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J. Wilkes (SS)
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By

William Flaherty

Oana Luca

Michael Monfreda

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Professor John M. Wilkes, Advisor

Abstract

This technological forecast uses an enhanced Delphi methodology to predict what breakthroughs in space technology are most likely by 2050. It especially concentrates on panelists' cognitive type in relation to their optimism, and includes panels from NIAC, current college students, and recent college graduates. The current study builds upon previous IQP's which developed and first applied the questionnaires used.

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1. Introduction

The NIAC Delphi Study is a modified Delphi approach assessing the way in which individual psychological type influences optimism with regard to space technology breakthroughs and envisioning possible socio-technical implications of a renewed international space race. The breakthroughs used in this space forecast study are technologies that, at least one source claims, can be can be developed in the next 25 to 50 years and might have a great impact on aerospace industry if they are developed. They range from new drives for space travel to life support and to other technologies needed to make space travel and colonization a reality.

This forecast study consists of a complex comparison of the results obtained from three panels that were assembled. The criteria for selecting the panels were based on educational background and/or expertise. Thus, fellows from the NASA Institute for Advanced Concepts (NIAC) offer assessments on the same technologies and scenarios as two other panels from WPI, one consisting of current students and the other, of recent alumni. These technologies consist of 21 aerospace and space-related ideas, some of which are the subject of grants funded by NIAC. The description of each technology ranges from a paragraph to half a page of text, typically mentioning the name of an author whose work has been acknowledged in that technology's specific area of research.

This type of forecasting is very important. Technology must be carefully considered and expert opinion critically analyzed. For strategic planning reasons, both government and industry support and sponsor Delphi research. It is expensive to develop technology and it becomes obsolete with time. However, in competitive environments losing the technological lead is even more costly and bureaucratic organizations tend to assume a more incremental breakthrough path for space development that is relatively predictable. From their perspective, breakthroughs are a threat, but at the same time might be an opportunity, depending on whether they are "surprised" and on who the technology leaders are at that specific point in time. Delphi research, in dealing with NIAC itself, is a way for NASA to anticipate what the next surprise will be and to ensure that they will always have a substantial technological advantage. The purpose of this study was to analyze the current results and Delphi instruments and provide answers to some very important questions. The role of expertise is going to be identified in comparing the scatter of results that the three different panels yielded. A conclusion about whether a specific "intuitive" cognitive type was more or less optimistic will be drawn by weighing the data points against the scatter in the two WPI panels. The hypothesis of the study was that one specific MBTI psychological type would dominate the NIAC panel, but with only four out of sixteen respondents completing the MBTI, it will remain untested. However, optimism and greater consensus is expected from the NIAC panel data sets compared against the WPI panels, as they are the ones more likely to have a personal investment in developing technologies that may seem like science fiction to students and alumni, few of which have entered or plan to enter the aerospace field. They are undoubtedly technologically literate, but not to the extent of an expert set of panelists with interest in space. The student panel has elected to do a project on a space topic. The alumni respondents are the 25 who were most interested, as the rest of the contacted individuals chose not to participate in the performed study.

The hypothesis advanced is that cognitive preferences, measured by the MBTI as Intuition (N) and Perception (P) influence the amount of optimism that each panelist has towards technology breakthroughs and scenarios of the future more than expertise. The starting point for this study was the work of a previous group of students who worked on assessing how individual psychological type influences the way a set of specific scientific and engineering breakthroughs are rated for likelihood and significance. The definition of "expert" was different in the previous study, but the phase one instrument was similar. The aim of the current study is to gather and make use of the contact with NIAC to obtain MBTI data from experts. Alas, the collection of enough information was not a success, but the study was enhanced in other ways.

Starting from this hypothesis, an attempt was made to confirm that cognitive type is indeed an important factor in determining the degree of optimism towards space breakthrough technologies and scenarios envisioned in the next 50 years. Also, it was decided to compare the results obtained from the non-NIAC panels (alumni and current WPI students) with the NIAC panel. It was felt that the NIAC sample consisted of mainly aerospace experts and that allows a comparison of their optimism levels with the data obtained from other less expert panels. Thus, a pattern or a link between relative expertise and space breakthrough optimism could be investigated. Also, one goal was to see if obvious divergence occurs between the results from different panels and pinpoint the reasons for these differences, in the event that they occur. To generalize, the main goal is to observe whether relative expertise or cognitive inclination (MBTI based preference) is a better predictor of technological optimism regarding technological breakthroughs.

NIAC stands for NASA Institute for Advanced Concepts. It is a governmental organization that accepts research proposals from scientists and engineers related to concepts that could influence the way NASA's future space missions will be developed in the next ten to thirty years.

It gives thinkers outside of the NASA centers an opportunity to get their ideas heard and receive enough funding to develop their projects to the point of feasibility testing. Their projects have to consist of groundbreaking ideas that would be a major advancement in the field of aerospace and not just be the next incremental step. The fellows awarded funding are scientists, engineers, in both academia and industry, and also remarkable students. The student fellowship awardees did not form a panel in this study, but such a study is recommended in the future.

The NIAC panel consists of individuals directly involved in aerospace breakthrough research and is a group of recognized experts in this field of study. They are the peers of those proposing ideas that were chosen by the prior breakthrough team from literature. The results obtained from NIAC are very important. They represent true expert opinion towards the matters under study: plausibility, likelihood and time period of space breakthroughs.

The contact at NIAC was Diana Jennings, NIAC Associate Director. She gracefully supported the project and encouraged fellows to get involved with this space technology forecast. There was also discussion of advancing the project to a new phase. NIAC is interested in using online questionnaire methods to attract more interest in the organization and get more people involved with aerospace-related science and engineering. This idea has been analyzed and it is agreed that a space technology forecast questionnaire, as part of their website, could in fact be very appealing to people interested in space and envisioning a new space era. Its appeal to college students would be in the ability to immediately compare their own personal views against the ones of peers and also NIAC experts. For students still attending high school, all panels could be viewed as expert.

Even if the collaboration with NIAC is not as fruitful as hoped (including if the website tool is not developed), the current project still offers a complex analysis of the three panels and correlates the data resulting from the first two waves of the Delphi process with cognitive preference types. It also provides a comparison of NIAC experts' views with the ones of WPI current and former students.

2. Methodology

Three tools were used to collect data for this space exploration forecasting study: the technology breakthrough questionnaire, the scenario questionnaire, and the Myers-Briggs Type Indicator (MBTI).

The breakthrough questionnaire featured in this study was composed in an Interactive Qualifying Project (IQP) at Worcester Polytechnic Institute by students Tim Climis, Amanda Learned, and Damon Bussey. This questionnaire was later provided in an online format by students Ryan Caron, David Anderson, and Ellery Harrington, and this is the medium by which the current NIAC and WPI student space exploration forecast was carried out. It consisted of 21 possible breakthrough space technologies that were considered to be on the verge of development in the 21st century. Climis, et al. had focused their efforts on five main categories: propulsion drives, launch vehicles, materials, shielding, and life support. Tsung Tao Wu, Paul Stawasz, and Dustin Gillis modestly revised the breakthrough survey for use with the NIAC fellows. The breakthrough questionnaire can be seen in its entirety in appendix A.1.

The questionnaire consisted of four entries to be inputted by the panelist, those being likeliness, significance, time period, and an optional box for their personal comments. From one to six the ratings for likeliness were (1) impossible, (2) improbable, (3) unlikely, (4) likely, (5) probable, and (6) expected. Similarly for significance, the ratings were (1) trivial, (2) marginal significance, (3) small significance, (4) moderate significance, (5) major significance, (6) and revolutionary. For time period, four inputs that could be chosen were early (present-2020), middle (2020-2035), late (2035-2050), and never.

Based on the results from the three previous breakthrough questionnaire administrations, an IQP by WPI student Robert DelSignore developed a scenario questionnaire to be used as the second wave in the modified Delphi study of this forecast study. Just as Ryan Caron and Ellery Harrington compiled an online version of the breakthrough questionnaire, they put the scenario questionnaire online as well, which was used for administering the survey for this forecasting study. The user was requested to rate the likeliness of each of the six scenarios on a scale from one to six, which featured the same wording used in the breakthrough questionnaire. Additionally, there was an optional box for their comments. The scenario tool can be seen in its entirety in appendix A.2.

2.1 The MBTI

Katharine Cook Briggs and her daughter Isabel Briggs Myers designed this personality test based on Carl Jung's theory of personality to assist a person in identifying psychological type. Instruments such as this one are usually based on traits or abilities such as intelligence as criteria of classification. The MBTI however, looks at preferences. These may be improved by the environment and practice to the point they differentiate individuals in terms of ability. The types of dichotomies the MBTI classifies are called factors. There are Extraversion/Introversion (E/I), Sensing/ Intuition (S/N), Thinking/Feeling (T/F) and Judging/Perceiving (J/P). The result of the classification instrument is a four letter combination, one letter from each of the pairs that indicate what the respondent's preferences are. However, proponents of the indicator will explain that to learn about one's natural inclinations is to create an opportunity to improve how one applies them in different contexts. In that sense, the MBTI measures something stable, but not static. It can yield much information about personal change and growth as each type "matures" in different ways, developing first the dominant and preferred qualities for processing information (S/N) and coming to a decision (T/F), and then later develops their less preferred side.[1]

2.1.1 Introvert (I) and Extravert (E)

Used in the context of psychology, the Introvert and Extravert terms define the way in which a person receives and orients their energies. The Extraverted attitude indicates that the energy flows outward and the focus of the person lies on external things and others (what is going on around the individual) while the introvert is its mirror image. The energy flows inward in this case and the subject is focused on their own personal ideas and thoughts (their own thoughts are more stimulating than the external reality).[2]

2.1.2 Sensing (S) and Intuition (N)

The Sensing and Intuition terms indicate the way a person prefers to receive and process data. They are not rational functions as one doesn't have control over the actual information input, but only on the way it is processed once obtained. Sensing individuals prefer to receive, and focus on, tangible data by means of their five senses. By contrast, the intuitive subjects tune into subjective and implicit data sources to recognize subtleties and process data obtained from other sources, such as seeing relationships through insight. They take this less tangible information just as seriously as objective sensory data.[3]

2.1.3 Thinking (T) and Feeling (F)

Thinking and Feeling are judgment functions. They link the functions previously described with rational decisions by analyzing the data received. Logical operators such as

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[1] Myers-Briggs Type Indicator. Accessed December 15 2006. <http://en.wikipedia.org/wiki/MBTI>.
[2] *Ibid.*
[3] *Ibid.*

"True/False", "If/then", and "While" are used by the function of Thinking. Feeling however, employs arbitrary evaluations. If a Thinking or Feeling individual is Introverted, then it can be reasonable to state that the subject's judgments are based on personal, internal criteria for order and assessment based on an empathetic connection with those affected. When a Thinking or Feeling individual is Extraverted, then the analysis of the matter in question is done by using already established conventions (clearly stated abstract principles will be applied dispassionately and consistently).[4]

2.1.4 Judging (J) and Perceiving (P)

Judging and Perceiving indicate characteristic standpoints of the previously presented functions. Judging types employ "Thinking" or "Feeling" in an extraverted manner. Also, the perceiving function that they choose is Introverted. These types of subjects are comfortable with a gradual approach on matters and reaching conclusions that are easily at hand. In Perceiving subjects, the perceiving function is Extraverted, while the Judging one is Introverted. Their approach to matters is through a non well defined, subjective, type of judgment. They like to keep an open mind, and have the opportunity to change their mind. Further, they continue to gather information while considering the options, hoping for clarification before making a commitment.[5]

2.1.5 Relevant Dichotomies

The two dichotomies that were focused on in this study were Sensing/Intuition and Judging/Perceiving. It would have been extremely difficult to effectively analyze all 16 of the MBTI types and trying to relate them to optimism. Therefore, it was decided to reduce the four

[4] *Ibid.*
[5] *Ibid.*

letter types to the two that would most relate to technical optimism. As a result, Thinking/Feeling and Extraverted/Introverted were omitted. How a person orients themselves in the world (Extraverted/Introverted) and their judging function (Thinking/Feeling) does not show any readily identifiable link to technical optimism. It is possible that these types do in fact have a relationship to optimism. However, including them in this study would require a completely different and modified methodology to test their significance. Due to time constraints, they were omitted on the premise that there is little to no noticeable indication of their connection to level of optimism.

Focusing on Sensing/Intuition and Judging/Perceiving resulted in four pairs of identification: NP, NJ, SP, and SJ. It was decided that an Intuitive person (N) would be more optimistic than someone who is more into Sensing (S). This is because an Intuitive person doesn't need definite data to believe something, while a Sensing individual requires verifiable and tangible facts. Regarding Judging/Perceiving, a Perceiving subject is more likely to be optimistic based on the premise that they have tendencies to be more open minded and require clarification before committing themselves. Someone who is dominant in Judging prefers definite goals. Therefore, it seems apparent that they might be less optimistic due to uncertainty. NJ and SP fall in the middle in terms of level of optimism. NJ was rated higher than SP because intuition might be a stronger link to optimism than Perceiving does, however, this may not be entirely true.[6]

To get a picture of how frequent these types arise in different studies, a few examples are provided. The MBTI manual published in 1985 contains percentages for the United States' population. About half is primarily the SJ type (42-53%), followed by SP (21-30%), NP (19-

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[6] Myers, Isabel Briggs. MBTI Manual: A Guide to the Development and Use of the Myers-Briggs Type Indicator. Third Edition. Palo Alto, California: Consulting Psychologists Press, Inc., 1998.

26%), and SJ (11-17%). Within the same manual, types for elementary, secondary, and university teachers are also presented. The numbers were consolidated by Professor John Wilkes and it shows elementary teachers were 40% SJ, 13% SP, 20% NJ, and 18% NP. Secondary teachers were shown to be 34% SJ, 7% SP, 26% NJ, and 24% NP. University professors were 29% SJ, 6% SP, 36% NJ, and 28% NP. Overall, most teachers were dominant in Sensing and Judging (SJ) while least dominant in Sensing and Perceiving. For SJ's and to a lesser degree SP's, there was a decrease in percentages as the level of education increased. For NJ's and NP's, the opposite was the case where there was an increase in percentages going from elementary teacher to university professor. These figures indicate that as the level of academia increased, there was a shift from Sensing to an intuitive type. Judging and Perceiving on the other hand were relatively consistent, increasing only slightly.[7] Regarding the United States' population again, Professor John Wilkes has indicated that through studies, the highest performers on the SAT were the NP type.[8]

An MBTI study on freshmen were conducted for 11 various schools. On the next page is a chart that consolidates the 16 different types into the four pairs used in this study which were then combined to show Intuition, Sensing, Judging, and Perceiving individually

[7] *Ibid.*

[8] Wilkes, John. "Does SMET Course Performance Typically Vary by Learning Style?" a Proposal for NSF, Nov 2003.

Table 1: Percentage of types at different colleges[9]

	NP (%)	NJ (%)	SP (%)	SJ (%)	N (%)	S (%)	J (%)	P (%)
Bucknell University	35.73	20.87	17.54	25.86	56.6	43.4	46.73	53.27
Worcester Polytechnic Institute	40.66	16.79	18.91	23.66	57.5	42.57	40.45	59.57
University of Wisconsin	31.35	12.09	28.25	28.31	43.4	56.56	40.4	59.6
University of Nebraska	25.91	10.01	23.68	40.4	35.9	64.08	50.41	49.59
OSU Agricultural Technical Institute	17.02	6.42	39.04	36.89	23.4	75.93	43.31	56.06
Nicholls State University	21.97	8.58	26.92	42.52	30.6	69.44	51.1	48.89
Wayne State College	26.26	9.86	33.87	30.01	36.1	63.88	39.87	60.13
Rollins College	38	17.6	17.5	27	55.6	44.5	44.6	55.5
Saddleback College	34.86	7.34	30.26	27.52	42.2	57.78	34.86	65.12
Lubbock Christian College	21.37	9.02	29.41	40.21	30.4	69.62	49.23	50.78
Hawaii Pacific University	35.26	14.22	23.5	27	49.5	50.5	41.22	58.76

Over the years, there have been several analyses that use the MBTI on the WPI population. A study relating the graduation rate of the Class of 2001 to MBTI types was conducted by students Navato, Turner, Lech, and Peterson in March 2005. Based on a pool size of 369 students, the dichotomy that had the highest percentage of graduating on time (in four years) was SJ (70 %), followed by NJ (66%), SP (62%), and NP (52%). Overall, only 57% of this class graduated on time.[10]

In a different study, a presentation by WPI student Gregory Doerschler showed the MBTI percentages of freshmen from the Class of 2002 were NP (43%), SJ (21%), SP (19%), and NJ (17%). He also showed for this class that SJ's were the highest performers where 74% passed six or more classes in the first semester, followed by NJ, NP, and SP the lowest with only 49%. An interesting find was made where while SP's started off the worst, percentage wise they improved the most by the end of the their freshman year. This same project also looked that the

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[9] Provost. E-mail to Professor John Wilkes.

[10] Navato, Turner, Lech, Peterson. "The Experience of the WPI Classes of 2002 and 2003: A Graduation Outcome Study by Learning Styles an Interactive Qualifying Project." Worcester Polytechnic Institute. March 2005.

frequencies of these types for the Class of 2003. It reflected that the types were stable with very little change between the two years, varying in only a couple points.[11]

In October 2003, WPI student Nathan Shuler carried out an IQP that had a focus on two WPI classes of the 2002-2003 school years, those being signal Analysis (EE2311) and Linear Algebra (ME2071). He concluded that both these courses require more abstractive thinking and overall, the NJ type succeeded the most, earning higher grades.[12] Both Shuler and Doerschler's results were replicated in a recent study by Christopher Colamussi submitted in June 2006. Colamussi verified that the NJ type did best in abstract classes and that SJ's had the highest rate of graduating on time.[13]

2.2 Delphi Method

The Delphi approach is a method of study that gathers the opinion of respondents on a subject of interest. What makes this unique is the indirect level of group communication that occurs. To make this happen, two phases are required. In the first round, panelists participate in a questionnaire and the responses are consolidated. A feedback summary is then composed from the results of the questionnaire. The results are then fed back to the panelists and they are asked to take the questionnaire a second time. In this second round, they are given the option to either defend their opinions or change them. The advantage of following this type of approach is that social interaction is eliminated. It avoids the complications that arise from expert bias and abandoning one's opinion, following what the majority of the group has to say. Doing so allows the responses from the panelists to be more accurate with fewer outliers. Using the Delphi

[11] Doerschler, Gergory (2000) unpublished presentation notes (viewgraphs) on the freshman year grades of the WPI Class of 2002 and 2003.
[12] Shuler, Nathan Corbin. "Timely Feedback Study." Worcester Polytechnic Institute. October 2003.
[13] Colamussi, Christopher. "Critical Class Study: Characterizing Trends in Specific Courses." Worcester Polytechnic Institute. 21 June 2006.

Method for a study is beneficial in that it allows the ability to target a unique expert pool without physically having to gather them in together all at once.[14]

This space exploration forecast slightly modifies the usual Delphi study approach. Instead of asking the panelists to retake the breakthrough questionnaire after viewing the results of the first administration and see if they were outliers, they were directed to the scenario questionnaire. This survey consisted of composite visions of the possible future of space exploration based on the results from the initial breakthrough questionnaire from the first expert panel. Since the scenarios, especially the first one, are based off of the breakthrough technologies' expert ratings, they are in effect rating the same technologies again but indirectly.

It was decided to follow this approach due to logistical reasons and to avoid the fate of previous projects that tried to do too many rounds of contact. In effect, time spent in administering an immediate feedback round was spent instead on doing the MBTI. Since the scenarios were composed in a previous project based on past breakthrough responses, they were readily available to use in this space exploration forecast. In prior project studies, gathering data in a timely manner from NIAC fellows proved to be a challenge. It would have been unrealistic in this study to expect NIAC fellows to take the breakthrough questionnaire a second time after compiling the data of the first administration and resending it out. This difficulty was exacerbated in this project by the expectation of them to take the MBTI. According to Wu, Gillis, and Stawasz, panelists kept agreeing to do so but never followed through. NIAC participation in both questionnaires was extremely limited and only a few completed the MBTI. To avoid this problem, the breakthrough and scenario questionnaires were introduced at the same

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[14] Climis, Tim, et al. "Forecast of Space Technological Breakthroughs." Worcester Polytechnic Institute. 3 March 2005

time, increasing the likelihood that both would be completed. More phases of data collection increase the risk that there will be dropouts mid-study, resulting in incomplete data sets.

2.3 Panel Selection

NIAC fellows, WPI students, and WPI alumni were the three panels that were studied for the space exploration forecast. Since each panel had various levels of prior participation from previous IQP projects, different methods were developed to augment the data set for each panel pool.

WPI students Tsung Tao Wu, Paul Stawasz, and Dustin Gillis contacted NIAC fellows in their IQP study and received 12 responses. For this exploration forecast study, an effort was made to reestablish communications with those 12 fellows. To advance the legitimacy of this project and increase the overall response rate, NIAC Associate Director Diana Jennings agreed to encourage NIAC fellows to participate in this study. A re-contact letter was devised and sent out to these 12 fellows electronically requesting their continued participation. There were two more phases of data collection these fellows were requested to take part in. The first phase consisted of both the breakthrough and the scenario questionnaires while the second phase was the MBTI. Information regarding the process to take the MBTI online was disseminated only after they completed the first phase. The NIAC fellows already had taken the breakthrough questionnaire in the project done by Wu, et al. The only data that was needed from them were the scenarios and MBTI. In order to refresh their knowledge of the ongoing study that this project is, they were sent the executive summary of Wu, et al.'s project. The re-contact letter that was sent out is in appendix A.9.

In order to expand the NIAC sample it was necessary to seek out a new pool of contacts. On the NIAC website there is a list of all the fellows and their funded studies. The names of new fellows were hand picked based on a decision rule that their projects were relevant to the breakthrough technologies featured in the questionnaires. For example, a study named "3D Viewing of Images on the Basis of 2D Images" is not necessarily indicative of technical knowledge regarding space exploration, resulting in its omission. Additionally, fellows were only chosen if their projects were between 2001 and 2006 in the hopes that they were currently still active in their fields of study. This would help avoid problems due to lack of connection and old contact information that would be out of date and invalid. From the list that was gathered, email contacts were acquired for most of the selected names via information readily available in the public domain. A compiled list of fellows was then sent to Diana Jennings and she made recommendations as to who to contact. A total of 53 fellows were selected after the screening by Ms. Jennings. A new contact letter was written that described the nature and purpose of this study and contained the online links to the two questionnaires. Similar to the re-contact fellows, the new contacts were asked to take the MBTI only after completing both the breakthroughs and scenarios questionnaires. The letter sent to the new NIAC fellows is located in appendix A.8.

WPI students from the current space IQP projects last year had participated in the project carried out by Tsung Tao Wu, Paul Stawasz, and Dustin Gillis and their results from taking the breakthrough questionnaire and the MBTI had already been gathered. As part of this study, the names and contacts of these students were provided by Professor John Wilkes and they were re-contacted and asked to take the scenario questionnaire to further expand that portion of the student panel.

WPI students conducting space IQP projects of this current year were also asked to participate to expand upon the student panel. Initially, contact was made with project leaders and they were asked to speak to their partners to take part in this study. With responses slow to accumulate, a mass email was delivered to all space IQP students requesting their involvement. Also, members of the space IQP oversight group, Alexander Levy and Elizabeth Villani, helped gather and encourage students to participate in this exploration forecast study. Similar to the new NIAC fellows that were contacted, data collection for these new students consisted of the same two phases, involving the same three instruments.

Alumni of WPI took part in two prior studies. Damon Bussey and Amanda Learned conducted the first one and gathered 15 responses. Later, Jeff Patrone and Jeff Wilfong further expanded the panel, increasing the total to around 30 responses. Both of these studies recorded breakthrough and MBTI data. No new contact was made with these alumni for this project, and as a result, there is no scenario data for them. The idea was considered, but in the end, it was decided it was more important to focus on the NIAC and student panels.

3. Literature Review

3.1 Forecast of Space Technological Breakthroughs

By** Tim Climis, Amanda Learned and Damon Bussey with the assistance of Brian Partridge, Tim Padden, and Vadim Svirchuk **and continued by

Jeff Patrone and Jeffrey Wilfong

The current study is in part a continuation of "Forecast of Space Technological Breakthroughs" by Patrone and Wilfong. That study is a continuation of one by Tim Climis, Amanda Leaned and Damon Bussey. The prior analysis consisted of a Delphi study based on information about possible technology breakthroughs gathered from WPI alumni. The breakthrough questionnaire and MBTI were used as central information gathering tools for a statistical comparative study. The questionnaire details are discussed in a different section of this report. The purpose of the forerunner study was to identify which of the technological breakthroughs would be more likely to occur and what relevance they would have for the future of space exploration.

The two panels present in this study were selected based on their educational background, profession and availability of cognitive type information. This selection process yielded two sets of panelists: the alumni, and the experts. Their responses were received and compared with the goal of obtaining results to the addressing the matters in question: Which technology breakthrough is more likely to occur? Which would be more significant if it occurred? How soon is it likely to happen, if it does?

The use of MBTI as a way of modifying and improving the Delphi approach was been previously suggested. The report by Climis, et al. focused on the expert panel results, but started collecting alumni data in part because MBTI results already existed for the students. They wanted to balance the likely optimists and pessimists in the panel. The low response rate was a matter of concern. It was feared that the optimists were more likely to respond, seeing how only one out of eight contacted experts agreed to participate in the study. MBTI information was only available for the alumni panel at that point. Not only that, but their goal was to reach a higher number of alumni respondents than they could get from the experts: thirty. The alumni response goal of 50% was not achieved and MBTI analysis was postponed until 30 respondents could be gathered at the actual rate of 25% response. Another factor that led to the deferral of the analysis was the interesting MBTI result distribution in the 16 responses that were obtained. After narrowing the sixteen MBTI types to four by making assumptions related to optimism and intuition, the distribution of the sixteen respondents by type indicated that only three of the four types were represented and almost half were on one type, thus a thorough analysis comparing the four types was impossible at that time.

Additional alumni data collection by Patrone and Wilfong, expanding the panel from 15 to about 30, balanced out the distribution of responses by MBTI type. The study's goal was to look at expert opinion and compare it to alumni opinion- ignoring the cognitive skew. The alumni results were inconclusive, without a proper MBTI result analysis. After dividing the respondents into two independent panels, Climis, et al. were struck by the similarity of the findings. They concluded that a case could be made for pooling the results on considering the expert panel to have been replicated. On the other hand, the alumni were slightly more optimistic especially with regards to a few controversial life support technologies. Knowing that the alumni sample had a cognitive skew and the dominant type were most optimistic was an interesting fact, especially since the expert distribution was unknown. Climis, et al. left the development of the details of the MBTI results to Wilfong and Patrone. Instead, they focused on the expert panel, noting that the relative optimists on it seemed to come from NASA and the Planetary Society, while the majority of the panel was universally uninterested, and tended to be more skeptical, hence pessimistic. The difference was not huge however, and the rank ordering the technologies was relatively consistent. Consequently, they reported the main effect on a consensus view rather than stressing the differences between panels and panelists by institutional affiliation. There was plenty to say about which technologies were considered more promising in each area. Further, they expected Wilfong et al. to expand both the alumni and expert panels- and build up the aerospace industry wing of the expert panel in the process. There was no reason to get into sub-panel results based on about five cases from NASA, mostly at one NASA program on propulsion systems.

For the first time the question of how expertise is related to optimism arose. They stressed the fact that the NASA experts showed more optimism than the university based panelists. Relative optimism was in part, a function of the technology in question. An MBTI analysis on the expanded and balanced alumni data set was also performed. After reviewing MBTI theory, the expectation was that the Intuitive Perceptive (NP) would be more optimistic, as they are characterized as being open to new ideas and change. The surprise was to discover that the NP results were at odds with the others' in some respect. The technologies rated as likely and very likely by other MBTI types were sometimes rated as relatively unlikely by the NP. Also, more optimism was shown towards the technologies with a longer developmental timeline. This phenomenon was analyzed as "challenging the conventional wisdom" by Patrone and Wilfong. In effect, the NP's saw less difference in likelihood of development calling for breakthroughs and those requiring only incremental improvement. Their cognitive opposites, the

SJ’s showed a large difference between the two. They rated the incremental as considerably more likely. Given that 21 WPI students did space related Interactive Qualifying Projects (IQP’s) that year, however, further student data collection would have allowed for a WPI student panel to be formed. The data was not collected that year. This would be done in the following year, when about forty students were involved in this type of projects.

The results of this alumni analysis led to the assumption that cognitive preference is a deciding factor in evaluating the degree of optimism towards space technology breakthrough forecasting. Their work was thorough and well organized. The data collection was carried out carefully and the analysis supplied a great deal of useful information. The idea of comparing expertise with cognitive preference originated in this project and also some of our initial hypotheses are based on their findings.

3.2 Forecast of Space Technological Breakthroughs by Rob DelSignore

This project comes as a sequel to the project Patrone and Wilfong worked on in a previous year. Concurrent with the alumni panel expansion, data was gathered from another public technically literate panel. The group consisted of middle school math and science teachers. Space enthusiasts with expert credentials were also contacted via the internet. DelSignore’s second aim was to reanalyze their findings and create a tool that would allow a more complex Delphi approach to space technology forecasting. After identifying the most likely technologies present in the breakthrough questionnaire, DelSignore’s goal was to create scenarios portraying possible technological development directions in space exploration.

The technologies evaluated as most likely were identified by comparing the results obtained from various different panels (alumni, space enthusiasts, high school teachers, experts).

The time period evaluations were used along with envisioning a logical course of events to yield scenario one. DelSignore was struck by the similarity of the rank orderings, though the middle school teachers and space enthusiasts broke the trend in one particular case, the space elevator. This stressed the expert/alumni data similarity. Other technologies and their development timelines, as present in the panel responses, have been evaluated and assembled to provide five other scenarios. The responses rating a technology as unlikely have also been taken into account and items on the scenario survey try to show how these technologies could have a practical application in the course of space technical progress. This is how the six scenarios were created. They offer both optimistic and pessimistic views of the future en route to generating a more complex analysis by connecting together the items present on the breakthrough questionnaire to reveal their social implications.

The newly created scenarios raised some interesting questions. They could allow the panelists to defend or revise their opinions (through the Delphi process) and generate an overall evaluation of an entire cluster of interrelated technologies. Also, as most of the panels agreed upon what technologies were going to be developed and which of them is most likely, the question DelSignore came upon was whether expertise had a major role to play in assessing what future technological development will occur and offering a timeline in which that would happen. Again, the question of cognitive inclination was present in the background. Based on Patrone and Wilfong's project, the most plausible answer would be negative. It indicated that an Intuitive cognitive type would be the one to provide a better estimate of relative optimism about technology development. Perhaps expertise does not play such an important role as prior Delphi enthusiasts have claimed. If not, other, more accessible, panels could be chosen, as long as one of them has a balanced cognitive mix and took panel differences into account.

Alas, DelSignore did not get to field test his scenarios due to spending too much time in development and assembling of the other panels. That would become a major concern in this project; to re-contact a panel that had completed the breakthrough survey and ask that the newly created instrument be completed as well.

3.3 Forecast of Space Technological Breakthroughs: The Influence of Expertise

By Dustin Gillis, Paul Stawasz, Tsung Tao Wu

This project's goal was to conduct a comparative study that would lead to a better evaluation of the future of space technology. A Delphi type study has been conducted in this case also. The focus panel, however, consisted of NIAC experts. They were asked to evaluate both the breakthrough and scenario questionnaires. Their responses were then compared to the results from the alumni and expert panels and analyzed.

The most interesting feature of the NIAC responses was the high level of agreement. It was hypothesized that this consensus arose from their relative expertise in part, but could also be a reflection of similar cognitive preference. This theory could no be tested, as MBTI responses were not collected at that point, but it remained in the background of planning for future studies.

Another conclusion drawn in this analysis was that the NIAC panel was clearly more optimistic than the other two panels that it was compared to. This suggested that their cognitive preference might be NP, if it was indeed similar. They saw the possibility of technology breakthrough to be more probable and also indicated the potential significance of specific developments. The panel's extreme expertise was considered to be the reason for this clear trend in the results. Thus, tentative plans to combine the Climis, et al. expert and the NIAC panel into one complete set of 28 experts was taken into consideration but abandoned. The optimism of the

NIAC panel was more similar to that of the alumni in some respect. More information was gathered by comparing the three individual panels, rather than pooling the three. The individuals present on the panel are scientists that were involved in proposing potentially breakthrough space technology research that was acknowledged and funded by NASA through a peer review process.

It was clear that the addition of cognitive preference (MBTI) results from the NIAC panel would add a whole new dimension to the study and allow a more in depth analysis to take place. This would have also provided information as to how much acknowledged expertise can influence the response pattern without taking into account the impact of psychological preference (that would be measured though MBTI results). There was also the hypothesis that NIAC was selectively biased towards the NP scientists and engineers, who among the alumni saw less difference between proven and theoretical lines of development.

Table 2: Average response from previous study[15]

	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
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
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
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
Aerogel	4.9	5.0	5.0
EM Shielding	3.6	3.7	3.7
Cold Plasma	2.6	2.7	2.7

Through a thorough evaluation of the three panels, a pattern of similar responses was identified. When a breach in this pattern was identified, however, the results coming from NIAC typically indicated a more optimistic view than the one that would have come from pooling the three sets of panel responses. This result went against the hypothesis of Gillis, Wu and Stawasz. They thought that expertise would endow the study with greater accuracy, as well as credibility. Thus, it was expected that the NIAC panelists would know more about the matters in detail and be somewhat less optimistic than the students and more like the other experts. This theory was proven erroneous. In this situation, other possible theories of cognitive self-selection were advanced. They also concluded that a panel of experts that is difficult to assemble, contact and

[15] Gillis, Dustin, Paul Stawasz, and Tsung Tao Wu. "Forecast of Space Technological Breakthroughs: The Influence of Expertise." Worcester Polytechnic Institute. 14 March 2006

convince to get involved in a complex space forecast report is not necessary. The WPI alumni were able to provide one with similar results in a more timely and efficient manner. Cognitive data on them can be collected on this pool, as well. Thus, an enhanced, balanced Delphi methodology could be devised.

4. Results

This section will contain the data collected from the breakthrough questionnaire, the scenario questionnaire, and the MBTI. These data will be displayed in three ways. First, the breakthrough data will be shown through percentage tables. The tables will be broken down into four columns and four rows, with each cell containing a different percentage. The columns are 'Significant & Likely', 'Significant & Unlikely', 'Insignificant & Likely', and 'Insignificant & Unlikely'. 'Significant & Likely' corresponds to the panelist having rated both the significance and likelihood factors greater than four. 'Significant & Unlikely' corresponds to the panelist having rated significance higher than four but likelihood lower than four. 'Insignificant & Likely' means that the panelist rated significance lower than four and likelihood higher than four. Finally, 'Insignificant & Unlikely' means the panelist rated both significance and likelihood below four. The four rows each correspond to an individual time period from the survey. Early is from present (2007) to 2020, Middle is from 2020-2035 and Late is 2035 to 2050. The percentages you see in the cells correspond to how many people in that panel responded in such a way that they matched up with the column and the row they fall under. For example, if you look at the 'Significant & Likely' column and then go down to the cell that lines up with the 'Middle' row this means that whatever percentage of panelists displayed thought the technology was significant, likely and would be developed between 2020 and 2035. In a few instances it may be observed that the totals at the bottom do not correspond to the cells above them. In these cases a time period rating was not collected from all panelists so their results only go into the total, not an individual cell. The next section will be the scenario data. Each scenario will be represented by a bar chart. Each bar represents a different panelist and the y-axis is the 0-6 rating they gave the scenario on its likelihood of coming to fruition. The final section will deal with the

MBTI data as it affects the breakthrough data. There will be two methods for analyzing this that will be explained in that section of the paper.

4.1 Breakthrough Results

4.1.1 Nuclear Drive

Table 3: NIAC Nuclear Drive Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	**5.0%**	**15.0%**
Middle	0.0%	**10.0%**	**5.0%**	**45.0%**
Late	5.0%	0.0%	5.0%	**10.0%**
Never	0.0%	0.0%	0.0%	0.0%
Total	5.0%	**10.0%**	**15.0%**	70.0%

Table 4: Alumni Nuclear Drive Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	3.2%	16.1%
Middle	0.0%	0.0%	0.0%	16.1%
Late	9.7%	0.0%	9.7%	0.0%
Never	0.0%	0.0%	0.0%	0.0%
Total	**16.1%**	0.0%	29.0%	54.8%

Table 5: Student Nuclear Drive Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	**4.5%**	**1.5%**	0.0%	**7.6%**
Middle	1.5%	**3.0%**	**7.6%**	**13.6%**
Late	1.5%	0.0%	**6.1%**	**7.6%**
Never	0.0%	1.5%	3.0%	1.5%
Total	**7.6%**	**9.1%**	**25.8%**	57.6%

The nuclear drive is a device that would superheat water or some other liquid and then use the vapor to either generate power or eject it directly for propulsion. Extremely high heats would be required to render this drive effective, and according to the summary in the survey dissipating this heat is a problem that would require a breakthrough. The summary also raises the issue of an aborted launch in atmosphere being devastating for the earth. The panelists predicted that this is probable breakthrough, with more than half of all the panels saying it was likely. The NIAC panel was the most optimistic about this technology with 80% responding that it was likely. The student panel was next with 63.7% saying it was a likely breakthrough. The alumni panel was the least optimistic at 54.8% saying it was unlikely. There was less agreement about the time period, but the results seem to point toward development during the middle time period (2020-2035). This technology most likely received high scores due to the fact that the basic science behind it is well established. Nuclear technology has been in use since the 1940's, and thus there is a lot of research already done in this area. The comments reflected this saying that the nuclear drive was more of an incremental advance than a huge breakthrough. The NIAC comments also took issue with the need to cool the drive with radiators. Instead, in the objection made, the gas that is propelled carries away most of the heat of the reaction. There is only a problem if the nuclear reactor is used to generate electricity. Finally the comments also discussed a need for more public and political education about nuclear technology because of the stigma that is associated with it. Before it can be widely accepted as a form of propulsion, public fears about the consequences of release in the biosphere need to be mitigated. Since these consequences are exaggerated at the moment, the NIAC fellows are more likely to favor other approaches for this non-technical reason.

4.1.2 Magbeam

Table 6: NIAC Magbeam Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	0.0%
Middle	0.0%	0.0%	14.3%	9.5%
Late	0.0%	0.0%	33.3%	33.3%
Never	0.0%	0.0%	9.5%	0.0%
Total	0.0%	0.0%	57.1%	42.9%

Table 7: Alumni Magbeam Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	3.1%
Middle	0.0%	0.0%	6.3%	6.3%
Late	3.1%	0.0%	25.0%	9.4%
Never	0.0%	0.0%	0.0%	0.0%
Total	18.8%	0.0%	43 8%	37.5%

Table 8: Student Magbeam Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	1.5%
Middle	2.9%	0.0%	2.9%	4.4%
Late	7.4%	2.9%	23.5%	7.4%
Never	4.4%	0.0%	4.4%	0.0%
Total	20.6%	5.9%	45.6%	27.9%

This technology is a way to travel between two space bodies by detaching the drive from the spacecraft. It works by pointing a concentrated beam of plasma at the spacecraft to propel it in its transfer to another planet. This plasma beam would come from a satellite that could be solar powered, thus reducing fuel costs. One complication is that there would have to be a second satellite in orbit around the destination in order the slow down the approaching spacecraft. The breakthrough here would be to develop a satellite that could actually create a plasma beam powerful enough to propel a spacecraft. The results from this item predict that it most likely will not happen, though NIAC shows an almost even split. Again NIAC was the most optimistic, with 42.9% saying that the technology was likely. In this case the Alumni panel was not far behind with 37.5% saying that the technology was likely. The students trailed the other two panels with only 27.9% saying it was likely. There was a strong consensus among all three panels that if this technology was developed it would not be until the late time period (2035-2050). The main criticisms of this technology were based around its cost and power requirements. The cost and complexity of this system above a normal drive system are immense, mainly caused by the upkeep the satellite would need. It would also require huge amount of power to create a plasma beam and current technology does not have that capability so it would require a major breakthrough in both power and plasma technologies.

4.1.3 Slingatron

Table 9: NIAC Slingatron Results

	NIAC			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	9.1%
Middle	9.1%	0.0%	9.1%	9.1%
Late	0.0%	0.0%	27.3%	0.0%
Never	27.3%	0.0%	0.0%	0.0%
Total	36.4%	0.0%	45.5%	18.2%

Table 10: Alumni Slingatron Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	9.4%	3.1%	0.0%
Middle	9.4%	0.0%	9.4%	3.1%
Late	3.1%	0.0%	12.5%	3.1%
Never	0.0%	0.0%	0.0%	0.0%
Total	46.9%	9.4%	34.4%	9.4%

Table 11: Student Slingatron Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	3.3%	6.6%	3.3%	3.3%
Middle	8.2%	1.6%	3.3%	4.9%
Late	3.3%	0.0%	6.6%	3.3%
Never	9.8%	0.0%	0.0%	0.0%
Total	44.3%	13.1%	18.0%	24.6%

The slingatron is both a launch vehicle to low earth orbit and a possibly drive for inter-planetary travel. It works by putting a spherical launch vehicle into a tube that is then spun up to extremely high speeds. The ball is the launched out of the tube and propelled to extremely high speeds in a short amount of time. The current model can accelerate a ball bearing to 200 miles per hour fairly quickly, though the full size version will have to be considerably larger. Also, the huge amount of acceleration experienced by the launch vehicle precludes this approach from use with human payloads, and limits its applicability to use with fuel or other sturdy payloads. It is important to note that the wording for this item was changed between the Alumni panel study and when the other two panels received the survey. There was also no mass driver item to compete with the slingatron. For this technology the student panel was the most optimistic, with 37.7% saying that the slingatron was likely to be developed. The alumni panel and NIAC panel were extremely close rating it 18.4% and 18.2% likely respectively. For time period the results had a large spread. There was little to no consensus on when this technology would be developed, if it were even possible. The comments generally agreed that while the idea is interesting the problems it posed far outweighed its usefulness. The huge amount of g-force placed on the launch vehicle would preclude it from carrying almost anything useful. Also, if the vehicle was shaped even slightly differently than a perfect ball bearing it could have catastrophic consequences. Finally, the comments asserted that there are other technologies that do a similar thing and are much easier to implement than the slingatron, thus making it unlikely.

4.1.4 Solar Sail

Table 12: NIAC Solar Sail Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	19.0%	4.8%	14.3%
Middle	0.0%	0.0%	0.0%	23.8%
Late	4.8%	0.0%	9.5%	14.3%
Never	0.0%	0.0%	0.0%	0.0%
Total	4.8%	19.0%	23.8%	52.4%

Table 13: Alumni Solar Sail Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	6.5%	0.0%	12.9%
Middle	0.0%	0.0%	6.5%	22.6%
Late	0.0%	0.0%	6.5%	3.2%
Never	0.0%	0.0%	0.0%	0.0%
Total	0.0%	16.1%	12.9%	71.0%

Table 14: Student Solar Sail Results

	Students			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	**4.5%**	0.0%	**16.4%**
Middle	0.0%	1.5%	0.0%	**26.9%**
Late	**1.5%**	0.0%	**1.5%**	**3.0%**
Never	4.5%	0.0%	0.0%	0.0%
Total	**9.0%**	**7.5%**	**9.0%**	74.6%

The solar sail is a large metal film that uses the pressure created by light to propel the ship. It has the possibility of achieving extremely high speeds, but currently a much better sail material is needed before a large scale solar sail can be constructed. Also due to the fact that solar energy lessens as you fly away from the sun it would be more useful for travel in the inner solar system than in the outer. All three panels responded favorably to the solar sail with all having over 70% responding that it was likely. The Alumni panel rated it highest for likelihood with 87% putting it as likely. The student panel was next with 82.1% of the panel saying it was likely. NIAC come up last with only 71.4% saying the solar sail was likely to be developed. The time period data shows a general agreement that it will be developed sometime in the early (Present-2020) or middle (2020-2035) time periods. NIAC did deviate slightly from this as almost a quarter of respondents (23.8%) put it in the late time period. The NIAC panel was also twice as likely to see this technology as likely but insignificant as the students or alumni. The comments reflected this disagreement over the usefulness of the solar sail. According to the comments, the problem of the solar sail lies in the amount of force it generates. Though it requires no fuel it may not be able to generate enough thrust to move anything of decent size, and is slow to accelerate. Thus, it would most likely be used for small unmanned probes. Also, one of the comments mentioned that the summary of the solar sail is misleading as there is more than one type, and depending on what type we were referring to the development time and usefulness would be drastically different.

4.1.5 Mass Driver

Table 15: NIAC Mass Driver Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	4.8%	4.8%	0.0%	0.0%
Middle	9.5%	0.0%	0.0%	38.1%
Late	0.0%	4.8%	4.8%	14.3%
Never	4.8%	0.0%	0.0%	0.0%
Total	23.8%	9.5%	14.3%	52.4%

Table 16: Student Mass Driver Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	11.1%	0.0%	11.1%
Middle	3.7%	11.1%	3.7%	22.2%
Late	11.1%	3.7%	7.4%	14.8%
Never	0.0%	0.0%	0.0%	0.0%
Total	14.8%	25.9%	11.1%	48.1%

The mass driver works by accelerating a payload carrier through a series of electro-magnetic coils. When the "bucket" hits the last coil it is stopped, but the payload inside continues using the momentum gained from being in the carrier. Due to atmospheric issues on earth this drive would be limited to launches from orbit or from the moon. The benefit of this drive is that it requires no fuel on the spacecraft, but a significant breakthrough in power supply would be necessary to provide it with the amount of power it requires. Since the alumni panel took one of the very first versions of the breakthrough survey they were never presented with the mass driver item. Thus, only the student and NIAC panels are available to analyze. In this case the majority of both panels rated the technology as likely. 74% of the student panel rated the mass driver as likely to be developed, while 61.9% of the NIAC panel said the same. For the time period the general consensus of both panels was that it would happen sometime in the middle (2020-2035) or late (2035-2050) periods. The significance of the breakthrough was also called into question by both panels with over a quarter of both rating it as insignificant. The comments raised many issues with the technology, such as the rate of acceleration, induction of electricity by the payload, and the need for a drive to decelerate the ship at the other end.

4.1.6 Ion Drive

Table 17: NIAC Ion Drive Results

	NIAC			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	33.3%
Middle	0.0%	0.0%	4.8%	28.6%
Late	4.8%	0.0%	0.0%	4.8%
Never	0.0%	0.0%	9.5%	0.0%
Total	4.8%	0.0%	14.3%	81.0%

Table 18: Student Ion Drive Results

	Students			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	7.1%	0.0%	25.0%
Middle	0.0%	3.6%	3.6%	28.6%
Late	3.6%	3.6%	3.6%	14.3%
Never	0.0%	0.0%	3.6%	0.0%
Total	3.6%	14.3%	14.3%	67.9%

The ion drive works by accelerating the space craft using an ion beam ejected out the back. It cannot be used to get to LEO from earth due to the fact that it leaves the craft with a net negative charge and ends up attracting the particles back to itself canceling the thrust. However, it has been used to successfully power craft already in space. While the drive is fuel efficient it has extremely low acceleration. This technology was part of the same revision to the questionnaire that resulted in addition of the mass driver, thus the alumni never saw this entry. This technology was resoundingly rated as likely by both panels. 82.2% of the student panelists voted the ion drive likely, while 81% of NIAC voted it likely. Both panels put development somewhere in the early (Present-2020) or middle (2020-2035) time periods. The comments generally said that since the drive already exists it will continue being used, but that a breakthrough in increasing acceleration may never happen. Also, some respondents took issue with saying the drive was extremely efficient instead saying that it was extremely inefficient.

4.1.7 Laser Propulsion

Table 19: NIAC Laser Propulsion Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	4.8%	0.0%	0.0%	9.5%
Middle	4.8%	0.0%	19.0%	4.8%
Late	0.0%	0.0%	38.1%	14.3%
Never	4.8%	0.0%	0.0%	0.0%
Total	14.3%	0.0%	57.1%	28.6%

Table 20: Alumni Laser Propulsion Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	0.0%
Middle	3.2%	0.0%	6.5%	16.1%
Late	6.5%	0.0%	16.1%	9.7%
Never	0.0%	0.0%	0.0%	0.0%
Total	32.3%	3.2%	29.0%	35.5%

Table 21: Student Laser Propulsion Results

	Students			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	3.0%	0.0%	6.0%
Middle	3.0%	1.5%	9.0%	10.4%
Late	3.0%	1.5%	9.0%	1.5%
Never	10.4%	0.0%	1.5%	0.0%
Total	31.3%	9.0%	31.3%	28.4%

Laser propulsion works by utilizing a two stage laser process. The first laser hits a surface and vaporizes a small amount of the surface material. A second laser is then applied in order to expand the vaporized material and then send a shockwave through it to propel the laser away from the surface. The actual drive would probably use a sponge-like material imbued with water for the surface the laser would hit, thus there would always be water at the top surface to vaporize due to the properties of a sponge. The breakthrough here would be a dramatic increase in laser technology. This technology requires an extremely powerful laser to generate any sort of reasonable thrust. This technology received relatively low likelihood scores from all the panels. The alumni and the students were in close agreement with NIAC less optimistic. The alumni rated it highest with 38.7% responding that the technology was likely to be developed. The student panel was next with 37.4% saying laser propulsion was likely. Finally, NIAC was least optimistic about this technology with only 28.6% rating it as likely. The bulk of all three panels placed development somewhere in the middle (2020-2035) to late (2035-2050) time periods. The comments reflected two substantial problems with this technology. First, it would be extremely difficult to focus such a large laser over long distances, especially in atmosphere, thus making it hard to keep the drive working. Second, there is the immense power requirement that a laser of that magnitude would require. Also the comments reflected the opinion that while it may be possible, the technology will not get funding because there are other less complicated ways to get to orbit.

4.1.8 Reusable Single Stage to Orbit (ReSSTO)

Table 22: NIAC ReSSTO Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	5.0%	0.0%	**25.0%**
Middle	**5.0%**	0.0%	5.0%	**30.0%**
Late	0.0%	0.0%	**5.0%**	**20.0%**
Never	5.0%	0.0%	0.0%	0.0%
Total	**10.0%**	5.0%	**10.0%**	75.0%

Table 23: Alumni ReSSTO Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	3.2%	12.9%	0.0%	19.4%
Middle	3.2%	3.2%	3.2%	6.5%
Late	3.2%	0.0%	0.0%	3.2%
Never	0.0%	0.0%	0.0%	0.0%
Total	**19.4%**	16.1%	3.2%	61.3%

Table 24: Student ReSSTO Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	1.5%	**7.4%**	0.0%	16.2%
Middle	**2.9%**	1.5%	1.5%	**19.1%**
Late	0.0%	0.0%	**2.9%**	**2.9%**
Never	4.4%	0.0%	0.0%	0.0%
Total	**14.7%**	**13.2%**	**4.4%**	67.6%

The ReSSTO is not so much a breakthrough as the next evolution of modern rockets. It is a conventional rocket booster, but it can be landed back on earth and reused. The key to this technology would be to develop a way to refuel it in space so that the rocket could be used beyond just launch. For example the rocket could launch from earth, refuel in orbit, and then proceed to the moon or some other destination. This technology was rated very likely by all three panels, and at nearly the same levels. The alumni panel rated this technology the highest, with 80.8% of the panel rating it as likely. NIAC followed very close behind with 80% rating the technology as likely. The student panel tailed the other two closely with 77.4% saying ReSSTO was likely. The time period was generally agreed upon to be somewhere in the early (Present-2020) to middle (2020-2035) time periods. The majority of panelists also thought that this technology would be significant to space travel. The comments reflected the idea that most of the technology is already there, but that economic factors as well as large propellant requirements may keep this from being developed.

4.1.9 Ram Accelerator

Table 25: NIAC Ram Accelerator Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	9.5%	4.8%	4.8%	9.5%
Middle	0.0%	4.8%	14.3%	9.5%
Late	0.0%	0.0%	14.3%	9.5%
Never	9.5%	0.0%	0.0%	0.0%
Total	19.0%	9.5%	38.1%	33.3%

Table 26: Alumni Ram Accelerator Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	3.3%	0.0%	0.0%
Middle	13.3%	3.3%	10.0%	10.0%
Late	6.7%	0.0%	6.7%	3.3%
Never	0.0%	0.0%	0.0%	0.0%
Total	46.7%	10.0%	20.0%	23.3%

Table 27: Student Ram Accelerator Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	6.1%	1.5%	7.6%
Middle	6.1%	1.5%	6.1%	12.1%
Late	1.5%	1.5%	1.5%	0.0%
Never	9.1%	0.0%	3.0%	0.0%
Total	25.8%	15.2%	22.7%	36.4%

The Ram accelerator works by placing an extremely long tube full of a combustible gas in the side of a mountain. The launch vehicle is placed inside the tube and the gases behind it are ignited. This propels the vehicle into low earth orbit. One drawback is that it would subject the craft to upwards of 30,000 g's, thus limiting it to non-human cargo. This was a generally low scoring technology among the panelists. 51.6% of the student panel found this technology to be likely. NIAC was the next with only 42.8% of the panel responding that it would be developed. The alumni were the least optimistic about this technology with only 33.3% responding that it was likely. All three panels showed little to no agreement on either the time period or significance of this development. The comments were generally critical of the loads that would be placed on the spacecraft, saying that there is very little that can survive a 30,000g load. Also the spacecraft would need a separate engine to circularize itself once in orbit, and there are currently no engines that can survive that kind of acceleration.

4.1.10 Nanotube Polymer Space Elevator

Table 28: NIAC Space Elevator Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	0.0%
Middle	0.0%	0.0%	4.8%	19.0%
Late	0.0%	0.0%	47.6%	19.0%
Never	0.0%	0.0%	4.8%	0.0%
Total	0.0%	4.8%	57.1%	38.1%

Table 29: Alumni Space Elevator Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	3.2%	0.0%	0.0%	3.2%
Middle	0.0%	0.0%	0.0%	6.5%
Late	12.9%	0.0%	32.3%	0.0%
Never	0.0%	0.0%	0.0%	0.0%
Total	35.5%	0.0%	45.2%	19.4%

Table 30: Student Space Elevator Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	1.5%
Middle	8.8%	0.0%	7.4%	7.4%
Late	2.9%	0.0%	14.7%	2.9%
Never	8.8%	0.0%	5.9%	0.0%
Total	27.9%	0.0%	42.6%	29.4%

The Space Elevator works by putting a 60,000 mile ribbon with one end attached to earth in orbit. A craft would then "climb" up the ribbon to deliver payloads to geosynchronous orbit. The major breakthrough here would be in carbon nanotubes technology which is required to build a ribbon strong enough to withstand the forces that would be placed on the space elevator. This technology received generally low marks from all three panels. NIAC was most optimistic about it, with 42.9% of the panel responding that it was a likely breakthrough. The students came next with only 29.4% saying it was likely and the alumni trailed with 19.4% responding positively to the technology. Though the panels did not expect the space elevator to be developed there was a high agreement among them that if it was to be developed it would be quite significant. Also, all three panels put the technology in the middle (2020-2035) or late (2035-2050) time period. The comments mainly criticized the economics behind the elevator. The huge cost associated with it would not be worth the reward of having a space elevator. Combine this with the fact that a failure would be extremely catastrophic and most likely require full reconstruction makes this idea much less appealing.

4.1.11 Memory Plastics

Table 31: NIAC Memory Plastics Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	4.8%	14.3%	0.0%	33.3%
Middle	0.0%	9.5%	0.0%	23.8%
Late	4.8%	0.0%	0.0%	4.8%
Never	0.0%	0.0%	0.0%	0.0%
Total	9.5%	23.8%	4.8%	61.9%

Table 32: Alumni Memory Plastics Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	28.1%
Middle	0.0%	6.3%	0.0%	18.8%
Late	0.0%	0.0%	3.1%	0.0%
Never	0.0%	0.0%	0.0%	0.0%
Total	0.0%	9.4%	15.6%	75.0%

Table 33: Students Memory Plastics Results

	Students			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	4.4%	0.0%	27.9%
Middle	0.0%	1.5%	0.0%	19.1%
Late	0.0%	0.0%	4.4%	2.9%
Never	0.0%	0.0%	0.0%	0.0%
Total	4.4%	7.4%	8.8%	79.4%

Memory plastics are a type of deformable material that have the ability to heal when ruptured. This has large implications for space suits and space habitats which would be able to heal themselves if they failed, thus reducing the risk of losing the lives of the humans inside. There was a high agreement among the panels that this technology will be developed. The percentage of panelists who responded that the technology was likely was about even between all the panels. 86.8% of the students, 85.7% of the NIAC fellows, and 84.4% of the alumni all rated memory plastics as a likely development. The time period was generally placed in the early (Present-2020) or middle (2020-2035) periods, and the breakthrough was thought to be significant by the majority of every panel. Though comments for this technology were sparse they generally agreed that it would be a huge breakthrough in spacesuit and habitat development.

4.1.12 Carbon Nanotubes

Table 34: NIAC Carbon Nanotubes Results

	NIAC			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	38.1%
Middle	0.0%	0.0%	0.0%	42.9%
Late	0.0%	0.0%	0.0%	14.3%
Never	0.0%	0.0%	0.0%	0.0%
Total	0.0%	0.0%	4.8%	95.2%

Table 35: Alumni Carbon Nanotubes Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	25.8%
Middle	0.0%	0.0%	3.2%	16.1%
Late	0.0%	0.0%	6.5%	6.5%
Never	0.0%	0.0%	0.0%	0.0%
Total	0.0%	3.2%	12.9%	83.9%

Table 36: Student Carbon Nanotube Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	19.1%
Middle	1.5%	1.5%	4.4%	27.9%
Late	0.0%	**1.5%**	1.5%	1.5%
Never	0.0%	0.0%	0.0%	0.0%
Total	2.9%	**2.9%**	11.8%	82.4%

This material offers the prospect of a huge strength to weight ratio beyond any current material. If developed it has implications for all sorts of applications, including solar sails and the space elevator. This technology received some of the highest ratings of any on the breakthrough questionnaire. 95.2% of the NIAC fellows found the technology to be likely, while 87.2% of alumni and 85.3% of the students felt the same way. The majority of all three panels rated the technology as significant. Development was placed in the early (Present-2020) and middle (2020-2035) time periods by the majority of all respondents. The comments generally agreed that this technology was very likely due to the fact that it is getting large amounts of funding. Also, applications beyond the aerospace sector will spur on development.

4.1.13 Solid State Aircraft

Table 37: NIAC Solid State Aircraft Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	9.1%
Middle	18.2%	9.1%	0.0%	9.1%
Late	0.0%	9.1%	9.1%	18.2%
Never	9.1%	0.0%	0.0%	0.0%
Total	27.3%	18.2%	18.2%	36.4%

Table 38: Alumni Solid State Aircraft Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	3.2%	0.0%	9.7%
Middle	3.2%	0.0%	0.0%	6.5%
Late	12.9%	0.0%	12.9%	9.7%
Never	0.0%	0.0%	0.0%	0.0%
Total	35.5%	6.5%	22.6%	35.5%

Table 39: Student Solid State Aircraft Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	1.7%	1.7%
Middle	5.1%	1.7%	5.1%	6.8%
Late	15.3%	1.7%	5.1%	8.5%
Never	1.7%	0.0%	1.7%	0.0%
Total	35.6%	5.1%	27.1%	32.2%

The solid state aircraft uses a type of material called ionic polymeric metal composites that have the ability to deform when subjected to an electric field, and then return to their original shape when the field is removed. This material would be used to create an aircraft that uses flapping wings as a way to propel itself and solar panels to power the material. This would create a better way to explore planets such as Venus or Mars. This was a generally low scoring technology with the most optimistic panel being NIAC (54.6% responded it was likely). 42% of the alumni and 37.3% of the students felt that the technology was likely. There was also a large division between significant and insignificant among the panels, but all three did lean towards rating it significant. The bulk of respondents placed development in the middle (2020-2035) and late (2035-2050) time periods. The comments reflected the idea that the controls required to create this technology are still a long way from being developed, also it is not clear whether it would be more efficient than current aircraft technology.

4.1.14 Electromagnetic Shielding

Table 40: NIAC Electromagnetic Shielding Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	9.5%	0.0%	0.0%	14.3%
Middle	0.0%	0.0%	4.8%	14.3%
Late	0.0%	4.8%	9.5%	28.6%
Never	9.5%	0.0%	0.0%	0.0%
Total	19.0%	4.8%	19.0%	57.1%

Table 41: Alumni Electromagnetic Shielding Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	3.2%	0.0%	3.2%
Middle	0.0%	0.0%	0.0%	25.8%
Late	6.5%	0.0%	9.7%	9.7%
Never	0.0%	0.0%	0.0%	0.0%
Total	12.9%	3.2%	19.4%	64.5%

Table 42: Student Electromagnetic Shielding Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	5.9%
Middle	1.5%	4.4%	5.9%	17.6%
Late	1.5%	0.0%	10.3%	11.8%
Never	1.5%	0.0%	0.0%	0.0%
Total	4.4%	5.9%	27.9%	61.8%

Electromagnetic shielding could be used to protect a spacecraft from radiation and possibly even objects floating in space. The major breakthrough would be in technology capable of generating enough electricity to create a strong enough field. Currently the technology would be able to repel small amount of radiation but significant gains will need to be made in order to repel a useful amount of radiation or a small object. While a majority of each panel rated the technology as likely, it wasn't as highly agreed upon as other breakthroughs in the survey. 67.7% of both the alumni and the student panel responded that the technology was likely. From the NIAC panel 61.9% said the technology would likely be developed. The majority of all three panels agreed that this technology would be very significant if it was developed. Most panelists placed development in the middle (2020-2035) to late (2035-2050) time periods. The main issues raised in the comments deal with how the field would interfere with onboard electronics, cause the degradation of fasteners on the spacecraft, and that it may have adverse effects on the crew.

4.1.15 Cold Plasma

Table 43: NIAC Cold Plasma Results

	NIAC			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	0.0%
Middle	4.8%	0.0%	0.0%	14.3%
Late	9.5%	14.3%	23.8%	14.3%
Never	4.8%	0.0%	4.8%	0.0%
Total	19.0%	14.3%	33.3%	33.3%

Table 44: Alumni Cold Plasma Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	3.1%	0.0%	0.0%
Middle	0.0%	0.0%	0.0%	9.4%
Late	9.4%	0.0%	28.1%	3.1%
Never	0.0%	0.0%	0.0%	0.0%
Total	15.6%	6.3%	56.3%	21.9%

Table 45: Student Cold Plasma Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	1.5%	0.0%	0.0%	0.0%
Middle	0.0%	1.5%	2.9%	4.4%
Late	8.8%	0.0%	16.2%	10.3%
Never	5.9%	0.0%	8.8%	0.0%
Total	23.5%	4.4%	48.5%	23.5%

Cold plasma can be used to absorb electromagnetic pulses. Thus, it can be used to absorb radar, microwave and laser energy. This could be used to completely disguise a spacecraft from radar. The breakthrough needed would be a light and extremely powerful power source. This technology received relatively low marks from all three panels. NIAC rated it highest with 47.6% rating it as likely. 28.2% of the alumni and 27.9% of the students gave it a positive likelihood rating. The majority of all three panels agreed that the development would be significant, though each panel had a good sized number of people who felt the opposite. The majority of all three panels put development in the middle (2020-2035) or late (2035-2050) time period. The comments mainly said that this technology was more geared toward military use and did not have huge implications for space. Rather, many comments placed the significance on the light weight high power source described. They felt that that would be the truly significant breakthrough for all sorts of space technologies.

4.1.16 Aerogel

Table 46: NIAC Aerogel Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	61.9%
Middle	0.0%	4.8%	4.8%	19.0%
Late	0.0%	0.0%	4.8%	0.0%
Never	0.0%	0.0%	0.0%	0.0%
Total	4.8%	4.8%	9.5%	81.0%

Table 47: Alumni Aerogel Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	6.7%	0.0%	43.3%
Middle	0.0%	0.0%	0.0%	10.0%
Late	0.0%	0.0%	0.0%	0.0%
Never	0.0%	0.0%	0.0%	0.0%
Total	0.0%	6.7%	3.3%	90.0%

Table 48: Student Aerogel Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	1.5%	0.0%	35.8%
Middle	0.0%	1.5%	0.0%	17.9%
Late	0.0%	0.0%	0.0%	3.0%
Never	0.0%	0.0%	0.0%	0.0%
Total	1.5%	7.5%	3.0%	88.1%

Aerogel is an extremely light solid that has a high rate of heat absorption. It would be used as a new form of insulation to protect crafts on reentry by ejecting it along the hull of the spacecraft during reentry. The problems facing aerogel are that it is currently very costly and time consuming to manufacture. This was an extremely high scoring technology with every panel. 96.7% of the alumni rated the technology as likely. 95.6% of students and 85.8% of the NIAC panel rated its likelihood positively. An overwhelming majority of every panel rated aerogel as a significant breakthrough, and most respondents but it in the early (Present-2020) to middle (2020-2035) time periods. The comments were overwhelmingly positive in support of this materials development; though many pointed out that it has applications beyond just heat shielding that should be mentioned.

4.1.17 Fusion Reactor

Table 49: NIAC Fusion Reactor Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	4.8%
Middle	4.8%	0.0%	0.0%	19.0%
Late	0.0%	0.0%	28.6%	33.3%
Never	4.8%	0.0%	0.0%	0.0%
Total	9.5%	0.0%	33.3%	57.1%

Table 50: Alumni Fusion Reactor Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	0.0%
Middle	0.0%	0.0%	0.0%	15.6%
Late	3.1%	0.0%	21.9%	9.4%
Never	0.0%	0.0%	0.0%	0.0%
Total	12.5%	0.0%	37.5%	50.0%

Table 51: Student Fusion Reactor Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	2.9%
Middle	0.0%	0.0%	7.4%	16.2%
Late	2.9%	1.5%	13.2%	13.2%
Never	2.9%	0.0%	1.5%	0.0%
Total	5.9%	1.5%	30.9%	61.8%

The description of fusion technology as presented in the breakthrough questionnaire is as a justification for going to the moon in order to mine helium-3 for fusion reactions. Unfortunately fusion technology is not yet developed to a level where it actually produces power so large breakthroughs in this area would be needed. This technology received a very divided response from the panels. The students were most optimistic here with 63.3% responding that the technology was likely. 57.1% of NIAC and 50% of the alumni responded positively to the likelihood of fusion. One thing the panels did agree on was that, if fusion was developed, it would be a significant breakthrough. Also there was high agreement that it would not be developed until the middle (2020-2035) or late (2035-2050) time periods. The comments were generally hopeful but skeptical that it will actually be developed. Also, some called into question the use of helium-3 in the description saying that it will not be the fuel of choice, thus limiting support for He-3 rector development.

4.1.18 Roving Lunar Base

Table 52: NIAC Roving Lunar Base Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	4.8%	0.0%
Middle	4.8%	0.0%	0.0%	9.5%
Late	4.8%	9.5%	14.3%	28.6%
Never	19.0%	0.0%	0.0%	0.0%
Total	28.6%	9.5%	23.8%	38.1%

Table 53: Alumni Roving Lunar Base Results

	Alumni			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	0.0%
Middle	0.0%	6.7%	0.0%	3.3%
Late	13.3%	6.7%	20.0%	3.3%
Never	0.0%	0.0%	0.0%	0.0%
Total	26.7%	13.3%	30.0%	30.0%

Table 54: Student Roving Lunar Base Results

	Students			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	6.0%	0.0%	3.0%
Middle	3.0%	1.5%	4.5%	13.4%
Late	6.0%	3.0%	4.5%	7.5%
Never	6.0%	0.0%	0.0%	1.5%
Total	23.9%	11.9%	16.4%	47.8%

The roving lunar base is a modular mining colony on the moon. It would settle in an area and proceed to mine the surrounding regolith for helium-3. When that region had been mined as much as possible the base would break into its modular parts and drive to the next mining site. This technology received mediocre scores from all three panels. The student panel had the highest number of those who thought it was likely with 59.7% saying that the breakthrough was likely. 47.6% of NIAC and 43.3% of the alumni panel felt that this technology was likely to be developed. The majority of each panel felt that it would be significant, though there were substantial fractions of each that felt the opposite. The time period was felt to be middle (2020-2035) to late (2035-2050) by most of the panelists. The comments brought into question the fact that it may use more power than it generates, or at least use a substantial fraction of it. Also, they put forth the idea that the mining and processing do not have to be located together, thus eliminating the need for a fully mobile base.

4.1.19 The Bionic Leaf

Table 55: NIAC Bionic Leaf Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	0.0%
Middle	0.0%	4.5%	13.6%	27.3%
Late	0.0%	0.0%	27.3%	18.2%
Never	4.5%	0.0%	0.0%	0.0%
Total	4.5%	4.5%	45.5%	45.5%

Table 56: Alumni Bionic Leaf Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	0.0%
Middle	0.0%	0.0%	6.5%	6.5%
Late	6.5%	0.0%	22.6%	9.7%
Never	0.0%	0.0%	0.0%	0.0%
Total	16.1%	0.0%	54.8%	29.0%

Table 57: Student Bionic Leaf Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	4.4%
Middle	0.0%	0.0%	8.8%	5.9%
Late	2.9%	0.0%	20.6%	10.3%
Never	2.9%	0.0%	4.4%	0.0%
Total	13.2%	0.0%	47.1%	39.7%

The bionic leaf is an enhanced plant. It would use a silicon imbedded black leaf that would be 15 times more efficient than green leaves and would also be hardy enough to grow on the moon. The leaf would be situated on the lunar surface and it would pipe the nutrients that it absorbed from the sun down into an underground growing habitat for some sort of plant, most likely a tuber. This was a generally low scoring technology with the most positive response coming from NIAC, 50% of whom thought the technology was likely. 39.7% of students and

29% of the alumni felt that it would be developed. Though the likelihood was called into question, the overwhelming majority of all three panels felt that this breakthrough would be significant. All thee panels also showed a strong majority placing development in the middle (2020-2035) to late (2035-2050) time periods. The comments generally agreed that while the implications would be enormous, implementing this will be difficult. Many respondents did say that a self-sustaining agriculture will be developed, but most likely not in the form described.

4.1.20 The "Gravity Implant"

Table 58: NIAC Gravity Implant Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	4.5%	9.1%
Middle	18.2%	4.5%	9.1%	22.7%
Late	0.0%	4.5%	4.5%	9.1%
Never	0.0%	0.0%	9.1%	0.0%
Total	18.2%	9.1%	31.8%	40.9%

Table 59: Alumni Gravity Implant Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	3.2%	0.0%	12.9%
Middle	0.0%	0.0%	3.2%	16.1%
Late	6.5%	0.0%	6.5%	6.5%
Never	0.0%	0.0%	0.0%	0.0%
Total	12.9%	3.2%	22.6%	61.3%

Table 60: Student Gravity Implant Results

Students	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	3.0%	16.4%
Middle	0.0%	3.0%	3.0%	11.9%
Late	4.5%	1.5%	6.0%	4.5%
Never	3.0%	0.0%	4.5%	0.0%
Total	16.4%	6.0%	28.4%	49.3%

The "gravity implant" would be a chip implanted in the spine of an astronaut in order to intercept neurological signals and transform them to trick the body into thinking it is not in microgravity. This would help keep astronauts from suffering sever muscular dystrophy and loss of bone mass after long periods in space. This technology received a mediocre response from all three panels. The alumni were the most optimistic with 64.5% responding that it was likely. 55.3% of the students and 50% of the NIAC panel felt that the technology would be developed. A much higher majority of the respondents felt that the technology would be significant, but there was little agreement on the time period of development with a standard spread among all three panels. The comments generally stated that the complexity of the human nervous system would be a huge block to this technology. Also, they questioned the morality behind reprogramming a human.

4.1.21 The LEO Compressed Air Collector (LEOCAC)

Table 61: NIAC LEOCAC Results

NIAC	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	0.0%
Middle	9.1%	0.0%	9.1%	18.2%
Late	0.0%	4.5%	18.2%	22.7%
Never	13.6%	0.0%	0.0%	0.0%
Total	22.7%	4.5%	31.8%	40.9%

Table 62: Alumni LEOCAC Results

Alumni	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	0.0%
Middle	3.3%	3.3%	10.0%	6.7%
Late	3.3%	0.0%	13.3%	13.3%
Never	0.0%	0.0%	0.0%	0.0%
Total	16.7%	3.3%	40.0%	40.0%

Table 63: Student LEOCAC Results

	Students			
	Insignificant Unlikely	Insignificant Likely	Significant Unlikely	Significant Likely
Early	0.0%	0.0%	0.0%	4.4%
Middle	1.5%	0.0%	4.4%	10.3%
Late	4.4%	0.0%	16.2%	8.8%
Never	1.5%	0.0%	7.4%	1.5%
Total	16.2%	2.9%	41.2%	39.7%

The LEOCAC is an orbiting vehicle that would swoop down into the atmosphere to collect gases. It would then return to its orbit and process these gases into usable fuel for conventional rocket boosters and also to start agriculture on the moon. This technology received a lukewarm response from all three panels, with NIAC being the most optimistic at 45.4% of the panelists rating it as likely. 43.6% of the students and 43.3% of the alumni felt that the technology would most likely be developed. Again the significance of the breakthrough was agreed upon by a large majority of every panel. For this technology the time period was generally rated as being middle (2020-2035) to late (2035-2050). The comments pointed out the fact that diving into the atmosphere would most likely have close to the same fuel costs as launching a rocket from the ground. Also, much of the gas collected would be nitrogen which is of limited use.

4.2 Scenarios

Scenario data proved to be extremely difficult to collect from panelists throughout the entire study. At the conclusion of data collection scenario questionnaire data was only collected on 31 respondents from the student and NIAC panels. No alumni panel scenario data was collected. Since the individual panels did not provide enough respondents to the scenarios to truly compare differences between panels, the bulk of the data analysis was done by grouping both panels together. This was further justified by the fact that all three panels responded in a very similar fashion to the breakthrough questionnaire. Despite this, the analysis comparing the panels was still done, though the statistical significance of the results is questionable. Each scenario is represented by a bar graph. Each bar of the graph represents a different respondent, and the y-axis is the likelihood rating they gave the scenario on a zero to six scale (0 being impossible and 6 being very likely). Also each graph has the last seven bars colored in black. These black bars are the responses of the NIAC panelists while the light blue bars are the student panel. Also for each graph the average and standard deviation was calculated in order to give a clearer picture of the spread of the data. An average and standard deviation was calculated for the overall data set, the student panel responses, and the NIAC panel responses for each scenario.

Table 64: Averages and Standard Deviations for all Six Scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Overall Average	3.4	2.6	3.1	3.5	3.1	3.0
Overall Std. Dev.	1.1	1.0	1.4	1.3	1.4	1.1
Student Average	3.5	2.5	3.1	3.7	3.0	3.2
Student Std. Dev.	1.1	1.0	1.5	1.3	1.4	1.0
NIAC Average	3.0	2.9	3.1	2.9	3.1	2.6
NIAC Std. Dev.	1.0	1.1	1.1	1.3	1.2	1.1

Table 65: Graph of Scenario One Results

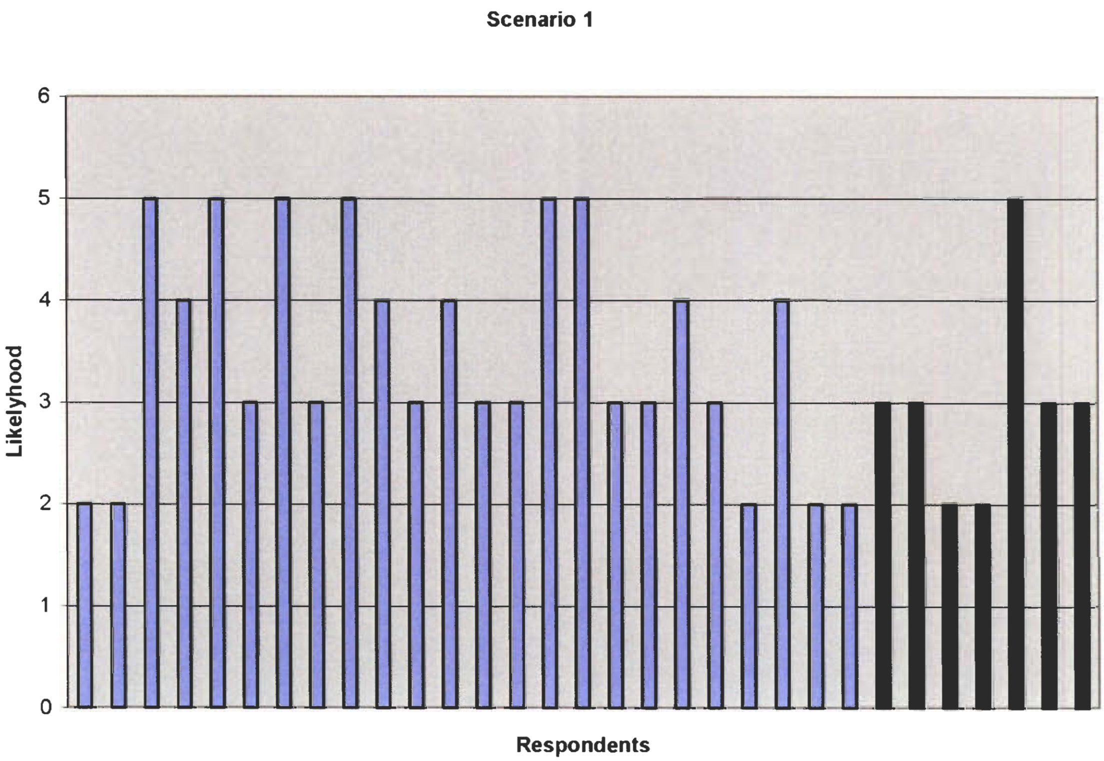


Table 66: Graph of Scenario Two Results

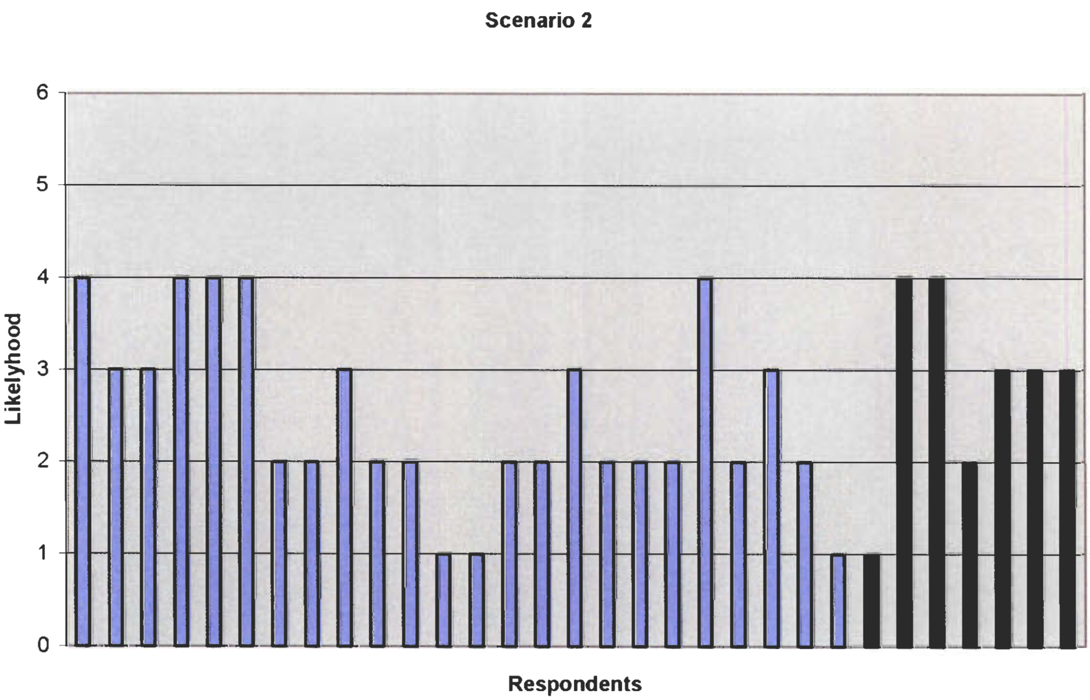


Table 67: Graph of Scenario Three Results

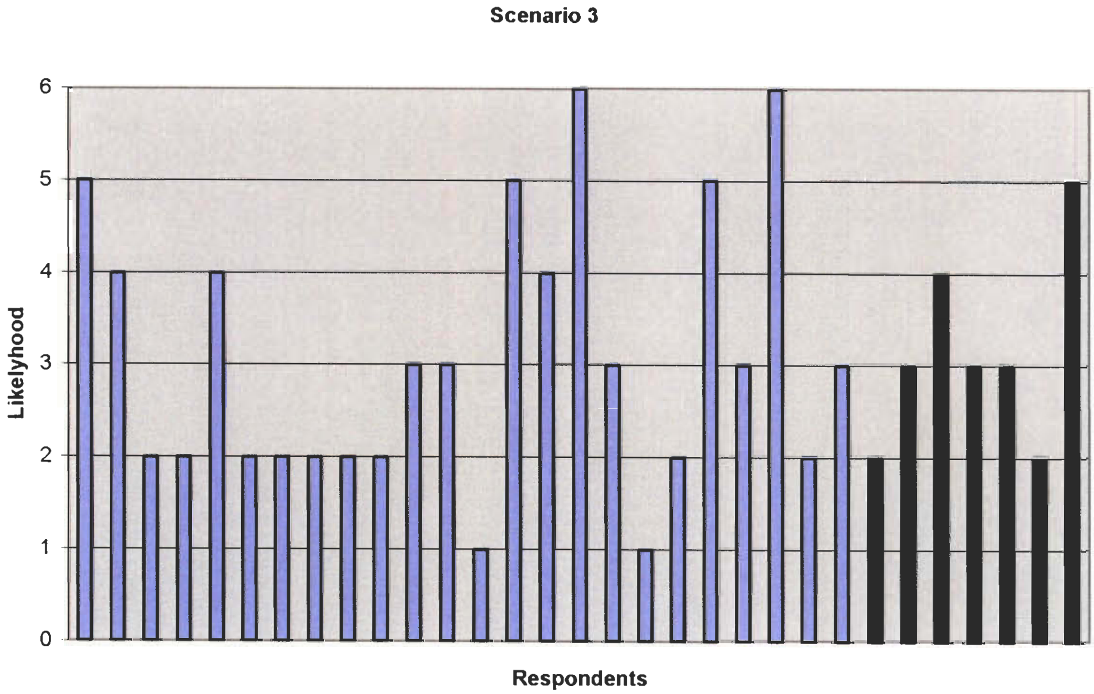


Table 68: Graph of Scenario Four Results

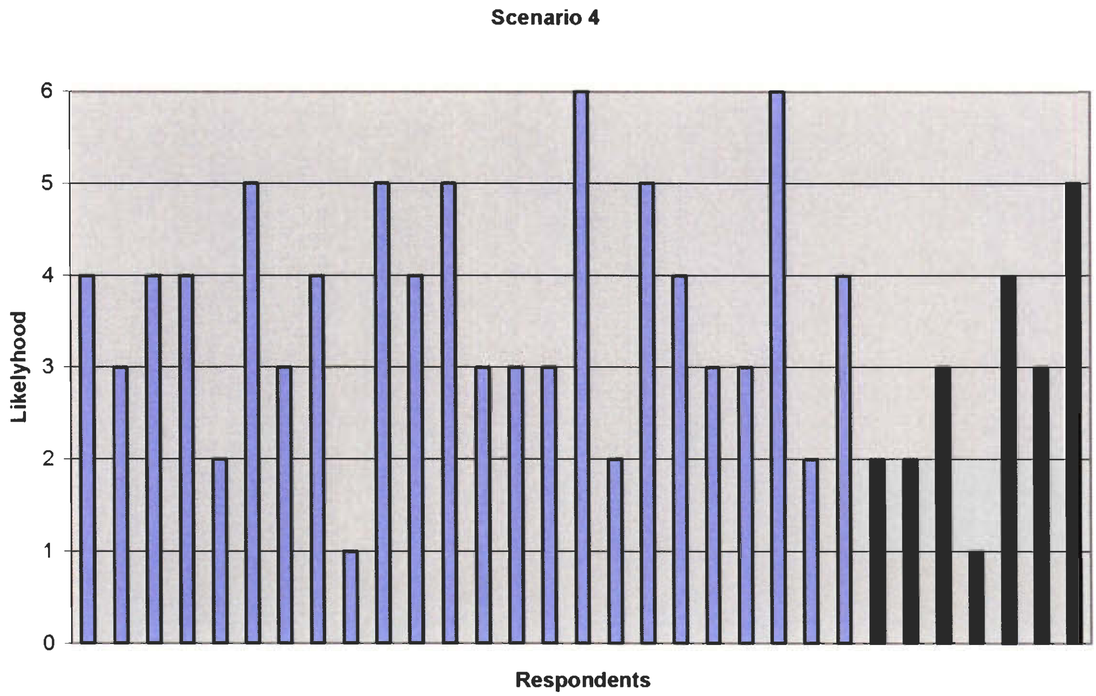


Table 69: Graph of Scenario Five Results

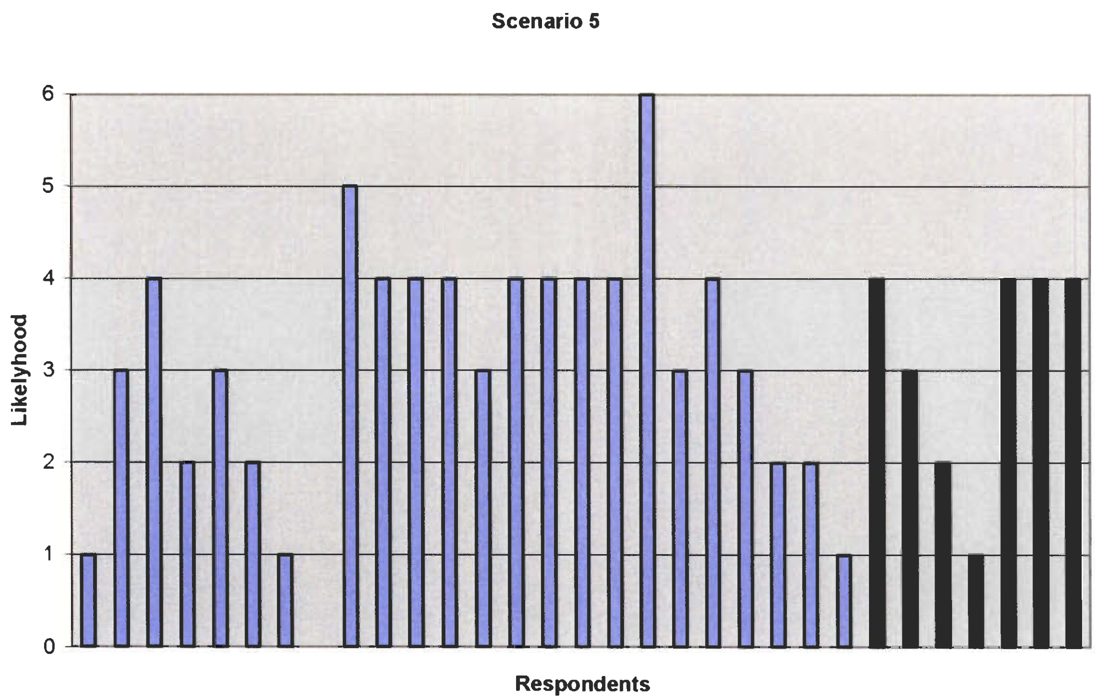
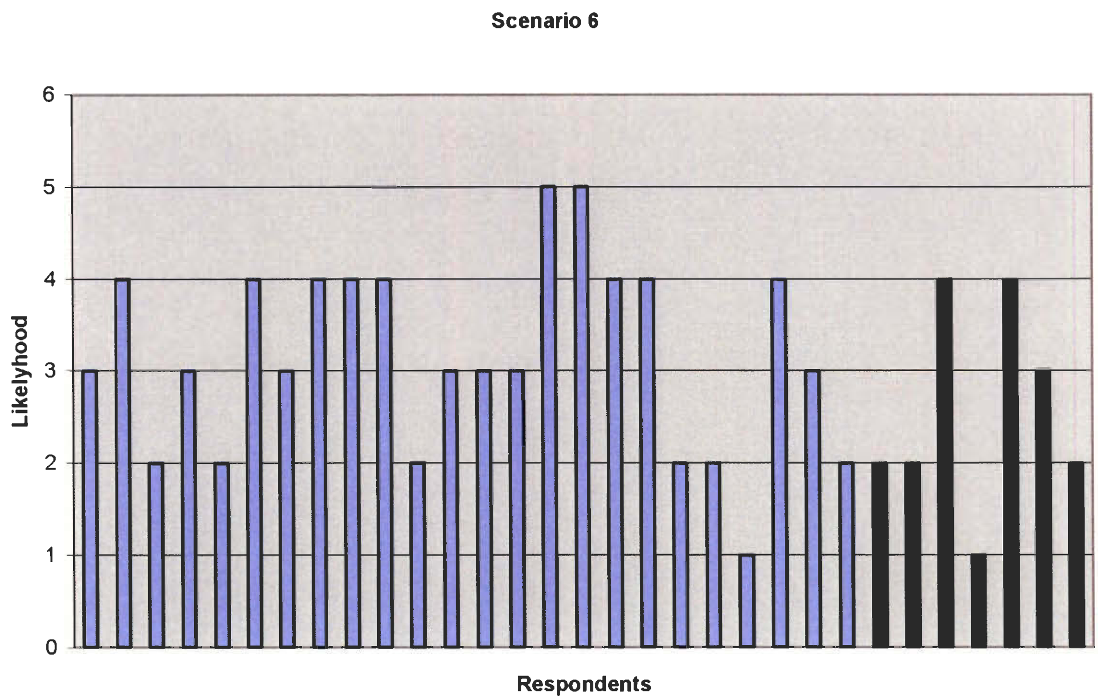


Table 70: Graph of Scenario Six Results



4.3 MBTI Results

The purpose of this analysis of the data was to compare the responses of individual panelists to the breakthrough survey to their MBTI type. The goal was to find evidence of a link between the person's cognitive type and their optimism, and see if the NIAC panel was strongly homogeneous in type. Originally, the intent of this project was to do this with NIAC MBTI data in addition to the two other panels, but due to an extremely low response rate from NIAC this was not an option. As such the two panels that were analyzed for cognitive orientation were the alumni and student panels. Due to the similarity between the two (due to the fact that they both attended WPI) it was decided that it was appropriate to merge the two panels into one large panel in order to get a decent sized sample for MBTI analysis. Also, since this analysis was already done with the alumni data by a prior team it would give an opportunity to see if the results could be duplicated with more data. When Wilfong and Patrone's data and analysis were re-examined, it was decided that their method for determining if one type was more optimistic than another was flawed. Their method was to take the average of each type's response to an individual technology. For example, all the responses to likelihood by NJ's were added together and then divided by the total number of NJ's to give an average rating by the entire type. This average was then compared against the averages for the three other types to see if it was higher or lower, thus being more or less optimistic respectively. It was determined that this method would tend to wash out small differences in the panel that could have huge significance for optimism. The problem lay in the fact that a rating of three meant the person though the technology was unlikely (and therefore was not optimistic) while a rating of four meant the person thought the technology was likely (thus making them optimistic). If, for example, 70% had rated a technology with a three, and then 30% had rated the technology as a 6, the resulting average would be a 3.9. By this method it appears that the type is optimistic, while in fact the bulk of the panel was not optimistic. Due to this methodological distortion it was decided that a new method for determining optimism was needed. The new method involved counting every respondent of a certain type who rated a technology as four or higher, the lower threshold for optimism. This number was divided by the total number of that type to give a percentage of that type that was optimistic. For example, for aerogel, 22 NJ's responded with a four or higher, and there were a total of 25 NJ's in the sample. Thus, using the new method, 88% of the NJ's were optimistic about aerogel. These percentages can then be compared to see if there is any significant difference between the types. Continuity required that the new data gathered from the students also be analyzed using the method from the original Alumni study, and that analysis is also included in this section. The data was organized into fives tables, one for each category. Each column represents a technology, and each row represents a different type. The number in each cell represents the percentage of respondents who felt that the technology was likely, thus the percentage of optimistic respondents.

Table 71: Optimism Percentage of Each Type in Drives Category

	Nuclear Drive	Magbeam	Slingatron	Solar Sail	Mass Driver*	Ion Drive*
NP	62%	41%	39%	68%	67%	92%
NJ	58%	40%	25%	88%	43%	57%
SP	76%	47%	46%	87%	67%	67%
SJ	53%	23%	22%	86%	80%	90%

* Denotes a technology with extremely low response rate due to it not being included in the alumni version of the questionnaire

Table 72: Optimism Percentage of Each Type in Launch Vehicles Category

	Laser Propulsion	ReSSTO	Ram Accelerator	Space Elevator
NP	41%	73%	23%	23%
NJ	32%	76%	36%	32%
SP	53%	67%	47%	33%
SJ	36%	91%	68%	18%

Table 73: Optimism Percentage of Each Type in Materials Category

	Memory Plastic	Carbon Nanotubes	Solid State Aircraft
NP	76	84	33
NJ	88	80	38
SP	73	87	29
SJ	82	77	53

Table 74: Optimism Percentage of Each Type in Shielding Category

	Electro Magnetic	Cold Plasma	Aerogel
NP	56%	36%	84%
NJ	72%	16%	88%
SP	47%	40%	93%
SJ	55%	18%	100%

Table 75: Optimism Percentage of Each Type in Life Support Category

	Fusion	Roving Lunar Base	Bionic Leaf	LEOCAC	Gravity Implant
NP	52%	44%	28%	36%	48%
NJ	64%	44%	44%	44%	60%
SP	47%	33%	40%	40%	73%
SJ	45%	64%	18%	41%	50%

The following tables show the overall data when broken down in the method used in alumni study of last year.

Table 76: Average Response of Each Type in Drives Category

	Nuclear Drive	Magbeam	Slingatron	Solar Sail	Mass Driver*	Ion Drive*
NP	3.9	3.3	2.6	4.8	3.6	4.0
NJ	3.9	3.3	3.0	4.3	4.3	4.7
SP	3.7	3.4	3.0	4.9	3.7	4.3
SJ	3.9	3.1	2.7	4.5	4.2	4.4

Table 77: Average Response of Each Type in Launch Vehicles Category

	Laser Propulsion	ReSSTO	Ram Accelerator	Space Elevator
NP	3.4	4.5	3.1	2.8
NJ	3.2	4.4	3.1	2.7
SP	3.7	3.9	3.3	2.7
SJ	3.2	4.8	3.6	2.6

Table 78: Average Response of Each Type in Materials Category

	Memory Plastic	Carbon Nanotubes	Solid State Aircraft
NP	4.9	4.9	3.4
NJ	4.6	4.6	3.1
SP	4.3	4.7	3.1
SJ	4.5	4.5	3.5

Table 79: Average Response of Each Type in Shielding Category

	Electro Magnetic	Cold Plasma	Aerogel
NP	4.0	3.1	4.9
NJ	3.7	2.4	4.8
SP	3.3	3.1	4.9
SJ	3.6	2.6	4.9

Table 80: Average Response of Each Type in Life Support Category

	Fusion	Roving Lunar Base	Bionic Leaf	LEOCAC	Gravity Implant
NP	4.0	3.4	3.1	3.2	3.6
NJ	3.7	3.7	3.0	3.1	3.6
SP	3.6	3.1	3.4	3.2	3.9
SJ	3.6	4.0	2.5	3.1	3.3

5. Analysis

The NIAC study had specific forecasting goals, and was also a methodological review of the Delphi approach as applied in this study. The hypotheses contained predictions dealing with each of the three questionnaires, the breakthrough, the scenario and the MBTI. The hypothesis based on the variable measured in the breakthrough questionnaire was that the NIAC panel would be consistently more optimistic. If so the data would then be analyzed to see why this was the case. Methodologically it was assumed that the breakthrough questionnaire was a fully functional tool. As for the scenarios, though it was the first application of the questionnaire to a large panel, it was predicted that they would act as a functioning second wave to the breakthrough Delphi study. They would accomplish this by allowing the respondents to either change or defend their responses to the breakthrough questionnaire. It was thought that scenario one would garner the highest rating due to it being composed of the technologies that were the highest rated in the breakthrough questionnaire. Finally, it was predicted that the technical optimism of the respondents would reflect their MBTI type. Specifically, NP's would be the most optimistic, with NJ's and SP's being situated in the middle, and SJ's being the least optimistic about the breakthroughs which required significant technological advancements. In prior studies SJ's had favored better established lines of development and had been skeptical of radical proposals.

5.1 Breakthrough Analysis

Before discussing the hypothesis it is necessary to give a summary of the results of the breakthrough questionnaire. Of all 21 technologies reviewed nine technologies were agreed upon as likely by all three panels. These technologies were the nuclear drive, solar sail, mass driver, ion drive, ReSSTO, memory plastics, carbon nanotubes, electro-magnetic shielding, and aerogel.

All three panel's responses were split over the following technologies: ram accelerator, solid state aircraft, cold plasma, fusion, roving lunar base, and the gravity implant. The only deviation in those technologies was in cold plasma where NIAC rated it as likely, and the other two panels did not. Finally, there was agreement among all the panels that the magbeam, slingatron, laser propulsion, space elevator, bionic leaf, and LEOCAC were unlikely.

The first prediction about the breakthrough results was that they would show that the NIAC panel was more optimistic than the other panels. This was first posited in the paper by Gillis, Stawasz, and Wu. Based on the first 11 NIAC responses, when compared to the other panels, the NIAC respondents were more optimistic on the whole. When the NIAC panel was expanded to 17 respondents in this study, this finding could be reexamined. With the added respondents to the NIAC and student panels (the alumni panel remained the same) the findings were not replicated. NIAC was only more optimistic on eight of the 21 technologies. Within these eight there were only three where NIAC panel was significantly more optimistic than the other two panels, these being the space elevator, cold plasma, and the bionic leaf. Their optimism for the space elevator could be explained by the fact that some NIAC fellows are personally invested in it and have done research tied to it. The others have certainly heard of the technology and possibly consider it a significant effort, though difficult to achieve in practice. With regard to cold plasma and the bionic leaf, both are complicated technical ideas. The high expertise of the NIAC panel may give them better insight into the workings of such technologies and thus cause them to rate them differently. The previous team of Gillis, Wu, and Stawasz believed that the higher optimism they observed from the NIAC panel may also have been due to the fellows possibly having similar MBTI types. The new results tend to refute this since the NIAC panel can no longer be shown to be consistently more optimistic than the other panels regardless of the fact that they may be all of a similar MBTI type. Unfortunately, there was not enough MBTI data gathered to determine if NIAC was dominated by a certain MBTI type. While this would be interesting to find out, the new results show that the NIAC panel is not more optimistic and therefore there is nothing to be explained by a cognitive skew, even if it were present. The findings that were gathered regarding MBTI type data and optimism will be discussed further in a later portion of the conclusion.

The fundamental assumption that was made before beginning this study was that the breakthrough questionnaire was a fully functional tool that had been rigorously screened for technical errors. This was essential because to obtain useful results from the survey the technology descriptions must be accurate and robust. Also, by sending the questionnaire out to the experts at NIAC it was important to have the technologies correctly framed and described to maintain credibility. This panel would more readily identify mistakes than the WPI students or alumni. Almost immediately after sending out the survey to the NIAC fellows one responded with a rather vehement email detailing mistakes in almost every technology description. This was originally treated as an anomaly and was ignored. As results from the NIAC panel began to be submitted, many of the comments reflected the same problems with the technology summaries that the original email pointed out. Simultaneously, the survey was sent out to the new panel of students. These students were all currently working on space-themed Interactive Qualifying Projects. Some of these projects were feasibility and social impact studies of technologies that were reviewed in the breakthrough questionnaire. When these students saw the descriptions of the technologies they were working on, they raised many of the same objections that the NIAC fellows did. Due to this, it was decided that the breakthrough questionnaire needs major revisions. Since the instrument had already gone out to the panelists it was too late to make changes in time for this study. An analysis of the inaccurate technology items was begun in order to create suggested revisions for future iterations of this forecasting instrument.

The first two technologies that need to be discussed for revision are memory plastics and the slingatron. Memory plastics were only criticized by the first feedback received. The fellow felt that the ideas of a self healing plastic and a memory plastic were two different things. The breakthrough questionnaire had conflated the two ideas into the one memory plastic entry. This distinction should be investigated when the breakthrough questionnaire is revised. The slingatron was a heavily criticized technology. The physics behind the idea was consistently called into question by every panel. Thus, in last year's NIAC study the item was left out of the instrument when it was sent out to the panel. The item remained in this study only because it was included in the online version of the questionnaire and the resources to edit the online database were not present. At any rate, it is felt that this technological summary, in its current form, should be excluded from future applications of the breakthrough instrument because of its absurdity. While these two technologies do need to be edited, the changes are small and do not require much investigation. The rest of the technologies that require change will need much more investigation.

The first technology that requires research for a re-write is the nuclear drive. The source of the item was Freeman Dyson, and one of the main obstacles according to him is the dissipation of heat from the engine. The summary calls for a breakthrough in the area of radiators in order to solve this dilemma. The comments from the NIAC fellows (some of whom have personally worked on nuclear drives) point out that for the type of drive described a radiator is not necessary. Dyson possibly had the idea of using the reactor to generate power, but the technology as presented uses the nuclear reactor to heat propellant that is then ejected out the rear of the spacecraft causing thrust. In this system the heat is carried away by the propellant, thus eliminating the need for radiators. If the drive had used the nuclear reactor to provide electrical power then the heat would not be dissipated and an extremely effective radiator would be required. Since the technology as put forth in the questionnaire uses nuclear heated exhaust no radiator is necessary. Also, the description calls for the use of water or another liquid as a propellant. Water is extremely heavy and therefore would be inefficient when compared to using hydrogen as the fuel source. To an expert this item appears poorly researched, and thus requires more research and a re-write of the item to be performed.

The solar sail received only one major complaint, but the criticism provided provokes investigation into the entry as written. As it stands, the solar sail is presented as one technology using a light metal filament as the sail. The comment charges that there are actually three different types of solar sails and that they have drastically different feasibilities and development times. The first type is similar to what is described in the questionnaire. It is made out of metal or carbon, has low thrust, and can be developed in the short term. The second is a carbon-fiber sail that can achieve higher velocities and will not be developed till the middle time period as presented. The third type is a sail that utilizes laser or microwave technology to produce higher thrust and could be used for interstellar travel. This type would not be developed until the late period or beyond. These three types must be more fully investigated and a decision must be made on whether one type is best for this survey or if all three must be included.

The ion drive did not itself receive direct criticism, but the group researching drives at WPI felt that using the ion drive as a specific item was leaving out a large portion of possible breakthroughs in electric propulsion. As most of the comments reflected, the ion drive is an already proven and tested technology with little possibility of further breakthrough. The general class of electric drives (including, but not limited to, resistor jet, Hall Effect thrusters, and pulsed plasma thrusters) is still a highly researched field with many possible breakthroughs left in it. When writing future iterations of the breakthrough questionnaire, the idea of replacing the ion drive item with a more general electric drive item, discussing the different types of electric propulsion and challenges faced by each type, should be seriously investigated.

With regards to fusion technology there was only one major issue raised with the item as presented. In the questionnaire the fusion entry is directly tied to the idea of using He-3 as its fuel source. As many of the comments showed, He-3 is not the fuel that is being used in current fusion research. As such, the first fusion reactors will have nothing to do with He-3, and will more likely use deuterium and tritium. Even after this first D-T reactor is developed it would take a long time to develop a He-3 system with the possibility of very little benefit over D-T reaction. Thus, it is not likely that a He-3 reactor will ever be built. Due to this the technology description in the breakthrough instrument needs to be revised. It should include the more likely scenario of using D-T reactions, and only mention He-3 as a possible breakthrough in the future.

The bionic leaf presented more of a conceptual problem than an actual technical error. Many of the comments reflected that the idea would be implemented differently, but that the capability was needed. This response to the technology was supported by a WPI team looking into agriculture on the moon. They found that if the bionic leaf was developed it would most likely resemble more of a factory than a bio-engineered leaf. Also, they found that this breakthrough was not necessarily required to grow plants in lunar habitats. The team proposed a system of using mirrors to redirect light around the radiation shielding and into the plant habitat. A revision of this technology would require investigation into the idea of a factory-like bionic leaf and a decision on if it is appropriate to include this new method of supporting lunar agriculture.

The LEOCAC presented the greatest need for full scale revision after some investigation. The comments were almost unanimous that the technology as presented had major engineering problems. The craft would most likely use more fuel than it would collect making it completely inefficient. A team of WPI students, with the help of inventor Paul Klinkman, came up with a new idea on how to make this technology work. Their idea dealt with using an electro-magnetic tether for propulsion and to keep the spacecraft at a constant altitude where the exosphere is mostly oxygen. This new system solves many of the engineering problems presented by the old technology summary. A future version of the breakthrough questionnaire should incorporate this new description of the LEOCAC (now the Low Earth Orbit Oxygen Collection System) in order to test the feasibility of this new idea. The group currently developing the LEOOCS has written a sample description that could be used as a new item in a future iteration of the breakthrough questionnaire. This can be found in appendix A.16.

These last two technologies also present a methodological problem with the Delphi method as applied in this survey. As time progresses new discoveries will render the technologies on the questionnaire obsolete or make them no longer a breakthrough. Also, incorrectly written or poorly researched technologies can result in summaries that are not accurate which can skew the results and cause the predictions to be meaningless. This is most evident in both the bionic leaf and LEOCAC cases. For the bionic leaf the summary itself is misleading and it may not be necessary to developing agriculture on the moon. Due to this, the results from the bionic leaf may not be statistically significant. When the case of the LEOCAC is examined it becomes obvious how an inaccurate technology summary can affect the responses of the panels. As presented in the questionnaire the technology would never work, and therefore received a low rating from all panels. If it was revised to use the new ideas put forth by this year's team the responses may not be so negative. Thus, for the same general concept the technology summary would have complete sway over how a panel responds. This raises a serious methodological problem for the study as currently performed. The survey must be constantly kept up to date or the data gathered becomes obsolete. Unfortunately, when a technology description is altered the comparability to the data already collected is compromised. Balance must be upheld between keeping the survey as accurate and up to date as possible and keeping consistency between old and new data. Items should be developed after extensive research into the technology in order to keep future revisions to a minimum.

5.2 Scenario Analysis

This study was begun with the hope that the scenarios would serve as a reasonable second wave for the Delphi study. It would be a forum in which the outlier panelists could confirm or change their responses to the breakthrough questionnaire by accepting scenario one. The first scenario was built using all the highest scoring technologies from the breakthrough questionnaire. This should result in the first scenario receiving a very high likelihood rating from the majority of respondents. The rest of the scenarios were built around different technologies in order to show less popular ideas in context and give the panelists a chance to reconsider them. When the data was analyzed it became apparent that the scenarios were not working in the intended fashion. The first scenario resulted in an average rating of 3.4, where four or higher was considered likely. The standard deviation was 1.1 suggesting that most responses were in the lower range. The most likely set of technological developments were not replicated meaning that a majority of panelists did not feel that the most likely technologies would develop in the way described. All of the scenarios followed a similar pattern with no one scenario emerging as a definitive vision of the future that a majority of panelists could endorse as most likely.

The comments were a logical place to look for explanation as to why the scenarios did not work in the way expected. The majority of respondents felt that the scenarios did not correctly portray social, political, and economic factors. Sometimes the problem was a logical lapse or timeline error. For example, in scenario two a He-3 mining colony is set up on the moon before a workable He-3 fusion reactor is developed. This is illogical as no one would invest money to mine something that they couldn't sell.

The scenarios need a complete revision before they are useful as a second Delphi wave. They must be made more realistic and not rely solely on breakthroughs to solve the problems presented by space exploration. They should be built around one or two related or complimentary breakthroughs with the rest held constant. Including even one technology that most panelists rated as unlikely can result in an entire scenario being evaluated poorly even though most elements seem reasonable. Thus, care must be taken in order to make sure that one breakthrough does not play an important role in every scenario.

Another criticism of the scenarios that was widespread was that the timelines were unrealistic, even though they were based on the responses to the first breakthrough questionnaire. The timelines need to be investigated and expanded to make the scenarios more credible. This presents a problem because the technologies on the breakthrough survey are only rated on a timeframe of present to 2050. One suggestion that has been made is to treat the scenarios as a completely different study than the breakthrough questionnaire. The scenarios would still rely on the results from the breakthrough instrument, but they would be used solely to attempt to create alternative visions of the future, not as a second wave in a Delphi study. One idea for this stand alone study would be to present the respondents with a set of pre-formed scenarios, and then let them create their own scenario at the end by choosing the technologies they feel are most likely. As for the second wave of the Delphi study, it could be done directly online by modifying the current tool to include an immediate feedback session after the respondent fills out the questionnaire. They would then be given the opportunity to change or defend their position and these data would be made available to the entire panel.

This is just one idea to implement a different approach to the Delphi second wave and others may be developed that would work better. At this point it is agreed that the scenarios do not work as a second wave to the study, but that the data collected shows how they need to be modified.

5.3 MBTI Analysis

The previous team started with the same hypothesis used in this forecast study. After analyzing their data they found that the NP type was not as optimistic as they expected and that differences in optimism were more observable between the J and P dimensions. As discussed in the results section, their sample and method of analysis could not support a reliable conclusion. This study used a larger panel and a method of analysis less dependant on averages. The new, more reliable and precise results can easily be interpreted as casting doubt on the optimism hypothesis. The data was also analyzed in the fashion used last year in order to preserve comparability between the studies. When this analysis was complete it was obvious that there was no simple correlation between the different cognitive types and technical optimism. What was observed were cognitive outliers which were sometimes drastically more or less optimistic than the other types. This result was replicated when the data was analyzed using last year's methods. This result is extremely important for Delphi studies. This could mean that a panelist's cognitive type does not affect how they respond to forecasting surveys. The implication of this interpretation would be that panel selection must be more rigorous to balance other factors that might skew the results. Factors such as education, expertise, field of study, and even a respondent's hobbies must be considered when choosing panelists. The first expert panel results suggested this when the university based experts were less optimistic than those in NASA or the Planetary Society. This also disproves the simple version of the hypothesis of the previous NIAC study who felt that the MBTI makeup of the NIAC panel was causing it to be more optimistic. Not only was the NIAC panel not more optimistic, but the data collected shows that MBTI type has almost no connection to a composite technical optimism measure created by combining all the technology items by category or overall. The previous differences observed between the J and P dimensions are as likely a statistical anomaly as a major finding. However, this study would have to be replicated with a separate panel to verify these findings. There is still the possibility that the other dimensions in MBTI type could relate to optimism in a simple manner. A direct measure of pessimism-optimism should be part of the next study both to correlate with the MBTI dimension and to use as an alternative way to sort the technical breakthrough data. However, another finding of this study was that the WPI student and alumni panels were approximately the same as the NIAC panel. It would be difficult to screen student panelists for their optimism and pessimism without asking about that subject in a screening survey. Originally it was hoped that the MBTI data would provide an easy way to screen panelists for their relative optimism and pessimism, and this was the original intent of the alumni panel since the MBTI data had already been collected. Though these findings show that the simple view of cognitive type versus optimism does not hold up, it does not show that MBTI data should be completely ignored in panel selection. The existence of cognitive outliers in the data suggests that if the data was analyzed extremely in depth on a technology by technology basis it would yield interesting correlations between the types and their responses. Experts with a greater understanding of the workings of the MBTI have reviewed the data collected and agreed that there is some pattern in the data but that it is not obvious. The pattern seems to suggest that the items be reorganized based not on the type of technology it is, but rather on how much of a breakthrough the technology requires.

6. Conclusion

The original goal of this study was to predict what breakthroughs are possible in the next 50 years and then to determine the climate in which they would develop. Due to factors such as inaccurate technology summaries and unrealistic scenarios, these goals were not achieved, but the data now exists to create a tool that could generate well grounded predictions. Luckily, the data collected is far from useless. The study transformed into an overview of the method and tools used, and resulted in a detailed set of recommendations on how to improve upon future rounds of Delphi approach forecasting studies. If these suggestions are implemented, upcoming iterations should result in meaningful data that can be used to predict what space exploration will look like in the foreseeable future. The data collected from this study is still of use to NIAC who could create a preliminary version of the interactive online tool discussed in the introduction. When the results from the new versions of the questionnaire are collected, the online tool could be revised to become more meaningful.

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Appendices

A.1 Breakthrough Questionnaire

Propulsion In Space
(Part 1 / 5)

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

Mass Driver

Mass Driver prototypes have existed since 1975, most of which were constructed by the Space Studies Institute. It is a form of spacecraft or cargo propulsion utilizing a linear motor to accelerate payloads up to high speeds. Payloads would be placed in a "bucket" which is fitted with an electromagnetic coil. This "bucket" is then accelerated by a series of electromagnetic drive coils spaced a certain distance apart forming a tunnel. The "bucket" is reusable and remains with the mass driver while the payload is sent on its way. Due to the thick atmosphere and high gravity of Earth, this is not currently suitable for Earth based launches, however ship and moon based configurations would not be as subject to these forces making them ideal. The mass driver requires no fuel for propulsion and instead can be operated solely on electricity from a local nuclear power plant or solar array. A breakthrough in this technology would come from providing the necessary power, possibly from solar or nuclear means.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

Ion Drive

In 1955 Dr. Ernst Stuhlinger presented a theory at a Vienna convention that described ion propulsion and promised a far more favorable fuel to thrust ratio than a chemical rocket. An Ion Drive is a type of spacecraft propulsion that uses beams of ions to accelerate. He worked under NASA contract from 1958-1968 but never solved the key problem, which was that ejecting the positive charged particles left the craft with a negative charge and it just attracted most of the particles back canceling most of the thrust. Though a failure from the standpoint of a drive that could launch a vehicle from the Earth to orbit, its value as a propulsion and control system for crafts already in space was recognized. The problem is that while one could theoretically accelerate to speeds that were a substantial fraction of the speed of light, the rate of acceleration is very slow.

How slow is the acceleration? The ESA's SMART-1 lunar mission was ion driven and took 15 months to reach the moon. However, the drives are very fuel efficient. In 1998 JPL's Deep Space 1 probe was successfully powered by a xenon Ion Drive. On Deep Space 1, 72kg of xenon gas resulted in 16,000 hours of runtime for the Ion Drive.

A breakthrough that results in faster acceleration is needed to realize the promise of this technology. Current speculation focuses on coupling it with another source of propulsion in order to "kick start" it.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

Launch Vehicles
(Part 2 / 5)

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

Materials
(Part 3 / 5)

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

"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 woud be a more beneficial way to explore the atmosphere of a planet like Venus or Mars than with a balloon or parachute probe.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

Shielding
(Part 4 / 5)

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

Life Support
(Part 5 / 5)

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

Fusion Reactors

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

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

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

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.

Significance: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Likelyhood: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

Time Period: ☐ Early ☐ Middle ☐ Late ☐ Never

Comments:

A.2 Scenario Questionnaire

1. Timeline:

2010 – Aerogel becomes the new standard for spacecraft insulation / protection
2015 – Reusable Single Stage to Orbit craft becomes available for use
2020 – Solar Sail technology is perfected / Nuclear Drive emerges as a new propulsion technology
2035 – Fusion Reactors are developed

2040 – Bionic Leaf becomes feasible
2045 – Fusion powered spacecraft

Scenario 1 begins with the full scale production and use of Aerogel in all spacecraft applications. Its ability to protect surfaces from the extreme heat of re-entry is invaluable and by 2015 allows for the first Reusable Single Stage to Orbit (ReSSTO) spacecraft to become viable. Aerogel's ability to prevent wear and tear to ReSSTO spacecraft directly relates to the extremely low levels of maintenance required (compared to the retired space shuttle) to keep the spacecraft in service. The low levels of maintenance result in a great decline in the cost of launching spacecraft (with payloads) into orbit.

ReSSTO spacecraft are used to "pave the way" for the future of space utilization. They deliver payloads as well as personnel into orbit at a relatively low cost. By 2020 solar sail technology is functional and is ready for use for travel throughout the solar system. ReSSTO spacecraft will provide the means to transport and assemble solar sails in geosynchronous orbit. All supplies necessary for a mission as well as personnel are sent into orbit on ReSSTO spacecraft. In case of an emergency fuel problem, refueling platforms are critically placed throughout low earth orbit. Solar sail spacecraft are developed with the intention of traveling to the moon and back repeatedly. Since solar sails rely on the Sun's pressure for propulsion, the only foreseeable costs of lunar travel are related to the initial cost of the spacecraft, the maintenance of the spacecraft, and the fuel required to land on and take off from the moon. Therefore trips to the moon and back are very cheap (compared to conventional, multistage, chemical rocket propulsion). Initial trips to the moon are strictly scientific. ReSSTO spacecraft are modified specifically for lunar trips such that they take off from Earth's surface and then meet up with a solar sail that is attached around the ReSSTO vehicle for transit to the moon. Due to the solar sail's nature, travel to the moon is executed such that the solar sail spacecraft will reach the moon when the moon is behind the Earth (with reference to the Sun). Upon reaching the moon, the ReSSTO spacecraft can detach from the solar sail and descend to the lunar surface (the solar sail stays in orbit around the moon). The process is then repeated to return to Earth except that the craft must depart from the moon when the moon is in front of the Earth (with reference to the sun).

In 2020 nuclear propulsion becomes available. Directly compared to the solar sail for lunar travel, the cost is much greater (since it requires radioactive fuel). Therefore nuclear propulsion is primarily used for missions to Mars conducted by the United States. The efficiency of solar sails greatly decreases as the distance of the spacecraft, from the sun, increases. Therefore nuclear propulsion promises a faster, more reliable trip to Mars, and will be needed for deep space missions.

In 2035 a breakthrough in the sustaining of fusion reactions involving helium occurs, and countries across the world start to make the 30-40 year change over to fusion power. Nations realize the Helium-3 potential on the moon (to fuel the fusion reactors) and begin developing mining operations in coordination with the existing lunar habitats, expanding their capacities. Private mining corporations also emerge in the competition for claiming lunar territory and mining rights. In order to sustain mining operations, more extensive lunar habitats are developed over the next few years that are constantly re-supplied via solar sail cargo ships from Earth. Small lunar colonies consisting of inflatable temporary shelters then start to appear in areas of mining activity.

A breakthrough in life support involving the bionic leaf takes place in 2040. The bionic leaf

allows for full scale lunar colonies that are permanent structures and self-sustaining (in terms of breathable oxygen). This breakthrough also holds potential for spacecraft life support systems since longer voyages throughout the solar system will become cheaper and more viable (no need to carry large amounts of oxygen). With the moon settled, nations and corporations alike will turn their eyes to tapping the potential resources of Mars or the Asteroid Belt.
From the developments in fusion technology, a fusion propulsion system is conceived in 2045. Since helium-3 is mined on the moon, it can be directly input into a spacecraft with a fusion reactor on board to produce fusion propulsion. Fusion propulsion is much faster than solar sail propulsion. The additional cost of using the fuel in transit is covered by the ability to increase the number of trips to and from the moon (greatly increasing profits). Solar sails are then gradually replaced by fusion powered spacecraft investments.

Likelihood: Select

Comments:

2. Timeline:

2015 - Carbon nanotubes become available
2025 - Space Elevator is constructed
2035 - Fusion reactors are developed
2040 - Magbeam is created for lunar travel
2045 - Roving Lunar Bases developed to harvest Helium-3
2050 - Lunar Space Elevator and lunar space station developed

Scenario 2 begins with the breakthrough of long thread carbon nanotubes (2015) in the field of material science. Coupled with the large amount of research conducted on the physics of the Space Elevator, carbon nanotubes provide the key to the development of a long composite cable reinforced by nanotubes . Many nations pool their funds to develop the Space Elevator since they see it is a long term investment that provides a low cost means to reaching Earth orbit. After 10 years of development the first Space Elevator becomes operational in 2025. The Space Elevator possesses a 5-ton per load capacity, capable of 4 loads (2 up and 2 down) at any given time to or from geosynchronous orbit (GEO). Electric motors are used to drive the "cars" up and down the Space Elevator. These cars are solar powered (when possible) and possess a rechargeable backup battery when direct solar power is unavailable or too weak.
Fusion reactors that utilize Helium-3 as a fuel source are developed in 2035. Many industrialized countries initiate the switch to fusion as a power source and see the Moon as the best location to harvest Helium-3. The potential lunar trade leads countries to find a cheap and effective means to travel and transport goods between the Moon and Earth. The magbeam system emerges in 2040 to meet this demand. One magbeam satellite is placed in orbit near the Space Elevator while the other magbeam satellite is placed in orbit around the moon. These satellites can propel and "catch" spacecraft in transit between the Earth and the Moon. All supplies and personnel

required for lunar operations are transported to the Moon via the Magbeam.
In order to have large scale harvesting of Helium-3 on the Moon, companies working for various nations develop roving lunar bases capable of mining a location and migrating to new locations once the resource is "strip mined" out of a region. These nomad bases are put into use in 2045. A helium-3 fusion reactor is placed on the equator and refueling and recharging vehicles transit between this reactor and the nomad bases for refueling purposes.
Initially chemical rocket vehicles are used to land and depart from the lunar surface. In 2050 the construction of a lunar Space Elevator as well as a lunar space station is completed. The lunar Space Elevator allows Helium-3 to be transported directly into lunar orbit where it is loaded on to magbeam spacecraft for transport back to the Space Elevator in Earth orbit.

Likelihood: Select

Comments:

3. Timeline:

2015 - Carbon nanotubes become available
2020 - Nuclear drive emerges as a new form of propulsion
2025 - Space Elevator is constructed / Solid State Aircraft achieve flight
2030 - Unmanned Solid State Aircraft visit Mars to find landing site for manned mission
2035 - First manned mission to Mars

In Scenario 3 the development of carbon nanotubes (2015) paves the way for the construction of the Space Elevator as a reliable means to get personnel and cargo into Earth orbit. Meanwhile, engineers develop a functional nuclear fission drive that is a safe and reliable method of propulsion for long distance travel (2020).
In 2025 construction of the Space Elevator is completed and shortly thereafter, a space station in the vicinity of the Space Elevator is constructed for scientific research.
NASA has the intention to make several visits to Mars in the near future and has been developing a solid state aircraft during the past decade. This spacecraft makes its first flight here on Earth in 2025 and is ready for unmanned exploration of Mars. NASA has essentially abandoned its lunar "practice base" in favor of devoting more time and effort to a manned presence on the Martian surface. The lunar base is now "run" by the Japanese Aerospace Exploration Agency (JAXA), which was NASA's partner during the lunar base's construction phase.
In the next 5 years, NASA assembles a nuclear propulsion craft that carries a solid state aircraft to Mars. All parts are transported to the space station via the Space Elevator (where they are assembled). NASA sends its solid state aircraft to cruise in the thin Martian atmosphere and to explore the surface of Mars in 2030. The solid state aircraft's mission is to monitor atmospheric conditions on Mars as well as to pick several favorable landing sites for a manned Mars mission. The solid state aircraft is more useful than a satellite (to monitor local conditions) because it is

capable of providing better and more reliable high definition images and video footage of very specific regions of interest. Since the Martian surface represents that of a desert, NASA has been training its astronauts in the deserts of Arizona as well as on the moon.
The first manned mission to Mars occurs in 2035. The next ten missions to Mars are strictly scientific. Nuclear propulsion and solid state aircraft become the standard means of carrying out NASA exploration of other moons, planetoids, and planets in our solar system suitable for "flying" probes. Satellites and landers remain the norm for exploring those without a gaseous atmosphere.

Likelihood: Select

Comments:

4. Timeline:

2010 – Aerogel becomes the new standard for spacecraft insulation / protection
2015 – Reusable Single Stage to Orbit (ReSSTO) spacecraft becomes available for use
2020 – ReSSTO spacecraft are modified to create Low Earth Orbit (LEO) Compressed Air Collector (CAC)
2025 – Ram Accelerator is developed to by the United States Air Force (USAF) to re-supply ReSSTO spacecraft / NASA uses refueled ReSSTO spacecraft for scientific lunar missions
2030 – ReSSTO bomber spacecraft is developed by USAF
2035 – Cold plasma is developed by USAF

This scenario begins with the full scale production and use of Aerogel in all spacecraft applications. Its ability to protect surfaces from the extreme heat of re-entry is invaluable and by 2015 allows for the first Reusable Single Stage to Orbit (ReSSTO) craft to become viable. Aerogel's ability to prevent wear and tear to ReSSTO craft directly relates to the extremely low levels of maintenance required to keep a reusable spacecraft in service. The low levels of maintenance result in a great decline in the cost of launching the craft (with payloads) into orbit. NASA completes develops a new space station in 2015 with extensive assistance (funding) from the United States Air Force Space Command (AFSPC). In order to provide a reliable life support system for long-term inhabitants, NASA develops a ReSSTO spacecraft specifically for the purpose of descending into the upper atmosphere of Earth to collect compressed air, some of which will be used directly on the space station, but most of which will be processed aboard a space platform nearby the space station to produce liquid oxygen to use in refueling spacecraft in orbit. This Low Earth Orbit Compressed Air Collector (LEOCAC) is put into use in 2020.
The flexibility of ReSSTO spacecraft to perform various duties becomes evident to the United States Air Force. They envision a ReSSTO "bomber" that can take off from the United States, rendezvous with the space station for refueling and descend back to Earth to drop GPS (global positioning satellite) guided munitions on to targets in a matter of hours anywhere in the world. After dropping its payload, the spacecraft will execute a burn back to LEO where it will then

descend back through the atmosphere to land at a designated USAF base.
In order to make this a reality, the USAF develops the Ram Accelerator in 2025 to propel rocket fuel into orbit to be picked up and stored at a specially designed fueling station attached to NASA's new space station. The ReSSTO bomber is completed and put into service in 2030. This marks a major acceleration of the weaponization of space to the point that it is called the Second Space Race. Other countries, namely China, seek to create satellite destroying weaponry to combat the United States' space superiority. As a counteraction the USAF develops cold plasma in 2035. Cold plasma is a defensive mechanism that can be applied to key satellites and spacecraft to make them virtually "invisible" in space, therefore nearly impossible to track or target with weapons. The refueling platform for the ReSSTO bomber is so inviting a target that defensive measures become a matter of great concern. Cold plasma provides the means to "hide" the space station and refueling platforms from enemy detection. The USAF is able to track the position of the platforms from knowledge of orbital mechanics. In order to increase the difficulty of detection, the space station and refueling platforms are able to make slight impulsive modifications to change their orbits.

Likelihood: Select

Comments:

5. Timeline:

2015 – Reusable Single Stage to Orbit (ReSSTO) spacecraft developed
2020 – Ram Accelerator developed
2025 – Solar sail spacecraft successfully tested
2035 – Solar sail / ion drive spacecraft developed for solar system exploration

After declaring the International Space Station a failure due to extensive maintenance problems and lack of overall commercial interest (as well as being in the wrong orbit to use for departure to the Moon or Mars), NASA turns its attention to solar system exploration and other long duration space missions. Seeking an alternative means to moving cargo into orbit the Ram Accelerator is put into development.
By 2015 the first ReSSTO spacecraft are developed in order to take personnel to and from the space station where microgravity experiments are conducted. NASA finishes work on the Ram Accelerator in 2020 and conducts test launches over the next decade. Research on the capabilities of solar sails comes to fruition in 2025. The massive Ram Accelerator is used to fire sections of solar sail spacecraft into orbit where they are assembled and undergo extensive testing and analysis.
The solar sail appears to hold a great potential for solar system exploration, however due to its operational parameters, it is only able to travel outward from the sun. In order to have a manned spacecraft with the potential to move inward and outward throughout the solar system, NASA couples ion drive technology (currently available as a viable propulsion method) with the solar

sail. One or both drives can be utilized in outward solar system travel. When the spacecraft needs to return inward, the solar sail can be retracted while the ion drive continues to accelerate the spacecraft to its destination.
The final solar sail / ion drive spacecraft is completed (2035). It is assembled in space by launching the component pieces into orbit via the ram accelerator. Personnel required to assemble the spacecraft are taken into orbit aboard ReSSTO spacecraft and are housed in a small space station until construction of the spacecraft is completed. For the next 20 years NASA uses, and continues to build more of these multiple drive spacecraft for solar system exploration.

Likelihood: Select

Comments:

6. Timeline:

2015 – Reusable Single Stage to Orbit (ReSSTO) spacecraft becomes available for use
2018 – Mining corporations begin to set up small lunar habitats for helium-3 extraction
2025 – Fusion reactors are developed
2028 – NASA / US fusion power corporations team up
2035 – Roving lunar bases constructed on lunar surface
2038 – Bionic leaf developed

Reusable Single Stage to Orbit spacecraft are put into use by NASA in 2015 to replace the aging transfer vehicle space shuttle for scientific research operations. Meanwhile, back on Earth, nuclear engineers are on the verge of a breakthrough in fusion power utilizing helium-3 as the fuel source. Energy corporations realize the potential close at hand and begin planning for full scale fusion power production. The first obstacle to overcome is reliable sources of deuterium and helium-3. The lunar surface presents itself as a mining location if the proper facilities can be developed on the Moon.
These corporations invest in ReSSTO spacecraft and start training personnel to begin setting up small lunar operations. ReSSTO spacecraft are flown from the Earth (refueled in Low Earth Orbit) to the Moon where they land on the lunar surface to unload personnel and cargo and then make a return trip to Earth. The first habitats and small mining operations begin in 2018. These modest operations consist of a small lunar habitat housing 8-10 people. The purpose of these habitats is to set the stage for a manned lunar presence for operations to come.
After operating like a mining town for a decade on the Moon, NASA approaches energy corporations with a bold plan. Its scientists and administration want to develop a self-sustaining "Homestead" colony of humans who actually live on as well as work on the Moon. NASA cannot afford the combination of facilities required to build such a "space town," much less a city, but energy corporations can invest at this level. These energy corporations would then have a labor force that is fully acclimated to the Moon (and couldn't come home due to long term exposure to lunar gravity) but had to be supported during the construction phase and would be

able to survive any foreseeable interruptions in supply. The collaboration begins in 2028.
NASA sees itself as a partner with several American energy corporations involved in lunar activity and uses its knowledgeable staff to begin developing the key components necessary to support a lunar colony. In essence NASA spins off a highly specialized engineering company, called Lunahab, to aid the work force of the lunar energy corporations mining helium-3 and oxygen on the moon.
In order to help make the lunar colonies self sustaining, NASA organizes the transportation of liquid hydrogen and carbon to the Moon for processing (to develop water) as well as delivering compressed air gathered from the upper atmosphere until a self-sustaining lunar alternative is available.
With NASA's expert help, US fusion power corporations complete construction of larger lunar habitats as well as roving lunar bases by 2035. Up to 50 people are on board the roving lunar bases mining Helium-3 at any one time. After completing an "Earth-day's work" small lunar rovers (similar to vans capable of carrying about 8 people) transport new mining personnel to the roving lunar mining base as well as pick up personnel who have completed their shifts for transport back to the main lunar habitat.
Persistent work at NASA leads to the development of the bionic leaf in 2038. The bionic leaf enables lunar colonies to make a major leap toward self sustainability. Bionic leaves can be placed atop lunar structures (that can be underground, or set up in a greenhouse type of building) where they use sunlight and carbon dioxide in order to produce breathable oxygen. Food facilities also exist where bionic leaves function in a similar manner except that in addition to the oxygen produced, the carbohydrate byproduct is fed directly into tubers (such as potatoes) and fruits in order to produce a self-sustaining lunar food supply. Food is still shipped from the Earth, but Earth-produced food is seen as a luxury item (meats, complex vegetables, etc.).
By 2040 over 500 people are living on the moon in various lunar colonies of 150-200 people. Much like any newly colonized region, the population continues to grow as current residents reproduce and residents of Earth decide to seek a lunar lifestyle.

Likelihood: Select

Comments:

Which of these scenarios would you like to see happen most? Include any comments about the scenarios.

A.3 NIAC Comments

Nuclear Drive

-Using provided nanoparicles to carry away heat or synthetic vibrational structures to absorb and radiate are possible ideas. The point is the science and technology are there or close, it is only an application of them to this particular problem that is required.

-This would be useful to many space applications, not just propulsion

-Works in principle, but big hurdles to jump over.

-I think political issues are the most pressing.

-Firstly, I am framing my answers in the light of personal experience in space nuclear engineering. I believe the significance of a conventional nuclear drive that you have described is moderately important technologically. The social stigma surrounding nuclear propulsion from conventional to advanced to exotic, needs to be addressed through reasonable means including education and leadership from both the scientific and political communities. If we consider the work historically, nuclear rockets and nuclear propulsion are not new ideas. One of the most intense and scientifically rigorous programs was Project Orion. The concept utilized a pulse unit for the 10-m diameter Orion vehicle and included a yield of 1-kt. The pulse unit weighed 311 pounds and was designed to provide between 2000 and 3000 charges for a voyage to Mars. Much of the work was based on the early Sherwood machines. Other projects of the period (1955 to 1973) included Project Rover which consolidated efforts from Livermore and Los Alamos and was conceptualized to use a reactor to heat hydrogen and expel the gas at a high velocity. The other project NERVA or Nuclear Energy for Rocket Vehicle Applications continued until 1973. During the 1970s significant efforts modeling ionic and magnetohydrodynamic (MHD) systems created a new foundation for advancement of codes to predict field, material and particle interactions. Other concepts that utilize nuclear drive from a simple mass driver to ion engines are numerous. One last comment: During the SP-100 era (US space power nuclear fast reactor) several discussions rendered new ideas for using sodium reactors for earth-based launch systems. Sodium reactors are required to be frozen for transport and would pose less of a risk in a launch failure than a conventional fast or water reactor. However, there are substantial issues in thawing sodium once in space. The other issue of assembling a nuclear reactor in orbit for use as a propulsion system does not preclude the need to launch special nuclear or fissile materials. In the mid-1980s (pre-Challenger) the US Air Force completed a study for the SP-100 reactor launch using the US STS shuttle with an estimated launch failure of 1 in 50. Discussions included US Navy data on submersion of nuclear reactors in salt water and containment of contaminants. The following year the Challenger demonstrated 1 failure in 25 launches. This put a real ketch in the SP-100 reactor program. A resource I suggest you may consider in the Space Nuclear Power Institute at the University of New Mexico. They have a unique experience in space nuclear power and nuclear drive systems. UNM has worked with Los Alamos, Sandia, Defense Nuclear Agency, NASA, DARPA, and Oakridge for years. They have with their partners at the national labs addressed through several engineering and design inventions many space reactor safety concerns. TIME PERIOD: Most importantly my choice for identifying a more near term potential for a functional space nuclear drive is based on some of the examples I have listed above, but also nearly two decades of experience. If there is the will and the funding, a nuclear drive is available within a few years (by 2015). We have the expertise. The science is established. Recent advances in materials and cooling technologies provide the technology to construct a nuclear propulsion system that could take us to Mars and beyond. In my opinion it is more a matter of leadership, not science and not technology.

-This seems like an evolutionary change of existing technologies rather than a radically novel, breaktrhough idea.

-You seem to misunderstand the operation of a nuclear thermal system, which requires no radiators; it is cooled by the propellant. Nuclear electric systems are radiator-limited in thrust/weight but workable with existing technology. Either could be operational in <10 years given a real mission need (such as a serious Mars exploration program) and either a shift in public attitudes to nuclear power or an overriding political need for a major space advance (such as a competition with China). Nuclear systems are almost certainly the only serious options for near term human missions beyond the Moon.

-Advanced radiators are only needed for NEP because it puts about 15% of the energy into power; NTR does not require radiators as it puts 95% of the energy into the thrust. NTR does not need a major advance and would be available in the early period.

-Safety and politics (non-technical issues) will slow it down. A lot was already demonstrated on NERVA in the '60s.

-Technical hurdles for reasonable performance have already been overcome. Increasing space travel incentives and earth based use of alternatives to fossil fuel energy will help overcome political and social barriers.

-Presently there is no reason why Nuclear drives cannot be made today. High temperature radiators, which is what I think you are talking about are mainly a material issue. The statement above is not correct. No particles are needed for radiation heat transfer in space. So I'm not sure what the particle comments were about. Also most nuclear drive designs would use hydrogen or

some other gas as the propellent and you would definately not use a water based steam reactor in space to generate electricity. There are many solid state technologies that could be used, thermoelectrics, thermeonics or thermal photovoltaics are examples.
-Like all research, the timing depends on how much funding is provided.

Magbeam

-Speed is most important for manned missions. For small versitile and less expensive probes, the magbeam is arguably not critical. Cant see the funding for this type of expensive solution in comparison to other types of missions.
-This may be difficult in the short term due to implementing the different acceleration/deceleration stations. Also, how quickly would this go through fuel? How does the power source stay stationary with such impulse?
-The magbeam satellite is the greatest stumbling block.
-My answers are based on cost and problems in maintaining station holding for platforms/vehicles and provide for complex targeting modes. Why not use an asteroid cycler system?
-The ability to apply this technology to things other than propulsion could accelerate and facilitate its development.
-Prof. Winglee is the inventor and sole major proponent of Magbeam. He is not a space systems engineer, and his plasma physics expertise is from geophysics. The Magbeam concept may not work at all (I'm personally skeptical); if it does, it has only modest advantages and several major disadvantages relative to laser or particle beam propulsion -- in particular, it absolutely requires a

space-based beam source, which would be much more expensive in the near term than a ground-based laser source. The M2P2 plasma sail (Prof. Winglee's entry into the space propulsion field) is an elegant concept; the MagBeam is a handful of optimistic viewgraphs.

Note that a more general item (some form of beamed-energy or beamed-momentum propulsion in space) would be a 4 or 5 in significance, a 4 in likelihood, and "middle" time period; the most likely and nearest-term version is a laser-electric or pulsed laser-thermal space propulsion system for cislunar propulsion.

-a focused beam of plasma is a very hard problem to generate with the currents needed to produce any real thrust. Divergence of the beam means you can only accelrate a short time before the craft is too far away. To get enough accelration in that short time means very large current in the beam.

-Current research by Winglee's colleagues suggest that the approach is more difficult than had been hoped.

-I have serious questions about the ultimate viability and potential benefits of this concept and see it incurring significant losses in conversion at the orbiting station, during beam transit, and at the travelling spacecraft that imply large design penalties compared to other alternatives.

-The main issues with this concept are providing sufficient power to run the beam generator and focusing the beam. The beam focusing may not be achievable to a level that would enable reasonable power system size. Also you menation using a plasm beam, which requires mass. Replenishing this mass will also be an issue. Using a laser, which won't required a mass source has also been proposed but this also suffers from the same concerns.

Slingatron

-The Slingatron is a very clever idea and an engineering nightmare. For ground-to-orbit launch, it has all the disadvantages of a "cannon" launcher (electromagnetic or gas gun) plus requiring payloads to take very large sideways acceleration loads for much longer than the in-line loads of a cannon. For in-space use, a Slingatron has no advantages and great disadvantages relative to a "flinger" -- a short rotating tether.

-The gravity loads are high so that any instabilities with cause catastrophic stresses on the system. Also, some past ideas have used chemical propulsion to get the system spinning so that no savings are incurred.

-There are many similar approaches, and all of them suffer from the high Gs. Saying "launching fuel and supplies" seems to make sense at first, but one has to realize that the subsystems (computers, sensors, actuators) that go along with the actual fuel and actual supplies must survive those enormous loads as well. There is also an issue of aerothermal heating as the projectile encounters the atmosphere, which people generally forget. All sorts of other non-ballistic and non-rigid dynamics issues arise for projectiles that are macroscopic or deviate from a ball bearing in other important ways.

-Parasitic energy requirements and momentum considerations as well as scaling in structural loads make this really doubtful in my mind.

-This concept is similar in operation to a mass driver or rail gun. I believe those other concepts are easier to implement and provide the same benefits. So if the acceleration and aerodynamic heating issues can be solved those other acceleration technologies would be used instead of this one.

Solar Sail

-Comments: If this is traveling in the inner solar system, what about particulates degrading the sail material over time?

-Again, the energy numbers have to be worked out to be feasible for even a modest mass of payload.

-This will probably be demonstrated in the near term though large scale use will likely be limited due to the low thrust levels. However, if a high temperature solar sail material is developed, an interstellar precursor mission might become practical.

-The significance of the solar sail isnt necessarily the technology, but the ability to engineer and construct lightweight propulsion systems that are reliable and inexpensive is extremely important. It provides access to interplanetary transport of robotic systems that otherwise would be overlooked or too costly. In terms of human transport for the near term 2020-2035 solar sails would need to be created as active systems and provide adaptable geometries. I believe it is more likely to be used for unmanned supply missions. Also in the near term multifunctional solar sails may be used to support communications nodes and navigational beacons.

-You are conflating three concepts: 1) conventional solar sails, either metal or carbon, usable for very-low-acceleration interplanetary travel in the inner solar system, which are near-term but of low significance given workable solar-electric propulsion. 2) High-temperature carbon-fiber sails suitable for "sundiver" missions with maximum velocities of order 70 km/s, suitable for cheap outer-planet or Kuiper-belt missions, of moderate significance in the mid-term, and 3) Relativistic laser- or microwave-driven sails which are highly significant -- enabling technology for interstellar travel -- but probably farther away in time than even your "late" category.

-This sounds good but the specific weight of the just the sail must be improved just to have enough thrust to move the sail. Very little payload capability. Also, it is only good for flybys

-I'm sure solar sails will be demonstrated successfully, but their usefulness is extremely limited for large spacecraft.

-Although too slow for human transport, this technology provides a viable path to large mass transfers between planetary orbits essential for a solar system commerce web. An investment in infrastructure can really be made to pay off here.

-Solar sail technology is pretty much at hand. The low acceleration and required sail size will limit its use however.

Laser Propultion

-The development of such a laser would have to be a federally funded project. Most commercial laser development is in the opposite direction small, less expensive, solid-state, narrowband etc

-The energy involved must be transferred efficiently without destroying the laser.

-Once again the time period is considered somewhat arbitrary not due to the actual scientific requirements or technology but due to the need to have the political support. Remember contractors can easily provide chemical rockets that are reliable. Contractors hate hard work and they like easy money.

-You haven't done your homework. Your "breakthrough" has already occurred.

Heat-exchanger (HX) laser propulsion using modular laser arrays requires no breakthroughs in laser or vehicle technology. See Kare, Jordin, "Modular Laser Launch Architecture" on the

NIAC web site. Since that report, at least one suitable laser has become available literally off-the-shelf. All R&D for a laser launch system could be done in well under 10 years for ~$200 million; an operational launcher could be deployed before 2020. The only obstacle is that there is currently no market for high volume launch that justifies commercial investment, and, so far, no budgetary niche at NASA or DoD that laser launch fits into. (Leik Myrabo's scheme (the "Lightcraft") does not use double-pulse ablation; that was the approach pursued by the SDIO Laser Propulsion Program in the 1980's. The "water sponge" is primarily a Japanese concept; the SDIO program used a solid propellant block both in and out of the atmosphere. All such pulsed propulsion schemes are well suited to in-space propulsion in your "Early" or "middle" time periods, but are unlikely to be the best option for ground-to-space launch before 2035, again barring a laser breakthrough or a national-scale mission requirement, such as nuclear waste disposal in space.)

-Thge laser powers required to lift any real mass are phenomenal. The power densities are huge. The main problem though is that orbital velocity is azimuthal and the laser does not provide that. Thus, a propulsion stage must be part of the payload to get into orbit reducing the gain realized by this idea.

-The primary issue is pointing the laser precisely enough across large distances. If I understand correctly, that difficuly prevented the Lightcraft from rising more than a few hundred yards at White Sands.

-I doubt that the use of reaction mass with this technology will provide a high enough ISP to realy make the use of off-board power pay off appreciably.

-The issues I see here are in the laser focusing and the power required. To apply this system to anything beyond very lightweigt craft I see as being very difficult. From just an energy balance point of view the amount of power needed to be transmitted by the laser to accelerate a heavy vehicle would be very difficult to gnerate and control.

Mass Driver

-Seems feasible to me. Just doesnt have an application right now.

-This is the best method from low earth orbit, coupled with the proper power source. Reusable and few consumables.

-Large nuclear power plants in space will cause real safety problems. Lots of solar cells are required to generate the energy to launch very modest payloads.

-If you have a sufficient infrastructure where lunar source payloads would be useful, you probably wouldnt bother with a mass driver.

-I would be surprised if the mass driver ever exceeded the experimental stage.

-First, a slight variant of the mass driver (usually known as a coilgun) is perfectly usable for ground to orbit launch. Second, mass drivers used for spacecraft propulsion (i.e. as reaction engines) do indeed require "fuel" (propellant), though it can potentially be any available mass. Third, the most commonly cited mass driver use -- launching construction material or oxygen from the Moon -- can be done more cheaply and easily with other technologies. However, the technology is likely to be developed because it is closely related to other electromagnetic technologies (e.g., MagLev trains) and has a wide range of applications.

-This ocncept needs a siginficant infrastructure present in Cis-lunar space to justify the expense and to enable its construction. It is not suitable for exploration but may be very good for continuous operations

-There are many similar approaches, and all of them suffer from the high Gs. Saying "launching fuel and supplies" seems to make sense at first, but one has to realize that the subsystems (computers, sensors, actuators) that go along with the actual fuel and actual supplies must survive those enormous loads as well. There is also an issue of induced electric currents (by interaction with magnetic fields) in the onboard electronics or other conductors, which people generally forget. So, known electronics are likely precluded from use in such a device. All sorts of other non-ballistic and non-rigid dynamics issues arise for projectiles that are macroscopic or deviate from a ball bearing in other important ways.

-Possible significance is limited by the fact that the accelerated mass must usually include a more conventional propulsion system for deceleration at the other end of the trip and limitation to vacuum environments. This makes required investment for system development unlikely despite technical feasibility given enough resources.

-Electromagnetic acceleration is a really good idea. If the track is made long enough, to reduce the acceleration load, and using the electromagnetic accelerator as the first stage and a conventioal rocket as the second stage it would be possible to use this type of system for human flight as well as cargo. I would expect to see an electromagnetic drive system implemented as a means of reducing launch costs at some point in the relatively near future.

Ion Drive

-Hybrid systems are a great way to go, but the severe constaints of weight etc., may mke this a very challenging engineering problem.

-Comments: This can still be used for appropriate missions, but would coupling it with another propulsion source be efficient?

-Low thrust and high power requirements will limit its ultimate utility.

-The technology as a unitary concept will be used without a doubt. However the lessons learned from beam dynamics and control for interplanetary space flight will be much more significant than the ion engines themselves. Both cesium and xenon are excellent ion sources. Since the current ion engines resemble TV electron guns the technology is simple enough to be reproduced and maintained on a significant scale. The ion beam geometry and improvement in power sources are areas that require much more work to create a large enough engine to propel exploration class spacecraft. The existing ion engines will be with us for many years to come and with enough innovation may be our means or reaching the outer solar system with humans by the end of the century.

-Ion drives (more generally, electric propulsion) is a large and fairly mature field; there are (probably) no breakthroughs left in the propulsion area itself. Efficiencies are around 50% and cannot be >100%; lifetimes are already too long to easily test (>>1 year). Wider use of ion propulsion depends on developments in power sources (especially nuclear-electric or laser-electric power) and straightforward engineering development of a wider variety of thrusters to cover a wider range of mission parameters. My evaluation is specific to your suggested "breakthrough" of faster acceleration (without correspondingly greater propellant and/or energy consumption) I could either put "small significance" and "likely/Early" (for routine development) or "major significance" and "impossible/never" for radical improvements.

-First, the ion drive is very inefficient not very efficient. The system will put 15-20% of the energy generated by any power source into thrust. The claim of efficiency is that it has a high

Isp which is not an efficiency measure. The mass flow in the ion ndrive would have to be increased by about 100-1000 to make it attractive.
-It's already demonstrated, although the first successful spacecraft was actually a commercial satellite (by Hughes), not Deep Space 1.

The general principle that you get high Isp only at the cost of low thrust can change only after a revolution in power systems. The propulsion technology itself is well understood but not the hard part.
-Ion engines are here to stay. They will continue to find use in space flight and there will be continual improvement in their performance.

ReSSTO

-This requires several breakthroughs but would be revolutionary for space travel.
-Comments: Since I have a personal interest in this area and have worked on hypersonic systems for more than 13 years, I have to believe that this is the one element to launching vehicles from earth to space that will make it possible to move our civilization to other planets. SSTO vehicles will reduce the cost and increase the availability to launch humans and materiel.
-Your "breakthrough" does not make sense. SSTO vehicles have never been intended to go beyond LEO as their primary mission, although a few designs have offered, as a bonus, the possibility of refueling on-orbit and going on to Lunar orbit or Lunar landing. In general, it's far more efficient to use an SSTO to take payloads to LEO, and a separate orbital transfer vehicle to move them onward from there. The problem with SSTO's is that, whether or not they are

refueled in orbit, they have terrible payload fractions and extremely tight design margins, and are thus expensive and risky to develop, and may be expensive to operate and maintain. Note that this evaluation is specifically for refueling in orbit. Development of a workable, reliable SSTO is significance 6 and likelyhood 3 - 4.

-This is a risky approach but would be good if proven reliable.

An alternative that may be considered by non-US countries is to use a solid core NTR to launch from the Earth. It can do the SSTO mission with slightly extended technology.

-This principle (absent the unncessary ram accelerator) is at the heart of many space-exploration architectures, including NASA's current Vision for Space Exploration.

-As I mentioned previously using an electromagnetic, rail accelerator in conjunction with a single stage vehicle could provide a cost effective launch system. If the rail is long enough the acclerataion rate can be kept low enough to enable it to be used for manned flight.

Ram Accelerator

-I am not sure that there is any advantage to this launch concept vs. conventional systems.

-Super guns are not new. The Paris Gun launched projectiles more than 81 miles. It is an efficient means of moving a mass. The Canadian firm Space Systems designed several gun launch systems.

-Does not seem like a particularly visionary/breakthrough idea.

-The ram accelerator is one of the more elegant "cannon" launch concepts, with the same advantages and disadvantages. The main advantage -- low cost per launch -- is in practice almost impossible to realize because of the need (in *all* cannon launchers) for a "circularization stage" -- a substantial rocket motor, and associated control system, which must withstand the launch acceleration. Other disadvantages of cannons include the limited payloads, limited orbit flexibility, high development risk, catastrophic failure modes, and uncertain operating costs; the ram accelerator is among the better cannons on most of these, but may not be able to reach sufficiently high velocities for a useful launcher.

-keeping the ship off of the walls; 30,000 gees!!. can a propulsion unit needed to go into orbit survive the gee load.

-The big gun idea has been around for a long time, but its weaknesses are the same as every other concept for high-impulse forces for launching from Earth.

-The advantage of this technology is primarily in launching large masses of bulk material (maybe suitable for some off-world scenarios) - few technological products are suited for 30000 G's, but the place where it would be used over alternative means is on Earth's surface (1 atm. pressure) - a fundamental mismatch between the technology and the needed capability.

-Again I think the electromagnetic rail lauch system has the same capabilities but enables more control and is easier to construct.

Space Elevator

-Very, very complicatedâ€"space environment issues, large amount of area to control. Ribbons and tethers have been difficult to get to perform to design.

-Safety issues with the ribbon breaking and falling to the earth will be a major impediment.

-Radiation belt transit a problem

-The Bradley-type space elevator is another elegant concept developed by a physicist with no aerospace or systems engineering experience. Even if the required material strength is achieved, Edwards underestimates both the cost and time required to develop and deploy a workable elevator, and overestimates the benefits. A space elevator might well be the ultimate solution to Earth-to-space transport in the post-2050 era, when there is a robust space economy that can benefit from a much heavier-duty elevator lifting and lowering 100- or 1000-ton payloads, and that can justify investing $30 - 100 billion in building it; it is extremely unlikely to be practical, or even possible, to build before 2035, or to compete with conventional or other advanced launch systems in the absence of large-scale space industry.

-Operational issues. What if the ribbon breaks? is the cost to replace it the same.

It is a good terrorist target too.

-Great concept, as are most from the golden age of science fiction, but the devil is in the details. One has to get past the simplistic (planar, rigid) version to understand how hard it is to manage the dynamics of a tether that long.

-The material issues are a major concern. Also there has to be some means of powering the vehicle so it can climb the line. Some type of power beaming will probably be required.

Memory Plastics

-Advances in our ability to design distributed, self-organizing systems will need to proceed hand-in-hand with the chemical/material elements of this research

-A nice technology with only small importance for space.

Carbon Nanotube

-While it is still unclear whether a 60,000mi nanotube ribbon will ever be feasible, it is likely that this material will lead to many novel applications, including applications in space.

-This could also be "Revolutionary/Likely". Nanotubes are clearly a major advance in materials, and will find a wide range of space applications; how important they will end up being in 20 years or more is anyone's guess. They could be as important as silicon transistors (=>IC's => personal computers) or as interesting-but-not-revolutionary as high temperature superconductors or diamond films.

-resistance to the space environment must be part of the development

-This technology will change engineering forever. I think it will be as important to 21st century as the transistor was to the 20th century.

-There are numerous applications of carbon fibers. And because of this there is significant development work going on. Because of this I beleive they will eventually come into use. However, weather they can meet their expectations is yet to be seen.

Solid State Aircraft

-This is a niche technology for space -- a new option for some uses, but not likely to improve more than incrementally on existing tech in most applications. Seems more likely to be significant in terrestrial robotics.

-this is an exciting development

-Aircraft as currently built are pretty efficient. Nothing I've seen regarding flapping-wing aircraft suggests they will represent enough value to convince anyone to adopt the risk and cost.

-Although feasible, this development is applicable and effective in few space environments. It does however represent a broader class of active materials based designs that in their totality will be highly significant and virtually certain in the long run.

-All of the component technologies exhist. However, the integration and controls needed will take significant development.

Electromagnetic Shielding

-This is a sound idea the science and technology are there or close supeconducting magnet technology are other advances in magnetization could help.

-This technology would benefit greatly from things like the mass driver, but will likely come much later.

-Compare system mass to mass of traditional shielding Also, consider failure modes relative to just bringing dead mass along.

-Vann de Graff systems are routinely used in conjunction with beam lines to deflect, reflect and refract particles and radiation. Work completed at Tullahoma in the 1970s provided considerable information on field coupling and induction in shielding. Many MHD and plasma/fusion containment systems utilize fields for confinement and to delay or eliminate parametric decay of heavy particle flows in plasmas. So the science is not in dispute. However, the problems arise when you actually attempt to integrate multipole electrostatic radiation shielding spheres These integration issues include field interaction with human physiology, spacecraft structures and reduction in the type of sensor systems that could still be effective for a vehicle utilizing a van de Graff shield. Simply the atomic degradation to ferrous alloy fasteners and electrical components could be catastrophic if not mitigated through some other means. During the National Aerospace Plane (NASP) X-30 program the air force found they could reduce some elements of drag by inducing fields or enhancing fields around the vehicle however they also recognized problems with damage to fasteners and certain bearing surfaces. In terms of using electrostatic or electromagnetic fields for reentry cooling or shielding both the US and Russia has done so successfully within weapons programs. The US has for many years utilized microwave spikes to cool reentry vehicles. ARSI is using active cooling systems in spaceplane design and tests indicate that in combination with high-temperature coatings active cooling/drag reduction may be effective for many reentry applications.

-Even if this can be done, it seems that many practical issues will get in the way of its deployment, e.g., interference with on-board electronics, weight, impact on humans,

-Magnetic and electrostatic shielding are old ideas, simple in theory and very hard to implement in practice. They're mainly relevant for crewed missions, as it's probably easier to radiation-harden robotic missions than to use active shields, and if nuclear or other advanced propulsion systems are available, it may be easier to simply take shielding mass along. But, especially with new supercondutors and other new materials, EM radiation shields are worth continuing to investigate; maybe a good option will be found.

-Electrostatic fields n space tend to equilibrate around 25 KV. This is insufficient to stop much of the radiation. This technology needs a major power source. This may be heavy.

-The potentials of interest (100 MV+) in this project are simply unachievable for many reasons. My work involves potentials of up to 5MV in space, which are incredibly technically challenging. The problems here are legion.

-Electromagnetic sheilding is a good idea. One of the main concerns/ obsticles is providing the power needed to operate and maintain the shield.

Cold Plasma

-While difficult for space travel, this would be excellently tested and used at space stations.
-Seems to mainly be geared towards military applications
-Cold plasma is one of those things that if it were really available it could be a multifunctional system providing power, propulsion and radiation shielding. If only. TIME PERIOD: The eternal optimist in me prevents me from saying NEVER
-Additional idea of applicability beyond cloaking devices and other Star Trek-like visions will be necessary to drive this forward. Perhaps if we discover hostile alien life forms?
-I'm not familiar with this work, but based on a quick Google it seems to be just an effort to exploit a slightly-obscure corner of plasma physics. Cold plasmas in a slightly different form are perfectly well known, and commonly used to "absorb radar, microwave, or laser energy" -- they're called metals. There might be a pony in this pile, but I'd be surprised.
-The creation of a low mass power source has huge implications for all aspects of space exploration. While the cold plasma may be of little significance or use, the power source needs to be developed.
-Light weigh high energy density power systems are the holy grail for space exploration as well as many other fields. If developed this would only be one of many applications, both on and off Earth.

Aerogel

-Very important, but what about consumability?

-Aerogel is great. Used it in designs. Do not over look its application to propulsion systems and electronics, etc. It can be used in potting stuff as well. Do not get hung up on heat shield applications, there are so many more things.

-This seems like a fairly interesting idea with near-term opportunities.

-Hmm. I talked a reluctant AFRL into funding a study of aerogels for thermal protection a decade ago, though the results were largely ignored. I guess NASA has finally caught on, though I suspect your description of how NASA wants to use them is wrong. (Aerogels are rigid and rather fragile foams, just as Shuttle tiles are; they'd most likely be either part of a multilayer "skin" or form a rigid (but perhaps replaceable) outer skin by themselves. There are other "spray on ablative" thermal protection concepts, but I've never heard of those being based on aerogels. Aerogels are way cool materials, and a cheap way to make them would certainly open up a lot of possibilities for both Earth and space uses, but would only incrementally change the overall performance of spacecraft.

Incidentally, the lightest aerogels (Seagel) have a density of less than .001 g/cm^3 and are thus 99.9% air by volume; they can be evacuated and sealed and are then literally lighter than air -- they float up to the ceiling.

Fusion Reactors

-Maybe even later. The stakes are too high not to solve this one, but who knows when weâ€™ll be able to crack it.
-The tie-in with helium mining on the moon could make this a major driver in space exploration.
-Major research efforts are underway in fusion reactors and any successes can be applied to space applications. The issues are about sustaining the reaction process.
-Can't say never there are so many possibilities with new helical accelerators and coaxial superconductors. TIME PERIOD: Wish I knew I would be the richest person in the universe.
-Hopefully the collective minds of our scientific society can come up with better reasons for a lunar base than this...
-We're still decades from a commercially-viable D-T reactor. D-3He reactors may just barely be possible, but we have no idea how to actually build them. And contrary to claims, D-3He reactors will produce significant neutron flux from side reactions, so the advantage over D-T is limited. 3He fusion is not quite a scam, but it's definitely being pushed because it's a reason to go back to the moon, not because it's the best solution.
(It's of course possible that some breakthrough will happen, like R. Bussard's electrostatic-confinement fusion actually working, that would make D-3He fusion practical, but still not allow p-B11 fusion, which is even cleaner. But I wouldn't hold my breath.)
-very low concentration of He-3 on the Moon; difficulty in harvesting what is there; fusion- always 20 years away no matter when you ask.
-Fusion reactors have been consistenly been 50 years away. Eventually they will be developed.

Roving Lunar Base

-No need to make the miner habitable better to have many mining machines serviced by a single central human base.

-Cool idea. Modular is always good

-The idea of a lunar base that is modular and potentially mobile is useful, and it could significantly expand the horizon of possible activities that will make lunar colonization a reality. Still not convinced about the He-3 idea...

-Umm, we solved this problem on Earth (bulk resources not located near their processing plants) with a breakthrough technology called "railroads" A couple centuries later, we did find a situation where it was easier to move the mining and processing equipment to the resource; the result is called a "factory ship" A mobile base is probably silly; calling it a conceptual breakthrough is definitely silly.

-should be doable- again needs a power supply.

-This idea is one of probably hundreds of architectures. It's not obviously much better than other possibilities. Cost will primarily determine how Helium 3 is mined, if ever.

-This is only one system concept of many to solve a resource recovery challenge and it is not at all obvious that it will prove superior under extant conditions if and when the need is real.

-The big thing here is the fusion reactor. Assuming there are fusion reactors, gathering the fuel can be accomplished in a number of ways.

Bionic Leaf

-The implications of such a breakthrough on terraforming would be enormous.

-Even if this could be made to work, how would we be able to consume these plants of extract nutrients from them? If they require transport of large amounts of Carbon and Hydrogen, its hard to see that it would not be best to simply transport the needed nutrients instead. In general, however, the idea of finding plant life suitable for lunar agriculture seems very good.
-The key part of concepts like this is self-reproduction. If we can make lunar (or more generally, vacuum/hostile environment) plants grow and spread, even with a little help, it's a major breakthrough. If we have to build them, it's an incremental gain. This particular solution seems unlikely to me, but some kind of self-reproducing system (biological or inorganic or mixed) for space use seems quite likely before 2035.
-I'm not at all sure the specific implementation described is appropriate, but outgrowth of current artificial photosynthesis studies wit a comparable capability are likely and will be very significant for space settlement and development.
-Creating artifical self sustaining biological environments will be a key aspect to sucessful space exploration. Suffieient development will be put into place to make these happen when needed.

Gravity Implant

-Much research in neuroscience must be undertaken for this achievement. Possible, but much further down the road.
-Unethical
-No way. We have no clue how to interpret, let alone manipulate neural signals. Now you are talking about understanding an incredibly complex system that includes endocryne, neural, lymphatic, gastric, vascular, and other elements, which are tightly interconnected. No way. Lets

focus instead of finding a way of generating artificial gravity or at least figure out how much exposure to a simulated earth environment is needed to keep us in shape.

-Some version of this seems likely, unless some combination of telerobotics and large space industry (=> habitats big enough to rotate for artificial g) makes significant time in zero-g unnecessary. The significance of this particular "implant" is moderate -- except for severely mass-limited Mars missions, there's no sensible reason for astronauts to spend many months in continuous zero-g. But physiological control technologies in general are very significant to revolutionary, and very likely.

-The response by the body is more complicated than just bio-chemical in a region. The calcium uptake/loss question is also a problem. Not clear how the implant can handle all responses.

-Something like this will be needed, but it's not clear that this precise solution will be the ultimate choice

-Bioengineering will play a big role in space exploration.

LEO Compressed Air Collector

-Is this efficient/worthwhile due to transportation issues?

-I am not sure that the tradeoff with direct supply from the solid Earth favors the upper atmospheric collector.

-There are other ways to accomplish the same thing without depending on purely defined vehicles.

-Any major attempt to colonize the moon will require some way of solving this problem. How about a small pipe made of carbon nanotubes that can be used from an orbiting station in LOE to suck up air from the upper atmosphere?

-Back in silly territory. It takes the same energy to accelerate air from the upper atmosphere to orbital velocity (and then to the moon) as it does to lift them from the ground, to within a small factor (<1.5), and most of the mass you'd collect with this idea is nitrogen and oxygen -- nitrogen is of modest value, and there's already plenty of oxygen on the moon. Far better and easier (and probably cheaper and safer) to build a decent bulk launcher -- laser launcher, cannon, even big dumb booster -- and launch what you actually need.

-good idea if it can work. applicable for large infrastructure period not early exploration

-As space exploration increases, all sorts of vehicles will be developed to provide and process the materials needed to sustain people in space.

A.4 Student Comments

Nuke Drive

-This would have a great significance in going to planets within, but especially going outside the solar system. However it is unlikely that it would be easy to do so, since the primary method of disipitating heat is through radiation.

-Since the technology for this is already mostly present, and the design of the drive dating back around 30 years, as well as the fact that nuclear reactors themselves have been around for 50 years should have this drive be developed very soon.

- The main problem to be solved is to find a way to radiate heat that can provide very high temperature in space. Other wise the idea seems doable.

-Already have much of the technology required for this.

- funding will only come if a permanent nad large base is established in space

-dont think it is worth the effort

-Too Messy

-Relying on water vapor for thrust presents significant problems seeing as a large amount of water would have to be on board

-Environmentalists might not like this one at all. Radiation scares people, no matter where it is, or where it could be. This technology of heat-radiation might come in useful elswhere too though.

-Not Very dangerous, could be used f/ Earth

-The heat dissipation issue is key - nuclear drives could be developed for use within the atmosphere, but then the possibility of radiation leakage becomes the primary issue

-I can't see it being used to haul people anytime soon, but moving big payloads from LEO to Mars? Perhaps. Of course that raises the question of how you're going to get large chunks of uranium into LEO.

-These types of drives were prevalent and studied in the 60s/70s, so I would expect them to be viable very soon. However, I doubt their significance due to public opposition to nuclear technology.

Magbeam

-Such plasma technology in this kind of application is quite still in the early development stage, about the level of nuclear research in the 1950's, so there will be some time when this technology is developed, let alone pursued due to the high cost of such a system

- The drawback is only that it takes long(2.5 years), but its worth the effort. Using solar energy is quite useful also.

-Why invest in this?

-This would allow for cheap mass-transit to other systems, such as mars, more easily allowing colonization of other planets.

- technology is way to raw and expensive to merit the kind of research money for breakthroughs

- how to create such a energy force?

-Questionable technology. Hope the other end doesn't malfunction or they would be SOL! Looks cool though!

-More vehicle control would be nice

-faster & easier travel to mars, but only after we actually set to mars first

-If possible this would cut down on the engineering challenge fuel transport presents

-It would dramatically increase speeds, however the setup might take a while and be rather unwieldy for any exploratory work.

-Great idea, expensive to implement

-perhaps even later than 2050 - perhaps elaborate on the power requirements - seems like it would require a large amount of energ to power the beam

-Problems: aiming, power, fuel supply, and stabilizing the satellite (the whole conservation-of-momentum thing.)

-Seems very technically complicated, but definitely important if done.

Slingatron

-Simple yet effective. It would certainly reduce fuel costs

-The cost is very high and the profit not as high, although it can do good in making satellite relocation and launch more efficient

-What if we miss? Are all variable predictable?

-What the hell is wrong with rockets? Also, how much real-estate woud it take to build one of these devices? I mean, if one is going to launch a significant amount of anything into orbit, it is going to weight a lot. Thus, this thing is going to eat power, and with rising power costs (40%), SCREW THAT!

-THey are doing a feasibility study on this at the University of Dundee, I believe. It seems a little fantastic though.

-Also perhaps later than 2050. Design seems very difficult. I could see this technology being bypassed for simpler propulsion methods.

-Interesting, might work, sounds really inefficient.

-Seems rather feasable, but significance is limited by it only carrying cargo (and only very strong cargo) due to g-forces

Solar Sail

-I believe this is very likely. Carbon Fibers are getting longer and longer every year and have all the necessary properties for this mission.

-Since the idea has been around for a while, there seems to be plausiblity in the technology being pursued and applied, however, there is still doubts as to control such a vehicle and there are limits to how far you can travel

- I think the benefits of better/cheaper solar panels would be more than that of a solar sail

- depends upon discovery/development of other materials, however actual flights would require little energy. most of the energy is completely renewable.

- seems doable and efficient

-There have been some recent attempts at solar sails, but I believe that have all failed to deploy correctly and burned up.

-Cool business. Why are we launching this on a Ukranian rocket? C'mon America, where is our lust for global domination?

-Use is limited

-not enough force to actually push a legitamately large aircraft through space.

-This is highly subjectto breakthroughs which have not yet been made.

-It sounds like something Jules Verne would have loved. If it could be done however, the technology could be used in many ways, and as a more renewable source of energy, it would be interesting and exciting.

-The materials required for a good solar sail are already under investigation. The sail is reusable and drastically cuts the need for fuel. Both of these qualities make it a pretty good choice for certain types of missions. Much of our exploration will be within the inner solar system for a while to come, so that isn't too much of a down side.

-If it works at all, once built, it'll have to be the cheapest way to move small payloads around the solar system. A bit slow, though, and hard to set up initially.

-Significance is limited by how far its really viable; however, it does seem to be a very conceptually sound and straightforward idea.

Mass Driver

-Good Idea, however somewhat similar, but not as good as the slingatron

-Good, but requires significant amount of power

-fast space travel that is cheap

-Reduces the amount of mars/moon docking for cargo pickup, cutting down on fuel and time

-Most likely after 2050, but way before 'never.' Bases would have to be well established before building a mass driver. The lack of atmosphere and gravity will help all kinds of propulsion techniques, so as long as we have some minor developments in other areas this doesn't seem overly significant.

-There's a definite upper limit to how much stuff you want to be launching at one time with a system like this. And most payloads wouldn't enjoy the acceleration. But maybe it has a place in bulk transportation.

-Being only an orbital or lunar device, its somewhat limited in scope and time frame.

Ion Drive

-Too many limitations and problems with the idea

-Worth Further Study

-could be a stepping stone towards other innovations

-anything that is possible for small governments and large corporations is probably a good solution.

-This could be done, and seems reasonable. As long as the mechanism to kick-start the reaction does not get too heavy, this could becpme very interesting.

-Power shouldn't be too much of a problem when you're going that slowly. The bigger question is where the fuel's coming from.

-These drives already largely exist, and being highly efficient they hold key promise for eventual long-duration missions into space.

Laser Propulsion

-expensive

- would require a vast breakthrough in laser technology to be significantly beneficial, and additionally would require significant energy investments.

- not worth the energy

-Interesting concept, but the power requirements and advances needed in laser tech but it a while off

-It would take a nuclear reactor to run this. Three Mile Island anyone? Just kidding. This actually looks fun.

-What if somethign should block the beam?

-very dangerous but cheap and effective

-I am limited in my knowledge here and can make only small judgement. How much power would such a laser consume?

-It would be interesting, yet there might be better ways to do this.

-Needs mountain and insanely more powerful lasers.

-The power and optical requirements for a laser of significant magnitude for this application are very difficult problems to overcome. Other launch techniques will most likely proove easier and more efficient.

-The big question here is power -- where's it coming from, how efficient will the system be, and If it could be used for carrying humans it would be somewhat significant, but the laser technology may take some time to get up to speed to cause it to be viable.do you really want to be anywhere near a laser that powerful?

-Nice idea but not practical at all, the energy need to power such a laser would so extreme it would probably not be worth too much investment.

ReSSTO

-Slingatron is a slightly better idea

- most of the technology is already in place, however its use coupled with other breakthroughs would be beneficial.

-Technology = limiting factor. Ceramic technology isn't there yet. It might be doable though when stuff catches up.

-The best bet so far

-cheap entry into space, but much more research is needed to make it economically feasible

-Other options would be on SSTO that do not regulate refueling ot a non-refuelable ship and both are not likely or economicaly viable!

-Refueling in orbit sounds as though it could work, yet there must be more efficient and less fuel-consuming ways to do this.

-Dry mass ratio far too low for use, but it would be great.

-The hard part is refuelling. I would suggest removing the last sentence of the description paragraph above - I think it's the only technology so far that the survey has had an opinion on.

-A reusable SSTO vehicle will be made, sooner or later. Refueling in orbit is an interesting concept but shouldn't be too difficult, relatively speaking.

-Very important but unsure how likely. Fully reusable spacecraft would definitely be handy for the monetary/efficiency aspects of the space program

-Potentially important but seems very unlikely or would take lots of development

-It would be very efficent to refuel in orbit if it meant being able to use a resusable launch vehicle. As it is now, rockets are very expensive and require tremedous amounts of power, and this seems like a very nice alternitive to the issue.

Ram Accel.

-The idea seems good,perhaps better then the slingatron, atleast in terms of energy requirements.

-expensive

- this would allow for significant transport of materials to LEO, which would significnatly aid any spacial construction projects.

- it is on movie gettca isnt it?

-The need for some of these technologies to be build on, or in mountains makes them seem less feasible

-Why are we turning mountains into....CANNONS? WTF? Seizmically (sp), I am not sure this is a good idea. Crazy Germans! A while back, there was this guy who put a 2800lb artillery shell into orbit by firing a 16" Navy rifle (battleship gun) into space. It was built up of course and had to withstand a bigger powder charge, but it worked. The shell was last seen in the Mir space station! Just kidding, but didn't Mir die? Hmmm....

-Nice, but sounds more akin to weaponry than transportation

-very expensive, very dangerous, very improbable, no real use

-In conjuction with an SSTO, this would be a useful tool. Please see above for SSTO comments.

-The concept doesn't seem too bad, but the canister design will be a challenge. This would be helpful in support other types of missions.

-That's an awfully big "boom." I'm not sure what sort of material would survive 30,000 G's, and this is another launcher I don't think I'd want to be anywhere near. Furthermore, the payload would still need its own engines in order to get itself into orbit.

-Nice idea conceptually, but not worth it at all. The same objective could probably be achieved with a simplier device, or at worst case an electric rail gun, which would probably be more efficient uisng electricity rather than combustion

Space Elevator

-too time consuming

-late if ever

-much profit can result

- It might take quite a long time to actually get this all set .. because nanotaube polymer research will take a long time. But its likely to work very well

-where? too unpredictable i would think

- this would require other breakthroughs, however it could provide a possibility for cheap transport into space, as well as an effecient method of transport into space for fragile cargo.

- problem is only when we can mass produce materiel to make the ladder

-Just plain stupid! I'll give 10 bux to the first F-15 fighter jock, probably McCaan, who flies right through it and breaks this multi-billion dollar investment, nanotubes or not.

-Horriffically Impractical

-excellent in theory, but unlikely in reality

-stability of nanotube? Intersteller particles 1 week to move. 13 tons   I would need a 1 oz evidence if I could support it.

-economically not feasible

-Not useful on Earth. Very good idea for moon or mars

-The nanotube breakthrough could come relatively quickly. This would be a great help in supplying many types of other missions.

-I find the idea very interesting and important, but it seems that the process involved and the potential funding/cost concerns make it very unlikely to ever take place (and if it does, it will be quite far from now).

-Seems like way too many things can go wrong with this idea to have someone actually invest the time and money into building it.

Memory Plastic

-the material appears to be extremely heavy

-This certainly sounds like a logical next step for space suits.

- this would allow for self-repairable vehicles and increase the safety of being out in space, as well as having countless applications on earth.

-Sweet. They should make glasses for little kids with this stuff...DING!

-Nice idea, likelihood is up in the air

-easy to make, may be expensive, but safe transfer of materials

-Highly beneficial to long term space flight

-Would be extremely interestig to know more about these. Also for earth use.

-We can already do it with foam, why not plastic?

-Likely toward 2020. Having more reliable materials will mean that NASA is able to mitigate more risk, allowing them to run more aggressive missions. This would help speed our space development.

-While good for space habitats and bases, it strikes me that there are other limiting factors on lunar/space bases that are more important.

Carbon Nanotubes

-This is definitely one of those "amazing for the aerospace world" type things. Take it home, chew it, love it.

-Someday

-high strength-to-weight would help with SSTO vehicles, but seems kind of unlikely

-THese would be interesting to see, even if they might bot be used for what is predicted.

-Carbon nonotubes have seen fairly significant advances recently. Toward 2020 they should be well enough developed to start putting to use as materials upgrades in various applications. It will probably be an additional 10 - 20 years before new applications arise that are possible only with the use of nanotubes, such as the space elevator technology.

-Definitely important and quite a bit of research is being done, so probable as well.

-anyting that boasts a very high strength to weight ration like this does is very much worth looking into.

Solid State Aircraft

-everything needed in this project is already invented and since it useds light weight structures-looks promising

- I think the artificial muscle would be more significant

- the lack of mechanical moving parts is very significant regarding exploration of vastly unknown terrain and atmosphere.

-I havn't seen enough excitement about this technology, and as such I'm not sure what it would have in the way of funding. Since other flight technologies would still function in the environments under discussion, this tech is not essential and as such may take a while to develop fully.

-Could be a necessary invention for certain climate conditions in certain atmospheres. Also, if there are any local birds on other planets, we can trick them!

-Planetary surface scanning is somewhat limited in scope, and the technology seems very "out there" in terms of feasability.

Electro Mag Shielding

-high energy demands. requires either nuclear or hydrogen fusion technology.

-Interesting, and likely to be significant in the future, but not much so now.

-military implications...

- when we have enough energy to generate such shield we prolly would use it on other things first than shield

-They shoud surround cities with this to protect them against artillery. Let's see, Bahgdad might want to look into investing in one of these! If they can scale down nuke reactors, then they have this licked.

-Safety benefits should outweigh power needs

-very expensive, seems too good to be true

-This seems like a very possible solution

-Not our biggest problem at the moment, it would seem.

-We can do this now. We just need more power.

-I think that a spacecraft in the presence of a strong EM field would have problems with its electronics.

-For the moderate power applications, simply deflecting the radiation, this seems likely. Shielding technology such as this would remove the radiation risk for space travel, allowing NASA to remove risk and fly longer missions. Stopping physical material seems a long way off - significant advances in power generation would have to come first.

-Having a significant electric charge might cause difficulties with other shipboard systems. But, it might work anyway.

-Possibly significant for Mars missions or outside of the magnetic field of the Earth

Cold Plasma

-I don't see how it'd be efficient to keep a plasma around a spacecraft.

-This may come online far past the 'late' era. A shield invisable to radar and impervious to lasers would have immense significance here on earth, but would also be useful space. In the timeframe where this technology will be developed space will become a crowded place. Military applications for spacecraft will then be essential.

-Too pseudoscience-like

-Not only does this seem highly unlikely, but the only significance it would hold would be military. Until there are wars between nations that incorporate space (which is a long, long way off), this technology is pretty much insignificant.

- this, coupled with other shielding such as electromagnetic shielding, could potentially shield a spacecraft from any hostilities in space (such as a stray electromagnetic pulse from an unknown origin) aside from large masses, removing most of the risk to the spacecraft and its systems.

-Hot. I say there should be more funding for this. We can take on the Romulans!

-Power needs greatly outweigh defense capability

-very expensive, but extremely significant if created cheaply

-The implications of light weight energy source would solve many problems

-Sounds like something that would have interesting uses.

-Do we really need cloaking devices?

Aerogel

-the idea is valid, however would it help against EM and radiations?

- creating a mroe cost-effective form of this would allow for on-the-fly heat shielding, essentially removing the risk of heat damage.

-The expanding need is obvious.

-Better manufacturing methods will be found

-cheap, ligh, and strong. enough said

-This substance has already been created its productable need only be streamlined

-Would take some interesting manufacturing changes.

-As an improvement over current technology it seems this is not essential, but would certainly help. The fact that NASA has pegged it as a technology of choice will help a great deal to reduce development time.

-The standard ceramics or other methods of reentry seem more than sufficient, typically.

Fusion Reactor

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

-Still highly theoretical and experimental

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

- we almost there yahoo French

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

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

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

-It could happen.

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

Roving Lunar Base

-Overly fancy and seems prone to flaws.

-Seems like it would take much more energy to run this base than the extra helium it gathers would be able to produce.

-Seems to be too time and energy consuming, especially since helium technology is not developed yet. It may be easier to put up filters that collect and filter gases that are blased in the solar flair, and put up many filters around the lunar surface to continually filter and collect.

-Goes in hand with fusion reactors

-along with the breakthrough in fusion technology, this would effectively provide a means for gathering the much-needed He-3

-We went there with Apollo, what the hell is taking so long this time? This, this, this is BS! Just get some people up there already! I am getting tired of all these questions.

-The best means of harvesting

-reactor must be built on the moon -> expensive

-this technology is extremely possible. I do not consider it significant through because it hinges greater ease of travel and transport

-Scary thought.

-Fusion techniques need to be shown as profitable before anyone will set up a H-3 mining facility on the moon. This will happen, it is simply a matter of time. The steady supply of fuel that the moon will provide will give humanity the energy we need to continue our blinding pace of progress.

-A mobile base would necessarily be smaller, hence less well shielded from radiation and meteorites. It also takes more work, and it's more likely for something to break, if you're trying to move the entire base, rather than a small excursion vehicle. But maybe 3He will be the next gold rush...

Bionic Leaf

-The technology is very promising as it eliminates the need for high demanding plants and increases the productivity and efficiency of the produced food.

- the fact that we use elements such as Al in the bionic leaf seems frightening

-in addition to having numerous benefits in space related to life support, this would also allow for additional advantages on earth to food production and air cleanliness

-Let's get people up there first.

-Will become prerequisite for space travel

-Lower CO2 ____ in atmosphere, add oxygen to the atmosphere. sheap also

-Developing a plant like this would be immensely difficult, and the return may not be very great. A source of food on the moon would be helpful.

-It sounds like more work than it's worth, at least for now. I doubt that such a system could be an order of magnitude more efficient than natural leaves, and I doubt that it could easily fulfill all the functions of a natural leaf.

-Potentially important but seems very unlikely or would take lots of development

Gravity Implant

-Likely, but will likely be more of a moral issue if anything.

-it could have a dramatic impact on how we see science and the definition of human being. A nature vs. technology debate is sure to ensue.

-This just seems unethical and unthinkable.

this would allow for much better control and maintenance of the human body in space, also potentially making it more efficient for space exploration. there are also numerous benefits on earth as well for technology similar to this.

-Cool. Nothing says, "I hate jello legs" like a computer chip in your spine!

-Will become prerequisite for space travel

-too good to be true, dangerous, expensive

-I can imagine the possibilities of abuse of a technology hat can reprogram neutral signals

-Assuming the public can be warmed up to proscpect of having chips implanted in them this could make space travel more desirable and therefore more profitable

-Seems like a somewhat scary yet significant tool.

-This requires a much better understanding of our nervious systems and brains. Being able to integrate something like this into the body would be incredibly significant however, as its applications both in space and on earth would be nearly limitless.

-Tricking the human body is harder than it sounds.

-Full utilization would take time, but definitely handy for expanding space to more casual audience (tourism?)

-Its one thing to trick the brain into not being concerned by gravity, but most cells and systems are based highly on having Earth's gravity as a given. The heart for example, would weaken a lot in a lower gravity enviroment.

LEO Air Collector

-If this option is to be viable, it needs to be utilized at or before the middle time period. Afterwich, if a solution is not close to hand, it will most likely be abandoned.

-this is still a means of lifting the resources from earth to space in bulk, just not doing so from the surface and seperating them out in space.

-We need to do a lot before we get to shenannigans like this!

-A lot of work for material collection

-necessary for a non-earth colony. still needs the details to be cranked out

-This would make a moon habitat a much more promising venture

-This doesn't seem like it would be as difficult to implement as many of the other technologies. Having a consistent supply of water would be very helpful for a moon base.

-Plausible but difficult.

-Refueling in LEO would certainly help, but there could be difficulty in manufacturing a sufficient amount of rocket fuel automatically in orbit.

-Seems like it would only gather a small amount of resources, and that the overall energy used to do this over time wouldnt be much different than launching the resources straight from Earth

A.5 NIAC Scenario Comments

Scenario 1

-Solar sail technology won't work as described for lunar missions; aerogel TPS won't enable SSTO. However, taking the spirit rather than the details (large scale lunar activity leading to colonies, SSTO + nuclear propulsion) it's possible. But 3He fusion reactor development makes it at best unlikely

-Solar sails will never be practical for use near the Earth. Fusion reactors are unnecessarily dangerous and expensive.

- The suggested timescale for maturation and use of many of these technologies is unrealistic based on historical precedents. A number of specifics in the scenario seem questionable to me as well including:

1) aerogel is great insulation, but poor structurally - it will be useful in reentry protection systems only in conjunction with other materials development that can support / protect the aerogel mechanically at reentry surface temperatures.

2) there is no real advantage to assembling a solar sail system in geosynchronous orbit that I know of and there are major disadvantages including radiation environments and interference with communications satellites that really need geosynchronous orbit locations as well as huge launch mass penalties. Assembly at a LEO station seems far more likely to me.

3) terrestrial SSTO craft will incur significant mass penalties for thermal protection systems and structural requirements that are totally unnecessary for lunar operations - use in both environments would be a very poor trade in comparison to using terrestrial SSTO craft to launch separate reusable lunar surface landers (assembled on earth or in orbit) for transfer to the moon.

4) the orbital mechanics for lunar transfers will not demand the kind of phasing restrictions cited - "tacking" like a sailing ship can support orbit raising and deceleration for lunar or earth orbit capture at multiple lunar phase conditions. This wil be essential since the low thrust available with solar sails will dictate transfers spanning months rather than days.

5) A mixture of solar sails and other propulsion technologies seems to me more likely than replacement of solar sails with fusion powered craft. Remembering that reaction mass, not power generation is likely to be limiting for nuclear propulsion, and ISP will be limited by the materials available (temperature of the exhaust), solar sails will always offer a large advantage for cargo that is not time critical.

Aside from timing and these specifics, this seems like a relatively probable technology path scenario, but, it seems to me, is likley to include significant activity beyond the earth moon system before the moon is settled given the limited real economic incentives for lunar development.

-The overall path outlined is very likely. Although the timeline for certain aspects is not accurate, (for example the ReSSTO is not currently under development and therefore will not meet the 2015 timeline). However, the individual technologies specified may or may not play a role. Also new unforseen technologies will likely emerge that will provide greater capabilities then the ones listed.

Scenario 2

- Space elevator by 2025 is as close to impossible as anything not forbidden by the laws of physics. Adding fusion, magbeam, and roving lunar bases adds three layers of "improbable" on top.

- This is probably unlikely, but I would like to think it could happen.

- As in the previous scenario, I seriously doubt the timeline is realistic. I also very much doubt that the magbeam part of this scenario will ever prove practical.

The energy needs of a space elevator crawler will be too large for direct solar capture on the crawler to be attractive (climbing rates and usage of the expensive infrastructure would be just too low). Beamed power from a nuclear powered earth surface station has been suggested and seems more attractive.

Additionally, the density of He3 in the lunar regolith is almost certainly very low. This will dictate colocation of a very large primary energy source - e.g nuclear reactor, with a recovery operation rather than transport of "fuel" from a central location to multiple recovery sites.

- Although very innovative the space elevator poses a number of technical challanges. I believe that the developments and breakthroughs required will extend beyond 2050.

Scenario 3

- I'll grant this an improbable only because you're only asking for one miracle, not three plus a silly idea.
- The timeline seems unrealistic given current plans and investment patterns as well as the technical challenges for the space elevator. The solid state aircraft is an interesting option for Mars, but as an unmanned probe does not require or especially benefit from a nuclear spacecraft for transportation. It does require a significant refueling / recharge capability that makes use in extended unmanned missions problematic. This could be provided by solar energy capture, but would yield a very low flight duty cycle making such a mission much less attractive. the aircraft seems much more promising as an adjunct to a human mission to me.

I would anticipate the first manned mission to Mars preceding both the space elevator and nuclear propulsion as operational capabilties.

- Again although many of these concepts are innovative and feasible I believe that the timeline for there development will extend beyond 2035. Also some of these technologies have limitations that are not captured in the scenario. For example the solid state aircraft is solar powered. Therefore it would only be useful on planets that have sufficient solar intensity (the inner planets, Earth, Venus and maybe Mars).

Scenario 4

- Improbable mostly because you included a silly idea (CAC) and an unlikely "breakthrough" (Cold plasma).

- Any one scenario is unlikely. This is a good one, and as likely as most.

- Multiple elements in this scenario make little technical sense to me.

- I feel that the scenario is probable but the timeline is probably too short. It would be more realistic to stretch this out to 2050 or so.

Scenario 5

- Taking "ram accelerator" as a standin for "some low cost bulk launcher" this is a reasonable path, though 2015 is probably too soon for an operational SSTO to happen.

- Forget solar sails. They don't have enough accelerattion to be commercially viable. Railroads revolutionized the world not because they could do things that horse and carriage could not. They just a lot more, faster.

- Several elements here don't hold together technically. In addition, the development of the ReSSTO on the schedule that NASA is currently pursuing for the much less ambitious CEV launch is not credible in the current environment.

- Some aspects of this are likely but others will not happen. At least in the time frame given. For example the ReSSTO will not be developed by 2015. It would have to be under development now to meet this deadline, which it is not.

Scenario 6

-Fusion reactors put this in "unlikely"; adding the notion of corporate investment before the reactors are developed makes it improbable. (Actually, sheer fantasy, but I'm a cynical old consultant...)

- The timelines suggested seem totally unrealistic and the fact that the scenario postulates large mining company investment in He3 recovery on the moon almost a decade before any possible market for the material flies in the face of economic reality.

- Again same comments as previously. Some aspects of this are likely to occure but others will not in the timeline given. The ReSSTO will not be in place by 2015.

A.6 Student Scenario Comments

Scenario 1

- Aerogel is already available to us. This seems to me that making it available cheaper is only a matter of time. Also, SSTO rockets are just big beefy chemical rockets like the ones we've used in the past, only without the added complexity of multi-staging. This would make them relatively easy to produce compared with other drive methods. The "small lunar inflatable colonies" seems rather unlikely given the fact that NASA is now dead set on other lunar base options, but this does not mean it's technically unfeasable. The bionic leaf holds the most concern for me, as it seems to be the most difficult of the above ideas to come to fruition.
- I really only said impossible becuase of the cold plasma part, the rest seems somewhat realistic
- Many of these technologies could be developed, but would be largely inefficient and not worth the money, and thus should be dropped.
- all the ideas presented are probable
- Nuclear rocket technology has been around for some time, and wouldn't take more than political support for it to be functional. Solar sails are probably unlikely as the first-stage mission rockets due to their somewhat slow travel time. Bionic leaf seems that it might be difficult to develop

Scenario 2

-The space elevator seems to be a worse proposition than the bionic leaf to me. Although it might be possible physically, there still needs to be too much development of the new materials, and if something were to happen, you now have a tower 30,000 km high crashing down on all the unsuspecting people below. Although that'd make a great fireworks show, it wouldn't be good for anyone unlucky enough to land beneath a 5-ton brick. In regards to the magbeam: it does not make sense to have two separate systems for propulsion on a ship, considering the following: if the "traditional" propulsion system used to get back from Mars wasn't working, but you didn't know that until you try to come home, you're now stranded on Mars for at least 90 days until the next magbeam propelled ship arrives, and that's assuming 0 prep time. Good luck is all I can say, no astronaut will be crazy enough to take that risk.

- The space elevator will be extremely difficult to construct politically, and the magbeam will mot likely not come to fruition.

- I think the magbeam idea is a bit weak but the space elevator could have potential

- For this to work a country would have to dump its entire resources into building the space elevator and maintaining it. Also, thanks to Newton, we know that if the magbeam can accelerate a vehicle, it itself will be accelerated in the opposite direction.

- Magbeam seems incredibly unlikely. Space elevator seems like a good idea, but unsure of political support for it.

Scenario 3

-Once again, the reliance on the space elevator makes this kind of scenario dubious.

-Seems more likely except for the space elevator, see previous comments.

- nuclear drive just has to happen

- The Space Elevator is a bad idea.

- Nuclear drive technology is availible now, all we need to do is use it. The space elevator may be somewhat unnecessary to this scenario.

Scenario 4

-While aerogel and ReSSTOs seem probable developments as discussed above, the Ram Accelerator and cold plasma just scare me into thinking they can never exist. Nevermind weaponizing space, if we're turning a mountain into a cannon, who's to say we won't pack a 500 gigaton nuke into it and aim at China? The international community will not likely allow this to happen. And that's assuming that it's technically feasable, which I'm not admitting. 30,000 G's seems likely to rip the materials and shaft apart. Cold plasma, as stated in the description, is "the stuff of science fiction." I'll leave it at that, despite the relative "normalcy" of the description.

- It probably could happen, excluding the cold plasma.

- I really only said impossible becuase of the cold plasma part, the rest seems somewhat realistic

- It probably could happen, excluding the cold plasma.

- Who would be stupid enough to try and waste the money to build a glorified, incredibly expensive, cannon tube.

- Cold plasma seems a bit iffy, but the weaponization of space is probably going to be the most likely impetus for a renewed interest in the space program.

Scenario 5

-Any solar sail that is to be constructed will be exceedingly fragile. Exerting 30,000 G's on that will undoubtably cause damage that you're not going to detect until the astronauts get up there and start to assemble to sail, which results in a massive waste of time, energy, and money.

-The solar sail just seems like a terrible idea....

- solar sail seems sooooooooooooo inefficient

- Solar sails work both ways - coming in and going out - but they both share the same weakness in their dependence upon the inverse square law, so the probability that they would be seriously considered for outsystem voyages would probably be very small. Other power systems could alter this, of course, but it would seem unlikely.

Scenario 6

-While each of the developments by themselves (discounting the bionic leaf) seems likely, the timeframe seems unrealistic. If you wree to have the mining operations set up around 2028 or 2030 instead of 2018 I could maybe see this happening, but as it stands, there's no way this is happening.

- The fusion system wont work, the helium is essentially worthless

- we are going to need energy other than oil at some point

- I dont think that the first serious lunar colonization efforts are going to be started by corporations, as they're probably going to be prohibitively expensive, dangerous, and not necessarily profitable within any time span.

A.7 First Contact Email to Diana Jennings

Dear Ms. Jennings,

My name is Oana Luca and I am a member of the 2006-2007 NIAC study project group at Worcester Polytechnic Institute. We tried to contact you a week or so ago, but we received no reply; this is why we decided to resend the email.

First of all, we want to thank you for your interest and support and hope that we will have a fruitful collaboration. We are all excited to start the study.

As you probably have been informed already, our study will have two phases. The first one consists in gathering the data from questionnaires from the panelists, and the second one is comparing the results of the questionnaires against the individual cognitive preference data (which will be collected through a Myers-Briggs type query instrument).

Secondly, attached to this email you have 5 documents: an executive summary of last year's results, the format of the contact letter, the format of the recontact letter (for the scientists from last year's panel), the contact information of the panelists involved in last year's study and also a list of possible new contacts.

We would appreciate if you could please select the potential panelists in the attached list of NIAC fellows; you are more aware of the eventual panelists' availability. We would also appreciate any comments and suggestions on any of the other attached documents.

We would also like to discuss the further development and implementation of the study.

Our contact information is:
niac@wpi.edu

Oana Luca
oanaluk@wpi.edu Tel. 508-369-8246

Bill Flaherty
bflats@wpi.edu Tel. 978-771-5565

Michael Monfreda
monfreda@wpi.edu Tel. 508-612-4842

Thank you again!

Regards,

WPI NIAC Delphi study project group

A.8 NIAC New Pane lists-First Contact Email

Dear NIAC Fellow,

I represent a project team of science and engineering students who attend Worcester Polytechnic Institute in Massachusetts. We are conducting a Delphi panel study of experts on possible space technology breakthroughs. The survey has three parts. First is a questionnaire in which you would rate 19 specific technologies for likelihood and the significance of the breakthrough, and estimate a possible timeframe in which it would most likely take place. Second is a questionnaire that describes six scenarios of what the future of space travel might be depending on what technologies are and are not developed. You would be asked to rate each scenario on the relative likelihood of their occurring. Finally, we are asking each panelist to take the Myers-Briggs Type Indicator. This instrument measures a person's cognitive preference, which we would then compare to their responses regarding the space technologies to see if the types considered most likely to be optimistic really are more optimistic. A prior study of WPI alumni suggested that the preferences are as important as relative expertise in ascertaining which technologies will be available by 2050. We hope to replicate this finding with a more expert panel of assessors. However, this is an add-on. We want you to participate, and if you can, do at least the two questionnaires, that is enough.

This study is part of a project that is a graduation requirement at WPI, and as such is taken very seriously. It is a continuation of three past studies conducted at WPI. These past studies all succeeded in gathering information from groups at different levels of expertise, such as current engineering students, alumni of WPI, experts in the Aerospace field, and now NIAC fellows. Our goal for this project is to expand the sample of NIAC fellows and to then use all of the data obtained by previous teams to do a complete analysis of the expertise and personality variables. As a former or current NIAC fellow we feel you are in a unique position to offer an expert opinion. As such, we would very much appreciate your involvement in the survey. It will be conducted in two phases. For the first wave we ask you to take the two questionnaires. The first deals with the 19 specific technologies, and the second involves the six scenarios. We feel that since these two assessments have shared content they should be taken in the same phase. Please take the technology questionnaire first as it feeds into the scenarios. The technology breakthrough questionnaire can be found at this link:

http://space.wpi.edu/~ellery/survey2/?panel=NIAC

The scenario questionnaire can be found at this link:

http://space.wpi.edu/~ellery/survey2/scenarios.php

The second phase of the survey will be to have the respondents fill out the MBTI to gather the cognitive preference data. When you have completed the first two questionnaires, please contact me to let me know and I will then provide you with the information on how to take the MBTI online. Thank you for your time and attention and we hope you decide to participate in this forecasting study.

Sincerely,

William Flaherty
bflats@wpi.edu
Michael Monfreda
monfreda@wpi.edu
Oana Luca
oanaluk@wpi.edu

A.9 NIAC Re-contacts-First Email

Dear NIAC Fellow,

I represent a project team of science and engineering students at Worcester Polytechnic Institute in Massachusetts which is continuing the Delphi study regarding space technology breakthroughs that you participated in last year. Unfortunately, my predecessors never completed their analysis and did not send you the results of what they did finish. The goal of this year's group is to finish what the previous group started, as well as incorporate data from other studies at WPI dealing with the same questionnaires to create one overall analysis of all the available data. An executive summary of last year's report can be found here:

http://users.wpi.edu/~niac/summary.doc

If you would like the full report you can contact me at bflats@wpi.edu and I will provide you with a copy. At the end of the project last year, the prior analysis team should have asked you to fill out two more questionnaires to make the NIAC panel a complete data set. The first questionnaire contains six scenarios of how space technology may develop. You are asked to rate each scenario based on the likelihood of their occurring. The second questionnaire is the Myers-Briggs Type Indicator which takes about 20 minutes to complete. This instrument identifies the cognitive preferences of the respondent, which we can then compare against the person's responses to the other questionnaire about space technology. One of the prior studies of WPI alumni suggests that cognitive preference is as important as relative expertise in ascertaining whether one is optimistic about the more radical space technologies that could be developed by 2050. Hence, we want to see if we can replicate this finding with a more expert panel. The scenario survey can be found here:

http://space.wpi.edu/~ellery/survey2/scenarios.php

We would like to carry out the continuation of the project in two phases. The first phase would consist of taking the scenario survey. After receiving your responses we will then ask you to take the MBTI. We would still like your reaction to the scenarios even if you decline to take the MBTI. We do apologize for the lapse in contact and the length of time it took to get you the results, therefore our team would very much appreciate your continued support of this project and promise to stay in touch and provide you with the results.

Thank you,

William Flaherty
bflats@wpi.edu
Michael Monfreda
monfreda@wpi.edu
Oana Luca
oanaluk@wpi.edu

A.10 NIAC Final Phase Email

Dear NAME,

Thank you so much for taking the time to complete the first two phases of our study. The final step that we request is that you fill out the Myers-Briggs Type Indicator (MBTI). This is an evaluation of your cognitive type that will help us in analyzing the data that has been collected so far. It can be taken online, and the directions to do so are as follows:

1. Go to http://online.cpp-db.com

2. Use the login "captg" (no quotes)

3 Use the password "takethembtig" (no quotes)

4. Leave the User ID blank and press login.

5. At the bottom of the next screen you can choose between two assessments.
Take the MBTI Step I (Form G).

You will now be logged in to take the MBTI. Fill out the demographic information and then start taking the assessment. After you complete it I will generate a PDF of your report and send it back to you so you can see what the assessment said.

Thank you again,

William Flaherty
bflats@wpi.edu

Oana Luca
oanaluk@wpi.edu

Mike Monfreda
monfreda@wpi.edu

A.11 2006 Student Panel First Email

Hi all,

My name is Bill Flaherty and I am a member of the NIAC Delphi study IQP. Our IQP is a forecast of possible space-technology breakthroughs that could occur by 2050.In order to accomplish this we are using two tools, a breakthrough questionnaire and a scenario questionnaire. The first deals with 19 possible technologies and asks the participant to rate them by significance, likelihood, and time period. The second is a set of 6 possible scenarios that technology development could follow. In an attempt to expand our panel and get more usable data we are requesting that all the members of this years Space policy IQP teams take the survey. This, combined with the data collected from previous WPI student, will give us a large complete data set to analyze. The surveys do not need to be taken at the same time, but the breakthrough questionnaire must be taken first. It can be found online here:

http://space.wpi.edu/~ellery/survey2/?panel=wpistudent06

The scenario survey can be found here:

http://space.wpi.edu/~ellery/survey2/scenarios.php

Once you have taken the survey we can make the results of it available to your team for use in your own IQP. Your participation is crucial to our project and we very much appreciate you taking time out of your busy schedules to help us.

Thank you,

Bill Flaherty

A.12 2006 Student Panel Second Email

Dear Space Policy Teams,

I emailed you three weeks ago asking you to take two questionnaires to help my team complete our project. So far we have only had three students complete the first questionnaire, and only one complete the second. We really need your support in filling out these questionnaires, as a student data set is integral to our project. The link to the first is:

http://space.wpi.edu/~ellery/survey2/?panel=wpistudent06

The link to the second is:

http://space.wpi.edu/~ellery/survey2/scenarios.php

In return, once you have taken the surveys, I can provide you with the data reports which you can then use in your own projects. The information gathered through these tools is of use in every space policy IQP. I would also be willing to meet with teams individually after they have completed both questionnaires to go over the data report system so you can manipulate it to fit your project. If you could fill out both these questionnaires before the end of the week we would be extremely grateful. If you have any questions or concerns feel free to contact me.

Thank you,

Bill Flaherty

A.13 2005 Student Panel First Email

Dear students,

I am writing to you today to request your participation in a current study on space policy at WPI. Your participation in a space policy IQP last year puts you in a unique position to assist this years study. My assistants (William Flaherty, Michael Monfreda, and Oana Luca) would benefit from last years teams filling out the Scenario survey, which lays out possible timelines for breakthroughs in space technology. The survey can be found at this link:

http://space.wpi.edu/~ellery/survey2/scenarios.php

Your response would be invaluable to this years study for analyzing and comparing data.

Thank you,

Professor Wilkes

A.14 Executive Summary of Wu, Gillis and Stawsz IQP Sent to NIAC Fellows

This study deals with creating a forecast for space technology. It is based on expert opinions on what technological breakthroughs are likely to occur by 2050. Robert Cassanova of NASA's Institute for Advanced Concepts was contacted and asked to encourage the study, and facilitate it by creating a contact list of NIAC fellows.

Last year's study, conducted by Wu and Gillis, involved contacting 19 NIAC fellows and asking them to fill out a questionnaire dealing with space breakthroughs. Of the 19 contacted, 12 responded that they would participate in the proposed Delphi panel. Wu and Gillis originally intended to have the panelists fill out the Myers Briggs Type Indicator (MBTI), but they never accomplished this task. Below we have summarized the findings that last year's group obtained from the data supplied by their panelists.

The analysis team began by comparing the data distributions obtained from the NIAC panel with the data produced by earlier studies utilizing a similar questionnaire. These previous studies consisted of alumni and non-NIAC experts from NASA and University settings. The general finding was that all three groups produced similar results, the main difference being that the NIAC panel was slightly more optimistic. This was predicted based on their greater expertise in the field and their having more information regarding the subject matter readily available to them. One theory advanced to explain the differences between the panels could be attributed to the psychological (MBTI) type that was most prevalent in the given panel. MBTI data collected in the Alumni study presented an apparent correlation between certain cognitive types and how optimistic they were in responding to the questionnaires. Unfortunately, since Wu and Gillis did not collect MBTI data from the NIAC panel they were not able to carry out an analysis with regards to cognitive type. We have attached some graphs that show the trends in the questionnaire data collected thus far at the end of this letter.

Our team's first goal is to expand the NIAC panel from 12 to about 24 panelists, doubling our original sample. This will make it roughly comparable to the 30 person WPI alumni panel. The new panelists will be asked to complete three questionnaires: the original breakthrough panel questionnaire, the scenarios questionnaire and the MBTI. Returning panelists will be asked to complete the MBTI and the scenarios questionnaire to complete the NIAC data set. The MBTI data is especially important because it will allow us to determine whether NIAC's increased optimism over the other panels was the result of a personality type which proved to be unusually optimistic in the WPI alumni panel dominates the NIAC panel or not. We hope you find these results as interesting and encouraging as we do, and look forward to your participation in the study.

A.15 Title and Abstract From IASTS Conference Presentation

Effect of Cognitive Preference on Forecasting Space Technologies

William Flaherty, Oana-Raluca Luca and Michael Monfreda, Worcester Polytechnic Institute

This technological forecast uses an enhanced Delphi methodology to predict what breakthroughs in space technology are most likely by 2050. It especially concentrates on panelists' cognitive

type in relation to their optimism, and includes panels from NIAC, current college students, and recent college graduates. The current study builds upon the work presented last year as the prior team presented on assessments of individual technologies and this research is based on the assessment of alternative composite scenarios of what the future of space technology will look like.

A.16 New LEOCAC Description Suggestion

As humanity branches out into space, the need for readily available resources will shape the economy of the future. The ability to harvest the upper layers of the Earth's atmosphere for gases such as oxygen, which is used for life support and oxidizer in rocket fuel, could create one of the first seller's markets in space.

A harvester orbiting at 400km, an altitude that, while very low in density, contains roughly 89% oxygen could harvest several tons of liquid oxygen per year. Using a large maw and vacuum pump, the harvester would operate continuously for about 10 years. In order to maintain momentum, the gatherer would use an electrodynamic tether, a form of propellantless propulsion, which utilizes a long wire infused with large current that pushes off of the Earth's magnetic field.

If the Low Earth Orbit Atmospheric Harvester is developed with the proposed technology it has the potential to revolutionize the space industry. Technologies such as the electrodynamic tether allow the harvester to maximize the amount of fuel it can gather by not consuming any resources during operation. The only weakness the harvester possesses at this time is the fact that some of its key components are unproven technologies such as the radiator to dissipate all the heat gained while harvesting and the electrodynamic tether.