| 132 | students | 6 | 5 | 1 |
| 133 | students | 4 | 3 | 3 |
| 134 | students | 5 | 2 | 3 |
| 135 | students | 5 | 3 | 3 |
| 136 | students | 6 | 4 | 3 |
| 137 | students | 4 | 2 | 2 |
| 138 | students | 6 | 6 | 2 |
| 139 | students | 6 | 4 | 3 |
| 140 | students | 6 | 5 | 3 |
| 141 | students | 2 | 2 | 4 |
| 142 | students | 4 | 3 | 2 |

| | | | | |
|---|---|---|---|---|
| 143 | students | 4 | 5 | 3 |
| 144 | students | 3 | 6 | 3 |
| 145 | students | 4 | 3 | 3 |
| 146 | students | 6 | 2 | 2 |
| 147 | students | 6 | 4 | 3 |
| 148 | students | 4 | 3 | 3 |
| 149 | students | 6 | 5 | 3 |
| 150 | students | 5 | 4 | 3 |
| 151 | students | 6 | 4 | 3 |
| 152 | students | 5 | 5 | 3 |
| 153 | students | 6 | 6 | 1 |
| 154 | students | 5 | 6 | 1 |
| 155 | students | 4 | 3 | 2 |
| 156 | students | 6 | 3 | 3 |
| 157 | students | 4 | 4 | 2 |
| 158 | students | 6 | 4 | 3 |
| 159 | students | 6 | 5 | 2 |
| 160 | students | 5 | 3 | 3 |
| 161 | students | 6 | 5 | 2 |
| 162 | students | 4 | 2 | 2 |
| 163 | students | 5 | 3 | 3 |
| 164 | students | 5 | 4 | 3 |
| 165 | students | 6 | 3 | 2 |
| 166 | students | 6 | 6 | 2 |
| 167 | students | 6 | 2 | 3 |
| 168 | students | 5 | 5 | 2 |
| 169 | students | 5 | 3 | 2 |
| 170 | students | 6 | 4 | 3 |
| 171 | students | 6 | 6 | 3 |
| 172 | students | 6 | 4 | 3 |
| 173 | students | 2 | 1 | 4 |
| 174 | students | 6 | 6 | 3 |
| 175 | students | 5 | 4 | 2 |
| 176 | teachers | 4 | 4 | 2 |
| 177 | teachers | 2 | 2 | 3 |
| 178 | teachers | 3 | 3 | 3 |
| 179 | teachers | 3 | 3 | 3 |
| 180 | teachers | 2 | 2 | 3 |
| 181 | teachers | 4 | 3 | 3 |
| 182 | teachers | 4 | 3 | 2 |
| 183 | teachers | 3 | 4 | 1 |
| 184 | teachers | 6 | 2 | 3 |
| 185 | teachers | 6 | 5 | 3 |
| 186 | teachers | 4 | 4 | 2 |
| 187 | teachers | 3 | 2 | 3 |
| 188 | teachers | 3 | 4 | 2 |
| 189 | teachers | 5 | 2 | 3 |

# Appendix C

This appendix contains the raw comments from all respondents on the fusion portion of previous Breakthrough surveys. The comments are sorted by respondent group.

**Alumni:**

I'm a strong believer in Helium-3 development, and when used on a base like the Moon, I believe it will be a nearly limitless power source.

**Students:**

Still highly theoretical and experimental

may be easier to create a dominoes effect, ignite a small amount of he-3 and allow it to ignire more and more until desidered reaction is achieved

The  prospect of clean-highly effective energy deserves all praises.

with several breakthroughs in fusion technology and in spacial transport of materials, this would be able to provide energy at a much cheaper rate than is currently possible on earth.

we almost there yahoo french

It's possible.  We are going to need a new energy source.  This country will fall apart without power.

It is possible to create solar pannels on the moon base using the lunar soil of very large dimensions, say 10mile*10mile, harvest the energy and use it to activate a hydrogen reactor during the "night" phase that lasts many days

production of helium-3 into usable fuel is a great significance. but reactor must be built on the moon -> expensive

until the fusion experiment is replicated this phenominon can only be reguarded as myth

It could happen.

I believe that more research time and money will be put into fusion in the near future. This will become the primary way that we create our energy once we have a steady supply of fuel (via a moon base) and the technology to harness it.  While many believe that the problem is simply too difficult to solve, the fact that we have already reached reactions that break even means that we understand the process enough to create a viable energy source in a moderate time period.

Inventing a poor man's nuclear fusion weapon is a curse upon the earth. Who would want to discover it?
Fusion has been the energy of the future for a long time, and it's still a long ways off.

Damn chemistry...

perfect dream come true device

**NIAC**

Maybe even later. The stakes are too high not to solve this one, but who knows when we'll be able to crack it.

The tie-in with helium mining on the moon could make this a major driver in space exploration.

Major research efforts are underway in fusion reactors and any successes can be applied to space applications. The issues are about sustaining the reaction process.

Can't say never there are so many possibilities with new helical accelerators and coaxial superconductors. TIME PERIOD: Wish I knew I would be the richest person in the universe.

Antimatter and fusion are the only known means of manipulating energy that are fuel-efficient enough to allow the promise of routine human spaceflight. It is fundamentally safe, too. In addition to the obvious more-energy-out-than-in problem, fusion must also be developed as a weight-efficient solution. Despite the energy density of the fuel, current tokamaks and electrostatic/electromagnetic confinement methods are simply not realizable in space.

Hopefully the collective minds of our scientific society can come up with better reasons for a lunar base than this...

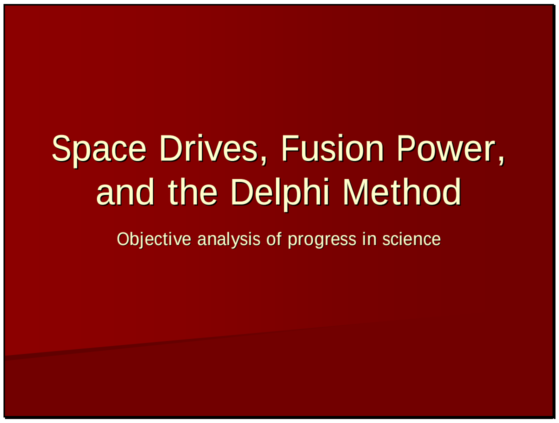
We're still decades from a commercially-viable D-T reactor. D-3He reactors may just barely be possible, but we have no idea how to actually build them. And contrary to claims, D-3He reactors will produce significant neutron flux from side reactions, so the advantage over D-T is limited. 3He fusion is not quite a scam, but it's definitely being pushed because it's a reason to go back to the moon, not because it's the best solution. (It's of course possible that some breakthrough will happen, like R. Bussard's electrostatic-confinement fusion actually working, that would make D-3He fusion practical, but still not allow p-B11 fusion, which is even cleaner. But I wouldn't hold my breath.)

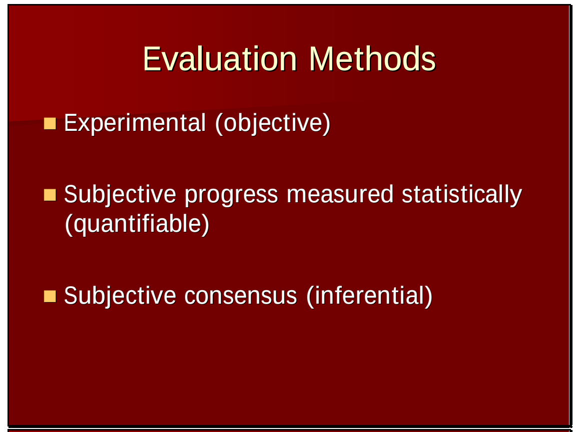
very low concentration of He-3 on the Moon; difficulty in harvesting what is there; fusion- always 20 years away no matter when you ask.

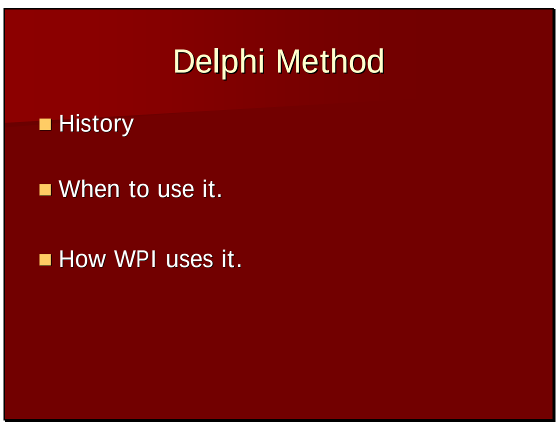
Fusion reactors have been consistenly been 50 years away. Eventually they will be developed.

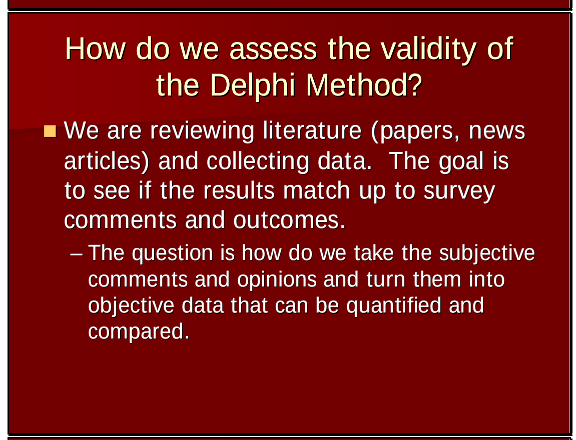
# Appendix D

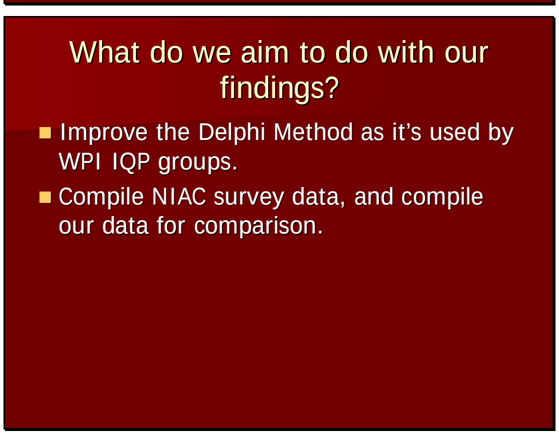
This appendix contains our Powerpoint slides and notes from a presentation given at a WPI Student Pugwash Conference on April 4th, 2007.

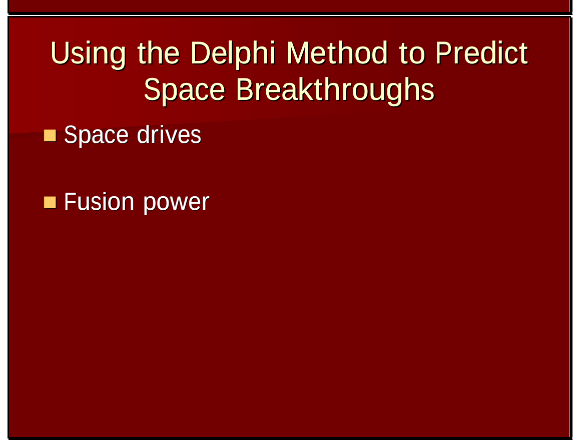


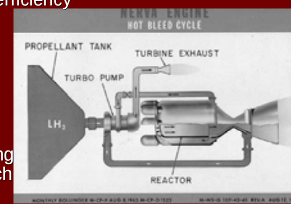



## Space Drives: Solar Sails

- Solar sails are propelled by light
- Solar sails must be at an angle to the sun to go anywhere
- They can be propelled into the sun as well as away from it
- They must be wide and thin

## Nuclear Thermal Propulsion

- Operates via heating exhaust gases with heat generated via fission
- Hydrogen typically used for fuel due to low molecular mass
- High thrust, moderate efficiency
- Only drive w/ability to launch from planets
- Technology seems mostly present; Testing done in 1960s
- Some may utilize liquid or gaseous fuel, enabling them to operate at much higher temperatures




Basic NERVA design from 1963

## Problems with Nuclear Drive

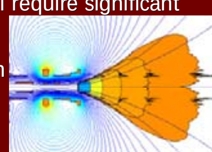
- Primary limitation with standard nuclear reactor is core melting temperature, which limits ‘fuel efficiency’
- Gas core and liquid core reactors may solve this, but could require additional research
- Safety concerns: political & technical
- Exhaust isn’t radioactive, though drive is while operating
- Shielding would be necessary for manned missions

## Electric Propulsion

- Electric propulsion utilizes electric power to accelerate propellant
- Broadly categorized into three drive types : electrothermal, electrostatic, and electromagnetic
- Electrothermal drives typically operate by electrically heating propellant, much the same as nuclear drives
  - Examples : Resistojet, arcjet
- Electrostatic drives use electric charges to accelerate charged particles to high rates of speed
  - Examples : Ion drive, DS4G
- Electromagnetic drives use a combination of electric and magnetic fields to accelerate charged particles.
  - Examples : MPD, VASIMR
- All three drives are typically very efficient in terms of propellant usage

## Problems with Electric Propulsion

- While typically very fuel efficient, require large amounts of power for very low thrust
- Manned missions will require high amounts of power and large numbers of thrusters, potentially requiring nuclear reactors for power
- These particular reactors will require significant cooling in order to operate
- Wear on drive components due to high power a concern
- Most of these drives are advanced and could require many years of research



VASIMR Electric Propulsion

## Fusion Power

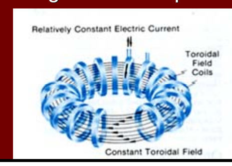
- The Basics
  - A pair of atomic nuclei can be forced to join into a single nucleus, releasing energy.
  - However, an initial input of energy is required to overcome the electric force that tends to repel the protons of each nucleus.
  - Fortunately, the amount of energy required to initiate the reaction is less than the amount that the reaction produces.

## Fusion Power

- Deuterium-Tritium Reaction
  - $^{2}H + ^{3}H \rightarrow ^{4}He + n$
  - The energy required to overcome the electric force is about 0.1 MeV, but the energy output by the reaction is about 17.6 MeV.
  - Among all possible fusion reactions, this is the most attractive since it requires the least initial energy.

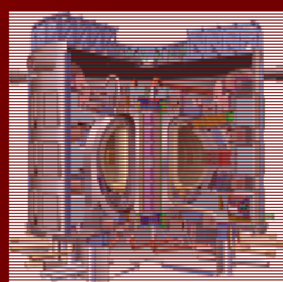
## Fusion Power

- Fusion Reactors
  - Superheated plasma is energetic enough to produce a fusion reaction; the problem lies in containing the plasma.
  - A tokamak is a machine designed to confine plasma using a torus-shaped magnetic field.




## Fusion Power

- ITER
  - ITER is an international tokamak project.
  - Its first operation is expected in 2016.
  - It is designed to be an experimental step toward future fusion plants.



## Any questions?

**Presentation Outline**

Evaluation Methods

- Experimental (objective)
  - Simple test to determine if something works, does not work.
- Subjective progress measured statistically (quantifiable)
  - Say a drug test had an 80% success rate. Subjectively, it was a success.
- Subjective consensus (inferential)
  - If a bunch of experts say we should look into something, we should do it. Delphi Method aims for stabilization by requesting a follow-up.

Delphi Method

- What is it? (History)
  - Paper that fusion2 wrote up.
  - Send out a questionnaire, compile, resend something
- When to use it.
  - Technology that's not advanced enough to experiment on right away, or too expensive. Predicting future outcomes and simulation gaming for the military.
  - How WPI uses it.
  - Space breakthrough IQP
- Example of a good study done with Delphi.
  - A Delphi study done in 1964 accurately predicted advances such as oral contraceptives and artificial organs, but it also predicted man would land on Mars by 2000 and that the population would be under 6 billion. Results have been mixed.

How Do We Assess The Validity of the Delphi Method

- We are reviewing literature (papers, news articles) and collecting data. The goal is to see if the results match up to survey comments and outcomes.
  - The question is how do we take the subjective comments and opinions and turn them into objective data that can be quantified and compared.
- Group up survey data, and group our data so that they can be compared.

What Do We Aim To Do With Our Findings?

- Improve the use of the Delphi Method by WPI IQP groups.
- Determine the significance, likelihood, and the time to feasibility of nuclear fusion, the solar sail, the ion drive, and the nuclear drive