06D276I
06D168I
05D168I
Project Number: JMW-EMTA - 46

Social Implications of a New Space Race if it Results in Breakthroughs

An Interactive Qualifying Project Report

submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

Aubrey J. Klaft

Christopher T. Osborn

May 5, 2005

1. breakthroughs
2. delphi
3. nanotube
4. fusion

Professor John Wilkes, Project Advisor

Introduction

The next 100 years will be an exciting time for humanity. Advances in all fields of science will change life for both good and ill. Technology holds the promise of improving the human experience, but if mis-applied, can lead to disaster.

Therefore, it is important to predict the effects this future technology can have on the whole of society. This will allow us to maximize benefits and minimize the negative side effects. By predicting events based on the adoption of certain technologies and their diffusion in society, we can avoid some of the mistakes of the past and maybe even some new errors.

This report will focus on aspects of space technology in which it has been determined that breakthroughs are most likely. It was not our task to assess the breakthroughs in terms of their likelihood. Ours was the challenge of trying to reason out the logical implications and consequences of such technological change.

In 2004, a WPI team of students began a technical assessment of a possible Chinese/American Space Race over the next 50 years; specifically concerning itself with competition over setting up bases on the Moon (Elko et al. 2004). They posited that as a result of China's desire to enter the world stage, and the United States' desire to remain the world premiere superpower, a new Space Race to the Moon commenced, and resulted in landings by 2018 followed immediately by construction of bases. So we accepted this forecast as "fact", that the US and China would both land on the Moon in 2020, within a few months of each other. They would both establish bases on or near the South Pole of the Moon, where there is water. The prediction was that by 2030, the US will be building a second base at the equator as a launch point for a nuclear-powered mission to Mars. The Chinese offer to help the US with supplies in return for having a Chinese taikonaut on board. The mission to Mars will have launched by 2040, if all goes according to their plan.

Currently another WPI team is working on the social implications and technical spinoffs of this race, and has created a fascinating scenario in which the use of nuclear fusion is commonplace in the medium-term future and the effects of aging have been greatly reduced by research spawned by the space program. Nuclear fusion would allow for cheap, clean energy to drive the world, and would start a $Helium_3$ trade between the Earth and the Moon.

However, these two teams were remiss in that they did not take into account the possibility of breakthroughs in space technology. Determining exactly what those breakthroughs will be is extremely difficult, though, due to their unpredictable nature. The example of Penicillin is most applicable. That discovery could not have been predicted, as it was done by accident. The helpful properties of Penicillin would probably have been discovered years later by careful analysis and study, but a happenstance occurrence in Fleming's lab moved that discovery up a number of years. It saved millions of lives since its discovery during World War II., In that .war, Sulfa drugs were the main advance, but by the end of the war penicillin was entering mass production and the postwar era was transformed by a whole new class of antibiotic drugs, of which Penicillin was the first.

Another team (Climis et al) drew the assignment of redoing the forecast. They undertook a Delphi study in order to attempt to forecast likely breakthroughs based on expert opinion. This consists of several rounds of questions aimed at experts in an attempt to assess their consensus on what technologies are most likely to develop and would be the most consequential if they did. The first round of results has come back from these experts, and we are using these results revise the estimate of the Social Implications of a New Space Race, this time factoring in the breakthroughs considered likely and consequential by the experts.

From the survey results, initial conditions for breakthroughs were determined by a statistical analysis of the responses of experts in space-related fields, and recently-graduated alumni of WPI trained in relevant general areas, such as physics or mechanical engineering, but are hardly experts in the field of aerospace. The average panel opinions were used as a baseline for two projections of technologies that had been considered not "promising."

We will also predict which technologies will get support and their likely impacts using today's socio-political climate as a guide to how to project a future modified by these breakthroughs. The non-breakthrough forecast produced by our colleagues will also be a valuable baseline for comparison to see how consequential the technological advances are.

We hope to illustrate the potential pitfalls of uncontrolled scientific growth by pointing out some of the unanticipated actions of purposeful events in the future of the space program. We also hope to demonstrate the beneficial effects that space technology can have on society, stressing the political effects as much as the economic considerations.

We will exclusively focus on space technology for this report. Developments in other technical sectors are assumed to be minor and incremental for the time period we will be covering. Non-space-related technological breakthroughs are outside the scope of this project. Also, the mindsets of the major players of the Space Race will be assumed not to undergo any radical shifts, despite the potential availability of new technologies that would help or hinder those goals. Major outside influences or large-scale natural or manmade disasters will not be taken into account.

Social Impact Assessments

Social impact studies are very important. They allow us to make predictions about how events, technology, or other changes will affect society, whether on a small scale, such as a town, or on a large scale, such as the planet Earth. The impact, however, can also flow in the reverse direction. Technology can be shaped by changes in society, as well.

Social impact assessment (SIA) is the process of determining the effects of a project, policy, or technology on a group of people (Vanclay). It is also the process of determining a plan to manage these effects. A SIA should consider changes to a people's way of life, and their culture, community, environment and their health.

Vanclay sums those up very well:

> A convenient way of thinking about social impacts is as changes to one or more of the following:
>
> - people's way of life – how they live, work, play and interact with one another on a day-to-day basis;
> - their culture – shared beliefs, customs, values and language or dialect;
> - their community – its cohesion, stability, character, services and facilities;
> - their environment – the quality of the air and water people use; the availability and quality of the food they eat; the level of hazard or risk, dust and noise they are exposed to; the adequacy of sanitation, their physical safety, and their access to and control over resources;
> - their health and wellbeing – where health is defined as "a complete state of mental, physical and social wellbeing, not merely the absence of disease or infirmity", and is applied to individuals and to the society in which they live; and finally,

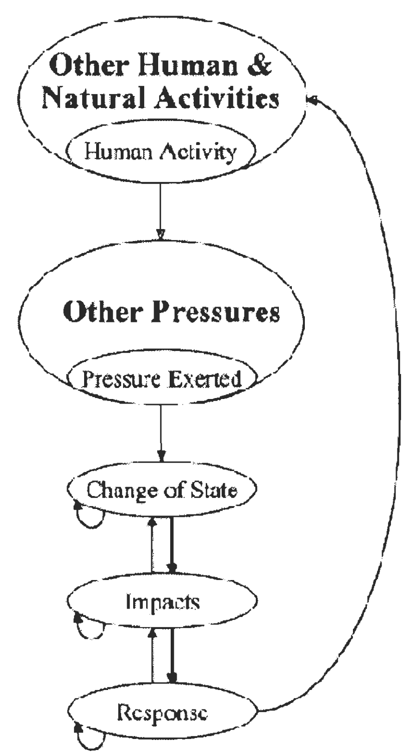
There is some debate over what exactly a SIA is, and what factors it should consider. The US government has a very narrow definition of what a SIA should be, and if the Congress commissions a study, it expects this form to be followed. By social impact they "mean the consequences to human populations of any public or private actions that alter the ways in which people live, work, play, relate to one another, organize to meet their needs and generally cope as members of society" (US Commerce). Their definition however goes on to become very concerned about equity. The Bill was originally passed in the late 1960's, the era of the civil rights movement. Therefore the creator of a government SIA is instructed to pay very careful attention to *all* populations that may be affected, and to make sure that everything is "fair" lest the government be sued. There is also a mandate for a section concerning the impact on American Indians. This is a very rigid and bureaucratic method.

Another kind of impact assessment is the application assessment. This kind attempts to determine the applications of a rather specific technology. One example is the Technology Identification, Evaluation, and Selection (TIES) study (Mavris). Through modeling and simulation, it attempts first to determine whether a technology will solve a given problem, and if not suggests alternatives. It also touches upon the technology's effects on the relevant industry, and on research into that area.

There are several pitfalls in SIA. One is bias. In a study of SIA's, it was found that the benefits of programs are rarely as good as proponents make them out to be, and the downsides not as bad as opponents portray them to be (Freudenburg). It may not be possible to totally eliminate bias, but it should at least be possible to identify where the bias lies, the better to inform policy makers and the public. It is also easy not to look broadly enough. One must look at the impacts of the impacts, and the impacts of the measures taken to overcome negative impacts. It is an infinite loop, but it behooves the authors of SIA to look at as many potential impacts as possible. The creator of an SIA must also beware of variations in factors not explicitly included in the report. A relevant example is the oil price hike in the seventies and the price decline in the eighties. Both invalidated many forecasts that were built into impact studies.

It is of course very difficult to deal with such a high levels of uncertainty, but predictions of consequence must be attempted, if we are to control technological development, rather than be controlled by it. The application of the logical induction of "this happens, therefore this is most likely" is somewhat flawed. What must be taken into account is should not be limited to that which is most likely. The low in probability but potentially catastrophic and irreparable consequences are sometimes the most important considerations. For example electrical companies have used "most likely" projections to justify building nuclear power plants. A combination of hideous cost overruns and increased conservation due to cost hikes caused by the same left them with massive debt incurred while building excess capacity. Therefore SIA's should incorporate some flexibility and encourage a range of possible outcomes, while trying

Figure 1 - Integrated Assessment



to specify their relative probability.

There is therefore a movement toward the reconception of SIA's into Integrated Assessments (IA) (Rothman). These are designed to take into account the second order impacts by reassessing the impacts at every level, and then repeating the process iteratively. This approach also attempts to take into account outside factors and other pressures. The downside is that such exhaustive studies are extremely time and resource intensive. It is also very difficult to know when to stop iterating. The authors themselves admit that their system goes above and beyond what most SIA's are trying to accomplish. However, if one has a large staff of experts, a high stakes problem, and enough time to do it, integrated assessments would provide an excellent framework for assessment.

This report takes elements from several different styles of impact assessment. Below is the basic model used. It is an attempt to avoid many of the pitfalls earlier mentioned. Secondary effects are considered. It is not a perfect model for what this report accomplishes. Since the report is an effort to follow through on a forecast and not an attempt at policy formulation, no monitoring program is developed. Similarly, no mitigation plan is created.

Aspects of other SIA types are used. Any forecast of the future involves uncertainly, so that should be taken into account. Finally, some mathematical modeling is used, mostly to check the feasibility of various concepts, and in certain economic matters.

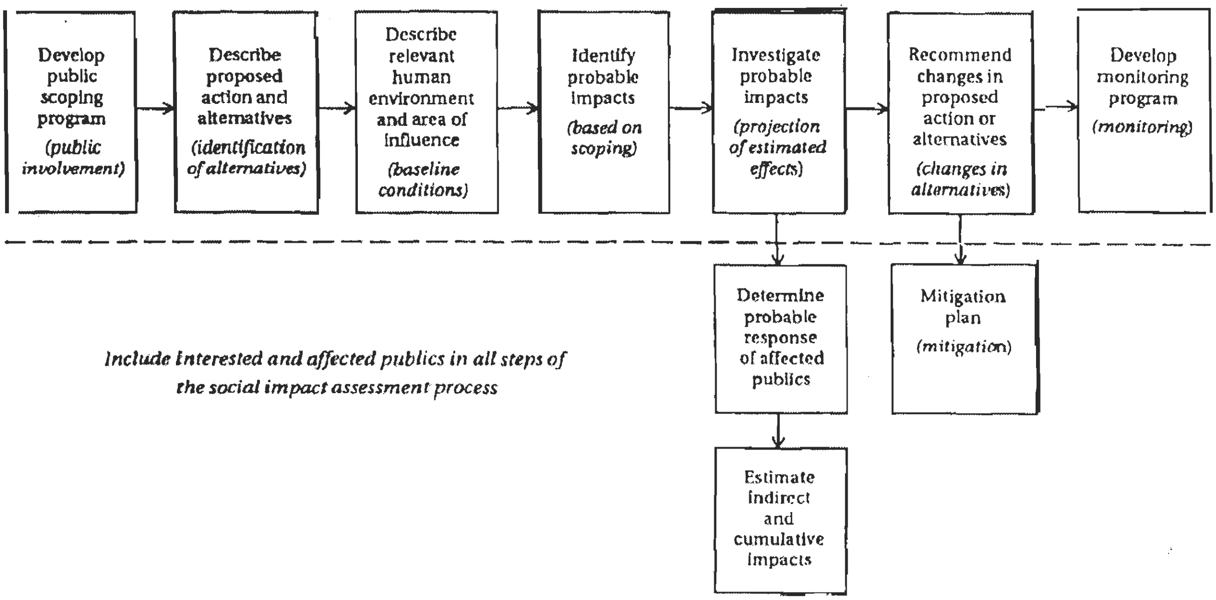


Figure 2 - Steps in the Social Impact Assessment

The Delphi Process

The main source of information for this project has been questionnaires designed to be distributed to the panel in a Delphi study. Another team designed the items and selected the panel, but we did our own analysis of the results. This was done in order to study some baseline data on what the experts felt the most likely and most important technological innovations of the coming years would be.

The name Delphi process was taken from the Greek Delphic Oracle's skills of interpretation and foresight. The Delphi technique was developed in the 1950s by the Rand Corporation in California (Iain). The objective of the original study was to "obtain the most reliable consensus of opinion of a group of experts... by a series of intensive questionnaires interspersed with controlled opinion feedback" (Linstone) It was originally conceived by the U.S. Air Force as a method for predicting future events by consulting panels of experts in a particular field of interest. Generally these were in the fields of science and technology.

The original Delphi techniques were consensus research methods that were designed to harness the insights of appropriate experts in a particular field in order to enable decisions to be made in areas where published information was inadequate or non-existent. The definition of what constitutes an expert varies according to the question. In the situation of a Delphi intended to result in production of guidelines an expert may be defined as either those with the knowledge (termed “the theoretical expert”) or those who will have to implement it (termed “the practical expert”) (Iain).

The Delphi survey technique has been widely used across industries, issues, and goals, and because of this, many variants of the Delphi have been described. Its broad application in recent years has led to new definitions, such as that by Linstone and Turoff: “Delphi may be characterized as a method for structuring a group communication process so that the process is effective in allowing a group of individuals as a whole to deal with a complex problem.”

There are four key features to the Delphi process, which are anonymity, iteration, controlled feedback, and statistical analysis of the group’s responses.

Anonymity is achieved through the use of questionnaires. By allowing group members to consider and present their replies privately, undue social pressures can be avoided. In some instances it may be appropriate for the members of the Delphi group to be identified. However their answers will be anonymous, meaning that the individuals’ answers are anonymous even if the participants themselves are not. Iteration occurs through the submission of a questionnaire over a series of rounds, allowing members to change their opinions. In this project, due to time limitations, only one iteration of questionnaires was performed, and another team is carrying on the process of feedback and response. Controlled feedback occurs between rounds. The results of each round are analyzed by a central researcher and the responses for each given statement are fed back to all members of the Delphi group. This allows members of the group to assess their views in the light of the group's distribution of responses.

A statistical group response is obtained at the end of the procedure. This is an expression of the degree of consensus of the group on a particular issue. It is commonly expressed as a mean value and spread of opinion, which can be combined to indicate the "strength" of opinion.

However, we made a slight modification to the classic Delphi study. The study does not adequately factor time, and relationships between different scientific discoveries. It is effectively a "two-dimensional" snapshot. For example, the study considered a space-elevator as very unlikely. However it considered fusion and carbon nanotube discoveries very likely. If fusion and nanotubes were brought into existence the elevator becomes much more likely (as we will show later).

Therefore we used some of the less likely "second tier" breakthroughs. The panelists did not consider them likely, but we felt that with the first set of breakthroughs, the second set, i.e. the space tethers and electromagnetic shielding became much more likely. Further, once the second set of advances becomes reality, a third set, the space elevator and the fusion drive, become possible. Essentially, we respectfully disagree with the panels as regards the likelihood of some of the more futuristic breakthroughs, because the earlier breakthroughs become a base upon which to build more.

There are three stages to the Delphi process, outlined below:

In the first stage, an expert may be considered to be an individual who has recognized expertise in a particular subject or may be anyone who can provide a worthwhile opinion on the subject in question. Some of those asked may be disturbed by considering the needs and opinions of groups to which they have traditionally dictated practice. However, as was written by Turoff, "[i]f policies are to change effectively then all views should be considered. It may be advantageous at an early stage to illustrate the experience, seniority, and diversity of the panel to all its members."

Stage two is sometimes called "The Delphi Rounds" (Anderson). Having selected the members of the expert panel, the Delphi process itself starts, in rounds that are a subdivision of the stage.

In "classical" Delphi, the first round is completely unstructured, asking members to express any opinions that they may have on the issue in question. In this project, the first round issues were determined by the students involved in this and other related projects here at WPI. In this way, this project does not follow the "classical" Delphi procedure, but was constrained by prior "research." The first round normally contains a synopsis of the issue in question together with the source and validity of the information upon which it is based.

From the first round results, a questionnaire is constructed containing a series of statements or questions that respondents are asked to express their opinion on. This is measured on a scale. Rankings for each consensus statement are summarized and fed back to the respondents for round three.

In the Delphi process participants re-rank their initial statements in the light of the results of round two. Their own answers from the second round are fed back to the panelists so that they may view their own answers in the light of the group's overall response. Members of the group who have expressed extreme views (as compared to the group mode or median) are contacted between rounds and asked to justify or explain their position. Their argument is supplied back with the other information from prior rounds. The majority of the observed shift in opinion view is likely to be seen between the second and third rounds. Questions which do not achieve consensus may be reiterated in a fourth or subsequent round.

In the third stage, the results of the process are sent back to the group members for a check on whether they feel their position is fairly rendered. One hopes to create a firm basis on which future researchers can use the study as the baseline for future work.

Some problems may arise with use of the Delphi process, most notably the time involved in completing the questionnaires. The Delphi panel of "experts" is therefore required to have a degree of commitment to the issue under consideration. The time saved in not having to travel to committee meetings or conferences may more than compensate for the time spent in pursuing the method. "It requires enthusiasm from both the respondents and organizers, but the results can be satisfying and informative for both" (Iain).

Through the Delphi process instituted for this project, expert opinions and the statistical analysis thereof led this project to pursue research into two areas.

The area of carbon nanotubes was looked upon favorably by the experts, as well as being seen as potentially very significant to the future of space travel. Nuclear fusion was also seen as very likely and important. However, upon further research, it became clear that these technologies did not exist in a vacuum, as it were. Their development would influence (and be influenced by) other technologies. Research into these fields built itself into a type of self-sustaining timeline. Therefore, although the main focus of this project is on the social implications of the technologies of carbon nanotubes and nuclear fusion on the people of Earth, material will also be devoted to space tethers and elevators—which are logical extensions of the cheap and easy manufacture of carbon nanotubes—and advanced electromagnetics and a nuclear fusion interplanetary drive—the first of which is a precursor to nuclear fusion, the second of which is a spinoff technology.

Carbon Nanotubes

Carbon nanotubes were first discovered in 1991 by S. Iijima of NEC. A carbon nanotube is a tiny tube about 10,000 times thinner than a human hair. There is no physical limit to the length of a nanotube. Put more scientifically, the carbon nanotube is a macromolecule consisting solely of sp^2 hybridized carbons, which has incredibly unique physical properties. The easiest way to define a carbon nanotube is to think of a large sheet of graphite on the molecular level. This sheet consists of multiple 6 carbon rings, referred to as hexagons, which form a lattice. (For the sake of accuracy, these are not true hexagons, as the midlines differ by approximately .4 angstroms [2.83 ´ horizontally vs. 2.45 ´ vertically] (Adams. However, they will be referred to as hexagons for ease of discussion.)

In a carbon nanotube, the sheet of hexagonal carbons is rolled into a cylinder. The rolling of this sheet of carbons hexagons allows the macromolecule to have outstanding physical and chemical properties which are not usually seen in organic carbon structures. Graphite (pencil lead), another carbon ring macromolecule, for example, is very brittle. It, unlike the nanotube, is made up of sheets of Carbon hexagons, which slide across each other laterally. The end of a nanotube is capped by more hexagonal carbon rings. Carbon Nanotubes are light, flexible, chemically inert, and thermally stable (Adams). The twist/chirality of the tube determines if the nanotube is metallic or semi-conducting.

The diameter of the carbon nanotube is determined by the chirality of the molecule. Chirality is the inability of a molecule to be superimposed on its mirror image. There are three types of carbon nanotubes, all of which depend on the way the molecule rotates to form its final cylinder. Armchair nanotubes twist the tube along the hexagonal structure (Fig. 3, red line). If the angle at which the tube will wrap is 30 degrees then the nanotube is considered to be of the zigzag type (Fig. 3, blue line). If the angle is between 0 and 30 degrees then the nanotube is said to be chiral (Fig. 3, green line). Chirality determines the conductance, density, and lattice structure of the nanotube. Approximately two-thirds of nanotubes formed are semi-conducting. The other third are metallic. The average diameter of a single nanotube is 1.2 nm.

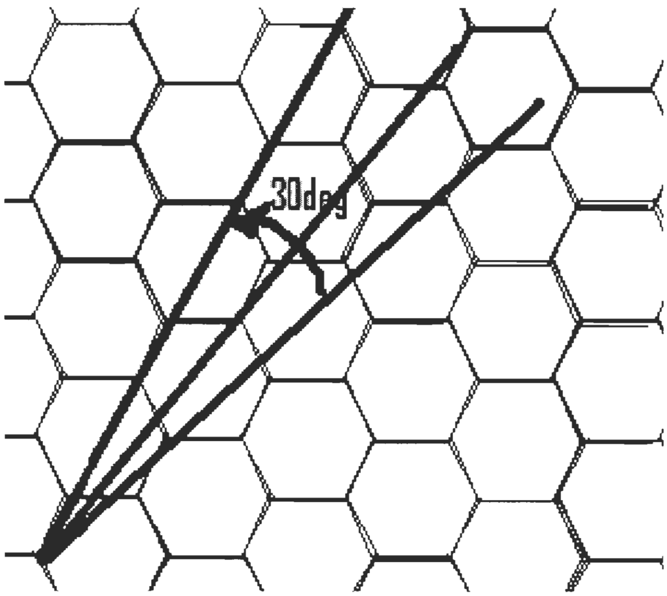


Figure 3 - An illustration of nanotube chirality angles.

Nanotubes are very conductive. Thess *et al.* determined the resistivity of a metallic nanotube to be approximately 10^{-4} Ω-cm. This makes nanotubes one of the most highly conductive carbon fibers known at this time. Frank *et al.* were able to reach a current density inside the tube of greater than 10^{7} ´/cm^{2}. This number has since been pushed to 10^{13} ´/cm^{2} (Baard)

Carbon nanotubes are considered to be 100 times stronger than steel and much more resistant to damage from physical forces, all at one-sixth the physical weight. Even current technology can produce a nanotube about 4 times stronger than spider silk. (Baard) This makes the carbon nanotube a better building material in all aspects.

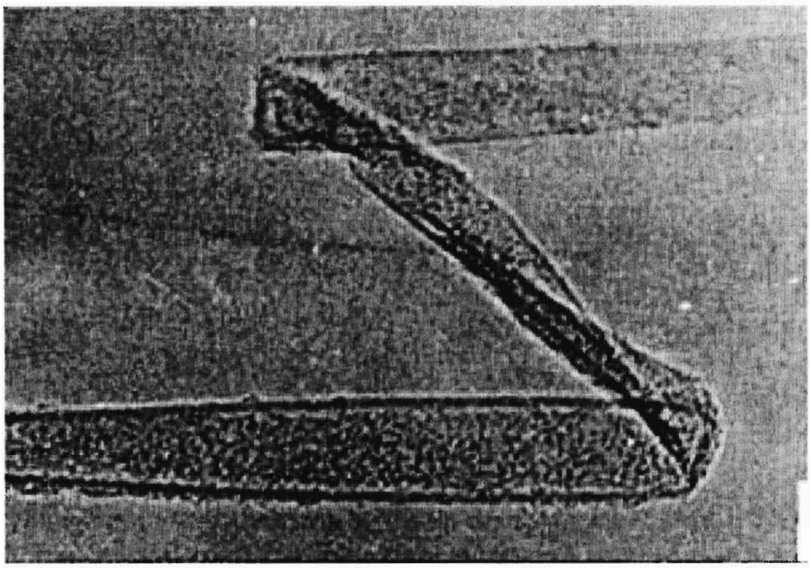


Figure 4 - A microscopic view of a nanotube undergoing a stress test.

Pressure applied to the rounded tip of the nanotube causes that tip to bend in; however, there is no damage to the surrounding structure. Also, after the force is removed, the nanotube will return to its original state. (Adams) Single-wall carbon nanotubes can also be stretched by several percents before they fracture. They can be twisted, flattened, and even bent into small circles before anything happens to the internal structure. Also, under extreme stress, nanotubes do not fracture. They instead form ridges which relax *elastically* once the stressor is removed. (Dresselhaus)

Carbon nanotubes can be made by one of four different methods:

1. Pulsed laser vaporization, in which a laser beam is shone through a catalyst of graphite and metal, which vaporizes the carbon. The nanotubes self-assemble from this carbon vapor in the presence of pressurized argon gas.

2. Electric arc discharge, in which the graphite and metal are both vaporized, then shocked with 100 amperes of electricity.

3. A method in which carbon-containing molecules are decomposed into nanosized particles using metal catalysts.

4. A method in which high pressure carbon monoxide reacts with high pressure iron pentacarbonyl (a five carbon chain containing a triple bond) and heated. Nanotubes grow around the iron gas clusters. (Baard)

One of the primary uses of carbon nanotubes today is in making processors smaller and faster. IBM is currently working on a way to manipulate the carbon nanotubes to place them where they want to on a chip. They are using Atomic Force Microscopy (AFM) to change the position, shape, and orientation of the nanotube. AFM also allows researchers to cut the nanotube. (Jameson) The Van der Waals forces (attractive molecular forces) of the molecules in the nanotubes allow them to stick to surfaces that they are placed on. The Van der Waals forces are actually strong enough to alter the shape of the nanotube. In general, nanotubes develop a slightly squished formation due to the forces inside the tube itself. IBM hopes to go into the possibility of conforming the properties of the nanotube to fit their applications by purposefully changing their shapes. The ultimate goal of this research is to use nanotubes as the basis for nanoelectric devices.

A controllable nano-diode has been unveiled. Previously, nano-diodes were made by linking two nanotubes with different piezoelectric properties together. Electric fields instead of chemicals are now being used to bind the two separate pieces of nanotubule together. Before this breakthrough the nano-diodes created were not controllable. Now they have predictable electronic properties and are reproducible, which is very important if nano-diodes are ever going to go into full scale use. (Knight)

Nanotechnology is also making strides in biology. Nanotechnology is being used as a way to create extremely sensitive sensors which allow small amounts of chemical and biological substances to be detected. They can also be used instead of blood tests to detect pathogens. Nanotubes can also be self-assembling. Currently, scientists in Israel have used DNA and hexagonal carbon sheets to create a self-assembling nanotransistor. The DNA molecule is coated with a protein, usually from *E. coli*. Then graphite nanotubes are coated with antibodies. The antibodies bind to the proteins, and the graphite nanotubes are added to the DNA strand. (Braun) The DNA self-assembles, adding the graphite nanotubes together. This can be used both for diode construction and for adding to a preexisting nanotubule.

Figure 5 - A mockup of several parallel nanotubes, showing the hexagonal structure and hollowness.

Carbon nanotubes also have other biological applications, rather than the aforementioned method of using DNA to self-assemble the carbon nanotube. The nanotube can be used as an exact way to deliver drugs to a diseased cell. Nanotubes are, after all, hollow, and can be used as a delivery system.

NASA has outlined its planned uses for carbon nanotubules in the near future. Firstly, the nanotube could easily be a substitute for nylon thread. It could make more reliable spacesuits, rope, webbing, and life support tethers. These fibers are incredibly strong, flexible, and damage resistant, making them ideal for use when the possibility of irrevocable damage is great. There is also talk of using the nanotubes as life support systems, with sensors naturally built in. Nanotubes would be used to make lighter weight, more resistant oxygen tanks. The surface area of the nanotubes is very high, making them perfect for pulling dangerous gasses into themselves and away from the environment. NASA eventually hopes that the size of the pores in a nanotube can be used as a basis for the catalytic conversion of nitrous oxides, which are toxic, to their nontoxic components of nitrogen and oxygen gas.

> Nanotechnology will revolutionize sensors and actuators, synthetic devices that mimic biological processes like the sense of smell and muscle contraction. The field could make possible craft with warping wings, noninvasive medical testing in space and materials that self-repair. The materials of nanotechnology promise to avoid degradation from radiation exposure, a common problem in space. Nanotechnology holds the key to the next century and a true revolution in the way we live and travel -- on Earth and in space.

> It's no wonder that interest in this new technology has spread from the academic research lab to the industrial sector to the investment community.
>
> --Cynthia Kuper-Rockman; Nanotechnologist

The greatest technological leap that carbon nanotubes could provide in the field of space technology is in propulsion. Not directly, as in making a new engine from this material, but rather from providing a new means for cargo and, eventually, people to reach low earth orbit and beyond.

The concept of a space tether has been described as a "space railroad," and this description is not far from reality. Far more versatile than a railroad, however, a space tether would have applications in a wide variety of fields. Aside from space debris collection, orbital transfer, space radiation detection, and satellite formation flying, tethers will be involved with propellantless propulsion of microsatellites and launching satellites from the edge of space to low earth orbit. As the following diagram illustrates, a space tether would be able to capture a payload launched from a sub-orbital "hop ship," and lob it into orbit.

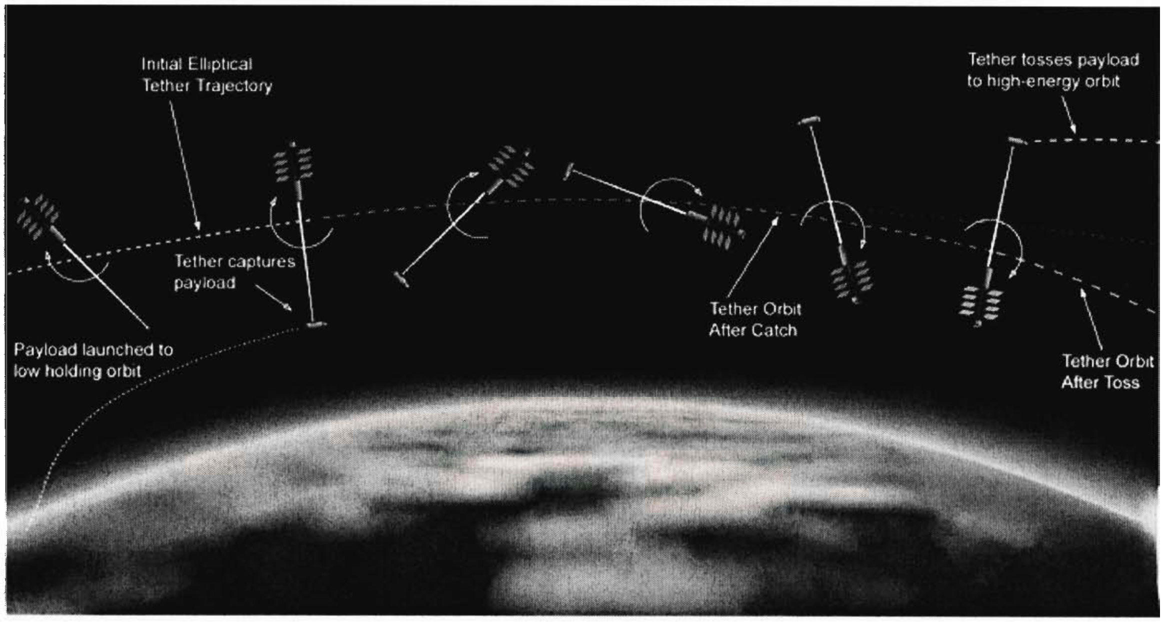


Figure 6 - An illustration of the orbital path of a "bolo" type space tether.

The preceding figure is an example of a momentum-exchange space tether. In general, an MXST connects two objects in space, so that one transfers momentum and energy to the other. A tether is deployed by pushing one of the objects away from the other. Once the two objects are separated by enough difference, the differing gravity in their orbital altitudes will cause the objects to separate on their own, which is called the "gravity gradient force." The tether is then let out at a controlled rate by resisting the gravity gradient force. Left to physics, the tether will eventually reach an equilibrium orientation that is vertical (more accurately, perpendicular to a line that is tangent to the surface of the earth).

The tether in the example is of a more advanced type, called a "bolo." A bolo is generally a long rotating cable in space that is used a sort of momentum energy bank. It catches a payload coming from any direction in its plane of rotation at any given speed less than its maximum rotation speed. It can later launch the payload in another direction in another speed. If the bolo has the property of being gravity-stabilized, then a release of the payload would result in the separation distance being up to seven times greater than initially, in the space of less than half an orbit. This can be used to throw the payload in to a higher orbit, into an escape vector, or (if the payload is closer to earth than the counter) even to de-orbit the payload. The tether's orbit would, of course, be changed by the release of a payload, but it would be boosted back into a proper orbit by interacting with the earth's magnetic field (due to the electromagnetic properties of the nanotubes).

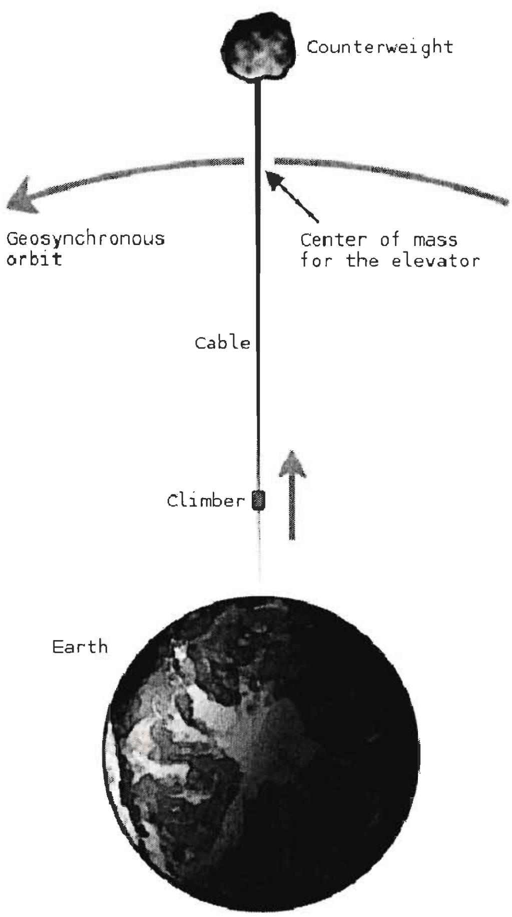


Figure 7 - An illustration of a space elevator.

More advanced than a space tether would be a space elevator. This is much farther in the future, however. A space elevator would be similar to a tether, but it would be anchored to the earth at one end, and to a counterweight at the other. It would allow a payload to be transported beyond low earth orbit without ever being transported by a rocket-powered craft. The elevator would allow very cheap satellite transport to just about any orbit desirable. If a station were constructed on or near the counterweight, human travelers who were transported up the elevator could be brought by another orbital ship to any destination: the moon and beyond.

Space tethers and elevators would allow for drastically reduced prices per pound to launch orbital payloads. Currently, it is $10,000 per pound to get into low earth orbit. A space tether would reduce this price to about $100 per pound. With the implementation of a space elevator, the price would be reduced to a point at which mass tourism would become commercially viable, speculatively $10 per pound. In addition, human and cargo would be subjected to acceleration forces far less than those brought about by conventional rocket travel.

To make all this possible, however, a breakthrough in the manufacture of carbon nanotubes would be necessary. The DNA self-assembly technique is the current leading method, and advances in that method seem to be the most likely. As our morphological understanding of macromolecules grows, this technique will be refined more and more. The creation of a protein-based nanomachine that does the job of assembly in the same way is not far beyond current technology, so it seems likely that in the near future (possibly around 2008), the new method will be developed and deemed commercially viable.

The proliferation of nanotubes will make its first impact in materials science. The strength of the carbon nanotubes will be utilized for reinforcing existing materials, such as steel in cars and boats, or plastics. Police and military bulletproof vests will take up the technology quickly, once trials showing it superior to Kevlar have finished. The nanotubes will not be created in sufficient quantities for a project such as a space tether for quite some time.

In or around 2020, the first space tether will be put into space, and, despite the initial investment, the drastically decreased launch costs will attract industry worldwide. In addition, there will be an immediate bottleneck of getting the payload up to the tether, which will encourage the development of privately-built suborbital hop ships.

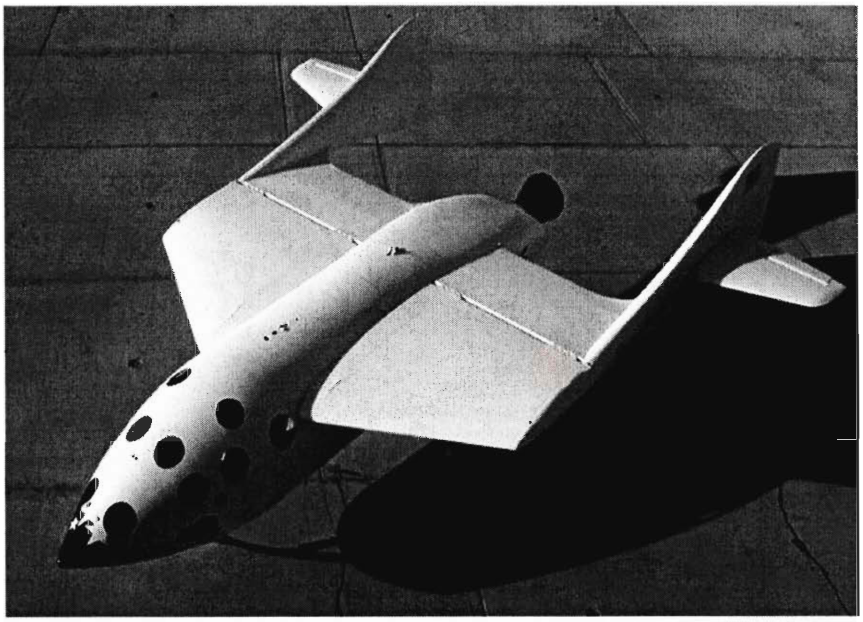


Figure 8 - SpaceShip One, winner of the Ansari X Prize in 2004.

After the success of SpaceShip One in 2004, industries have seen the possibilities inherent in the burgeoning space industry. Around 2022, or some short time after the launch of the space tether, a majority of the traffic frequenting the tether will be composed of private ships. Telecommunications corporations such as telephone and television providers will not be as dependent on governmental vehicles for satellite launches. This is not to say that every company that needs to put something into orbit will have its own spaceship, or that the government will be cut out of the picture entirely.

In or around 2027, NASA will roll out the next generation of the Space Shuttle, called the Columbia class. These ships will be designed to carry cargo and passengers up to the space tether. The ability to ferry passengers will be a feature that the government has exclusively at first, but that advantage will not last for long, as entrenched corporations will simply modify their current designs to include passenger capability. This will, however, provide an alternative for companies that need satellite launches infrequently, such as satellite radio providers.

The ability to cheaply ferry people into orbit will have great effects on the industrial sector. However, scientists and technicians will continue to be the largest population in orbit for quite some time. The first industries to require that humans be put into space and stay there will be in the fields of crystal manufacture and industrial gem fabrication. For example, the current "next step" in the manufacture of semiconductors is to use what are called "alloy crystals." These alloy crystals are proposed to be made out of a special blend of germanium and silicon, and would possess highly desirable thermoelectric and electro-optic properties—far beyond those that current materials science can produce. These crystals, however, are impossible to grow on Earth because of the effects of gravity. Experiments onboard the Space Shuttle have shown that these pencil-thin crystals grow quite readily in a microgravity environment. Cheap, reliable creation of these crystals will become possible, and the space tethers will continue to be a cheap, reliable method of orbital transport for many years to come. They will not, however, remain the cheapest forever.

Electromagnetic Shielding

One of the greatest dangers in space is radiation. There are two main classes of radiation in space. One type comes from solar flares. Solar flares are an unpredictable phenomenon related to the Sun's magnetic field. At random times a flare of charged particles will be sent sweeping through the solar system. These manifest themselves on Earth in impressive aurora effects, and are a hindrance to telecommunications. The Earth's magnetic field protects us from the worse effects. An unprotected human in deep space would fare more poorly (Buttaro).

Radiation sickness would be crippling. Death is almost certain, most likely immediately, and if not that, then within a few years from cancer. The other type of radiation is cosmic radiation. This radiation is constant. A few months of exposure uses up the astronauts' lifetime quota of safe radiation levels, but is not immediately dangerous. The only perceived effect is an occasional flash of light as a cosmic ray interacts with the vitreous fluid in the eye (Buttaro).

The current solution to this problem is straightforward. All current manned flight occurs within low-Earth orbit. This is within the earth's magnetic field and the astronauts are protected by it. In an extreme event astronauts could abort their mission and land. The only manned mission outside of the magnetic field of Earth was the Apollo missions. Their solution to this problem was to abort the mission and come home. This may or may not have been successful; if they were too far from Earth, they would not have been able to get back in time. In fact, current spacecraft construction techniques exacerbate the problem. On collision with an atom in an insufficiently thick layer of metal, a cosmic ray splinters an atom of metal into several charge particles of various sorts, which are more likely to be harmful than the original ray.

There are several proposed solutions to this problem. One is to surround the spacecraft with a radiation absorbing material. Thick metal and water are good radiation blockers. The problem is that these are very heavy. If the spacecraft's reaction mass was placed around the crew, it would block the rays. Unfortunately, as the re-mass is used up, it protects less and less, until it is gone. There would be at least a week long interval in a typical Mars mission where a solar flare would kill the crew. An intermediate solution would be to only armor portions of the ship. The crew would retreat to these "storm shelters" in the event of a radiation flare. This does not address cosmic radiation, and it may be impractical for the astronauts to remain in a shelter for days at a time.

As early as the 1960s scientists have proposed that spacecraft be shielded from radiation with EM fields (Landis). Research in magnetic and electromagnetic fields has been ongoing for hundreds of years. Both solar flare radiation and cosmic rays are positively charged. Therefore a strong magnetic field will cause

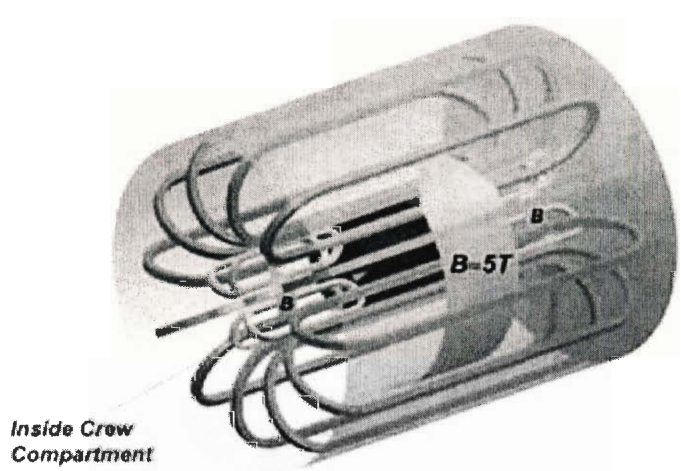


Figure 9 - Possible Superconducting Coil Configuration

them to curve around the ship. For even more protection one could also give the hull of the ship a positive charge, which would help repel the particles. This, combined with NASA's lightweight composite radiation shielding, would provide a great deal of protection.

The main enabling technology for these shields is a high temperature superconductor that can be made into wires (Landis). A superconductor is necessary to generate the type of fields in the sizes necessary. The current generation of low-temperature superconductors is not practical. They are extremely complex, and require liquid helium to cool them. They are also quite heavy.

The necessary next generation superconductors will come in the form of nanotubes. As discussed above, carbon nanotubes have many interesting electrical properties, and they will make an adequate high temperature superconductor.

The development of EM radiation shields will bring about many interesting effects and spinoffs. They will be used in space both on spacecraft and possibly in setting up space colonies. It may be more economical to bury the bulk of the colonies, but certainly the shields will see use wherever facilities must be on the surface, possibly at helium mining sites, which will have to be “roving” around on the surface of the moon, unless robots can do al the He3 mining.

There will also be effects back on Earth. A new generation of stealth aerospace craft may result, as the shield could be adapted to scatter radio waves. Consumer electronics may benefit from an improved command of electromagnetism. The superconducting properties of nanotubes would allow any plastic surface to be turned into a computer screen. A screen similar in nature to an overhead projector transparency sheet would be possible. Depending on energy requirements it may be possible to shield commercial satellites against solar flares with this technology. The most important effect of these shields, however, is that the expertise and technology gained from them will be used to perfect Helium3 nuclear fusion.

Nuclear Fusion

The main source of energy in the future will be nuclear fusion. It is one of the two main forms of atomic energy. In fusion, atoms are placed under such an extreme level of heat and pressure that they fuse together, forming heavier atoms, and releasing a great deal of energy. This energy is used to continue the fusion reaction, and some may be siphoned off for electrical energy, heat, and propulsion (Wikipedia).

Fusion is distinct from, and superior to, nuclear fission. In fission atoms are bombarded by particles, causing them to split, creating lighter particles, and energy. Unfortunately this has a number of side effects. First, since the particles used to split the atoms are the same as those that are released by the reaction, the reaction can run out of control, creating a great deal of heat, resulting in an event known as a “meltdown.” Second, when the nuclear fuel is split, the pieces that are left are a very harmful byproduct, often known as nuclear waste. This waste is highly radioactive, and will remain so for thousands of years. It must be stored deep underground. Additionally, some byproducts of fission can be used to create advanced nuclear weaponry (Holdren).

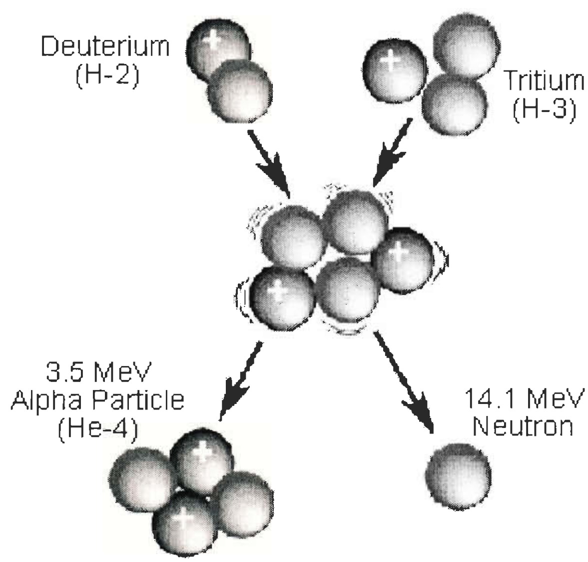


Figure 30 - Deuterium-Tritium Fusion Reaction

Fusion, by contrast, is very safe. The waste products of fusion are virtually harmless. The main waste from a fusion reactor would be reactor components that are irradiated, and must be replaced. Compared to conventional fission byproducts, this is negligible. The plasmas involved in generating fusion energy are extremely hot; however, there are a very limited number of molecules involved at any one time. Even if plasma containment was completely lost, little more than the reactor itself would be damaged (Holdren).

There are three main 'tiers' or 'generations' of fusion, based on the technical difficulty in achieving them (Rosenbluth). The bottom tier fusions consist of deuterium-tritium or deuterium-deuterium reactions. They suffer from a higher level of radioactivity than the 'higher' forms. They release a neutron, rather than a proton. Neutrons have more mass, and therefore do more damage to the reactor, 'pitting' the metals used to construct it. Since a neutron carries no charge, it is also far more inefficient to pull electricity out of the reaction. Instead of a direct conversion, an intermediate step (generally a steam turbine) is necessary. Conversely the magnetic confinement required to use these fuels is approximately 85 times less powerful than higher fusion. Deuterium is plentiful in the oceans, and tritium can be developed in breeder reactors.

The next generation of fusion reactions is the deuterium – helium3 reaction. It is cleaner than DT or DD. The particles emitted are light, and do less damage to reactor structures. Additionally the particles carry a charge, and so could be directly converted to electricity instead of with an intermediate step. Unfortunately the reactor needed is much more complex. Helium3 is extremely rare on Earth, but plentiful on the Moon. The next level of fusion is a Helium3-Helium3 reaction, which would be very clean, and powerful, but would require a very high level of technology.

Fusion research is continuing across the globe. The University of Wisconsin Fusion Technology Institute is researching many promising avenues. In France, the European Union is funding an exciting new reactor project, called ITER. The reactor actually breaks even on power, and may actually generate an extra megawatt that could be sold to the power grid.

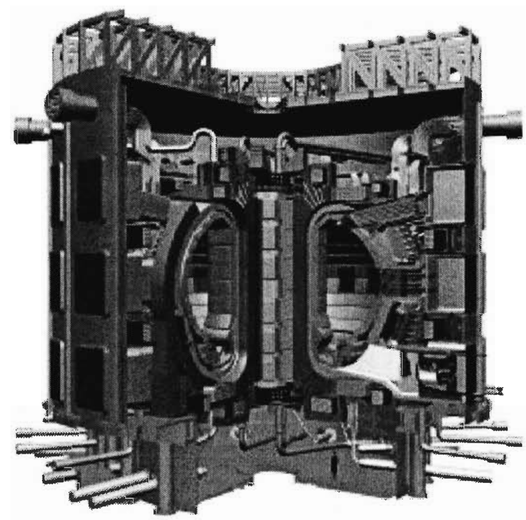


Figure 11 - ITER Reactor

Despite the benefits, fusion does not exist commercially today, because of two main technical challenges. Most research into fusion is conducted using the theory of magnetically confined plasma. This uses magnetic fields to squeeze the fuel until it fuses. Unfortunately our ability to generate these fields is generally still not up to the task. The other main problem is that of energy return. Currently almost as much energy must be put in to maintain and contain the reaction as is returned from it. This is an undesirable state of affairs (ITER).

We project that in 2020 a commercial fusion reactor will go online, most likely in Europe. The EU has the most practical experience right now in building large scale nuclear reactors. Currently they project commercial reactors by approximately 2050. However the breakthrough in carbon nanotube production would move up that timetable. Nanotubes have been shown to have many properties useful in electromagnetic field applications. Additionally, they have the potential to be a superconductor. This has the effect of speeding up the timeline that only incremental advances would suggest, with the first commercial-type fusion reactors appearing in the 2020s. Most likely the American fusion program will lag a year or so behind that of the Europeans. The USA is not spending as much, and has not built any large scale fusion reactors. However, as the fusion age looms, the Americans will not want to be left out, and will start new programs, and heavily fund those in progress that show progress.

Then, in 2030 we posit a breakthrough in electromagnetic shielding technology. This breakthrough allows us to create sufficient reactor pressures to spark He3 fusion. The Americans, with their eyes on Mars and stinging a little from the European victory in fusion, immediately begin work on a fusion space drive. Several candidates are tested and the tandem mirror drive is chosen. Then, in 2035 a commercial-style He3 reactor comes online.

The tandem mirror fusion drive is a fairly old concept (Santarius). It uses magnetic fields to maintain a fusion reaction. These same magnetic fields also allow some of the plasma to escape the rear of the drive, at a very high velocity. This produces thrust, heat, and electricity. A linear arrangement is chosen over a

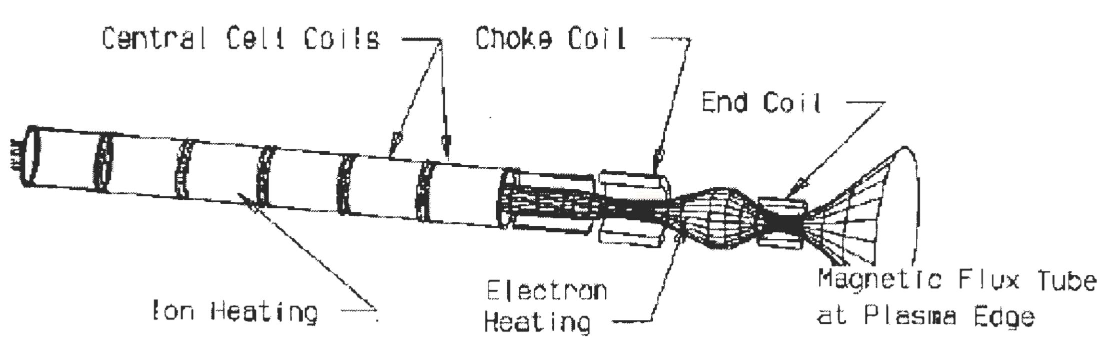


Figure 12 - Tandem Mirror Fusion Drive

more conventional toroid due to easier maintenance, more efficient heat radiation, and more design flexibility. Unfortunately, such a drive may be more than half a kilometer in length. However, the reduced cost of bringing mass to orbit makes this feasible. A spacecraft built around this drive could travel to Mars in about fifty days. If one could accept a four month trip, more than 75 percent of the spacecraft could potentially be cargo (that is anything other than drive and propellant, such as crew) (Santarius). Bulk shipments would surely travel in this fashion.

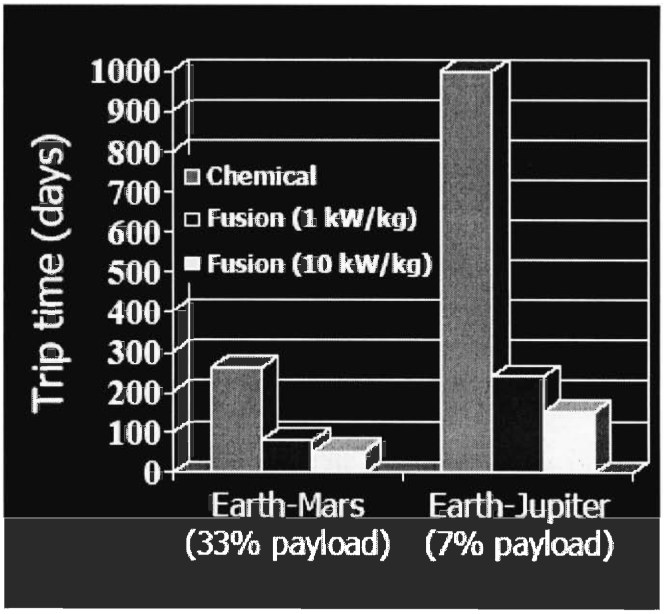


Figure 13 - Interstellar Travel Times

The social implications of fusion are vast. It opens the solar system to us. With chemical rockets, Mars and Venus are just barely within reach. With fusion drives the trip to Mars is no longer than a Victorian-age trip to the New World on an ocean liner. The outer solar system comes into our grasp. The possibility of large Martian and even Jovian colonies becomes real. Perhaps a new wave of colonization will bring humanity throughout the solar system.

On Earth, fusion power from Helium3 reactions should be quite cheap. It would be very difficult to predict how much it will cost, as that is a function of construction costs, fuel costs, and the economic climate. However, it should be considerably cheaper than fossil fuel derived power, especially as fossil fuels become rarer, and thus more expensive. Cheaper energy means more money for consumers to spend on other things, which means that a smaller overall portion of the economy will be devoted to energy production. This should raise the overall quality of life for countries that construct such reactors. Fusion drive equipped ships will make the Earth–Moon run cheaper and faster which will in turn reduce the price of fusion by shipping the fuel more cheaply.

In 2002 the United States imported 3,336,175,000 barrels of oil (DoE). At $50 per barrel that is $166,808,750,000. The per barrel price of oil will only go up in the next century, as supplies dwindle and more creative methods of extraction must be employed. Apollo 11 cost $1,740,210,000 in 2002 dollars. One ton of He3 from the moon would supply about three months of power. Three months of oil cost $55,602,916,666. Suppose it costs $2,000,000 to mine that He3 from the moon. Once the He3 deliveries become regular, it is not unreasonable to assume that they will be cheaper than Apollo 11, however, even if they don't we are replacing 55 billion dollars worth of oil with 4 billion dollars worth of helium. In Ohio, currently 27.1¢ from each dollar charged the customer on their electric bill goes toward fuel. If we use the above ratios that becomes 1.9 ¢ and the consumer's electric bill is reduced by 26%. This figure is even better if it costs less than $1.7 billion per ton to make a round trip.

The worldwide dependence on fossil fuels will be markedly reduced. Fusion produces a great amount of power that doesn't pollute, and doesn't come from oil or coal. Many first world countries will be eager to cut their strings to the oil producing nations. Perhaps some nations in close proximity to the Middle East will take advantage of plummeting oil prices and decline to change their economies over, but most will want to have the fusion option in place. This will probably reduce the west's interest in political control of this area, which may ease tensions that have led to so much violence today. Instead, the Moon will become the new "oil field," and political tensions over mining rights will require international authorities like the UN to become involved.

Lines of research that involve very high levels of energy become much cheaper. This may allow an increased pace of scientific progress in certain areas. Nuclear fusion will also advance the state of the plasma sciences by itself. This will boost the semiconductor industry

All these fusion reactors will have to be built. In the United States, they will be built by private corporations, much like the current crop of fission reactors. They may be given tax breaks, or subsidized by the government. As with any large investment in the infrastructure, there will be winners and losers. Some companies may go bankrupt, and some may be very successful. It is almost impossible to predict which energy companies will make the transition to fusion. A similar situation will exist in the European Union. France will maintain its lead in nuclear technology, but many of the other member states will opt in, in order to move away from the oil economy. Sweden, with its long history of nuclear research will also be on the forefront of fusion integration when costs decline enough to allow countries of that size to operate independently of pan-European institutions such as CERN, ESA, or the European Union.

China may be tempted to stay with a fossil-fuel-based economy as they have large coal reserves. The low complexity of fossil fuel based power plants is attractive to a large developing economy. However, they will also have several reasons to pursue nuclear fusion power. Around this time there is a strong possibility that oil will start to become extremely scarce, and therefore expensive. This is an undesirable trend. China will want at least a small fusion generator on which to do research. They will want to build a fusion drive to remain competitive in the space race with the United States. Lastly, China is attempting to enter the world stage and gain prestige, and one way to do so would be to build fusion reactors. The environmental impact of the use of coal on a scale necessary to fuel the Chinese economy when fully modernized is also a worldwide concern.

Fusion reactors are expensive. A large fission reactor costs anywhere from four to eight billion dollars to build. A fusion reactor will most likely be more expensive, due to higher complexity and exotic components like magnetic containment systems. However, the fission plant costs are often estimated to be much lower. For example, the Seabrook power plant in New Hampshire was initially estimated at $850 million. One of the two proposed reactors was finished at a cost of $9 billon and the other reactor was abandoned 23% completed. This is an extreme example, but a cost overrun of 1000% is not uncommon. This is largely because of activist opposition to the plants. The Seabrook plant's construction was marred by 25 years of court battles, constant protests and sabotage, nonviolent site occupations, and more than 4000 arrests. All this activity cost far more than the plant itself. Construction crews were often standing idly by a component and deliveries were blocked by protesters lying across the road, blockading barges with small boats.

An efficient construction program would be possible if public opinion of nuclear fusion compared to fission reactors changes. Many people will understand that fusion is much less dangerous than fission. Those who don't will undoubtedly be informed by aggressive educational and PR campaigns funded by the industry. There will still be activists, but they will be fewer in number, and less aggressive. With less public support their efforts may yield less obstruction, leading to a deal with government regulators who will address their concerns. The end result will be a net reduction in power plant construction cost. The facts that fusion pollutes far less than any fossil fuel plant and that the dwindling supply of those fuels will force a transition to nuclear or hydrogen sources make fusion much more palatable than other potential fission or fission breeder technologies or the use of coal.

All this will cause the developed world to be extremely dependent on the supply of He3. The reliance will not be total, however. Other types of power will still exist, especially the DT fusion reactors built before He3 fusion is practical. Countries with without a space program but with easy access to the sea will keep their technology alive, despite its drawbacks. Other renewable sources such as hydroelectricity and gasohol will still exist. In an extreme case the coal plants could be started back up, but these will typically be for meeting "peak" power demand, and the nuclear plants used for the "base" load.

In this brave new world, He3 related facilities on Earth will become prime targets for terrorism. They will have to be well guarded. The He3 itself, worth billions and billions or dollars per ton, will have to be well guarded as well.

In the event of conflict, a major weapon will be the interdiction of the helium supply. For smaller non-spacefaring countries this is as simple as not selling it to them. However, in the event of a conflict between the large powers it is possible that there will be economic warfare in space. A helium blockade would be utterly crippling. The best way to enforce this would be to intercept the spacecraft carrying the helium with conventional fighters in the atmosphere, before it lands. However, this may be impractical for a number of reasons, such as air defenses or escorts. If it became necessary to interdict the helium in space or seize lunar mining facilities, a situation similar to WWII's Battle of the Atlantic could result. Large fusion drive spacecraft would be highly vulnerable to current kinetic satellite killers. Smaller chemical craft, perhaps with radar stealth technology, would be much harder to detect. The best times to detect them would be during burns. They would be vulnerable slowing down to enter earth orbit, or during their deorbit.

The revolutionary new source of electricity combined with rising oil costs will result in a reduced consumption of petrochemicals. Consumption won't come to zero, because oil is absolutely needed as petrochemical feed stocks for some things, such as plastics manufacturing. Electric cars will become a reality. Cheap power, combined with new batteries derived from carbon nanotubes will finally make electric cars practical.

The reduced use of oil and fossil fuels more generally will mean a cleaner environment. Hundreds of millions of tons of dirty chemicals put into the biosphere by cars and power plants will no longer be emitted, replaced only by a few tons of slightly radioactive reactor components. Air quality will improve and be safe to breathe in severely impacted areas once again.

Conclusion

Breakthroughs are a very important facet of social impact assessment. They have the potential to transform the future enormously. As much as the world will change in the next fifty years, it will change far more if there are significant breakthroughs in the areas we predict.

Bergeron et. al. did a study similar to our, except without breakthroughs. Both studies predict fusion. However, our timeline has fusion arriving much earlier. They predict a severe oil crisis, with the world being forced to change over before it is really ready. An earlier introduction of fusion allows a smoother transition to alternative energy, which would leave a supply of oil for other uses, especially plastics and lubrication.

Their team predicted a buildup of the space industry. They predicted a small lunar base, and a buildup of platforms in LEO. A platform is a large man-tended structure that would take over the duties of several satellites, and would be easier for a human to visit, for upgrades and repairs. We predict a huge buildup the space industry. A large lunar base, possibly with permanent colonists is possible. Large scale mining of He3 would require a large infrastructure and personnel buildup. Tethers and eventually the space elevator cheapen space, so that large amounts of research and industry may be moved to zero gravity. In short, Earth’s spaceflight capacity will be increased epically.

A large amount of their report concerned the medical consequences of space flight, and they posited several advances that would help alleviate the symptoms. These advances would spin off to Earth, and result in greater health and longevity. We do not address this specifically, but it is very probable that this would occur in our predictions. However, with the breakthrough in nanotubes, there may be advances in nanomedicine that would accelerate these medical changes.

Overall, the changes we predict will be positive for humanity. The exploitation of LEO should be positive scientifically and economically. The switch to nuclear fusion will help clean up the planet. The revitalized space program will provide services for everyone. Cheaper spaceflight will allow even poorer nations to launch satellites that will make life better for their citizens.

In this study we used the Delphi method to determine the social implications of space flight in the next fifty years. While we deviated from the opinions of our Delphi panel slightly, we have shown how carbon nanotubes and fusion will pave the way toward space elevators, electromagnetic shields, advanced propulsion, space colonization and eventually, the stars.

Future Work

There are many avenues of potential future investigation. The most obvious is to create a different scenario by investigating a different set of breakthroughs. There are nearly infinite combinations of possible breakthroughs, the social implications of which could be different from our findings. A less optimistic scenario is another possible spin-off project. A look at the next half century as one of conflict, perhaps over the dwindling oil supply, could be fascinating. A different scenario would emerge from one country or bloc far outstripping the others and controlling space, compared to our relatively equal set of conditions would also be thought provoking. In several years it may be feasible to simply redo or update the forecast, taking into account actual new discoveries about fusion, carbon nanotubes, and the solar system. Our forecast has private companies entering the space arena. The situation would be very different if governments monopolize the control of space. A study which took into account technological advances in other fields, like computing and biotechnology would also be more complete and allow one to look for more interaction effects.

Bibliography

Bergeron, Aaron, et. al. Earthly Implications of a Return to the Moon; Fusion, Health and the Space Industry. 2005

Buttaro, Vincenzo. http://people.roma2.infn.it/~lazio/html/sb/. 2005

DoE, Petroleum Use Statistics. http://www.eia.doe.gov/pub/oil_gas/petroleum US Dept. of Energy Energy Information Association. 2005

Freudenburg, William R. Social Impact Assessment. 1986

Holdren, JP. SAFETY AND ENVIRONMENTAL ASPECTS OF FUSION ENERGY. 1991

Iter. ITER Website. http://www.iter.org/index.htm.2005

Landis, Geoffrey. Magnetic Radiation Shielding: An Idea Whose Time Has Returned. NASA Lewis Research Center, Cleveland, OH. 1991

Mavris, Dimitri. Implementation of a Technology Impact Forecast Technique on a Civil Tiltrotor. 1999.

ORPC. Ohio Rural Power Cooperatives. http://www.buckeyepower.com. 2004

Rosenbluth, MN. Generic Issues for Direct Conversion of Fusion Energy from Alternate Fuels. 1994

Rothman, Dale. Growing Pains: A Conceptual Framework for Considering Integrated Assessments. 1996

Santarius, John. Fusion Propulsion – Opening the Solar System Frontier. (#28 in a series of lectures). 2004

US Dept. of Commerce. Guidelines and Principles for Social Impact Assessment. 1994

Vanclay, Frank. Social Impact Assessment. 2002

Wikipedia. Nuclear Fusion. http://en.wikipedia.org/wiki/Nuclear_fusion. 2005

Yolculuk, Zamanda, Nuclear Thermal. http://www.zamandayolculuk.com/cetinbal/nuclearthermal.htm. 2004