

REGULATORY MECHANISMS FOR MOLECULAR NANOTECHNOLOGY

Jason Wejnert*

ABSTRACT: Molecular nanotechnology will present enormous technological as well as legal, social, and ethical challenges as the science develops. In order to ensure a safe introduction and implementation of molecular nanotechnology, current control, dissemination, and property protection regimes will need re-evaluation to account for the fluid nature of the technology.

CITATION: Jason Wejnert, Regulatory Mechanisms for Molecular Nanotechnology, 44 *Jurimetrics J.* ___–___ (2004).

Molecular nanotechnology represents the next generation of technology beyond the current applications of organic chemistry, chemical engineering, and semiconductor fabrication. Science fiction writers and earnest futurists present a scenario where molecular-size devices and machines can be fabricated effortlessly and on a scale such that all manufacturing and economic needs can be solved for all mankind.¹ Early proponents of molecular nanotechnology likened the future potential as one so revolutionary it will exceed the development of fire, writing, the printing press, modern medicine, and electricity combined.² Many writers and scientists have speculated about nanosubmarines to fight illnesses and counter

*Candidate for the degree of Juris Doctor at the Arizona State University College of Law and Center Scholar with the Arizona State University College of Law Center for Law, Science, and Technology. The author will be working for the law offices of Brinks, Hofer, Gilson & Lione in Chicago, Illinois this fall.

1. See K. ERIC DREXLER, *ENGINES OF CREATION: THE COMING ERA OF NANOTECHNOLOGY* (1990).

2. Jason Wejnert, *Atomic Reach: Atomic Forces & Scanning Tunneling*, at <http://www.rso.cornell.edu/scitech/archive/95spr/atom.html> (last visited Apr. 30, 2004); see also DREXLER, *supra* note 1.

infectious microbes; cubic micron supercomputers that can exceed today's most advanced computer capabilities; material manipulation on an atomic level to produce "smart" substances; and even fantastic notions of "utility fog," a distributed-intelligence "gas" that can assume whatever shape or purpose is desired, from nuclear weapons shields to adaptable body armor.³

Yet, the promise of molecular nanotechnology has a potential dark side, which some have likened to an imminent apocalypse rivaling global thermo-nuclear war.⁴ Authors have considered bleak scenarios like runaway intelligent nanodevices that will devour all material they encounter, rendering the Earth into "grey goo."⁵ Still others consider the danger of a rogue state producing nano-weapons that can either kill off the state's enemies like a supervirus,⁶ or an Orwellian government forcing its citizens to "love Big Brother" through mind-control agents introduced into the water supply.⁷ More measured scenarios consider how self-replicating machines will interact with the environment if released.⁸ Even if the most benign future scenarios are realized, scientists and politicians will have to deal with profoundly new consequences of a technology never imagined before.

This paper will consider the background and potential development of molecular nanotechnology (MNT). The paper will then examine the regulatory mechanisms available and their possible applications to managing MNT. Risk management and cooperative agreement mechanisms will be considered, as well as prohibitory mechanisms and their feasibility. In addition, governmental incentive programs and technology management will be considered as alternatives for promoting as well as controlling some of the risks of early-stage MNT.

I. BACKGROUND

Not until the beginning of the 20th century did physicists understand the nature of matter at a discrete level. From the time of the Greeks, philosophers attempted to describe what matter was. Aristotle characterized matter as made up of four elements—earth, fire, water, and air. Others proclaimed that the nature of matter was one of infinite divisibility. Democritus provided the first realistic model of matter when he proposed that matter was made up of particles at the smallest levels that were indivisible—atoms, Greek for "uncuttable." It was 24 more centuries, however, before scientists obtained empirical evidence of matter

3. See DREXLER, *supra* note 1, at 171–91.

4. See Bill Joy, *Why the Future Doesn't Need Us*, WIRE, Apr. 2000, available at <http://www.wired.com/wired/archive/8.04/joy.html>.

5. See MICHAEL CRICHTON, PREY (2002).

6. See Frederick A. Fiedler & Glen H. Reynolds, *Legal Problems of Nanotechnology: An Overview*, 3 S. CAL. INTERDISC. L.J. 593, 605 (1994).

7. Joy, *supra* note 4.

8. Paul C. Lin-Easton, Note, *It's Time for Environmentalists to Think Small—Real Small: A Call for the Involvement of Environmental Lawyers in Developing Precautionary Policies for Molecular Nanotechnology*, 14 GEO. INT'L ENVTL. L. REV. 107, 112–16 (2001).

smaller than that visible in the most powerful optical microscopes. Robert Brown observed the random oscillations of pollen in water solutions with his microscope and pondered the meaning of this motion. Albert Einstein finally answered this question by explaining the nature of “Brownian motion” as water molecules buffeting the much larger pollen. Likewise, advances in the physics of scattering by such scientists as Rutherford and Goldstein led to quantitative formulations of the size and interaction volume of atoms and their nuclei. The development of quantum mechanics by Planck and Schrödinger completed the new model of how atoms and electrons interact to produce matter as we know it.

For most of the early 20th century, scientists focused on the gross chemical interactions of molecules when they studied chemistry. At most, physicists would study crystallography and how atoms formed microscopic structures. Not until physicist Richard Feynman—a scientist of great popular clout due to his recent Nobel Prize and eccentric personal style—gave a lecture on what was later recognized as the birth of molecular nanotechnology, did scientists think of the purposeful manipulation of molecules and atoms to construct devices and machines.⁹ Feynman delivered a lecture to the annual meeting of the American Physical Society about futuristic control of matter on an atomic scale. He speculated about manipulating atoms to construct machines, storing enormous amounts of information on a microscopic level. Feynman even proposed writing the entire 24 volumes of the Encyclopedia Britannica on the head of a pin, stressing the theoretical plausibility of the venture.¹⁰ In Feynman’s calculations, even one of the half-tone dots used in the printing of the encyclopedia would be 1,000 atoms in area when demagnified 25,000 times to fit on the head of a pin.¹¹ Feynman remarked that perhaps in the year 2000, “they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.”¹² Feynman even proposed a set of prizes for accomplishing certain engineering feats that would satisfy his call for “racing to the bottom.”¹³

9. K. ERIC DREXLER, NANOSYSTEMS: MOLECULAR MACHINERY, MANUFACTURING, AND COMPUTATION 511–12 (1992). The full text of the speech may be found in Feynman, Richard P., *There’s Plenty of Room at the Bottom*, 23 Eng. and Sci., 22-36. (1960), available at <http://www.zyvex.com/nanotech/feynman.html> (Last visited May 13, 2004).

10. Feynman, Richard P., *There’s Plenty of Room at the Bottom*, available at <http://www.zyvex.com/nanotech/feynman.html> (Last visited May 13, 2004).

11. *Id.*

12. *Id.*

13. *Id.* Feynman stated:

[i]t is my intention to offer a prize of \$1,000 to the first guy who can take the information on the page of a book and put it on an area 1/25,000 smaller in linear scale in such manner that it can be read by an electron microscope.

And I want to offer another prize—if I can figure out how to phrase it so that I don’t get into a mess of arguments about definitions—of another \$1,000 to the first guy who makes an operating electric motor—a rotating electric motor which can be controlled from the outside and, not counting the lead-in wires, is only 1/64 inch cube.

Id. Feynman even proposed high school competitions where schools would carry on cute challenges to each other in shrinking down writing and responding in prank-like fashion.

Remarkably, it was another 20 years before another took up the cause of taking advantage of the “plenty of room at the bottom.” K. Eric Drexler published a popular book called *Engines of Creation* in 1990, which outlined the possibilities that the molecular control of matter would provide in the future.¹⁴ Drexler received a Ph.D. in Molecular Nanotechnology from MIT, the first of its kind, for his work on space technologies. His dissertation dealt with using molecular manufacturing techniques to produce space vehicles. In 1992, Drexler published *Nanosystems*, considered to be the first textbook on MNT.¹⁵ In this text, Drexler addressed the many technological challenges confronting the developers of MNT, offering potential solutions to get past the theoretical difficulties.

A. “Nanotechnology” and Paths to MNT

Until a few years ago, engineers and technologists did not mean “molecular” when they spoke of nanotechnology. “Nanotechnology” was reserved for discussing semiconductor technology, as engineers shrank the dimensions of transistors on integrated circuits down to sizes a thousand times narrower than a human hair—in the nanometer scale range. At Cornell University, for example, the Knight National Nanofabrication Laboratory was not interested in medical submarines or “grey goo,” but rather in developing chemical and physical processes to create ever smaller transistors. In addition, scientists have made great strides in creating the “micromachines” that Feynman challenged others to work on. These are known as MEMS—microelectronic machine systems.¹⁶ MEMS were the conventional semiconductor industry’s first attempts at producing microscopic machines—some that could be used as blood pumps, accelerometers, and micron-scale watches.¹⁷ Though this seemed to be a path to molecular nanotechnology, it was still a world away from achieving the scales imagined by Drexler.

To manipulate matter at atomic scale precision, atomic scale techniques are needed. Physicists developed some early promising tools with the scanning tunneling microscope and the atomic force microscope (AFM).¹⁸ The AFM allows atomic-level precision positioning of a cantilever tip that is controlled by feedback electronics and modulated by covalent forces between the tip and the atoms in the surface. Finally, there was a tool that could move and place atoms. Though the possible applications for AFM-positioned structures are limited at this time because of the physical difficulties of crafting tips, chemists have proposed alternative pathways to MNT using the AFM.¹⁹ By using protein engineering and biotechnology, scientists may be able to devise AFM tip structures that can bind

14. See DREXLER, *supra* note 1.

15. See DREXLER, *supra* note 9.

16. See generally Gabriel, Kaigham J., *Engineering Microscopic Machines*, SCI. AM., Sept. 1995, at 150-52.

17. *Id.* at 151-52.

18. Wejnert, *supra* note 2.

19. DREXLER, *supra* note 9, at 458-67.

desired components and allow stable placement and construction of molecular scale structures.²⁰ In fact, it is this cross-pollination of ideas between biosciences and physics that is considered to be the most likely pathway to MNT.²¹ Considered by many to be the epitome of nanotechnology, living cells accomplish many of the tasks that futurists propose for mature nanotechnology—self-replication, self-assembly, self-powered systems that function at the molecular level.²² Scientists hope to model flagella on bacteria for motion, ribosomes in the cell for energy production, and DNA-RNA cycles for information and replication.²³ For this reason, many consider MNT to be a future offshoot of biotechnology or protein engineering more than mechanical engineering or applied physics.²⁴

In addition to the technological pathways, Drexler tackled some of the societal and political questions that nanotechnology would necessarily engender. As a result of Drexler's push to get nanotechnology on everybody's mind, others joined Drexler to create the Foresight Institute as a think tank devoted to promoting MNT, confronting the technological, societal, political, and ethical challenges of the growing technology.²⁵ Prominent on the Foresight Institute's website is a list of "guidelines" for responsible development of MNT, incorporating some safeguards to prevent serious incidents that nanosystems might cause.²⁶

Drexler and the proponents of MNT were not without serious skeptics and challengers from the beginning. From the technological perspective, physicists pointed out that the thermal motion of molecules and atoms at that scale—Brownian motion—would be a serious if not fatal obstacle to coordinating atoms in machine-like structures and making them last.²⁷ Indeed, the much-hyped writing of "IBM" on a metal substrate with an atomic force microscope in 1987 was a flash in the pan—most who viewed this image did not know that the logo evaporated almost immediately after it was created.²⁸ Also, other skeptics point

20. *Id.*

21. George M. Whitesides, *The Once and Future Nanomachine*, SCI. AM., Sept. 2001, at 78–83.

22. ALLEN J. BARD, INTEGRATED CHEMICAL SYSTEMS: A CHEMICAL APPROACH TO NANOTECHNOLOGY 30–35 (1994).

23. *Id.*

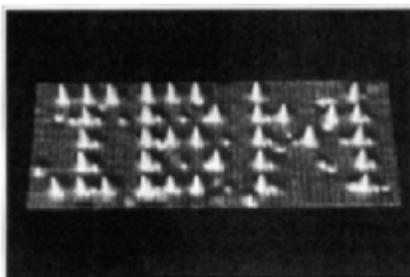
24. Fiedler & Reynolds, *supra* note 6, at 610.

25. Foresight Institute, at www.foresight.org (last visited Apr. 25, 2004); see also *infra* discussion of risk management considerations for MNT.

26. *Id.*

27. Whitesides, *supra* note 21, at 80.

28. Wejnert, below is composed of substrate. The system was due to the More stable structures evidenced by the very biological molecules our cells.



supra note 2. The logo 35 xenon atoms on a platinum instability of the nature of the materials. could be built, as existence of stable built every day within

out our primitive understanding of how genetics dictate why life even exists poses enormous obstacles to creating a self-replicating system at a molecular level.²⁹

Critics and skeptics ponder about the control of MNT because it represents a challenge unlike that presented by most other technologies. At a minimum, MNT will allow humans to alter matter at a molecular level in a new way, creating new economics. In the past, scientists have modified matter chemically or with nuclear reactions, but only in a crude fashion. MNT will allow the precise modification and placement of atoms and atomic structures to create machines and devices. Perhaps the elimination of poverty and hunger will finally be within the grasp of humanity for the first time in history. On the other hand, critics have suggested that MNT could be wielded in such a way that an even greater technological and economic divide than that imagined by biotechnology critics would result.³⁰

From a societal and legal perspective, skeptics point out the catastrophic potential that MNT has for altering the environment and human society.³¹ The scale and autonomy of the proposed applications of MNT are such that critics fear the release of nanodevices into the wild where they would propagate uncontrollably like a virus.³² If nanodevices were given the ability of self-replication using ambient fuel, critics fear that the devices would reproduce and consume all available resources, turning what they encounter into “grey goo,” a substance that has been metabolized by the nanodevice swarm and rendered useless, or “infested” to the point of contagion by the nanodevices.³³ Also, a rogue state might gain the technology and hold the world hostage to the state’s demands on the threat of release of a genetically targeted “virus.” Such fears were present in early debates about biotechnology and, though not realized or even realizable, have colored the debate on the introduction of biotechnology products and research around the world.³⁴ These control fears will need to be dealt with for successful implementation and management of MNT in the future.

A societal concern that is often not addressed in the technological management discussions is how the technology will affect society at its ultimate level—the purpose and direction of society.³⁵ Bill Joy, CEO of Sun Microsystems, wrote a controversial article for *Wired* in 2000 about the role of robotics and MNT in future human society.³⁶ In it, he speculated that intelligent robotic

29. Whitesides, *supra* note 21, at 83.

30. See Ronald Bailey, *Rage Against the Machines*, REASON, July 2001, at 26, available at <http://www.reason.com/0107/fe.rb.rage.shtml> (last visited Apr. 30, 2004).

31. Lin-Easton, *supra* note 8, at 119.

32. Arnall, Alexander Huw, *Future Technologies, Today's Choices*, available at <http://www.greenpeace.org.uk/MultimediaFiles/Live/FullReport/5886.pdf> (Last visited May 13, 2004).

33. *Id.* at 114.

34. See Gabrielle J. Persley et al., *Application of Biotechnology to Crops: Benefits and Risks* (CAST Issue Paper #13, Dec. 1999).

35. See Joy, *supra* note 4.

36. *Id.*

systems, coupled with omnipotent nanotechnology, would make humanity “obsolete” in the sense that we would have little purpose.³⁷ Without the day-to-day requirements of working for a living or striving to satisfy our needs, Joy fears we will realize a warped utopia, where our every need is satisfied except for the one of purpose.³⁸ Others have voiced these fears, Drexler included,³⁹ but the futurists believe that when liberated from working for a living, mankind will be free to pursue arts and leisure that will actualize our potential rather than pervert it. Clearly, this scenario has never been tested, and one can only speculate as to the outcome.

With any discussion of MNT applications and the proper approach to controlling or encouraging their development, there must be a segregation of applications into those that present a credible hazard and those that are by their nature controlled and thus not appropriate for extensive control and regulation. The former category includes the devices and applications that futurists most often promote as the promise of MNT, while at the same time are demonized by detractors. Such applications include self-replicating, free-roaming nanodevices that can replicate in the wild, environmental nanorobots that can operate autonomously with distributed intelligence, and medical nanomachines that can operate at a cellular level on the human body, repairing and augmenting it. The latter, less-dangerous, applications include solar electricity-generating materials built into roads and buildings, “smart walls” that can change their appearance, and controlled laboratory or factory replicators that rely on a finite fuel supply and have limited autonomy. The focus of this paper will be on the regulation of MNT applications that present a threat of “release” into the wild where they can do significant harm.

Even though MNT is probably decades away from even the most realizable applications that Drexler and the Foresight Institute have proposed, proponents and critics alike agree that rational planning is called for to mitigate the fears and prepare for the radical changes that MNT will bring.⁴⁰ Reactions to managing MNT range from outright prohibition (“relinquishment” as Bill Joy calls for⁴¹) to cooperative promotion of the technology while implementing safeguards, as the Foresight Institute advocates. One of the major problems that future nations will have to face is adapting current solutions and mechanisms to deal with novel problems that MNT will pose. As will be shown in this paper, perhaps some radical solutions will need to be tried.

II. REGULATORY AND RISK MANAGEMENT SOLUTIONS

37. *Id.*

38. *Id.*

39. DREXLER, *supra* note 1, at 181–90.

40. Lin-Easton, *supra* note 8, at 129–30.

41. Joy, *supra* note 4.

At the end of the 20th Century and the beginning of the 21st, all parties to decisionmaking are aware of the dangers of unmitigated technology development. From nuclear physics to CFCs to VX gas, well-intentioned discoveries turn into unimaginable nightmares even if well regulated. Critics of biotechnology early on pointed out the potential risks of GM organisms escaping into the wild uncontrolled, of gene transfer to wild plants creating “superweeds,” and garage-built “superviruses.”⁴² Though none of these fears have come to pass yet, opponents of the technology stress that active measures must be taken to prevent their realization in the future.⁴³

Most of the literature analyzing MNT regulation focuses on creating technological safeguards that will prevent runaway releases of the technology into the environment⁴⁴ or applying the precautionary principle in conjunction with restricted development of MNT.⁴⁵ Others examine the regulation of nanodevices from the perspective of how they fit into existing regulatory standards.⁴⁶ What is not well-considered is how to adapt other existing regulatory and prohibitory conventions to control MNT risks. What is less considered is how to actively promote the development of MNT while still retaining control of the applications. The former involves considering how conventions like the Nuclear Non-Proliferation Treaty, the Chemical Weapons Convention, and Biological Weapons Convention can be used as models for a nanotechnology regulatory convention and how FDA and export-control regimes can be applied to MNT. The latter involves examining government incentive programs like patent systems and incentive programs for application to MNT. Lastly, other regimes are considered, such as outright nationalization of MNT or imposition of technology controls as a condition for conducting research.

A. Prohibitory Control Mechanisms for Molecular Nanotechnology

The most extreme form of control for a technology is outright prohibition of any research and development of the technology, much less implementation. Though some have called for such a ban on MNT,⁴⁷ most acknowledge that any attempts to prevent MNT completely will meet with failure.⁴⁸ A prominent example mentioned by Glen Reynolds is the British Explosives Act of 1875, which forbade private research in rocketry experimentation.⁴⁹ This led to a dearth in rocketry research in England, while the United States under Goddard and

42. See Bailey, *supra* note 30, at 26-27.

43. *Id.*

44. See Joy, *supra* note 4.

45. See Lin-Easton, *supra* note 8.

46. Fiedler & Reynolds, *supra* note 6, at 611-12.

47. Joy, *supra* note 4.

48. Fiedler & Reynolds, *supra* note 6, at 603-04.

49. *Id.*

Germany under von Braun surged ahead in the technology with near disastrous consequences for England during World War II. Other examples from history involving prohibiting technology include bans on knives in China and the ban on guns in feudal Japan, leading to the samurai class with its violent application of sword weaponry. Consequently, it does not seem likely that any technology can be completely banned worldwide or without unforeseen, unintended consequences.⁵⁰

1. International Regulation Mechanisms

If prohibitive control of MNT once developed or “released” is desired, something on the order of a modern weapons control convention is needed. To provide international compliance in preventing unauthorized “release” or use of nanotechnology, an effective convention would need international buy-in at the United Nations level, involving the main powers in control of MNT. An enforcement and verification mechanism is also required to bring noncomplying nations in line—otherwise the convention is useless, especially in the face of a pernicious release of nanotechnology. One mechanism that could be applicable is the Nuclear Non-Proliferation Treaty (NPT).⁵¹ This treaty, a product of arms control negotiations between the United States and the USSR, was ratified by the United Nations in 1968 and signed by the United States in 1970.⁵² The chief goal of the NPT is for nations which possess nuclear weapons to prevent the distribution of such weapons to nonpossessing nations, including preventing assistance to these nations in nuclear weapons research.⁵³ As an incentive to discourage independent nuclear research in nonpossessory nations, member nations are required to assist other nations in the development of peaceful nuclear technology under international supervision.

To enforce the NPT and promote the exchange of peaceful nuclear research, the United Nations created the International Atomic Energy Agency.⁵⁴ Its primary functions are to (a) receive, take custody of, and provide nuclear material, services, equipment, and facilities; (b) to encourage, assist, and carry out research to foster the exchange of scientists and scientific and technical information; (c) to establish and administer safeguards to prevent diversion to military uses; and (d) to establish, adopt, and apply health and safety measures.⁵⁵

50. *Id.*

51. Treaty on the Non-Proliferation of Nuclear Weapons, July 1, 1968, 21 U.S.T. 483, 729 U.N.T.S. 161.

52. Edwin J. Nazario, *Note & Comment: The Potential Role of Arbitration in the Nuclear Non-Proliferation Treaty Regime*, 10 AM. REV. INT’L ARB. 139–40 (1999).

53. *Id.*

54. Statute of the International Atomic Energy Agency, *opened for signature*, Oct. 26, 1956, art. II, 8 U.S.T. 1093, 276 U.N.T.S. 3.

55. Nazario, *supra* note 53, at 140.

The Agency governance consists of a General Conference, a Board of Governors, and a Director General.⁵⁶ The General Conference meets once a year and is composed of all the signatories to the treaty.⁵⁷ The Board of Governors is made up of 34 representatives selected from the General Conference.⁵⁸ The selection of these members was modified in 1968 on the request of nonnuclear weapons states which felt the Board was not representative enough.⁵⁹ The Director General is the chief administrative officer, appointed by the Board of Governors for a term of four years.⁶⁰

For enforcement of treaty breaches, a signatory state to the NPT and IAEA could attempt to bring a breach of treaty claim before the International Court of Justice.⁶¹ If the breach involved only the IAEA Statute, then the ICJ could hear the case because all the treaty signatories have accepted its jurisdiction in Article 17(A) of the treaty.⁶² However, if the dispute also involved the NPT, both the state bringing the breach of treaty claim and the state allegedly breaching the treaty must have submitted to the “compulsory jurisdiction” of the ICJ because the NPT has no internal provision establishing ICJ jurisdiction.⁶³ Such acceptance has been rare, and if this voluntary acceptance is lacking, the ICJ may have no grounds to hear disputes concerning the NPT at all.⁶⁴

As applied to MNT, the NPT provides some guidance on what minimum factors would be necessary to have international enforcement of a nanotechnology control regime. First, there would need to be agreement among the major nanotechnology-possessing nations to participate in a control convention policing the nonpossessing nations. Coupled with that is the need for a technology exchange mechanism like that incorporated into the IAEA to assist in peaceful, and perhaps highly controlled, exchange of MNT between nations, including implementing health and safety measures and proliferation safeguards. Like the NPT and IAEA, an MNT control regime would need some governing board, reflecting representation from the entire world body. It would most likely need to be implemented through the United Nations to gain supranational approval and to prevent jealousy and suspicion of a few nations controlling the proliferation to all others.

An MNT nonproliferation convention would need an enforcement mechanism, but one that has more teeth than the current NPT. If a nation now decides it does not want to submit to the jurisdiction of the ICJ, the IAEA has little recourse to imposing sanctions, so the work would be left to the U.N. Security Council, unilateral, or multinational coalitions to enforce the convention. Even

56. *Id.*

57. *Id.*

58. *Id.*

59. *Id.*

60. *Id.*

61. *Id.* at 144.

62. *Id.*

63. *Id.*

64. *Id.*

now, the NPT has been fairly ineffective in controlling rogue nations that seek neither international approval nor acceptance in the international fold.⁶⁵ North Korea has flouted IAEA disapproval over their weapons development programs, and countries like Pakistan, South Africa, and Israel have all developed nuclear weapons with the assistance of nuclear weapons possessing nations, while Iran has apparently managed to hide an advanced nuclear fuel processing capability while proclaiming a peaceful nuclear energy development program.

An MNT enforcement mechanism would need absolute compliance and immediate recourse. The development of nanotechnology would not take as long or involve as much infrastructure as a nuclear weapons development program and could be much more easily secreted away from international inspectors. This difficulty of detection would seem to be the greatest flaw of an NPT-like convention, simply because the NPT and IAEA were developed to control a technology that is capital intensive, involves heavy infrastructure, and can be detected remotely with radiation sensors. Hiding a nuclear test is difficult, even when done underground; nanotechnology research can eventually be done in a university laboratory or garage.

Indeed, it might be impossible to impose an NPT-like convention on rogue states. However, some elements of the treaty, such as multinational involvement, a board of governance, and an enforcement mechanism, in theory should be adopted for an MNT nonproliferation convention.

Perhaps more appropriate for controlling MNT is the use of conventions like the Chemical Weapons Convention and the Biological Weapons Convention. Molecular nanotechnology shares more attributes of chemical and biological weapons than of nuclear weapons.⁶⁶ The Chemical Weapons Convention (CWC) is a proposed international treaty that would impose an obligation on signatory nations to destroy any chemical weapons they possess and agree not to develop chemical weapons.⁶⁷ Article VII of the Convention provides that each cooperating state shall provide the appropriate legal assistance to implement the obligations of the treaty and that "each State Party shall designate or establish a National Authority to serve as the national focal point for effective liaison with the Organization and other States Parties."⁶⁸ Article IX clarifies how such consultations, cooperation, and fact-finding shall take place.⁶⁹ The purpose of the convention is to provide an international framework for the destruction of existing chemical weapons, and the prevention of future military development of chemical technology, in a voluntary inspection protocol. Member states would provide

65. *Id.* at 140.

66. K. Eric Drexler, *Machine Phase Nanotechnology*, *Sci. Am.*, Sept. 2001, at 58.

67. Chemical Weapons Convention, art. I, available at http://www.cwc.gov/treaty/articles/art-01_html (last visited Apr. 30, 2004).

68. *Id.* art. VII, para. 2, 4, available at http://www.cwc.gov/treaty/articles/art-07_html (last visited Apr. 30, 2004).

69. *Id.* art. IX, available at http://www.cwc.gov/treaty/articles/art-09_html (last visited Apr. 30, 2004).

focal points for conducting and coordinating compliance with the protocols of the convention. Disputes and fact-finding requests would be adjudicated with bilateral agreements. The presence of inspectors is probably the most useful aspect to incorporate into an MNT convention because relying on voluntary compliance with a nanotechnology control regime would be fruitless because of its low detectability. This feature is also the most controversial and held up ratification by the United States until 1997.⁷⁰ The U.S. Senate had feared the convention would force open American chemical plants to foreign inspectors, some interested in stealing trade secrets unrelated to chemical weapons.⁷¹ Under the CWC, each State Party has the right to request an on-site “challenge inspection”⁷² “for the sole purpose of clarifying and resolving any questions concerning possible noncompliance with the provisions of this Convention and to have this inspection conducted anywhere without delay by an inspection team designated by the Director-General and in accordance with the Verification Annex.”⁷³

These challenge inspections can be requested when a dispute arises over the contents or operations of a particular facility that a member State wants to understand. The problem with this provision, as with the NPT, is that the enforcement of the inspections has no teeth. Without threats to use force to inspect a facility, force that is adequately backed up by a sufficiently powerful state or international coalition, inspections would likely go unconduted.

This underlies a danger in not winning the support of major nations in an MNT convention. Without enforcement and participation of major producers or researchers of nanotechnology, any convention will inevitably fail and potentially lead to a technology race or, more likely, to a release of nanodevices.

Another major convention that may have applications for an MNT control regime is the Biological Weapons Convention (BWC), enacted in 1975. Article I of the convention states that no member nation shall “develop, stockpile, or otherwise acquire or retain” biological agents that have no “prophylactic, protective, or peaceful” purpose.⁷⁴ Article VI provides for implementation of the convention, allowing any member state that finds any other state acting in breach of the convention to lodge a complaint with the U.N. Security Council.⁷⁵

The BWC provides more enforcement mechanisms than the CWC, with the Article VI provision of presentation to the Security Council. However, the BWC still has been criticized, much like the CWC, for its weak safeguards and recourse. Undersecretary of State for Arms Control and International Security John Bolton said the BWC provides a “false sense of security” and that more stringent

70. Thomas W. Lippman, *Senate Foes Derail Chemical Weapons Treaty*, WASH. POST, Sept. 13, 1996, at A1.

71. *Id.*

72. Chemical Weapons Convention, art. IX, para. 8.

73. *Id.*

74. Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on Their Destruction, Apr. 10, 1972, art. I, 26 U.S.T. 583, 1015 U.N.T.S. 163.

75. *Id.* art. VI.

proposals are needed to strengthen the effort against biological weapons.⁷⁶ These proposals include adoption of strict standards for the security of “pathogenic microorganisms,” the establishment of mechanisms for international investigations of suspicious disease outbreaks and alleged bioweapons incidents, and adoption of strict bio-safety procedures, based on World Health Organization guidelines.⁷⁷ The United States has refused to ratify the most recent protocols because of the lack of such safeguards. Again, as in the NPT and CWC, without a strong enforcement mechanism and buy-in from major nations, any international control mechanism for MNT will likewise encounter bickering, stalling, and hold-outs from a convention that will have any effect on enforcing MNT prohibitions and controls.

The adoption of some of the above proposals in an MNT control regime would do much to strengthen the enforcement and monitoring mechanisms of an international convention. A mechanism to investigate suspicious nanosystem incidents would be strongly needed because of the relative secrecy that nations would engage in to develop MNT. Nations would necessarily have to submit to more intrusive inspection, bolstered by WHO safety guidelines, in order to resolve any suspected unauthorized development of MNT agents. It is unlikely that any MNT regulatory regime would succeed without a transnational inspection body that would have the authority to investigate incidents. Few major nations, the United States especially, are likely to submit to such inspections.

To successfully implement an MNT control regime that actively seeks to prohibit unauthorized development of the technology, several mechanisms must be used. First, as stated for the NPT, the agreement must be multinational and include all the major nations involved in MNT. Considering past experience with international conventions, there will be rogue states that either refuse to sign the convention or secretly (or openly) flout the convention even after signature. Second, there needs to be a democratic and representative governing board so that all members are included in the decision-making process. As evidenced by the 1968 amendments to the IAEA, member nations will be more willing to cooperate if they feel that they are not being controlled by a distant governing body dominated by First World affluent nations.

Third, there must be a realizable enforcement and verification mechanism that has teeth. This will be the most controversial provision because sovereign nations do not readily accept intrusions on to their soil, especially those based on accusations by their political or ideological enemies. A practical MNT convention enforcement would require voluntary inspectors stationed in each country, as with the BWC, along with recourse to an effective governing body. As recent events show, even agreed-upon areas like biological weapons monitoring and destruction face failure with U.S. intransigence to signing on to a weak convention. It should

⁷⁶ John R. Bolton, Remarks to the 5th Biological Weapon Convention RevCon Meeting (Nov. 19, 2001), available at <http://www.state.gov/t/us/rm/janJuly/6231.htm>.

⁷⁷ *Id.*

Wejnert

be apparent that the NPT system of appeals to the ICJ are ineffective at best and dangerous when relied upon with a rapidly developing and easily concealed technology like MNT. Indeed, when a governing body cannot compel jurisdiction over compliance, enforcement is not even present.

Based on these criteria, it is difficult to believe that any such convention could be crafted in today's political environment. Even if the United Nations were capable of sponsoring such a convention, the United States would likely be an obvious hold-out, just as it has resisted conventions like the CWC, BWC, and Land Mine conventions because of concerns about sovereignty and espionage. The only possible application for an international MNT control convention would be a monitoring body that could alert other nations of noncomplying MNT use. Absent a sea change in international law and cooperation, that monitoring function would be all that could be expected in practice, leaving the enforcement to unilateral or coalition action by interested nations. Any conventions would be powerless to stop the rogue nation or faction that can develop and release a lethal nanodevice in secrecy.

2. National Level Regulation Mechanisms

Without an international convention to control the proliferation of MNT, nations can regulate the development of MNT within their own borders more effectively. The United States can control the development of technology in three different ways: regulation of interstate commerce, regulation of exports, and regulation of medical and consumer products. Also, the federal government plays an enormously influential role in technology development by deciding what areas to fund and what restrictions and incentives are tied to that funding.

Though not often used for the regulation of technological matters, Congress has the authority to regulate interstate commerce.⁷⁸ This broad power has ebbed and flowed based on judicial review, but it has recently been interpreted to allow the regulation of channels of commerce, instrumentalities of commerce, and regulation of activities bearing a substantial relationship to interstate commerce.⁷⁹ After *Lopez*, the standards for regulating activities that are not specifically "commerce" are stricter and no longer construed to reach everything that could be connected with commerce, as earlier Supreme Court jurisprudence allowed.⁸⁰ Still, Congress has recently approached "noneconomic" subjects like human cloning with the 2001 Human Cloning Prohibition Act.⁸¹ This act attempts to prohibit any human cloning activities that result in interstate commerce, seeking a ban on a technology that is at a very early stage of development, but is controversial enough to motivate the House to act. Though the Act has been

78. U.S. CONST. art I § 8, cl. 3.

79. *United States v. Lopez*, 514 U.S. 549, 558 (1995).

80. *See Katzenbach v. McClung*, 379 U.S. 294 (1964); *Heart of Atlanta v. United States*, 379 U.S. 241 (1964).

81. H.R. 2505(a) 107th Cong. (2001).

criticized for its vagueness in defining a human embryo for the purposes of research, the mechanisms provided by the Act could be a model for structuring a regulation of MNT within U.S. jurisdiction by restraining unauthorized experimentation and research and development on potentially equally controversial technology. The efficacy of the Congressional response to human cloning will need to be evaluated if the resolution passes and is held to be constitutional—First Amendment challenges claiming a right to free speech through scientific research are likely. Nonetheless, it provides a national mechanism for at least theoretically controlling MNT distribution.

Article I of the Constitution also provides for Congressional power over commerce with foreign nations and thus control over exports from within the United States.⁸² Most relevant to control of sensitive technology export is the International Trade in Arms Regulations (ITAR) Act.⁸³ Congress delegated to the President the power to control the import and export of certain defense items under the Arms Control Export Act (ACEA).⁸⁴ The ACEA authorizes the President to create a list, the United States Munitions List, of items subject to export and import restrictions.⁸⁵ Included in this list, among items like tanks, missiles, and armaments, are encrypting devices, software, and source code.⁸⁶ This last category caused significant controversy, as well as providing a mechanism for the control of the proliferation of MNT beyond the United States.

Under ITAR, the Secretary of State determines whether an item is within the scope of the Munitions List. If the Department of State determined the item to be within the scope of the Munitions List, that item cannot be exported without a license. If an item is on the Munitions List, that means that exporters and manufacturers of that item must register with the government as arms dealers or manufacturers.⁸⁷

That encryption devices and software are considered to be within the ambit of the Munitions List and subject to ITAR restrictions was justified on the basis that encryption products could be used by enemy forces or terrorists to conceal information that could not be accessed by the U.S. military or National Security Agency.⁸⁸ The United States has promulgated further restrictions on supercomputers to designated nations like China, Syria, and Libya, which is consistent with its determinations on encryption devices. Therefore, placing MNT technology on the Munitions List would be reasonable because of the potentially catastrophic misuse of the technology by enemy states. This mechanism might be more effective in accomplishing control of MNT than regulation of interstate commerce because

82. U.S. CONST. art I, § 8, cl. 3.

83. Ryan Allan Murr, Comment, *Privacy and Encryption in Cyberspace: First Amendment Challenges to ITAR, EAR and Their Successors*, 34 SAN DIEGO L. REV. 1401, 1415 (1997).

84. *Id.*

85. *Id.*

86. *Id.*

87. *Id.* at 1416.

88. *Id.* at 1411.

it serves the interests of the United States more to prohibit the export of MNT than to suppress its development completely. An export control regime coupled with a national incentive program would allow the development of MNT while preventing its international distribution, much as encryption technology developed within the United States.

Unfortunately, the portable nature of MNT and the increasingly porous international borders will probably not allow the suppression of nanotechnology. It has been generally acknowledged that export controls have done little to prevent the proliferation of strong encryption when it can be easily stored on a disk and transported worldwide or over the Internet.⁸⁹ In addition, ITAR restrictions may have impeded encryption research in the United States, while competing nations, unrestrained by such restrictions, developed and implemented strong encryption without the predicted criminal implementation of the same technology.⁹⁰

A more reasonable approach to regulating MNT on a national level without an objective of outright suppression would be to implement a product regulatory mechanism like the Food and Drug Administration.⁹¹ Proponents of legal approaches to managing nanotechnology, like Glen Reynolds, have discussed regulating medical applications of nanotechnology as drugs or devices under the Federal Food, Drug, and Cosmetic Act.⁹² Though the details of whether nanodevices would be regulated as “drugs” or “devices” are uncertain, there is merit to regulating MNT applications as consumer products when they are used for medical applications. Indeed, as Glen Reynolds points out, the early stages of MNT will be marked by jumps and starts down different paths, and some applications, like medical “devices,” will require enhanced oversight and consideration.⁹³ By vesting power over the regulation of nanodevices in a body

89. See generally BRUCE SCHNEIER & DAVID BANISAR, *THE ELECTRONIC PRIVACY PAPERS* (1994).

90. BRUCE SCHNEIER, *APPLIED CRYPTOGRAPHY* 801 (1997).

91. Fiedler & Reynolds, *supra* note 6, at 607.

92. *Id.* at 607–08. The Federal Food, Drug, and Cosmetic Act defines “drug” as:

(A) articles recognized in the official United States Pharmacopoeia, official Homeopathic Pharmacopoeia of the United States, or official National Formulary, or any supplement to any of them; and (B) articles intended for use in the diagnosis, cure, mitigation, treatment, or prevention of disease in man or other animals; and (C) articles (other than food) intended to affect the structure or any function of the body of man or other animals; and (D) articles intended for use as a component of any article specified in clause (A), (B), or (C). . . .

Furthermore, the term “device” . . . means an instrument, apparatus, implement, machine, contrivance, implant, in vitro reagent, or other similar or related article, including any component, part, or accessory, which is -

(1) recognized in the official National Formulary, or the United States Pharmacopoeia, or any supplement to them,

(2) intended for use in the diagnosis of disease or other conditions, or in the cure, mitigation, treatment, or prevention of disease, in man or other animals, or

(3) intended to affect the structure or any function of the body of man or other animals, and which does not achieve its primary intended purposes through chemical action within or on the body of man or other animals and which is not dependent upon being metabolized for the achievement of any of its principal intended purposes.” 21 U.S.C. 321(g)(1) (1988).

93. Fiedler & Reynolds, *supra* note 6, at 607–09.

analogous to the Food and Drug Administration, the federal government could exercise more control over the development and production of medical and consumer applications of MNT. It is exactly this class of nanodevices that should be directed by some regulatory oversight, considering the risk that a poorly defined and developed nanosystem could pose to the human body once released. Nanosystems working as pharmaceutical products could have the toxicity of conventional drugs coupled with the self-replicating power of a “living” organism.⁹⁴

The advantages include universal interaction with manufacturers and researchers who seek approval for MNT applications, a standardized mechanism for how appropriate research in MNT would be conducted, and follow-up on how MNT applications perform in the market. In addition, an administrative agency would be accountable to judicial review and public comment, as well as transparency of its conduct.

The negatives of controlling MNT devices through a federal regulatory body include the traditional laments of the bureaucratic agency: lack of efficiency, duplication of effort, and subjection to Congressional and judicial requirements in enacting regulations. In addition, the FDA primarily regulates consumer products. While FDA regulation might be useful as MNT applications proliferate, the initial research and development poses many risks which cannot be accounted for or controlled by the FDA, risks that are just as great as end-use applications. Some proposals for handling this interim research are discussed below. When MNT is involved, perhaps a more secretive operation might be needed to maintain control over the proliferation of the technology. As discussed later, perhaps a secret application and protocol for testing and research could be combined with a “need to know” review of MNT applications. This would involve a dramatic departure from the traditional model of administrative law but might be warranted for regulating molecular nanotechnology.

As in the case of international control conventions, MNT creates new contingencies and dangers that traditional models of government regulation are not equipped to address. While Congressional powers exist to regulate MNT in a traditional manner, the intellectual property aspect of MNT makes any tangible controls subject to evasion as the intangible aspect of MNT develops. Export controls will be of little assistance when the “source code” for a nanodevice can be transmitted anywhere worldwide instantaneously to a “universal assembler.” Likewise, control of MNT through administrative agencies like the FDA provides a framework for how MNT could be approached from a definitional perspective, but administrative agencies do not currently have the capabilities to suppress the dangerous possibilities of unrestrained MNT. The analysis makes clear that current governmental powers are inadequate to ensure secure, confidential, and effective regulation of MNT applications.

94. *Id.*

B. Risk Management for Molecular Nanotechnology

After considering how prohibitory and strict regulatory mechanisms might work for MNT, it is clear that there may be other mechanisms that can be used to control the development of MNT that actually encourage growth and use of the technology without forcing it into predefined control regimes. In some cases, the futurists who push nanotechnology have done too good a job—their fantastic predictions for what MNT could conceivably do are taken by its “anti-futurist” critics and warped into doomsday scenarios unlikely to ever take place.⁹⁵ Skeptics of the technology who predict runaway machines converting the world into “grey goo” sometimes forget about the limitations that all self-replicating “machines” in nature face. Bacteria cannot double in number indefinitely, and so MNT nanodevices will not be able to propagate ad infinitum.

Nonetheless, prudent technology management calls for an assessment of the risks that new technologies present and how these risks can be understood, controlled, and mitigated. There are two competing viewpoints that dominate the nanotechnology debate today—the Foresight Institute guidelines and the environmentalist-advocated “precautionary principle.” Each approaches MNT from a cautious perspective, but the former advocates controlled development by using certain safeguards and limitations, while the latter seeks to eliminate all risk in developing MNT, if MNT is developed at all.

The Foresight Institute was created by K. Eric Drexler and other MNT futurist proponents to educate the scientific and public communities about the background, possibilities, potentials, and risks of the new technology.⁹⁶ The Foresight Guidelines are principles that were proposed to manage MNT risks in the face of pernicious nanosystem development and release. The Guidelines are primarily divided into two lists—Development Principles and Specific Design Guidelines. The guidelines are directed at preventing the release of self-replicating, “intelligent” nanosystems into the wild where they can cause catastrophic damage to people and the environment. Less malignant applications need not be subjected to such controls, though the design principles will be useful additions to any consumer products that are developed.

1. *The Foresight Guidelines*

The Development Principles focus on the characteristics that mature, controlled MNT should incorporate. Some of the more important principles are: (1) uncontrolled replication in the natural environment must not be allowed; (2) evolution of complex self-manufactured devices is discouraged; (3) developers should consider the environmental consequences of the technology and limit the consequences to intended effects; (4) industry self-regulation should be

95. George J. Annas, *The Man on the Moon, Immortality, and Other Millennial Myths: The Prospects and Perils of Human Genetic Engineering*, 49 EMORY L.J. 753, 778 fn. 86 (2000).

96. See *supra* note 25.

encouraged with economic incentives when possible; and (5) distribution of MNT development capabilities must be restricted to those who agree to the Guidelines (while no restrictions on end products of development process need apply).⁹⁷

The Specific Design Guidelines incorporate some novel communications theory principles to prevent error transmission in replication, along with technological principles to limit the autonomy and power of self-replicating nanodevices. For example, the Specific Design Guidelines call for (1) encrypted design blueprints that are scrambled upon error to prevent error transmission; (2) audit trails generated upon replication; (3) built-in safety mechanisms such as artificial fuel sources not found in nature, outside broadcast-transmission-dependent replication, and programmed termination dates built into the self-replicating units; and (4) systematic security measures to avoid unplanned distribution of design and technical capabilities.⁹⁸

These design guidelines represent the most comprehensive risk assessment generated for MNT. By considering solutions to replication error, uncontrolled “wild” replication, and leakage of development technology to unauthorized actors, the Guidelines promote sound development and security features foremost in MNT propagation. Many of the features duplicate the goals of the aforementioned Nuclear Non-Proliferation Treaty, in preventing access of the development technology by actors who have not agreed to the Guidelines while encouraging the peaceful and safe use of the end products by the entire world community.

The Foresight Guidelines have been criticized for being “naïve for relying on an honor system”⁹⁹ that often breaks down under competitive national and economic pressures. Environmentalists fear that the Guidelines tip the balance towards unrestricted development and lack any real enforcement mechanism for preventing a release of “nonconforming” nanodevices into the environment.¹⁰⁰ In addition, environmentalists are skeptical of the Foresight Institute’s reliance on “risk management science,” which is often criticized for providing a false sense of rigor or objectivity that in many cases fails to prevent harm to people or the environment.¹⁰¹

2. Precautionary Principle

In response to the Foresight Institute’s guidelines, environmentalist critics of MNT development look instead to the “precautionary principle” as a mechanism to control the dangers of unrestrained nanotechnology development.¹⁰² The precautionary principle is, at its simplest, a burden-shifting approach to technological development. It calls for precaution in the face of any actions that

97. *Id.*

98. *Id.*

99. Lin-Easton, *supra* note 8, at 131–32.

100. *Id.* at 132.

101. *Id.*

102. *Id.* at 120–22.

may affect people or the environment, despite what the science may say, or be unable to say, about the risks of the technology in question.¹⁰³ The precautionary principle has been incorporated into several international treaties, including the Framework Convention on Climate Control¹⁰⁴ and the Kyoto Protocol,¹⁰⁵ and generally includes some or all of the following components: (1) proponents of a potentially hazardous technology have the burden of showing that the technology will not harm humans or the environment; (2) a full evaluation of the alternatives available, including serious consideration of no action at all as an alternative; (3) taking anticipatory action to avoid potential threats; and (4) an open and democratic decision-making process.¹⁰⁶

In its most reasonable incarnation, the precautionary principle is a more conservative formulation of risk management, by placing the burden on the proponent of the technology to examine the consequences of that technology, exploring the alternatives in developing the technology, and possibly not pursuing the technology. In that light, the precautionary principle seems relatively tame and prudent in the face of the catastrophic potential of MNT if developed unchecked. Unfortunately, the actual presentation of the precautionary principle usually takes the form of calls for outright bans on any potentially dangerous technologies, meaning that if the technology poses a risk at all, it is too dangerous to pursue.¹⁰⁷ Proponents of the precautionary principle often stress a more radical version of the components, based on their viewpoint that technology often presents unanticipated risks that are not evaluated before general release.¹⁰⁸ Viewed through this lens, MNT will certainly present risks too large to allow under an application of the precautionary principle, and will likely result in calls to ban development of the technology.¹⁰⁹ The Foresight Guidelines will be too weak a restraint on the danger to humans and the environment that MNT will pose.¹¹⁰

Though advocates of the precautionary principle often advocate extreme anti-technology positions, their public influence is not inconsiderable.¹¹¹ Their presence in academic debates and on international science panels presents a formidable counterweight to risk management approaches to developing MNT. The precautionary principle does not provide many helpful guidelines for approaching MNT beyond outright prohibition. By placing the burden on the proponents of the technology to prove no harm to humans or the environment,

103. *Id.*

104. United Nations Framework Convention on Climate Change, available at <http://unfccc.int/resource/docs/convkp/conveng.pdf> (Last visited May 13, 2004).

105. Kyoto Protocol to the United Nations Framework Convention on Climate Change, available at <http://unfccc.int/resource/docs/convkp/kpeng.pdf> (Last visited May 13, 2004).

106. *Id.* at 121–22.

107. Ronald Bailey, *Precautionary Tale*, REASON, Apr. 1999, at 36–41.

108. *Id.*

109. Lin-Easton, *supra* note 8, at 124.

110. *Id.* at 129.

111. Bailey, *supra* note 106, at 36–37.

advocates of the principle seek proof of a negative. This goes beyond normal hypothesis testing or risk assessment methodology and in a politicized environment presents a losing battle for proponents. In hindsight, if the principle had been invoked for any major technology, one cannot imagine any that would have passed the test—fire, steam power, pharmaceuticals and industrial chemicals, plastics, the automobile, and the Internet. By aiming such a blunt tool at MNT, not only would the technology be “relinquished,” in the parlance of Bill Joy, but any other future products and benefits from advanced technologies would fall to a ban. Any honest risk assessment produces nonzero risks, and when uncertain and novel technologies like biotechnology and nanotechnology fall within the purview of the precautionary principle, press releases and inflammatory web sites make hay with fantastic headlines.

C. MNT Development Mechanisms, Standards, and Controls

Another perspective that is seldom considered in the literature is how to encourage the development of molecular nanotechnology in its formative stages. Futurists and critics focus on the endless possibilities and devastating pitfalls of a mature MNT society, but the road to this future is far from certain given current capabilities. While risk management techniques like the Foresight Guidelines provide helpful design specifications that should be incorporated into MNT, these blueprints are little more than abstract maps to guide the process, rather than specifying the product itself. Technology critics quickly point out that current capabilities are limited to etching silicon structures at about 0.05 μm , so atom-specific placement is probably decades away. Though biotechnology and chemistry development pathways offer a different creation mechanism, they too face daunting obstacles in bringing even the most rudimentary MNT applications into reality.¹¹²

Given this enormous gap in the potential that Drexler imagines and the promising steps in 2002, perhaps scientists should focus more on encouraging development of MNT rather than proscribing development limits *a priori*. Nonetheless, with an eye on managed control of the technology, there are current mechanisms that could be adapted for promoting MNT while limiting its dangerous potentials. Some of these pathways include economic incentives such as patent-like grants and development prizes; governmental controls like research partnerships and nationalization; and mandatory controls like disabler technologies, “defense shields,” and blueprint “escrow” plans.

Under the U.S. federal system, Congress has the power to grant patent rights to inventions for “limited times.”¹¹³ The general purposes of the patent system are to encourage the development of technology by rewarding inventors with exclusive rights for a limited period of time, currently 20 years under U.S. law.¹¹⁴

112. Whitesides, *supra* note 21, at 79.

113. U.S. CONST. art. I, § 8, cl. 8.

114. *See* *Bonito Boats, Inc. v. Thunder Craft Boats, Inc.*, 489 U.S. 141, 146 (1989).

Patent systems worldwide generally provide a quid pro quo exchange of exclusive rights for an enabling disclosure of how to make and use the invention that the patent application describes.¹¹⁵ As a consequence, the inventor's technology becomes a publicly accessible record for others to view. When the limited grant expires, the technology becomes part of the public domain and may be freely used. From a darker perspective, infringers locally or abroad are given notice of the invention and may attempt to produce the invention, albeit possibly illegally. This trade-off deters many inventors and corporations from applying for patent rights, opting instead for developing the technology under a trade secret regime. Nonetheless, most agree that patent systems on the whole encourage innovation, especially for risky and unproven technologies.¹¹⁶ If the risk-adjusted investment return on a technology is potentially low, an inventor will rationally pursue development only with some guarantees of protection during the exploitation phase. Patent systems provide this incentive.

Not all inventions may be protected by patent grants, though. Under U.S. law, the Commissioner of Patents may withhold issuance of a patent for an invention which he determines to be detrimental to national security.¹¹⁷ The patent application will be kept secret for a period of one year, renewable upon expiration.¹¹⁸ In addition, during periods of national emergency, a secrecy order issued may remain in effect during the duration of hostilities and one year after cessation of hostilities.¹¹⁹

Secrecy orders carry a penalty of abandonment of the invention if there is unauthorized disclosure during the period of the secrecy order.¹²⁰ As an equitable measure, U.S. patent law provides for nominal compensation during a secrecy order period, and the government may use the invention consequently.¹²¹ Secrecy orders are not used as frequently in patent office prosecution as in the past and generally deal with inventions relating to nuclear weapons systems.¹²² In addition, the U.S. Patent Office does not grant patents on human clones as a policy matter, indicating that for issues which pose significant ethical or social implications, technology controls will be implemented.¹²³

Since patent applications are published either upon issue of the granted patent, or 18 months after the filing date,¹²⁴ any patents issued for MNT devices and methods would become public knowledge within a short time frame. The United States, along with most other countries that have secret patent orders, could maintain control over patents issued for MNT, but that would probably

115. 35 U.S.C. § 112 (2000).

116. See 1 DONALD S. CHISUM, CHISUM ON PATENTS, §7 (2003).

117. 35 U.S.C. § 181 (2000).

118. *Id.*

119. *Id.*

120. *Id.* § 182.

121. *Id.* § 183.

122. 37 C.F.R. § 5.20 (2003).

123. 1077 Off. Gaz. Pat. Office 24 (Apr. 21, 1987).

124. 35 U.S.C. § 122 (2000).

discourage filing. MNT applications would be much more profitable to develop than nuclear weapons systems or high energy lasers, which are currently nonpatentable or subject to secrecy orders, so to encourage innovation the Patent Office would need a modified procedure for granting patents for nanodevices and methods. However, if there is an invention that may be deemed detrimental to national security, surely MNT will fall under this designation. Military planners already recognize MNT applications as crucial to the superiority of U.S. forces and would quickly move to have MNT applications deemed secret and possibly unpatentable.¹²⁵

Despite the policy goal of supplying invention information to the public domain, Congress has the power to modify the Patent Act to grant “unpublished” patents, which would be a hybrid of secrecy order and confidential prosecution of patents. Some other countries, like Germany, used to issue “secret” patents that granted limited rights to the inventor but were not available for public viewing during a defined period.¹²⁶ MNT inventions could be promoted and still controlled by allowing for confidential and secret applications reviewed by a select group within the Patent and Trademark Office and granted secrecy—not as a detriment to the applicant, but as an incentive in the face of the aforementioned possibility of an unpatentable technology holding. The secret patent could then come under the purview of the Department of Defense or other administrative agency specialized for the purpose of regulating MNT. As mentioned earlier, an administrative agency on its own would have little competence to control the development and proliferation of MNT, but, coupled with the force of administrative secrecy, might be effective.

As for how such a secret patent might be enforced, there would be conflicts with the current system, which provides notice of infringement of a valid patent. Granted patents are public record, so an infringer has constructive notice of a valid patent upon issue of the patent. Secret patents would by default be unpublished, so questions of fairness and due process would arise when infringement of a secret MNT patent is alleged. Such questions would need to be addressed in a future regulatory regime that promotes MNT development but also seeks suppression of and control over unauthorized development.

Another interesting economic incentive for MNT development, either outside of or as an added inducement to patent grants, would be the encouragement of national competitions and prizes for MNT application development. Richard Feynman spoke of using prizes in his now-famous talk, “There’s Plenty of Room at the Bottom,” delivered to the American Physical Society in 1959.¹²⁷ He imagined \$1,000 prizes for creating micron-scale motors and machines and successively larger prizes for larger accomplishments.¹²⁸ Analogous to this initial nanotechnology “dare” is Carl Zubrin’s promotion of a Mars expeditionary

125. Lin-Easton, *supra* note 8, at 112.

126. 2-1 BAXTER, *WORLD PATENT LAW & PRACTICE*, § 1.06 (2003).

127. DREXLER, *supra* note 9, at 511.

128. Feynman, *supra* note 10.

mission, in which he calls for establishment of a "Mars prize" sponsored by the government to spur innovation and accomplishment of certain key goals in a manned mission to Mars.¹²⁹ Zubrin emphasized the economy and ingenuity of asking private entrepreneurs to develop technology when their own money is at stake, spurred on by the monetary as well as marketing incentives of accomplishing the objectives.¹³⁰ As Zubrin noted, Charles Limburgh set off to cross the Atlantic encouraged by a government-sponsored prize to do so. Explorers in the past set sail for unknown lands on the promise of state-sanctioned prizes and grants. Zubrin proposed successive stages of development to reaching Mars, in increasing complexity and increasing value of the prize. Fundamental steps to landing a private manned mission to Mars include placing an imaging mission in Mars orbit, a robotic lander on Mars, and a long-term life support system in space, all with certain strict conditions. Though costly to attain, these accomplished challenges would be met with equally impressive prizes, on the order of \$500 million to \$1 billion. Another advantage of sponsoring such prizes is that desired protocols and standards can be imposed as a condition for winning. The government could specify that later stages of MNT development must conform to the Foresight Guidelines or variations thereof.

A similar nanotechnology challenge program could be created to spur private development of key MNT steps. For example, some fundamental steps to creating self-replicating nanosystems would be Brownian assembly of medium-scale materials, mechanosynthetic assembly of small building blocks, first generation solution-based systems, and creation of complex diamond-like materials in an inert environment.¹³¹ More advanced challenges would be to create simple manipulators and sorting and ordering molecules.¹³² Notice that even these more advanced stages are still decades away from self-replicating super-machines that threaten to churn the world into grey goo. Yet they represent Drexler's basic vision for MNT development as an optimistic scenario. By providing generous prizes for meeting these steps, a mature MNT might be accomplishable in the private sector without enormous government funding. Engineering companies like IBM, Xerox, or perhaps biotechnology companies like Monsanto or chemical companies like Dow Chemicals will have the funding to pursue such a competition, though if the history of innovative technology is any guide, early MNT applications will come from spin-off ventures from these corporate giants.¹³³

Economic incentives like prizes and competitions will likely spur MNT development, but these pathways lack the critical element of control over development that is so emphatically stressed by both proponents and skeptics alike. If concern about a dangerous release is of paramount concern, leaving the development race open to any private venture that seeks a commercial success

129. ROBERT ZUBRIN, *THE CASE FOR MARS*, 283–90 (1997).

130. *Id.*

131. DREXLER, *supra* note 9, at 485–88.

132. *Id.* at 471–81.

133. *See* CLAYTON M. CHRISTENSEN, *THE INNOVATOR'S DILEMMA* (1997).

will probably not satisfy this concern. This option may be open only for a short period in the early history of MNT, as the initial useless, but essential building blocks are established. After that point, when practical MNT devices are within reach, other mechanisms will need to be asserted. Some of these options include joint government ventures, where private companies work in cooperation with each other or directly with the government as overseer and eventually controller of the technology, or the outright exercise of eminent domain over the technology as a last resort. Practical examples, like the approaches used by the national labs (Lawrence Livermore, Sandia, and Los Alamos), exist for defining how a successful collaboration with private entities can be accomplished to develop top secret technologies in nuclear weapons development and aerospace. In addition, as an intermediate step, the government can promote technological controls over MNT development with extensions of the Foresight Specific Design Guidelines discussed earlier.

Private-government cooperative ventures are increasingly promoted for complex, uncertain, and capital-intensive technology development. In such fields as alternative fuels, nuclear power, low-emission vehicles, aerospace, and biotechnology, government funding and incentives like access to exclusive development rights have made dramatic advances in otherwise unapproachable technologies. The risk involved with some of these technologies is just too great, in the eyes of many technology critics, to believe that private companies will undertake the burden alone, without some assurance of government assistance and risk-sharing.¹³⁴ Others disagree; they point to the excessive waste generated in the development process of “government darlings” and point out that the Japanese Ministry of International Trade and Industry (MITI) has not been very impressive in picking and assisting “key” technologies.¹³⁵ Nonetheless, much as in space exploration, if a mature MNT is desired within a reasonable time, then government assistance and direction will be required to coordinate the diverse fields that will contribute to MNT.¹³⁶ In addition, a cooperative private-government venture will have the advantage of built-in government oversight and management of nascent risks in the technology, rather than overseeing the technology after it has been released to the general scientific and public community.

One option of last resort that has similar shortcomings to outright prohibition is nationalization of MNT either in its early stages or after MNT applications are realizable. The U.S. government took this tack with nuclear weapons development, and early on with nuclear power research, until Eisenhower’s cooperative nuclear research development program, “Atoms for Peace,” was established.¹³⁷ Nationalization of MNT would provide government control over the development, proliferation, and access to the technology. It would also allow more

134. *Id.*

135. David R. Henderson, *The Myth of MITI*, FORTUNE, Aug. 8, 1983, at 114.

136. See DREXLER, *supra* note 9, at 507–08.

137. T.A. Heppenheimer, *Nuclear Power: What Went Wrong?*, AM. HERITAGE OF INVENTION & TECH., Fall 2002, at 46–58.

stringent standard-setting and implementation of control and security guidelines, which both proponents and critics agree needs to be a component of mature MNT.

A major disadvantage of nationalization is that it likely will deter development if private companies view appropriation of their investment efforts as an eventuality. Also, it is uncertain if nationalization of the technology will provide the security that is needed to prevent proliferation of MNT to unauthorized users. Experience with the NPT regime has shown that determined and financially motivated seekers of a technology will find motivated providers of that technology.¹³⁸ Lastly, though the U.S. government has the power to appropriate property, both through Fifth Amendment “takings”¹³⁹ and potentially through the Patent Act if that route were elected,¹⁴⁰ it is highly uncertain that such a takeover would be constitutionally sustained. Absent extraordinary circumstances, such as war, the government’s only likely recourse is a regulatory process that subsumes MNT as it is developed to prevent unauthorized transfers or exposures in the wild.

The government may have more success with setting standards for MNT development, rather than assuming direct control over development or application. As discussed above in reference to administrative regulation and joint private ventures, the federal government has a role in coordinating activities and setting guidelines for safe and secure technology development. A possible beneficial role for government could be in encouraging and perhaps even mandating the adoption of variations of the Foresight Guidelines in MNT research and development. As mentioned, the Foresight Guidelines provide a useful blueprint for the properties a secure and controlled MNT should possess to avoid dire exposures and releases of nanodevices into the natural environment. Unless the Guidelines are incorporated along the development route, however, they may become afterthoughts when a rogue application is created unintentionally or, more seriously, intentionally. Some further extension of the guidelines include “terminator” technologies, much as in biotechnology, that will prevent uncontrolled replication in the wild.¹⁴¹ Also, other mechanisms might be employed that would require a central governing body, such as blueprint “escrow,” in which replication codes or “enabling” components for MNT could be stored in a depository body and accessed upon agreement to follow responsible protocols like the Guidelines. Such a mechanism could work like the depository institutions used by the Patent Office for biotechnology and plant samples,¹⁴² though for MNT this would be for a much different purpose—security, rather than verification.

The federal government may also be in a position to provide the resources that more advanced applications of the Foresight Guidelines call for. Proponents of the Guidelines, such as Ralph Merkle of Xerox, have advocated pre-emptive

138. Nazario, *supra* note 53, at 139.

139. U.S. CONST. amend. V.

140. 35 U.S.C. § 183 (2000).

141. Lin-Easton, *supra* note 8, at 129–30.

142. 35 U.S.C. § 114 (2000).

protocols in developing MNT as prerequisites to advanced experimentation.¹⁴³ Merkle, along with Drexler and others at the Foresight Institute, has proposed ideas like a “bioshield” around development laboratories to prevent releases, and Drexler has advanced the idea of an automated defense shield composed of programmed nanorobots that would seek out and destroy dangerous and uncontrolled replicators.¹⁴⁴ Such a complex undertaking is best undertaken by a federal government body that can marshal the resources and has a greater stake in safeguarding the public against the release of nanodevices. Much like the bio-safe laboratories that the Center for Disease Control maintains for biohazard research and response, the government could establish national centers for MNT development that conform to the proposed safeguards and not authorize research at unqualified facilities. Such a mandate would be within congressional powers as well as Executive Branch powers under the Department of Health and Human Services, and there is ample precedent for setting up and maintaining such protocols.

It is in this area that the government can have the greatest impact on MNT development and security. With its experience in regulating nuclear energy, infectious disease research, and biotechnology, the federal government can provide an organizing mechanism and set standards at complying facilities so that secure MNT research and development can take place. The government can then exert a substantial amount of control without retarding development. This may be the best compromise to the bipolar options of outright control and suppression versus unrestrained private development.



Molecular nanotechnology presents an unprecedented control over nature that warrants extensive preparation for securing the technology against uncontrolled releases into the environment. It has been said that nanotechnology presents the first technology that has almost the same power to destroy the environment as it does to restore and replenish it.¹⁴⁵ While futuristic scenarios of human immortality and creation of any desired material seem other-worldly, just as nightmarish are scenarios of super-predators in the form of micron-sized killing machines or rampant uncontrolled replication. Though neither scenario may come to pass, the promise and danger of MNT must be prepared for appropriately.

As experience with weapons-control conventions has shown, unexpected leakage of prohibited technology and insufficient enforcement mechanisms lead to failed control regimes. Such shortcomings must be addressed in any future MNT control regimes. It is doubtful that 20th Century conventions, which attempt to control easily detectible technologies like nuclear weapons facilities and chemical weapons production plants and still fail, could regulate a technology like

143. Lin-Easton, *supra* note 8, at 130.

144. *Id.* at 131.

145. *See* Lin-Easton, *supra* note 8, at 112–15.

MNT, which could theoretically be implemented in a garage—and has been.¹⁴⁶ If a rogue agent like Saddam Hussein disguised weapons plants as baby food factories, how hard would it be for his successor to hide a replicator laboratory in a restaurant kitchen?

Likewise, national-level control regimes provide more adequate enforcement and control mechanisms, but they fail to address the porosity of today's international borders and the intangible component of MNT that is reproducible worldwide at the click of a mouse and the switch of an Internet router. While the Interstate Commerce Clause and export restrictions like ITAR may restrain American businesses from trafficking in unauthorized MNT, these mechanisms will not prevent industrial espionage or transnational development.

From a different perspective, national states can influence the development of MNT by providing economic incentives through patent systems and "prizes." MNT will not spring to life overnight and may face some overwhelming obstacles along the way. If a nation does not want to see this baby smothered in its cradle, it may have to create government-industry cooperative ventures and establish national development centers that satisfy certain design and safety guidelines to prevent unrestrained creation of nanodevices that pose more danger than benefit. By implementing variations and enhancements of the Foresight Guidelines, a country may do more to influence the security and safe application of MNT than it would by attempting to prohibit or nationalize the technology at some stage.

At this point it is debatable that any of the discussed mechanisms would be of use for controlling MNT applications that can replicate in the wild and organize with distributed intelligence. While it may be tempting to propose an outright "relinquishment" of any MNT as being too dangerous, that will not happen. One potential prohibition that might allow development of MNT but avoid some of the more drastic outcomes would be to prohibit self-replication of devices. The Foresight Guidelines discuss in some detail the safeguards that should be implemented to prevent uncontrolled replication of nanodevices in the wild. Perhaps a prudent measure would be to restrict development of distributed-intelligent devices that can control their own replication. Much like the control rods used in nuclear reactors to moderate the reaction rate, perhaps an internationally imposed manufacturing control regime that limited the capacity of replicators would prevent MNT "release" into the wild. However, given the weakness of international conventions today, as discussed earlier, such control is laughable.

Perhaps then the only strategy is to not "encourage" MNT along any path, but to subject it to an international deposit like that first suggested for atomic weapons and energy. This was ultimately disregarded by U.S. policymakers, and historians often ponder what effects this "depository" would have had. The unlikelihood of this outcome, given historic U.S. distrust of international institutions, leaves one to sigh in despair. Based on all of these impossible hopes for international

146. There is at least one high school student who has created a crude Atomic Force Microscope in his garage, a potential enabling technology for MNT development.

Regulatory Mechanisms for Molecular Nanotechnology

cooperation, it seems then that the best approach will be a cooperative government-industry initiative in which there can be open dialog and input from many different technological and administrative bodies with some expertise in managing technology. If this is the choice that allows MNT to develop in some useful and not overregulated form, then it is better than a world of prohibition and envy.

Technology is a form of information, and information is hard to “uninvent.” Despite daunting technological obstacles, some form of molecular nanotechnology will exist in the coming decades. Whether as a diamondoid-material solution-phase system or a bioreactor-like factory, MNT eventually will produce devices that answer Feynman’s call to reach the bottom. Whether that future is one plagued by roving nanoswarms devouring the environment, or a utopia of endless abundance and freedom from disease, or merely a much better standard of living than we experience now depends on prudent planning and risk management as MNT unfolds. We need not fear the future, but neither should it depend on a roll of the dice.