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Forecast of Space Technological Breakthroughs

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By

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Abstract

Significant and plausible technological breakthroughs for the future of space travel are formulated based on cutting-edge technologies and ideas, then sent for assessment by two Delphi-type panels: one of "experts in the field," and one of cognitively-known WPI Alumni. The results show the most likely and significant potential breakthroughs within the next 25-50 years. These breakthroughs will be used to form portrayals of alternative futures in space to be assessed by the panelists in later rounds of the study.

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Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

This project is a forecast of future space technologies and is designed to be used in conjunction with, and to be expanded upon by other IQP projects, as part of a greater technology assessment of the social Implications of space technology advance in the next 25-50 years. The project forecasts both manned and unmanned space technology which can be used by the aerospace industry and exploration by taking possible technological breakthroughs into account over the next 50 years. Originally this study team was divided between two groups. Brian Partridge, Tim Padden, and Vadim Svirchuk dealt with manned space technologies while Amanda Learned, Damon Bussey, and Tim Climis focused on the unmanned space technologies. Having seen that the two individual projects were in essence dealing with the same base technology but with different foci of application, the groups agreed that it would make more sense to combine their efforts into one larger project dealing in both realms.

The six members of the original group used current literature and two panels of individuals, to identify significant and likely breakthroughs. Recruiting panelists to participate in a Delphi-type study allowed for the evaluation of the likelihood and significance for the future of unmanned and manned space flight of about 20 technical developments. The results represented a plausible forecast of what would happen in the fields of manned and unmanned space technologies in the area where there was consensus among the panelists.

The original group sought to create two panels of approximately 25 each, but fell short of their goal by 20. Hence, a continuation team was recruited to more closely approximate the original panel size goal, and conduct a more detailed analysis of the data. The new group, Jeff Wilfong, Jeff Patrone, and Rob DelSignore, decided to increase the number in the alumni pool to

30 cases, for a total of 46 respondents. The original data indicated that the rank ordering of the technologies by the two panels was similar, therefore the decision to increase only the alumni panel was made. There was also more information available for the alumni, allowing a more detailed final analysis of the data.

Rather than re-write an entire report, the new team instead added to the original. There are new chapters, new tables, new analysis, and occasionally new findings. However, the new panelists tended to support the views of the original panels, allowing a more focused look into how the cognitive styles would change the prediction, since it was clear that expertise did not. If so, this would be an important finding, therefore increasing the number of alumni panelists would be helpful since cognitive data for them was known.

1.1 Breakthroughs Make a Difference

A previous IQP team conducted a similar study of the likelihood and social implications of a new space race to the moon. However, the possibility of technological breakthroughs was not taken into account. Working from a current technological base and applying historical analogy, this group neglected the possibility of technological innovation of the "Breakthrough" variety. This view of simple incremental technical advance was not one that we reasoned to be a suitable basis for prediction of the social implications of renewed interest in space technology.

History shows that breakthroughs do occur and do drastically alter the course of technological development. A clear example is the early stages of the Wright brother's development of the airplane, in that they "worked by isolating a problem, finding a system to test potential solutions and integrating [them back into the] design," [1] a method which was not widespread until their methods were publicized. In short, by inventing the Wind Tunnel and testing control systems on kites, the Wright Brothers did not have to build a whole airplane to test every new wing configuration. A graph of the premature development of flight due to this breakthrough is seen in figure 1.1 below.

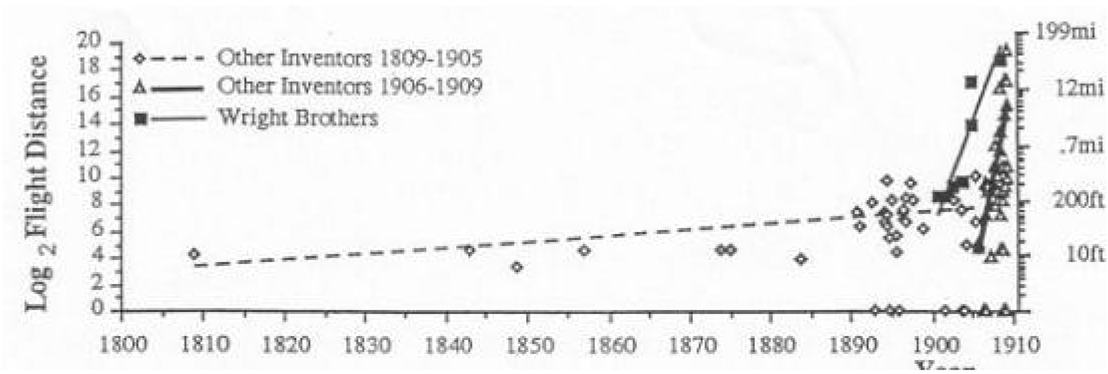

Figure 1.1: Flight Attempts Between 1809 and 1909

Basically, flight occurred approximately 50 years earlier than expected due to a "breakthrough" and was a factor in WWII and especially WWII as a result. The concept of creating a second forecast, taking potential breakthroughs into account originated from comments made by Professor Sergey Makarov in the Electrical Engineering Department at Worcester Polytechnic Institute. Professor Makarov saw the work done by the previous forecasting IQP group at WPI and posed the question: "Why did they not consider at least the possibility technological breakthroughs?" He noted that they were ruled out in advance by their methodology. It is with this question in our mind that the hunt for potentially important technological breakthroughs began. However, since these are cutting-edge and not currently in-use technologies, a challenge was presented in getting their likelihood and significance assessed objectively, since most breakthrough ideas would be coming from the expert community developing them. Therefore polling the assessments of an assortment of experts with sufficient knowledge in the fields in which these technological breakthroughs may occur is important, but the experts also may have vested interests that could bias them, at least individually and possibly in a group. Hence, obtaining of opinions from the people who will be working with these technologies once they become feasible is important, but one also wants assessment from technically knowledgeable people outside the aerospace community. Combining the two panels might just allow for the future to be "predicted", not through a historical projection, but through an informed examination of leading possibilities viewed through the lens of technical "promise."

1.2 Current State: World Technology Policies

In order to predict the future, one must have a firm grasp on the present, since the future is based upon this unique beginning. As Freeman Dyson points out, "Technology only gives us tools. Human desires and institutions decide how we use them" (Dyson 15). Thus, the project reviewed the current state of the agencies working with these new technologies. There are several agencies interested in space: NASA and their Space Science division in the United States, the China National Space Administration (CNSA) in China, the Japan Aerospace Exploration Agency (JAXA) in Japan, the European Space Agency (ESA) in Europe, and the Russian Space Agency (RSA) in Russia. Some of these agencies are more focused on manned space missions and others on unmanned space missions.

The United States' National Aeronautics and Space Administration (NASA) has fallen on hard times during the past decade. NASA used to constantly make headlines when it raced against Russia to put men in orbit and again to put men on the moon. However due to a lack of public interest, the agency's funding has declined significantly since then. It barely maintains the space shuttle program along with its endeavor to build a space station. NASA tends to concern itself with manned space travel much to the dismay of the space scientists that would prefer to deal with unmanned space technology. The space scientists get 20% of NASA's budget to do unmanned scientific missions like the rover missions to Mars and the Voyager 1 mission through the Solar system. They also have to be creative and find ways accomplish missions through international cooperation with other, more unmanned, technology friendly agencies like JAXA and the ESA because of budget constraints. These budget problems exist in part due to NASA's need to get missions approved and funded by Congress. Congress likes public visibility and leans toward manned missions. Disagreements within NASA about how to fulfill its mission statement exacerbate this bias and leave the scientists in the minority. The space scientists believe that unmanned space research is the safest and most efficient way to explore the universe, but the administration feels that manned exploration would be more valuable in the long run and easier to fund.

Japan is unique because it has three separate space programs with different goals, which merged into one, JAXA. This space agency has only existed for slightly longer than one year. JAXA is a combination of the National Space Development Agency (NASDA), the Institute of Space and Astronautical Science (ISAS), and the National Aerospace Lab (NAL). NASDA dealt mainly in making a viable industry out of space and performing commercial launches in Japan. ISAS concentrated on the space science and relied on NASDA to launch some satellites (having just one per year on its own). ISAS was university based, and it had 15% of the budget for space operations in Japan. Its sole responsibilities were space and planetary research and to train new scientists. The NAL was responsible for next generation aviation and space research and development. Previously, the Space Activities Commission (SAC) coordinated the projects of the three Japanese agencies. The SAC published "Fundamental Guidelines for Space policy into the 21 Century," a document emphasizing international cooperation, peaceful use of space technology and homegrown technology. Now, the agencies still follow similar guidelines, but are merged in order to facilitate the sharing of research and development, facilities and equipment, researchers and engineers, and cooperative education. Thus, Japan now has an agency that operates all the processes within one organization, with the hope to be ranked with American and European space agencies in terms of capabilities. The space scientists have now lost the autonomy that their space science colleagues in the United States envied.

ESA is an international cooperation among the countries of Europe. It is non-military by charter, and budget restrictions are very strict. Nothing is allowed to go more than 10% over budget without either canceling the project or re-appropriating the necessary money. The commercial organization (Arianespace) has the clear majority of the current commercial launch market due to inexpensive, reliable, expendable rockets, and an excellent launch location in French Guiana. 15% of the budget is mandatory and meant primarily for space science, and the other 85% is voluntary; the contracts going proportionally to contributing nations. The space scientists at ESA use the mandatory budget as they see fit. This has been in unmanned research as of late, but is sometimes invested in the development of new launch vehicles.

China has a developing space program funded by the Chinese military. The CNSA can do reliable launches cheaper than the ESA, but there has been little impact on the current market because this is a recent development. They are run and developed by the Chinese military and are trying to enter the international market for economic and political gain. The Great Wall Corp markets launch services on the Long March Rocket. The goal seems to make the program self supporting. China is cooperating with Brazil, with which it builds satellites, and then launches them in China. In the past, China has also cooperated with Russia and American companies in rocket development. The CNSA has access to previous technologies used by the Russians in their forays beyond the upper limits of our atmosphere to space station MIR and others. Two Chinese taikonauts were trained at Star City, near Moscow, and they are now training the rest of the taikonauts. China has also developed the Shenzhou space capsule which is a modestly improved version of the Russian Soyuz spacecraft.

In Russia, the RSA has had a lot of long-term manned experience, but has also done several interesting unmanned projects including missions to Mars and Venus. Currently the RSA is training cosmonauts, as well as astronauts, for the International Space Station (ISS) and launching ISS modules. The RSA has significant experience with manned space flight, most notably with the space station MIR and its predecessors. They are also helping the Chinese taikonauts with their training. However, due to current military influence and budget restrictions, the RSA has not been focusing on space science or even developing new manned space capabilities. It is now seeking commercial contracts outside of the country for funding. Today the Russian space program has started to cut into ESA's share of the launch market, using its powerful Proton rocket.

1.3 Project Overview

Many new space technologies are already under serious development by these space agencies. Meanwhile, there are others that are just the dreams of science fiction writers. Therefore, the first step was to outline up-and-coming technologies or ideas in launch vehicles, propulsion, materials, and life support in which a breakthrough would create a turning point in a forecast.

Research was initiated by reading Freeman Dyson's book, The Sun, the Genome, and the Internet: Tools of Scientific Revolutions, and then furthered by attending a conference where he was speaking at Cornell University. There, the team was able to speak with forecaster, Freeman Dyson, as well as with space scientists and engineers working for NASA and the Jet Propulsion Laboratory (JPL). The team discussed cutting edge technologies with space scientists and also with aerospace engineers and physicists on our own campus as well. An expansion of the search for breakthroughs was made into online publications as well as science fiction. The science fiction ideas were predominately found through another IQP, being conducted simultaneously, which analyzed literature to find technologies that were being taken more seriously than just, "Beam me up, Scottie," by the applied scientists in the field. Once 20 promising technologies were gathered, the assessment panels needed to be set up.

This study is conducted by polling the opinions of panelists to predict which technological breakthroughs will be the most "significant" and "likely". These advances could impact the future of space exploration; thus, the results are intended to be used along with the results from simultaneous and forth-coming IQP study's in order to show possible outcomes of the future of space, derived from the use of the most probable and momentous advances predicted by our panelists.

This style of surveying that is conducted is known as the Delphi technique; it is a technique that works with the belief that the opinions of many are more likely to be accurate than those of a select few. It is incorporated into the forecasting methodology due to the accurate results of previous studies using this approach. The Derek Price study of the telephone's early days is an example of a beneficial Delphi study that produced a reasonably good forecast that the telephone would be used for point-to-point communication, while "experts" saw it as a evolving into a mass broadcasting method (Linstone & Turoff 2).

For the first round of study, a diverse panel of experts, hobbyists, and people in the aerospace industry was recruited and asked to rate a variety of breakthroughs on significance and likelihood. History has shown through other studies that who was chosen for our panel would make a large difference in the accuracy of the forecast. As Brody points out, "technological breakthroughs can especially skew the vision of normally level-headed planners" (152). Thus, those who enjoy to "think-big" and would consider themselves "visionaries" were sought out.

However, as part of the Delphi study, along with a panel of experts and enthusiasts in the field, a group of technically trained individuals of known cognitive style, was also assembled (all WPI graduates from the classes of 2001 and 2002). This was to help determine whether the range of opinion reflects cognitive variables rather than training and background knowledge, as well as to help determine whether our expert respondents were likely to be self-selected, thus biasing the opinion towards one personality type. Furthermore, people not directly related to the field of communication predicted the future uses of the telephone far more accurately than those persons directly working on the technology. These people included doctors, firemen, pharmacists and hotel managers. Also, Dyson admits "…a French cartoonist with no technical training and no love for technology portrayed the twentieth century more accurately than either Verne or Wells" (172). Thus, the second panel will help maintain balance in the responses, by asking rank-and-file engineers in several fields and physics majors what they think about the breakthroughs being assessed by "the experts."

The questionnaires sent to the panelists were constructed from the ideas found most "breakthrough" worthy in the research phase. A similar method was used to create the questionnaire as was used by Gregory Doerschler in his prediction of the future of the fire service, under the impact of the newly-emerging fire protection engineering, which predicted the likelihood of given scenarios of the future of fire protection technology based on opinions of fire service leaders. However the questionnaire style was to be shorter, since there were 20 breakthroughs, so that participants wouldn't need to take too much time from their busy schedules to complete it.

The first round results of the panelist selections and Delphi study are presented in the appendix. These results represented the first conclusions used to complete a 25-year forecast of unmanned, and 50-year forecast of manned space technologies. In the words of Freeman Dyson, the results will be "describing one possible course among the million other courses that the future might take."

1.4 Project Overview Update

The second breakthrough team continued the IQP where the first group left off. The debate rounds of the Delphi study had not been conducted, and this was the primary goal of the second team. Tim Climis was still onboard at this point and his in-depth conclusions can be found in Appendix A.3. Overall the debate rounds for both panels produced no significant changes in the distribution of responses, which allowed for more "official" conclusions to be drawn; at that point, the Delphi study for the original panels was finally concluded.

The present team held the opinion that the alumni panel was not evenly distributed between cognitive types. At this point it was unclear as to whether cognitive types clearly played a role in the type of response given. Therefore the alumni panel was doubled to see if the cognitive type distribution would even out. In a manner similar to the first breakthrough team, this group selected alumni panelists according to cognitive type (in an attempt to even the numbers). In the end it was discovered that no significant changes in distribution occurred. The increased panel size presented the alumni panel with a more comparable cognitive distribution, but it was still clear that some types are more likely to respond. The results in Section 4 have been updated to reflect the new data set. The first team also set out to compare experts from NASA, Academia, Industry, and the Planetary Society, however, did not report on their findings on job types. It was decided that this analysis was a major gap in the IQP which must be filled.

1.5 Future Project Intentions

Jeff Wilfong and Jeff Patrone have concluded their work on the project and have left the breakthrough IQP team. Rob DelSignore is the only remaining student working on the project at this point. There is there is much work to do in order to conclude this study.

One item in this report found to be particularly interesting was the original group's introduction of the Derek Price study of the telephone. They pointed out the fact that in some cases it was the general public who had a more accurate prediction of how a new technology was going to be best utilized in the future. In order to incorporate this aspect into their study they selected an alumni panel to serve as their "general public." However, since they selected alumni with highly technical degrees, they realistically only have a "semi-expert" panel rather than a "general public" panel. Since it was one of their goals to compare the expert panel and alumni panel to prove, through a Delphi study, that alumni could be used in place of experts, it seems that the alumni panel is too alike the expert panel to be considered unbiased independent.

The immediate goal is to create a new panel consisting mainly of middle school and high school math and science teachers, as well as anyone interested enough to take the online survey. The hope is to have a new panel of 30-50 people who better represent the "interested" general public opinion. All of this reasoning is based upon the hypothesis that the expert/alumni panel will have accurate predictions of what will become possible in the next 10-20 years (since they are the ones directly working with new technologies and know what is immediately possible), and the general public will have a better prediction of what is to come in the next 20-50 years.

Once any significant breakthroughs have occurred in the next 10-20 years, the public will be much more interested in the utilization of space and the major work and funding on new space technologies will come from the civilian sector.

Once the data for the new pool is acquired it will be compiled initial conclusions will be made. Time permitting, an anonymous debate will be run to allow for the distribution to reorganize itself into a final opinion distribution. Meanwhile attempts will be made to have the expert panel take the MBTI test in order to make cognitive type comparisons between the expert and alumni panels. These comparisons should show whether the cognitive types play a factor in the distribution of responses and whether or not the expert panel had an even cognitive distribution. If the distribution is even, it should provide sufficient evidence to conclude that the expert and alumni panels are interchangeable. This will allow for closure to be placed on one of the goals of the initial team: to show that an alumni panel can be used in place of an expert panel in order to make technological predictions. Creating an expert panel is very difficult, while getting alumni responses is much easier, despite the response rate of only 25%. Therefore this will be a very significant conclusion in terms of future methodology; Delphi panels will be used more often if they produce interesting results and can be assembled from broader pools, rather than "alumni" or "expert."

If the general public and alumni/expert panels come to different conclusions, then this will potentially prove the hypothesis. If they are the same then it will arguably be possible to combine all the panels into one large very convincing panel since expertise is not a factor in future assessment. Either way, the data on hand will be evaluated, allowing for possible future space scenarios to be devised. These scenarios may or may not be accurate predictions of what is to come in the next 50 years in the utilization of space, but they will reflect what looks most reasonable today and will get the initial emphasis in terms of funding and expert attention.

2. METHODOLOGY

2.1 A Delphi Approach

The Delphi Method is a process by which effective group communication can take place, while negating the unwanted effects of social interaction which surpasses individual judgment and individual thinking. The Delphi method at its simplest is a structured process for collecting expert opinion, interspersed with controlled feedback. The opinions are gathered by way of a series of questionnaires, each followed by feedback of results to the panel. This method of forming a single opinion from those of many individuals is based on the assertion that decision-makers, when lacking full scientific knowledge, must rely on either intuition or expert opinion. This method arose in response to an unreliable formulation of opinion when using single interviews or group discussions. Opinions of single experts are considered unreliable due to possible bias, whereas group discussions tend to suffer from 'follow the leader' tendencies and reluctance to abandon previously formulated ideas. The solution to this was to allow effective group communication while providing anonymity, separation, and variance of opinion.

Named for the site of the Oracle of Apollo in ancient Greece, the Delphi method is at its most useful when applied to extremely complex problems for which there are no adequate analytical or statistical models. This method was first applied in the 1950s in order to study the "broad subject of inter-continental warfare" involving airborne and undersea weapons as well as surface ships and landmines. The idea was to provide a forecast of future technological innovations that would be of interest to the military. The Delphi method has since been used primarily in technological forecasting, and the prediction of the social and economic impact of such technological changes. This method has also found its way into studies involving industry, public health, and education. Corporate use of the Delphi method is common at present, yet little information is available on their "in house" studies. Specific study details, being proprietary, are usually kept from the public, thus the lack of information regarding corporate studies. (Day, III.C.1)

The Delphi method at its core is a group communication between a panel of geographically dispersed experts, which allows them to systematically approach an issue or task of immense complexity. The steps of a Delphi study are fairly simple. A panel of experts is assembled, comprising a certain level of diversity without compromising the relevance of their expertise. A series of questionnaires is then sent to these pre-selected experts by way of mail, email or otherwise. The aim of these questionnaires is to extract and develop individual opinions to the problems presented and to enable the experts to refine their opinions based on group feedback as the study progresses. The interactions between panel members are controlled by a monitor whose task it is to filter out material not related to the study's subject and protect the identities of the participants.

The ten integral steps of the Delphi Method are the following:

1. Formation of a team to undertake and monitor a Delphi on a given subject.

2. Selection of one or more panels to participate in the exercise. Customarily, the panelists are experts in the area to be investigated.

3. Development of the first round Delphi questionnaire

4. Testing the questionnaire for proper wording (e.g., ambiguities, vagueness)

5. Transmission of the first questionnaires to the panelists

6. Analysis of the first round responses

7. Preparation of the second round questionnaires (and possible testing)

8. Transmission of the second round questionnaires to the panelists

9. Analysis of the second round responses (Steps 7 to 9 are reiterated as long as desired or necessary to achieve stability in the results.)

10. Preparation of a report by the analysis team to present the conclusions of the exercise

One of the most important issues in the application of this method is that all participants are aware of the direction and ultimate aim of the study, such that their opinions are directed toward the topic at hand. If improperly informed as to their goals, panelists may offer irrelevant or unhelpful information, or may become frustrated and lose interest.

Criticisms of the Delphi study have come primarily in the form of its application. The isolation of future events would lead to the judgment of such developments independent of the others. Since many technological forecasts deal with the competition of breakthrough developments, such a view is obviously impedance. The specialist nature of an expert panelist may lead them to view the forecast in an inappropriate manner. Format bias in the form of ambiguity or otherwise would lead to an inaccurate transference of information. Expert responses could also be manipulated by the monitors with the aim of moving the study in a desired direction. Finally, problems related to sloppy execution may occur, as with any other method of inquiry. These critiques, as can clearly be seen, are either the result of poor application of the study, or can be sufficiently dealt with by proper application. These problems are not critiques of the Delphi system itself, but reflect a proper awareness of the sensitivity of this method to human error.

The reasons that we selected the Delphi method for our technological forecast are numerous. The method has already been used extensively in the area of technological forecast. Our most relevant experts, those being in related fields of study such as Aerospace, Biomedical Engineering, Physics and others are likely to be involved in specific projects, and might thus be strongly biased in favor of their own work as individuals, but are unlikely to be biased as a group. The Delphi study allows effective group communication with no commitment to gather in the same physical space, thus allowing a far-ranging sample of experts. Such a group would have been almost impossible and certainly costly, had we attempted a physical group meeting. By allowing us to direct the progress of the study without hampering the formulation of opinions or the resulting information, the Delphi study gives us control over the flow and schedule of the communication process. For all these reasons, the Delphi study was deemed the best data collection strategy. This method allows us maximum control of simple structural elements, while leaving the formulation of opinions to knowledgeable experts.

2.2 Selecting Panelists

2.2.1 Selection of Alumni Panelists

The process of forming Delphi panels includes snowball sampling, i.e. requesting peoples' opinions, based on snowball "effects". Thus, there is naturally self-selection in who are the final respondents to our questionnaire. It has been shown in a study of middle school students that personality, or more generally, physiological type, as measured by the MBTI, , has a role in one's predictions of the future. Soddy, one of the most significant forecasters at this century, knew "scientific knowledge and logical involvement had…to be supplemented by emotional involvement, intense creativity, and social awareness" (Sclove 164). Also, cognitive type probably also effects whether or not one will take the time to fill out and return a questionnaire in a timely fashion. Therefore, we predict it may be beneficial to interpreting our respondents' results if we include data on personalities. In order to see correlations between personality, response rate, and forecasting responses, we sought a second panel of cognitively known individuals.

A good way to understand someone's personality or psychological type is to administer a Myers-Briggs Type Indicator (MBTI) instrument. Therefore, the candidates for this second panel of individuals consist of graduates of the WPI classes of 2001-2003, since over 1500 of them took two cognitive style measures while on campus. More specifically, the WPI graduates are chosen from Professor Wilkes' database of the results of the MBTI instrument for the classes of 2001 and 2002. We believe the MBTI is a reliable instrument because it is "the world's most widely used personality inventory" ("Introduction to Myers…" 1). Professor Wilkes, et al. has used the results of this instrument to predict behavior patterns of undergraduates at WPI. Choosing students from the classes of 2001 and 2002 implies that the students have been working or researching for at least over two years after completing their undergraduate work. It also implies that these are the individuals who are going to be working in their respective fields, and experiencing the technological changes that occur over the next 25 to 50 years, the timeframe of our forecasts. Potentially, the second panel will give us another perspective in forecasting the future of space technology, beyond allowing us to examine the influence of cognitive style on the rate and nature of the responses.

We were very selective in which WPI alumni from these classes were asked to participate in our Delphi panel. The first step was to cross-reference their MBTI results with data from the alumni office, on the degrees that these alumni obtained. We selected alumni that differed on the MBTI scales of both sensing versus intuitive perception and judgment versus perception. This gave us four personality categories for our alumni; yet, beyond that, we wanted individuals from specific fields. Our original sample included a distribution of individuals with mechanical engineering, electrical engineering, physics, biotechnology, and chemical engineering degrees. Since they would be responding to technically advanced scenarios, we sought individuals with a high likelihood of being involved in cutting edge technologies. Since mechanical and electrical engineers were the most apt to be in a relevant technical field, we choose our first panel with the following distributions: 33 mechanical engineers, 14 electrical engineers, seven physics majors, seven biotechnology majors, and seven chemical engineers; this totaled to 68 alumni. Later, more alumni were chosen for the second panel in a similar fashion – 16 from each of the four cognitive types being investigated, mostly mechanical engineers, then electrical, and so on. Within each of these fields, we selected even cognitive type distributions across our four types.

For the first panel, our sample decreased to 60 alumni, due to non-updated contact information from the alumni office. The final distributions can be seen in Table 2.1 below. Our goal was to have a response rate of fifty percent. We expected a higher response rate than the experts, due to compassion from the alumni, who all at one time had to complete an IQP. The following explains how we went about pushing our selected alumni to respond to our questionnaire.

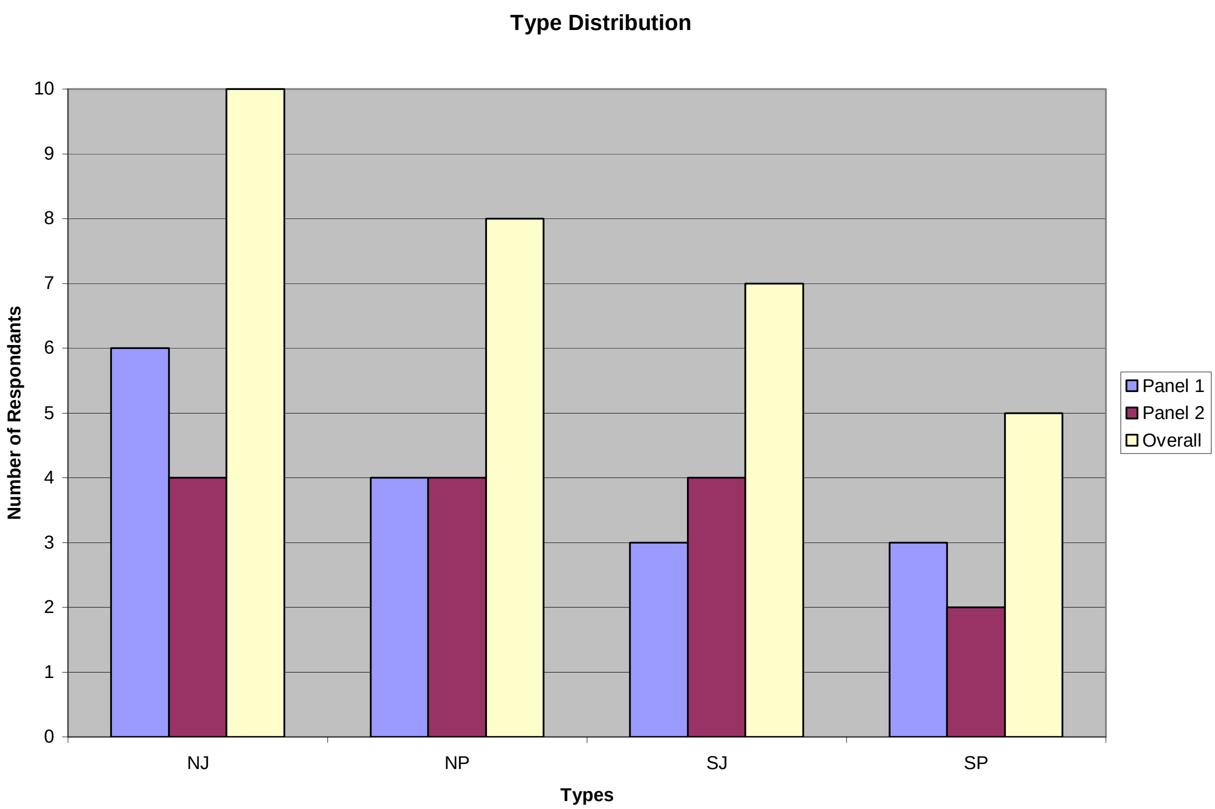

Table 2.1: Alumni Distribution

2.2.2 Alumni Panelists Recruitment

First, we mailed a paper copy of the questionnaire, technology descriptions, and a cover letter to each alumnus of our sample. A copy of these three items can be found in Appendix A.1. From these 60 unreturned mailings, a total of 14 were filled out and returned within a few weeks. Second, an email was sent to those with existing email addresses, which did not respond after the first mailing. This email (that can be found in Appendix A2) reminds them or our request and tells them we gave a time extension. Also, within this timeframe, an online version of our survey was created; therefore, the web address and the option of responding electronically were also given to them in the email. By this time, we had received as many "NJ-types" as the other three categories of cognitive type combined. Therefore, thirdly, phone calls were placed to each of the alumni we had not heard from at this time, who had a phone number on record, but only to those who were of non-NJ type. We asked them in person or on a message, whether they were still interested or not and to please email us if they did not want to participate, noting that we still needed respondents. Also, we gave the web address of the online survey to those that were spoken to.

We cut off the gathering of responses to the first questionnaire on the 23rd of February. At this time, we had gathered 16 completed questionnaires from alumni, a 27% response rate. The response rate for four individual cognitive type can be seen in Table 2.1 above.

2.2.3 Selection of Expert Panelists

The selection process of an "expert" panel is a much more complicated process. Most typical of the Delphi study goal and concept is to get panelists with working knowledge of the technologies in question and/or applications in question. Hence, the "expert panel" was born. The expert panel selection started on a trip to Cornell to see Freeman Dyson speak.

We had read Dyson's book, <u>The Sun, the Genome, and the Internet</u> and it caught our attention for two reasons: one, he wrote of a whole new means of gaining access to space, and two, he examined how developments in seemingly unrelated fields like biotechnology would interact with space technology and politics to predict social implications by logical extrapolations. We hoped that he could help us in a couple of areas. If Dyson could suggest visionaries from whom to glean ideas for breakthroughs in a developing technology that would make a large difference in the ability of the human race to explore space, in person or robotically, it would help us greatly. Additionally, he could nominate potential panelists to evaluate the probability of these breakthroughs.

At the time of the trip, we only had contacts at MIT and WPI for our 25-person Delphi panel, which is not a very diverse group. We believed that Dyson could help us to find experts at the University of Arizona, his home university of Princeton, and other schools and businesses active in the field since he is a revered, active member of the area himself.

Cornell, being a major research university with a space science program, also presented us with an excellent opportunity. In addition to speaking with Dyson and hearing his lecture on biotechnology becoming as familiar to the society of the future as computers are to us, we introduced ourselves to the members of the Space Science Department. There we spoke with several people about our project. There was a lot of excitement about it and several members of the department volunteered to be on our panel or to help in other ways. We left Cornell with a research assistant, a 'space science' graduate student, and a 'science, technology, and society' graduate student agreeing to participate.

2.2.4 Expert Panelists Recruitment

Phase	***Yield***
Cornell Trip	4 Academics, 0 NASA, 0 Professionals
University Mailing	4 Academics, 0 NASA, 0 Professionals
WPI and Project Centers	7 Academics, 0 NASA, 3 Professionals
Russian Search	0 Academics, 0 Russian Space Agency, 0 Professionals
Student NASA Search	0 Academics, 0 NASA, 0 Professionals

Phase	*Yield*
Professor's NASA Search	0 Academics, 9 NASA, 3 Professionals
Supplemental Search	2 Academics, 0 NASA, 0 Professionals

Table 2.2: Expert Recruitment Summary

Shortly after our Cornell trip, we started putting together a list of the faculty at universities with prestigious space science or aerospace departments. At the completion, we sent a mass emailing to 25 professors at the Massachusetts Institute of Technology (MIT), the University of Washington (UWA), Cornell University (Cornell), the University of Arizona (UAZ), Princeton University (Princeton), the California Institute of Technology (CalTech), and Stanford University (Stanford). This mailing resulted in four panelists: one physics professor at Whitworth College in Spokane, WA and one Princeton graduate student of physics, both associated with the Electric Propulsion and Plasma Dynamics Laboratory (EPPDyL) at Princeton, an aerospace engineering graduate student at MIT, and an aerospace engineering professor at UWA.

Hoping for a response rate better than the 16% in the previous mailing, we turned home to WPI, sending emails to a few of the aerospace professors in the mechanical engineering department and to the Goddard Research Laboratories (Goddard Labs), Glenn Research Center (GRC), and Lincoln Laboratories (Lincoln Labs) project centers. This was far more fruitful, resulting in two professors, three industry professionals, and five researchers at Lincoln Labs. No one from Goddard Labs or GRC responded, however.

By this point, we had 16 expert panelists promising to participate, a goal of 25, and no one from NASA or any other space related organization. The gap was obvious, and while recruiting nine NASA personnel seemed a little ambitious given our previous success rate, it did not seem to be out of the question. To augment our numbers, in the case that we could not get enough NASA people, we decided to take advantage of our uniquely bilingual group. Since our co-advisor and one of our members are fluent in Russian, we had them try to recruit some Russian scientists and cosmonauts. This avenue proved to be a dead end, but it would have put an interesting perspective on our project. Simultaneously, the English speakers among us started searching the NASA website and sending letters to a variety of head engineers, project managers, directors, and astronauts at the Jet Propulsion Laboratory (JPL), GRC, Goddard Labs, and the Johnson Space Center (JSC). Nothing sent out by a student returned any results. Professor Wilkes was much more successful and through snowball sampling recruited two engineers from the Marshall Space Flight Center (MSFC), one from GRC, the director of the NASA Institute for Advanced Concepts (NIAC), two people at the Office of the Chief Engineer, and three officers of the Planetary Society. This was 25 people, our goal.

By this time, however, we had started getting results back, and some of our panelists were not responding. In order to guarantee 25 panelists, we decided to start using personal connections from our aerospace engineering member, who recruited two more panelists, one, a graduate student at the University of California at Berkley (UCB) and the other, a graduate student at WPI. Now we had 27 panelists, just in case two of them did not respond.

Nevertheless, it was not quite enough. By looking in the appendices, it is easy to see that there are in fact only 17 expert panelists. None of the Cornell people who promised to respond actually participated; nor did the UWA professor or two people from Lincoln Labs. One of the industry engineers never got back to us. We recruited the representatives from the Office of the Chief Engineer rather late, and they, unfortunately, did not complete the form before the deadline for this project. We also had problems with the server holding the online version of our survey so we lost the results of at least one person that way, and he never resubmitted. The last missing result came from an unfortunate miscommunication causing the loss of one NASA respondent's survey before we could input the data from it, although we hope that data will eventually be found.

2.3 Gathering Potential Breakthroughs

In order to construct a questionnaire that represented a wide range of technological possibilities, different types of sources had to be consulted. The breakthrough possibilities are separated into two main groups: those currently under development and receiving serious financial consideration, and those existing primarily in literature, as yet, unproven theory.

The first group of possible breakthroughs was researched chiefly by way of the internet. Information from sources such as NASA and the Jet Propulsion Laboratory were the basis of these breakthrough ideas. The breakthroughs that exist in this category are as follows: Reusable Single-Stage to Orbit (SSTO), Carbon Nanotubes and by extension the Nanotube Polymer Space Elevator (NPSE), Memory Plastics, "Solid State" Aircraft and Aerogel.

The second group of breakthrough possibilities was one in which we were particularly interested, as these technologies are less likely to develop, but could potentially be more significant. These ideas derived from three chief sources; *The Sun, the Genome, and the Internet*, by Freeman Dyson, the WPI Science Fiction research group, and prompting by our advisor, Professor John Wilkes.

Dyson's book was the inspiration for the following breakthrough possibilities: The Slingatron, Laser Propulsion, the Ram Accelerator, and the Bionic Leaf. From the Science Fiction group we received information on the Magbeam, Solar Sails, Electromagnetic Shielding, Cold Plasma, and Fusion Reactors. The breakthrough research on the ideas initiated by Professor Wilkes includes the Roving Lunar Base, the Gravity Implant, and the LEO Compressed Air Collector (LEO CAC). Special credit must also be given to information derived from NASA's Project Prometheus IQP team, courtesy of WPI Professor John Blandino, which coupled with research from the Science Fiction group gave us the breakthrough ideas related to the Nuclear Drive.

2.4 Formatting the Questionnaire

The Format of the questionnaire was kept as simple as possible. The explanations for each breakthrough were stapled together. The panelist was given a separate set of pages to fill out their responses. This was because only the responses section had to be mailed back and we wanted to reduce the weight of return mail to save on postage. This also allowed a panelist to read an explanation on one page and fill out their response on another with out having to flip back and forth between an explanation section and response section.

Some thought had to go in to formatting the response section of the questionnaire. We wanted the panelist to be able to easily give concise and meaningful input. Because our goal was to predict the most import breakthroughs in the next 50 years we had to not only know if a breakthrough would occur, but also if it would have a large impact.

The metrics we finally decided on were significance, likelihood and time period. The significance would rate a breakthrough's potential impact and likelihood was a measure of how likely a particular breakthrough was to occur in the next 50. Panelists could rate a breakthrough's significance as trivial, of marginal significance, small significance, moderate significance, major significance or revolutionary. Similarly the likelihood of a breakthrough could be rated as impossible, improbable, unlikely, likely, probable or expected. There were four options available for the time period: present-2020, 2020-2035, and 2035-2050. We also provided a space for the comments in case a panelist wished to elaborate on their opinion. The space provided for comments was intentionally set to a couple of lines. We wanted to encourage comments but we didn't want each panelist to write excessively on each breakthrough.

An online version of the questionnaire was also made available to panelists that had nor responded or did not receive a hard copy of the questionnaire. The format of the online version was kept similar to the paper version with a few small differences. The online version provided a place for responses immediately after each explanation. There was no need to separate the responses from the explanations with the online version. One other small change was made to the online version of the survey. The option of "never" was added the estimated time period of a breakthrough. This is because many of the panelists that received the paper version of the survey wrote response of “never” as the time period even though it was not one of the provided responses. We decided we wanted to give panelist using the online version the choice to say that a breakthrough would never happen.

Below is an example of what a panelist was provided with to record their response. To see the survey in full please refer to appendix A1.

	Significance	Likelihood
Name of Breakthrough	1 2 3 4 5 6	1 2 3 4 5 6

Time period: ________________

Comments: ____

____

2.5 Respondent Follow-up

Since the cut-off date for collecting the first questionnaire responses was extended, a letter was written to the initial respondents, letting them know that the project was being extended. This letter also informed those of the initial respondents who were "outliers" amongst our collected data where they stood. The opportunity was given for them to defend their case on those particular items, by giving us their comments to be distributed to our entire panel. This letter of request can be seen in the Appendix A2. From this, three cases were received and can be found in Appendix A3.

3. LITERATURE REVIEW

Forecasting events of the future and predicting technological breakthroughs has been popular among scientists for years and various methods have been used in their research. From using historical references to studies of currently advancing technologies, researchers have used every conceivable way to gather accurate information to aid in creating a forecast for the future. Some of the notable researchers in this area include Freeman Dyson and Michio Kaku, and the research in their works has spread to influence research by groups of students at Worcester Polytechnic Institute.

Prior work had been done by an IQP group from WPI where students forecasted the future of space technologies and a space race between the United States of America and The People's Republic of China. However, in their work they assumed that there would be no technological breakthroughs affecting either side in the space race. Such a narrow view of the future seems unlikely due to the constant research being done across the country/world everyday. It is with this in mind that we began researching for possible ideas of what types of technologies could be considered breakthroughs and useful in the future of space travel.

3.1 Historical Projection

The question of future of space technology is an important one. This is made ever more so by the apparent emergence of a new space race, that being the efforts of Chinese and American lunar missions. The forecast for such a race is thoroughly discussed in *The Future of Space Exploration: A Second Moon Race*, by Milat Sayra Berirment, Sebastian Ziolek, Kemal Cakkol and Chris Elko. This report details the current technological capabilities of the United

States and China as applies to a moon landing and subsequent construction of a lunar base. The direction and pace of this race is evaluated by the use of historical analogy. Specifically, the space race between the United States and the Soviet Union is used to construct parallels to the proposed "Second Moon Race." The report concludes with a forecast for the year 2030, detailing the accomplishments and future goals of the respective nations.

The current state of the American space endeavor is lacking in funding and technological ability as compared to the previous space race. "NASA's share of federal budget reached an all-time peak of 4.4% of the total federal spending in 1966; today it is around .5%." (Berirmen 80) This restriction of budget has forced NASA to rely on Apollo-era technology to achieve its lunar goals, appearing to "...[take] a step backwards technologically." (Berirmen 87)

The Chinese situation seems to be one of slow but constant progress. The Chinese program has proven remarkably reliable, achieving a 90% success rate. This success rate enables the Chinese to undercut Arianespace in the commercial satellite market, allowing the space program to potentially pay for itself. (Berirmen 64) Chinese space technology is very similar to that of the former Soviet Union. For instance, the Chinese vehicle *Shenzhou* is nearly identical to the Soviet *Soyuz*, albeit with a few modifications considered to be improvements. These parallels in technology reflect the era of cooperation between the communist governments, later to dissipate.

American technological ability in the previous space race reflected the major driving forces behind it, those being the American economy and enormous public and federal support. Left behind early in the space race, the United States acted largely in the shadow of the Soviet Union for several years. However, the advantage in resources available to the space program allowed the United States to catch and eventually surpass the Soviet Union when an American was the first man to land on the moon. This period saw subsequent unequalled levels of funding and public support for NASA, whose entire mindset was geared towards the advancement of human space travel. (Berirmen 23)

The Soviet space program enjoyed many early successes in manned spaceflight, and continues to be the leading authority on space station technology and research to this day. The first artificial satellite, the first space passenger, the first man and woman in orbit all headline the list of Soviet successes in the early manned space program. The space program was a great source of national pride and propaganda, as in the United States. Although limited by a smaller economy, the Soviet program achieved stunning successes, largely due to the genius of an engineer named Korolev. (Berirmen 27) The Soviet space program suffered a great loss by his death, and the subsequent recoil of the space program kept the Soviets from attempting a manned moon landing. Their attention was turned to space stations. The space stations *Salyut* and *MIR* are direct results of this shift in focus. The *Soyuz* was to be the vehicle of choice, later to be emulated by the Chinese.

This report predicts that both nations will arrive on the moon by the year 2020, the Americans landing less than a year before the Chinese in 2018. The race is predicted to be relatively even for much of the time, with the Americans the eventual victor due to a "final push" involving more advanced technology and a stronger economic backing. (Berirmen 30) The Chinese are predicted to have constructed space stations in both Earth and Lunar orbits by 2027, with construction of a lunar base beginning in 2029. The base is to be located near a crater at the pole in order to mine the frozen water there. Secure in their position as a space power, China will then offer cooperation in the reach for Mars. (Berirmen 100)

In 2030, the United States is completing construction of their most recent lunar base, "...the largest manned base ever to exist anywhere off the Earth's surface." (Berirmen 101) This is only the most recent in a series of bases, the first being comprised chiefly of inflatable in preparation for a Mars mission. The current base is constructing a large "hangar-like" structure, intended to be a stepping stone for Mars. (Berirmen 102)

Concerning the application of historic analogy in the question of technology forecasting, this study respects the relevance of historical context. The absence of technological innovation, or breakthroughs, is unfortunate. Such occurrences are fundamental to periods of intense competition, such as is evidenced in a space race. A breakthrough event could wildly shift a forecast, allowing one faction a distinct edge over its competitors. This study reasons that such breakthroughs are not only significant and possible, but also likely, and must be taken into account when creating a forecast of space technology.

3.2 Published Forecasts

What path will developments in space technology take in the next 25 to 50 years? This question is not an easy one to answer. Michio Kaku, in his book *Visions: How Science Will Revolutionize the 21st Century*, has made predictions about the state of space technology in 2020, 2050 and beyond. Kaku believes we will "undoubtedly … witness a vast number of stunning discoveries and milestones in space in the twenty-first century as scientists expand the present boundaries of knowledge" (Kaku 295). However, he mainly predicts incremental changes in the near future and technological breakthroughs only after 2050.

Kaku only mentions small incremental changes before the year 2020. For example, he mentions the expensive space shuttle and planes to replace it. In 1996 Lockheed Martin was paid one billion dollars to develop a new cheaper more efficient launch vehicle. X-33 Venture Star will take off and land on a conventional airfield, and only use rockets when it leaves the atmosphere. He predicts that by 2012 it will have completely replaced the shuttle. Kaku also mentions the aerospace plane that can take off and like an ordinary jet but uses rockets to reach Mach 23. He says "the goal of the hypersonic launch vehicles is to reduce the cost of launching low-earth-orbit satellites by 95% by 2009" (Kaku 303). Even though, the development of the X-33 and many of the other projects he mentions have already been canceled there are similar project going on today. For example, Space Ship One can land and takes off from an airfield then uses rockets to approach the "edge of space." Projects like Space Ship One may very well lead to reduction of cost launching low-earth-orbit satellites.

By the year 2050, Michio Kaku foresees much more drastic changes in space technology. "Beyond the year 2020 radically different types of rockets will be required to serve a new function: to carry out long-haul interplanetary missions in deep space" (Kaku 304). For these longer trips new kinds of rockets will be needed. Michio Kaku lists four possibilities: nuclear rockets, rail guns, solar sails and the ion engine. He feels that first three types all have serious drawbacks. A nuclear rocket could have a meltdown, rail guns accelerate too fast and solar sails are difficult to maintain in space. Kaku feels that ion engine will be the most popular type of propulsion for long voyages. The ion engine uses solar cells to produce electricity ionized gas ability to produce thrust. This thrust may be small but it can be maintained for long periods of time.

It is important to mention that Kaku believes that there are compelling reasons to travel to other planets in our solar system. Thousands of years ago meteors, believed to have originated from Mars, landed in Antarctica. Some of these meteors contain evidence that life existed on Mars 3.6 billion years ago. Kaku feels that these findings will entice scientists to explore our solar system. He believes that "The pace of space missions to Mars will uncountable quicken if the findings by scientists at the Johnson Space Center concerning the existence of microbial life on Mars are substantiated." (Kaku 296).

After 2020 he predicts that "long-haul" missions in space will be possible but colonization will still be too expensive. However, Kaku claims, "this will not stop thinkers from laying reasonable scientific hypotheses about the cost of constructing space colonies" (Kaku 308). Kaku even mentions attempting to "terraforming" our neighboring planets by building robot chemical stations that would produce green house gasses capable of raising the planetary temperature. Even though this process would take hundreds of years but Kaku believes we can attempt to start the project in the between 2020 and 2050. Although changing the landscape and climate of an entire planet is an amazing feat, Kaku does not provide much explanation and the effects would not be witnessed anytime in the near future.

Between 2050 and 2100, Kaku's forecast of space technology predicts vast changes and advances. He writes about building starships that can approach the speed of light allowing humans to travel to distant stars. He also discusses suspended animation and other technologies that are currently only mentioned in science fiction.

Kaku's predictions for 2020 seem based on what NASA and other organizations plan to fund and develop in the next 20 years. Predictions for 2050 seem to be idea taken from technologies that are still in the early development. There were only few mentions of breakthroughs in technology, mainly in propulsion, in the next 50 years. However, he favors the ion engine, which we did not consider a technological breakthrough, but a progressing current technology. Kaku's predictions only seem to predict large changes after the year 2050, which is outside the scope of our study.

Unlike Michio Kaku, some forecasters believe that outer space travel will not be a dominant part of our technological future in the next 25 years. Hamish McRae is one such forecaster, who makes 25-year predictions of various aspects of the future of the world in his book, The World in 2020: Power, Culture, and Prosperity. McRae touches upon demography, resources and environment, trade and finance, and government and society amongst the leading and forthcoming powerful countries in his forecast. He also predicts technological advances. He strongly believes extremely rapid advances in electronics are the dominant forces, and mechanical changes will only be incremental (166). McRae does not mention space travel in any part of his predictions.

Contrary to Michio Kaku, his belief is that, "there will be important changes which will indeed alter the lives…of many people a generation from now, but the technologies involved will be ones that in some form already exist" (164). He does not believe we are at a point in history where dramatic changes to the home and society will occur due to new mechanical technologies. There will be continuous progress, but it will parallel that between 1965 and 1990 rather than the revolutionary progress between 1900 and 1925, when completely new vehicles were created (168). Also, the question of which current technologies will be advanced is ambiguous. McRae feels that “few people managed to predict the new products and services, driven by social changes, that have been made possible by improved technology” (165) because of constantly changing patterns of peoples lives.

However, even though the direction of technological advances is unstable, McRae predicts electronics will be the key player. If breakthrough-type advances are to be made in the next decade, this is where they will occur. Many electro-mechanical technologies require advances in electronics, thus why people will not see drastic changes until this period occurs. In his book (written in 1995) he claims, “Much has been made of the idea that we are entering some kind of ‘information society’, where knowledge is king. The reality is more mundane. Information is of two main kinds: that which is available to all, and that which is particular to an individual or business” (175). He describes this “information” in terms of data-basing and states that countries that are good at creating software will beat out those that are better in hardware.

More broadly, McRae forecasts steady advance in thermal efficiency, carbon fiber technology, fuel cells, data compression, and fiber optics, with the world racing for electronic breakthroughs. Contrarily, we believe breakthroughs are apt to happen in any area, including mechanical advances. Electronics are tightly tied into current mechanical technologies and many breakthrough-type ideas. Therefore, leaps in electronic technologies are only part of the picture.

Advances made on earth, have implications for advances made in space travel and exploration. Aside from the extraterrestrial view of earth on the front cover, McRae does not include outer space in his forecasting book. This is surprising because space travel and exploration have a strong impact on "power, culture, and prosperity", the topics he expands upon in his book. Much research, both government and privately funded, is driven towards spacecraft dynamics. Also, space travel is becoming more commercial so everyday people will become more involved. International technological advances in space exploration will influence countries' standing. Therefore, leaving this factor out of a forecast is to say space travel is not a dominant force in the next 25 years. We feel it is influential enough to write an entire forecast about it as a worthy issue in its own right, and with transforming potential in interaction with other trends.

Another notable published forecast is that of Marvin Cetron and Owen Davies. Cetron is the president of Forecasting International, a think tank that advises the government and Fortune 500 companies. Davies is a freelance writer about science and technology. With Cetron's forecasting experience, and Davies' ability to write about science and technology, what better to write than a book about the future of technology? So, between the two of them, they wrote, <u>Probable Tomorrows: How Science and Technology Will Transform Our Lives in the Next Twenty Years</u>. Their book was published in 1997, and only projects into the next 15 to 20 years, thus leaving the reader of 2005 the ability to evaluate their success to a large degree. Cetron and Davies were astoundingly correct on many things; foreseeing the boom of Internet commerce, for example.

They were, however, also trapped into making mistakes common to the era. They picture the same Internet as a giant research library with the entire published works of the world, as people were apt to do in the mid 1990's. We know eight years later however, that such libraries are subscription services only available to universities and far from complete, and that the Internet of the common person is mainly limited to email and shopping; it is the modern bazaar. Cetron and Davies fell into a trap often sprung by forecasters. They state in their preface that "For an idea of what is to come … look to the past" (Cetron and Davies x). They look in the past for trends, and then project those trends into the future. The possibility of breakthroughs, political change, or cataclysmic events is ignored, even though history itself is littered with them.

This book, like McRae's does not see space taking a prominent role in the near future. There is a chapter on space travel, but this chapter's title is "The Long Climb Back to Space" and states "…there will be no dramatic surprises in space. Humanity will not return to the moon. We will not establish our first Martian colony, or even commit ourselves to doing so," (Cetron and Davies 133). The two predicted a much heavier development of unmanned probes and were unsure of the fate of the International Space Station. They believed it would fly, but doubt its proposed completion date of 2002. In 2005, we know that the station is still unfinished. Cetron and Davies also rightly predicted the cancellation of the X-33 project. Furthermore, this duo predicted the commercial space race which came to a head in late 2004 with Scaled Composite's Space Ship One, a launch vehicle which performed the stated goals of NASA's prematurely killed X-34. The international community is also looked at and given just as bleak a forecast, mainly based on the Russian's economic troubles and other nations' complete lack of any manned program.

Due to the accuracy of their forecast, thus far, the prediction that man will not go back to the moon is not to be taken lightly. However, in 1997, before even the Monica Lewinsky scandal, these men could not have known of President Bush's call back to space in January 2004 or of the Chinese plans to land on the moon before 2020. It is important to note that there are three years between 2020 – the year Bush wanted to be on the moon – and 2017 – the end of *Probable Tomorrows*' scope. However, our premise, breakthroughs will accelerate the placement of people on the moon, combined with the previous WPI projection forecast that the landing would be in 2018 demands that our moon landing be within the period of this book. Thus, we can compare our "breakthrough" future with this projected one.

Space was not the only area covered in *Probable Tomorrows* relevant to our project. We include several supporting technologies, and so did they. In the chapter entitled "Bricks for the High-Tech Future," Cetron and Davies spend several pages discussing "intelligent materials" like the memory plastics we put in our list of possible technologies. They picture a self-healing bridge built from these materials by 2012 (Cetron and Davies 71). In contrast to our view on a moon landing, we do not see structures like their bridge happening until around 2030. In addition, Cetron and Davies include a chapter on the energy of the future. They spend most of the chapter discussing global warming and power from photovoltaic cells, wind, and biomass. The only one of these that has any use – or even exists – in space is photovoltaic cells. These are, however, dreadfully inefficient and so we left them out of our future entirely. All is not lost though, for at the end of the chapter is a section on fusion power. Cold fusion dominates the discussion, only to be abandoned as implausible. When hot fusion is finally considered, Cetron and Davies predict a prototype fusion reactor around 2012 (Cetron and Davies 173). Our panels' initial response however was that fusion, if it ever became feasible, would get to a similar stage about 40 years later.

3.3 Potential Breakthroughs

3.3.1 Dyson

In Freeman Dyson's The Sun, the Genome, and the Internet, Dyson delves into new technologies that have a hold in both social and political areas, but also influence science as a whole. He provides scenarios of possible futures with the new technologies that he discusses ranging from foreseeable possibilities to pure science fiction. Each of the technological breakthroughs he mentioned that had some bearing on space travel was used in our own research.

Dyson first introduces the reader to a form of propulsion that uses high powered lasers to launch objects into low earth orbit (LEO) based on the work of Leik Myrabo at Rensselaer Polytechnic Institute (RPI). It works by applying a laser to a surface in two stages to propel it upwards. The first pulse of the laser is short, and is designed to vaporize a thin layer of the surface material. The second, longer, pulse is applied a few microseconds after the first to let the vapor from the first pulse expand, and `sends a shockwave to the surface projecting it away from the laser. After the second pulse, the process waits until the vapor clears, and then repeats 10 times per second. While launching in the atmosphere, water could be used as the "surface" held in a sort of sponge. As water vaporizes from the surface of the sponge, more water seeps through the sponge to the surface to get hit by the laser. However, to carry a heavy payload to LEO would require a breakthrough in laser technology. Dyson speculates that with a powerful enough laser it would take about 6 minutes of powered flight to reach LEO from a mountaintop with such a system.

Dyson also describes a scenario using a ram accelerator as a launch method. The ram accelerator works as a stationary ramjet engine by accelerating a launch vehicle inside of a steel pipe. The pipe would be built into the side of a mountain, measure about 750 feet long, and be filled with a yet-unknown combustible mixture of gasses. When the gas is ignited, it projects the launch vehicle upward at about 30,000 G's. The launch capsule must be designed long and slender to prevent drag in the atmosphere, and have a sharp point at the top to prevent the force of the launch from igniting the gases above the launch vehicle in the pipe. To prevent friction against the pipe, the launch vehicle is slightly smaller in diameter then the pipe, and uses the gas in the tube as a cushion. The extreme g-forces make this style of launch impossible for humans, but could be used to transport various types of cargo (especially fuel) to LEO.

Dyson describes a device know as the slingatron as well, a device that could be used to propel launch vehicles and cargo both on earth and in LEO. The slingatron was designed by Derek Tidman of Datassociates to hurl things into space; however, there is also a great potential in propelling supplies already in orbit to further destinations. The slingatron consists of a smooth ball-shaped launch vehicle within a hollow ring shaped tube. Also, within the pipe is a pressurized gas used to prevent friction between the launch vehicle and the ring. To launch, the ring is moved in a circular motion (around points on its base as opposed to rotating around its center), which continually increases the speed of the ball until it is released from the ring and is launched into orbit. The final version would have to be at least a few hundred feet in diameter to achieve velocities high enough to escape from orbit and would subject the launch vehicle to accelerations as high as 1,000 gees making it viable for launching fuel and other supplies (but not humans) to destinations outside of orbit.

Dyson also inspired an idea that could prove to be of importance in technologies for life support during extended visits beyond our atmosphere, a bionic leaf. His premise was to engineer a tree with black leaves that would be 15% efficient in using solar energy rather than the paltry 1% of Earthly green tree leaves. We turned his genetic engineering into a machine made of black silicon and aluminum honeycombed with fine hair-like tubing that is the outside part of the plant situated on the lunar surface. It can synthesize carbon dioxide and water into a carbohydrate in direct or indirect (reflected from a satellite) sunlight. Inside or underground (in a protected area) the tubers, ears of vegetables and fruits store the resulting sugar coming in from the leaves in tubes as in normal agriculture they travel through the stem or trunk of a plant. So, the key is to supply this system with carbon dioxide and water. Oxygen can be mined from moon soil (regolite), so carbon and hydrogen are the elements in short supply that must be "imported" to kick off the system and then be recycled without serious loss.

Dyson's work opened our eyes to what types of biological and agricultural technologies could prove to be breakthroughs. With these breakthroughs in mind we had a better idea of how to discover other possible breakthroughs in other literature.

3.3.2 Science Fiction

Another IQP group working simultaneously at WPI studied potentially realistic space technologies within science fiction literature. They provided a few technological breakthroughs, and also some information on breakthroughs being researched by our team. The information provided was in areas of propulsion in space and shielding. This proved to be important in the decision process of which technologies are considered breakthroughs. Propulsion methods include a magbeam, solar sails, a thermal drive, and an ion drive. The shielding method they describe used electromagnetic fields.

The magbeam that was researched is unique in that it removes the propulsion mechanism / power source from the launch vehicle. The power source is kept in stationary orbit and it "fires" a focused plasma beam to accelerate a vessel in a particular direction until the desired velocity is reached. This technique requires another stationary source at the destination point to decelerate the ship in the same fashion. This scenario can be used to propel several vehicles at once and could use solar panels for power. A breakthrough in the engineering of a full-scale "magbeam satellite" that is easily placed into orbit would allow a huge advance in space travel.

A solar sail propulsion system is of great interest as it works by capturing light pressure within large metal film sails, and using the force to push a "ship" through the within the solar system. The advantage to this is the theoretical speed that could be achieved, which is some large fraction of the speed of light. The limiting factor is material. It must be light and strong enough to create a sail many times the size of the spacecraft that could withstand the solar forces. A breakthrough in solar sail material has potential to rid onboard fuel requirements and influence space travel time and distance.

The thermal drive is very similar to the nuclear drive and Prometheus project that is currently being researched at WPI. It is based primarily on nuclear reactions causing high temperatures, and these high temperatures are used to heat water, or some other liquid, to vapor and then to use the vapor to either generate power or for use in propulsion. In the form of propulsion, the vapor is then forced out an exhaust port and creates thrust. However, there is a need for radiators that can manage this excess heat efficiently due to the lower heat dissipation performance in space. The benefit of nuclear drives is that if the core temperature is brought to a sufficient level, around 2000 to 3000 K, then this drive will have the best thrust to propellant ratio of any of our current forms of propulsion.

The Ion drive is works by charging a particle to either negative or positive (making it an ion) and then making a network a distance away from it the opposite charge, therefore making the particle accelerate and then, when the particle leaves the craft, it causes the craft to accelerate. The problem with such a drive is that it requires a significant amount of energy to ionize the particles and to create the opposite net that creates the acceleration. With current technology it takes 15 months to move a probe to the Moon. The major benefit of an ion drive is that the drive requires small amounts of material to create movement. 72kg of xenon gas on a satellite allowed for 16,000 hours of run time of the ion drive.

A form of shielding that would be important for space travel in the future involves the use of electromagnetic fields. Electromagnetic fields can be used as a method of protection from elements in space and can be used to repel radiation. A limitation of the technology is that it may not be able to assist in atmospheric reentry as a result of a planet's magnetic field. The major concern is that a lot of power is required to make a field that is large enough to provide any considerable amount of protection. Thus a breakthrough in energy production would be able to sustain the necessary protective electromagnetic shields for an extended period of time.

This group’s work provided us with ideas for the majority of the propulsion technologies that would appear in our questionnaire and also provided an idea for a future form of shielding. Despite these technologies’ origins in science fiction, their use in the future seems entirely possible and would definitely constitute a breakthrough.

3.4 Methodology Literature

3.4.1 Delphi Methods

The application of the Delphi Method to a corporate or industrial environment is important to our understanding of the process applied to space technology. Future forecasts are the central reason for Delphi studies in the corporate environment, and are researched and analyzed by Lawrence H. Day in his article, “Delphi Research in the Corporate Environment.” This article is found in *The Delphi Method: Techniques and Applications*, edited by Harold A. Linstone and Murray Turoff. Day begins by stressing the importance of the Delphi method in corporate forecasts, despite the lack of detailed information on specific studies. This he attributes to the proprietary nature of the studies' results, which are often, if not always, kept confidential.

Day describes three distinct types of corporate Delphi studies. Each differs from the other in the source of the monitors, those who actually perform the study and analyze the results. These types of studies are “Industrial Grouping or Professional Association Sponsorship”, “Individual Corporate Sponsorship,” and “Corporate In-House Delphi Research.”

Day comments on various benefits and drawbacks of the Delphi method. Such issues include the predilection of the Delphi method for future forecasts and technology assessments, the question of long-term versus short-term reward as applies to funding of Delphi studies, the undesirable posture of Delphi results as they affect corporate policy, among others. The concerns about the Delphi method are directed chiefly towards the marketing applications of the results and the application of the study itself. As these are largely unconcerned with the Delphi study as a practice, they can be affordably discounted or compensated for.

The first type of corporate Delphi study, with which our project is most concerned, is the "Industrial Grouping or Professional Association Sponsorship." As Day explains, "These studies are usually of a broad nature and are concerned with projecting the future of an industry or perhaps even some broader societal field." These studies are conducted primarily by professional organizations that are independent of the sponsor. They are conducted on a very broad subject, and generally examine the future of an industry or the societal impact of that industry's technological development. These studies are not usually concerned with developing corporate strategies. However, individual corporations often consume the results of the study rather than conduct it themselves. Such studies are often undertaken by multi-client organizations such as consulting firms.

The second type of corporate Delphi study is the "Individual Corporate Sponsorship." This type of study is made up of "...Individual corporations who sponsor Delphi studies at research organizations on subjects of general or specific interest." An individual corporation initiates these studies, and then out-sources them to an independent organization, which then performs the study and reports the results directly to the initiating corporation. This type of

Delphi research is relatively rare, although Day offers reasons to expect an increase in its frequency.

The third type of corporate Delphi study is the "Corporate In-House Delphi Research." The title is rather self-explanatory. The initiating corporation has within it a division, usually related to marketing or research and development, which conducts the study entirely within the confines of the experts in the corporation. This type of study includes most proprietary uses of Delphi, and so is not likely to be published. This method is one of the most popular techniques of companies interested in technology forecasting, explains Day.

The type of study most applicable to our project is the first. Although we do not represent a professional organization, we are operating independently of any of the concerned corporations, such as NASA, an aerospace company, physics department, or biotechnology companies. Our project is concerned with the very broad field of space technology, and as such is not overly concerned with its application towards company policy.

A detailed example of a corporate Delphi study is presented by Day. This is the study conducted by Bell Canada, a telecommunications company serving the provinces of Ontario and Quebec. The study was performed in order to "evaluate future trends in the visual and computer communication fields." The lack of data relating to the potential of these fields, especially in the Canadian environment, prompted the use of the Delphi method. A standard Delphi study was conducted. The experts were grouped in four panels related to education, medicine, business, and the future of home services. Internal disputes over what constituted an expert in the field of home services were avoided due to the inclusion of housewives as well as experts through research and planning. This was done primarily because of the focus on customer reception of the future technologies.

Day comments on some of the benefits of the Delphi method applied directly to corporations. The nature of North American technology companies to be individually owned yet federally regulated is suited to the Delphi study. The sharing of Delphi results can lead to a common assessment of technological direction in both the private and public sector.

The educational tool for management that is embodied by the Delphi results are important for corporate use. Future planning is greatly helped by the knowledge of technological direction and acceptance or use of the developed technologies.

The use of the Delphi method can achieve results not possible with ordinary market research. For example the use of polling leads to a limited foundation of data, i.e. participants are limited in their responses, so full, developed opinions can not be determined. No communication or integration of ideas can take place in a study such as polling, whereas the Delphi method fosters those very things.

Concerns about the Delphi study as it applies to the corporate environment do exist. The primary objection to the use of Delphi is the cost. Such in-depth research projects are typically quite expensive, as they may continue for several years. The cost-effectiveness of such a study is not apparent, as the benefits are long-term by definition. As long-term planning (along with societal impact) becomes more and more important in corporate policy decisions, the cost-effectiveness of the Delphi method increases.

The perceived precision of the Delphi results can be detrimental. The nature of Delphi research is very subject to interpretation. The data exists to provide a quantitative measure of amalgamated opinion. As such, uninformed users of the research data could easily misinterpret, and thus misuse, the data available.

It is important to corporations for it to be understood that the Delphi results are not official policy. The fear that the results might be wrongly portrayed as a company stance is a real one, and one to be guarded against. Also, the publication of Delphi results as a public relations tool can be detrimental to the integrity of the study, as it would have been carried out with an initial guarantee of anonymity.

The perceived negative aspects of the Delphi study addressed by Day are of little application to our project. Being chiefly connected to market applications and policy decisions, these detriments are not directly related to the actual assessment of future technology.

Day's focus on the corporate aspects of Delphi research is appropriate enough to the future of space technology. The corporate emphasis on future forecasts mirrors our focus on future technological development. In applying the Delphi method to a problem that is complex, which has no analytical solution and can only be solved through an aggregation of opinion, our project corresponds in several ways to the corporate concerns that prompt Delphi research.

3.4.2 The MBTI

The Myers-Briggs Type Indicator (MBTI) is an instrument used to identify people's preferences among sets of mental processes (Lawrence 1995). Each item answered is counted on one of four scales, each scale having two extremes. This creates 16 combinations, which represent 16 cognitive types. The four scales are Extraversion versus Introversion, identified as

E versus I; sensing perception versus intuitive perception, S versus N; thinking judgment versus feeling judgment, T versus F; and judgment versus perception, J versus P.

Based on Lawrence's descriptions of these categories, we choose to use two of the four scales, separating our panelists into only four types. The first scale is S versus N. According to Lawrence, someone who uses sensing (S), perceives with five senses, attends to practical factual details and the present moment, and lets 'the eyes tell the mind;' while someone who uses intuition (N), perceives with memory and associations, sees patterns, meanings and possibilities, projects possibilities for the future, and lets 'the mind tell the eyes'. Since the basis of our questionnaire is thinking into the future, from this literature it seems essential that someone is willing and able to use intuitive perception to do so. The second scale we use is J versus P. According to Lawrence, someone who takes a judging attitude, uses thinking or feeling judgment outwardly, decides and plans, is goal oriented and wants closure, even when data are incomplete; while someone who takes a perceiving attitude, uses sensing or intuitive perception outwardly, takes in information, is open-minded and resists closure to obtain more data. Whether our panelists take a judging or perceiving attitude may influence their interpretation of our questionnaire, especially in their responses to scenario-based questions.

In an article about the MBTI, Peter Geyer gives an example of how to interpret S versus N; however, he notes that there are more complexities to the concepts than seen in the example:

People preferring Sensing can be seen as practical and down to earth, relying on either past experience or what they see in the moment, while people preferring Intuition can be seen as visionaries or idealists, more interested in the future, or some timeless principle (1).

He claims that in academic institutions, N-type people "outnumber [S-type] people quite comfortably". S-type people are "often attracted to work in large organizations" and "predominate in teaching, small business, banking, law enforcement, sports etc." (1).

Peter Geyer also gives an example of how to interpret J versus P:

A person preferring Judging likes to make decisions and may want to be scheduled and ordered, driven by lists and timeframes and expecting the same of others, whereas a person preferring Perceiving may not make a decision until the last possible moment, preferring a more spontaneous approach to life and work and resisting closure until it's time (1).

He also claims those who use their judgment "predominate in management positions" and those preferring a perceiving attitude "predominate in marketing, entrepreneurial activities and counseling" (1).

When S versus N and P versus J scales are viewed simultaneously, four personality types can be compared: SP-type, SJ-type, NJ-type, and NP-type. We categorized our alumni panelists in this manner. However, Lawrence describes the characteristics of all 16 types (2-5). Therefore, each of the following descriptions for our panelists comes from a combination of two of Lawrence's descriptions, based on those with sensing or intuitive as the strongest determinant of psychological type.

SP-type panelists are the "realistic adapters" in either the world of material things or in human relationships (Lawrence 4). They are oriented to practical, firsthand experience. Extraverted or Introverted sensing being their strongest mental process, they are at their best when free to act on impulses, responding to concrete problems that need solving or to the needs of here and now. They value plunging into new adventures; finding ways to use the existing system; clear concrete, exact facts; learning through spontaneous, hands-on action, by following inspirations; nonconformity; being caught up in enthusiasms (4).

SJ-type panelists are the sympathetic or analytical "managers of facts and details" (Lawrence 5). They are dependable, conservative, systematic, painstaking, decisive, and stable. Having introverted or extroverted sensing as their strongest mental process, they are at their best when charged with organizing and maintaining data and material important to others and to themselves or when using their sensible intelligence and practical skills to help others in tangible ways. All of our SJ respondents are indeed, ISTJ-types. Therefore, they value: a controlled outer life grounded in the present; following a sensible path, based on experience; proved systems, common sense options; skepticism. From this it seems they would not be as likely to volunteer to be breakthrough-oriented panelists (5); the task is too speculative.

NJ-type panelists are people-oriented or logical, critical, and decisive "innovators" of ideas (Lawrence 4). They are serious, intent, concerned with work that will help the world, and may be stubborn. With intuition as their strongest mental process, they are at their best when inspiration, envisioning turns insights into ideas and plans for improving human knowledge and systems, and/or it empowers them and others to lead more meaningful lives. They value imaginative problem solving, probing new possibilities, taking the long view, and maybe theorizing (4).

NP-type panelists are inventive, analytical or warmly enthusiastic "planners of change" (Lawrence 5). They are enthusiastic and independent, pursue inspiration with impulsive energy, seek to understand and inspire. They are at their best when caught up in the enthusiasm of a new project and promoting its benefits. Within this category, those who are

ENTP-type are the most "out there"; they are the most future-bound visionaries. Therefore, based on this knowledge, this is the type of experts we expected to be attracted to participate in our panel. These types value conceiving new things and initiating change; analyzing complexities; ingenuity, a fresh perspective, flexibility and adaptability; both spontaneous learning and work made light by inspiration; and improvising, or looking for novel ways (5).

4. RESULTS

The following tables are grouped by the five categories: launch vehicles, life support, materials, propulsion, and shielding technologies. The likelihood and significance of each technology was rated on a 1 to 6 scale; details of which can be found in appendix A1. The time frames were rated on a 1 to 4 scale with 1 being early (in the next 15 years) and 4 was never.

4.1 Alumni Panel Results

4.1.1 Likelihood Ratings

	Likelihood				
	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
SSTO	4.5	4.0	4.7	4.7	4.3
Ram Accelerator	3.2	3.4	3.4	3.3	2.8
Laser Propulsion	3.3	3.4	3.1	3.3	3.4
NPSE	2.6	1.8	3.0	2.5	3.4

Table 4.1: Likelihood of Launch Vehicles – Alumni

For the likelihood of launch vehicle breakthroughs, single stage to orbit (SSTO) is the clear favorite among the alumni panel, with the nanotube polymer space elevator (NPSE) receiving far less support though the NPs are the only ones to see it as more likely than the ram accelerator. All four cognitive groups seem to agree to a certain extent about these technologies; there are few striking differences for the likelihood ratings for the launch vehicles.

Likelihood

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
The Gravity Implant	3.7	4.6	3.0	3.6	4.0
Fusion Reactors	3.6	3.0	4.0	3.3	3.9
LEO CAC	3.2	3.2	3.4	3.0	3.1
Roving Lunar Base	3.3	2.8	3.4	3.4	3.3
The Bionic Leaf	2.9	3.4	2.1	3.0	3.3

Table 4.2: Likelihood of Life Support Technologies – Alumni

There is no clear-cut technology which likelihood is strongly dominant over the others, however, the gravity implant and fusion reactors are preferred, and the bionic leaf is not. For the gravity implant, there seems to be much disagreement between the Ps and Js; perhaps this variable will be a factor as we look at other controversial technologies as well. However, the SJ and SP types each have a clear favorite, the fusion reactors for the SJs and the gravity implant for the SPs. The NJs consider the gravity implant and the roving lunar base approximately equally likely and the NPs consider the gravity implant and fusion reactors equally likely. Hence, the leading choice of three of the four types is the gravity implant, which is a far newer and radical idea than fusion energy generation.

Likelihood

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Carbon Nanotubes	4.8	4.8	4.6	4.5	5.5
Memory Plastics	4.7	4.0	4.6	4.4	5.5
Solid State Aircraft	3.3	3.6	3.1	3.0	3.5

Table 4.3: Likelihood of Material Technologies – Alumni

There is no overwhelming favorite in the likelihood of material technologies category, as the carbon nanotubes and memory plastics received similar marks, however, the likelihood of the solid state aircraft is clearly being questioned. The NP group of participants is the most optimistic about all three technologies, but the Ps overall are rating the solid state aircraft at a level roughly comparable with their view of fusion in the last section. It is the Js that consider it a long shot.

	Likelihood				
	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Solar Sail	4.6	5.2	4.6	4.7	4.3
Nuclear Drive	3.8	4.0	4.3	3.3	3.9
Magbeam	3.4	3.4	3.0	3.7	3.4
Slingatron	2.7	3.0	2.3	2.6	2.9

Table 4.4: Likelihood of Propulsion Technologies – Alumni

For the likelihood of propulsion breakthroughs, the alumni panel prefers solar sails, and the slingatron's likelihood is clearly questionable. All cognitive style groups gave the same ranking order of responses, which could prospectively disprove the theory that a specific cognitive type might be more optimistic about visionary ideas. However, the actual ratings for the leader varied from 4.3 to 5.2, so the question is not settled yet after looking at three sets of potential breakthroughs. What is emerging is a pattern in which the NP spread between the most and lease likely possibility is not as great as for the other types. For both launch vehicles and propulsion technologies, they rated the leader relatively low and the lest likely one relatively high – seeming to see them as a more equally likely contender than the other types. For life support and materials, they were relatively optimistic; they do seem to be the group to watch – that they break from the consensus.

Likelihood	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Aerogel	4.9	5.0	5.1	4.7	4.9
EM Shielding	3.8	3.6	3.7	3.6	4.3
Cold Plasma	2.8	3.2	2.7	2.2	3.4

Table 4.5: Likelihood of Shielding Technologies – Alumni

Aerogel's likelihood is the strong favorite across the board, with electromagnetic shielding the obvious second. The NPs are the most skeptical about the leader this time, but are the most positive about the other two technologies. The cold plasma idea received little support, with the exception of the NP group, who were the most optimistic for two of the three shielding technologies; the NJ group was the most skeptical of all the groups for the technologies in this category.

4.1.2 Significance Ratings

Significance	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
SSTO	4.1	4.4	4.1	4.7	3.8
Ram Accelerator	3.4	3.6	3.4	3.3	3.3
Laser Propulsion	3.9	4.2	3.1	3.3	4.1
NPSE	4.1	4.6	3.0	2.5	4.5

Table 4.6: Significance of Launch Vehicles - Alumni

In terms of the launch vehicle breakthroughs, the alumni split along the J-P line. The Js dislike the SSTO and the Ps like the space elevator idea, which the Js rated in last place for significance. Overall, the alumni produced the same average rating for both of these technologies. The NPs then gave the second place to laser propulsion, while the SPs gave it to

SSTO, rating laser propulsion a close third. The ram accelerator average rating is similar for each cognitive group ranging only from 3.3 to 3.6. However, that is *second* place for the SJs after SSTO, and last place for the SPs and NPs. The NJs considered the ram acceleration and laser propulsion ideas equally significant and clearly more significant than the space elevator idea which they seemed to consider truly insignificant.

Significance

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
The Gravity Implant	4.6	4.4	4.1	3.6	4.6
Fusion Reactors	4.7	4.8	4.7	3.3	4.9
LEO CAC	4.4	4.8	3.7	3.0	4.3
Roving Lunar Base	3.6	4.6	3.1	3.4	3.1
The Bionic Leaf	4.3	5.0	3.6	3.0	4.1

Table 4.7: Significance of Life Support - Alumni

For the significance of the breakthroughs in life support, the alumni consider the creation of fusion reactors to be slightly more important a development than the other possible breakthroughs, with the gravity implant a close second. Only the roving lunar base was widely considered to have little significance. The most optimistic type in terms of the significance of these breakthroughs was the SP group, with their cognitive opposites, the NJ group seeming to be the most pessimistic about the value of these developments.

Significance

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Carbon Nanotubes	5.1	5.2	5.2	4.5	5.0
Memory Plastics	4.8	4.6	4.1	4.4	5.3
Solid State Aircraft	3.8	3.8	3.0	3.0	4.4

Table 4.8: Significance of Materials - Alumni

For the most significant of the breakthroughs in materials, the alumni believe carbon nanotubes will have the most significance; they had the highest rating for significance from all of the cognitive types except for the NPs who favored memory plastics but still gave the nanotubes a high rating. The most optimistic type in terms of significance was the NP group, other than the SPs, and again, the least optimistic nanotube rating came from the NJ group. The SJs were equally or more pessimistic about the other two technologies. One has a J-P split again, with the Js less optimistic overall, but the NJ and SJs not agreeing on what the most promising technology is. The Ps would concur on what the least promising is, but not how low the significance rating should be.

Significance

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Solar Sail	4.7	5.2	4.4	4.7	4.8
Nuclear Drive	3.7	3.6	3.7	3.3	4.1
Magbeam	4.3	5.4	4.1	3.7	4.0
Slingatron	3.0	4.0	2.6	2.6	2.8

Table 4.9: Significance of Propulsion - Alumni

In the category of propulsion, the alumni overall think the magbeam and solar sail would have the most significance compared to the other possibilities, and the slingatron has the least significance of all. The SP group frequently stood out with high ratings, with the NJs usually had the lowest ratings.

Significance

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Aerogel	4.7	5.0	4.4	4.7	5.0
EM Shielding	4.2	4.4	4.3	3.6	4.6
Cold Plasma	4.4	4.2	3.7	4.6	4.9

Table 4.10: Significance of Shielding - Alumni

For the significance of the breakthroughs in the shielding category the alumni saw little difference in the options, but rated the aerogel slightly more significant than the other possible breakthroughs. Most of the results in this category are high and the results only differ slightly for each breakthrough. The most optimistic cognitive type in terms of significance, was the NP group, with the least optimistic group overall being the NJs again. However, it is worth noting that the possibilities in aerogel excited the Ps more than the Js and that cold plasma was nearly as exciting to the Ns as aerogel. The Ss were inclined to put cold plasma in last place, but not the Ns. Hence the most notable difference is in the J-P ratings with some intertwined S-N difference.

4.1.3 Timeframe Ratings

Timeframes	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
SSTO	1.5	1.8	1.7	1.2	1.6
Ram Accelerator	2.2	2.3	2.0	3.3	2.2
Laser Propulsion	2.6	2.5	2.3	3.3	2.2
NPSE	2.7	3.0	3.0	2.7	2.2

Table 4.11: Timeframes of Launch Vehicles - Alumni

In the timeframe category, it appears as though the single stage to orbit will be the first to be developed, with laser propulsion and the space elevator lagging well behind. There do not appear to be any consistent correlations between cognitive style and the timeframe rating, other than the NPs estimate that laser propulsion and the space elevator will arrive earlier than everyone else think they will. However, the result is a total N estimate for the space elevator well before the Ss expect to see one.

Timeframes	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
The Gravity Implant	2.0	1.3	2.7	2.2	2.1
Fusion Reactors	2.7	2.8	2.7	2.6	2.8
LEO CAC	2.5	2.5	2.7	2.6	2.4
Roving Lunar Base	2.8	2.8	3.0	2.8	2.8
The Bionic Leaf	2.8	2.3	3.0	3.0	2.8

Table 4.12: Timeframes of Life Support Technologies - Alumni

In the life support timeframe category, the overall alumni believe that the gravity implant will be the first technology to be implemented, while the roving lunar base and the bionic leaf will take a long time. The SP group’s rating of the gravity implant is interesting, as they believe it will be implemented within the next 20 years, a much more optimistic outlook than any of the other alumni groups. The skeptics are the SJs who do not expect to see it anytime soon. While there is a high consensus on the LEO CAC and roving lunar base, there is not on the bionic leaf, which received the same average ratings as the lunar base. The Ps expect to see the bionic leaf as soon or sooner than fusion reactors. The Js consider that the lease likely and hence latest development to appear, well after fusion reactors.

Timeframes

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Carbon Nanotubes	1.8	2.0	1.7	2.0	1.4
Memory Plastics	1.6	1.8	1.7	1.5	1.4
Solid State Aircraft	2.4	2.3	3.0	2.3	2.2

Table 4.13: Timeframes of Material Technologies - Alumni

The alumni believe that memory plastics will be the developed slightly sooner than the carbon nanotubes, however, solid state aircraft is not as far behind as expected. The NP group is the most optimistic, overall, with the NJs again being the most pessimistic group – this is now a continuing trend in this study. The NPs not only expect to see carbon nanotubes early, they expect to see memory plastics at the same time. Combined, that would make for a very different field in aerospace design. By contrast, the NJs and SPs expect to see memory plastics first then carbon nanotubes 20-30 years from now. That implies that spacecraft of the more traditional type will be able to “heal” well before a space elevator is attempted. The NPs are essentially envisioning an early space elevator using both new materials.

Timeframes	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Solar Sail	1.8	2.0	1.3	1.5	2.4
Nuclear Drive	2.0	2.5	1.3	2.0	2.0
Magbeam	2.6	2.5	3.0	2.6	2.6
Slingatron	2.1	2.5	2.3	2.2	1.6

Table 4.14: Timeframes of Propulsion Technologies - Alumni

For the propulsion timeline, solar sails, nuclear drives, and the slingatron might all be created within 20-30 years, with the magbeam taking a while longer, possibly 40 to 50 years. The cognitive scores seem to be fairly close together, therefore no distinguishable analysis can be done in this category based on the averages, but the tank orders differ in an interesting way. The NPs, normally the optimists, see problems with the solar sail. Indeed, the sail is something the Js are more optimistic about than the Ps. The NPs join in a generally skeptical view of magbeam but are very optimistic about the slingatron, considering it the most likely to be developed early – in the next 15 years. Second place is the nuclear drive and at least the NJs and NPs agree on when it will appear, 20-25 years from now. The SJs expect to see it earlier and the SPs later than that, but in rank order, it is always number two, usually after the solar sail.

Timeframes	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Aerogel	1.2	1.0	1.0	1.3	1.2
EM Shielding	2.3	2.3	2.3	2.8	1.8
Cold Plasma	2.7	2.3	3.0	3.0	2.6

Table 4.15: Timeframes of Shielding Technologies - Alumni

Aerogel has amazing support from all of the cognitive types that it will be plausible in about the next 15 or 20 years. Again, the NJs are estimating the latest, but their rating is similar to that of the NPs in their case. The Ss are a group that are optimists. The NPs as a group break ranks and see EM shielding as arriving sooner than anyone else and right after aerogel. The SPs are the cold plasma optimists, though the Ps in general expect to see it before the Js.

4.1.4 Alumni Response Discussion

From these 15 tables, it can be said that memory plastics and carbon nanotubes will be the most significant, nanotubes and aerogel are the most likely, and single stage to orbit and aerogel will be the first technologies developed, around the year 2020. On the other end of the spectrum, the slingatron and the ram accelerator will not be of much significance, the slingatron and the space elevator will not be very likely, and the roving lunar base and the gravity implant will not be developed until 2050 or longer. However, the different cognitive groupings picture things a bit differently.

The most obvious difference in cognitive styles is the SJ group had a lower average score for the significance for all of the technologies, however, when the technologies are grouped together, it is clear to see that the NP group is regularly optimistic about the long shots, and the NJs are usually pessimistic. It was earlier stated that the N (intuition) types prefer to read between the lines and not be too affected by the current reality than sensing people; they focus on possibilities and relationships that can be subtle. The J and P differences are even more striking in the data - J-types are defined as tending to prefer a step-by-step approach to life, relying on external rules and procedures, and preferring quick closure. On the other hand, in P-types the perceiving function is stronger, and they rely on subjective judgments, and a desire to leave all options open. It appears as though those who rely on subjective judgments are often more optimistic than those who rely on external rules and procedures. They see to expect one of the “dark horse” technologies like the space elevator to come through and change space science drastically. The Js seem to resist the idea that that could happen.

4.2 Expert Panel Results

The panel of experts also completed the same survey, and their responses were also categorized in the same way; launch vehicles, life support, materials, propulsion and shielding technologies. One object of the survey was to determine if there was a significant difference in the responses based upon the professional base of the panelist. The panelists were divided into four professional bases; NASA, Academia, Planetary Society (space advocates), and Aerospace Industry. Each group was compared on each question to determine the rank order for the professional grouping and the panel overall. If there was no significant variation, it would justify an analysis comparing the Expert Panel as a whole with the Alumni Panel. The overall distribution of the panel was 5 from NASA, 6 from Academia, 3 from the Planetary Society, and 2 from Industry.

4.2.1 Likelihood Ratings

	Likelihood: Total	NASA	Academic	Planetary	Industry
Number in Group	(16)	(5)	(6)	(3)	(2)
SSTO	4.5	3.6	4.7	5.0	5.5
Ram Accelerator	2.8	2.4	2.5	3.7	3.0
Laser Propulsion	2.6	2.8	2.5	2.3	2.5
NPSE	2.4	2.4	2.2	3.3	2.0

Table 4.16 Likelihood of Launch Vehicle – Experts

For the likelihood of launch vehicle breakthroughs, single stage to orbit (SSTO) received far more support than any of the other launch vehicles, with the nanotube polymer space elevator (NPSE) receiving the lowest likelihood estimate. The four groups individually tend to identify the same extreme, but were not consistent in rank ordering the ram accelerator and laser propulsion systems. The Academics saw them as equally likely. Only the Planetary Society saw the space elevator as more likely than the laser system. There is no striking difference and overall the similarities are more striking than the differences.

Likelihood	Total	NASA	Academic	Planetary	Industry
Roving Lunar Base	3.4	3.5	3.3	2.7	4.5
Fusion Reactors	3.4	4.0	3.2	3.3	3.0
The Bionic Leaf	3.0	3.0	2.8	3.7	2.5
LEO CAC	2.7	2.5	2.8	2.7	2.5
The Gravity Implant	2.4	2.0	1.7	3.3	4.0

Table 4.17 Likelihood of Life Support Technologies - Experts

There does not appear to be as much agreement between the people in the different professional bases in reference to the likelihood of life support technologies. Overall, the panelists favor the roving lunar base and the fusion reactors, and do not foresee the gravity implant as likely as the rest. That result is due to the predominance of Academics on the Panel. Industry and Planetary Society were far more receptive to the idea. Although there is not always a significant disagreement between the professional bases, it does happen. There is not a noticeable consensus for these technologies.

Likelihood	Total	NASA	Academic	Planetary	Industry
Carbon Nanotubes	4.6	4.8	4.3	5.0	4.5
Memory Plastics	4.1	4.8	3.7	3.7	4.5
Solid State Aircraft	3.1	3.8	2.8	3.7	3.5

Table 4.18: Likelihood of Material Technologies – Experts

The expert panel is in complete agreement across the board for the likelihood of material technology. Carbon nanotubes are the most likely and the solid state aircraft is the least likely. Each job type also follows the same trend, although NASA members seem more confident in each technology than the others, except the Planetary Society experts.

Likelihood	Total	NASA	Academic	Planetary	Industry
Solar Sail	4.7	5.2	4.2	4.7	5.0
Nuclear Drive	4.3	4.6	4.2	4.3	4.0
Magbeam	2.5	2.6	2.3	2.7	2.5
Slingatron	2.0	1.8	1.7	2.7	2.5

Table 4.19: Likelihood of Propulsion Technologies – Experts

The likelihood of propulsion technologies was another that received complete agreement among the occupation types. The technology that is deemed most likely to work out is the solar sail, while the slingatron does not seem to be a very likely method of propulsion to the NASA or the Academics people. Although not a significant difference, the experts from the academic field are generally less optimistic about the workability of the non-rocket propulsion technologies.

Likelihood	Total	NASA	Academic	Planetary	Industry
Aerogel	4.9	4.8	4.8	5.0	5.0
EM Shielding	3.8	4.0	3.3	4.0	4.0
Cold Plasma	2.8	2.0	2.7	4.3	2.5

Table 4.20: Likelihood of Shielding Technologies – Experts

The aerogel is considered to be the most likely of the three shielding technologies, with cold plasma being the least likely. Once again, the job types are in agreement, with the exception of the Planetary Society, who are far more optimistic about cold plasma than the rest of the people expert in the field.

4.2.2 Significance Ratings

Significance	Total	NASA	Academic	Planetary	Industry
NPSE	4.6	5.4	3.7	5.3	4.0
SSTO	4.1	4.2	3.3	5.0	5.0
Laser Propulsion	3.6	5.0	2.8	3.7	2.5
Ram Accelerator	3.0	2.8	3.0	3.3	3.0

Table 4.21: Significance of Launch Vehicles – Experts

Although the experts are generally in agreement about the likelihood of these technical developments, they are not in agreement about the significance of them. There are very few similarities between the professional groupings and their significance ratings. This is clear in the narrow difference between the most significant space elevator (NPSE) and the least significant ram accelerator among Academics, whereas the NASA and Industry people see substantial differences between them.

Significance	Total	NASA	Academic	Planetary	Industry
Fusion Reactors	4.9	5.4	4.0	6.0	5.0
The Bionic Leaf	4.3	4.5	4.0	5.3	3.5
Roving Lunar Base	3.9	3.8	4.0	4.0	3.5
The Gravity Implant	3.6	3.5	3.0	5.0	3.5
LEO CAC	3.5	3.5	3.2	4.0	3.5

Table 4.22: Significance of Life Support - Experts

Fusion Reactors received the highest rankings from the experts, and the Planetary Society and NASA rank it very high in significance. The Academics are less impressed by the idea and rank it the same as two other breakthroughs. The experts for the most part are in agreement on the rank order of significance, with the Planetary Society being the most optimistic about the significance of all the potential breakthrough technologies.

Significance	Total	NASA	Academic	Planetary	Industry
Carbon Nanotubes	5.0	5.0	4.7	5.7	5.0
Memory Plastics	4.4	4.4	4.7	4.0	4.0
Solid State Aircraft	3.1	3.2	2.3	4.3	3.5

Table 4.23: Significance of Materials – Experts

Carbon nanotubes are the clear favorite among the expert panelists on significance. These three breakthroughs produce an agreement between three of the four groups, with each type following the same rank order of the technologies, with the exception being the Planetary Society forecasting the solid state aircraft as more potentially significant than the memory plastics.

	Significance				
	Total	NASA	Academic	Planetary	Industry
Solar Sail	4.4	4.6	4.0	4.7	4.5
Nuclear Drive	4.4	4.4	4.5	4.7	4.0
Magbeam	3.8	4.2	3.3	4.3	3.5
Slingatron	2.8	2.6	3.0	2.7	2.5

Table 4.24: Significance of Propulsion – Experts

The table shows an equal score for the solar sail and nuclear drive as the most significant. Once again, each job type is near consensus, with one exception, the Academics being the only group to consider a breakthrough in nuclear drive more significant than one involving the solar sail. In general, the experts do not see the slingatron as a very significant development.

	Significance				
	Total	NASA	Academic	Planetary	Industry
EM Shielding	4.4	4.4	3.8	5.0	5.0
Aerogel	4.3	4.6	4.0	4.3	4.5
Cold Plasma	3.8	3.0	3.8	4.3	4.5

Table 4.25: Significance of Shielding Technology – Experts

The range of ratings by the experts for the significance of shielding technology is very small as compared to the other data that has been collected. Overall, each professional has their preference, but they do not agree so the difference cancels out. The range from the most significant to the least significant is only 0.6. The EM shielding is rated the most significant and cold plasma is considered the least significant.

4.2.3 Timeframe Ratings

Timeframes

	Total	NASA	Academic	Planetary	Industry
SSTO	1.6	2.0	1.3	1.3	2.0
Laser Propulsion	2.4	2.3	2.3	2.5	3.0
Ram Accelerator	2.6	2.5	2.8	2.7	2.0
NPSE	2.8	2.8	2.7	3.0	3.0

Table 4.26: Timeframes of Launch Vehicles – Experts

For the timeframe predictions by the experts, it is important to remember that the lower number corresponds to an earlier timeframe. Hence, the single stage to orbit is considered likely to be the earliest breakthrough, with the ram accelerator and the space elevator developed in a much later timeframe. The order shows that professional base group is in basic agreement, with very minor differences that are not significant enough to change the overall data.

Timeframes

	Total	NASA	Academic	Planetary	Industry
The Bionic Leaf	2.3	2.3	2.3	2.3	2.0
Roving Lunar Base	2.4	2.3	2.3	2.5	3.0
LEO CAC	2.4	1.7	2.8	2.5	3.0
The Gravity Implant	2.6	2.7	3.0	2.0	2.0
Fusion Reactors	2.6	2.8	2.4	2.5	3.0

Table 4.27: Timeframes of Life Support Technologies – Experts

The experts did not generally see any of the life support technology breakthroughs appearing in the very near future. All of these technologies receive scores in the 2-3 range, and all with a very small range overall. These particular technologies do not show an overwhelming agreement between the professional category, but it once again there is not a significant difference between them. This can be shown because there is no real ranking among any of the job types; each job type predicts the technologies will all arrive in about the same timeframe.

Timeframes

	Total	NASA	Academic	Planetary	Industry
Carbon Nanotubes	1.5	1.6	1.2	2.2	1.0
Memory Plastics	1.7	1.5	1.8	2.0	1.0
Solid State Aircraft	2.0	1.3	2.0	3.3	2.5

Table 4.28: Timeframes of Material Technologies – Experts

Overall, the experts believe that the carbon nanotubes are the material technology breakthrough that will occur first, with the solid state aircraft having the longest timeframe. The groups for the most part agree, with NASA and the Planetary Society members both predicting the memory plastics slightly ahead of the carbon nanotubes, but they all concur that solid state aircraft will be arriving in the longest timeframe with the exception of NASA based professionals.

Timeframes

	Total	NASA	Academic	Planetary	Industry
Solar Sail	1.7	1.4	2.0	1.3	2.0
Nuclear Drive	1.7	1.2	1.7	2.0	2.5
Slingatron	2.7	2.8	2.8	2.5	2.0
Magbeam	2.7	2.8	2.7	3.0	2.0

Table 4.29: Timeframes of Propulsion Technologies – Experts

The propulsion technologies timeframe prediction produces one of the most interesting expert responses. The solar sail and nuclear drive have the same exact timeframe prediction, and in addition the slingatron and the magbeam also have the same prediction. This puts the solar sail and nuclear drive as the nearest breakthroughs, and the slingatron and magbeam as the furthest away. As the expert data has shown, there is a general agreement between each profession, with a few exceptions that are not significant enough to change the overall data pattern.

Timeframes

	Total	NASA	Academic	Planetary	Industry
Aerogel	1.3	1.2	1.4	1.5	1.0
EM Shielding	1.9	1.8	1.8	2.0	2.5
Cold Plasma	3.0	3.3	2.8	3.0	3.0

Table 4.30: Timeframes of Shielding Technologies - Experts

The expert opinion of the timeframe of shielding technologies shows a very large range from the predicted soonest breakthrough of aerogel to the predicted last breakthrough of cold plasma. These breakthroughs show an exact agreement between the different job types, with no differences in the rank order of them.

4.2.4 Expert Response Discussion

Based on the data collected from the expert responses, the professional groups have not made any significant difference in the overall ranking of the technologies. The similarities were more striking than the differences within each technology. In fact, most of the different technologies had a rank order consensus by three of four groups. The extreme tended to be the Academics group, with the ratings predictably more cautious, especially with the significance and the timeframe ratings. This finding allows us to group the expert responses into the larger expert panel, enabling a more reliable analysis of the expert vs. alumni responses. If there was no consensus, we would hesitate to pool the data. If there were no difference, it would not matter if we did it or not. The differences are just enough to enrich the data set by pooling the results without implying there is a consensus where the pattern is completely random. The second reason this benefits the analysis is simply because there was not an equal number of panelists from the different fields. When there was disagreement, the much larger and relatively conservative Academic and NASA groups would have overwhelmed the much smaller Planetary Society and Industry groups. We know where the minority disagreed before letting the majority rule.

From the data of the expert panel as a whole, it can be concluded that the aerogel, single stage to orbit, and the solar sail are the most likely of the breakthroughs. The most significant of the breakthroughs as predicted by the experts are the space elevator, carbon nanotubes, and the fusion reactor. The experts also predicted the aerogel, carbon nanotubes, and the single stage to orbit as the earliest breakthroughs to occur with the solar sail and nuclear drive shortly behind. Also according to the expert predictions, space elevator, gravity implant, and slingatron would be the least likely, the ram accelerator, slingatron, and solid state aircraft would be the least significant, and the cold plasma, space elevator, magbeam, and slingatron would have the longest timeframe to their creation.

4.3 Alumni and Expert Comparison

After careful analysis of both the alumni panel responses and the expert panel responses, the next step was the comparison of both these panels to examine the similarities or differences between the expert and the alumni predictions about the future of space and the rank ordering of the likelihood of breakthroughs.

The analysis of the alumni panel has shown the rank order of the alumni predictions, and this can be used in a comparison with the experts. In addition, the analysis of the expert panel also has shown no major difference between the different professional bases and the response to the likelihood, significance, and timeframe of the breakthroughs. What this does is enable us to pool the entire expert panel and the entire alumni panel to be analyzed against each other. If there is no major difference between the two panels, then another conclusion can be drawn as to whether or not we can use the alumni responses, which are both much easier to acquire and more information is available, to draw conclusions about the breakthroughs without the need to draw an expert panel in the future.

4.3.1 Likelihood Comparison

	Alumni	Expert
SSTO	4.5	4.5
Ram Accelerator	3.2	2.8
Laser Propulsion	3.3	2.6
NPSE	2.6	2.4

Table 4.31: Likelihood of Launch Vehicles – Alumni vs. Experts

The experts and the alumni are in close agreement on the likelihood of launch vehicle. The two panels concur that the single stage to orbit (SSTO) would be the most likely, and the space elevator (NPSE) the least likely, but the ram accelerator and laser propulsion are considered about equally by both groups and are switched in rank order between the two, with the experts thinking the ram accelerator is more likely than laser propulsion and the alumni thinking the reverse. The experts also are less optimistic about those two technologies being developed.

	Alumni	Expert
The Gravity Implant	3.7	2.4
Fusion Reactors	3.6	3.4
LEO CAC	3.2	2.7
Roving Lunar Base	3.3	3.4
The Bionic Leaf	2.9	3.0

Table 4.32: Likelihood of Life Support Technologies – Alumni vs. Experts

In the likelihood of life support technologies, there is much less agreement. In fact, this actually shows a large disagreement, with the alumni predicting the gravity implant as the most likely, and the experts predicting it as the least likely. Of the five technologies, only one received the same rank, both panels saw the LEO compressed air collector as the second to last likely life support technology. The rank order is different, but three out of the five technologies are rated similarly between the two panels; fusion, roving lunar base, and the bionic leaf.

	Alumni	Expert
Carbon Nanotubes	4.8	4.6
Memory Plastics	4.7	4.1
Solid State Aircraft	3.3	3.1

Table 4.33: Likelihood of Material Technologies – Alumni vs. Experts

Carbon nanotubes are the most likely material technology for both the expert and the alumni panels; however they are a little more likely for the alumni and substantially more likely for the experts than the memory plastics. Both panels also vote the memory plastics second and the solid state aircraft as the least likely of the technologies. Not only does each panel have the same rank, but they also are very similar in magnitude for all but the memory plastics, which the alumni see more likely than the experts see the carbon nanotubes. Again, the alumni seem more optimistic; in this case about the likelihood of all three, but especially in memory plastics.

	Alumni	Expert
Solar Sail	4.6	4.7
Nuclear Drive	3.8	4.3
Magbeam	3.4	2.5
Slingatron	2.7	2.0

Table 4.34: Likelihood of Propulsion Technologies – Alumni vs. Experts

The likelihood of propulsion technologies shows another rank order agreement between the experts and the alumni panels. Once again, the rank is the same with the solar sail being predicted as the most likely, and the slingatron the least likely. However, the magnitude of each prediction varies in the middle technologies and even the slingatron. The alumni are much more optimistic about the magbeam and the experts are about nuclear drive.

	Total	Expert
Aerogel	4.9	4.9
EM Shielding	3.8	3.8
Cold Plasma	2.8	2.8

Table 4.35: Likelihood of Shielding Technologies – Alumni vs. Experts

This group shows a very interesting comparison of the alumni and the experts, not only do they follow the same rank, but they also predict each technology with the exact same score, with the aerogel voted most likely and cold plasma voted least likely.

4.3.2 Significance Comparison

	Alumni	Expert
SSTO	4.1	4.1
Ram Accelerator	3.4	3.0
Laser Propulsion	3.9	3.6
NPSE	4.1	4.6

Table 4.36: Significance of Launch Vehicles – Alumni vs. Experts

The alumni panel has the same significance score for the likelihood of the space elevator and the single stage to orbit, but for the sake of the analysis, if the space elevator is put as rank first, then the expert and the alumni will have the same rank order for each of these technologies. Both panels rank the space elevator as the most significant and the ram accelerator as the least significant. The alumni seem to see a rapid reliable means of accessing low earth orbit as significant, and have tightly grouped all the ratings. The experts see a great advantage to the space elevator and are sensitive to the limitations of the laser and ram approaches. They agree with the alumni only on the single stage to orbit.

	Alumni	Expert
The Gravity Implant	4.6	3.6
Fusion Reactors	4.7	4.9
LEO CAC	4.4	3.5
Roving Lunar Base	3.6	3.9
The Bionic Leaf	4.3	4.3

Table 4.37: Significance of Life Support – Alumni vs. Experts

The alumni and the expert panels agree on the fusion reactors as the most significant of the life support technologies, but that is about the extent of the agreement. Though the average ratings are the same for the bionic leaf, the leaf is ranked second on the experts list but fourth on the alumni list. The data shows the alumni rating the roving lunar base as the least significant by a considerable margin, and the experts predicting the LEO compressed air collector as the least significant, but only a little less than the gravity implant. The rank orders are completely different after fusion, and overall the alumni are relatively likely to see the more radical LEO compresses air collector and gravity implant ideas as substantially more significant than the experts do.

	Alumni	Expert
Carbon Nanotubes	5.1	5.0
Memory Plastics	4.8	4.4
Solid State Aircraft	3.8	3.1

Table 4.38: Significance of Materials – Alumni vs. Experts

Carbon nanotubes are the favorite items of significance among both the alumni and the expert panels. They both predict the nanotubes as the most significant, both with a very high score. The solid state aircraft is predicted as the least significant by both panels as well. These panels agree perfectly on the rank order, but again the alumni give higher significance scores, especially for the radical solid state aircraft idea. On the other hand, if you ignore the decimals, they rank them 5, 4, 3, in order with the same general magnitude of significance.

	Alumni	Expert
Solar Sail	4.5	4.4
Nuclear Drive	3.9	4.4
Magbeam	4.7	3.8
Slingatron	3.1	2.8

Table 4.39: Significance of Propulsion – Alumni vs. Experts

Both the experts and the alumni predict the slingatron as the least significant of the propulsion technologies, but there is disagreement on which will be the most significant. The alumni predict the magbeam, the experts predict nuclear drive or solar sail. They both concur that development of a solar sail would be significant, and it is ranked second or tied for first by both panels.

	Alumni	Expert
Aerogel	4.7	4.3
EM Shielding	4.5	4.4
Cold Plasma	4.4	3.8

Table 4.40: Significance of Shielding – Alumni vs. Experts

For these technologies, the level of agreement between the experts and the alumni can be deceiving, since only one out of the three technologies have the same rank and the most significant on the expert list has the same significance average rating as the least significance rating by the alumni. Although they both predict cold plasma would be the least significant, they both vote EM shielding almost equally significant. In fact, the tight cluster of 4.3-4.5 ratings suggests that they see little difference between them in significance. Only the alumni rating of aerogel and the cold plasma by the experts are substantially different. The important rank order difference is that the alumni predict the aerogel as the most significant, and the experts predict the EM shielding as the most significant.

4.3.3 Timeframe Comparison

	Alumni	Expert
SSTO	1.5	1.6
Ram Accelerator	2.2	2.6
Laser Propulsion	2.6	2.4
NPSE	2.7	2.8

Table 4.41: Timeframes of Launch Vehicles – Alumni vs. Experts

For these technologies, the alumni and expert panels both believe the single stage to orbit will be developed first and the space elevator has the longest timeframe. The actual rating averages are similar but they disagree as to the overall rank. The alumni rank the ram accelerator as arriving earlier than laser propulsion and the experts rank them the other way around. Both groups expect one or the other to be developed about the same time.

	Alumni	Expert
The Gravity Implant	2.0	2.6
Fusion Reactors	2.7	2.6
LEO CAC	2.5	2.4
Roving Lunar Base	2.8	2.4
The Bionic Leaf	2.8	2.3

Table 4.42: Timeframes of Life Support Technologies – Alumni vs. Experts

These technologies all are ranked with about the same timeframe with one exception by both the alumni and the experts. They disagree on which is the exception that will arrive first; the gravity implant for the alumni and the bionic leaf for the experts. They are all rated within the 2-3 range, so even though there is a disagreement on the ranking, there is little disagreement on the timeframes of all of these technologies. The experts are actually the optimists this time for fusion, LEO CAC and the roving lunar base and especially the bionic leaf. They are much more skeptical about the gravity implant than the alumni. The expert rating are very similar for the group of technologies, from the 2.3 – 2.6, for all five of them. They see all these technologies as 20-25 years away. The alumni ratings range from 10 – 30 years.

	Alumni	Expert
Carbon Nanotubes	1.8	1.5
Memory Plastics	1.6	1.7
Solid State Aircraft	2.4	2.0

Table 4.43: Timeframes of Material Technologies – Alumni vs. Experts

The assessment of material technologies is another where the rank orders may not be the same by the two panels, but the timeframe prediction is very similar with the experts being a bit more optimistic in two out of the three cases. Both panels predict that solid state aircraft has the longest timeframe. However, the alumni believe the memory plastic has the shortest. For the experts, the carbon nanotubes are the nearest to be implemented, and half of them expect to see it within 15 years.

	Alumni	Expert
Solar Sail	1.8	1.7
Nuclear Drive	2.0	1.7
Magbeam	2.6	2.7
Slingatron	2.1	2.7

Table 4.44: Timeframes of Propulsion Technologies – Alumni vs. Experts

The expert panel for these technologies has two sets of equal scores, but even if we are considering them equivalent, they can be ranked. At the extreme, solar sail and magbeam, the timeframe ratings are similar between the two panels. The timeframes of the other two represent a modest discrepancy in magnitude for nuclear drive. The major difference is in the rating on the slingatron, which the alumni consider almost as close as nuclear drive, the experts totally disagree. Both panels rank the solar sail with the shortest timeframe and the magbeam with the longest.

	Alumni	Expert
Aerogel	1.2	1.3
EM Shielding	2.3	1.9
Cold Plasma	2.7	3.0

Table 4.45: Timeframes of Shielding Technologies – Alumni vs. Experts

Aerogel is the clear favorite among both the alumni and the expert panels for the earliest development. In addition, both rank cold plasma with the longest timeframe, giving us another complete agreement for both panels. However, the EM shielding ratings are significantly different; the experts seeing it as about 15 – 20 years until the development, and the alumni as 20 – 25 years.

5. Conclusion

After careful comparative analysis of the data received by both alumni panels and the expert panels, many questions raised at he beginning of this study can be answered. The cognitive data that was known about the two-wave alumni panel allowed a detailed look into how cognitive style would affect the way each individual responded to questions involving the future breakthroughs. Due to the increased size of the alumni panel, a more reliable data set was created. The data does show that there is a connection between the psychological type and their responses. However, while the cognitive style apparently matters, in our study, the variation in results is different from what MBTI theory would imply. The Intuitive Perceptive types were most pessimistic toward many of these possible breakthroughs. This is counterintuitive since they are known for "conceiving of new things and initiating change." (Lawrence 5). We expected them to be accepting of the future and open to quick change. Instead, we found a restricted range of ratings such that they were pessimistic of those that other types embraced, and optimistic about the ones others considered long shots. Perhaps they are jus contrary, challenging the conventional wisdom. Many times the differences were between the Js and Ps, rather than the Ns and Ss in this study.

For the Expert Panel, there was no MBTI data, so the cognitive differences could not be replicated with the alumni data set. Future work on this project could include gathering MBTI data from the experts, in order to try to verify the Alumni findings. There was data, however, on the expert's institutional base. This information would allow analysis on whether the occupation in the field would be associated with any differences in response. Based upon only 17 respondents, the data shows that there is no systematic difference between the expert's field and the way they predicted the future breakthroughs other than to say that the Planetary Society were more optimistic than the others. This data is not conclusive, though, since there was not an equal distribution in each of the four job types. Any future work on this component should include an increase in panel size to the point that the people in Industry and voluntary organizations equal the number of experts from NASA and Academia. For the purpose of this project, though, the bulk of a clean, systematic and significant variation in the responses based on job type allows one to pool the available careers for further analysis of the data set. Since all of the expert panelists can be grouped together, this panel can be compared to the alumni as a whole. If the field did clearly affect response, this comparison would not have been justified.

The next question that can be answered is whether the Alumni responses differed from the Expert responses. The data shows that the overall rank order of the technologies does not vary significantly from the Alumni to the Experts. With a rank-agreement of 60%, the data shows that an expert does not predict the future much differently than a technically trained person who does not have a specific expert professional background in the space sciences. There was a difference, however, in the magnitude of optimism between the alumni and the experts. The experts generally were less optimistic than the alumni panel, which verifies the original prediction that that the experts, who work in the field and have a greater understanding of the forces at work, would be more pessimistic than the relatively uninformed alumni. For the majority of technologies, that is exactly what our results show. The alumni panel generally rated the likelihood and significance of the technologies higher than the expert panel, and suggested that the breakthrough occur within a shorter time period. However, for some technologies, the Alumni were only slightly more optimistic, and for some, less optimistic.

not necessarily significantly more. Moreover, there were a few technologies for which the alumni were slightly less optimistic. If only the ranking of the technologies is taken into consideration, then the experts and the alumni were in agreement, however if the magnitude of the likelihood, significance, and timeframe is studied, then the experts and the alumni often disagree. Still, a case can be made for collecting data from people with technological backgrounds rather than specific expert credentials in future Delphi studies.

APPENDICES

A.1: Questionnaire

A.1.1 Breakthrough Descriptions

Dear Panelist,
Reports from pretest respondents, as to how long it takes to review these 20 ideas, is varying from 1-2 minute each. We asked for 30 minutes of your time, so if you are not able to complete them all in a half hour we will understand if you just stop when you reach that point in your time commitment. We cut out some real favorites (such as the Ion Drive) that are currently to the point that incremental improvements(rather than a breakthrough) may be all that is needed, to bring this rating task down to an estimated 30 minute job.

Possible Breakthroughs

A) Propulsion In Space

The following section includes possible means of moving through space without the use of conventional chemical rocket drives. Look over the advantages and problems besetting each and rate them in terms of what system or system you think is most likely to be available to space craft designers and space mission planners 25 or 50 years from now and which would be the most significant breakthrough, if it occurred.

Nuclear Drive – Thermal nuclear drives are based primarily on nuclear reactions causing high temperatures which is then used to heat water, or a similar liquid, to vapor. The vapor is then used to either generate power to for use in propulsion. For propulsion, the vapor is forced out an exhaust port to create thrust. However, the use of nuclear power is controversial due to fears that an aborted launch will spread radiation in the Biosphere. Thus, it is more likely to be used as a drive leaving from LEO rather than launching from Earth.
In space, high temperatures of 2000K are needed to have an acceptable thrust to propellant ratio (3000K would be close to optimal). However, in space, excess heat cannot be readily dissipated, and so far no one knows how to radiate more than 1000K. The lack of particles to transfer the energy to limits the ability to radiate heat.
A breakthrough in our conception of how to radiate heat is needed to use this drive effectively. Alternatively, some means of gathering , attracting or finding existing concentrations of particles in space has to be found to make existing radiators more effective.

Magbeam – Proponents, such as Professor Winglee of the University of Washington, claim that Magnetized-beam plasma propulsion technology promises a round trip to Mars in 90 Earth Days. "Magbeam" works by separating the power source from the spacecraft. The power source is kept in stationary orbit and it "fires" a focused plasma beam to accelerate a vessel in a particular direction. The beam shuts down when the desired velocity is reached. This technique requires another stationary source at the destination point to decelerate the ship in the same fashion.

The advantages to magbeam technology are quite significant. First, one power source can be used to power several vehicles. Second, the power station can be powered using solar panels and the vessels' fuel requirement is drastically reduced. The drawback is that the second stationary source must first be placed at every destination by another means. With current rocket technology, it is possible to reach Mars (with such a set up) within 2.5 years. Alternatively one could utilize magbeam to go one way quickly (say to Mars orbit) and then use traditional fuel to enter and leave the Mars atmosphere and return home. A breakthrough in the engineering of a full-scale "magbeam satellite" that is easily placed into orbit at popular destinations would be needed to use this propulsion system effectively for round trips.

Slingatron – Derek Tidman of Datassociates invented the slingatron to hurl things into space. The current conception is as a door to low earth orbit. We see a greater potential propelling supplies already in orbit to further destinations.

The slingatron consists of a smooth ball-shaped launch vehicle within a hollow ring shaped tube. Also, within the pipe is a pressurized gas used to prevent friction between the launch vehicle and the ring. To launch, the ring is moved in a circular motion (around points on its base as opposed to rotating around its center) which continually increases the speed of the ball until it is released from the ring and launched into orbit. The three foot diameter prototype can accelerate a ball bearing to 200 mph in a few seconds. A full-sized version would have to be at least a few hundred feet in diameter to achieve velocities high enough to escape from orbit and would subject the launch vehicle to accelerations as high as 1,000 gees making it viable for launching fuel and other supplies (but not humans) to destinations outside of orbit.

Solar Sail – The Planetary Society has invested in an experimental mission that is being launched by a Ukrainian rocket this year. Solar sails work by capturing light pressure within large metal film sails, and using the force to push a "ship" through space. The advantage to this is the theoretical speed that could be achieved, which is some large fraction of the speed of light. The limiting factor is material. It must be light and strong enough to create a sail many times the size of the space craft that could withstand the solar forces. Also, due to the rate at which solar energy declines as you move away from the Sun (within the solar system anyway) it's more attractive for travel in the inner solar system than beyond Jupiter.

Research on the idea began in the 1950's and now NASA has a science team looking into carbon fiber as the most promising material at present. A breakthrough in solar sail material has potential to radically reduce onboard fuel requirements and dramatically change space travel time and distance limitations.

B) Launch Vehicles

The challenge of how best to escape the Earth's gravity is a separate question from that of how to move around in space. Missions to other celestial bodies would depart from a Space Station. Let's assume this for the moment and consider the alternative concepts that would compete with the ELV and Shuttle concepts over the next 25-50 years.

Laser Propulsion – Dr. Leik Myrabo at RPI is doing research in laser propulsion. His laser propulsion works by applying a high power laser to a surface in two stages. The first pulse of the laser is short, and is designed to vaporize a thin layer of the surface material. The second, longer, pulse is applied a few microseconds after the first to let the vapor from the first pulse expand, and then the longer pulse sends a shockwave to the surface projecting it away from the laser. After the second pulse, the process waits until the vapor clears, and then repeats 10 times per second. While launching in the atmosphere, water could be used as the "surface" held in a sort of sponge. As water vaporizes from the surface of the sponge, more water seeps through the sponge to the surface to get hit by the laser. The strongest Air Force laser that Myrabo received access to lifted a small prototype 75 ft. Clearly to carry a heavier payload to low earth orbit will require a breakthrough in laser technology. Freeman Dyson speculated that with a powerful enough laser it would take about 6 minutes of powered flight to reach LEO from a mountain top with such a system.

Reusable Single Stage to Orbit (SSTO) – The use of a SSTO as a launch vehicle has been abandoned by NASA since 2001 when the X-33 project was put on the back burner. However, since such a launch vehicle is still capable of reaching Low Earth Orbit (LEO), the only major problem is its fuel capacity. If the vehicle was redesigned so that it could be refueled in orbit, then fuel capacity would not be an issue when traveling beyond LEO. The rocket would launch as it has in the past, from a tower on Earth, and once it reaches LEO it would rendezvous with fuel canisters or a refueling station in orbit. These canisters could be launched into LEO by the Ram Accelerator described in the next item in this section. Due to the extreme g-forces in the Ram Accelerator launch, transport of materials and supplies is the only viable use of this launch system. People and fragile cargo would go up in the SSTO vehicle. The two in tandem would create a capability worthy of being called a breakthrough.

Ram Accelerator – The ram accelerator concept was developed by Abraham Hertzberg at the University of Washington in Seattle. It works as a stationary ram-jet engine by accelerating a launch vehicle inside of a steel pipe. The pipe would be built into the side of a mountain, measure about 750 feet long, and be filled with a yet-unknown combustible mixture of gasses. When the gas is ignited, it projects the launch vehicle upward at about 30,000 G's. The launch capsule must be designed long and slender to prevent drag in the atmosphere, and have a sharp point at the top to prevent the force of the launch from igniting the gases above the launch vehicle in the pipe. To prevent friction against the pipe, the launch vehicle is slightly smaller in diameter then the pipe, and uses the gas in the tube as a cushion. The extreme g-forces make this style of launch impossible for humans, but could be used to transport various types of cargo and especially fuel to LEO.

Nanotube Polymer Space Elevator - The space elevator is a 60,000 mile, three-foot-wide ribbon anchored on one end to a platform on Earth and to a counter weight in space on the other. First an initial spacecraft will have to be launched with the ribbon into geo-synchronous orbit. Once in orbit, the ribbon will uncoil as the spacecraft moves higher to keep the center of mass at the same point. When the ribbon reaches the Earth's surface, the craft will unroll the last 10,000 miles of ribbon, moving up to its geo-synchronous station. Once constructed, 13 tons of cargo can be moved up the "ladder" at a time. The vehicle that moves the cargo would use a couple of tank-like treads that tightly squeeze the ribbon. It will take about a week for cargo to reach geo-synchronous orbit at 22,300 miles up. The ribbon will be constructed out of carbon nanotubes (explained below), which are lighter and seven time stronger than steel. Currently the longest nanotube ever made is just a few feet long. However, if a nanotube-polymer breakthrough occurs, it will be possible to build the 60,000 mile ribbon.

C) Materials

In this section Materials and Shielding and other support technologies are addressed. Please assess them in terms of your view of their significance to the space program as well as the likelihood that they will emerge in the period before 2050.

Memory Plastics – Memory Plastics are deformable materials that regain their original shape when subjected to a transition temperature. Basically, it is a polymer capable of 'healing' itself through the rupture of embedded microcapsules containing some healing element. Possible breakthroughs with memory plastics would be in the resealing of life support structures and suits that had failed. Inflatable habitat units are planned for the Moon and Mars, at least initially. The NASA plan is to construct them in LEO and transport them to the Moon. This development would increase the structural resilience and durability of such units and allow them to stay in service longer. The reduced risk of catastrophic failure of a life support or greenhouse system is attractive.

Carbon Nanotubes- Carbon Nanotubes are fullerene-based materials with extraordinary strength-to-weight ratios, and variable conductivity. Possible breakthroughs include translation of properties from nanoscopic fibers to macroscopic materials; use of nanotubes within polymer composites that would offer variable conductivity for thermal management, etc. Carbon Nanotubes could prove to be an important material is the production of a space elevator as well. They just might be strong enough to produce a solar sail as well, if they can be woven like fibers.

"Solid State" Aircraft - NASA is currently researching a new type of aircraft, powered by solar energy and propelled by flapping wings. The use of ionic polymeric metal composites (IPMC) is a key feature of the "Solid State" Aircraft concept. When an electric field is applied to this material, it has the ability to deform. Once the electromagnetic field is removed, the material returns to its original shape. This deformation process resembles a flexible artificial muscle. Mohsen Shahinpoor at the University of New Mexico is currently working on the IPMC and hoping to increase efficiency. If the efficiency is 10% or higher, it has the capability to fly in certain environments. A complex grid of electrodes controlled by a central processor will distribute the current to create a controllable electric field that dictates the motion of the wing, including "flapping". With its lightweight structure and lack of mechanical parts, a "solid state" aircraft would be a more beneficial way to explore the atmosphere of a planet like Venus or Mars than with a balloon or parachute probe.

D) Shielding

Temperature extremes, reentry frictional heat, asteroids and radiation are hazards in the space environment that lead to concerns about shielding and insulation. However, lead, steel, and other heavy materials used on Earth as shields to these types of elements are unsuitable for space applications where minimizing weight is a primary concern. In this section, you are asked which, in your view, "materials" research or "electromagnetic fields research" offers the greater promise in dealing with the shielding and/or insulation challenges of space.

Electromagnetic Shielding - Electromagnetic fields can be used to repel radiation and shield against smaller objects in space. A limitation of the technology is that it may not be able to assist in atmospheric reentry as a result of a planet's magnetic field. Robert Youngquist, a physicist who leads the KSC-Applied Physics Lab at Kennedy Space Center in Florida, is leading a team that is betting on electromagnetic fields as the solution to many of NASA's manned and unmanned problems with radiation in space. "Youngquist's team envisions a spacecraft equipped with what's called a multipole electrostatic radiation shield, a radiation guard made up of three, electrically charged spheres set in a line along the axis of the ship. The center sphere, set close or even attached to the crew module, would be positively charged, while two outrigger spheres on either side would carry a negative charge. Together, the combination should be enough to repel both high-energy protons and electrons that would otherwise penetrate a spacecraft (Malik 1)."
As for stopping incoming objects, the electromagnetic fields of the strength currently used in containing the materials in a fusion reactor would stop a cannon ball or a bullet, but that is about it for now. The breakthrough in EM fields would require a larger supply of energy to the electromagnets. This would probably allow for a sufficiently large and strong bubble of protection to be created.

Cold Plasma - Cold plasma is based on a phenomenon that scientists witnessed in space around 30 years ago, but had no way of creating on earth. Now, with more recent developments in technology, creation of this substance is possible. The main benefits to cold plasma are that cold plasma stop electromagnetic pulses and so can be used to absorb radar, microwave and laser energy. The radar absorption effectively makes a spacecraft invisible to a whole class of sensors and the military implications are obvious, but other space applications are less obvious.

This is the stuff of science fiction though, cloaking devices and warding off hostile attacks from laser or beam weapons. The breakthrough that would allow cold plasma to realize its promise would be an energy source light enough to carry and as powerful as a nuclear reactor. There may be natural threats in space to which it is applicable as well.

Aerogel - Aerogel is an ultra light solid also known as "solid smoke." It is the lightest known solid, (90-99% air) with abnormal levels of heat absorption. Aerogel has the ability to protect crayons from melting when aerogel is placed between the crayons and a butane torch. Aerogel has the same heat insulation in a 1" pane as a 32" thick pane of a normal, air insulated window. The downside to aerogel is that creating aerogel can be difficult, and expensive, as it is best done in microgravity, but it has been used successfully to insulate the Mars Rover and Space Lab 2.
As of January 13, 2004, NASA announced that Aerogel is the new insulation of choice. An attempt is likely to be made to use it to replace the ceramic heat shield tiles on the Shuttle that are so vulnerable to chipping and costly to replace. Aerogel can be used as a heat shield simply by ejecting it out along the surface of the vessel as the spacecraft prepares for reentry. The gel is expendable, it would be burned away, but will prevent heat damage to the aluminum hull as it burns away. The Aerogel breakthrough that is needed involves its ease and cost of production" on the fly", since in space shielding applications it tends to get used up and requires replacement.

D) Life Support

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

Roving Lunar Base - The Roving base is a mining colony gathering Helium-3 for the powering of fusion reactors. Helium-3 is not highly concentrated at one site like a vein of gold or uranium on Earth. Hence, a roving nomad habitat is needed to do a kind of strip mining in areas where the right beta “signature” is found in the regolite.
The “morphlab” base, as proposed by Albritton et al. of the University of Maryland, is composed of multiple parts that allow it to be disconnected and driven or towed from one site on the Moon to another. Once set up in a promising mining area, robotic/remote controlled harvesters would be sent off to collect the nearby Helium-3. The habitat modules will provide life support systems for the occupants of the base. The robotic harvesters will gather Helium-3 in a 50 mile radius and then the base will be disassembled and the separate modules “driven” or “towed” 100 miles to a new mining area.
The necessary breakthrough will be in the devices that locate, gather and safely transport the precious fusion reactor fuel, assuming that there is a related breakthrough in the fusion reactor field on Earth before its oil supplies run out in 50-75 years. Overall, think of the mobile base as a conceptual breakthrough.

The “Bionic Leaf” - One of the breakthroughs that could make a moon habitat productive enough to be self sufficient in agriculture is the bionic leaf. The idea was inspired by Freeman Dyson who has been commented about the need for a silicon black leaf that would be 15% efficient in using solar energy rather than the paltry 1% of Earthly green tree leaves. What is needed for lunar agriculture is a cyborg half plant- half machine hardy enough to “grow” on the moon mostly outside of a greenhouse.
The “bionic leaf” is made of black silicon and aluminum honeycombed with fine hair-like tubing that is the outside part of the plant situated on the lunar surface. It can synthesize carbon dioxide and water into a carbohydrate in direct or indirect (reflected from a satellite) sunlight. Inside or underground (in a protected area) the tubers, ears of vegetables and fruits store the resulting sugar coming in from the leaves in tubes as in normal agriculture they travel through the stem or trunk of a plant. So, the key to lunar agriculture is to supply this system with Carbon Dioxide and Water. Oxygen can be mined from lunar rocks, so Carbon and Hydrogen are the elements in short supply that must be “imported” to kick off the system and then be recycled without serious loss.

The “Gravity Implant" - Mankind did not evolve with the right biochemical feedback system for space. So, to avoid the disorienting impacts of low or no gravity giving the body all the wrong signals (about where to put the calcium, when and how hard to tense the muscles to exercise them and which antibodies to maintain etc.) an implanted translator is put under the skin and along the spinal cords of most Astronauts toward the end of their training.
It senses changes in gravity and compensates for them by essentially intercepting and changing the bio-chemical and electrical neuro-signals that help the body stay in equilibrium in the Earth environment. The Astronauts call it being "reprogrammed" for space and they worry about what else the re-programmers might change to make the mission more likely to succeed at their expense. However, they volunteer for it anyway after they see the films of what the Russian Cosmonauts looked like after 500 days in space.

LEO Compressed Air Collector and Processing Plant - Two important resources that a self sustaining Lunar base will need to start or expand agricultural production are water and carbon dioxide. Lifting these bulk resources from the surface of the Earth is expensive. One alternative to this problem is the use of a vehicle that collects water vapor and carbon dioxide as part of a load of compressed air taken from the upper atmosphere. This collection vehicle would "swoop" down into the upper atmosphere and collect air, compressing it as it went back out of the Atmosphere for delivery to a separation and processing plant in LEO. The necessary breakthrough is in the design of a large hollow ended skimming vehicle that can repeatedly withstand reentry stresses and then close its nose and escape back into space on orbital momentum or with a short "burn".

The orbiting processing and compression plant that separates water, carbon dioxide and oxygen etc. from compressed air is also going to be a challenge. It must not only separate these resources but also convert them into a compact solid form. Carbon dioxide and water can be readily frozen into solids, but then they must be wrapped in a protective layer to avoid dissipation into space. One wants a block of dry ice or water ice ready for transport to the Moon. Some of the oxygen must be left in a liquid form (LOX) so that can be used to power a rocket to give it a "push" in the direction of lunar orbit or wherever else it is needed. On arrival it needs to slow down, requiring another "burn" for insertion into lunar orbit or to be delivered to an agricultural production facility.

Once charged with thawed Earth atmospheric products, the agricultural plant will recycle the precious delivery of Hydrogen and Carbon endlessly. These are rare elements on the Moon and essential to human and plant life. Oxygen can be mined out of the oxide rocks on the lunar surface. Water is to be found mainly in a deep crater at the South Pole. Setting up for agricultural production anywhere else will require imported water as well as carbon dioxide.

A.1.2Questionnaire Format

Name______________________________________

Below is a list of possible breakthroughs described in the attached packet. Under each breakthrough are two scales ranging from 1 to 6 to help you gauge each breakthrough's significance on the future of space travel should it occur, and the likelihood that such a breakthrough would occur within the next 50 years. Beneath each breakthrough there is room for some brief comments, should you wish to elaborate on your opinion, as well as your estimate of which time period such a breakthrough is most likely to occur (Present-2020, 2020-2035, 2035-2050). Once you complete this questionnaire, please return it in the prepaid envelope enclosed within this packet.

Significance/Likelihood	Time period
1: trivial/impossible	Early: Present-2020
2: marginal significance/improbable	Middle: 2020-2035
3: small significance/unlikely	Late: 2035-2050
4: moderate significance/likely	
5: major significance/probable	
6: revolutionary/expected	

	Significance	Likelihood
Propulsion in Space		
Nuclear Drive	1 2 3 4 5 6	1 2 3 4 5 6

Time period: ________________
Comments: ____
____

Magbeam	1 2 3 4 5 6	1 2 3 4 5 6

Time period: ________________
Comments: ____
____

Slingatron	1 2 3 4 5 6	1 2 3 4 5 6

Time period: ________________
Comments: ____
____

Solar Sail	1 2 3 4 5 6	1 2 3 4 5 6

Time period: ________________

Comments: ____
____

Launch Vehicles

Laser Propulsion 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____
____

Reusable Single Stage Orbit (SSTO) 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____
____

Ram Accelerator 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____
____

Nanotube Polymer Space Elevator 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____
____

Materials

Memory Plastics 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____
____

Carbon Nanotubes 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____
____

"Solid State" Aircraft 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____
____

Shielding

Electromagnetic Shielding 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____

____

Cold Plasma 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____

____

Aerogel 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____

____

Life Support

Fusion Reactors 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____

____

Roving Lunar Base 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____

____

The "Bionic Leaf" 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____

____

The "Gravity Implant" 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____

____

LEO Compressed Air Collector 1 2 3 4 5 6 1 2 3 4 5 6
Time period: ________________
Comments: ____

____

A.2: Panelists' Comments

A.2.1 Expert Comments:

Nuclear Drive

Much interest in DC leads to increase funding and attention

The sigma associated with "nuclear" is biggest obstacle, Not technology

How far can regenerative cooling be pushed?

Many errors in statement! No problem in heat transfer >1000k. Mass is the factor in radiators. Earth launch is impossible because of low thrust to weight.

Magbeam

Power requirements are enormous even if high efficiencies are assumed. Physic is questionable if not completely impossible/ impractical.

Self contained propulsion is the norm and much simpler, less chance of error, and less expensive. Still a theory.

Would require infrastructure development and cost. Multi agency, mission, government plus the time delay is setting up. Don't think it will happen.

Programmatically unlikely. Would require infrastructure development at high cost. (Multi-agency, mission, government) plus time delays in setting up… don't think it will happen.

Slingatron

Within space propulsion? Do you mean space to space or planet to space? High material stress make it unlikely …………..

Stepping up in size will prove an engineering challenge. What about re-capture?

Would be useful for heavy loads such as water, but not likely

What is the advantage of this?

You can not use Slingatron in space. It mast be on planet or it deorbits itself (see MXER reboost). Perhaps on the moon only. Not responsible for ETO either.

Within space propulsion? Do you mean space to space or planet to space? High gee-loads and material stresses make it unlikely and costly for such specialized use.

Solar Sail

Certainly useful for paternal asteroid impact diversion hence the like hood of it accruing. It's a favorite in that community.

If suitable materials and manufacturing techniques are found, this could change unmanned missions significantly.

Low tech versions are on the way. Interstellar is sometime off and fraction of the speed of light is far term but likely to happen. I do not agree that carbon fiber is the only promising material. Sails will only take small pay long so significance will always marginal.

The material issue is bi. Also, such a large structure must be robust in terms of debris interactions

Laser Propulsion

Very high power laser have political implications but would be significant for launch

Laser tech not withstanding, sealing this ides up would require a lot of energy/ power. Better suited to small / micro solar thrust

Such powerful lasers have a hard time going through the atmosphere and tracking is a major problem not to mention no technical data showing any indication on how the physics would work effectively.

Energy efficiency of the laser; focusing a laser for 300km; atmospheric decay/ distortion of the laser.

Reusable Single Stage Orbit

Technologically we can almost do this now. Not sure about usefulness for space exploration. Current plants are for refueling satellites.

Can be done, but is it worthy of being called a "breakthrough"? (even with the Ram accelerator)

Some form of adding a "SSTD" while such as a spinning tether catch is likely. I believe air launch will be used as a "stage and hall" for safety reasons since vertical tower launch is extremely expensive and dangerous.

The next logical step using current technology and experience

Rocket equation makes this concept unattractive…

Ram Accelerator

May not this exact concept but ram accelerator are needed for non fragile, low-cost launch

A gun idea. High shed, low control

All “gun launch” type approach are not economical since you put all your energy into the pay long at low altitude (yes even up a mountain) and you burn it off in to seconds of flight. You can not put the energy in tangentially so the losses are so high it make no sense.

New twist on centuries old concept (Jules Verne, “Supper Gun”…), that does not solve the problems that are already known about this. Beside that is not a breakthrough.

Not likely, but useful for heavy loading

Nanotube Polymer Space Elevator

So much attention, it’s getting $$so if might happen.

Takes the gross national production of the word to build. Must “give up” LED for satellites – more technical and serious problem to solve then almost any other system known and the throughout is not that much after all the investment and risk

This would be huge, but the technology has a long way to go. Ground to space ladder or elevator technology needs to be proven to world

Memory Plastics

Some early form of this are expected to be used but will have significant limitation on how well it will heal itself

Carbon Nanotubes

Perfect structures are unlikely but imbedding carbon nanotubes in other things to enhance quality will be coming soon and make significant benefit to all areas – probably to tethers before a space elevator!

Lightweight and strong, a key feature (hingepoint) for numerous technologies. Materials dictate the scope of macro-technologies.

Solid State Aircraft

Lack of mechanical parts? How about components that are even more prone to failure!!! This is a backward step in the history of flight

This is might be a reasonable application of the technology on a small robotic scale.

I don't believe this is suited for large scale; nature would have done it first. But suitable for mall scale crash.

Electromagnetic Shielding

Would require a nuclear power source on the spacecraft. Known technology that needs scale up, really just depends on the power source.

The conference that I just attended found that the charge limitation prevent this form working as proposed and power requirement are excessive. Fusion fields are on the order of cm^2 so you can only protect a very small object.

Yes, it would stop <u>collisionless</u> charge particles. What else?

Cold Plasma

Already witnessed. DoD applications therefore likely to happen

Seems to violate known laws of plasma physics.

No evidence … exists = you lose scientific credibility when you write this way! If you had a small nuclear reactor = who cares about cold plasma?

Lots of power in a small space. Not easy to do.

Aerogel

Obvious use in atmosphere. Again, easier o scale up a proven tech than develop a new one.

This is here- invest in it. Unsure of new application explained here but this will be used for many things.

Founded by NASA + industry

Fusion reactors

All pure sci-fi in my opinion.

Helium-3 wont become a sought after commodity until fusion is a proven … . Fusion is far to lofty a goal at our current tech understanding.

Don't agree with idea of trying to force a market for moon. Fusion has already been a decade away.

Roving Lunar Base

All pure sci-fi in my opinion.

Is that tech depended or previous? How is that useful if fusion never works out?

I say this is possible if the need is there. It's mainly a design challenge, there is a tech available to create a structure.

The "Bionic Leaf"

All pure sci-fi in my opinion.

Very important can it be done is unknown as described. Something like is likely to emerge.

The "Gravity Implant"

All pure sci-fi in my opinion.

The science behind this is questionable

Human body chemistry is extremely complicated and you are under estimating its complexity! Complication will have this not a good solution.

Is description like a mechanism to reverse negative effects of non-Earth gravity on human bio chem? If so, make significance 5 or 6

Adaptation is key, Adaptation is also not fast. See: Evolution. I think we will strive to a quick solution, but only true body adaptation will solve the problem.

LEO Compressed Air Collector

All pure sci-fi in my opinion.

Don't see money-matching politics to actually develop this.

Gathering resources on site will be more importable. Easier to self-sustain.

A.2.2 Alumni comments:

Nuclear drive

Safety issues and acquiring the required temperature may be too large of hurdles to overcome quickly.

2000K temperatures are strongly materials-prohibitive such a system could not be implemented given public opinion of nuke

NASA and Lockheed martin are currently working on this. As an engineer currently working in the nuclear field, politics will be a large obstacle. Direct propulsion or ION drive will not likely occur before thermal dual system propulsion.

This seems more of an extension of current technology; it's a small leap

Reactors powering electric drives in the near future, direct propulsion somewhat less likely and farther in the future

Radiating that much heat will likely delay this technology even further with the present focus on manned flight

Magbeam

Seems the most promising

How does one fuel the magbeam with "pre-plasma-gas?" Solar power requirements are huge, especially at mars

It appears that larger models are needed for this technology. However, a 90-day round trip to mars would be significant to space travel.

This sounds nifty but it would need to be built on another technology

Shooting a beam of plasma to mars seems a bit unrealistic

Even plasma has mass, stations require refueling

Would work well for one destination; would be very expensive to have multiple set-ups

Slingatron

Safety Issues?

How is it to be rotating while in orbit? How do you supply it with gas?

Again, larger prototypes may reveal major problems and obstacles.

Seems a bit too "wacky invention" to be taken seriously enough to get funding

Requires large investment to get such a "sling" orbital but sounds promising

Ground area requirement would be too large to only send supplies and not humans

Solar Sail

Requires a lot of "material" which could cause problems

This is not likely to be as fast as desired if "fast strong light" sails predicated on major materials advances are required, this then becomes a late/impossible

With the current rate of advances in materials, a major breakthrough seems likely

Possibly more politically acceptable than nuclear power. Without laser augmentation, might be too slow to be worth effort. Solar sail: blimp :: nuclear: jet

Serious investment in materials is necessary

Currently being used now, the technology will improve

Laser Propulsion

Seems most promising!

Lasers of this power level/accuracy have military applications. Their absence from the field indicates their difficulty.

I really don't know much about laser technology

Military laser research might help

I don't want to be sitting in a craft that has that strong a laser firing at it!

Lasers of that power require hefty power sources, which will feel a crunch as power becomes more scarce in the next 50 years.

SSTO

Requires Ram accelerator which could slow things down!

Why not use Apollo/Saturn V? At least it work. Reusability is not necessarily economical

As is the case with many of these potential "breakthroughs" the success or failure is dependent on the time and funding put into their research

Will happen eventually but conventional throw-away rockets are cheaper/ more reliable for now

Ram Accelerator

Requires a pipe 750 ft in a mountain; doesn't seem practical.

It's dangerous to send almost anything at these kinds of accelerations (even bolts) [also a star wars- defeating weapons system]

The principle sounds very simple. However, convincing the government/Americans that this is feasible and necessary is the difficult part

Too much infrastructure to be worth it

What happens if/when a projectile doesn't make orbit?

Liquid fuels will likely be the only materials able to withstand 30,000 Gs, certainly not any crafts

Might be too dangerous to humans on ground to only lift cargo

Nanotube Polymer Space Elevator

Seems too unpractical to be likely.

Material strength is governed by defects, not raw material inherent strength. Many, many other issues are being over-looked in this proposal (lightning, thermal stress, fatigue, terrorism)

Nanotechnology is rapidly progressing, but this concept does not seem likely. Anything that long would always need repairs. What if something drops? Would these be over the ocean?

I'm concerned about the failure mode of this idea; 60,000 miles = approximately 2 times Earth's circumference

Requires huge leap in nanotube polymers which may not ever be strong enough

Winds have still not been discussed as a problem, esp. in the mid atmosphere, let alone how such a tether would affect weather

I believe this would be too difficult in the next 45 years.

Memory Plastics

Seems like the most likely (with long-term significance)!

Risk adverse culture will simply add this layer of redundancy: no weight savings… also, UV plastic breakdown!

Memory plastics and/or memory alloys should prove useful in some capacity to the space program

Carbon Nanotubes

Strength-to-weight ratio is a major plus

Claims at this stage are all out of proportion to result produced. People are exaggerating for funding.

Heavy funding and investment is going into nanotechnology, but we have not even begun to scratch the surface in this field. Carbon nanotubes will be used in a variety of industries. The Albany, NY region appears to be a hot bed for this field.

They seem right around the corner

We've only begun seeing the vast amount of uses for nanotubes

"Solid State" aircraft

An early advance that will be considered a dinosaur quickly

Solar cells and other solid-state parts don't last nearly as long as desired in radiation-rich environments

IPMC may probe very useful, but perhaps not to create flapping wings

Similar materials being used/designed by the Navy and other defense contractors now, can be adapted

Electromagnetic Shielding

Seems furthest off in terms of being developed to usefulness (see [1st cold plasma comment])

Gamma radiation, neutron radiation are the real threats. Power/protection ratio poor (need nukes for this)

Shielding against objects and radiation would be very useful. However, a device strong enough for the required field must also be compact.

Power requirements for fields, strong enough to protect against objects in space would be enormous. Not impossible but very difficult

EM fields are not easy to control let alone shape – their interaction with other fields could easily lead to catastrophic problems

Cold Plasma

This and aerogel seem effective for heat; radiation, etc. whereas ES may be most useful for "objects" such as asteroids

(You haven't provided enough info on requirements) if it worked, the F22 would use it; power/protection

I really don't know about this one!

Doesn't sound too useful until we get into a spacecraft based war

Don't know enough of what cold plasma actually is to give a good answer on how likely it is. Sounds good though.

If such an energy source "light enough to carry and as powerful as a nuclear" is invented, cold plasma will <u>not</u> be one of the first things it will power

Aerogel

Seems the most likely to succeed first

NASA isn't about to change heat tiles with <u>anything</u> that <u>might</u> be less reliable

After the shuttle disaster it is clear that alternative modes of insulating on re-entry are necessary. More "super insulators" will likely follow"

Unlikely to be used for reentry. More likely it will be used for conventional insulation.

Might be used to dissipate the heat of nuclear propulsion?

Fusion reactors

A long road to perfect He-fusion.

There isn't much fusion research –on earth- fusion itself is a "6/2" (i.e. not in 50 yrs) (on earth) … and can't require <u>lunar</u> materials to work

Nuclear research has continually declined over the last 3 decades. For this to occur, large investments into fusion reactors are needed

Always one breakthrough away…

Roving Lunar Base

Would be more significant if the appropriate advances in fusion reactors were made!

He-3 is a pipe dream in the first place, why use a manned station for this?

This will only be developed if advances are made in fusion reactors. However, the concept appears to be one that may work.

If buses on the moon are actually established, a roving base shouldn't be much harder to build if there is a need

The "Bionic Leaf"

Lunar agriculture would help make a lunar colony more self-sufficient.

Yeah right.

Sounds like something out of science fiction, but I will believe it when I see it. Has a prototype been assembled yet?

Might be better for Mars. Probably cheaper/easier to build greenhouses 15X bigger and just use normal plants

Why bother w/ a leaf? Better solar cells and energy storage would provide a better energy source for catalyzed "photosynthesis"

Would be a great benefit

The "Gravity Implant"

Manipulating the human body is not only challenging (near impossible) but dangerous. Who knows what new diseases or disorders would occur!

Bio-rejection… we don't know how the body works well enough to say we can do this.

Man will need some way to deal with extended stays in environments very different than earth.

Artificial gravity would probably be safer for the astronauts.

You're description makes it sound as if it's already used?

Would be beneficial to astronauts, but would need a lot of testing

LEO Compressed Air Collector

Seems the most important to the success of a lunar colony

Given gravity well economics (even though it might not have to go too far into earths, still must return to higher orbit) you're unlikely to get more gas/O2 than you burn. Anything which can withstand the materials requirements is dense and expensive

Yes, a method is needed to provide H20, 02, CO2, to people/plants in space or the moon, but this may not be the best, or the technology will advance to make this all possible

If there was a need and launch costs were still prohibitive, this could probably be done.

A.3: Round 1 Debate (In Progress)

Vital to the Delphi Method is the controlled, anonymous communication between panelists, enabling them to explain their reasoning and persuade others to their positions. As such, our Delphi study had an inter-questionnaire debate for each panel. The debates were run similarly.

A.3.1 Expert Debate:

After the original data analysis, we determined the outliers for each technology on a per panel basis. After soliciting comments, we put together a list of the explanations received from outliers. Lacking comments in some cases, we used comments written on the outliers' original questionnaires. We then compiled these by technology and sent them to the panelists together with an opinion distribution. The letter can be viewed in Appendix 4. The letter sent to each panelist had his personal response highlighted. Approximately every two hours, all the responses received in that time were again compiled and sent out to the panel. For the experts there were only two such rounds. Debate died off after the first 24 hours.

Following the debate, a request was sent asking for a record of changes in opinion resulting from the debate. As of this writing, seven of 17 panelists have responded saying that their opinions were completely unchanged, although they found the comments they read interesting.

A.3.2 Alumni Debate

The alumni panel debate is intended to happen in two stages. The first stage of debate includes our 15 original alumni panelists, and happened a week after the expert debate. The second debate is scheduled tentatively for the beginning of July to include additions to the alumni panel. The second round debate will include all pertinent comments from the first debate in an attempt to reconcile the two panels. When this second debate is finished, by the middle of July, the two phases of the Alumni panel can be merged, and both panels will be ready to receive the Round 2 Questionnaire at the beginning of September.

As of this writing, one panelist has shifted his views, while another did not. Thus far, these have been the only two responses.

Expert Debate Round 0

These are the comments made by outliers on the respective technologies. People with more mainstream positions are now invited and encouraged to reply to these comments. If you don't recall the descriptions or rating scales, the survey can be viewed at http://space.wpi.edu/survey/.

Bionic Leaf (Significance) –

rank	1	2	3	4	5	6
# of people	1	0	2	4	6	3

"All pure sci-fi in my opinion."

Carbon Nanotubes (Likelihood) –

Rank	1	2	3	4	5	6
# of people	0	1	0	5	9	2

"I am not qualified to comment on the likelihood of this section."

Fusion (Significance) –

rank	1	2	3	4	5	6
# of people	2	0	0	3	6	6

"Helium 3 will not be needed for 10,000 years on the Earth, if ever. How many billions do you need to prove that fusion is NOT economical for Earth power production!?"

"All pure sci-fi in my opinion."

Laser Propulsion (Time Frame) –

rank	2005-2020	2020-2035	2035-2050	After 2050/Never
# of people	1	6	7	1

"My opinions on Laser Propulsion were rooted in the work of Leik N. Myrabo, where the operating principles for cargo (not human) launch and orbit insertion have been worked out, plus ground tests with small lasers have experimentally verified many of the models. The assumed availability of higher-power lasers is based on military versions and extrapolations (via Dr. Frank Mead of USAF). If I recall correctly, current projections could have small payloads inserted into low earth orbit based on foreseeable technology - just assembling the system and working out all those inevitable details. The laser costs (more than one required), and getting approval to fire them, are the biggest hurdles, if I recall correctly."

"Such powerful lasers have a hard time going through the atmosphere and tracking is a major problem along with safety, not to mention no technical data showing any indication on how the physics would work effectively."

Editor's comment – Also, to answer a question that came up about this technology, it is only intended as a way to move to LEO, not as a method of deep space propulsion.

LEO Compressed Air Collector (Significance) –

rank	1	2	3	4	5	6
# of people	1	2	5	4	4	0

"All pure sci-fi in my opinion."

Magbeam Propulsion (Significance, Likelihood) –

Significance –

rank	1	2	3	4	5	6
# of people	1	3	2	4	7	0

Likelihood –

rank	1	2	3	4	5	6
# of people	1	7	9	0	0	0

No comments

Solar Sail (Significance, Time Frame) –

Significance –

rank	1	2	3	4	5	6
# of people	0	0	2	7	8	0

Time Frame –

rank	2005-2020	2020-2035	2035-2050	Never
# of people	7	7	3	0

"The materials question is big. Also, such a large structure must be robust in terms of debris interactions."

SSTO (Significance) –

rank	1	2	3	4	5	6
# of people	0	2	2	5	6	2

"An SSTO is almost necessary for the efficiency of future space exploration."

Expert Debate Round 1

Due to the nature of some of the responses I feel that some explanation on the source of these comments is needed. An email request asking for further explanation from the outliers returned only a few additional comments, and so we were forced to use comments from participants' original individual questionnaires. This led to the noted frequent appearance of "All pure sci-fi in my opinion" (It was a blanket statement applied to the entire Life Support section), and other rather self-defeating arguments like "I am not qualified to comment on the likelihood of this section," (another blanket statement applied to the entire materials section.).

Bionic Leaf (same comment for Fusion and LEO CAC – partially addressed above):
"All pure sci-fi in my opinion."

"Considering the frequent appearance of the feedback: 'All pure sci-fi in my opinion.' I think it would be prudent to ask this reviewer for their assessment of where is the line between fact and fiction today – to calibrate the source. This could be a case where the reviewer is up-to-date and well qualified to render this opinion, or it could be a simple case of a pedantic reaction. It is important to know which situation we are dealing with to qualify the source."

Fusion:
"Helium 3 will not be needed for 10,000 years on the Earth, if ever. How many billions do you need to prove that fusion is NOT economical for Earth power production!?"

"This is a good point and brings up the issue of what form of fusion and for what purpose. Fusion for ground energy production has indeed failed to reach expectations and no real solutions appear in sight. Fusion for propulsion, however, *might* be different. Propulsion fusion has the advantage that you want the reactor to leak, so to speak, in a preferred direction (for thrust). Also, it does not have to "break even," it just has to surpass its competing propulsion methods. And therein lies the biggest question: on a system level, how does fusion propulsion compare with alternatives?"

Editors response: Fusion was indeed intended for ground power not propulsion, and our focus on the helium-3 helium-3 reaction was based on a previous student project at WPI that suggested shipping helium-3 back to Earth was the only thing that would make a colony on the Moon economically viable.

Laser Propulsion:
"Such powerful lasers have a hard time going through the atmosphere and tracking is a major problem along with safety, not to mention no technical data showing any indication on how the physics would work effectively."

"If I recall correctly, the 'Light-craft' versions are self-aligning, meaning that if the laser veers a little, the vehicle follows the beam. The question then becomes 'how quickly' can the vehicle stay in step with a wavering laser. The vehicle has inertia, while the laser beam does not. There will be a limit, but I do not know what that is. What is certain is that low-altitude tests have been conducted and the designs for higher-altitude versions are sufficiently advanced to proceed to tests. The critical question then becomes if the tests would work. If funded, the tests could happen in the near-term (2005-2020). If the tests work, then we are there. If not, then it's worth dropping."

Editor's note: Thanks for that little tidbit on guidance. We hadn't been able to find that information and have wondered how it stayed with the beam ever since our introduction to the technology in September.

Solar Sail:
"The materials question is big. Also, such a large structure must be robust in terms of debris interactions."
"Some studies have shown that a sail can still function adequately even if eroded by debris. Although a hole in a more familiar type of spacecraft is a bid deal, a hole in a sail is less traumatic."

SSTO:
"An SSTO is almost necessary for the efficiency of future space exploration."

"Here I must disagree. SSTO has become a kind of "holy grail" for rocket designers, but 2-stage to orbit can actually accomplish the job. SSTO still remains an elusive challenge. Efficiency is relative. If SSTO still does not work, its efficiency is moot. The "significance" of a technology should not be based on the significance of the technical challenge (where SSTO ranks high), but on whether the technology actually meets the mission need (where lower-tech alternatives are likely to be superior). As a community, we need to make sure that our work meets the need, rather than chasing after the coolest technology."

Expert Debate Round 2

And more comments…

Laser Propulsion:

"If I recall correctly, the 'Light-craft' versions are self-aligning, meaning that if the laser veers a little, the vehicle follows the beam. The question then becomes 'how quickly' can the vehicle stay in step with a wavering laser. The vehicle has inertia, while the laser beam does not. There will be a limit, but I do not know what that is. What is certain is that low-altitude tests have been conducted and the designs for higher-altitude versions are sufficiently advanced to proceed to tests. The critical question then becomes if the tests would work. If funded, the tests could happen in the near-term (2005-2020). If the tests work, then we are there. If not, then it's worth dropping."

"Many serious fundamental and practical shortfalls have to be overcome for this to be taken seriously.
Cost: high-power lasers have extremely low efficiency (wall-to-light).
Collimation length: maintaining a collimated laser beam for 100s of km is harder than people think.
Atmospheric distortion: in order to hit the satellite accurately, one needs to have an unprecedented capability to predict, and correct for, localized atmospheric fluctuations.
Put all these pieces together, and the picture that emerges is of an unrealistic technology, which even if demonstrated, will hardly provide the benefits its proponents claim."

Magbeam:

"Many serious fundamental and practical shortfalls have to be overcome for this to be taken seriously. Keeping a plasma beam focused for 100s of km is a very difficult. In order to curb beam divergence over such a large distance, the ratio of directed kinetic energy to random kinetic energy must be ridiculously high, and/or have a magnetic "channel" type guide over that range of distance. Creating such high-power quasineutral plasmas that have such a high ratio of directed KE to random thermal KE is unrealistic (granted, such high-speed collimated jets are found in some astrophysical situations – but they are created by black holes). Creating any magnetic "channel" over that distance is unphysical. Put all these pieces together, and the picture that emerges is of an unrealistic technology, which even if demonstrated, will hardly provide the benefits its proponents claim."

Alumni Debate Round 0

These are the comments made by outliers on the respective technologies. People with more mainstream positions are now invited and encouraged to reply to these comments. If you don't recall the descriptions or rating scales, the survey can be viewed at http://space.wpi.edu/survey/.

Bionic Leaf (Significance, Timeframe) –

Significance –

rank	1	2	3	4	5	6
# of people	0	1	1	6	6	1

Timeframe –

rank	2005-2020	2020-2035	2035-2050	After 2050/Never
# of people	0	3	11	0

"Why bother with a leaf? Better solar cells and energy storage would provide a better energy source for catalyzed "photosynthesis."

Carbon Nanotubes (Likelihood) –

rank	1	2	3	4	5	6
# of people	0	1	1	3	6	4

"The category of carbon nanotubes includes a number of application sub-topics. While it is clear that there will be continued developments in carbon nanotubes over the next 45 years, I don't feel that they will be integrated into critical structural materials in the space program in that time. While the diameter to length ratio is quite large, nanotubes are in general quite short in length. Adding nanotubes to a composite will most likely be much more like making a particle dispersion composite than a fibrous composite. The corresponding improvement in properties will probably not be worth the effort and cost, since the properties achieved can be more efficiently produced by other means."

Cold Plasma (Likelihood, Timeframe) –

Likelihood –

rank	1	2	3	4	5	6
# of people	2	5	5	2	1	0

Timeframe –

rank	2005-2020	2020-2035	2035-2050	After 2050/Never
# of people	0	2	12	0

"This and aerogel seem effective for heat radiation, etc. whereas electromagnetic shielding may be most useful for 'objects' such as asteroids."

Electromagnetic Shielding (Likelihood) –

rank	1	2	3	4	5	6
# of people	1	2	1	8	2	1

"In electromagnetic shielding, there are a few telling statements which lead me to reject this as a likelihood in the next 45 years. 'As for stopping incoming objects, the electromagnetic fields [used in fusion reactors] would stop a cannon ball or a bullet.' Power sources which can produce electromagnetic shields of these strengths are themselves very heavy. Electromagnets aren't especially light. While the first paragraph of the section makes somewhat more moderate claims with regards to stopping alpha and beta radiation, shielding must do three things. Shielding of a space probe/manned vessel must protect the craft from charged radiation, uncharged (gamma) radiation, and high energy particulate matter (micrometeors, etc).

If we assume that Cold Plasma technology is impractical and/or heavy (as I have), then there is no strong reason to pursue electomagnetic shielding. When the weight of power sources are considered, high strength aluminum and titanium alloys to provide all needed shielding as well as structural strength seems like it will remain more efficient."

Fusion Reactors (Likelihood) –

rank	1	2	3	4	5	6
# of people	1	3	3	7	1	0

No comments.

Gravity Implant (Significance) –

rank	1	2	3	4	5	6
# of people	0	1	2	2	8	2

No comments.

Laser Propulsion (Likelihood) –

rank	1	2	3	4	5	6
# of people	0	3	7	4	1	0

No comments.

Magbeam (Significance, Likelihood) –

Significance –

rank	1	2	3	4	5	6
# of people	0	1	0	2	6	6

Likelihood –

rank	1	2	3	4	5	6
# of people	0	2	9	3	1	0

"Seems the most promising."

Memory Plastics (Likelihood, Timeframe)–

Likelihood –

rank	1	2	3	4	5	6
# of people	0	1	0	6	5	3

Timeframe –

rank	2005-2020	2020-2035	2035-2050	After 2050/Never
# of people	7	7	1	0

No comments.

Nanotube Polymer Space Elevator (Timeframe) –

rank	2005-2020	2020-2035	2035-2050	After 2050/Never
# of people	2	1	12	0

No comments.

Nuclear Drive (Significance) –

rank	1	2	3	4	5	6
# of people	0	1	2	11	0	1

"I predicted nuclear drive will have a high significance because of all the technologies I've read about it seems the most realistic and closest to becoming reality. The nuclear drive I considered mostly was Nuclear Electric Propulsion (NEP) Rather than Nuclear Thermal Propulsion (NTP) (the wording seemed a little vague as to which Nuclear Drive was being proposed). NEP does not need the extreme temperatures of NTP so radiating excess heat is less of an issue. You would only need to add more radiator panels to match your reactor rather than some more exotic means of heat transfer. NEP wouldn't provide nearly as much thrust but would be extremely fuel efficient. The benefits of NEP over traditional methods can be seen in the proposals for Project Prometheus. A spacecraft going to Jupiter would get there quicker, be able to stay longer, and conduct much more in-depth research with more powerful instruments. As long as there is political support for nuclear reactors in space, NEP is poised to make huge contributions to deep space exploration. NTP on the other hand, may or may not become a reality due to the extreme temperatures involved."

Ram Accelerator (Significance, Timeframe) –

Significance –

rank	1	2	3	4	5	6
# of people	1	1	6	5	1	1

Timeframe –

rank	2005-2020	2020-2035	2035-2050	After 2050/Never
# of people	1	8	5	0

"What happens if/when a projectile doesn't make orbit?"

Reusable Single Stage to Orbit (SSTO) (Likelihood, Timeframe) –

Likelihood –

rank	1	2	3	4	5	6
# of people	0	1	2	2	7	3

Timeframe –

rank	2005-2020	2020-2035	2035-2050	After 2050/Never
# of people	10	3	2	0

"I predicted a late time frame for SSTO because a vehicle like that is fairly complex and most players in the aerospace world are either busy with other things (capsules, multi-staged space planes) or just don't have the money and/or know-how to successfully pull it off. Also there needs to be some more significant advances in materials that will probably take a few years."

"Requires ram accelerator which could slow things down."

Roving Lunar Base (Timeframe) –

rank	2005-2020	2020-2035	2035-2050	After 2050/Never
# of people	0	2	12	0

No comments.

Slingatron (Significance, Likelihood) –

Significance –

rank	1	2	3	4	5	6
# of people	1	1	4	8	0	1

Likelihood –

rank	1	2	3	4	5	6
# of people	0	4	7	3	1	0

"Safety issues?"

Solar Sail (Time) –

rank	2005-2020	2020-2035	2033-2050	After 2050/Never
# of people	6	7	2	0

No comments.

Alumni Debate Round 1

Here is the first round of comments – giving us some comments for technologies that previously had none.

Bionic Leaf –
"Why bother with a leaf? Better solar cells and energy storage would provide a better energy source for catalyzed 'photosynthesis.'"

"Freeman Dyson's concern is sustained human habitation of the moon.
Consequently, he desires not just electrical power/storage but the conversion of CO_2 and water into breathable oxygen and ingestible food products.

"Unfortunately, like many of F. Dyson's ideas... there is no direct, logical connection between modern technology and this cyborg potato. There is also a decided lack of both CO_2 and water on the moon, presenting additional difficulties with this idea."

Magbeam –
"Having the power source disconnected from the vessel seems to be an excellent way to reduce the weight of the vessel. Thus, you're not doing the unnecessary work carrying around the weight of the propulsion system. I wonder about how effective the magbeam would be at longer distances, though, as the beam is bound to lose strength and focus as distance from the power source increases. There's also the danger of the vessel being struck off course by stray objects, solar flares, etc. The vessel would need to carry some sort of emergency propulsion system to correct for such things."

Memory Plastics –
"We have had shape memory alloys for 40 years, so it doesn't seem like much of a stretch to use them in space technology. In fact, some of these alloys return to their original shape through application of a magnetic field rather than through temperature. In combination with, say, electromagnetic shielding, rapid self-repairing hulls might be possible."

Alumni Debate Round 2

And here's the next 2-hour update:

Memory Plastics –

"We have had shape memory alloys for 40 years, so it doesn't seem like much of a stretch to use them in space technology. In fact, some of these alloys return to their original shape through application of a magnetic field rather than through temperature. In combination with, say, electromagnetic shielding, rapid self-repairing hulls might be possible."

"Shape memory alloys and shape memory plastics are clearly not the same thing. A coil of wire which can change from coiled to straight with the application of a stimulus is not the same as a piece of plating which can change from a randomly punched hole to an airtight seal at the application of a stimulus.

"Space vessels should be adequately protected in the first place if we seek to safely transport personnel. Planning on their being holes which we can 'just fix later' is not sound thinking. Frankly, given space agencies shrinking budgets, refinements of existing technologies and the improvements of designs are much more likely to produce sustentative and timely returns on investments. High strength to weight ratio metals in a protective capacity passes the 'Keep it simple' test."

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