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President's Column

by Thomas McKendree (tmckendree@msmail3.hac.com)

This is the first MMSG newsletter in a long time. A very long time. We have had a lot of failures, and a lot of successes in the last year.

Our biggest and most obvious failure was the loss of our treasurer and secretary without replacements. Steve Williams, our former secretary, is a wonderful person. In the last several years has gone on to graduate school, and fathered two children. In 1994 he told us that the mounting time pressures would force him to regretfully step down as our secretary. Even more unfortunately, at our meeting at 1994's ISDC, no one else was willing to accept the secretariat. In extremis, he agreed to continue for some time, but said time pressures were getting worse, and he really, really would have to step down soon. Being an honorable man, he was telling the truth, and stepped down last Spring. Since then, we have had no formal secretary, which is a major reason why it has been so long since you received this newsletter. This fall, charter member Tihamer Toth-Fejel got a new computer for his birthday, and so agreed to take over for the time being as Secretary. He has taken over all of the former secretary's files and activities.

Unfortunately, the loss of our previous treasurer was not as smooth. She had been treasurer for some time as well, but with less coordination, stopped. As things stand now, all of our files are not yet as in order as we would like them to be, and maintaining proper chapter relations with the NSS National headquarters has been difficult.

One of the major lessons from all this is how difficult it is to keep an organization going when it is as spread out as MMSG. Finally, with all of the turmoil in who are our officers, only one attended the last ISDC in Cleveland. So, there was no MMSG business meeting as it is supposed to be at ISDC. This was particularly bad. Since we are so spread out, the annual ISDC is the best chance to get together and build cohesion. Further, we missed an opportunity to fully and properly replace the secretary and treasurer.

All has not been failure, however, and and we can be proud of our successes. One of the most obvious successes is our position paper. MMSG and several members jointly developed a position paper on MMSG and Space. After some thought and revision, National Space Society adopted the position paper as an official NSS position paper (http://www.islandone.org/MMSG/NSSNanoPosition.html), which got the paper some exposure in Washington DC, and publication in Ad Astra. Another benefit of the position paper was indirect. Early drafts of the position paper were written by engineers, and despite being ostensibly a statement of policy, lacked political savvy. I asked Max Nelson, who was a graduate student at RAND, to look over the paper. He provided very useful and incisive comments, and in the process he was introduced to molecular nanotechnology. That became particularly evident this year, when RAND released a study he coauthored, "The Prospects of Nanotechnology for Molecular Manufacturing" (http://www.rand.org/publications/MR/MR615/mr615.html)

This is an accurate and useful report, which is helping legitimize nanotechnology in some eyes, and usefully guiding public policy. I made arrangements for as many of you as possible to receive copies. For those who did not, you may call RAND at (310) 451-7002, and order a copy. Ask for MR-615-RC.

Another success is attributable to one member, Dale Amon, who set up an MMSG site on the World Wide Web (http://www.islandone.org/MMSG/). This site has been running for over a year, and has thus become well integrated into the web of molecular nanotechnology-related web sites. We can be proud, in fact, that we are among the few sites pointed to by the Foresight Institute's Web page (http://www.foresight.org/). This honor creates a duty to maintain a good site, and we could use much more material related to MNT and space.

I have also done some work educating the public about molecular nanotechnology and space. On the usenet group sci.nanotech, a message was posted by Lenny Shaw looking for someone to interview about nanotechnology on a TV show. I volunteered as President of the Molecular Manufacturing Shortcut Group. (There was insufficient room to display all that on the TV, so I became electronically "Tom McKendree, Nanotechnology Expert": :) The show, an episode of "Studio Seven," was recorded last spring, and shown last summer on public access cable in LA. The show is a basic introduction of molecular nanotechnology for the general TV audience, using a "talking heads" format. It is possible to order copies of the tape for personal use at (Price and Studio 7, 827 Lincoln Blvd, Ste G, Santa Monica, CA 90403, (310) 394-7847, fax: (818) 341-0642, email: ad541@lafn.org). They are $15.00 per tape for 2 to 5 tapes, $10 for 6 to 10, and $8 for 11 to 20, plus postage. We may make arrangements to ensure that everyone can buy tapes at the $8 price. Also, once you have a tape in hand, you can go to your local cable operator and request that it be shown on the public access channel.

My other two MMSG efforts were papers that I presented. The first, "Planning Scenarios for Space Development," was invited from the Space Studies Institute for their tenth Space Manufacturing conference May 4-7, 1995. It presents two scenarios for how space development may proceed over the next couple decades. In each case, molecular nanotechnology becomes the most important factor for space operations. The scenarios differ in how thought out and well prepared the world is for molecular nanotechnology and its space application. This paper will be made available on the MMSG website. The second paper was for the Foresight Conference. "Implications
of Molecular Nanotechnology Technical Performance Parameters on Previously Defined Space System Architectures" discussed what space transportation and space colonies could look like, given molecular nanotechnology. A draft of the paper is available on the web (http://nano.xerox.com/nanotech/nano4/mckendreePaper.html). The intent is that this will help kick-start a process of developing worked out mission and system concepts for space operations using molecular nanotechnology.

Having discussed our successes and failures from the past, let me turn to our needs needs for the future. Our membership sign-up and renewal process is broken, and our first need is for someone who can come in and fix it. For organizational reasons, it would be best if this person could become our treasurer. If anyone is willing to help with this, particularly someone who has experience as an NSS chapter officer, please contact me. If we cannot fix this, it will be very difficult to do anything else as an organization.

Our second need is for web support. MMSG has a web site (http://www.islandone.org/MMSG/), but we need to place as much good material as possible on that site. This is the one area where we can reach a large number of people, many of whom are in a position to influence how humanity deals with the prospects of nanotechnology and space. How well the MMSG web site educates visitors may become synonymous with how well does MMSG achieve its goals.

Finally, we need good support for our newsletter. Someone willing and able could relieve Tihamer Toth-Fejel of desktop publishing and the distribution function, but what we really need are people to write articles. Could you write a review of the Ed Regis book Nano? How about reviewing fiction, like The Bohr Maker (Linda Nagata) or The Diamond Age (Neal Stephenson)? If nothing else, write letters to the editor discussing what you believe MMSG should be doing.

Molecular nanotechnology has done very well over the last couple years, gaining a great deal of credibility and academic respectability. MMSG is well positioned to capitalize on that interest, especially since why space is important in a future with molecular nanotechnology, and what we need to do about this. Now is the time to rededicate MMSG

Ad Astra per nanotechnologia!

Tom McKendree

**MMSG Appears on NASA's Radar**

At the NASA's Advanced Technologies Office in Washington, DC, John L. Anderson, Manager of the Technology Frontier Studies group is organizing a workshop on applying molecular nanotechnology to space applications. He saw a xerox of the Ad Astra article and wants to use our paper (and our officers) to inspire NASA and aerospace managers to do some innovative thinking. Specifically, Anderson is planning a workshop on February 27-29 at Disney World employing his Horizon Mission Methodology (see the January/February '95 issue of Ad Astra). The starting premise is the existence of a Lunar Territory fifty years in the future, and the task of the workshop is to back-track and identify the technologies necessary to make it happen. Our thanks to David Brant for steering him our way!

Meanwhile, the NASA educational web page on nanotechnology (http://www.nasa.gov/NAS/Education/nanotech/nanotech.html) has a pointer to the NSS Position Paper that MMSG members worked so hard to bring to completion. NASA employees Al Globus and Creon Levit are responsible for including a link called "Nanotech in Space Essay", which points to Iowa State University's Brad Hein's directory (http://www.public.iastate.edu/~bhein/xt/mmsg.txt) In addition to the Nanotech page (http://www.nanotechinc.com/NanoWorld/NanoSpace/nospace.html), to which Paul Green added the Ad Astra version including the flexible lunar crawler image, and our own MMSG web page (http://www.islandone.org/MMSG/), maintained by Dale Amon), and the NSS copy (http://www.global.org/bfreed/nss/papers/molenano.html) that means that the NSS position paper has four copies on the World Wide Web! Congratulations to all concerned! The word is getting out!

**Editor's Notes**

After a long and hard-working tenure as MMSG Secretary and Assembler Editor, Steve Williams is taking a break to fulfill his other responsibilities in life. I will be trying to follow his outstanding leadership in making this newsletter the leading publication of the intersection of Space activism and molecular nanotechnology. In order to make the job more manageable, I would like to split the job functions as much as possible. First, we are searching for a Secretary to handle the MMSG mailing list, generate mailing labels for the newsletter, coordinate with the treasurer on keeping track of members, and initiate a membership drive. Second, I am always on the lookout for good material. If you have a good idea about the synergy between nanotechnology and the human settlement of Space, The Assemble is the place to publish!

Joseph Michaels, whose article on flexible robots was published in The Assembler recently (Vol 3, No. 2), was just named "European Inventor of the Year" by the Government of Monaco, winning first prize for creativity in an invention. He also had an eight page article in Electronics Today International (December 1995 issue). It feels good to scoop the world!

**Micro Technologies for Spacecraft**

Though most MNT (molecular nanotechnology) experts agree that microtechnologies are not necessary to develop nanotechnology, these technologies may still be useful in developing Space, in addition to inspiring new ways to develop or apply MNT. At the Practical Robotic Interstellar Flight Conference in New York (August 1994), Roger G. Gilbertson and John D. Busch presented "A Survey of
Micro-Actuator Technologies for future Spacecraft Missions.* They reviewed ten basic actuator technologies, including electromagnetic, electrostatic, thermomechanical, phase change, piezoelectric, shape memory, magnetostrictive, electrorheological, electrohydrodynamic, and diamagnetism effects. The presentation covers recent micro-actuator developments in each of these technologies, their method of operation, design limitations, comparative performance, and their potential spacecraft applications.

They found that actuator methods which have already been realized as micro machined products or in advanced laboratory studies include electromagnetic, electrostatic, piezoelectric, thermomechanical, phase change, and shape memory alloy technologies. Methods for actuation which have been demonstrated in the laboratory on a micro scale include electrohydrodynamic, magnetostrictive and diamagnetism technologies. The other methods have been demonstrated in macro devices and will likely be studied in micro devices in the near future.

For use in small spacecraft, different technologies have different advantages. For example, electrostatic and electromagnetic type devices provide efficient operation and low forces. Piezoelectric devices are excellent for large force, small displacement applications where higher voltages are available. Phase change actuators exhibit large amounts of work output per unit volume and are good choices for applications where ambient temperatures remain fairly constant. Shape memory alloy devices provide extremely high work output density and can be actuated directly by joule heating. Both of these technologies, as well as thermomechanical methods, are best suited to applications with moderate ambient temperature variations.

Several methods await appropriate space applications. Magnetostrictive can provide extremely high work output density and fair energy efficiency. Electrorheological and electrohydrodynamic techniques provide ways of directly manipulating fluids and may provide great mass savings by reducing the supporting parts needed for pneumatic and hydraulic systems. Superconducting materials exhibiting the Meissner effect should find wide use in space applications, where low operating temperatures are readily produced.

Additionally, appropriate combinations of various methods should lead to synergetic gains. For example, the Meissner effect may find application in reducing friction in micro scale electromagnetic and electrostatic devices, thereby increasing their performance and efficiency.

The full report, with excellent graphics, is available on the web at http://www.nanothinc.com/nanosci/microtech/mems/ten-actuators/gilbertson.html

Announcements

International Space Development Conference (ISDC)

will be May 23-27 (Memorial Day weekend) 1996, at the Grand Hyatt New York. Detailed conference information at:
http://pages.nyu.edu/~rjn1039/isdc96/isdc.htm
or write to:
Greg Zsidisin, Chair
c/o Space Expos
PO Box 71, Maplewood, NJ 07040

The Fifth Foresight Conference on Molecular Nanotechnology

The conference will be held in the fall or winter of 1997, in or near Palo Alto, California. It will be a multidisciplinary meeting on molecular nanotechnology, that is, thorough three-dimensional structural control of materials and devices at the molecular level.

We will be making even more extensive use of the web for the 1997 conference. In particular, all papers must be submitted in HTML. For more info, see http://nano.xerox.com/nanotech/nano5.html

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Subscription and Membership
Nanotechnology has turned a large corner in terms of growth, interest, and acceptance.

The Fourth Foresight Conference on Molecular Nanotechnology

by Thomas McKendree (tmckendree@msmail3.hac.com)

The best and shortest review of the Fourth Foresight Conference on Nanotechnology is to say "go to the conference web site (http://nano.xerox.com/nanotech/nano4.html)." What follows is an extensive personal review.

The conference was held in Palo Alto November 9-11, 1995, with side meetings on November 11 and 12. It was clear from the meeting that molecular nanotechnology has turned a large corner in terms of growth, interest, and acceptance.

Major Highlights:

- Roughly 300 people attended, making this was the largest Foresight conference ever.
- Most of the speakers were more prestigious than before. In the case the person had spoken at a previous conference, their intervening work had often raised their prestige.
- Of particular interest for those of us who want to see nanotechnology developed and used in space, NASA Ames has announced the launch of a major effort in "computational nanotechnology," the molecular simulation of nanotechnology engineering concepts. Their long-term goal is to simulate an assembler. This is roughly estimated as requiring the simulation of 100 million to billion atoms. Subhash Saini, who spoke of their plans, showed a computer roadmap which included the use of strong molecular nanotechnology in aerospace systems in 2015. NASA Ames is soliciting collaborators (who will be able to use their computers), and will hold a "Computational Molecular Nanotechnology Workshop" at Moffett Field March 4-5 (http://www.nasa.gov/NAS/Training).
- The Feynman prize grew. It was first awarded two years ago for $5,000. This time the award was $10,000. At the conference someone raised the idea of establishing a fund endowment and adding a grand prize (criteria still being defined). This idea raised $200,000 from four individual donors at the conference in ~24 hours. Anyone who wished to contribute money or ideas to this effort should contact the Foresight Institute directly (PO Box 61058, Palo Alto, CA 94306 USA, tel 415-324-2490, fax 415-324-2497, email: inform@foresight.org)
- Eric Drexler unveiled the full atomic detail of all the parts for a fine motion controller, able to move its tip in fine six-degree-of-freedom trajectories, under cam control. The particular cam shown implemented the push-slide-rotate-pull operation analyzed in detail for one sequence in the mechanosynthesis of diamond.
- In less formal discussions of business implications, there was some agreement that ideas for how molecular nanotechnology should grow over the next two decades implies an annualized growth rate on the order of 100%.

Thursday, November 9

The conference was opened by Dr. Ralph Merkle. He welcomed the roughly 300 people, which more than doubled the previous conference. In his introduction he said the conference about achieving the following long range objectives:

- Every atom in its place
- Manufacturing costs near raw material and energy cost
- for a broad range of structures

This set of objectives is increasingly viewed as achievable and worth pursuing. Most people also add two further objectives, positional control (to put parts precisely where desired) and self replication (for low capital cost).

His second point was to emphasize using the World Wide Web:

- Learn HTML
- Put your work on the Web
- Link to others
- Quality control
- Back-links are coming
- A lot of people are working hard on sorting mechanisms.

He emphasized the need for nanotechnology research, which is interdisciplinary, complex, filled with important implications for business and governments, and fast moving, to use web extensively. Dr. Merkle maintains an excellent nanotechnology web site at http://nano.xerox.com/nano
He then discussed a figure that showed branching growth from our current capabilities due to experimental progress. At the same time, there could be work using computation exploration, branching backward from the final goal of molecular nanotechnology. At some point nearer the middle, a branch from one direction will link up with a branch from the other direction, and we will have a final roadmap for developing molecular nanotechnology.

Research can fall into a number of points in such a figure. We can examine proposals in remarkable detail, even though we cannot yet build them. This "meet in the middle" strategy will allow us to get to our goals more quickly and effectively. Since there are multiple pathways, the answer to the question: "Is a particular experimental result moving us towards MNT?" depends on an assumption of what MNT is.

Dr. Merkle suggested that the goal looks something like Convergent Assembly (http://nano.xerox.com/nanotech/convergent.html). He discussed the results in this paper, the main conclusion being that high throughput low cost manufacturing of large, complex, atomically precise products is scientifically feasible.

Dr. Merkle then previewed the various speakers, and discussing where each person's work fit into Dr. Merkle's figure. His concluding chart was:

"Molecular Manufacturing:
Its feasible -- Its valuable. -- Let's do it."

Richard Smalley

Richard Smalley, head of the Rice Nanotechnology Initiative, said "It's a thrill to come to the conference and see how its flowering. There must be something good going on for so many people to show up."

He discussed the Nanotechnology Initiative at Rice. The first premise is that the size scale of 1-100 nanometers is a key future area for nearly all science and engineering disciplines. The second premise is academic departments form self-centered clusters, like Feudal Kingdoms. The Rice Nanotechnology Initiative is increasing interactions between disciplines. He said, "The science/engineering barrier is one of the hardest to break down."

Dr. Smalley sees three parts to nanotechnology, Dry, Wet, and Computational Nanotechnology. Different Institutes at Rice are already focusing on these different areas. The Nanotechnology Initiative is meant to bring them together. The initiative's External Advisory Board includes such luminaries as Heinrich Rohrer, Peter Schultz, Paul Chu, Jean-Marie Lehn, George Whitesides, J. Fraser Stoddart, Calvin Quate, and Stanley Williams (of UCLA).

The rest of his talk focus on particular capabilities and projects in wet and dry nanotechnology, particularly at Rice. One key point was that he did not want the whole field to be identified with the necessity of a universal assembler. There was discussion during and after the talk on what this meant, and it was made clear that the proponents were in favor of a very flexible assembler, but not a "universal" assembler. Part of the difference was clearly different time scales. Discussing one project, Dr. Smalley said "In the long distant future, we hope meaning within a year, ..." while none of the proponents believe that an assembler is plausible before the turn of the century.

William Goddard

Dr. Goddard from Caltech spoke on different sorts of models and specific work from his group. At Caltech they are able to do molecular dynamics with on the order of ~1,000,000 and more atoms. They also have molecular modeling software, MPSim, in which the methods scale linearly with size for large systems. The method also scales linearly with the number of CPUs, and thus parallelizes nicely.

Recent work includes a simulation of all the roughly 516,000 atoms of the protein coat of a virus, and a simulation of the molecular planetary gear from Nanosystems. The gear was loaded with a 500 GHz impulse on the axle, which is much greater than the gear was designed for. It survived in the simulation, but wobbled and slipped in ways it would not have if run slower. Dr. Goddard made some suggestions for how the gear could be improved for greater performance. He reviewed other work in his group, including computational examinations of self assembled monolayers, and a proposed mechanism for the formation of C60 from the roll up of two C30 rings.

J. Fraser Stoddart

Dr. Stoddart has synthesized a number of separate covalent structures which mechanically interlink, including his "molecular shuttle" work. He discussed his chemical synthesis strategies. This included catenanes, and by implication he is looking at the concept of self-assembled catenane arrays usable for information processing as dense molecular mechanical components.

Feynman Prize Luncheon

The Feynman prize is awarded every other year at the conference to the researcher who has made the greatest contribution towards the exact goal of molecular nanotechnology. Last conference's winner was Charles Musgrave, who conducted ab initio calculations of mechanosynthetic steps for the fabrication of diamond, including the selection of a hydrogen abstraction tool.

This year's winner was Nedrian Seeman, who has been working on building complex structures out of DNA. The advantage of this approach is that he can easily define complimentary surfaces, and have particular parts bond to particular other parts.
The first year's award was $5000. This year the award was $10,000. At the conference, the idea of a permanent endowment for the Feynman Prize was raised. This led to the donation of $200,000 for the endowment, with the intention of establishing a grand prize, for the major final step, perhaps building the first self-replicating, easily programmable, general purpose assembler, which will pay-out the entire endowment to the recipients.

**Eric Drexler**

Dr. Drexler began by explaining that much of his work is in the area of possible, understandable systems which are not yet manufacturable, which he calls exploratory engineering. He presented a second generation planetary gear design, and "In a continuing program of putting automotive technology into the nanometer realm" he presented a molecular differential gear which he had designed. With the casing, this gear is comprised of roughly 4,500 atoms.

He then discussed a series of molecular designed mechanical parts. A particularly difficult challenge had been designing properly behaving molecular springs. This part of the talk culminated with of summary of how the parts fit together into a 6 degree of freedom fine motion controller (a very accurate robot). In the approximation that a cam can be called a program, it is a programmable machine. This device consists of roughly 10,000 atoms.

His overview of long-range goals set the target of simultaneously accomplishing synthesis that is: 1) atomically precise; 2) aperiodic; and, 3) three dimensional. Examples of 2 and 3 are trucks and nanolithography. Examples of 1 and 3 are crystals. Examples of 1 and 2 are one dimensional DNA and two dimensional surface modifications using scanning probe devices, such as the 35 Xenon atoms that spelled out "IBM" on a Nickel surface. Combining 1, 2, and 3 will give us molecular manufacturing.

In a review of how achievable performance parameters will improve, one we develop molecular nanotechnology, Dr. Drexler sees the strength of materials going from ~1 GPa to ~50 GPa, power conversion densities going from ~10 megawatts per cubic meter to ~10^9 megawatts per cubic meter (for systems small enough to not melt themselves), desktop computation going from~10^9 IPS (Instructions Per Second) to ~10^18 IPS, and the period required for capital doubling to go from ~1 decade to ~1 Hr. To accomplish this, he sees as necessary, and feasible parts density going from ~10^6 to ~10^26, and parts counts for systems going from ~10^6 to ~10^26. His sense of the time scale for all this is that it will occur early in the 21st century. In less than 10 years would be surprising. In more than 30 years would also be surprising. Maybe 20 years. This was a particularly compelling talk.

**Aristides Requicha**

Aristides Requicha, a roboticist from the computer scientists at USC spoke on "Molecular Robotics." This was primarily a review of robotics, with the relationship to scanning probe nanotechnology made clear where possible.

**Admiral Jeremiah**

Admiral David Jeremiah (retired) was Vice Chairman of the Joint Chief of Staff. During that time he got very interested in molecular nanotechnology as a possible major component of the future. His talk was a fascinating overview of the "middle" view of possible scenarios for early in the next century, the world just before molecular nanotechnology is introduced. This was also a very interesting talk about the possible future, although not really about molecular nanotechnology.

**Demos, Exhibits, Posters**

There were a number of good posters. Two were by Dr. James Ellenbogen of MITRE, who has completed a two-year internal MITRE study on nanotechnology, focusing primarily on nearer term applications for nanoelectronics. His posters were, "Technologies and Designs for Electronic Nanocomputers," and "Self-Assembly, Virtual Fields, and Matter as Software."

A group of researchers from Oak Ridge National Labs presented a number of posters on different molecular modelings of nanotechnology possibilities.

**Friday, November 10**

Dr. Merkle, while chair of the conference, also gave a talk on "Design Considerations for an Assembler" Friday morning. The objectives for the device were that it could flexibly synthesize diamondoid objects, including itself, to minimize assembler complexity (by increasing complexity appropriately in the environment). The approach is a broadcast architecture, wherein the assemblers are controlled from off-board computers via acoustic signals. One very good contribution was a design for a constant force spring. Much of the talk was taken up with possible designs for simple binding mechanisms that could selectively bring building materials in from the environment.

**Richard Colton**

The Naval Research Laboratory has been paying close attention to molecular nanotechnology for at least four years. Richard Colton gave a talk on "Tip-Surface Interactions." He mentioned a wide array of scanning probe microscopies. He discussed applying positive forces, and testing the mechanical properties of nano-scale regions and nano-indentations. The rest of the talk then focused on the chemical force microscope.

His group has mounted individual tips and made and measured nanoindentures, which may be systematically underestimating material
properties. On the other hand, thin film mechanics could be different than bulk mechanics, so there are many unknowns involved. Dr. Colton thought buckytubes would work ok tips, as long as they were not too long. Their lab plans on using the SPMs to measure chemical affinities.

Charles Musgrave

Dr. Musgrave is examining the reactions which occur on the surface during the fabrication of Large Scale Integrated circuits (computer chips). More specifically, he is studying the reactions using ab initio techniques. Nanotechnology-related research interests for his group is the positioning of scanning tips to initiate:

- Patterning,
- Transport,
- Surface reactions

Since Dr. Musgrave developed the nanomanipulation sequence that Dr. Drexler used in his fine motion controller (push, slide, twist, pull), that process was reviewed in some detail.

Donald Brenner

The talk "Simulated Engineering of Nanostructures" should have been "Towards...," as it did not actually reach the level of actual engineering exercises. Dr. Brenner was at the Naval Research Laboratories, but now is on faculty at North Carolina State University Raleigh. This talk reviewed molecular simulations of three approaches for manipulating with an SPM:

- Application of Mechanical Forces
- Application of a Potential Bias
- Use of Chemical Forces

Elizabeth Enayati

During lunch, Elizabeth Enayati discussed changes in intellectual property law over the last year or so. There were many interesting general points. With respect to mature molecular nanotechnology (which is many years off), provisional patent applications are the only approach besides trade secrets in the US for trying to protect specific ideas for such future products, and they do so poorly.

George Whitesides

Many believe that Dr. Whitesides will someday win the Nobel Prize in Chemistry, and his talk on "Self Assembly and Nanotechnology" was quite anticipated. His talk was a number of points and advice for the molecular nanotechnology research community.

New top-down approaches are coming, delaying the need for bottom-up methods. Trying to make small things which are not at thermodynamic minima is too hard, he claimed, arguing for chemical self-assembly.

He suggested that when thinking of assembly, think about assembling molecules, not assembling atoms. Atoms and molecular fragments are real reactive--avoid this pain. He urged us to think about cells, which have a lot to teach us, at every level. He also discussed work on self assembled monolayers (SAMs), and suggested examining various light technologies, such as light molasses, subtractive patterning of light and guiding patterning with light, optical tweezers, and optical traps. Much of his talk was also on microcontact printing (an alternative to photo-lithography), which has a limit of a few tens of nanometers.

Tracy Handel

Tracy Handel spoke at the first Foresight Conference on work done in de novo protein design. Here she discussed reasons for de novo protein design, such as making proteins with novel properties (catalysts, new materials, therapeutics), and the fact that proteins have single molecular weights while polymers have dispersed molecular weights. At this point, we can predict reasonably secondary structure of proteins (motifs) from primary structure (sequence), but not tertiary structure (overall folded shape) from primary structure.

Bruce Gaber

Also at the Naval Research Laboratory, Gaber gave the talk "Towards the Molecular Machine Shops", based on the premise that scanning probe microscopes are similar in some respects to milling machines. At the Second Foresight Conference in 1991, he speculated on molecular machine shop, and that became a story in the 26 November 1991 issue of the NY Times. In an attempt to work toward this goal, his group has sheared a lipid tubule, re-annealed the tubule using an SPM. They demonstrated SPM manipulation in a number of ways, developed a means of addressing a surface so that one can returning to the same spot, demonstrated that beads with bound enzymes can be enzymatically active, and are on the verge of scanning surfaces with enzymatically active beads using the atomic force microscope.

Neil Jacobstein

Neil Jacobstein is President and COO of Teknowledge. This was an excellent presentation. His situation assessment of molecular nanotechnology is that the applied science basis for feasibility in place, we are currently experimenting with designs, we are still in the R
Molecular manufacturing will do to molecules what computing did to bits. This will provide precision, speed, scale, programmability, economics, radically new application possibilities. It is important to remember, however, that a technological revolution by itself does not equal to a business. A business needs revenues and profits. Most of the talk was Jacobstein's ten lessons for businesses, taken from the computer industry, which he felt would be applicable to molecular nanotechnology. Each was discussed in some detail.

- Lesson 1 Being first is not enough.
- Lesson 2 Clarity of vision is not proximity to the goal.
- Lesson 3 Innovate in as few dimensions as possible.
- Lesson 4 Distinguish Technology from Markets.
- Lesson 5 Patents provide limited competitive advantage.
- Lesson 6 General purpose architectures absorb special purpose solutions.
- Lesson 7 Harvest R & D and people from ripe, publicly funded research projects. There is no substitute for a first rate, ramped, highly motivated technical talent.
- Lesson 8 Creating common business goals, shared values, and effective culture is not optional.
- Lesson 9 The road to riches is built upon core competencies.
- Lesson 10 There is no finish line.

Panel: Paths to Molecular Nanotechnology

The panel was moderated by Dr. Merkle, and consisted of Dr. Whitesides, Dr. Colton, Dr. Handel, and Dr. Gaber. Dr. Whitesides the following test: "Imagine every experiment works perfectly and better than anticipated. So what? Once the answer to that is clear, there is an infinite amount of money." Dr. Colton was concerned about the semiconductor industry, in which projected roadmaps run out of steam in 2007-2010 time frame. Dr. Handel observed that this was the first good year in protein design. Dr. Gaber suggested that the appropriate lessons for molecular nanotechnology are from the biotechnology industry, not the computer industry. The breakthrough products are likely simple with huge markets, and he foresaw mature molecular nanotechnology in 30-35 years.

Panel Conclusion

In response to questions from the panel on what could be accomplished using molecular nanotechnology, Dr. Merkle mentioned space applications, medical applications, waste treatment and land reclamation. The potential is extraordinarily powerful, and "If we have not communicated to the world at large that there is useful things that we can do with this, we have not communicated well, or we have not thought well what we can do."

Saturday, November 11

Paul Sheehan discussed using an atomic force microscope (AFM) to manipulate molybdemum trioxide nanocrystals on a molybdemum disulfide cleaved surface. The nanocrystals will not "derail" from the atomic rows in the surface, but could be slid along the rows and rotated. He was able to slice the nanocrystals using the AFM, and he built a latch and notch locking mechanism between two nanocrystals.

Geoff Leach

After speaking at the last conference, Geoff Leach was back from the Royal Melbourne Institute of Technology in Australia. He has used his skills to design software to assist in the creation of files of atoms which represent molecular mechanical designs. The software is called "Crystal Sketchpad." He illustrated how it works, and it can best be described as a 3 dimensional "MacDraw" operating on molecular crystals.

He showed a design of two wheels on bearings with a conveyor belt running between them, all of several thousand atoms. This software does not do the energy minimization for finding the exact relative positions of atoms. His software is intended to be available on the web in a couple of months.

Rod Ruoff

Rod Ruoff of SRI looked at nanotubes (buckytubes) embedded in a plastic called Formvar, which he was able to deform and then examine. He also performed computer simulation of tubes under stress. His conclusions were that single walled tubes can be very flexible, that nested tubes can be very stiff, and that all are very strong. The tensile strength of these nanotubes were measured at ~20 GPa. Also, his analysis of pure continuum models found results not too far from ab initio techniques.

He found that nanotubes can experience local buckling without breaking, which pinches off potential flow, and perhaps could be used as a switch. Nanotubes often have internal closures. These act as local reinforcement, so buckling tends to occur nearby. Theoretical calculation says that one can stretch a nanotube 50% and still be in the elastic range. Nanotubes could be used as plumbing, axles, tension elements (wires), joints (bending at specific points), mechanical switches, and conducting elements. Nanotubes could be the fiber of choice for fiber composite materials.
There was discussion of attaching chemicals to the end of a nanotube. Enormous functionalization may be possible. One audience comment near the end was "Nanotube is a two-by-four, and all we need is a nail."

**Subhash Saini**

There were many people from NASA Ames at the conference. They are kicking off an effort to do intensive computer simulation of molecular nanotechnology systems to atomic detail. This provided the motivation for Subhash Saini's talk.

There is a great deal of computing power at NASA Ames. They have several supercomputers, including two C-90 clusters, and an aggregate capability of 80 GFLOPS with 44 Gbyte of storage. He showed several pretty pictures illustrating their computational fluid dynamics efforts. These took many hours of supercomputer time.

He mentioned as possible NASA-related uses for molecular nanotechnology nanocomputers and smart nanorobots for in situ exploration. Much of the talk was devoted to a review of different possible future computing approaches, including some exotic approaches (e.g. Single-Flux-Quantum Circuits), and different supercomputer architectures. He presented a roadmap for improving silicon computer chips -- a roadmap that started to run into significant uncertainty in the 2004 time period.

He also discussed the different models of molecules that exist, from Semi-Empirical through Full Configuration Interaction, and their tradeoff of more speed and complexity or faster running time. Their approach will be to do extremely accurate simulations in small systems, and fold up the results to larger objects.

Their long term goal is the "modeling capacity to simulate the entire assembly of a hundred million to on billion atom assembler." They presented a roadmap for the development of molecular nanotechnology, and of the computers necessary to support that development. The roadmap had in 2005 Peta Flops available for nanoCAD and nanoCAM, planned for nano devices in 2010, and saw in 2015 both future nanocomputers and nanotechnology based future aerospace systems.

One of the questions asked how we could say that we will need a certain shown level of computing power for atomic modeling years in the future, given ongoing work in developing faster running and better scaling algorithms? The answer was that the charts shown assumed no improvements in algorithms, and algorithm improvements would lead to the capability to design and model more powerful molecular systems sooner.

Note: NASA Ames is holding a "Computational Molecular Nanotechnology Workshop" at Moffett Field on March 4-5. Information on this workshop will be maintained at [http://www.nas.nasa.gov/NAS/Training](http://www.nas.nasa.gov/NAS/Training) and there will be no registration fee.

**Tom McKendree**

I gave a talk based on my work at USC on space applications of molecular nanotechnology. The paper started with a review of how to think about implications at different levels and discussed the need to grapple with the future through iterative approximation. I reviewed molecular nanotechnology implications for rocket launch vehicles, solar powered interplanetary propulsion, and space colonies.

**Stephen Gillett**

Stephen Gillett gave a talk on using early versions of molecular to extract particular elements from a background of many elements. This is an enormously important and commercially significant area, encompassing mining and environmental remediation amongst other tasks. It was his contention that primitive molecular nanotechnology could provide the materials for appropriate sorts of filters, which would not need moving parts, and that this would have enormous economic benefits, hastening the further development of molecular nanotechnology.

**Paul S. Weiss**

This was an interesting presentation discussing ongoing experimental work at Penn State University, measuring the properties of self-assembling molecular systems.

**Tanya Sienko**

As a member of the Japanese government, Sienko said that all her remarks should be considered unofficial. In Japan, Nanotechnology seems to refer to anything on a nanometer scale, usually inorganic. She gave a long list of examples. The most unusual inclusions on the list were cellular automata, evolutionary techniques, and micromachines. Basically, any Laboratory with an STM hidden in the back will claim to be working on nanotechnology. She discusses a number of locations where relevant research is in progress, including NAIR, ETL, and ATP, all under MITI, several universities, and under the Science and Technology Administration, Riken and the ERATO projects of JRDC.

Her most significant point was that molecular nanotechnology is being taken so seriously in Japan that the Ministries are talking to each other about it, which is nearly unheard of behavior. She discussed many projects and organizational structures that seem to be related. One the phenomena is that Japan has decided that it is behind and needs to catch up on biotechnology, and this is creating a great deal of related effort that is confusing when looking at molecular nanotechnology.

She spent some time on a Delphi study conducted by NISTEP that expects some molecular nanotechnology precursors in 2001, and
more mature molecular nanotechnology in the 2008-2011 time frame. She said that despite appearances to the contrary, Eric Drexler’s ideas of “strong nanotechnology” have not yet permeated the Japanese research establishment. This is in part because Japanese research projects are defined at policy level, and these people do not really understand the technology or its implications.

Nonetheless, work is going on in all the relevant areas, except virtual [computational] nanotechnology. When asked if Japan was in a state where, given some motivation, the nation could refocus ongoing projects into a very powerful effort focused on strong nanotechnology, Ms. Sienko said that this could happen very fast.

Hypertext Publishing Overview

There was a meeting in parallel with the conference discussing the evolution of the World-Wide Web, and prospects for hypertext using that as a basis. Markus Krummenacker is working under a grant from John Walker to develop three software packages that would allow people to establish backlinks (links to pages which can be made to appear as if embedded in the original documents). Issues included filterable link types, making sure the protocol does not require the active assistance or permission of the pages, and was how to develop fine-grained backlinks (to particular words or phrases), all using the web as the basis from which to build.

Sunday, November 12

The conference Chair, Merkle, felt the conference went very well. They had anticipated 150-200 attendees, and got roughly 300. The major groups of molecular nanotechnology researchers which have emerged are:

- The Material Process and Simulation Center at Caltech (Bill Goddard’s group)
- The Naval Research Laboratory
- The emerging group at NASA Ames, which may bring fantastic computer resources to bear, but are just starting up
- A group of researchers centered at Oak Ridge National Laboratory

And these groups are spreading. (Charles Musgrave from Caltech is at a Post-doc at MIT, and will join the faculty soon at Stanford.) He didn’t mention, but there is also most notably the group centered around the Foresight Institute, which includes himself and Eric Drexler.

Dr. Merkle also discussed the involvement of NRL, and noted that the military does have efforts in long-range planning that reaches out 20 years (and even 40 years sometimes), and they are technologically informed. Almost no other institution in the US even looks out this far. It came out in the discussion that NRL has put together a report on nanotechnology efforts in Europe, and is trying to do one for Japan.

Dr. Merkle also discussed briefly the limited assembler design he is working on. When done, he will then work on creating an even more primitive and limited design, that possibly could be built from proteins or macromolecular synthesis, and could lead to the fabrication of the design he is currently working on.

Web Upload Project

I sat in on a discussion of how to implement the plans the Foresight Institute has for Web uploading. This is more ambitious than I realized, in that they intend to be a “Web based” organization rather than a “paper based” organization. This means that every word and file they generate will be accessible on-line using HTML browsers and HTTP servers. This includes all internal documents. They will continue to print a paper newsletter, but that will become just a summary of the “official” newsletter, which will be printed on the Web and have more extensive articles.

Business Exploration Presentation

There was an afternoon discussion of possible business opportunities in molecular nanotechnology. Most of the discussion was based on a model of developing early application of assemblers in roughly 2015, with a very roughly estimated of total revenues in a molecular nanotechnology industry at that point of $1 trillion (and rapidly growing).

Simple-minded calculations suggest that the total level of investment, e.g. people working per year in the field, must grow at an annualized rate of ~100%. The main presenter then argued that this growth cannot be a sudden jump, but must be smoothed out somewhat for various reasons of institutional inertia. Many of these phenomena imply that in the later stages the revenues would also be growing at an annualized rate of ~100%.

Conclusion

Audio and video tapes of the conference can be ordered from Sound Photosynthesis. Audio tapes each hold one presentation, and cost $10 (plus CA tax and shipping). Video tapes hold two or three presentations (roughly two hours total), and cost $35 each (plus CA tax and a $3 shipping charge). Address: Sound Photosynthesis, PO Box 2111 Mill Valley, CA 94942-2111, USA; soundphoto@aol.com; 1-800-815-7999.

In summary, the conference went very well. Molecular nanotechnology is starting to enter the main stream of thought in long-range science and technical research, although the implications of actually developing molecular nanotechnology remain largely unexplored in the policy mainstream. From MMSG’s point of view, it is important that the NASA Ames research goes well because it may be important for the development of molecular nanotechnology for space operations.
"Nanotube is a two-by-four, and all we need is a nail."

Using Mechanosynthetic Assemblers to Build an Orbital Tower

by Jerome D. Rosen (rosen@walnut.csp.mmc.com)

%From nanotech@cs.rutgers.edu Tue Apr 4 18:43:22 1995

Space advocates have long desired to decrease the cost of space travel. A method known since the 1960s is the construction of an orbital tower, a long structure or cable in synchronous orbit with one end touching the surface of the Earth. Such a tower could support elevators moving freight and passengers up to synchronous orbit and beyond, and down to the surface, at a cost per kilogram orders of magnitude less than modern rocketry, with passenger safety comparable to a train or subway. However, no ordinary material has the tensile strength needed to build such a structure.

Nanotechnology is the anticipated industrial capability of specifying and building products atom by atom, resulting in atomically perfect structures of any desired chemical composition. A favorite product material of nanotechnologists is diamondoid, a generic word describing any mechanosynthetic object that relies on tetrahedrally (sp³) linked carbon atoms forming a rigid, space-filling lattice as a major part of its design. Diamondoid should be strong enough to serve as a construction material for an orbital tower, and cheap enough to make the tower's construction feasible, given an already orbiting source of carbon and other elements. The construction of an orbital tower would be an excellent bootstrap project for nanotechnology specifically, and a huge benefit to humanity in general.

The Orbital Tower

The idea of an orbital tower is originally credited to Yuri Artsutanov, a Russian engineer who in 1960 published his idea of a "heavenly funicular" [1]. Other authors [2,3] have expanded on this concept in technical literature, while Clarke [4] and Forward [5] have furthered the idea in popular fiction and non-fiction respectively.

An essential attribute of the orbital tower is that, despite appearances, it is in orbit. In order to keep that perspective, the following visualization exercise is helpful.

Start with a synchronous satellite (technically, an object in a 36,000km circular prograde orbit of zero inclination). Its orbital period is 24 hours, in lockstep with the Earth below. To an observer on the Earth, the satellite appears motionless in the sky, because it is orbiting the Earth at the same speed with which the Earth is turning. This is very useful for communications satellites, because ground antennas can be pointed once and then left alone. (I am ignoring orbital perturbations and station keeping for now.) Now give the satellite a rotational period of 24 hours, so that it always presents the same face to the Earth. (Commsats do this as well.) The satellite can be any shape, as long as its center of attraction is at the proper distance from the Earth. Now elongate the satellite like a spear, with the point towards the Earth and the tail away from Earth. Again, as long as the center stays where it was (meaning for every bit of stretching of one side towards the Earth, there is a complementary stretching of the other side away from Earth), the situation remains the same, that is, the satellite still orbits the Earth, apparently motionless as seen from the ground. As it gets longer, the near end gets closer to the Earth. Eventually you can stretch the satellite so that one end touches the surface.

What you have now is a solid object, in orbit, that looks like a very tall tower, stretching 36,000km over your head and beyond. If it had an elevator, or an electric car, or steps, you could climb it, right up to orbit. In fact, in order to maintain its center of attraction at 36,000km, the tower must extend significantly further than this, because of decreasing Earth gravity and increasing centrifugal force. Pearson [3] and Forward [5] assume cables extending 110,000km beyond synchronous orbit, rather than Clarke's [4] more solid structure, extending a shorter distance. Despite appearances, the tower is actually in orbit, and its attachment to the ground is for tension, not stability. If the ground attachment were severed, the tower would probably drift upwards in response to its counterweight; it certainly would not crash to Earth.

At the center of the tower (synchronous orbit), a passenger experiences free-fall, because she's in orbit next to the tower's center. At the Earth end of the tower, a passenger experiences 1G, just as if she were standing on the Earth next to the tower. At the far end of the tower, centrifugal force far exceeds the Earth's gravity, and our passenger has to hang onto the tower to avoid being thrown into space. Thus, apparent gravity varies smoothly from 1G at the Earth's surface, to free-fall at the center, to some significant value outwards at the outer end of the tower. The far end is useful for launching objects away from Earth; just wait for the right time and let go of the tower. Alternatively, cargo destined for off-Earth can simply be flung off the end without stopping, or accelerated electrically for even greater range. Pearson [3] and Forward [5]'s design places the end of the tower 150,000 km from the center of the Earth, moving at a horizontal speed of 11 km/ sec. Thus, simply letting go of the end of the tower at the right time is adequate for a minumum-energy orbit to Saturn, or a faster orbit to planets closer than Saturn. (Nothing is free; the energy to launch an escape payload comes from the Earth's rotational energy.)

Using the orbital tower, the energy cost of placing a kilogram of cargo in orbit is simply the cost of the electricity needed to lift that cargo against Earth's diminishing gravity, counteract any atmospheric friction for the first 100km or so, and stop it at the end of its trip. Forward [5] quotes a price of $2 per kilogram, compared to $5000 per kilogram using rocket-based methods. Note that this price does not take into account the fact that electricity can be generated by the momentum of incoming cargo, so the entire system can be rigged to be pretty energy-efficient.
Like any object in orbit, the tower would be subject to a variety of perturbations that would tend to degrade its orbit. The Moon and the Sun are the chief contributors, along with irregularities in the Earth's mass distribution and shape. Proper scheduling of incoming and outgoing loads can help maintain the tower's orbit. Note that if the tower were to break, the first 25,000 km of it could fall to Earth, but anything higher would remain in orbit.

A counterweight is required at the far end of the orbital tower, to maintain tension along the structure. Forward [5] notes that diamond fiber would be a suitable material for construction of the tower, but laments the unavailability of an industrial source of diamond fiber. This situation, however, may change within the next 10 to 50 years, as described below.

**Diamonoid Construction**

The literature on nanotechnology [6,7] describes a new industrial infrastructure based on the precise, mechanical manipulation of atoms and molecules (mechanosynthesis) to build eutactic (atomically perfect) products. Biochemistry provides many examples of the mechanical manipulation of atoms and molecular fragments (enzyme catalysis, protein synthesis, etc.), so the overall concept has precedent. One can visualize a nanometer-scale machine called an assembler, capable of programmable construction of any desired eutactic product, given feedstock, energy, and instructions. Assembly speeds of one million molecular manipulations per second are considered feasible in even the earliest (first-generation) assemblers.

Assemblers themselves are expected to be very small, atomically precise machines. Thus, it is expected that assemblers will be able, once properly programmed, to build additional assemblers. This allows assemblers to be created in geometrically increasing numbers, once the first one is created through some non-nanotechnological means. Such replication is required to build products at a reasonable rate; although a million operations per second sounds fast, a kilogram of carbon contains over 5x10^25 atoms.

For a variety of reasons (see [7]), many mechanosynthetic products will be built around diamondoid, a lattice composed chiefly of tetrahedrally-linked carbon atoms. Diamondoid is expected to have many of the mechanical properties of naturally occurring diamond, especially hardness and tensile strength. However, constructing diamondoid products through mechanosynthesis is expected to be no more or less expensive than constructing any product through mechanosynthesis. In fact, because of assemblers' ability to self-replicate, all mechanosynthetic products are expected to be very inexpensive (comparable to agricultural products) and extremely high quality (atomically perfect, with a defect rate less than 1 in 10^15) by today's standards.

**The Next Apollo Program?**

The combination of geometric assembler growth, eutactic products, and low cost make the construction of an orbital tower using assemblers attractive. Huge numbers of assemblers can construct tower components at whatever speed is desired, limited only by raw materials, energy, and the coordination of product flow. The tower components will be atomically perfect, an almost ludicrous property of such a gigantic object, but a natural property of any mechanosynthetic product, and a necessary property to handle the stresses involved. Estimates vary on the mass of an orbital tower, from a million tonnes (Forward) to a billion tonnes or more (Clarke), depending on the exact design. Enough assemblers can be created through self-replication to convert raw materials into diamondoid at whatever rate is required to complete the construction.

Estimates also vary on the timeframe within which assemblers and other nanotechnological capabilities will be available. Most estimates range from between 10 and 50 years. Progress on a variety of fronts (microscale electronics, biochemistry, human genome decoding, electron microscopy) is encouraging, and seems faster than recent progress in space development. It is possible that mechanosynthetic capabilities will exist to build an orbital tower well in advance of the availability of any off-Earth carbon resources (asteroidal or Lunar) from which to build it.

Many proponents of nanotechnology are concerned about the use of assemblers in any context in which they might be introduced to the biosphere. They believe that a nanomachine is a potential threat to the biosphere because it may somehow compete (with machine-like and potentially brutal efficiency) with lifeforms for some essential resource. Because of their self-reproductive capabilities, if nanomachines "get loose", they could cause irreparable damage to the Earth and its life.

Orbital construction of an orbital tower is an excellent opportunity for nanotechnology to prove its worth and extend its capabilities, with only minimal risk to the biosphere. Working in orbit, with appropriate self-destruct devices as needed, nanomachines can perform useful work in complete safety and isolation, improving along the way as new efficiencies and capabilities are invented. The orbital tower could be to nanotechnology what the Apollo program was to miniaturized electronics and ultimately the computer industry -- simultaneously a market, proving ground, and stimulus.

**Advanced Tower Properties**

The earliest nanomachines are expected to provide only the most basic mechanosynthetic techniques, such as the construction of relatively simple eutactic materials (e.g., diamondoid) and a small variety of nanoscale parts (e.g., those in an assembler). However, the capabilities of nanotechnology in both its techniques and its products are expected to grow rapidly, once initially developed. Not only will assemblers become better (faster, cheaper, more general-purpose, etc.), but the products of assemblers will employ active nanotechnology even after their initial assembly. Thus, the first generation of orbital tower components might be relatively static diamondoid blocks, fibers, cables, and so forth. But, later generation assemblers will be able to build active tower components, able to change shape, self-repair, or self-modify in response to orbital perturbations, meteor damage, or other events.
Conclusion

The use of nanotechnology to build an orbital tower is a potentially synergistic enterprise for both nanotechnologists and space technologists. It would provide an excellent proving ground for nanotechnology, and the final product would open the solar system to humanity.

References


The Drexlerian Terraformation of Mars: A New Ark for Humanity

by Robert J. Coppinger

Compared to the other planets in our Solar System, Mars is the best candidate for terraforming. It has a reasonable gravity, sunshine, rate of rotation, and length of seasons. The Martian surface gravity is 38% of Earth's, and the amount of sunlight that reaches Mars is only 43% of what we are used to, but it is sufficient for photosynthesis.

There are two major problems for human habitation on Mars -- a lack of atmosphere, and very low temperatures.

The Martian atmosphere is presently 6-7 millibar's, less than one tenth of Earths. For plants and anerobic microorganisms pressures as low as 10mbar [MCKAY C P, TOON O B, KASTING J F, Making Mars Habitable, Nature, Vol 352, 8 August 1991.] would be adequate, but to exploit the resources of Mars fully it would be advantageous to have a biosphere that is compatible with human needs. For human habitation, the minimum tolerable partial pressure of oxygen is 130mbar. For the entire atmosphere to be oxygen only, it's known that long term exposure to pure oxygen at 345 mbar (a more comfortable pressure) can be tolerated but oxygen is flammable, and there are problems with oxygen toxicity. Consequently, a buffer gas is necessary, and this buffer gas can be nitrogen, which might be available from nitrates in the regolith.

The average surface temperature on Mars is 210K, [MOORE P, HUNT G, The Atlas of the Solar System, Royal Astronautical Society, 1984, p.212.] far too low for human habitation -- a minimal temperature of 273 K is preferable, though anything above the freezing point of water would be even better. Since the surface temperature of a planet depends very much upon the difference between the differences between incident sunlight and reflected radiation, the primary means for raising the temperature will involve increasing the mass of the atmosphere to keep more solar energy from re-radiating into Space.

At present, the Martian energy flow is one of interception and dissipation with no useful work, biological or otherwise, done. It's energy budget is never in any really useful surplus.

Models for energy systems of useful work include biospheres with one bar pure carbon dioxide atmospheres with mean temperatures just above freezing [FOGG, M J, Dynamics of a Terraformed Martian Biosphere, JBIS, Vol 46, 1993]. Mars in this state can be described as a slowly thawing anaerobic desert. For Mars to be habitable for humans, the atmosphere will need to hold this dissipated solar energy, trapping this warmth so there is a net energy gain from the solar radiation. Molecules with infrared absorption abilities, e.g. carbon dioxide, would be of most use to us by creating a greenhouse effect on Mars.

Another mechanism for raising average Martian temperature is to reduce the albedo by darkening of the planets surface. Unfortunately, this method may have a limited efficiency after the biosphere's average temperature has increased by 10K.[FOGG M J, A Synergic Approach To Terraforming Mars, JBIS, Vol 45, 1992.]

Radiation

The energy from the sun that is not wanted is the radiation damaging to life. It is believed that problems of cosmic radiation can be overcome with a gas column mass of 390 mbar and above[MCKAY C P, TOON O B, KASTING J F, Making Mars Habitable, Nature, Vol
Partial pressures of oxygen, nitrogen and carbon dioxide at 195, 10 and 185 millibars respectively would give us more oxygen than necessary and the absolute minimum of 10 millibars of nitrogen will aid the control of combustion and provide a reservoir for biological nitrogen fixation; in case plant life is to be introduced as part of a longer term project. [FOGG M J, A Synergic Approach To Terraforming Mars, JBIS, Vol 45, p315, 1992].

The ten millibars of nitrogen may also be a maximum amount possible due to the fact that little nitrogen has been located on Mars so far and questions exist as to the quantities of nitrates that could really exist in the regolith. So 390 mbar (or 1.5 x 10^14 kilograms of [ideal] gas) could be a target value. [MCKAY C P, TOON O B, KASTING J F, Making Mars Habitable, Nature, Vol 352, 8 August 1991]

Quantities Necessary

The mass quantities of the material needed to create this atmosphere are the following; (1.45 x 10^14 is Martian surface area) and

1. 195 mbars of Oxygen

2. 10 mbars of Nitrogen

3. 185 mbars of Carbon Dioxide

The total atmospheric mass of 390 mbar, is;

These new quantities of atmospheric gas will mean a change of the mean molecular weight of the Martian atmosphere, to the values shown below:

<table>
<thead>
<tr>
<th>mb</th>
<th>Molecule</th>
<th>Molar Fraction</th>
<th>Molar Mass</th>
<th>Mean Mole Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>185</td>
<td>CO₂</td>
<td>0.470(47%)</td>
<td>44</td>
<td>20.68</td>
</tr>
<tr>
<td>10</td>
<td>N₂</td>
<td>0.025(2.5%)</td>
<td>28</td>
<td>00.70</td>
</tr>
<tr>
<td>195</td>
<td>O₂</td>
<td>0.500(50%)</td>
<td>32</td>
<td>16.00</td>
</tr>
</tbody>
</table>

The total of 37.38 is then the mean molecular weight of one mole of the new Martian atmosphere.

To calculate the number of particles in this atmosphere, that is the number of molecules that need to be processed by these molecular machines, the molecular weight of the elements/compounds involved (see above) are divided into the mass quantities previously calculated.

Number of Oxygen Moles:

Number of Nitrogen Moles:

Number of Carbon Dioxide moles:

Avogadro's law [LAPHAM C W, Letts Chemistry, p.37, Charles Letts and Co., 1983.] states that for one mole of any element or any compound there will be 6.02 x 10^23 particles (molecules). Therefore;

\[
\begin{align*}
195 \text{ mbar Oxygen} &= 2.38 \times 10^4 \times 6.02 \times 10^23 = 1.43 \times 10^43 \\
10 \text{ mbar Nitrogen} &= 1.36 \times 10^4 \times 6.02 \times 10^23 = 8.18 \times 10^41 \\
185 \text{ mbar CO}_2 &= 1.6 \times 10^4 \times 6.02 \times 10^23 = 9.85 \times 10^42 \\
\text{Total:} &= 2.496 \times 10^43
\end{align*}
\]

The new mean molecular weight and volume will give the Martian atmosphere a new height value:

With the new atmospheric mass and height, how will the temperature rise required to achieve 280K be accomplished?

How to create a Martian Greenhouse Effect

As well as infrared absorbing molecules more effective greenhouse gases have been found polluting the Earth. CFC's are one suspected method of increasing a biosphere's mean temperature. CFC's are also useful because they have long lifetimes against UV radiation damage, from the sun.
One part per billion of CFC's will increase the temperature by about 0.1 Kelvin [LOVELOCK J E, ALLABY M, The Greening of Mars, Warner 1984). For a real temperature increase, CFC levels really need to be at parts per million, this is not toxic and this would result in 0.01 mbar's of the atmosphere being CFCs and this requires 4 x10^13 kilograms of material. Concentrations of 0.06 or 1 part per million might warm Mars by 40K, that's two thirds of the target value needed.[MCKAY C P, Terraforming: Making An Earth Of Mars, The Planetary Report, VII(6), 1987.]

Due to ultraviolet damage there would have to be continuous production of CFC's though UV destroyed CFC's could be reconstituted from their parts that would then be floating in the atmosphere; annual production quantities given are around 3 x10^15 kilograms, deemed impractical previously [FOGG M J, A Synergic Approach To Terraforming Mars, JBIS, Vol 45, 1992.] although such quantities are plausible with molecular machines.

**Material Sources and Extraction Methods**

With oxygen, carbon, nitrogen and chlorofluorocarbons necessary where can all the material for this endeavour be located? Will materials need to be imported or does Mars contain all the sources needed.

**Carbon**

Sources of CO2 can be found in the regolith/soil of Mars. It is estimated that the regolith contains 300 mbars of carbon dioxide. Another source is the south pole where a 350 km diameter carbon dioxide 'cap' which may be 1km thick will provide 100 mbar of atmospheric pressure.[MCKAY C P, TOON O B, KASTING J F, Making Mars Habitable, Nature, Vol 352, 8 August 1991]

Extraction methods for carbon that have been suggested have included atomic explosions, heat rays [BIRCH P, Terraforming Mars Quickly, JBIS, Vol 45, 1992], orbiting mirrors, and seeding the surface with cyanobacteria [FRIEDMANN EI, HUA M, OCAMPO-FRIEDMANN R, Terraforming Mars: Dissolution Of Carbonate Rocks By Cyanobacteria, JBIS, Vol.46, 1993.].

Dr. Eric Drexler, states that disassembling molecular machines could break down rock, thus release the carbon, or any other necessary material that resides in the regolith; and with better process energy efficiencies than bulk technology methods, e.g. heat rays from space.

Estimates for heating layers of regolith to release carbon dioxide have suggested figures of 10^6 J/ cm^2 for 2 bars of carbon dioxide. [MCKAY C P, TOON O B, KASTING J F, Making Mars Habitable, Nature, Vol 352, 8 August 1991] This estimate though (which assumes 100% efficiency) is for 2 bar of carbon dioxide, the target value here is only 185 millibars, less than one tenth of that value.

A figure of 92,500 J/ cm^2 is therefore acceptable, for the release of the 185 mbar of carbon dioxide through the warming of the regolith. Another method of obtaining the 185 millibar of carbon dioxide wanted would be to heat the southern polar cap of Mars and sublime the 100 millibars that exists there into the atmosphere.

The carbon dioxide is frozen at a temperature of -190 farenheit. At -20 Farenheit the energy required to turn frozen CO2 to vapor would be 70 Calories per gram. Therefore with 4 x 10^20 grams of CO2 to turn to vapor, 2.8 x 10^22 calories will be needed to bring the CO2 to it's latent heat of vaporisation. The energy required for vaporising this carbon dioxide at -190F could be as high as, 664 calories per gram.

If this were done then the regolith carbonate needed would decrease to only 85 millibars. The choice as to which strategy was best, all-regolith or a regolith-polar cap combination would depend upon which was quickest, and most cost effective.

**Oxygen**

Oxygen exists within the water in the northern polar cap and photosynthesis generates oxygen from water. Photosynthesis utilises a super-oxidiser to draw from the water electrons to split the hydrogen and oxygen molecules a part and the oxygen is discarded as waste. In this process there are four photons of energy used and in a secondary process there are another four photons, therefore all together to obtain one molecule of O2 from H2O (which is actually 2H2O - you need an extra H molcule) the energy requirement is eight photons or, 2.34 x10^-18 Joules.

Multiplying the molecular energy requirement by Avogrado's constant to obtain the Joules per mole figure, the answer is:

\[ \text{6.02 x 10}^{-23} \times 2.34 \times 10^{-18} = 1,408,680 \text{ Joules.} \]

For the total energy requirement for the entire mass of oxygen gas needed;

\[ 1,408,680 \text{ Joules x 2.37 x 10}^{-19} = 3.35 \times 10^{25} \text{ J} \]

Estimates for the photosynthesis of carbon dioixde to obtain oxygen [BIRCH P, Terraforming Mars Quickly, JBIS, Vol 45, 1992.] with efficiencies of 8% state that 240 mbars of oxygen can be obtained from 330 mbars of CO2 in around 140 years. For 195 mbar (our target figure) the period would still exceed one hundred years, according to Birch's figures.

With molecular machinery you have the ability to directly affect events at the smallest level. If the splitting of the water molecule into it's constituent parts involves 2.5 electron Volts [source: Chris McKay, NASA Ames, E-mail dated 9th November 1994, 18:17:23 hrs.] then
with a requirement of $1.43 \times 10^{43}$ oxygen molecules the total energy required with this direct process is $3.6 \times 10^{43}$ electron volts or $3.44 \times 10^{45}$ kJ/mole.

Another method is electrolysis, yet this does require, relative to photosynthesis, a lot more energy. [FREITAS R A, Terraforming Mars And Venus Using Machine Self Replicating Systems (SRS), JBIS, Vol 36, No.3, 1983.]

Electrolysing the water for oxygen will generate hydrogen. Molecular machinery could utilise this hydrogen, for molecular fuel cells utilising hydrogen and oxygen, though it may be that the quantities of oxygen needed to produce the energy required to extract the oxygen from the ice cap may preclude this method.

Another option is to store the hydrogen, as levels of storage of 10% of the total volume, for a cell, of 'waste' material is seen as plausible, without affecting the functioning of the molecular machines operations [DREXLER K E, Engines of Creation].

Such hydrogen waste problems will need to be addressed as excess hydrogen is expected to be a by-product of diamondoid structures built from molecular manufacturing [K E DREXLER, Nanosystems, p.425].

Nitrogen

Estimates suggest that in Mars' early existence there could have been up to 300mb of nitrogen in it's atmosphere, and that that nitrogen was been absorbed into the soil as nitrate in the early 'wet' stages of Martian geological history [POLLACK J B, KASTING J F, RICHARDSON S M, AND POLIAKOFF, K, Icarus 71, pp. 203-224, 1987].

These highly pure deposits of nitrates within the top 1 kilometre of the Martian regolith could generate 84 millibars of nitrogen through the use of great heat rays which devolatise/ vaporise the regolith releasing, as well as the nitrogen, 240mbar of oxygen, in 10 years [BIRCH P, Terraforming Mars Quickly, JBIS, Vol 45, 1992.]. However, it would seem much more efficient, and less capitol intensive to use molecular machinery instead of giant orbital mirrors to break the bonds of the nitrate N2O5 in the martian soil to release nitrogen.

Chlorofluorocarbons (CFCs)

Chlorofluorocarbons are an effective way of trapping heat, the Earth's own predicted problems with temperature rises have shown this to be true. The constituent parts for the CFC's, CF6, CF3CL, CF2CL2 and CF3Br can all be found on Mars, so these CFC's could be manufactured there [MCKAY C P, TOON O B, KASTING J F, Making Mars Habitable, Nature, Vol 352, 8 August 1991].

Nanotechnology: Molecular Machines

In Engines of Creation, Dr. Drexler writes of machines that clean the world of pollution, "With replicating assemblers we will even be able to remove the billions of tons of carbon dioxide that our fuel burning society has dumped into the atmosphere."

In a paper given at a USA/ Japan symposium on nanotechnology and it's affect on manufacturing the time line given for the development of nanotechnological manufacturing systems gave the year 2010 as the year inwhich systems that could synthesise substrate would be viable. This would appear to be a complex task, with atom deposition rates far higher than we have today[HOCKEN R J, MILLER J A, Nanotechnology And It's Impact On Manufacturing, JAPAN/ USA Symposium on Flesible Automation - Volume 1, ASME 1992.]. Yet the numbers of particles required already presented show that productivity rates will have to be substantially improved.

Von Neumann suggested architectures for self replicating systems, with two main components, the universal computer and the universal constructor [VON NEUMANN J, Theory of Self-Reproducing Automata, University of Illinois Press, 1966.].

Of course the self replicating systems will need to be able to perform the terraforming processes as well and whilst initial design specifications will stress simplicity, Dr. Drexler believes that one day, "the difference between an assembler system and a replicator will lie entirely in the assembler's programming." [DREXLER K E, Engines of Creation, p.58].

These self replicating molecular factories, yet to be designed in atomic detail even theoretically, would broadly consist of, a static structure, actuators, sensors, internal transport mechanisms - for moving those various molecules into position - sensors and information processing capabilities.

Estimates for the mass of these molecular devices state atomic mass units of $10^9$ AMUs [DREXLER K E, Engines of Creation, p.57]. Even if we had $1.8 \times 10^{17}$ of these machines they would only weigh 30 grams, yet their 'body weight to material-released weight' ratio could be great.

With molecular nanotechnology the Neumann architecture description can be modified to consist of a molecular computer with molecular positional capabilities and tip chemistries which will construct copies or disassemble martian rock.

The expected environment is particularly important because of the unique Martian environment, which has temperatures ranging from 150K to 210K.

The Internal Environment

The assumption about mechanosynthetic environments for molecular machinery is that a vacuum is required [MERKLE R C, Self Replicating Systems And Molecular Manufacturing, JBIS, Vol 45, 1992.]. There will be a need to ensure that this inert internal
environment is protected against possible contaminants which exist external to the machinery's cell wall.

Present thinking also views the external environment as being one of liquid (the gas Xenon is at its triple point at 161K therefore at temperatures of 150K it may exist as a liquid and could be a candidate as an inert liquid for the internal structure of the molecular machine) because liquid is seen as the medium for fuel delivery and heat loss for Earth based manufacturing systems [MERKLE R C, Self Replicating Systems And Molecular Manufacturing, JBIS, Vol 45, 1992.].

Yet on Mars, heat is what is needed and therefore the initial low pressure/enthalpy of Mars external to the cell wall will provide a great dissipator of heat energy.

Materials will need to be transferred through this wall to 'feed' the machine. A rotating cylinder has been put forward as one possible inter-environment transfer system [K E DREXLER, Nanosystems, p. 374]. Such a cylinder with pockets in its exterior to capture molecules is assumed to operate in a liquid environment.

In an environment where the fuel is ice, probably including impurities, and the molecules are locked into a lattice structure, the external-internal environmental interface may need to be more proactive than the passive systems that Drexler suggests i.e the cylinder with pockets. Perhaps a 'molecular drill' which uses shear forces at a molecular level to break apart the lattice structure to guide, molecular 'swarf' into a collection channel for transfer to the internal environment.

**Tip Chemistry**

Once through the cell wall this material must be processed, carried by conveyor belts along a production line. Carbon is viewed as the tip atom most likely to ensure success in dealing with hydrogen reactants and carbon tipped carbon deposition tools have also been proposed. Such tools will enable the extraction of oxygen from the hydrogen atoms in the frozen Martian water and to bond carbon, breaking it away from the carbonate molecules of the martian rock.

**The Computer**

The computer, as with all components of the molecular machine, will need to operate at cryogenic temperatures. Single electron devices, using individual electrons for digital ones and zeros, are believed to be more reliable at low temperatures [MERKLE R C, Self Replicating Systems And Molecular Manufacturing, JBIS, Vol 45, 1992.] and therefore more applicable than mechanical computers.

These electron computers which will control these devices could fit into an area less than one cubic micron, using some 10 nanowatts of power[DREXLER K E, Molecular Engineering: Assemblers and Future Space Hardware, (AAS 86-415) Aerospace Century XXI: Space Sciences, Applications, And Commercial Developments, Vol 64 (Part III), Advances in the Astronautical Sciences, Proceedings of the 33rd Annual AAS International Conference, Colorado, October 1986.].

**Sources of Energy**

Sources for the quantities of energy needed will be few. There is of course the sun with solar energy interception quantities on Mars of some 590 Watts per metre. Models for terraforming have suggested a need for some ten years worth of sunlight [MCKAY C P, TOON O B, KASTING J F, Making Mars Habitable, Nature, Vol 352, 8 August 1991].

The orbiting solar mirrors [BIRCH P, Terraforming Mars Quickly, JBIS, Vol 45, 1992.] that have been suggested to re-direct and magnify solar energy could increase this 590 Watts to 1370 Watts, like on Earth, and there is work on going (Green Energy, New Scientist, 14-20th November issue) to create artificial solar energy collectors that mimic plants; which would eventually lead to artificial photosynthesis processes.

Power density being a measure of the potential power within a given mass of a battery/ fuel cell, if 100 million atoms (1.66 x 10^-19 kg) or 16,666,666 molecules (6 atoms per molecule of 2H2+O2) of Dr. Drexler's billion (10^9) atom replicating assemblers were hydrogen and oxygen molecules then the potential power for each machine could be 7,916,666,666 maJoules (1 maJ = $10^-21$ Joules.).

To convert the materials we know we can find on Mars into the gases we need to support life we would need a highly energy efficient conversion organism. Molecular mechanosynthesis appears to present one possible answer to the energy quantities, that are necessary to process the billions (10^9) of kilograms that have to be produced to create the 390 mbar atmosphere.

**Self Replicating Molecular Machinery: Genesis Engines**

Two factors make molecular Machinery the genesis engines that will transform Mars into a habitable planet, their energy efficiency and their productivity.

**Molecular Productivity**

Nanotechnology is desired for terraforming for one reason, it's speed. It's rapidity of construction gives rise to this authors hypothesis that a nano-terraformed planet could be available for colonisation within a generation.

Fast enzymes such as carbonic anhydrase or ketosteroid isomerase can both process almost a million molecules per second [DREXLER K E, Engines of Creation, p.57].
There are other enzyme molecules which can break down 40 million (hydrogen peroxide) molecules per second, forty times the speed of carbonic anhydrase [K E DREXLER, *Engines of Creation*, p. 251].

The molecular 'break down' speed ("at Earth temperatures") can be 100 molecules per trillionth of a second (mps) or $10^{14}$ molecules per second. With two oxygen atoms to every oxygen molecule that means that it has, for oxygen, an atomic productivity rate of $5 \times 10^{13}$ atoms per second.

For the man made terraforming assembling replicators projections for productivity rates are currently in the 1 million atoms per second range [K E DREXLER, *Nanosystems*, p.407].

Assemblers with production rates of 1 million atoms per second per atomic robotic assembly arm could complete 100 atomic layers per second, a paper thick object would take an hour. As atomic deposition rates increase to 1 meter per day a great deal of heat will also be generated [DREXLER K E, *Engines of Creation*, p.57-58].

The masses of material needed for the 390 mbar atmosphere were given previously to show the great volumes of gas needed and the apparently insurmountable task ahead.

Questions must now be answered, to the best of our abilities, one, how fast can these machines replicate, two, how fast can these molecular machines release the material required.

**Replication**

Ultimately, replication times are determined by the mass of the assembler, the number of atoms that constitute it's architecture. Flexible replicators, with productivity rates of one million atoms per second could self replicate in a total of 1000 seconds, meaning that there are a billion atoms in each replicator [K E DREXLER, *The Engines of Creation* p.58].

These machines, assuming adequate material and energy supplies, will have exponential growth, and therefore, Dr. Drexler calculates, after ten hours there will be 68 billion molecular machines. If each assembling replicator has a mass of $10^9$ AMU's and one AMU has a mass of $1.66 \times 10^{-27}$ kilograms [K E DREXLER, *Nanosystems*, p.514] then this would give a total mass of $1.13 \times 10^{-7}$ kilograms. Not much.

Yet, as it will be shown below a greater mass of machines will be needed though the geometric rate at which replicators replicate will mean that within forty eight hours the machines would out weigh the Earth [K E DREXLER, *The Engines of Creation*, p.58].

The replication requirements may specify a replication rate less than 1000 seconds, or more than 1000 seconds; it will depend upon the rate at which the terraforming project is required to progress.

**The Terraforming Time Frame**

Assuming that present estimates of replication rates are correct and that there is sufficient available materials for all activities needed and that sources of energy and energy storage capabilities of the micromachines, nanotechnological molecular factories and self replicating molecules are sufficient, how long could this all take?

From calculations above the total number of molecules in a CFC free Martian atmosphere of 390 mbar (at 210K) will be $2.5 \times 10^{43}$. To process this many molecules within twenty years, productivity will need to be very high.

To process $2.4 \times 10^{43}$ molecules in twenty years there would need to be a production rate of $3.95 \times 10^{34}$ molecules per second. If there were 68 billion assemblers on Mars each machine would have to have a productivity of, $5.8 \times 10^{23}$ molecules per second.

Taking the time frame of one year, the time it would take for astronauts to efficiently travel to Mars, there are 1,314,000 seconds available in which to complete the terraforming process. If all of the molecular machines needed could be manufactured spread across the equator and the polar caps these machines, upon receiving an activation signal could operate all at once, their energy consumed in an instant, heating, subliming, the effect would release the required material in a very short time frame, perhaps the time it takes to process one mole, perhaps a year.

The total number of atoms is $(3.12 \times 10^{43} + 2.86 \times 10^{43}) 5.98 \times 10^{43}$. Divided by the time allotted this gives a figure of $4.54 \times 10^{37}$ atoms per second, which, at 1 million atoms per second means a need for $4.54 \times 10^{31}$ machines which have a mass of $75,500,000,000,000$ kilograms.

**Conclusion**

As the machines process the surface and polar caps once the atmosphere reaches one hundred millibars it is believed that global sublimation will be activated, certainly in the regolith and this will in turn create a run away greenhouse effect, though at a rate that, to reach our target pressure independently, would take thousands of years. But with the added help of drexlerian assemblers, the process speeds up tremendously.

Twenty years, within a life time, within a generation, a second biosphere for humanity, where as other periods for terraformation given are in the order of 300 years. Twenty years and there could be an atmosphere which will last for thousands of years. The Valles that exist on Mars could eventually be filled with water and the canals that Lowell saw would be a reality. By 2055 a habitable Mars could
exist and the author will only be 84 years of age. But the only intelligent life there will be human life. A Martian Gaia will come alive, it will be, life from lifelessness, literally, Genesis.

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Once molecular manufacturing is developed, it will provide us with a thorough and inexpensive system for controlling the structure of matter. In a relatively short time period following the development of the first nanofactory, mankind will appear to have complete dominion over the physical universe. How Molecular Manufacturing Works. The central, but not the only, component necessary to achieve molecular manufacturing is a fabricator, or assembler. A fabricator will be nano-scale device capable of precisely positioning molecules. Using current computer technology, we could then direct fabrica Molecular Manufacturing Enterprises, Inc., Eagan, Minnesota. 147 likes · 2 were here. Nanotechnology Consulting and Public Speaking. See more of Molecular Manufacturing Enterprises, Inc. on Facebook. Log In. or. Create New Account. See more of Molecular Manufacturing Enterprises, Inc. on Facebook. Log In. Forgotten account? Molecular Manufacturing Shortcut Group: A Chapter of the National Space Society. "Some Novel Space Propulsion Systems", by Forrest Bishop, presented at the Fifth Foresight Conference on Molecular Nanotechnology. "The Logical Core Architecture", by Tom McKendree, presented at the Fifth Foresight Conference on Molecular Nanotechnology. Much of the research now building toward molecular manufacturing is taking place in universities across the globe; however, commercial companies are beginning to emerge as the time horizon for the technology grows closer. One of the early entries into the race to build a molecular assembler and product assembly process is the Texas-based corporation, Zyvex Corp.