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Forecast of Space Technological Breakthroughs

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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" including NASA employees, academics, and enthusiasts, 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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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. The project forecasts both manned and unmanned space technology, industry, and exploration by taking possible technological breakthroughs into account over the next 50 years. Using current literature and two panels of individuals, significant and likely breakthroughs are identified. Furthermore, using panelists in a Delphi-type study the most possible scenarios for the future of unmanned and manned space flight will be predicted based off of these breakthroughs. This resulted in a plausible forecast of manned and unmanned space technologies and their applications.

1.1 Breakthroughs Make a Difference

A previous group conducted a similar forecast; 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 measure of prediction.

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 had not been duplicated until their methods were publicized. A graph of the premature development of flight due to this breakthrough is seen in figure 1.1 below.

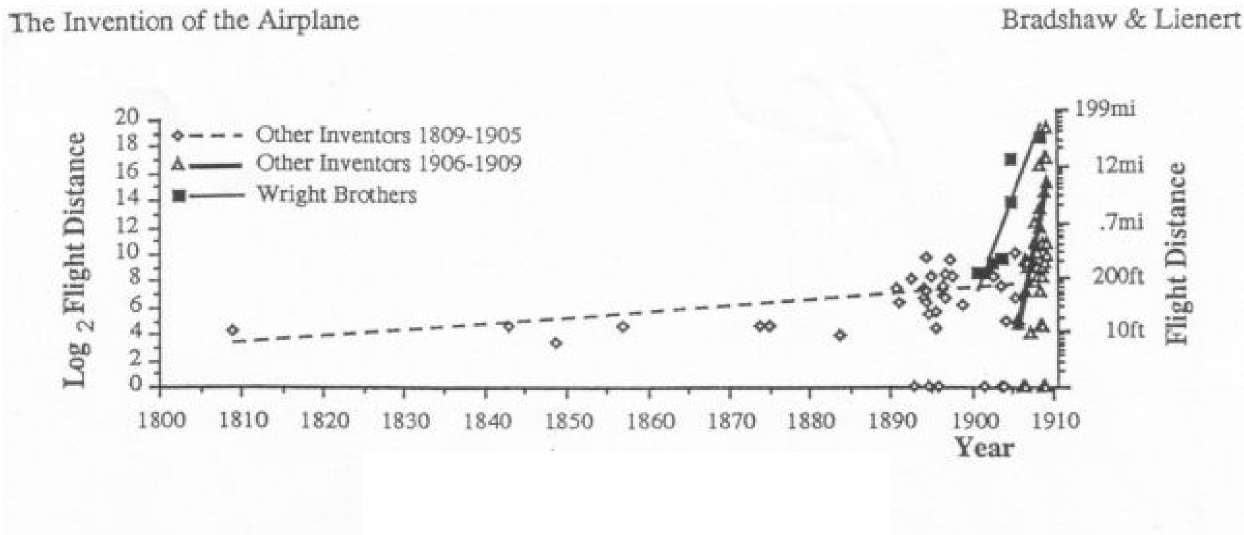

Figure 1.1: Graph of flight attempts between 1809 and 1909 to show the effects of a breakthrough occurring (Bradshaw and Lienert 606)

The concept of creating a second forecast, taking potential breakthroughs into account originated from 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 leas the possibility technological breakthroughs?" They are 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 them assessed objectivity, since most breakthrough ideas would be coming from the developers themselves. A big source, therefore, polling the assessments of an assortment of experts with sufficient knowledge in the fields in which these technological breakthroughs may occur is important. This will allow us to obtain opinions from people that will be working with these technologies once they are ready for use so that the future can be predicted, not through a historical projection, but through an informed outlook into the future, 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, off of which that future is based. As Freeman Dyson points out, "Technology only gives us tools. Human desires and institutions decide how we use them" (Dyson 15). Thus, we 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 was constantly making headlines when it was racing against Russia to put men in orbit and again to put men on the moon, but due to a lack of public interest, the agency's funds have dropped significantly since then. It can barely maintain the space shuttle and build a space station today much less return to the moon. 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 to do missions through international cooperation with other more unmanned friendly agencies like JAXA and the ESA because of the budget constraints. The space scientists have these budget problems due to the prestige in Congress of manned missions and disagreements within NASA about how to fulfill its mission statement. The space scientists believe that unmanned space research is the best way to explore the universe, but the administration feels that manned exploration would be more valuable.

Japan is unique because it had three separate space programs with different goals, which merged into one, JAXA, which has only existed for just over 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 launches in Japan. ISAS concentrated on the space science and relied on NASDA to launch some satellites, doing 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 lost the autonomy that their colleges in the United States envied them for.

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, have 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 service 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 business 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 Soyaz 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 man space flight, most notable with the space station MIR. 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. It is now seeking commercial contracts outside of the country for funding. Today the Russian space has started to cut into ESA's share of the launch market.

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, we were able to speak with forecaster, Freeman Dyson, as well as with space scientists and engineers working for NASA and the Jet Propulsion Laboratory (JPL). We discussed cutting edge technologies with space scientists and also with aerospace engineers and physicists on our own campus as well. We expanded our search for breakthroughs into online publications, and also into 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 the filed. Once 20 promising technologies were gathered, the assessment panels needed to be set up.

Our 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 our 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 individuals saw it as a evolving into a mass broadcasting method (Linstone & Turoff 2).

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 whom we choose for our panel will make a big difference in the accuracy of our 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 our Delphi study, along with a panel of experts and enthusiasts in the field, we also assembled a group of cognitively known individuals, all WPI grads from the class of 2001 or 2002. This was to help us determine the range of opinion reflects cognitive variables rather than training and background knowledge, as well as help us to determine whether our expert respondents are 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 uses of the telephone far more accurately than those persons 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 we help us maintains balance in our responses, by asking rank-and-file engineers in several fields and physics majors what they think.

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

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

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 result feedback. This method of forming a single opinion from those of many 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" other than surface, and to provide forecast of future technological innovations that would be of interest to the military. (IIT) 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 home" 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. (IIT)

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 (IIT)

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 may be manipulated by the monitors with the aim of moving the study in a desired direction. Finally, in any 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.

Our 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. 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 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 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 some studies that personality, or more generally, cognitive type, 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 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 found 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[1]) 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 beyond 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 helping us to distinguish cognitive influence within responses.

Therefore, we were very selective in which WPI alumni from these classes were asked to participate in our study. 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 technical field, we choose our sample 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, 12 of which were marked as having an aero-related concentration or were working in a closely related field. Within each of these fields, we selected even cognitive type distributions across our four types.

Our sample decreased to 60 alumni, due to non-updated contact information for the alumni. The final distributions can be seen in table 2.1 below. Our goal was to have a response

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[1] ® MBTI, Myers-Briggs, and Myers-Briggs Type Indicator are registered trademarks or trademarks of the

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.

Myers-Briggs Type Indicator Trust in the United States and other countries.

Major	**Y.O.G.**	**Potential Panelists, named by MBTI Results**							
		Panelist	type	Panelist	type	panelist	type	panelist	type
Mechanical	2001	SJ 1		**SP 1 +**	**ESTP**			**NP 1 +**	**ENTP**
Engineering:		SJ 2		SP 2				**NP 2 +**	**ENTP**
		SJ 3 *		SP 3				NP 3	
		SJ 4		SP 4				NP 4	
		SJ 5 *						NP 5 *	
	2002	**SJ 6 *+**	**ISTJ**	**SP 5 '+**	**ESTP**	**NJ 1 +**	**INTJ**	NP 6	
		SJ 7		SP 6		**NJ 2 +**		NP 7	
		SJ 8 *				NJ 3		NP 8	
						NJ 4 *			
						NJ 5 *			
						NJ 6 *'			
Electrical	2001	SJ 9		SP 7		**NJ 7 +**	**INTJ**	NP 9	
Engineering:		SJ 10		SP 8		NJ 8		NP 10	
		SJ 11		SP 9				NP 11	
								NP 12	
	2002	SJ 12 *							
Physics:	2001					**NJ 9 *+**	**INTJ**	NP 13	
	2002	SJ 13				**NJ 10 *+**	**INFJ**	NP 14	
						NJ 11 *+	**INTJ**	NP 15	
						NJ 12 *			
Biotechnology:	2001	**SJ 14 +**	**ISTJ**	**SP 10 +**	**ISTP**	**NJ 14 +**	**ENFJ**	**NP 16 +**	**INTP**
		SJ 15		SP 11				NP 17	
Chemical	2001	**SJ 16 +**	**ISTJ**					NP 18	
Engineering:								NP 19	
	2002			SP 12 '					
Total Respondants:		3		3		7		3	16
Total Pool:		16		12		13		19	60
Response rate:		18.75%		25.00%		53.85%		15.79%	**27%**

* Aerospace related
' married to another requested panelist
\+ responded to first questionnaire

Table 2.1: Alumni sample, categorized by cognitive type and B.S. degree; the bolded names are those who participated

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 A1.

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" [2] 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 individual mind 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

[2] An explanation of an NJ-type can be found in the literature review.

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, The Sun, the Genome, and the Internet 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 who 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, 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
Professor's NASA Search	0 Academics, 9 NASA, 3 Professionals
Supplemental Search	2 Academics, 0 NASA, 0 Professionals

Table 2.2: Expert recruitment summary; organized by recruitment phases and types of panelists yielded

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 missed 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 initialized 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: ____

____

2.3 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 contend 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. 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 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 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 in the year 2020, the Americans landing less than a year before the Chinese. 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 now offers cooperation in the reach for Mars. (Berirmen 100)

In 2030, the United States is undergoing 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 played $1 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 theses 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 to fast and solar sail are difficult to maintain in space. Kaku feels that ion engine will be the most popular type of propulsion for long vogues. 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 finings by scientists at the Johnson Space Center concerning the existence of microbial life on Mars" (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 would is an amazing feat, Kaku does not provide much explanation and the affects 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 more v, 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 foretelling 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, Probable Tomorrows: How Science and Technology Will Transform Our Lives in the Next Twenty Years. 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, than 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 have 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 detractors 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 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. As such, 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 initializing 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 well 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, 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, 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 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 some 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 are “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 mental 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 breakthrough-oriented panelists (5).

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 recruit for 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

4.1 Alumni Panel Results

The following tables are grouped by our five categories: launch vehicle, life support, material, 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 where 1 was early (in the next 15 years) and 4 was never.

4.1.1 Likelihood Ratings

	Likehood				
	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
SSTO	4.6	5.0	5.3	4.5	3.7
Ram Accelerator	3.3	4.0	4.0	3.0	3.7
Laser Propulsion	3.2	3.3	3.3	3.2	3.0
NPSE	2.3	1.3	2.0	2.7	3.0

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. The breakdowns in terms of cognitive inclinations are interesting, with the NP group being the only one to keep a relatively even level of support for each breakthrough, while each other group had SSTO as the clear favorite, and NPSE as the clear loser in terms of likelihood.

	Likelihood				
	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
The Gravity Implant	3.5	4.7	2.3	3.5	3.7
Fusion Reactors	3.3	3.0	3.7	3.0	3.7
LEO CAC	3.2	3.3	3.7	2.8	3.3
Roving Lunar Base	3.0	2.3	3.0	2.5	4.3
The Bionic Leaf	3.0	3.7	2.0	2.8	3.3

Table 4.2: Likelihood of Life Support Technologies – Alumni

For the likelihood of life support breakthroughs, there is no clear favorite, with all breakthroughs receiving almost equal support. Again, the NP group is an exception, favoring the Roving Lunar Base over the others. The SJ group gave the Gravity Implant its lowest score by far, as it was the favorite among the other two groups.

	Likelihood				
	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Carbon Nanotubes	4.7	5.3	4.3	4.7	4.7
Memory Plastics	4.6	4.0	4.7	4.3	5.7
Solid State Aircraft	3.4	3.3	3.0	3.5	3.7

Table 4.3: Likelihood of Material Technologies – Alumni

For the likelihood of materials breakthroughs, it is obvious that both Carbon Nanotubes and Memory Plastics received heavy support, while Solid State Aircraft received significantly less. Both SP and NJ groups appear to favor Carbon Nanotubes, while the SJ and NP groups favor Memory Plastics. The most optimistic group seems to be the NP group.

	Likelihood				
	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Solar Sail	4.5	5.0	4.7	4.3	4.0
Nuclear Drive	3.8	3.7	5.7	3.0	3.7
Magbeam	3.2	3.0	3.0	3.2	3.7
Slingatron	3.1	3.0	3.0	2.7	4.0

Table 4.4: Likelihood of Propulsion Technologies – Alumni

For the likelihood of propulsion breakthroughs, the alumni panel prefers Solar Sails. Nuclear Drive comes in not too far behind, with the others receiving relatively little support. The NP group again appears to be almost evenly divided. The NJ group shows a fairly slanted distribution favoring Solar Sails. The SP group heavily favors Solar Sail above the others. The SJ group is by far the strongest supporter of Nuclear Drive, but also offers heavy support for Solar Sails.

	Likelihood				
	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Aerogel	5.0	5.0	5.0	4.7	5.7
EM Shielding	3.7	3.3	4.3	3.2	4.7
Cold Plasma	2.7	3.0	2.3	2.2	3.7

Table 4.5: Likelihood of Shielding Technologies – Alumni

For the likelihood of shielding breakthroughs, Aerogel is the strong favorite across the board, with EM Shielding the obvious second. The Cold Plasma received little support, with the exception of the NP group, who were more optimistic than all the other groups for all three of these breakthroughs, the NJ group offered the least optimism of all the groups for each breakthrough.

4.1.2 Significance Ratings

	Significance				
	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
SSTO	3.5	4.7	3.7	3.5	2.0
Ram Accelerator	3.3	3.3	3.7	3.7	3.0
Laser Propulsion	4.3	4.0	4.0	4.5	4.3
NPSE	4.3	4.3	4.0	5.3	3.0

Table 4.6: Significance of Launch Vehicles - Alumni

In terms of the launch vehicle breakthroughs, the alumni consider Laser Propulsion and the NPSE to have potential to really shake things up compared to the other launch vehicles. However, Laser Propulsion has a steady average across the four cognitive inclinations, but the NPSE has one high group and one low group. The most impressed, optimistic cognitive type in terms of significance was the NJ group, who felt the NPSE was very significant. The least optimistic mindset was the NP group, who felt the NPSE was not particularly significant.

Significance	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
The Gravity Implant	4.5	4.7	4.7	4.7	4.0
Fusion Reactors	4.7	5.3	4.7	4.5	4.3
LEO CAC	4.5	4.7	4.3	4.5	4.3
Roving Lunar Base	3.3	5.0	3.0	2.8	2.7
The Bionic Leaf	4.3	4.7	4.0	4.5	4.0

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. It maintained a high perceived significance for all of the cognitive types, slightly more so than the Gravity Implant and the LEO Compressed Air Collector (LEO CAC). The most optimistic type in terms of the significance of these breakthroughs was the SP group, which also had the highest average score for the Fusion Reactors. The least optimistic type was the NP group, which was less impressed by the Fusion Reactor and was relatively unimpressed by the Roving Lunar Base.

Significance	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Carbon Nanotubes	5.1	5.3	5.3	5.3	4.0
Memory Plastics	4.5	4.7	3.7	4.3	5.7
Solid State Aircraft	4.0	4.0	3.3	4.0	4.7

Table 4.8: Significance of Materials - Alumni

For the most significant of the breakthroughs in materials the alumni nominate Carbon Nanotubes over the other breakthroughs. The Nanotubes had an extremely high significance rating from all of the cognitive types, even the NP group which thought the Nanotubes would be the least significant of the materials. The most optimistic type in terms of significance was again the NP group, which thought the Nanotubes would be the least significant of the materials, despite the consensus amongst the other three types that it was the most significant breakthrough. The least optimistic mindset was the SJ group, went to the extreme in claiming that the Solid State Aircraft would not be very significant.

Significance	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Solar Sail	4.7	5.3	4.7	4.2	5.3
Nuclear Drive	3.9	3.0	4.7	4.0	3.7
Magbeam	5.1	5.3	5.3	5.2	4.3
Slingatron	3.5	4.7	3.7	3.3	2.7

Table 4.9: Significance of Propulsion - Alumni

For the significance of the breakthroughs in the category of propulsion the alumni think the Magbeam would be the biggest breakthrough compared to the other possibilities. The Magbeam has high scores in all of the mindsets, even in the least impressed NP group which did not think it was the most significant breakthrough. It was rated quite high. In terms of significance, the SP and SJ groups had similar high scores for the Magbeam and Solar Sail, but differed in opinion on the Nuclear Drive and Slingatron. The least optimistic group was the NP group which had moderately high results for most of the breakthroughs, but thought the Slingatron would not be very significant.

Significance

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Aerogel	4.6	5.0	4.3	4.5	4.7
EM Shielding	4.4	4.0	5.3	4.5	4.0
Cold Plasma	4.5	4.3	4.0	4.5	5.3

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. All 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, which thought Cold Plasma was the most significant breakthrough followed by Aerogel and then the Electro Magnetic Shielding. The least optimistic mindset about something totally new coming along was the SP group which gave their lowest results to Cold Plasma and the Electro Magnetic Shielding, but considered Aerogel a significant development.

4.1.3 Timeframe Ratings

Timeframes	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
SSTO	1.5	1.7	1.7	1.2	1.7
Ram Accelerator	2.3	2.3	2.0	2.4	2.3
Laser Propulsion	2.6	2.3	2.3	3.0	2.3
NPSE	2.7	3.0	3.0	2.7	2.0

Table 4.11: Timeframes of Launch Vehicles - Alumni

There do not appear to be any consistent correlations between cognitive style and the time rating like one type always being more optimistic about everything. For example, the NJ's are the most optimistic on the SSTO, while they are the least optimistic about the Ram Accelerator and Laser Propulsion.

Timeframes	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
The Gravity Implant	2.1	1.3	2.7	2.2	2.2
Fusion Reactors	2.6	2.7	2.7	2.6	2.7
LEO CAC	2.5	2.7	2.7	2.6	2.2
Roving Lunar Base	2.9	3.0	3.0	2.8	2.7
The Bionic Leaf	2.8	2.3	3.0	3.0	2.7

Table 4.12: Timeframes of Life Support Technologies - Alumni

The SP's rating of the Gravity Implant is truly remarkable. They believe that it will happen during the next 20 years, a much more optimistic outlook than any of the other alumni or expert groups have.

Timeframes

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Carbon Nanotubes	1.8	1.7	1.7	2.0	1.7
Memory Plastics	1.6	2.0	1.7	1.5	1.3
Solid State Aircraft	2.5	2.3	3.0	2.3	2.3

Table 4.13: Timeframes of Material Technologies - Alumni

The Alumni believe that Memory Plastics will be the first of the Materials breakthroughs. The SJ group is very optimistic about the Carbon Nanotubes and Memory Plastics, however, they are they seem to think a Solid State Aircraft is many years away.

Timeframes

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Solar Sail	1.7	2.0	1.3	1.5	2.3
Nuclear Drive	2.0	2.7	1.3	2.0	2.0
Magbeam	2.7	3.0	3.0	2.6	2.3
Slingatron	2.1	3.0	2.3	2.2	1.0

Table 4.14: Timeframes of Propulsion Technologies - Alumni

With the exception of the NP's, the Alumni seem to be in consensus that the Solar Sail with be the first of the Propulsion breakthroughs to occur. The NP's have it tied for last. The most pessimistic of the cognitive types is the SP group which believes that the Magbeam and Slingatron are far off and only the solar sail is promising for an early breakthrough.

Timeframes

	Total	SP Avg	SJ Avg	NJ Avg	NP Avg
Aerogel	1.1	1.0	1.0	1.3	1.0
EM Shielding	2.4	2.3	2.3	2.8	1.7
Cold Plasma	2.9	2.7	3.0	3.0	2.7

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. The most pessimistic mindset in terms of what time frame the breakthroughs will occur was the NJ group, followed by the SJ group, both of with gave Cold Plasma a very late arrival time.

By looking over the tables we may say that Alumni believe that Carbon Nanotubes and the Magbeam cuased the most optimistic reactions for all the technologies listed in the tables. It is also fair to say that Ram Accelerator and Roving Lunar Base counted as the least significance factors. However, the Alumni believe that Aerogel will realize its full potential first. Cold Plasma and Roving Lunar Base will be happen latest. Also, we noticed that overall the opinion of the NP's and SJ's were at opposite ends of the general distribution, with only a few exceptions. This is to be expected since they are cognitive opposites. The types congregated at different ends of the distribution than we had expected, however. MBTI theory would suggest that the NP's would be more optimistic and the SJ's less, but this was the opposite of what we found for numerous technologies.

4.2 Expert Panel Compared with Alumni Panel

4.2.1 Likelihood Ratings

Likelihood	Experts	Alumni	Overall
SSTO	4.4	4.6	4.5
Ram Accelerator	2.7	3.3	3.0
Laser Propulsion	2.5	3.2	2.9
NPSE	2.4	2.3	2.4

Table 4.16: Likelihood of Launch Vehicles

Overall, the Experts and Alumni were in consensus on the likelihood of a Single State to Orbit being the most likely breakthrough in launch vehicle technology. They also agreed that the Space Elevator would have the smallest likelihood of becoming useful in the future. The Alumni were somewhat more optimistic about the Ram Accelerator and Laser Propulsion options.

Likelihood	Experts	Alumni	Overall
The Gravity Implant	2.4	3.5	3.0
Fusion Reactors	3.3	3.3	3.3
LEO CAC	2.8	3.2	3.0
Roving Lunar Base	3.3	3.0	3.2
The Bionic Leaf	3.1	3.0	3.1

Table 4.17: Likelihood of Life Support Technologies

The Experts and Alumni were in consensus on all of the Life Support breakthroughs except for the Gravity Implant and maybe the LEO CAC, where the Alumni were more optimistic. The Alumni, although they didn't give it a high likelihood rating, gave it much more of a chance of happening than the Experts did. This may prove to be a topic of discussion in future rounds, when the panelists are allowed to defend their point of views.

Likelihood	Experts	Alumni	Overall
Carbon Nanotubes	4.6	4.7	4.7
Memory Plastics	4.1	4.6	4.4
Solid State Aircraft	3.4	3.4	3.4

Table 4.18: Likelihood of Material Technologies

For materials, the expert and alumni likelihood averages only differ significantly with reference to memory plastics. The difference is still fairly small with experts averaging at 4.1 and alumni averaging at 4.6. Again, the Alumni tend to me more optimistic.

Likelihood	Experts	Alumni	Overall
Solar Sail	4.8	4.5	4.7
Nuclear Drive	4.3	3.8	4.1
Magbeam	2.5	3.2	2.9
Slingatron	1.9	3.1	2.5

Table 4.19: Likelihood of Propulsion Technologies

The experts and alumni disagree on the likelihood of some of the propulsion technologies. The Alumni believe that the slingatron and magbeam are more likely to occur than the experts believe them to be. However, the experts give a higher likelihood rating for the nuclear drive. Both groups gave high likelihood ratings to the solar sail, and the experts were especially enthusiastic about it.

Likelihood	Experts	Alumni	Overall
Aerogel	4.9	5.0	5.0
EM Shielding	3.6	3.7	3.7
Cold Plasma	2.6	2.7	2.7

Table 4.20: Likelihood of Shielding Technologies

There does not seem to be any significant differences in the average likelihood ratings given by the Experts and Alumni. The averages are all very similar.

4.2.2 Significance Ratings

Significance	Experts	Alumni	Overall
SSTO	4.2	3.5	3.9
Ram Accelerator	3.0	3.3	3.2
Laser Propulsion	3.7	4.3	4.0
NPSE	4.5	4.3	4.4

Table 4.21: Significance of Launch Vehicles

Overall, the panelists consider the nanotube polymer space elevator to have the greatest significance in the future of space amongst the launch vehicle technologies, with moderate to major significance. They considered the ram accelerator to have only small significance. The expert panel believed that success in getting single stage to orbit working would be more significance for the future of space than the alumni felt it, and laser propulsion was considered to have greater significance for the expert than the alumni.

Significance	Experts	Alumni	Overall
The Gravity Implant	3.8	4.5	4.2
Fusion Reactors	4.7	4.7	4.7
LEO CAC	3.5	4.5	4.0
Roving Lunar Base	3.7	3.3	3.5
The Bionic Leaf	4.4	4.3	4.4

Table 4.22: Significance of Life Support Technologies

From this table, it is seen that opinions of both the expert and alumni panel are similar. However, experts appear to see less value in both the gravity implant and LEO compressed air collector than the alumni, who felt they would have moderate to major significance. A roving lunar base would have only a small to moderate impact for the future of life support according to both groups (though the experts were more impressed) and both agree that a bionic leaf would have at least moderate significance, according to both points of view. There is also consensus that a fusion reactor would be the most significant breakthrough for life support in space, having major significance.

Significance	Experts	Alumni	Overall
Carbon Nanotubes	5.0	5.1	5.1
Memory Plastics	4.4	4.5	4.5
Solid State Aircraft	3.2	4.0	3.6

Table 4.23: Significance of Material Technologies

Both of the groups believe that Carbon Nanotubes will have a significant impact in the future of materials in space. The Solid State Aircraft was the least significant to both the Alumni and the Experts, but the alumni saw more potential in the concept. This may prove to be a topic of discussion amongst the panelist in later rounds when they can defend their point of views.

Significance	Experts	Alumni	Overall
Solar Sail	4.4	4.7	4.6
Nuclear Drive	4.4	3.9	4.2
Magbeam	3.8	5.1	4.5
Slingatron	2.8	3.5	3.2

Table 4.24: Significance of Propulsion Technologies

For the significance of Propulsion breakthroughs, the alumni panel is shown to be much more impressed by all the possibilities, with the exception of Nuclear Drive. The significant disparities between the alumni and expert panels as regards Magbeam and Slingatron are of particular interest. The Solar Sail is the overall favorite, and is the only breakthrough which received high support from both panels, and even here, once again, the alumni were more optimistic.

Significance	Experts	Alumni	Overall
Aerogel	4.3	4.6	4.5
EM Shielding	4.4	4.4	4.4
Cold Plasma	3.6	4.5	4.1

Table 4.25: Significance of Shielding Technologies

For the significance of Shielding breakthroughs, all received mid range support. The expert panel expressed slightly more excitement about EM Shielding commpaired to the others, especially Cold Plasma, while the alumni panel rated its significance as equal to the other breakthroughs. The alumni panel shows general optimism relative to the expert panel, although this is mosr obvious in the case of Cold Plasma.

4.2.3 Timeframes Ratings

Timeframe	Experts	Alumni	Overall
SSTO	1.7	1.5	1.6
Ram Accelerator	2.7	2.3	2.5
Laser Propulsion	2.5	2.6	2.6
NPSE	2.8	2.7	2.8

Table 4.26: Timeframes of Launch Vehicles

Both the experts and alumni indicated that the single stage to orbit would be an "early" development likely to happen within the next 30 years, or earlier and that the nanotube polymer space elevator will not happen until beyond the next 30 years. There was also consensus between experts and alumni on the timeframe of laser propulsion to be perfected.

Timeframe	Experts	Alumni	Overall
The Gravity Implant	2.7	2.1	2.4
Fusion Reactors	2.7	2.6	2.7
LEO CAC	2.5	2.5	2.5
Roving Lunar Base	2.5	2.9	2.7
The Bionic Leaf	2.3	2.8	2.6

Table 4.27: Timeframes of Life Support Technologies

As seen in this table, our panelists do not predict any of the listed life support breakthroughs to happen early on in our forecast period. The expert and alumni panels concur that none of the technologies will become available until beyond 2020. Overall, the alumni believe the Roving Lunar Base and Bionic Leaf will happen later than the experts believe them to happen, yet they believe the Gravity Implant will occur earlier than the experts believe it likely to happen.

Timeframes	Experts	Alumni	Overall
Carbon Nanotubes	1.6	1.8	1.7
Memory Plastics	1.8	1.6	1.7
Solid State Aircraft	2.2	2.5	2.4

Table 4.28: Timeframes of Material Technologies

The alumni and experts are in consensuses on the timeframe on all the materials breakthroughs. Carbon Nanotubes, and memory plastics averaged in the middle time rage (2020 to 2035). Solid state aircraft averaged a little higher at 2.4.

Timeframe	Experts	Alumni	Overall
Solar Sail	1.7	1.7	1.7
Nuclear Drive	1.8	2.0	1.9
Magbeam	2.7	2.7	2.7
Slingatron	2.7	2.1	2.4

Table 4.29: Timeframes of Propulsion Technologies

For the Timeframe of Propulsion breakthroughs, there are few differences in opinion between the expert and alumni panels. The Slingatron represents the only notable difference and that seems closer to the alumni than the experts. Solar Sail and Nuclear Drive are both predicted as middle-era (2020-35) breakthroughs, while Magbeam and Slingatron are late-era (2035-50) breakthroughs.

Timeframes

	Experts	Alumni	Overall
Aerogel	1.4	1.1	1.3
EM Shielding	2.0	2.4	2.2
Cold Plasma	3.1	2.9	3.0

Table 4.30: Timeframes of Shielding Technologies

For the timeframe of Shielding breakthroughs, it is clear which breakthroughs are favored by both panels. The expert and alumni panels varied in their predictions, but not significantly so. The advent of Aerogel, EM Shielding, and Cold Plasma, in successive eras respectively, is the uniform opinion of both panels.

5. Recommendations

From our study, the following technologies should be included in the next round of surveying:

Launch Vehicles – SSTO

Life Support – Fusion Reactors

Materials – Carbon Nanotubes

Propulsion – Solar Sail

Shielding – Aerogel

Also, cognitive data is significant to this Delphi study so it would be worth while to get such data for our expert panelists, if possible, to see if the expert panel responses are as skewed as the alumni panel responses were do to cognitive type. 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.

Not all of our hypotheses were so blatantly mistaken. We believed that the experts, who work in the field all the time and had a greater understanding of the forces at work, would be more pessimistic than the relatively ignorant 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, not necessarily significantly more. Moreover, there were a few technologies for which the alumni were slightly less optimistic.

Note also, this study is a work in progress. Due to time constraints and the delays that inevitably happen while dealing with gathering and sampling a large pool of people, not enough information could be gathered to complete this project to the degree that had originally been planned. Luckily, future groups have already been recruited to continue our data gathering and analyzing, in order to find conclusions and create a proper breakthrough-incorporating forecast. The final forecast is intended to include a set of possible scenarios of the future if consensus is not found amongst the panelists.

APPENDICES

A1: Questionnaire

Sample Cover Letter

December 17, 2004

Professor NAME
Physics Dept.
WPI

Dear Professor NAME,

First of all, we'd like to thank you for considering the possibility of participating in this Delphi Study. At this point the proposed panel includes only 5 WPI faculty members. The rest of the 25 will be from MIT, Cornell, Princeton as well as some people that they suggested from other places. So far, 19 people have agreed to participate, but we were unable to reach you to ask you in person before the break. We hope that you will look over the items and decide to participate.

This is the first of two, or time permitting, three, questionnaires designed to produce a more accurate prediction of the future than one would get with a simple historical projection. The idea of a Delphi Study, for those unfamiliar with the technique, is that through a series of questionnaires, estimates of the likelihood of certain outcomes and technical development are produced by pooling expert opinion. Sometimes that is a consensus immediately. More often there is a range of opinion, which moves toward consensus in successive rounds of panel evaluation as the people taking various positions defend and debate them anonymously, to persuade the rest of the panelists.

The questionnaire accompanying this letter asks you for a rating on a 1 to 6 scale. Descriptions of each "breakthrough" technology are provided and you are asked to rank each one in terms of both their likelihood and in terms of the significance such a development would have. The second questionnaire will combine multiple breakthroughs into short scenarios of a possible future in space, based on this panel's assessments of which technologies are most likely to be available in the next 50 years.

For those who can make it, an oral presentation of the results is scheduled as part of the International Association for Science, Technology and Society Studies (IASTS) meeting in Baltimore, Maryland Feb. 11-12, 2005. An executive summary will be distributed soon after that time and those interested in the full report will be sent an electronic copy upon request.

Again, thank you for your time and for providing us with your input.

Sincerely,

Damon Bussey, Tim Climis,
Mandy Learned, Tim Padden,
Brian Partridge, Vadim Svirchuk

WPI Box 936
100 Institute Rd.
Worcester, MA 01609-2208

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) <u>Propulsion In Space</u>

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) <u>Launch Vehicles</u>

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) <u>Shielding</u>

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) <u>Life Support</u>

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.

Questionnaire 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: ____
____

A2: Letters

Cornell Dyson Letter

October 21, 2004

Dear Dr. Dyson,

We are undergraduates from WPI representing two research project groups. WPI is committed to project based education and in the junior year everyone has to do a project focusing on the Society-Technology interface worth 3 courses of credit. We are now doing our junior year projects. Some of us have read your book, *The Sun, the Genome, and the Internet* and found it inspirational. The theme of both of our projects is a forecast of space technology. One is focused on a manned space race between the United States and China to the Moon and Mars, making a 50-year forecast. The other is composing a 25-year, scenario-based forecast of developments in unmanned space technology, industry, and exploration. Both projects are based on the assumption that breakthroughs will occur in this Timeframes. Other teams are doing forecasts assuming incremental advances in current technology over a period of time without breakthroughs. Future WPI project teams will subsequently use our forecasts to work out the social implications of the developments we predict to produce a full technology assessment of the impact of space technology in the next period.

Your book caught our attention for two reasons. First, you are talking about whole new means of gaining access to space in Chapter 3. You also do something we had not thought of doing: trying to see how developments in other areas of technology such as bio-technology will interact with what is going on in terms of power and space to see what new kind of civilization might emerge. That is daring, and interesting.

In order to perform our forecast in a way that is open to breakthrough, we are using a Delphi study. Historical analogy only seems to take you just so far. The history of aviation suggests that the Wright Bros. were "early" by about 50 years. The development of the wind tunnel changed things radically. So, we want to know if anything so momentous is on the horizon in space technology. Only the experts at the forefront of the field in propulsion and drives would know what looks crazy-but-promising at the moment. Our hope is that you would know who should be part of our plans to identify and assess the probability of a breakthrough in this field, or a related one that could make a large difference in the ability of the human race to explore space, in person or via unmanned technology.

Currently, we only have access to contacts at MIT and WPI for our 25 person Delphi panel. We are trying to expand our panel to include experts in space science from Princeton and Cornell, since these universities are active in the field. It would also be beneficial to our study if we could find experts at the University of Arizona and other places that you consider active in the field. This would allow us to get opinions beyond New England and possibly throughout the country. We will also be including a second panel of recent WPI graduates in the classes of 2001-2003 who are not directly involved with space technology research, but watching developments in their fields for all kinds of different reasons. What is interesting about their inclusion is to see if they agree with the experts about what scenarios for the future are most likely. We also know something about their cognitive styles. They can be grouped into those most and least likely to be interested and receptive to innovative and speculative ideas.

We are in the process of finding possible breakthrough technologies in both the manned and unmanned areas of space. We are hoping to find experts and enthusiasts who have ideas for which a breakthrough would make the technologies viable to help us write scenarios that include their ideas. Any leads you can give us to such people would be appreciated.

Contact information:

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Tim Climis

tim@wpi.edu

JMW-FSIR (manned)

Vadim Svirchuk

vadim81@wpi.edu

Brian Partridge

brianp@wpi.edu

Tim Padden

tpadden@wpi.edu

Cornell STS Professors Letter

October 21, 2004

Dear Professor,

We are undergraduates from WPI representing two research project groups. WPI is committed to project based education and in the junior year everyone has to do a project focusing on the Society-Technology interface worth 3 courses of credit. We are now doing our junior year projects. The theme of both of our projects is a forecast of space technology. One team is focused on a manned space race internationally, and the most likely one would be between the United States and China to the Moon during the period of a 50-year forecast. The US will then want to go on to Mars. It is not clear whether China would be interested in doing so. The other team is composing a 25-year scenario-based forecast of developments in unmanned space technology, industry, and exploration. Both projects are based on the assumption that breakthroughs will occur in this Timeframes. Other teams are doing forecasts assuming incremental advances in current technology over the same period of time without breakthroughs. Future WPI project teams will subsequently use our forecasts to work out the social implications of the developments we predict to produce a full technology assessment of the impact of space technology on the Earth and the Moon in the next period.

We are in the process of finding possible breakthrough technologies in both the manned and unmanned areas of space. Therefore, we are hoping to find experts and enthusiasts who have ideas for technical breakthroughs in spaceflight that are plausible and potentially consequential. If we can find some likely candidates, we will write them up into scenarios that include these ideas to try out on a panel of experts who would assess them relative to one another. So part of what we are asking from you is for any leads you could give us to such people or ideas (including yourself); that could change the course of space history or the names of people who should be on the panel of experts. Help in either area would be greatly appreciated. Space drive or propulsion systems, life support concepts, lightweight or heat resistant materials, navigation and communication concepts are all fair game. In effect, we are looking for the space equivalent of the wind tunnel, the innovation that led aviation to arrive 50 years earlier than it would have had the Wright brothers not come up with it. This device allowed them to test 1000 possible wing configurations using cardboard cutouts to assess their relative lift and drag properties before building their successful flier.

In order to perform forecasts in a way that is open to the breakthroughs, we are using a Delphi study procedure. This methodology implies we will need a panel of individuals to reply to a short series of questions. Only the experts at the forefront of the field in propulsion, drives, etc. would know what currently radical-but-promising ideas are being pursued that might trigger a breakthrough in the cost of access to space or our ability to live on another planet or be able to help us assess the viability of those that we find relative to one another.

Our hope is that you would be willing to join our panel of expert evaluators or nominate someone that you think would be good at making this kind of speculative judgment. This could be either a colleague or a graduate student. The panelist will receive a series of 3 or 4 short questionnaires, over a period of 30-40 days presenting about a dozen possible breakthroughs in the fields relevant to space activity. Scenarios describing 4-6 alternative futures over the next 25-50 years will be developed based on these breakthroughs. It is not yet clear if the scenarios will be in the first or second round of questions. Probably they will be based on the assessments of likelihood given in the first round of answers. Certainly they will deal with developments that we think will make a large difference in the ability of the human race to explore space, in person or via unmanned technology, and Freeman Dyson has agreed to consult with us on the question of which ones have the potential to be very consequential. He is openly interested in the questions of when and how space colonization will become possible.

Thank you for your time,

JMW-IRAC (unmanned)

Amanda Learned

ajl@wpi.edu

Damon Bussey

busseyd@wpi.edu

Tim Climis

tim@wpi.edu

JMW-FSIR (manned)

Vadim Svirchuk

vadim81@wpi.edu

Brian Partridge

brianp@wpi.edu

Tim Padden

tpadden@wpi.edu

Cornell Space Science Professors Letter

October 21, 2004

Dear Professor,

We are undergraduates from WPI representing two research project groups. WPI is committed to project based education and in the junior year everyone has to do a project focusing on the Society-Technology interface worth 3 courses of credit. We are now doing our junior year projects. The theme of both of our projects is a forecast of space technology. One team is focused on a manned space race internationally, and the most likely one would be between the United States and China to the Moon during the period of a 50-year forecast. The US will then want to go on to Mars. It is not clear whether China would be interested in doing so. The other team is composing a 25-year scenario-based forecast of developments in unmanned space technology, industry, and exploration. Both projects are based on the assumption that breakthroughs will occur in this Timeframes. Other teams are doing forecasts assuming incremental advances in current technology over the same period of time without breakthroughs. Future WPI project teams will subsequently use our forecasts to work out the social implications of the developments we predict to produce a full technology assessment of the impact of space technology on the Earth and the Moon in the next period.

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In order to perform forecasts in a way that is open to the breakthroughs, we are using a Delphi study procedure. This methodology implies we will need a panel of individuals to reply to a short series of questions. Only the experts at the forefront of the field in propulsion, drives, etc. would know what currently radical-but-promising ideas are being pursued that might trigger a breakthrough in the cost of access to space or our ability to live on another planet or be able to help us assess the viability of those that we find relative to one another.

Our hope is that you would be willing to join our panel of expert evaluators or nominate someone that you think would be good at making this kind of speculative judgment. This could be either a colleague or a graduate student. The panelist will receive a series of 3 or 4 short questionnaires, over a period of 30-40 days presenting about a dozen possible breakthroughs in the fields relevant to space activity. Scenarios describing 4-6 alternative futures over the next 25-50 years will be developed based on these breakthroughs. It is not yet clear if the scenarios will be in the first or second round of questions. Probably they will be based on the assessments of likelihood given in the first round of answers. Certainly they will deal with developments that we think will make a large difference in the ability of the human race to explore space, in person or via unmanned technology, and Freeman Dyson has agreed to consult with us on the question of which ones have the potential to be very consequential. He is openly interested in the questions of when and how space colonization will become possible.

Thank you for your time,

JMW-IRAC (unmanned)

Amanda Learned

ajl@wpi.edu

Damon Bussey

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Tim Climis

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Vadim Svirchuk

vadim81@wpi.edu

Brian Partridge

brianp@wpi.edu

Tim Padden

tpadden@wpi.edu

Asking Dyson for Names Letter

November 18, 2004

Professor Freeman Dyson
dyson@ias.edu

Dear Professor Dyson,

This is Amanda, on behalf of the space technology forecasting teams at Worcester Polytechnic Institute, with whom you met at Cornell, before giving your talk on biotechnology. First off, we would like to thank you once again for meeting with us. We all very much enjoyed your talk as well.

My team is currently making contact with the space scientists and enthusiasts we would like to question in order to formulate possible scenarios for the future of space technology, so I am asking you to send us a membership list, if available, of the Space Manufacturing Conference (the group that you mentioned to us, which meets every two years). Any recommendations of people you think would be beneficial to our project would be appreciated. We are looking for enthusiasts (like yourself) who enjoy thinking "big" about potential breakthrough technologies.

We will be contacting you again after Thanksgiving to ask if you can review the breakthrough possibilities that we compile, along with the questionnaire we will be sending to our panelists. After review, if you are willing to write a cover letter for us to send with our questionnaire, it would be greatly appreciated.

Thank you for your time,

Amanda Learned

Asking Debbie Martin at RPIF - JPL for Names Letter

November 19, 2004

Dear Ms. Martin,

I'm a member of a team of undergraduates at Worcester Polytechnic Institute in Worcester, MA working on a project to create a forecast of space exploration, both manned and unmanned. Last year, a group of students did a similar project using historical projections. However, history has told us that breakthrough technologies appear regularly. For example, the innovation of the wind tunnel helped the Wright brothers advance flight by what some analysts say to be fifty years. We have thus decided to formulate a projection while taking into account possible breakthroughs in aerospace and biological technologies in hopes of having greater accuracy.

You were recommended by Rick Kline at Cornell University as someone who could possibly identify researchers in the field of new technologies in materials, drives, power sources or other areas, that could make space travel more available.

We are requesting that you compile a short list of such researchers with their contact information. Also, if you are knowledgeable or enthusiastic in these areas and wish to talk to us about breakthrough technologies, we would be very grateful. Any contacts or ideas would greatly benefit our project. Also, if I was misinformed and you don't have this information, I would thank you to please pass this letter on to a person that may be helpful to our request.

Thank you for your time. If you wish to speak with us, you may call Amanda Learned, one of my partners, at (508)-380-7237. Otherwise, please reply to the email address in the header.

Sincerely,

Tim Climis

Asking Rose Steinat at the National Air and Space Museum for Names Letter

November 29, 2004

Dear Ms. Steinat,

I'm a member of a team of undergraduates at Worcester Polytechnic Institute in Worcester, MA working on a project to create a forecast of space exploration, both manned and unmanned. Last year, a group of students did a similar project using historical projections. However, history has told us that breakthrough technologies appear regularly. For example, the innovation of the wind tunnel helped the Wright brothers advance flight by what some analysts say to be fifty years. We have thus decided to formulate a projection while taking into account possible breakthroughs in aerospace and biological technologies in hopes of having greater accuracy.

You were recommended by Rick Kline at Cornell University as someone who could possibly identify researchers in the field of new technologies in materials, drives, power sources, or other areas that could make space travel more available.

We are requesting that you compile a short list of such researchers with their contact information. Also, if you are knowledgeable or enthusiastic in these areas and wish to talk to us about breakthrough technologies, we would be very grateful. Any contacts or ideas would greatly benefit our project. Also, if I was misinformed and you don't have this information, I would thank you to please pass this letter on to a person that may be helpful to our request.

Thank you for your time. If you wish to speak with us, you may call Amanda Learned, one of my partners, at (508) 380-7237. Otherwise, please reply to the email address in the header.

Sincerely,

Tim Climis

Expert Invitation Letter – Academics

December 7, 2004

Dear Professor,

This letter is an invitation to participate in a "Delphi" study, a forecast for the most likely "breakthrough" level developments in applied space science in the next generation. Our goal is to recruit five people, in a mix of faculty and graduate students, with a visionary bent from each of five major centers for the study of space science. Freeman Dyson tells us that we should contact MIT, Cornell, and the University of Arizona in addition to Princeton. The University of Washington will also be contacted.

We envision that each panel will answer at least two rounds of surveys with three to five sets of questions. The first questionnaire will contain information about a number of possible breakthroughs. The following questionnaire will contain scenarios that combine sets of likely breakthroughs. After each round of questioning we may be back in touch to mediate an exchange of views in the case that there was no consensus among the panel. In this case you would receive a distribution of the results of your fellow panelists and those in "extreme" positions would be encouraged to explain their logic or defend their positions. In any case, you and your fellow panelists will remain anonymous.

This study will focus on manned and unmanned space technology over the next 25 to 50 years. During this period a moon base is expected to be established, and so life support and habitat technology will be covered. Currently we are in the process of finding possible breakthrough technologies in both the manned and unmanned areas of space travel. We are hoping to find the most likely and significant technical breakthroughs in spaceflight from spaceflight experts, enthusiasts and the science fiction literature. When we find likely technology breakthrough candidates, we will write the first questionnaire. It will be distributed to the panels we have organized by mid December.

We would like anyone who joins a panel to fill out two questionnaires. Each questionnaire round should take about 20 to 30 minutes to complete. Participating in a panel will take up about an hour over a span of two months. We assume that a questionnaire will be completed and returned in about two weeks.

The successes of this project will depend on a timely response from you. We are hoping that this e-mail will help us recruit members for our panels. Would you or any of the graduate students or colleagues you work with be interested in participating in a panel? Please respond to this e-mail if you are interested in participating, any response will be appreciated. We plan to send the questionnaires by mail, so if you are interested pleases make sure to include a mailing address in your response. It would help us greatly if you could forward this letter to graduate students studying space technology that might also be interested.

Thank you for you time,

Damon Bussey, Tim Climis,
Amanda Learned, Tim Padden,
Brian Partridge, Vadim Svirchuk
spaceproject@wpi.edu

Expert Invitation Letter – Dyson Recommended

December 7, 2004

Dear Paul,

This letter is an invitation to participate in a "Delphi" study, a forecast for the most likely "breakthrough" level developments in applied space science in the next generation. Our goal is to recruit a mix of faculty and graduate students, with a visionary bent from major centers for the study of space science. Freeman Dyson recommended that we contact you.

Each volunteer will be placed in one of several panels. We envision that each panel will answer at least two rounds of surveys with three to five sets of questions. The first questionnaire will contain information about a number of possible breakthroughs. The following questionnaire will contain scenarios that combine sets of likely breakthroughs. After each round of questioning we may be back in touch to mediate an exchange of views in the case that there was no consensus among the panel. In this case you would receive a distribution of the results of your fellow panelists and those in "extreme" positions would be encouraged to explain their logic or defend their positions. In any case, you and your fellow panelists will remain anonymous.

This study will focus on manned and unmanned space technology over the next 25 to 50 years. During this period a moon base is expected to be established, and so life support and habitat technology will be covered. Currently we are in the process of finding possible breakthrough technologies in both the manned and unmanned areas of space travel. We are hoping to find the most likely and significant technical breakthroughs in spaceflight from spaceflight experts, enthusiasts and the science fiction literature. When we find likely technology breakthrough candidates, we will write the first questionnaire. It will be distributed to the panels we have organized by mid December.

We would like anyone who joins a panel to fill out two questionnaires. Each questionnaire round should take about 20 to 30 minutes to complete. Participating in a panel will take up about an hour over a span of two months. We assume that a questionnaire will be completed and returned in about two weeks.

The successes of this project will depend on a timely response from you. We are hoping that this e-mail will help us recruit members for our panels. Would you or any of the graduate students or colleagues you work with be interested in participating in a panel? Please respond to this e-mail if you are interested in participating, any response will be appreciated. We plan to send the questionnaires by mail, so if you are interested pleases make sure to include a mailing address in your response. It would help us greatly if you could forward this letter to graduate students studying space technology that might also be interested.

Thank you for you time,

Damon Bussey, Tim Climis,
Amanda Learned, Tim Padden,
Brian Partridge, Vadim Svirchuk
spaceproject@wpi.edu

Expert Invitation Letter – NASA, JPL (Timothy O'Donnell)

December 8, 2004

Dear Mr. O'Donnell,

This letter is an invitation to participate in a "Delphi" study, a forecast for the most likely "breakthrough" level developments in applied space science in the next generation. Our goal is to recruit between five and ten people involved in the field of space technology with a visionary bent to get an inside opinion.

We envision that each panelist will answer at least two rounds of surveys with three to five sets of questions. The first questionnaire will contain information about a number of possible breakthroughs. The following questionnaire will contain scenarios that combine sets of likely breakthroughs. After each round of questioning we may be back in touch to mediate an exchange of views in the case that there was no consensus among the panel. In this case you would receive a distribution of the results of your fellow panelists and those in "extreme" positions would be encouraged to explain their logic or defend their positions. In any case, you and your fellow panelists will remain anonymous.

This study will focus on manned and unmanned space technology over the next 25 to 50 years. During this period a moon base is expected to be established, and so life support and habitat technology will be covered. Currently we are in the process of finding possible breakthrough technologies in both the manned and unmanned areas of space travel. We are hoping to find the most likely and significant technical breakthroughs in spaceflight from spaceflight experts, enthusiasts and the science fiction literature. When we find likely technology breakthrough candidates, we will write the first questionnaire. It will be distributed to the panels we have organized by mid December.

We would like anyone who joins a panel to fill out two questionnaires. Each questionnaire round should take about 20 to 30 minutes to complete. Participating in a panel will take up about an hour over a span of two months. We expect that a questionnaire will be completed and returned in about two weeks.

The successes of this project will depend on a timely response from you. We are hoping that this e-mail will help us recruit members for our panels. Would you or your colleagues be interested in participating in a panel? Please respond to this e-mail if you are interested in participating, any response will be appreciated. We plan to send the questionnaires by mail, so if you are interested please make sure to include a mailing address in your response.

Thank you for your time,

Damon Bussey, Tim Climis,
Amanda Learned, Tim Padden,

Brian Partridge, Vadim Svirchuk
spaceproject@wpi.edu

Alumni Invitation Letter

December 26, 2004

Dear «Alumnus»,

This letter is an invitation to participate in a "Delphi" study, a forecast for the most likely and significant "breakthrough" level developments in applied space science in the next generation. You would benefit two groups of students working on IQP's. Our goal is to recruit a panel of 25 WPI alumni, who took the MBTI while at WPI, with a range of science and engineering backgrounds. We have selected alumni from the classes of 2001 and 2002, who filled out the MBTI when they arrived as freshmen. We are also recruiting a second panel of faculty and graduate students, from each of five major centers for the study of space science, to compare with the WPI results.

We envision that each panel will answer at least two rounds of surveys with three to five sets of questions. The first questionnaire is enclosed, and contains information about a number of possible breakthroughs. The subsequent questionnaire will arrive in about a month and will contain scenarios that combine sets of breakthroughs you consider likely. After each round of questioning we may be back in touch to mediate an exchange of views in the case that there was no consensus among the panel. In this case you would receive an anonymous distribution of the results of your fellow panelists and those in "extreme" positions would be allowed to explain their logic or defend their positions.

This study will focus on manned and unmanned space technology over the next 25 to 50 years. During this period it is anticipated that a moon base will be established, so life support and habitat technology will be covered. We have compiled the most likely and significant technical breakthroughs in both the manned and unmanned areas of space travel, from space flight experts, enthusiasts and science fiction literature.

We would like anyone who joins a panel to fill out both questionnaires. Each questionnaire round should take about 30 minutes to complete. We are assuming that each round of panel evaluations will take about 2 weeks, so please don't hold onto a panelist questionnaire longer than that. The success of this project will depend on a timely response from you panelists. Classes resume at WPI on Jan 13th and we really need to have a full set of responses awaiting us by then, as we are supposed to report the results on Feb 11th or 12th in Baltimore. Soon after that, in March, you will be able to view our final report on line.

If you have any questions about the Delphi study panel or questionnaire or simply do not wish to participate, please email us at spaceproject@wpi.edu.

Sincere Thanks,

Damon Bussey, Tim Climis,

Amanda Learned, Tim Padden,

Brian Partridge, Vadim Svirchuk

WPI Box 936

100 Institute Rd.,

Worcester, MA 01609-2280

Expert Invitation Letter – Astronaut Trainees

January 11, 2005

Dear «Astronaut Trainee»,

This letter is an invitation to participate in a "Delphi" study, a forecast for the most likely and significant "breakthrough" level developments in applied space science in the next generation. Our goal is to recruit a panel of 25 "experts" from NASA, academia, and industry.

We envision that the panel will answer at least two rounds of surveys with three to five sets of questions. The first questionnaire is enclosed, and contains information about a number of possible breakthroughs. The subsequent questionnaire will arrive in about three weeks and will contain scenarios that combine sets of breakthroughs you consider likely. After each round of questioning we may be back in touch to mediate an exchange of views in the case that there was no consensus among the panel. In this case you would receive an anonymous distribution of the results of your fellow panelists and those in "extreme" positions would be allowed to explain their logic or defend their positions.

This study will focus on manned and unmanned space technology over the next 25 to 50 years. During this period it is anticipated that a moon base will be established, so life support and habitat technology will be covered. We have compiled the most likely and significant technical breakthroughs in both the manned and unmanned areas of space travel, from space flight experts, enthusiasts and science fiction literature.

We would like anyone who joins the panel to fill out both questionnaires. Each questionnaire round should take about 30 minutes to complete. We are assuming that each round of panel evaluations will take about 2 weeks, so please don't hold onto a panelist questionnaire longer than that. The success of this project will depend on a timely response from you panelists. Unfortunately, due to a late start, we need these questionnaires back as quickly as you can possibly manage, as we are supposed to report the results on Feb. 12th in Baltimore. Soon after that, in March, you will be able to view our final report online.

If you have any questions about the Delphi study panel or questionnaire or simply do not wish to participate, please email us at spaceproject@wpi.edu.

Sincere Thanks,

Damon Bussey, Tim Climis,

Amanda Learned, Tim Padden,

Brian Partridge, Vadim Svirchuk

WPI Box 936

100 Institute Rd.,

Worcester, MA 01609-2280

Alumni Reminder Letter

February 2, 2005

Dear «Alumnus»,

Greetings from WPI! We are a group of undergraduates working on an IQP. Our project is to form a space technology forecast, based on the assumption that breakthroughs will occur within the next 25 to 50 years. In order to form an accurate forecast, we need opinions from individuals in selected fields, pertaining to the significance and likelihood of the possible breakthroughs we have researched. So we are asking for just 30 minutes of your time.

You recently received a letter in the mail from us, which included a paper survey. We have not received a response, but we are still very interested in your input! For your convenience, we have made an online version of the survey available.

Link to online survey: http://www.acm.wpi.edu/~spacesurvey

If you would prefer to complete the paper survey, we would still appreciate mailed responses. To request another paper copy, or ask any questions about the online version, please let us know by emailing spaceproject@wpi.edu. In addition, if you did not receive the letter that we mailed and would like a more in depth explanation of our project, we attached our original cover letter.

Thank you for your time,

Damon Bussey, Tim Climis,

Amanda Learned, Tim Padden,

Brian Partridge, Vadim Svirchuk

SPACEPROJECT@WPI.EDU

Expert Reminder Letter

February 10+, 2005

Dear «Expert»,

This is Amanda, writing on behalf of the WPI space technology forecasting team. Near the beginning of December, you agreed to participate in our study. Though you probably received a letter in the mail from us, which included a paper survey, we are not sure it arrived, or that it was not mislaid. Nevertheless, we are still very interested in your input. Our goal was 2 panels of 20 and so far we have only 28 responses. At the advice of one of our respondents from NASA, and for your convenience, we have made an online version of the survey available.

Link to online survey: http://www.acm.wpi.edu/~spacesurvey

To refresh your memory, this project is to form a forecast, based on the assumption that breakthroughs will occur in space technology within the next 25 to 50 years. In order to form a grounded forecast, we need your unique, knowledgeable perspective amongst our "expert" responses. There are 20 questions pertaining to the significance and likelihood of some possible breakthroughs we have researched. Most respondents tell us it takes just 30 minutes of their time. Others added long comments to several items, which we appreciated and read with care and interest, but that is not necessary.

If you would prefer to complete the paper survey, we would still appreciate mailed responses. To request another paper copy, or ask any questions about the online version, please let us know by emailing spaceproject@wpi.edu.

Thank you for you time,

Damon Bussey, Tim Climis,
Amanda Learned, Tim Padden,
Brian Partridge, Vadim Svirchuk
SPACEPROJECT@WPI.EDU

Server Down Apology Letter

February 21, 2005

Dear «Alumnus or Expert»,

We are writing you from the space forecasting team at WPI.

The server handling our web-based survey was upgraded on February 9th. Unfortunately, we were uninformed of this, and because of the upgrade, our online survey was not working properly. We were notified of this yesterday, and the problem has now been fixed and the program improved so that if it happens again, we will not lose any data.

However, as a result of this, if you submitted a survey between February 9th and February 16th, we did not receive it. We apologize profusely for this major oversight on our end. If you submitted a form during this time period and would like to do so again, we would appreciate it. If you would like us to send you a paper copy instead, we would be glad to do so. If this frustration means you do not want to go through the survey again, we regret that decision, but we completely understand. Whatever you decide, please let us know. Also, we will be sending verification to those persons from whom we receive a survey as soon as we get one. If you do not receive a verification from us within 24 hours, please send us a note saying you filled out our survey.

Thank you for the time you have already invested in this, and we apologize again that it was all for naught.

Sincerely,

Damon Bussey, Tim Climis, Mandy Learned,
Tim Padden, Brian Partridge, Vadim Svirchuk

Sample Outlier Update email

Dear Respondent,

Thank you very much for responding to our questionnaire of technological space breakthroughs. Your timely response and generous input was greatly appreciated!

We are writing to keep you updated on our developments. From the results of initial respondents like you, we presented a progress report to a social science conference (IASTS) in Baltimore this past weekend. However, responses to the first questionnaire are still slowly coming in. We will not be cutting them off until February 21st.

Thus, the time period of this study will be extended until the end of the academic year. This will allow us to send a second questionnaire, and properly compile the results into a "scenario-based" forecast.

The current results distributions prepared for the Baltimore conference show agreement in some breakthrough categories and an array of opinions in others. You are personally an outlier in the following areas:

MAGBEAM (you predict low significance)

SLINGATRON (You predict high likelihood)

SOLAR SAIL (You predicted a late timeframe)

BIONIC LEAF (You predicted an early timeframe)

We would like to give you the opportunity to justify your position on the likelihood of these technologies. If you would like, we will anonymously distribute your comments to the others on those particular items.

Sincerely,

Damon Bussey, Tim Climis,

Amanda Learned, Tim Padden,

Brian Partridge, Vadim Svirchuk

SPACEPROJECT@WPI.EDU

Sample Respondent Update Airmailing

Dear RESPONDENT,

Thank you very much for responding to our questionnaire of technological space breakthroughs. Your timely response and generous input was greatly appreciated!

We are writing to keep you updated on our developments. From the results of initial respondents like you, we presented a progress report to a social science conference (IASTS) in Baltimore this past weekend. However, responses to the first questionnaire are still slowly coming in. We decided not to cut them off until February 21st.

Thus, the time period of this study will be extended until the end of the academic year. This will allow us to send a second questionnaire, and properly compile the results into a "scenario-based" forecast.

The current results distributions prepared for the Baltimore conference show agreement in some breakthrough categories and an array of opinions in others, so it should be fun to see how it all turns out. Thank you again for your generous responses!

Also, to expedite communications in the future, we ask you to email us at spaceproject@wpi.edu, so that we may have your email address on record, in order to send future updates on our project to. If you do not prefer electronic communication, do not email us, and we will continue to send you paper copies. Thank you again.

Sincerely,

Damon Bussey, Tim Climis,

Amanda Learned, Tim Padden,

Brian Partridge, Vadim Svirchuk

SPACEPROJECT@WPI.EDU

A3: Panelists' comments

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 mountan) 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 collisionless 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.

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 <u>manned</u> 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 lunar 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.

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