MANAGERIAL ISSUES INVOLVED IN THE DEVELOPMENT OF NANOTECHNOLOGY PRODUCTS

THESIS

Presented to the Graduate Council
of Texas State University–San Marcos
in Partial Fulfillment
of the Requirements

for the Degree

Master of BUSINESS ADMINISTRATION

by

Ryan Josef Klepetko, B.S.T.

San Marcos, Texas
December 2004

ACKNOWLEDGEMENTS

I would like to thank my family, especially my parents, Ronald and Rayla-Jeanne Klepetko, and friends for supporting me and acting interested in all the things I told them about nanotechnology. I would also like to thank my committee members, Dr. Cecilia Temponi, Dr. Gary Beall, and Dr. Jeymeen Shah, who with patience helped me work through all the different things I wanted to write about and who allowed me to explore their wealth of knowledge. I especially want to thank Dr. Cecilia Temponi who, beyond being a resource, was able to help me keep focused during many days of frustration so that I was able to complete this thesis.

I would like to thank my interviewees, Dr. Hamill with Nanotechnologies Incorporated, Dr. Yaniv with Applied Nanotech, and Dr. Yowell with NASA's Nanomaterials Project for their valuable time they spent with me. I would like to thank Dr. Mary Pat Moyer for her help with narrowing down my topic. For help with proof reading my thesis I would like to thank Dr. Chittenden in the Business Department and the staff at the writing lab. Finally, I would like to thank the law offices of Winstead Sechrest & Minick for hosting the Nanoparticle Application Center's biweekly nanotechnology colloquium and for the free lunch they provide. This series has been able to keep me interested and in the loop on the developments in the nanotechnology field in Texas and around the world.

This manuscript was submitted to my thesis committee on November 16, 2004.

TABLE OF CONTENTS

TABLE OF FIGURES

ABSTRACT

MANAGERIAL ISSUES INVOLVED IN THE DEVELOPMENT OF NANOTECHNOLOGY PRODUCTS

By

Ryan Josef Klepetko, B.S.T.

Texas State University-San Marcos

December 2004

SUPERVISING PROFESSOR: DR. CECILIA TEMPONI

With the rapid development of and paradigm shift involved in the new field of nanotechnology, this thesis poses the question whether there are any new management approaches, techniques or meta-knowledge that firms working in this field should apply. To approach this question a large and diverse collection of non-technical sources related to nanotechnology was gathered and analyzed. After reviewing these sources with the above question in mind, an outline was created and refined thus giving the organization of this thesis. To supplement the information gathered in the literature, an in depth

interview was conducted with managers at several different organizations working in the nanotechnology environment.

Through this research it has been surmised that firms working in nanotechnology basically have the same issues as any firm working in a rapidly changing and highly technical field. These issues include intellectual property (IP) protection, market share, problem solving, adoption of technologies, analysis of the environment, creating a skilled team, product assessment, and, perhaps most importantly, cash flow. The unique aspect of nanotechnology that firms face is the level of expertise and varieties of skills required by the teams working in this field.

It is the conclusion of this thesis that the unique managerial implication of nanotechnology is management of such diverse and skilled workforces. The convergence of the sciences involved in the study and fabrication of molecular interfaces means that highly educated people from entirely different backgrounds, lexicons, and perspectives on the issues need to be united effectively. While managing cash and intellectual property is undoubtedly very important, creating systems to skillfully and efficiently unify the team members will distinguish the firm from others in the field and determine its long term dominance. This thesis reveals that new approaches to project management need to be researched and developed to manage the development process of products in rapidly changing technical environments. These techniques need to incorporate the ideas of knowledge management, system focus, and flexibility as identified in the body of this thesis.

I. INTRODUCTION

There are two objectives of this thesis.

1. Develop a broad overview of the managerial issues involved in managing the development process of nanotechnology products.
2. Identify if there are any managerial issues unique to the development of nanotechnology products.

The vast majority of the literature on nanotechnology is highly technical in nature. Because nanotechnology is a relatively new field, literature on managerial aspects of it has not been written. This thesis is written for either managers or entrepreneurs that are not knowledgeable about nanotechnology or for scientists or researchers that do not have managerial or business experience.

This thesis will begin by defining what nanotechnology is and why it is an important topic to study. After this discussion it is relevant to identify what governments are doing to sponsor the development of nanotechnology and to address the ethical implications in the development of nanotechnology. This will conclude section I. Section 2 is an overview of nanotechnology's applications and is split into two subsections: Process and Products. The process subsection is an overview of nanotechnology's enabling technologies, measurement or metrology of product features, and some of the different production methods. The products subsection will identify nanotechnology products currently on the market and products that are still in development.

Sections I and II are an overview of nanotechnology and are designed to give a lay reader a background understanding of nanotechnology so that they can better understand section III which is titled Product Development. Section III is the essence of this thesis. This section has 5 subsections and is built around **Figure A** on page 22. The first subsection is Knowledge Management and is used to tie the following four subsections together: Idea Generation, Feasibility Assessment, Funding, and Production. Section IV consists of three case studies used verify the validity of Section III. Conclusions follow the case studies which are then followed by recommendations and suggestions for future research.

A. Defining Nanotechnology

Nanotechnology is the art and science of manipulating matter at the atomic or molecular scale (Ghosh 2002). When matter is manipulated on the nano level, new and novel nanoparticles can be created, thereby creating new and novel materials and devices. The possibility of building things atom by atom was first introduced by Richard Feynman. In 1959, he said, "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom" (Evans et al. 2003).

Although nanoparticles have been around for a long time, since shortly after the first supernova, humans controlling the distribution of sizes and manipulating single atomic reactions has not been a reality until now (Newberger 2003). The theoretical implications of this are that everything humans have ever produced can be re-engineered to be better (stronger, lighter, harder, smarter, etc.) using nanotechnologies (Kordzik 2002). The central thesis of nanotechnology is that almost any chemically stable structure that is not specifically disallowed by the laws of physics can in fact be built (Evans et al. 2003).

Economic implications involved in the development of nanotechnology are unprecedented. Theoretically, because everything that humans have ever manufactured can be made better, even the manufacturing tools and processes will be made better, thus spiraling humanity towards increasingly efficient systems. The National Science Foundation predicts that nano-related goods and services will be a one trillion dollar market by 2015 with over two million people employed (Ratner 2002) worldwide, which is more than General Motors, Ford, Intel, Microsoft, and Daimler-Chrysler combined (Evans et al. 2003). Today, however, the industry is still in its "pre-competitive" stage and the vast majority of discovery is by scientists in the laboratory and not by engineers and managers on the production floor (nano.gov 7 2004). This is evident when trying to find literature on nanotechnology, which is either hard science or fanciful, unfounded journalism.

While there are many different interpretations of what nanotechnology is, the Federal Government's National Nanotechnology Initiative (NNI) identifies a technology as nanotechnology only if it meets the following three conditions: 1) It is research and technology development at the atomic, molecular, or macromolecular levels in the length scale of approximately 1 - 100 nanometer range; 2) It is creating and using structures, devices and systems that have novel properties and functions because of their small and/or intermediate size; and 3) It has the ability to control or manipulate matter on the atomic scale (nano.gov 6 2004).

"Nano" refers to a nanometer, which is one billionth (1×10^{-9}) of a meter. A nanometer is larger than individual atoms, which are measured in angstroms (one tenth of a nanometer or 1×10^{-10} meters). A Helium atom, the smallest (but not lightest) atom, has a radius of 0.36 angstroms, while the largest naturally occurring atom is the Cesium atom, which has a radius of 2.65 angstroms. Nanoscience is on the nano level because it represents the sciences of manipulating groups of atoms/molecules to learn and manipulate the interactions between them. Scientists already know all of the stable elements in the universe, which are all listed on the periodic table. Now scientists are learning how to build materials and devices utilizing these atomic building blocks.

One of the most profound aspects of nanotechnology for this author is that it represents a convergence of all the physical sciences. This convergence occurs because science is interested in understanding how life and everything in it works, and almost all of the interactions that we observe in life are on the nano level. It is the convergence of traditional chemistry, physics, and biology that forms the new nanotechnology field (Zhao and Ming 2002). This field is also being developed and converging with biotechnology, which holds many new promises for improving the environment, or at least nullifying the effects of industry on the environment (Kordzik 2002). This convergence of science also has the implication of a convergence of industry such as with the confluence of the computer, telecommunications, and media industries. Managers need to recognize that this convergence will cause rapid product development in unpredictable directions: little appears stable (Iansiti 1995).

B. Impact of Nanotechnology

Nanotechnology will have an immense impact on society, including improved comprehension of nature, increased productivity, better healthcare, extending the limits of sustainable development, and of human potential (Roco 2003). Although society hopes that this impact is a positive one, the ones who are liable, such as managers, cannot afford to take positive outcomes for granted. Managers must conduct proper due diligence.

Unfortunately, society cannot count on managers and industry to do the right thing and fully investigate the implications of their actions. Although the consequences of misusing these new technologies are much greater than ever before in human history, there are no conclusive research results to show that nanotechnology consequences could not be addressed within the existing system applications (Roco 2003).

C. Government Sponsorship

The Federal Government has historically funded research and development for technologies that have the promise to have the greatest impact on the economy but does not have much venture capital due to high technical risk at the early stages (nano.gov 3 2004). Some examples include locomotives, the oil and gas industry, and space exploration. Nanotechnology is inherently capital intensive, especially at early stages (Evans et al. 2003). Attempts to coordinate federal work on the nano scale began in November 1996 when staff members from several agencies decided to meet regularly but informally to discuss their plans and programs in nanoscale science and technology. The group continued until September 1998 when it was designated the Interagency Working Group on Nanotechnology under the NSTC (nano.gov 2 2004). In 2001, President Clinton first put the National Nanotechnology Initiative (NNI) on the budget (nano.gov 2 2004). The NNI was established to coordinate the multi-agency efforts in nanoscale science, engineering, and technology (nano.gov 1 2004) and is rapidly becoming the Apollo program of our generation (Evans et al. 2003). This initiative and the direction it stands for is creating an unprecedented level of inter-agency collaboration in the United States Government (Evans et al. 2003). The NNI has four main goals (nano.gov 1 2004:

1. Conduct R&D to realize the full potential of this revolutionary technology
2. Develop the skilled workforce and supporting infrastructure needed to advance R&D
3. Better understand the social, ethical, health, and environmental implications of the technology
4. Facilitate transfer of the new technologies into commercial products.

Although the NNI has been doing much to facilitate the development of nanotechnology, people in industry are talking about the pressing need for the United States to put together active collaborations between private industry and the state and federal government. They feel collaboration needs to happen fast or the US could see a negative economic impact in the next five to ten years because of the strong collaborations that foreign governments are sponsoring throughout the world (Hurd 2003). Relative to size and infrastructure, there are many other countries doing more than the United States in nanotechnology including Japan, China, Switzerland, Finland, and France.

D. Ethical Conduct

Ethics or the science of morals is an important part of living within society. Being ethical means that an entity should always consider and weigh the negative repercussions of its actions. Ethical conduct is important for societies to function. With the developing field of nanotechnology, ethical dilemmas abound because of uncertainty regarding the repercussions. Assessing ethical issues regarding nanotechnology is difficult because nanotechnology is such a broad term (Brumfiel 2003). The ethical issues fall into the areas of equity, privacy, security, environment, and metaphysical questions concerning human-machine interactions (Mnyusiwalla et al. 2003). The first guidelines for molecular nanotechnology were produced by Foresight Institute (Mnyusiwalla et al. 2003). Newt Gingrich notes that nanoscience is such an explosive technology that it is bound to catch the attention of government regulators at some point. When it does, researchers will need to be ready to stand up for their work (Brumfiel 2003).

Nanotechnologists are increasingly concerned about the lurid descriptions of the dangers of their work being promulgated by environmental campaigners. However, the field's proponents aren't helping their cause by making exaggerated claims of what the technology will bring (Anonymous 6, 2003). When government and the private sector invest billions in emerging fields such as nanotechnology, they rarely think of legal consequences. That is especially true in cases where more than one party teams up to nurture a technology (Tsuruoka 2003).

"The lack of dialogue between research institutes, granting bodies, and the public on the implications and directions of nanotechnology may have devastating consequences, including public fear and rejection of nanotechnology without adequate study of its ethical and social implications" (Mnyusiwalla et al. 2003). Biotechnology and in particular Agribusinesses ignored public concern over transgenic crops during the 1990's, and many consumers now reject genetically modified crops (Brumfiel 2003). Sue Mayer, Director of GeneWatch, a UK pressure group, said, "The lessons from biotechnology don't seem to have been learned. If there are assumptions made about a technology which aren't broadly shared by the public, it will cause problems" (Anonymous 5, 2003).

Lobbyists to the EU are urging the EU to take a more proactive role in regulating a range of nano-, bio-, and genetic technologies and products. The EU will also hear calls for a moratorium on research while a regulatory framework can be put into place (Pullin 2003). However, the question remains how can regulations be made on technologies that don't yet exist? How does the EU know what to regulate? In truth, people should realize that governmental regulation usually creates negative consequences by not allowing market dynamics to work and through creating more bureaucracy, as in the classic economic example of rent control in New York City. Examples of moratoriums on research include when Britain had the best rocketry science program in the world.

However, in the 1870s a moratorium on research was imposed by the government, so they lost their technological edge. Then came the Germans with their V1 and V2 bombs of World War II. As Mike Horton, Professor of Medicine at University College London and Co-Director of the London Center for Nanotechnology said, "The impact would be exactly the same as the moratorium on genetic modification in Germany which wiped out a whole area of biological science for 30 years. That would be a disaster" (Hirschler 2004).

On the other side of the issue, some scientists feel that nanotechnology posses no serious risks. Nanoparticles have been used for centuries, such as in gold in stained glass windows and clay minerals for grease and cosmetics (Brumfiel 2003). Other nanotech advocates, tired of dispelling myths about predatory nano machines that will take over the world, question whether it is worth responding to such speculation (Brumfiel 2003). However, either the ethics of nanotechnologists will catch up, or the science will slow down (Mnyusiwalla et al. 2003). Most scientists are calling for more studies to be done to learn about the behavior of nanoparticles in the environment and to identify the health risks (Anonymous 1, 2003). Opponents seem to forget that the disciplines that are making up nanotech already have strict regulation and ethical standards. However, there should still be a debate, even though it is disconcerting that the voices of those who really know what is going on in these areas of nanotechnology are either not loud enough or are being drowned out by scaremongers. Scientists really shouldn't be afraid to tackle the complexities of these issues (Pullin 2003).

Journalists need to be involved at the early stages of nanotechnology since they have an important influence on public perceptions (Mnyusiwalla et al. 2003). However, "note that, as a rule, the less an author is engaged in nanotechnology in practice, the more adventurous and enormous their forecasts. This is most true in the nano-bio fields" (Serov et al. 2003).

The risks of nanotechnology need to be evaluated on many different levels including ethical, environmental, economic, legal, and social research (Mnyusiwalla et al. 2003). But whose responsibility is it? In the opinion of this author, it is management's responsibility. It is a cost of doing business in this competitive and litigious modern society. It is called doing due diligence. Science needs to have the free hand to investigate the workings of nature in an open environment and with minimal government regulation. The producers, those who bring technology to the consumers, need to ensure the safety of society. However, these people need help from science to understand the physical risks, help from journalists to understand the social risks, and help from the government to ensure their competition is also held liable.

In summary, nanotechnology is creating new materials through manipulation of particles at the nano level. It is forecasted to have unparallel economic implications and represents a convergence of all the physical sciences. Due to the infrastructure required, governments are actively supporting nanotechnology development through funding and coordination however, more is needed. Due diligence and ethical responsibility is essential if society is going to reap the benefits of this new technology.

II. APPLICATION

This section is an overview of different processes and products that have developed in the nanotechnology field.

A. Processes

The discussion of processes will begin with a history of the enabling technologies that has lead the development of nanotechnology. Following that will be a discussion of metrology or the methods of measuring properties on the nano level. This section will end with an overview of different production processes.

1. Enabling Technologies

Transmission electron microscopes (TEM), also called electron microscopes, have been around for about 60 years and were the first type of microscopes with resolution in the nano range. Recently TEM resolution has been refined enough to measure individual atoms; however, the electron beam is so intense it will burn up many samples. The Atomic Force Microscope (AFM) and the Scanning Tunnel Microscope (STM) were the first technologies that enabled scientists to be able to observe individual atoms. These later two microscopes were developed by IBM in the early 1980's and can be considered the founding technologies of nanotechnology because they not only allowed the researcher to observe at the atomic level but also allowed them to manipulate individual atoms (Kordzik 2002). In 1986, Gerd K. Binning and Heinrich Roher received the Nobel Peace Prize in physics for the STM. These microscopy techniques work more like a profilometer or a non-contact record needle measuring the surface with a very sharp (single atom) tip on a cantilever measuring either the atomic force or electron release (amperage) to indirectly see and manipulate the atoms (Ghosh 2002). This is in contrast to the reflection of light used in traditional microscopy which does not have the resolution to see individual atoms due to the larger wavelengths of light. In the late 1980's, the older style scanning electron microscope were further refined and now also have the resolution to distinguish individual atoms. However, the higher voltage required to increase the electrons wavelength has a tendency to burn lighter atoms/molecules including organic, carbon based samples.

2. Metrology

Since the invention of the AFM and STM, several other techniques have been developed to measure features at the nanometer level. In 2002, more then one-quarter of all patents filed pertain to instrumentation (Compano and Hullmann 2002). One of the greatest challenges in nanotechnology development is testing (Peters 2003). Beyond the actual size and distribution of nanoparticles there are many other properties that need to be measured including: thermal and electrical conductivity, magnetic resonance, tensile strength, elasticity, even the smell. In fact, almost every macro property is of interest to nano-researchers.

When it comes to metrology, one of the most important rules is the 'rule of ten.' This means that if one wishes to measure an element with a given degree of accuracy, say 2 centimeters, they need to use an instrument that has ten times the resolution, a ruler marked off at every other millimeter. Although it is a lot easier to get a ruler scribed at each millimeter, this is not so at the nano level. The point is, if a laboratory is working with features from 20 to 30 nanometers, they only need instrumentation that has a resolution of 2 nanometers. This means that they do not need to invest capital into equipment with higher resolution. If the laboratory/company needs a few higher resolution images, they should outsource.

An important metrology issue with nanotechnology is the aspect ratio of nanoparticles. Aspect ratio is the difference between the thickness of a particle compared to its length and width. A Montmorillonite clay nanoparticle, for example, is a platelet that is around 1 nanometer thick by 200 nanometers wide. This is a difficult problem because equipment that measures 1 nanometer well does not measure 200 nanometers easily, and if the researcher decides to use to different instruments, finding the same nanoparticle is difficult.

Other metrology methods that have been developed include Magnetic Force Microscopy (MFM), Spectroscopy, Electrochemistry, and Confocal Microscopy. MFM is like AFM and STM except in MFM the tip is magnetic and can sense local magnetic structures on the surface (Ratner 2003 p. 40). Spectroscopy uses the scattering of either electromagnetic radiation (light, x-rays, etc) or electrons to characterize nanoparticle structures en masse. Because the wavelengths are too long (400 to 900 nm for light) individual nanoparticles can not be measured using these techniques (Ratner 2003 p. 41). However, a spectroscopy technique developed by the Daresbury Analytical Research and Technology Service (DARTS) uses small angle x-ray scattering to measure nanoparticles in a liquid suspension or dry powder form, making the measurement of 'true' nanoparticles possible (Anonymous 3, 2003). Electrochemistry measures chemical processes through the application of electric currents and is a good way to measure surface atoms in an array (Ratner 2003 p. 42). Confocal microscopes have started to become popular due to their ability to image three-dimensionally which is excellent for life sciences and material researchers, both sciences that will be heavily impacted by nanotechnology.

Computer nanoparticle simulation is a cost effective method to further develop concepts before using expensive laboratory resources. This is also an excellent way to teach a new generation of scientists and engineers the ideas of nanotechnology.

3. Production

If nanotechnology is to become a real force, nanostructures need to be made cheaply and consistently (Ratner 2003 p. 44). Many of the promised nanotechnology are possible if made individually with an AFM or STM but cannot be made commercially.. An analogy would be trying to make all of the lights in Los Vegas by hand. There are three basic ideas in producing nano products, which include top-down, bottom-up, and self-assembly.

Top-down is basically whittling down macro-sized clumps of material to the nano-level. This is the approach that electronics manufactures are taking with advanced lithography processes to reduce the size of integrated circuits, which are just beginning to get below the 100 nm level. Top-down is also used to break down naturally occurring products, such as montmorillonite clay, Titanium Dioxide, and Aluminum Oxide, by using energy or emulsions to reduce the products to the nano level. Molecular Imprints, a Texas based company, has developed a new process to replace lithography techniques that can repeatably produce features less then 1 nanometer at a fraction of the cost, higher quality, and more versatility.

The next approach of fabrication is bottom-up. This is the method that the AFM and STM use. By pushing around individual atoms, more complex products are able to be produced. This is great for research; however, as discussed above, it is impractical. Nanoscale crystal growth would also be considered bottom up because they use a nano-sized seed to begin growth. However, this does not require the attention that the other methods require.

The last approach is called bio-fabrication, molecular-synthesis, or self assembly. This is, in theory, building a nano-sized manufacturing plant where specially designed molecules are able to repeatably produce the desired nano-product. This major milestone has yet to be reached. It is the opinion of many that the major product innovations will not occur until self assembly is realized (Yaniv 2003).

No matter the approach used to produce nano-products, it will be important to develop surrogate measures to ensure product quality and keep costs low (Beall, 2004). Surrogate measures are indirect means used to measure a phenomenon by defining the correlation between X, what needs to be measured, and the properties that X bestows. For instance, it would be totally impractical to ensure the proper dispersion of nanoparticles throughout a polymer by dissecting the polymer and physically measuring the dispersion, especially on the production floor. Instead, a surrogate measure should be used, such as a tensile or UV opacity test. Surrogate measures will reduce time, cost, and training in the production arenas. Process control should be as real-time as practical.

B. Products

"As in any emerging technology, the taxonomy of the field is not yet clearly established, although there is progress in that direction" (Evans et al. 2003). While some identify different materials as nanites and nanates (Mnyusiwalla et al. 2003), others identify nanotechnology as either nanomaterials (small particles, composites, and nanotubes) or nanodevices (nano-products that give us the ability to manipulate or measure) (Peters 2003).

Nearing completion of this thesis, the author found an excellent web site at www.azonano.com. This website has an extensive alphabetical listing of nanotechnology products and industries in which all of the below products are discussed.

1. Currently on the Market:

When compared to the promises of nanotechnology, the applied use of nanotechnology is limited, which means that it is in its pre-competitive stage. However, many industries are using nanoscale materials to enhance their products. Applications include electronic, magnetic and optoelectronic, biomedical, pharmaceutical, cosmetic, energy, and catalytic products (nano.gov 7 2004). The industries that are experiencing the greatest economic impact include chemical-mechanical polishing, magnetic recording tapes, sunscreens, automotive catalyst supports, biolabeling, electroconductive coatings and optical fibers (nano.gov 7 2004). However, Compano and Hullmann (2002) write that the industries that are currently most effected by nanotechnology are the information technology and pharmaceutical industries.

One of the first types of nanomaterials that are having an impact on the market is nano-sized ceramics such as Titanium Dioxide (TiO_2) and Montmorillonite Clay. As platelet thickness decreases, aspect ratio increases which in turn increases the mechanical properties of the composite materials (Lloyd, Lave 2003). Also, in the case of cosmetics, automobile finishes, and sunscreens, when the platelet thickness of the ceramics are a couple nanometers thick, the material becomes transparent to visible light but almost opaque to ultraviolet light which dramatically increases the sun protection factor (SPF). Altair Technologies has the potential to make large quantities of high-purity nanomaterials at costs approaching the costs of making regular titanium dioxide pigment (Challener 2003).

Other examples include Lithium Titanate which is used on electrodes for Lithium Ion batteries and allows charge and discharge rates that are 10 to 100 times faster than conventional leads (Challener 2003). Applied NanoMaterials is producing an inorganic multi-walled nanotube product called NanoLub, which is a solid lubricant that offers an order of magnitude improvement for lubrication in pipelines and works especially well under extreme conditions such as in tools, bearings, and engines (Challener 2003).

A company named Degussa is producing ultrahydrophobic materials for waterproofing clothing, ESpin Technologies has demonstrated feasible large scale production of highly efficient filters to remove volatile organic compounds (VOCs) from industrial emissions, and Molecular Diamond Technologies formed by ChevronTexaco is producing nanosized diamonds (Challener 2003). An interesting example of nanotechnology is that of silver nanoparticles. Ancient cultures knew that silver had special medicinal properties because when silver was rubbed on a wound, the wound healed faster and with less complications (hence a silver bullet to help with a werewolf bite). Today we know that it is because silver has anti-microbial properties and we also know that silver nanoparticles is much more effective than a silver charm and will soon, if they are not already, be available on band-aids (Newberger 2003)

2. Prospective Products

One of the problems with prospective products is that they are not already available, so marketers, producers, and researchers can only guess what the future will hold. As the Director of Physical Sciences at IBM Research, Dr. Thomas Theis, says, he is extremely agnostic about the materials that will make up the devices of the future (Anonymous 2, 2003). An example of why it is safe to be agnostic is the story of the Carbon Nano Tube (CNT). This is perhaps one of the most amazing materials created in the field of nanotechnology. Its chemical, electrical, thermal, and structural properties are just amazing. Because of these properties, for the last 13 years, hundreds of millions of dollars, and over 1,000 universities and companies have been working on them to be able to produce them in a repeatable and economic manner. As one Material Scientist at Penn State said "Carbon Nano Tubes are so oversold that it makes your head spin. It's absolutely horrible how much money has been dumped on them with no meaningful results (Anonymous 2, 2003)." Although this is not the right attitude to take, this does illustrate the risk involved in the development of nanotechnology. It is the hope of this thesis to develop some managerial awareness of the importance of knowing who is doing what in the field so that efforts are not duplicated, knowledge is communicated, resources are conserved, and organizations should be flexible. Maybe it is better to focus on inorganic Nanotubes; they have some interesting properties and are already easy to manufacture (Anonymous 2, 2003). According to Zvi Yaniv, President of Applied Nanotech, "The main reason why there are not that many nanotechnology based products on the market today is because the majority of businesses are taking the 'long-view strategy' to commercialization (Yaniv 2003)."

Another future nanotechnology product, totally different than CNTs, are to use viruses that connect themselves between gold leads to create nanowires, in effect, transistors that are 10nm wide (Schmidt 2004). Using viruses to connect leads is not only technically impressive, it is also environmentally friendly. The viruses perform at lower temperatures, in solvents that are nontoxic, and may efficiently use energy and materials when compared to current industrial processes (Schmidt 2004). Other examples include protein engineering, drugs and drug delivery systems, electronic noses, flexible ceramics, and a host of sensors and structural materials.

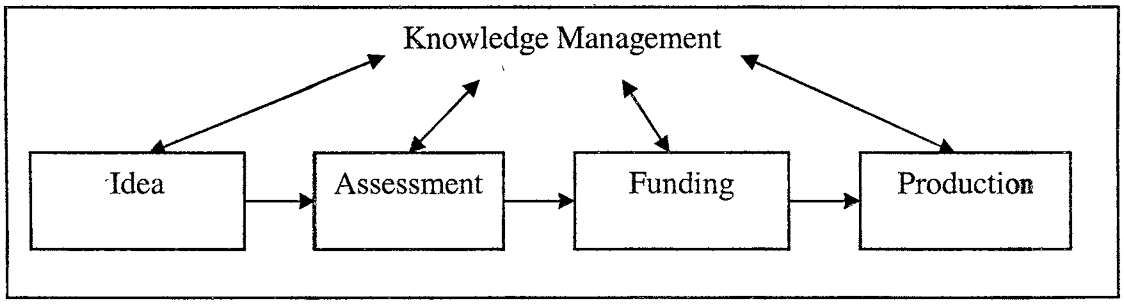
In summary, the ability to directly manipulate matter on the nano level began in the early 1980's with the development of the AFM and STM. In essence, every material property that can be measured on the macro level also needs to be measured at the nano level. To do this efficiently, new methods of material testing are continuously being developed. There are three approaches to production of nanotechnology products: top-down, bottom-up, and self-assembly. There are already many products in the market utilizing the top-down approach. The bottom-up approach is also being used but mainly for research purposes. The vast possibilities of nanotechnology will not be unlocked until the self assembly approaches are developed.

III.PRODUCT DEVELOPMENT

This section is the essence of this thesis and is built around the product development process which is illustrated in **Figure A** on the following page. The definition of Product Development is the transformation of a market opportunity and a set of assumptions about product technology into a product available for sale (Krishnan and Ulrich 2003). The economic well-being of manufacturing enterprises ultimately depends upon their ability to develop new products or improve existing products (Alderman and Thwaites 2001) while maintaining their ability to deliver what they promise.

Figure A below shows a four-step model of the product development process which includes Idea, Assessment, Funding and Production. Whether the model is two steps or eight steps, the literature reviewed pertaining to product development has always been shown as a linear process, starting with something like need or idea and ending with something like production or use. However, other literature reviewed that reflected management in highly uncertain environments discuss the communication, knowledge, and flexibility needed during product development. Therefore, in the model presented below is an iterative knowledge management step of the process. The process of knowledge management has been an assumed and natural part of the development process. However, the assertion of this thesis is that the knowledge management process cannot be an assumed part of the process but an intentional and well defined aspect of the process due to its increased importance in uncertain environments such as the nanotechnology environment.

Figure A: Iterative Product Development through Knowledge Management



"Doubts can be raised about the universal usefulness of product development models in all industries, firms or establishments most product development models are based on multinational auto or electronics industries" (Alderman and Thwaites 2001). The focus of these industries is different from the soon-to-be nano industries because component integration is not an issue in nanotechnology. The issues that are important to nanotechnology include the following: cash flow management, intellectual property, metrology, patent analysis, life cycle considerations, manufacturability/reproducibility and time to market.

Recently a lot of work has been done to minimize the development cycle for rapidly changing environments and to maximize the cycle's efficiency. There are two different approaches to doing this. The first approach is to rearrange the development cycle in different ways to help make it more efficient. For example, Richard Draman's (2003) 'new product journey' looks at the development process as two steps. The first step is the 'proof of concept' which combines the idea generation, assessment, and feasibility. The second step combines prototype, funding, and full-scale production. Other models use a 5-step process that includes a prototyping stage after funding. And still other models use eight stages such as The Civil Engineering Research Foundation's Technology Commercialization Process: 1) conceptualization, 2) definition / assessment, 3) design / development, 4) demonstration / pilot, 5) reassessment, 6) production, 7) sale or transfer, and 8) use (NanoExpress Vol 9).

The second approach to improve the product development cycle is to integrate the steps. The results of this work have brought about new buzz words such as *systems focus*, *iterative problem solving* and *project management*, which for this thesis are under the banner "knowledge management."

It appears to this author that it does not matter how the process is divided because each approach is unique to a company's products, market, culture, vision, resources and management approach. What appears important is how the steps work together. For rapidly changing markets like nanotechnology more communication is necessary throughout the development process so that good decisions can be made rapidly by informed people/teams and those decisions are in turn communicated. Both internal and external knowledge needs to be effectively disseminated throughout the process, both upstream and downstream. Furthermore, it is important that this process of communicating knowledge is helpful and efficient, not annoying and cumbersome, hence the need for knowledge management. Ideas and processes involved in knowledge management are discussed in the next section. Following that discussion, each of the four processes involved in this product development model are explained: Idea, Assessment, Funding and Production. These four processes are discussed as related to the unique circumstances of nanotechnology and within the insight of knowledge management.

Before the discussion of knowledge management, it is important to identify what is arguably the most important managerial concept of nanotechnology: collaboration. Nanotechnology is unique because collaboration between entities is essential (Evans et al., 2002). Research by Bucher et al. (2003) showed that no single Swiss organization, no matter how large, had enough resources to take a leading role in introducing nanotechnology. The specific knowledge required to develop a nanotechnology based product is beyond the core competencies of any single company. One must create a product; identify its market; assess the implications of producing, selling, and disposing of the product; find sources of funding; manage the production, supply chain, legal aspects and customer service. All of this must occur while researching the market to make sure there is not another product or disruptive technology coming out that will make the company's product obsolete. Dr. Mary Pat Moyer, CEO of Incell and Teksa in San Antonio, Texas, explained that it is also extremely important to have a strong, diverse, and collaborative management team because the skills and knowledge used to develop nano- and bio- based products are extremely specialized.

Nanospectra Biosciences, Inc, a Houston, Texas company understands the need for collaboration, but like most nanotech companies, does not have the resources to hire the minimal 10 to 15 specialists required to do the work to develop their company. Therefore, they use what they call the consortium method, which is contracting out to specialists they need on part time basis and offering stock, money or other exchange for their effort. This strategy allows the company to keep very low overhead while their cash flows are dependent on equity capital due to their very small team of 4 people.

The introduction of disruptive technologies is only possible in intense cooperation with all stakeholders. Therefore, the building and cultivation of a broad research network is crucial for success (Bucher et al. 2003). An example of the type of collaboration that is occurring in the nanotechnology spectrum is the New Jersey Nanotechnology Consortium. The consortium's CEO, Larry Thompson, is quoted as saying, "We believe we have a unique advantage because we are bridging the gap between nanotechnology research and turning that into products that companies can sell. Using the design and manufacturing expertise of Lucent/Bell Labs scientists, our real value is our ability to turn concept into a device, eliminating the large investment (~$400mil) required to do that for a lot of companies that might lack the infrastructure or expertise" (Peters 2003). The consortium's niche is to identify a technology and deliver it to the manufactures. Collaboration will be discussed further in the Production - Outsourcing section of this thesis.

A. Knowledge Management

Knowledge Management is the development of tools, processes, systems, structures, and cultures to improve the creation, sharing, and use of knowledge critical for decision making (Kreitner and Kinicki, 2004, 378). Following this definition, knowledge management is the banner under which modern product development concepts fall. The following list are seven knowledge management competencies identified by Kasvi et al. (2003), the words in parenthesis are the words used in this thesis to describe the competency: Interest Groups (Collaboration), Technology (Technology Evaluation), Process and Procedures (Documentation), Leadership, Project Management, Communication, and Interaction (System Focus).

There are two types of knowledge: 'explicit,' which is information that can be easily put into words and shared with others and 'tacit,' which is the information gained through experience which is hard to express and formalize. Therefore, there are two strategies for managing knowledge: 1) codification to databases and documentation for explicit knowledge and 2) face to face, team meeting, and mentoring strategies to communicate tacit knowledge.

Motivation to use a knowledge management system needs to be intrinsic (Kasvi et al. 2003). Therefore, project management should be integrated with knowledge management. Kasvi et al. (2003) argue that successful project management should be based on two things: 1) accumulated knowledge and 2) individual and collective competencies. This is important with nanotechnology because such a high level of cooperation is required. However, this is in contrast to trends typical to project organizations, such as employee empowerment and information decentralization, which results in organizational knowledge fragmentation and loss of organizational learning (Kasvi et al. 2003).

The following subsection of knowledge management is Project Management, which is applying knowledge, tools, skills, and techniques to project activities so project requirements can be met (Gray and Larson 2003). The next subsection is System Focus, which is the idea that individual entities or interest groups should not exist in isolation. It is a holistic approach to problem solving that emphasizes the interactions between entities (Gray and Larson 2003). A discussion of the types of problem solving used in management will be in the Problem Solving subsection. After that discussion, knowledge management needs to collect and document the lessons that are learned by entities so that issues are efficiently communicated and projects are better defined. This collection will be discussed in the Documentation subsection. Finally, because the nanotechnology environment is a rapidly changing environment it is essential that the management systems in place are very flexible. Flexibility is discussed in the last subsection of the knowledge management discussion.

1. Project Management

"We believe that the evaluation and introduction of disruptive technologies have to be perceived as discontinuous, time-limited processes. Therefore they are best managed in projects" (Bucher et al. 2003). A project is a complex, non-routine, one-time effort to create a product or service limited by time, budget, and specifications (Gray and Larson 2003). Gray and Larson further describe project management as a two-part whole much like the Chinese philosophy yen and yang in which yen represents the sociocultural aspects of project management and yang represents the technical aspects.

Below is **Figure B** which illustrates sociocultural and technical aspects of project management for traditional, well defined projects compared to projects encountered in the rapidly changing and very uncertain environment of nanotechnology. "The literature on project management has been dominated by techniques and methods for separating activities and making thought-out plans" (Soderlund 2002). Because of the rapidly changing environment and unknown future developments of nanotechnology, creating well-thought-out plans may in fact hurt the organization because the plan's sponsors will naturally become married to the plan even when the plan is no longer relevant, akin to the dot com bust. **Figure B** is an assimilation of literature and represents more a continuum of issues than a qualitative traditional versus nanotechnology breakdown.

Figure B: Project Management Differences

Yen: Sociocultural	Yang: Technical
Traditional Project Management Techniques	
• Static Leadership • Linear Problem Solving • "Workgroup" Teamwork • Negotiation • Politics	• Scope • Work Breakdown Structure • Schedules • Resource Allocation • Baseline Budgets
Nanotechnology Project Management Techniques	
• Dynamic Leadership • Iterative Problem Solving • "Systems Focus" Teamwork • Collaboration • Politics	• Living Documentation • Technology Evaluation • Time Lines, Forecasts • Resource Management • Status Reports

The most difficult issue to explain from above is leadership. Talented leadership is arguably the most important factor required for the successful completion of all types of projects. Traditionally the project manager is the de facto team leader, hence the label "static" in **Figure B**. Since an effective leader must have task relevant knowledge, be innovative, and inspire others to think outside the box, this author argues that the project manager may not necessarily be the best leader in projects involving nanotechnology. However, it is still the project manager's job to manage the progress of the project. Furthermore, due to the collaborative nature of nanotechnology and the changing challenges of the project, having fluid leadership may be needed. The idea of fluid leadership is what is meant by "dynamic." This approach could easily create chaos in the project if the team does not have excellent communication, is not highly motivated, does not have a clear understanding of project deliverables, or does not have a high degree of respect for each other.

As explained earlier, it is difficult to identify whether project management falls under the scope of knowledge management or vice versa, it works both ways. Although this thesis has project management as a subsection of knowledge management, "projects and project organizations require exceptionally efficient knowledge management if they are to learn from their experiences" (Kasvi et al. 2003). There are many different types of knowledge created during a project, such as new technology, business procedures, software, industry practices, and scientific knowledge. However, according to Kasvi et al (2003), new organizational practices are considered the main new knowledge area created in the projects. These practices and lessons learned need to be archived and communicated throughout the team on multiple but similar projects. When a team works on a stream of related projects, a cohesive group will develop from project to project (Iansiti 1993). Team leaders feel their most important job is to develop individuals by assigning them to the right projects, thereby providing the best learning opportunities in other areas (Iansiti 1993). "Managing Product development projects is a matter of enabling the crossing of functions and knowledge bases" (Soderlund 2002). The literature stresses that the best practices in product development is to use multifunctionality and concurrency by using integrated teams across departments and across the supply chain (Alderman and Thwaites 2001).

When looking for the right people to be on the nanodevelopment team, most employees feel that the new, flat, team oriented, and flexible organizational structure with absence of bureaucracy and hierarchy are empowering. However, it is important that the team members know what is expected of them; some miss the opportunities for pursuing a career by moving up a corporate hierarchy, while others would have preferred to be managed more traditionally (Larsen 2002). One interesting approach to developing interdependence while minimizing managerial control is to have employees develop their own "jobs" around their skills and interests, thereby accumulating a portfolio of functions for each employee. They are in charge of finding and doing the right thing and properly communicating what they've done. If an employee does not have anything to do, they need to either find functions and or tasks, or the organization does not need them (Larsen 2002). This approach can only be done in a highly skilled, open, and committed environment. It requires a belief in the strength of the organic, flexible project management. However, failure will occur from managers' inability to steer the investigations productively (Iansiti 1995). While everyone has the latitude to do what they think is the right thing to do, they all must understand what the goals and deliverables of the project are, what resources are available, and what has already been done.

To help create more group work, deadlines have been shown to be effective in promoting communal and interactive problem solving (Soderlund 2002). However, this is different than a schedule or Gantt chart, which progress is measured against, the iterative nature of nanotechnology development means that more general evaluation-type timelines or sub-projects should be used. This is at least until design-freeze where the project becomes defined and the project becomes more traditional in form. An important caveat to deadlines is that they need to be realistic.

Computer systems designer Silicon Graphics, a leader in the rapidly growing, highly uncertain environment of computers during the early nineties, developed a different approach to visualizing a project. Instead of using the Work Breakdown Structure (WBS) of traditional project management, they developed a comprehensive block diagram to investigate the modularity of the product and to highlight the most important interdependencies. This method helped in predicting the areas of most frequent change and in portioning Project tasks to create the tightest problem solving loops around the most critical interactions between design choice and system performance (Iansiti 1995).

Vartiainen et al. (1999) discussed The Project Learning Model in the Proceedings of the 6th International Product Development Conference. This model is based on two living documents: The Project Plan and the Team Contract. This model is developed on the premise that in order to systematically manage knowledge created in a project, the projects themselves must be systematically managed. The model is based on two documents: the project plan and the team contract. The Project Plan includes hard project knowledge, which involves project definition, activities, and results. This is synonymous with the yang (technical or explicit knowledge). In contrast, the Team Contract contains organizational knowledge like experiences and capitalization of lessons learned. This is synonymous with the yen (sociocultural, or tacit knowledge).

2. Systems Theory

Systems theory is the idea that an organization is a system with many parts -- marketing, accounting, manufacturing, research, etc. -- and that all of these parts are interdependent. That is, any aspect of each part's performance impacts all of the other parts, impacting the whole system. This is systems theory: an organization whose parts understand their interdependencies will have a distinct advantage over competitors in dynamic environments (Temponi 1997). Taking this theory one step higher, "All organizations are sub-systems in a larger organization and may have to subordinate their desires for the betterment of the larger system" (Draman 2003). This can be taken as meaning each business up and down the supply chain contributes to the supply chain, and their performance has consequences on that supply chain. Multiple supply chains create larger systems: local, regional, national, and the world economy. With the development of nanotechnology, collaboration is essential. So, understanding the interdependency between entities within an organization may be just as important as the vertical and horizontal interdependencies of the supply chain. The most important commodity of the supply chain is knowledge, from best practices to intellectual properties to market forecasts.

One of the most important implications of systems theory is product development. "The current approach to today's business would not support the development of the new knowledge, actions, and decisions needed to bring nano-based technology to the forefront" (Draman 2003). "New imperatives deeply contrast with traditional models" (Iansiti 1995). System focus integrates the entire R&D process. The integration team investigates the impact of various technical choices on the design of the product and the manufacturing process. Iansiti (1993) believes that for the system focus to succeed, basic researchers must provide the integration team with a broad array of technical possibilities. This includes patent analysis, market research, and literature review. Most successful companies in the study have a vibrant internal research organization of their own. "Group members became an invaluable repository of knowledge about the interactions between the many elements of the product and production system" (Iansiti 1995).

There are 2 different issues management needs to be aware of in a system focused environment. One issue is that not all employees can function in this manner. In what is referred to as the 'pressure-cooker crisis' (Hunger, Wheelen 2003 p.128) employees in collaborative environments may grow emotionally and physically exhausted from the heavy pressure for innovative solutions and the intensity of teamwork. The other issue is that technology companies need to have a mix or marriage between both technology and business (Beall, 2004). There should be respect between the two; each side has input. If one side dominates the other, it is a formula for disaster. If the technologist is focused on the research and is not paying attention to the cash management, the company will fail. If the business manager does not understand the technology, does not understand the problems involved in it, the company will fail. Success depends on good business with good technology.

3. Problem Solving

Most people do not put much thought into their process of problem solving. They intuitively come up with what they feel is the best solution to the problem such as when someone is hungry or when a light bulb does not work. Therefore, identifying the process of solving problems is not very relevant for laypeople, even when facing serious problems. On the other hand, professionals, especially engineers and scientists, need to identify and document their problem-solving process for several reasons. First, when problems are complex, they need to be able to show how they arrived at a conclusion. Second, if things are not going as planned, they need to be able to go back and see where things, what assumptions, went wrong. Third, using a process helps to improve the structure of their work and provide a better learning experience. And forth, should the solution be wrong, a well documented process can show that due diligence was performed to top management or in a court of law (CYA). However, serendipity can also play a role in problem solving in which unexpected solutions to a problem are discovered during the process of solving the problem.

Rutledge (2002) identifies several different ways to solve problems, each method appearing best in different situations. The first method, story-telling, has been used for thousands of years to solve problems by telling stories that illustrate the type of thinking that is necessary to solve the problem; this process is used to solve cultural, ethical, or attitude type problems. The second method is linear or scientific problem solving. This method was developed relatively recently in human history as part of the scientific revolution and involves the problem solver to proceed slowly through each step of the problem: problem identification, idea generation, selection, implementation and evaluation, making sure that all exceptions are addressed and all boundary conditions are met before proceeding to the next step. This method is excellent when problems are not changing and are definable, such as in building a bridge. Also, from a commercial aspect, the tools and ideas used to solve the problems need to be relatively static, which is not a characteristic of the nanotechnology field. The third type of problem solving is iterative problem solving, meaning that the researcher moves quickly through the steps approaching the end and then returns to the beginning, repeating the process, cleaning up the exceptions and boundary conditions as they go (Rutledge 2002). This type of problem-solving best meets the dynamic challenges that nanotechnologists face and call on the researcher's intuition and knowledge of subject material.

Managerial decision making can also follow these three problem solving techniques. When management relies on its past experience, heuristics, and intuition, it is likened to the story telling approach. The second method of decision making is the Planning method. This strategic decision making process is a well designed, formalized, and analytical process. This is an effective approach for businesses that need to ensure consistent quality to their customers. It is formalized in Standard Operating Procedures (SOPs) and more recently in quality standardization procedures like ISO9000 and Six Sigma. The third method of decision making is the learning or iterative approach, which is based on the understanding that decision-making is a dynamic, incremental, and self-organizing learning process (Bucher et al. 2003). "While some of the up-front detailed design work will inevitably be wasted, the need to respond rapidly to unpredictable changes in technical or market environment makes iteration essential" (Iansiti 1995). "Against the backdrop of high uncertainty and complexity inherent to disruptive technologies, the learning approach to decision-making seems to be more promising" (Bucher et al. 2003).

4. Documentation

In the opinion of this author, Documentation is the most important aspect of running an organization efficiently. The key is to document what is important while not wasting resources on documenting what is not. Plus, circulating what is documented to people who need to know in a format that is useful to them. This makes effective documentation very difficult. The documentation's beginnings are based in accounting for tangible and quantifiable goods such as bushels of wheat and pounds of copper, which are traded and inventoried. As any accountant can testify, even accounting for the tangible and quantifiable can become cumbersome and confusing. A knowledge management system needs to be able to account for the intangible lessons learned, the qualifiedly good, bad, and OK, and the knowledge management system needs to get that information to the people who need to know it in a format that is useful. Similar to managerial accounting, a project management system should address all of the various stages of knowledge management:

1. Knowledge collection (from inside and outside the organization)
2. Knowledge combination, refinement and creation
3. Knowledge storing and administration
4. Knowledge distribution and dissemination
5. Knowledge utilization (Kasvi et al. 2003)

The use of a knowledge management system is intrinsic in job design and the communication processes of the organization. It should, on average, enhance each of the users' ability to contribute to the system. However, this is not a reality in industry yet, and information systems that support project collaboration and reuse past experiences are still primarily restricted to document sharing (2003 Kasvi et al.). Facilitating inter- and intra-organizational interaction will be a distinct source of competitive advantage for companies in the realm of nanotechnology. This interaction will require a new kind of communication, knowledge management, competences, and tools to support these practices. "People need to feel that they gain personal benefit from experience documentation and perceive its utility" (2003 Kasvi et al.).

The current process of knowledge management is based on document creation. Documents created in the course of the projects are rarely managed in any way. As a result, the information from different projects is not synchronized and there is a considerable possibility of errors (2003 Kasvi et al.). Also, people do not have the time to read through all of the documents created during the course of a project. In the field of nanotechnology, those documents include reports, theses, dissertations, journal articles and patents. New knowledge is clearly created, but its accumulation and storage is unsystematic (2003 Kasvi et al.). In addition, reports are used as a way to accumulate and store knowledge. Reporting has been found to be a competence and resource problem. "People are interested in working on their project and saw reports as a 'dry bun' and did not see the big picture" (2003 Kasvi et al.). Documents were produced within the individual projects, summarized by the project managers, and delivered to the program manager for a final report to disseminate results between the projects and across the business field.

When it comes to design work, living documentation is widely used. Living documentation works like an algorithm in which the variables are constantly improved upon until the desired result is achieved. QS9000, the American automotive quality standard, develops a series of documents through its advanced product quality planning (APQP) process whereby each document builds upon the previously created documents. When you have a computer with different templates and a "save as" command, the APQP process can be viewed as one document that is continuously evolving or "living."

However, when it comes to developing a knowledge management system, documents need to be appended with meta-knowledge that links knowledge items with their environment (Kasvi et al. 2003).

5. Flexibility

Nanotechnology is characterized as an industry that is developing very rapidly. As identified in the first section of this thesis, there are many promises of what nanotechnology can bring but has yet to deliver. The questions how, if, when, and who will deliver these promises create an environment that is highly uncertain. "In environments characterized by extreme turbulence, the emphasis should shift from the capability for focused and rapid project execution to the capability to react to newly discovered information during the course of the project itself. "Uncertainty requires extreme flexibility and responsiveness, particularly in the development and introduction of new products (Iansiti 1995)."

The traditional models of product development developed from studying product development in mature markets such as the automobile and consumer electronics markets. The focus is on developing a structured process with clearly defined and sequential phases. The emphasis is on achieving focused and efficient project execution through strong project leadership, integrated problem solving, and team-based organizational structures (Iansiti 1995). These traditional models have developed managerial concepts such as concurrent engineering and the work breakdown structure

(WBS) and are designed to optimize speed and efficiency, not to react to turbulence in the environment (Iansiti 1995).

In contrast to the traditional model, the flexible model should embrace change, not fight it. The flexible model should have the ability to rapidly respond to new technical and market knowledge as a project evolves, which means the management team must proactively seek new knowledge. The flexible model should use project design principles that avoid hierarchical, sequential, and rigidly defined phases (Iansiti 1995). The flexible model project design focuses on system interactions between concept and details, product and process, and are usually built around prototype cycles (Iansiti 1995). "Simulations and partial prototypes uncover problems before committing to a very expensive complete and representative prototype" (Iansiti 1995). When utilizing the flexible design model, the most critical time to market measure is the time after concept freeze because any new information from the marketplace can be incorporated into the design up to the design freeze point (Iansiti 1995).

Flexible product development requires individual skill, organizational managerial processes, and technical methodologies. It is founded in a system-focused approach to product development (Iansiti 1995). This list of requirements is more difficult than traditional product development. However, the ability to adapt to external and internal uncertainties during a project's evolution has become a critical source of competitive advantage. As Ed McCracken, the Chief Executive Officer of Silicon Graphics Inc. said, "The source of our competitiveness in this industry is our ability to manage in a chaotic environment. But it's more proactive than that. We actually help create the chaos in the first place – that's what keeps a lot of potential competitors out" (Iansiti 1995).

In Summary, product development is the transformation of a market opportunity and a set of assumption about product technology into a product available for sale. To make the product development process more relevant and efficient for different industries, two different approaches are being taken. First is to further define the steps involved in the development process and second is to integrate the steps of the process so that knowledge gained can be more freely exchange throughout the process. Due to the rapidly changing, highly technical, and highly collaborative environment of nanotechnology, the literature suggests that integrating the steps of product development is the best way to gain competitive advantage. This is done through what this thesis titles Knowledge Management. There are five issues involved in Knowledge Management: Project Management, Systems Theory, Problem Solving, Documentation, and Flexibility. The following four subsections are Idea Generation, Assessment and Feasibility, Funding, and Production.

B. Idea Generation

The first step in the development of any product is developing the idea of the product. There are many ways to develop ideas for new products, including the following: Laboratory Research, R&D, Market Niche, Patent Analysis, Journal Research, and Brain Storming. Issues involved in each of these idea generation mechanisms will be discussed below. The process of generating nanotechnology based product concepts are basically the same as in any product development. Therefore much of the past literature of product development is relevant to nanotechnology. However, there are issues that need to be addressed within the knowledge management framework discussed in the preceding framework. One significant issue involved in nanotechnology is deciding which technology to use. This is called developing a technical concept. A *Technical concept* is a detailed specification of how the complete set of technical options will combine to provide the new product with good quality and low cost (Iansiti 1993).

1. Technology Evaluation Process

The technology evaluation process is a continuous and iterative process which includes the following: monitoring, evaluation, selection, and integration. The product of this process is a technical concept of a product and the purpose of the process is to identify what set of technologies the organization can competently use to efficiently produce the best product for the market. This process consists of a gradual, iterative accumulation of technological knowledge and capabilities, and it is of interest to note that those organizations having a higher degree of structure during the valuation of nanotechnology seem to achieve more satisfying result (Bucher et al. 2003). Although the technology evaluation process's product is the technical concept, the idea of the product, it also takes into account the feasibility, funding, and production of the product. This is contrary to the linear fashion of traditional product development. For ease of discussion and conceptualization, this thesis is organized using the linear approach. However, when reading the following sections, it is important to keep in mind the model that this discussion is founded upon: See figure A: Iterative Approach to Product Development through Knowledge Management.

To develop a technical concept, different technology options need to be evaluated. It is important to define the organization's core competencies which should support the products' core technologies (Bucher et al. 2003). With the development of nanotechnology, new technologies can provide dramatic opportunities in dynamic environments. Environments such as nanotechnology are characterized by significant technological uncertainties. The effect of these uncertainties is that the conceptualization of a project's technical approach and direction will have a critical and significant impact on its success (Iansiti 2000). However, to maximize the effectiveness of new technologies, their new possibilities must be carefully and continuously matched to the product's application, manufacturability, supply chain, disposal, and the organization's competencies. To do this well, the project needs a process called technology integration (Bucher et al. 2003) which is used in a systems focus approach to ensure that the technologies chosen during the evaluation process work efficiently within the entire system.

To make monitoring, evaluation, and decision making successful, the evaluation project needs to be interdisciplinarily staffed and headed by middle or even top technology and business managers (Bucher et al. 2003). People doing the evaluation should be part of the decision making process and critical decisions are made rapidly and jointly by a "core" business team meeting daily (Iansiti 1995). Although Iansiti (1995) recommends that the evaluation team should consist of a couple dozen people, the literature on team performance suggests that teams should not be composed of more than 7 people (Fowler, 1995). While the addition of each team member reduces the amount of work per member linearly, the amount of necessary communication increases exponentially. Is it practical for 24 technical and managerial professionals to meet daily? And, can a team that large make decisions quickly? It is the opinion of this author that this size of a team is inefficient; instead the organization should develop a knowledge management system so that issues can be communicated efficiently and resolved quickly.

The aim of technology monitoring is to meticulously aggregate qualitative and quantitative information required during the processes of nanotechnology evaluation and technological decision making. Iansiti's (2000) analysis shows that experimentation and experience are critical building blocks in a process aimed at managing a technological transition. Iansiti's (2000) article also identifies what managerial designs can have an impact on product development performance, and these include the following: the structure and dedication of the project team, the cross-functional integration, the influence of the project leader, the internal and external communication processes, and overlapping product and process engineering.

During the technology evaluation process, it is imperative that top management is involved. Although they do not necessarily need to be a part of the daily meetings, they do need to help select the technologies to develop for use in the product and manufacturing of the product. This is so that they can develop the hands-on tacit knowledge necessary to understand the inter-workings of the technologies selected on the products development and production processes. Should a chosen technology not be working out as well as planned, top management needs to understand why that technology was selected over other technologies, be able to do a cost benefit analysis, and if necessary be a change agent in the middle of the process. This is the iterative problem solving approach described in the above section titled "problem solving." It is also extremely important to understand what effects changing technologies in the middle of the process will have on the rest of the system, which is by default done when a systems focused approach has been properly nurtured.

a) Different Technology Genres

During the technology evaluation process, there are several different genres of technologies that need to be evaluated, each with their own recommended evaluation processes and implications. The following are the technology genre classifications that have been identified: existing technologies, sustaining technologies, and disruptive technologies. Each of these classifications has the sub genres of latest trends and interdisciplinary technologies.

Existing technologies are technologies that are already on the market, and it is the job of the organization to decide whether or not the technology is appropriate for the product. Existing technologies have the advantage of already having been developed, so the organizations evaluating them should have enough resources available through journal, patent analysis, and conventions to accurately decide whether the technology is the right fit for their product and cost. However, the problem with existing technologies is that another organization has already developed it; so there will probably be a premium on the use of the technology so that the organization that developed the technology can recoup their investment. Bucher et al's (2003) research showed that in the case of existing technology and application fields, the most qualified gatekeepers are internal professional researchers (technology experts) that are exempt from about 15% of the daily business for each of their scanning areas.

Sustaining technologies foster improved product performance or reduced production cost and are what most new technologies are grouped into. Sustaining technologies are developed by internal research and development groups within established companies and are developed to either keep or increase that company's market share of their products. Examples include Intel's processors speeds, Clorox's color safe bleach, IBM's hard drives capacities, and material substitution in the automotive industry which will have to happen incrementally (Lloyd, Lave 2003). All of the currently existing nanotechnology products that are listed in section two of this thesis are examples of sustaining technologies. However, the great promises of what nanotechnology may bring are examples of disruptive technologies.

Disruptive technologies are technologies that displace existing technologies. Examples of these include the telephone displacing the telegraph, the calculator displacing the slide rule, digital cameras displacing film, and email displacing snail mail. Products based on disruptive technologies are typically manufactured cheaper, simpler, and usually more convenient to use. In a multitude of cases studied in a variety of industries, it was a disruptive technology that caused the leading firms in an industry to fail (Christensen, 1997, xv). Clayten Christensen's premise in his excellent 1997 book *The Innovator's Dilemma* is that many of what are today are considered widely accepted principles of good management are, actually, only at times appropriate. There are times in which it is the right thing to not listen to customers, in which it is right to invest in developing lower-performing products that promise lower margins, and in which it is right to aggressively pursue small rather than substantial markets. Disruptive technologies create a highly dynamic environment and although nanotechnology is not a disruptive technology per se, some of the technologies produced through nanotechnology will be highly disruptive, such as flexible ceramics and nano-robots (Bucher et al. 2003). One classic example of how an industry can be destroyed by a disruptive technology is that of carriage manufacturers. When the automobile industry was in its infancy, the companies that could have gained the largest market share were the ones already making carriages. However, they didn't think that this new novelty, the automobile, would ever amount to anything. They were wrong, and the only company that survived into the twentieth century was Body By Fisher.

It is self evident that evaluating and introducing disruptive technologies may cause trouble for most organizations. Evaluation is complicated by high uncertainty and complexity. During introduction internal resistance and inertia need to be overcome (Bucher et al. 2003). This author predicts that with the rapid development of nanotechnology, there will be many organizations that will lose huge investments in developing products because the technologies they use to develop the product will be quickly replaced by another firm with a technology that produces a simpler, cheaper and easier product. Some life cycles of very promising nanotechnology-based products will be over before the product can get out of the introductory stage. Limiting this risk of product development will be discussed in the Economic section of Risk Analysis. Because few organizations have experience with disruptive technologies, it has been proved to be crucial to include external experts as early as possible into the monitoring process (Bucher et al. 2003).

When evaluating the latest trends in technology, the literature recommends utilizing post doctorial researchers who have been immersed in the subject (Bucher et al. 2003). When evaluating trends, it is important to identify the difference between what is fashionable and what is practical. A good way to do this is with cost benefit analysis. Take Microsoft for instance; there were many different software suppliers, most better then Microsoft, but the cost benefit analysis showed that Microsoft was the best. The Microsoft OS already came with the system, so it had really low cost. Now, due to the intangibles, Microsoft is the best because most everyone knows how to use it. Another example includes the Beta to VCR, Beta was a superior product but the market penetration of VCR made them obsolete in the States. Then came the DVD which is much easier, cheaper, and more convenient then VCR. However, cost benefit analysis and other similar managerial analyses can be very dangerous because it is difficult to quantify the intangibles and to anticipate the unforeseen forces that can completely negate the analysis. If a project's expected return on investment does not meet a company's requirements they will end what could turn out to be extremely profitable project. For instance, Xerox giving the ideas and design of the personal computer to Apple.

As mentioned before, with nanotechnology collaboration is the key. It is interdisciplinary, and external networks should be formed to help evaluate its different repercussions (Bucher et al. 2003).

2. Brainstorming and Feedback

Brainstorming and Feedback are the cheapest and arguably the most effective methods to generate new ideas for products. However, for both of these methods, the people involved need to understand the market and technology they are working with. However, perhaps the most important thing they need to understand is the management team they are working with. There have been many great products that disappeared through poor management and many average products that have thrived through great management. Effective management is the key to product success. Boucher et al. (2003) recommends that management should work together forming a monthly innovation meeting. The aim of the innovation meetings is solely to identify or even generate promising technology-market combinations. This meeting should be multi departmental and feedback should be collected throughout the organization. Sometimes the best ideas come from the accountant or laboratory technician.

3. Laboratory Research, R&D and the Market

Nanotechnology is still in its first precompetitive stage of development, which means that it is still in the laboratory. To succeed in nanotechnology innovations, new views and approaches to the research and development process are necessary because nanotechnology is interdisciplinary. There needs to be a strong coupling of basic research and industrial development (Yaniv 2003). The R&D department is where new revolutionary approaches and products are developed. On the other hand, most of the evolutionary product development is from operations (Alderman and Thwaites 2001). Robert Morris, the vice president of research for IBM, responded to the question how does IBM decide what to research, what becomes product, and what doesn't?

> "We are very careful to maintain a balance between free-ranging basic exploratory research and undirected research on the one hand, and on the other hand, research that is very intimately tied to the customer and product requirements. We spend a lot of time making sure that we balance these. If you do just one or the other you will fail, even if you have those two, you're not guaranteed success. You have to fill in the in between. There's a kind of a middle third, a middle area of pre-product. That's developing things that after a bit of research you realize and hope one day could become some useful technology or product" (Dubie 2003).

This way of approaching research is probably one of the main reasons why IBM has been able to maintain its technological edge for over a half a century. As Clayton Christensen (2002) suggests, a company must always be on the look-out for the next disruptive technology that cannot afford to concentrate on making their technology better. The market place is a dynamic entity, always changing in ways that are not expected because it will be changed by technologies that don't yet exist and therefore can not be imagined. Therefore, it is essential that management keep an open mind and review the new technologies that are being patented and written about.

4. Patent Analysis & Journal Research

One effective way to find out what developments and trends are occurring in nanotechnology is to review the scientific papers that are being written and the patents that are being filed. The number of published papers indicates the scientific activity occurring in the field and the number of filed patents indicates the ability of research and development to transform science into application (Compano and Hullmann, 2002). It takes application to create products. The first thing to occur in nanotechnology was the enabling technologies, the patents for the AFM and STM, these technologies spurred new technology, but the number of papers written was relatively few till 1990. In the 90's interests began to grow exponentially, especially with the discovery of the carbon nano tube, thus spurring an exponential growth the number of papers written. In analyzing the industrial growth of other industries compared to these two variables Compano and Hullman (2002) show that the real breakthroughs in production of nanotechnology products are still several years away. The production of biotechnology products, on the other hand, is about to see dramatic increase.

Patents and Scientific Papers, especially those written for/through standardization bodies, can also be used to forecast what the next new technologies will be because there is a certain order to developing new technologies; foundations need to be made. According to Rashba and Gamota (2003), the first step in the development and standardization of nanotechnology will most likely address material characterization methods and equipment classification. The second step will be device and component fabrication. The third step will be system architecture and interoperability. The development of standards will help unify the science and develop structured methodologies so that institutions can independently verify discoveries. Although the exact breakthroughs can not be known until they occur; knowing how technology develops will let managers understand what type of research to expect from industry.

There are several interesting issues that are coming up between business and academia today as a result of restrictive budgets (Newberger 2003). In the past, academia has been primarily concerned with publishing papers. The ultimate reward for the researcher has been predicated on the rapid and wide distribution of research results (Newberger 2003). However, today many new businesses in nanotechnology could be spin-offs from academia in which the researcher does not necessarily want everyone to know what they have discovered; also, a patent can be seen as a source of revenue in ways a research paper cannot. Procuring patents instead of writing papers not only affects the spin-offs from academia, but it affects universities themselves because they can gain large revenue with proper IP licensing (Shock 2003). The second issue is that businesses, who traditionally seek patents, are stuck between the need to maintain confidentiality pending the patent and the need to advertise what they are doing in order to raise capital (Newberger 2003). The final issues are the litigation issues, which in general are not particular to nanotechnology and will have a significant impact on nanotechnology due to the breadth of the field and the opportunity for broad patent coverage. This may create significant tension between the monopoly rights of the "first comers" and ongoing research in the field (Newberger 2003).

C. Feasibility Assessment

The most important managerial aspect in developing products based on nanoscience is the need for a diverse group of highly skilled people. Diversity and experience are required to collaborate effectively for accurately identifying and assessing risks involved in the research, manufacturing, distribution, and use of products with features in the nano level.

For each idea that is generated, the feasibility of producing it, marketing it, and disposing of it needs to be addressed on many different levels. The following subsections are short discussions of the breadth of assessment needed. Because every product that has ever been manufactured can theoretically be enhanced through nanotechnology, this discussion does not attempt to be thorough but rather to identify the issues that need to be addressed: to serve as a check list to help managers do their due diligence. First is a discussion of the risk management methodology.

1. Risk Management Methodology:

Step 1: Risk Identification

Analyze all aspects of the project through multi discipline cooperation. The types of risks that need to be identified include the following: marketing, funding, manufacturing, disposal, legal, technical, schedule, cash flow, toxicological, environmental, life cycle, and supply chain. However, the sources of project risks are unlimited. Good techniques to identify risks include brain storming, panel of experts, and Delphi.

Step 2: Risk Assessment

Risks need to be assessed in terms of the following: severity of impact, likelihood of occurrence, and controllability. A good way to be able to identify which risks are more relevant than others is to use a Failure Mode and Effects Analysis (FMEA). Using this analysis will help managers proportionally allocate resources to further evaluate the risks affecting project success.

Step 3: Risk Response Development

After risks are assessed, the management team should develop a plan to either control the adverse effects of the risk or develop a contingency plan to use should a foreseen risk event become a reality. There are several methods for controlling a risk, including the following: reducing the likelihood the event will occur, reducing the adverse impact the event would have on the project, transferring or sharing the risk with another party, or accepting the risk, which is legitimate because acceptance will still avoid crisis management.

Step 4: Risk Response Control

The final step in the risk management process is to manage the process. This includes monitoring the trigger events, executing the risk response strategy, and watching for new risks. An essential part of risk control is to establish a change management system that will allow the organization to quickly respond to events in an informed and organized manner in order to maintain the flexibility that is needed in the nanotechnology environment (Gray, Larson p.209).

2. Areas to be Assessed

a) Toxicological

Toxicology is a very important issue to assess with nanotechnology-based products. An excellent analogy to demonstrate the need for assessment is that of asbestos. As nanotechnology-based products will certainly be thought of, asbestos was thought of as a miracle material. It has excellent insulative and fire retardant properties; however, it also gives people cancer. Had the producers and marketers assessed the toxicology of asbestos and put warning labels on the products and packaged the product differently, the asbestos producers would not have created the burden to society that they did. There would not have been the burdensome public and governmental backlash, nor the multi million dollar law suits, the destruction of thousands of perfectly good walls, the bankruptcies of several insurance firms and the increase in premiums of most others. Asbestos based products would still be a cash cow today. Clearly, the past is full of mistakes. Nanotechnologists need to be aware that they can hurt their market by not fully investigating product impact. For the naysayer that believes nano will not have toxicological impacts, the few studies that have been done show otherwise.

"British scientists called on Thursday for more research into the safety of nanoparticles following evidence they can lodge in the brain" (Hirschler 2004). Ken Donaldson, Professor of respiratory toxicology at the University of Edinburgh, said "The big worry would be if a nanotechnology business designs nanoparticles that are fundamentally different from the ones we are already exposed to and seem to cope with reasonably well" (Hirschler 2004). Chiu-Wing Lam, senior toxicologist at Johnson Space Center, reported that rats exposed to micrometer clumps of CNTs experienced the same effects as exposure to dust. However, individual stains of CNTs will develop lesions in their lungs and intestines. "CNTs are not innocuous" (Brumfiel 2003). In another experiment, Gunter Oberdorster, professor of environmental medicine, has been studying the effects of ultra fine particles on the body for decades. His studies show that a lot depends on the size of the particle. Rats exposed to nanometer particles of Teflon experience respiratory irritation while micrometer clumps are relatively un-reactive (Brumfiel 2003).

It is imperative that nano-businesses learn from the past and do not do the same mistakes as the producers of asbestos. Even though nanotechnology is a huge field with so many different materials and applications, if just one company produces a "miracle nano-material" that ends up killing people, the whole industry may feel the repercussions. It is critical that managers do their due diligence.

(1) Industrial Hygiene

Nobel Laureate Dr. Richard Smalley's team found that nanoparticles tended to spread around the laboratory. These particles cling to the clothes and skin of people working in the lab (Brumfiel 2003). This is an example of the importance of controlling the diffusion of nanoparticles, especially in the workplace where employees are constantly exposed to the particles. No studies have shown the levels of exposure that are considered safe. A search of the Occupational Safety and Health Administration's (OSHA) web site shows that they do not yet have any regulations on the duration of exposure allowed. As nanotechnology expands in industry and workers are disabled due to exposure, regulations can be expected to follow. Managers should take proactive steps to ensure the safety of their workers.

(2) Environmental

One of the promises of nanotechnology is that processes and products will be developed to help clean up the environment or at least reduce the effects of industry on the environment. While this may come to pass, for some products, other products may continue to have a detrimental effect on the environment.

Rice University researcher Mason Tomson discussed an experiment his team performed in which they suspended bucky-balls in water. When they allowed the bucky-balls to aggregate together to form micrometer clumps, they were absorbed into the soil like any other organic compound. But when they were dispersed, the water formed a protective sheath around each ball, allowing them to travel through the soil with out being absorbed. Unpublished reports show that the nanosized particles could easily be absorbed by earthworms, allowing the bucky balls to move up the food-chain (Brumfiel 2003).

On the other hand, aspects of nanotechnology can help the environment. For instance, carbon- or glass-filled plastic composites can not be recycled because their aspect ratios will change. Nanoparticle composites do not change in aspect ratio and therefore can be reused and maintain the same engineering properties. Also, nanoparticle composites can have the same or better performance as aluminum but are much lighter. Replacing them in cars will decrease fuel consumption, which decreases CO_2 emissions, which means fewer toxic releases (Lloyd, Lave 2003).

(3) Disposal

Disposal is an issue gaining importance as the world becomes more polluted. Products such as cell phones, computer CRTs, and car batteries already leach into the soil and pollute water supplies. As discussed above, nanoparticles can have a detrimental effect on the environment. Beyond leaching into the environment, other nanotechnology-based products in the future will be ultra resistant to the environment. The management/product development team needs to take care during the assessment phase of development to plan for a products disposal.

b) Market Potential

Evaluating the market potential of nanotechnology-based products is difficult because of the potential substitution of many different nano-materials and the multitude of applications. Continuously emerging future markets will further complicate the evaluation of the market potential of nanotechnology, even in the rather distant future (Bucher et al. 2003). Take, for instance, the future composition of the motor vehicle. It will be determined by intensive competition among the future cost/performance ratios of candidate materials, whether they are nano-based or not (Lloyd, Lave 2003).

Quantifying the future growth rate of a current market is unsatisfactory because those growth models are based on past events. Instead, identifying or even predicting the emerging markets, the disruptive technologies are essential. "It is crucial that the evaluation of disruptive technologies takes an iterative course. On the one hand, this allows necessary phase-specific cooperation with individual experts as well as research institutes; on the other hand, it enables a gradual adjustment of the resources assigned to the technology evaluation project" (Bucher et al. 2003).

There are two ways to develop a market for a product: the push-through and pull-through methods (Beall 2004). The push-through method occurs when a novel new material is found and the company looks to develop a market need for the product. This method of hunting for applications is a high-risk endeavor because customers may not see the need for the product, and the company may run out of cash before the product can catch on. The push-though method is widely used in nanotechnology startup companies. The researchers who discover novel new materials in the laboratory create companies to look for and develop the product's market potential. As in any business environment, starting a business without cash flow is a risky proposition. The second method is the pull through to market. Pull-though market development occurs when an entrepreneur identifies a technical problem in industry and searches for a solution. From a marketing viewpoint, inadvertently discovering a new material and trying to develop a market for it is much more difficult than deliberately solving a problem that already exists (Beall 2004).

(1) Life Cycle

As product life cycles decline, the time available to recover one's investment is reduced. Therefore, getting products to market faster is becoming a competitive advantage (Draman 2003). When product life spans become too short to recoup investment, continual analysis of patents and trade shows may help identify whether the product should be discontinued or shifted before investments are lost. This coincides with the knowledge management approach discussed earlier. As mentioned earlier, being tied to the numbers and being a slave to the return on investment can lead to trouble. While it is important to understand what the numbers are, management needs to also consider the industry, the trends, the risks, and follow their intuition.

c) Technical

Technical risks can be considered either the most important or least important risk because if an organization runs into a technical problem that cannot be solved, the project is over, no matter the skill of management. Yet, at the same time, how does one evaluate them? The technical risks of nanotechnology are obviously great, which is why developing nanotechnology is a high-risk endeavor. The degree of science and engineering required makes many of the promises impossible to achieve with today's knowledge. Anytime one is dealing with what can be considered impossible, one is dealing with risk. In this author's opinion, the best way to deal with technical risk is with confidence.

(1) Manufacturing

One type of technical risk is manufacturability. As a manufacturing professional, this author has seen and heard many situations in which a design team mandates things that cannot be manufactured, or in which the product can be manufactured at much less cost with minor changes to the design. For these reasons, Iansiti (1993) recommends that the integration team be in daily contact with manufacturing. This is in keeping with the systems approach to product development. Team members often deal with major problems in the product line, which allows them to evaluate the impact of new technology on production. "The most essential part of choosing a new technology is to establish its impact on the production process. And the integration team still never gets it quite right" (Iansiti 1993).

When developing the manufacturing process it is a good idea to concurrently develop the process and quality control. If the focus is just on volume manufacturing, the process parameters allowed for may not be able to be control the process or the quality standards created, such as surrogate measures, may not accurately identify critical issues.

(2) Supply Chain

Developing and ensuring the supply chain's integrity is an important issue to assess to ensure stable, high quality, and uninterrupted production. However, nanotechnology-based industries do not have the supply chain integration issues that most other discrete manufacturing industries have such as the automobile and cell phone industries. Integrated circuit manufacturing, however, has similar supply chain issues. Although this comparison is certainly not all-inclusive, both industries demonstrate the need for high purity gasses or base materials like CNT's and Nano-Clays, complicated processing equipment, and secondary equipment such as specialized transportation, handling, and protective paraphernalia. Because the nano industry is in its infancy, literature does not yet exist for the supply chain. Also, the nanoparticles being manufactured today are at the beginning of the supply chain. This is discussed in more detail in the case studies. In the future issues relating to how nanomaterials are packaged, transported, and distributed need to be defined.

d) Legality

Legality is an issue that management should not have much of a choice about. An organization should always stay within the frame work of tort law, common law, and industrial and governmental regulation.

e) Cash Flow and the Schedule

Perhaps the issues most under the control of management are the cash flow and schedule management. However, the dynamic and uncertain environment of nanotechnology makes this control very difficult. "That innovation is collective, cumulative, and uncertain implies that the process through which resources are allocated to innovation is developmental, organizational, and strategic (Zhao and Ming 2002)." As was discussed in the knowledge management section, nanotechnology-based organizations should use a flexible project methodology. Although using major milestones is useful to measure and verify progress, hard dates and specific time to accomplish tasks should be avoided until after design freeze due to the iterative nature of the product development. Using a flexible project methodology in uncertain environments is shown to have shorter lead times, on average require less than a third of the resources, and have a relatively lower financial risk compared to a traditional project (Iansiti 1995). Also, because the flexible project model is cumulative, resource allocation should be done over time (Zhao and Ming 2002). This makes measuring projects using the traditional baseline Net Present Value or breakeven comparisons difficult and somewhat irrelevant.

3. Intellectual Property

Several articles discuss how nanotechnology will be affected by intellectual property laws and patent protection. Mark Grossman, the chair of technology law group of Becker & Pliakoff, said "Law always develops behind new technology. It's in the nature of the beast, and nanotechnology is no different (Tsuruoka 2003)." Therefore developers must anticipate how and what laws will be developed so that they may position themselves into the best legal framework. However, nanotechnology will inevitably run into legal issues, just like internet gambling and music piracy (Tsuruoka 2003).

According to Kelly Kordzik (2003), the area of law that will see the most significant impact from nanotechnology is in the area of intellectual property and more specifically, patent law. To illustrate the difficulties of patent law in nanotechnology, the patent examiners at the U.S. Patent and Trademark Office are having trouble even understanding the unique aspects of nanotechnology-based patents. As a result the examiners have been inviting nanoscientists to the Patent and Trademark Office to give them tutorials on various aspect of nanotechnology. As a result of the difficult and demanding nature of nanotechnology, attorneys with hard science degrees will be needed.

When a company is looking for a patent attorney they should look for an attorney that has an understanding of the subject matter. The better the patent attorney is able to comprehend the technology, the better the quality of the patent application and the resultant claim protection (Kordzik 2002).

Newberger (2003) wrote that unlike other technologies such as computer software and Internet issues that have recently emerged, there are no doctrinal issues that need to be worked through with regards to nanotechnology because it falls squarely within the present, and indeed historical, IP protection regime. Nanotechnology products are products in the traditional sense; they are items that are manufactured with definable manufacturing processes. However, it is important to note that just like in any other developing industries, the absence of prior art affords the opportunity for broad patent protection (Newberger 2003).

Figure C: Legal Question

Legal Questions: (Tsuruoka 2003)	Possible Answers
Can you patent an atomic or molecular structure?	The U.S. Patent Office website (USPTO.gov) states that "...any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof..." can be patented.
How do you protect an atom or molecule-sized device from being illegally copied?	It's the process, not the structure, the same way as today. Naturally occurring material cannot be patented
How do you regulate and tax trade in devices too small to be seen?	Why is there a difference between small and large? Taxes are about cash flows, not about the product. It requires corporate transparency.
Should nano devices that alter human genes or cells be controlled?	This is a question that ethicists are dealing with.
Should government limit how nanotech is used in surveillance or other security technology?	Would not this be the rooster in charge of the hen house?
What health, safety and product liability issues are raised by devices and processes too small to be seen by the naked eye?	These are very important issues, but would they not be the same as most chemicals.

Patents are the primary regime for IP protection for nanotechnology; they provide strong protection, but the down side is cost to get a patent, maintain it, and protect it. Patents only protect within the boundary of the issuing country, and it may be desirable to seek foreign or international patents as well, however, this takes more cash (Newberger 2003).

Intellectual property can also become its own revenue-generating engine. "The success of many technology-based companies inherently depends on the strength of its intellectual property" (Yaniv 2, 2003). For small companies the strength of their intellectual property may not be enough because a weak cash flow will make them unable to protect their patents, licensing is their life blood (McKee 2003). However, this may be a sound strategy for larger companies. For the fiscal year 1990, Texas Instruments Corp. reported revenues from patent royalties exceeded its revenues from manufacturing and DuPont earned more than $380 million in 2001 through the licensing and sale of intellectual property. IBM has added $10 billion in royalties from licensing since 1993" (Yaniv 2, 2003).

D. Funding

After an idea has been assessed and found to have market potential it is essential that funding be secured. The number one reason why businesses fail is their inability to manage their cash flow. A lot of cash is needed to develop and market any product and the only exception with nanotechnology based products is that much more cash will be needed. Because of the very technical and difficult nature of these technologies, problems will occur and money will be lost. No matter how much market potential a product may have, no matter how much work the team has put into it, no matter how much money has already been spent, if the project runs out of money, its over with. Therefore, it is essential that money is secured and managed.

When it comes to accounting for money, today's business models and cost accounting systems are based on an assumption of independence. The problems businesses faced one hundred years ago and the solutions that were developed became the foundation of today's accepted business practices (Draman 2003). Throughput Accounting compared to Cost Accounting, treats all costs that are not truly variable as period expense, which removes the financial incentive to make and hold inventory (Draman 2003). This is a desirable accounting methodology for project accounting because the decision on whether to go ahead with a project is often based on the project's net present value, which combines all expected future cash flow, discounted at the cost of capital, to a present value. This NPV can be used as a baseline for the project progress and compared to the period expenses summarized with Throughput Accounting. Using Cost Accounting will misallocate some of the funds as variable costs and the project may surprisingly run out of cash.

The level of risk is too high for any one company to afford therefore; no one source of investments can develop a product based on nanotechnology. They must seek investment; the most successful nano-based company to lure investment is Alien Technologies, which has received $90 million in investment to this point (Evans et al. 2003). There are a variety of different options for getting capital. Each method is best at a different time and need of the company seeking funding. While the discussion of the best debt-to-equity ratio is best left to a financial textbook, the following table tries to summarize what the different sources of capital are, each one's pros and cons, and the best point in the life cycle to seek each source of capital.

1. Debt

There are several different types of debt a company can obtain including: Line of Credit from banks, industrial development bonds, small business development bonds, etc. Although it is easier to find sources of debt financing, it much harder to acquire then equity because debt must be paid back and therefore requires collateral. However, using debt to finance product development projects has the advantages of allowing management to retain control.

Debt usually carries a lower cost of capital than equity for several reasons. First, the debtee needs to offer some type of collateral to secure the loan. This means there is lower risk for the debtor than for an equity partner, and where there is lower risk, there is lower cost. Second, the debtee needs to show the debtor when and where positive cash flow will occur so that a realistic payment schedule can be created. Debtors like to get their money back because they are not in the business of liquidizing capital. The third reason why debt carries a lower cost than equity is because it is tax deductible. So, although debt carries a lower cost, for the above reasons, debt is a good thing to use late in the product development process, perhaps not even until production.

2. Equity

Equity is where the company seeking funds sells ownership of the company to investors. It is more difficult to find equity and then debt; however, it does not carry the burden of payback, but the promise of growth. One important aspect of equity is controllership. Depending on management's point of view, this is either a positive or negative thing. While the investors may be able to offer good advice and additional experience to the management team, the team may lose control of their business if the investors feel they are not doing an adequate job. There are a variety of equity options available, including private investment from friends and family or managers themselves, public investment done through an Initial Public Offering (IPO), Venture capital and angel investors, royalty financing, and employee stock ownership plans (ESOPs).

Although all of these are good sources of capital, each has its time and place. Managers in nanotechnology companies looking for capital to get started often approach angel investors. Angel investors are private individuals that are not risk averse, have money, and are looking to help develop good ideas. They are usually retired or have already developed successful companies of their own and want to help develop new companies. Angel investors understand what it is like to have little more than an idea. And, if they like the idea, they may be willing to invest when no one else is. However, because these are private funds, the amount is usually not much, just enough to sustain operations. Because their concern is solid and sustainable company growth, they are excellent sources of capital at the beginning of the product development process and are a source of managerial experience. The difficulty with angel investors is that they are hard to find, which is what they want. They want people who are hungry enough to find them, who have exhausted all other sources of capital for their new business.

On the balance sheets, venture capitalists could be categorized as angel investors. However, they are usually institutional investors who are looking for good investments and therefore are looking for a solid growth company. Because they are usually a consortium of investors, they are able to offer much more capital then the angel investor. For these reasons, they are better to use later in the development process, perhaps after concept feasibility but before production, the time when a large investment in equipment and personnel is needed. Venture capitalists who are evaluating nanotechnology-based companies are looking for the same things they usually do, including good technology, excellent management, a well-thought-out business plan, near term products, large markets, and strong intellectual property (Thayer 2003; Shock 2003). In 2002, $250-$350 million of the nanotechnology market was venture capital investments (Thayer 2003). An important aspect of seeking investment from venture capitalists is that they usually feel that if the company is funded by venture capitalists, then the scientists should not be in charge (Shock 2003).

3. Grants

The third way to generate capital is to get government grants. In the federal government alone, funding has increased six fold in 8 years: from $116 mil in 1997 to $849 mil in 2004 (nano.gov 3 2004). A positive aspect of this rapid rise in federally funded nanotechnology research and development is that consideration of societal benefits will have a larger role in setting the research and development agenda (Lloyd, Lave 2003), such as in 2001 when the NNI earmarked \$16-\$28 million to societal implications. However, it spent less than half because the NSF could not find one project to spend it on (Mnyusiwalla et al. 2003).

While 65% of the grants are going to academic research, the rest promotes partnerships between researchers and private enterprise to leverage the public funds (nano.gov 3 2004). The huge benefit in acquiring government grants is that they do not have to be paid back. The disadvantage is the difficulty and resources required to write the grant proposal, which are usually turned down, and that if a patent is earned with the aid of government funds, other researchers may be able to work with the technology in the patent for the government's interests, such as in defense (Newberger 2003). The federal government has historically funded the research and development at the early stages of development due to the risk that is considered too high for most venture capitalists.

E. Production Options

Although the production of products based on nanotechnology will utilize new processes, the methods of structuring the production operations are based on the same structures utilized in other industries. Once an idea has been developed, found feasible, and capital has been attained, there are a variety of different structures management can use to produce the product. In reality, identifying the best structure for production will occur early in the process, possibly even before the idea has even been thought of, logically it is easiest to visualize at the end of the process. There are four different approaches to producing a product. One can create a new company, sell the idea to an existing company, outsource, or if a company owns the idea they can expand their company. Each of these alternatives is discussed below.

1. Company Formation

Forming a new company to develop and produce a new product is conceptually the easiest route but, requires the most man hours to achieve. There are many books and organizations to help start new companies. One helpful and easily accessible organization is the Small Business Administration, http://www.sbaonline.sba.gov/, a government run organization that helps with all aspects of starting a new business, including developing the business plan, finding investors, developing a market etc. There are three basic forms of ownership: sole-proprietorship, partnership, and corporations, each with their advantages and disadvantages.

Figure D: Advantages and Disadvantages of Different Forms of Ownership

Form of Ownership	Advantages	Disadvantages
Sole-Proprietorship	• Total Control • Easy to Form • Few Regulations	• Unlimited Liability • Hard to get Capital
Partnership	• Liabilities Split Between Partners	• Arbitration of Disagreements
Corporations	• Easy to Find Capital • Over 50% Ownership Retains Control • Minimal Liabilities	• Difficult and Expensive to Start • Must Follow By-Laws • Double Taxation of Dividends • Equity Owners can Control Firm

2. Developing and Licensing

If an individual or group develops an idea but does not have the resources or competencies to market or produce it, they can sell the idea to another company. This idea has really taken off with people in the nanotechnology field. For instance, Applied Nanotech, an Austin, Texas, based company has changed their business plan to be developers of ideas or as their president Zvi Avi calls it, an incubator. Their plan is to take an idea, an egg, and do the feasibility studies and sell or license the ideas, or hatch them, to the producer. In other words, they plan to license or outsource all manufacturing activities (McKee 2003). This is a new twist to the supply chain where companies are not selling raw materials but developed ideas.

3. Expanding the Company

If a company is already in existence they can produce a new product in two different ways, creating a strategic business unit (SBU) or creating a cost center. An SBU is used when the new product is utilizing a new set of competencies from the parent organization and is a good strategy to diversify the company's portfolio. An example of an SBU is General Electric's ownership of NBC. On the other hand, a cost center is a product or family of products that are part of the company's competencies, such as Bic's disposable pens, razors, and lighters. Each is a cost center because they are different products with different margins, but they are still all insert-molded plastic injection-produced products and all have close to the same point-of-sales, grocery and convenience stores.

4. Outsourcing

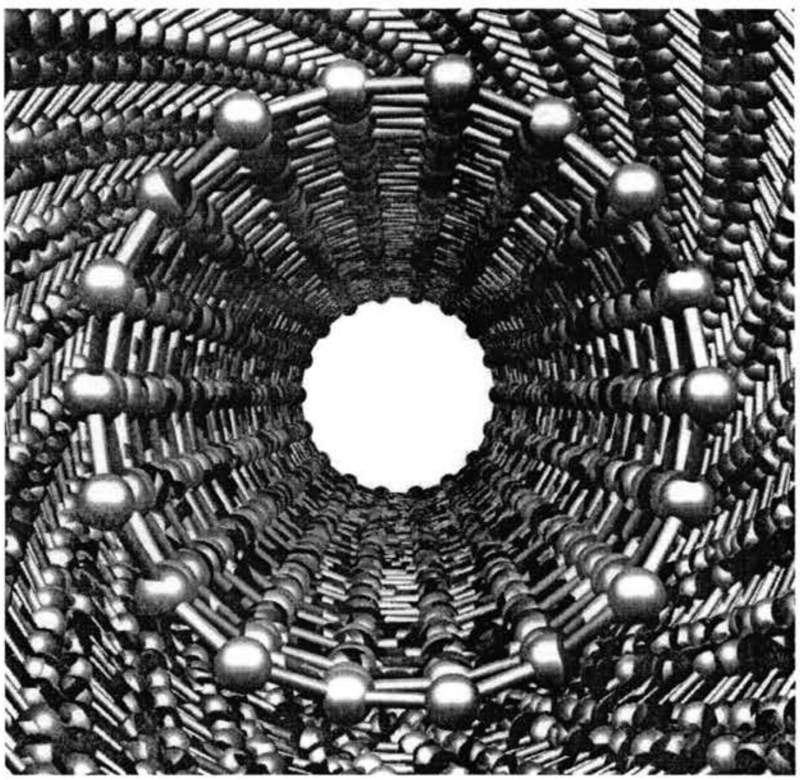
The final method of production is outsourcing. In today's business environment, outsourcing is becoming a source of competitive advantage. Outsourcing is paying another company to do jobs that have traditionally been done in-house. For example, many companies are utilizing temporary labor, which is where they pay another company to find and manage employees. Also, many manufacturing activities are being outsourced, such as plating, machining, and high-end metrology. For example, Nanotechnologies Inc. outsources material characterization (Evans et al. 2003). In fact recent studies have shown an increased significance of external technology sourcing in various industries (Bucher et al. 2003).

What should be outsourced? In the past this used to be simple; a corporation would identify what their core competencies were: if a process or activity did not create a competitive advantage or clear market differentiation, it was deemed non-core. However, with today's information super-highway, inroads have been opened up into businesses that allow people, who perform functions essential to any enterprise, to be outsourced (Hill 2003).

By creating such strong and networked interdependence between business entities, organizations are creating a stronger world economy and, it is argued that over the mid to long term outsourcing could actually improve the domestic economy. The market environment is rapidly changing; therefore flexibility is essential to remain profitable. Outsourcing increases flexibility which in turn increases profitability (Hill 2003). The added profits will be spent in the US economy. Through outsourcing, companies will focus more on their core competencies which means that more money will be pumped into R&D and into ways the industrial complex can reduce their negative externalities. Both of these will create high value jobs. The positives include increased efficiency, exchange, and agility.

In summary, to competitively manage the process of product development of products based on nanotechnology the development team should recognize and apply the ideas and concepts of project management, systems theory, iterative problem solving, documentation, and flexibility that are described in the above knowledge management section to the entire development process. When generating an idea for a product, there are many sources that can be utilized including pure laboratory research, research and development, market niches, patent analysis, journal and industry research, and brain storming. Due to the significant uncertainties involved in the development of nanotechnology products evaluating how technologies should be integrated and which ones to use is critical to the competitiveness of the organization. When developing a new idea the team should assess its feasibility. Areas to be assessed include toxicological, market potential, technical, legal, cash flow, schedule, and intellectual property. Using a risk management methodology is useful in assessing the feasibility of each of these issues. This four step methodology includes: 1) Risk Identification, 2) Risk Assessment, 3) Risk Response Development, and 4) Risk Response Control. The next key issue that needs to be addressed is funding. The vast majority of business failure is caused by lack of cash flow. This is a key issue for nanotechnology companies because the development costs are high and the product technologies are not proven which can make market penetration difficult. To cover the development period the firm has three methods of raising capital: debt financing, equity financing, and grants. The final issue that needs to be addressed is how to adapt the organization to produce the product. The options are developing a new company, licensing, expanding an existing company, or outsourcing. The following section consists of three case studies which were designed to verify the validity of the above analysis of literature.

Figure E: Illustration of a Double Walled Carbon Nano-tube



The above picture is an artist's interpretation of a double walled carbon nano tube (CNT). This is an example of two different chiralities or twists.
Courtesy of Dr. Chris Ewels ©2002

IV. CASE STUDIES

The following case studies were performed in face to face interviews. The interview questionnaire is available in appendix 1.

A. Nanotechnologies Incorporated

Nanotechnologies, Inc. is a supplier of custom engineered nanoparticles. This privately funded company was founded in 1999 and currently has 25 employees, mostly scientists and engineers, and uses a proprietary pulsed plasma fabrication process. The author interviewed Dr. Denny Hamill, who is the vice president of business development and has over 30 years experience with product development in highly technical environments. The following is a summary of the interview performed August 12, 2004.

Dr. Hamill identified several challenges of working in the nanotechnology field. First is the fact that the science that his company is dealing with is still not fully understood, for instance, how nano-powders interact with the base materials to enhance the desired applications and to better quantify the chemistry of dispersion. The second challenge Nanotechnologies, Inc. faces is that the general inertia of adoption for breakthrough technologies is very slow. Their customers move slowly, even after proof of concept, because these companies have assets and processes already in place. It takes time to change them. The third challenge is that the products that Nanotechnologies, Inc. sells need to be solutions to critical problems or needs. For this challenge, Dr. Hamill emphasized the need to work with partnerships, to identify problems that need to be solved, and to be able to enable the technology. The final challenge is one of the greatest problems that small nanotechnology firms face today: cash. Cash flow is a critical problem because the time between demonstrated feasibility and commercial production can be years. The ability of a company to get through that gap and reach breakeven is critical. Small companies get punished with venture capital, so finding other non-equity revenue to cover the gap is important and difficult.

To manage the development of new technologies, Nanotechnologies, Inc. use a monthly IP review meeting that documents ideas generated by their team. They currently have 5 patents and 5 in the works and have a goal of filing one patent per month. To assess the feasibility of new products, they use a two-step approach. First is a technical demonstration which shows that a product or concept is technically feasible and has an improvement in the desired properties. This is done through demonstration with a partner. Second is market feasibility, which looks at the existing market and quantifies how the new product will impact the existing market, thus identifying the amount of market share the product may attain. This helps Nanotechnologies generate a preliminary P&L (profit and loss) statement to help them decide whether to develop the product or not.

Dr. Hamill agrees with the premise stated in this thesis: in uncertain technological environments, a system focused integration team should be used during the product development process. This team should use iterative problem solving skills and knowledge management techniques to remain flexible and increase competence. This approach to product development requires a high level of communication between the phases of development, both upstream and downstream and even into production. With Dr. Hamill's years of working in product development teams he added two insights to the above statement. First, the customer needs to be apart of the team. And second, with a small company, there are trade offs between getting things done and process control. He stated that while he would like a more structured commercial development plan that would force decision points and make sure everything is covered and that his team is developing one, with the lack of resources Nanotechnologies, Inc. faces, it is a challenge for them to have that discipline. While people have to wear multiple hats, they try to find the balance. Until they have a standardized commercialization model, they are using a small business development team of about 8 people to facilitate communication during the development cycle. By being in daily and weekly discussions with the technical team, the business development team identifies the key commercialization technical/business issues.

When asked about how Nanotechnologies, Inc. gains and manages knowledge, Dr. Hamill responded that the main source the company uses to learn about developments in nanotechnology is through trade shows. They used to have booths at these events but they have become visible enough that they do not use them anymore. They also learn about developments in nanoscience by working with the government and with universities.

They currently document/manage knowledge gained from outside the organization though email and shared drives on the network. However, Dr. Hamill indicated that he would like this to be a more organized effort, perhaps by using a customer resource management (CRM) solution.

For managing knowledge gained from inside the organization, they have developed a good discipline of documenting ideas in notebooks to track for IP protection. IP was less important an issue two years ago because they thought they could keep all of their work proprietary. However, they realized how important it is to work with partners, so documenting IP has become very important.

Dr. Hamill said that while they analyze their direct competition and are very knowledgeable about competing nanoparticle firms, they do not spend resources on analyzing and learning about other technologies. They maintain profiles on their direct competition to ensure that their process remains differentiable. While they know about gas dynamics and plasma physics, they do not know much about their customer applications. However, discoveries made by their partners spur a tremendous level of communication, which inspires the development teams to actively search out new information; re-education though application.

Nanotechnologies uses project managers when they have traditional projects with time lines, deliverables, and reports. However, they use less ridged approaches with partnerships and/or internal projects. Customer projects drive internal projects or opportunity driven, sidebar projects. While Dr. Hamill agrees that traditional project management skills are certainly required at times, technology innovation requires something outside of the box. As an example, he mentioned MIT's development of "Lead User," which is a unique Delphi approach to project management.

Dr. Hamill listed three business functions that Nanotechnologies Inc. outsources: 1) Legal services -- patent and corporate law, 2) Technical Consultants, and 3) Government Lobbying. They manage these activities with one or more of the following: a clear schedule, a task document, or a consulting agreement which includes time, task and deliverables.

B. Applied Nanotech

Applied Nanotech is a subsidiary of SI Diamond Technology which was incorporated in 1989. They began operations as an artificial diamond research organization and later switched to Carbon Nanotubes. Applied Nanotech began as a center to commercialize technology based on the field emission properties of CNTs as a substitute product for Liquid Crystal Displays (LCDs). The largest market value is for large corporations that make large televisions, billboards, and other electronic displays. Applied Nanotech has since changed its focus to developing a large intellectual property portfolio to take advantage of broad patent coverage that one can gain in an industry's infancy. The following is the summary of an interview with Dr. Zvi Yaniv, President and CEO of Applied Nanotech, on August 18, 2004.

Dr. Yaniv identified several challenges with working in the nanotechnology field. First is that the field is misunderstood technically, financially, and publicly. Second is the "cast": nanotechnology is an interdisciplinary discipline that requires a cast of specialized professionals. Third is that the technologies being developed do not have immediate market impact and are just improving current products. This leads to the forth challenge, which is that nanotechnology is on the bottom of the food chain because nanotechnology involves, in essence, materials, and therefore a nanotechnology company is a material supplier.

Dr. Yaniv generates ideas by looking at industries with large markets that have problems. From the idea, they use a computer simulation to enhance the concept. Then they look at the physics and chemistry of the molecular interfaces. If the science holds, they feel they have a proof of concept that works at the macro level, so their final step is to gain IP protection on their "invention" and license it to industry. Through this simplified approach to product development where their product is their IP, they do not see the need for a system focused integration team. This also means that they do not need to tie up capital in the development process. As Dr. Yaniv explained "We love to be detached."

Dr. Yaniv acknowledged the importance of being informed and said that the two most effective ways to stay informed are through reading and participation in conferences. When asked about managing knowledge, Dr. Yaniv took it to mean "managing creativity" and further explained "I strongly believe that creating knowledge is the biggest business, being creative." There are two forms of managing creativity: Documentation and a well designed IP process. Documentation involves keeping a lab journal or notebook during the creative stage and making disclosure once the idea hits maturity. The IP process starts at disclosure, then moves through provisional, patent, define and finally search.

In order to document knowledge from outside the organization, Applied Nanotech uses search engines; they read a lot and use internal communication because different people have different interests. When knowledge is created, it is disseminated to individuals throughout the organization by using frequent meetings to discuss problems and inventions and to brainstorm. Dr. Yaniv feels it is not too important to monitor the business horizon to ensure their product's viability, because they have no products. Instead he said, "Others need to worry about me." When good information does come along through the use of search engines, they either drop the invention they are working on or acquire IP.

Applied Nanotech uses traditional project managers along with their skills and tools. However, those skills and tools are adaptable to the invention process. Dr. Yaniv declined to further explain and gave Pert Charts as the only example of a PM tool that they use during their invention process. Applied Nanotech outsources equipment fabrication and IP services.

C. NASA's Nano Materials Team

The final interview for this thesis was performed on October 13, 2004. The interviewee was Dr. Leonard Yowell, team lead for NASA's nanomaterials project which is composed of several subprojects. This person was interviewed in order to identify managerial approaches to nanotechnology development by an organization that does not need to be focused on cash flow. The nanomaterials project began in 1997 under the Materials and Processes Branch of NASA in order to develop nanomaterials for space applications. The nanomaterials project has four areas of study: 1) growth and synthesis of single walled Carbon Nanotubes (SWCNT), 2) processing and purification, 3) Characterization Strategies, and 4) Applications. It is interesting to note that no current standards exist to characterize a SWCNT and that the project team has partnered with NIST and ANSI to develop standardized lexicon, tests for the chirality, tests for composition, and to bridge the gap between the nano-, micro-, and macro scales. To achieve the mentioned deliverables they combine variety of metrology equipment in a standardized way.

Dr. Yowell said that one of the most difficult challenges he faces working in nanotechnology is the multidisciplinary team required to work in the field. This is difficult because the team members come form a variety of different educational backgrounds, technical jargons, and scale of work (as in nano-, micro-, macro-scale). The different team members might also measure success in different ways. For example a successful test for a physicist would be of minimal importance to an engineer. As an industry, the workforce needs to become accustomed to the multidisciplinary aspect of nanotechnology. Another difficulty that exists in the nanotech field is in managing expectations. There is so much "hype" about the possibilities with nanotechnology that people can become excited. Stakeholders can then become disheartened and lose interest in the science by the realization that there is still a lot of basic research that needs to be done. Fundamental answers need to be understood before application can become widespread. The final difficulty that Dr. Yowell mentioned is analogous to other firms need for additional cash flow. He thinks that the federal government needs to significantly increase funding for the research community.

When asked about idea generation, Dr. Yowell said that the best method for generating new ideas is to have intelligent and creative people on your team that are always thinking, always at work. Intelligent and creative people combined with a multitude of technical problems that need to be addressed means that new ideas are plentiful, some of which are realistic and some are not. In order to address the feasibility of new ideas, the term "lowest hanging fruit" is common at NASA. This means that they use the ideas that are the most practical, direct, and understood to solve their problems.

Being that the nanomaterials project team is a multidisciplinary team, it is by definition focused and integrated. Also, through the scalable nature of nanotechnology, where a CNT needs to be studied on the nano-, micro-, and macro- levels, the nanomaterials project is also an iterative study. For example, the Application Team (works in macro) meets with the Advanced Research Team (nano) on a weekly basis so that the Application Team will have a better understanding of the characteristics of the materials that they are creating applications for, and so that the Advanced Research Team will have a better understanding of what properties are important and what issues the Applications team is having with the materials. This is system focus in real time.

Scientific literature is the most common source used for learning about the developments in nanotechnology field. This includes newsletters, journals, and popular literature like *NanoApex* and *Small Times*. The members of the nanomaterials team attends conferences and has a large collaboration network. They also publish articles internally and externally, have internal presentations and issue reports. However, the main method of communication is through meetings and emails. The average team member spends approximately three hours a week in prearranged meetings.

According to Dr. Yowell, the team is skeptical about new information on nanotechnology developments. They do not rush into changing any of their current work because of all the hype on nanotechnology. If the information is pertinent, they will contact the researchers to ensure the viability of the new development. If the development is real and applicable, they will try to setup a working relationship with the researchers. Dr. Yowell said that they do not use any standardized methods of gathering, retaining, and communicating knowledge as part of a structured knowledge management system.

As the nanomaterials team lead, Dr. Yowell is the project manager. The main method he uses for tracking progress is through team meetings each Tuesday in which he meets with each team for 45 minutes and the subordinate team leads present a status report. Dr.

Yowell feels that traditional project management tools are not very useful. This is interesting because "traditional" project management tools began at NASA during the Apollo program before being refined by the IT industry. Dr. Yowell feels that with the research they are doing, traditional tools are too time consuming and he has found that they almost always come to the wrong conclusions. Instead, Dr. Yowell thinks the most important thing is to have a plan, or as he said what General Tommy Franks calls "the way ahead." The management approach that he takes is to let his team leads come up with their own deadlines, to which he usually adds a couple weeks. Then, through weekly meetings he tries to enforce the deadlines.

The nanomaterials team outsources for specialized equipment and materials, specialized characterization, and some core research which is usually with universities and paid for through academic grants. Outsourcing activities are managed through a statement of work, and is subject to the government's procurement regulations.

V. CONCLUSIONS

As stated at the beginning of this thesis there are two objectives:

1) Develop a broad overview of the managerial issues involved in managing the development process of nanotechnology products.
2) Identify if there are any managerial issues unique to the development of nanotechnology products.

In light of the above objectives, the following conclusions are made from combining the information from the interviews to the literature review. The case studies have shown to either supplement or enhance the review of literature.

- There are four main issues to working in nanotechnology.
    1. The science needs to be better understood. Currently, nanotechnology is merely enhancing products that are already on the market, and the truly disruptive products won't occur until the science is better understood.
    2. The second issue is common to all developing businesses. They need to solve a problem. Akin to the software industry, no matter how neat a product is, businesses are not going to adopt the technology unless it can solve a problem of theirs.
    3. The third issue is IP protection. While this is not relevant to NASA, this has become a very important to the other two companies because they both

understand that with the rapid development of the field, it is possible to gain broad patent coverage. Both companies begin the protection process through the use of notebooks or journals that their employees have religiously begun to keep. Due to the specialized nature of patent law, IP protection is a service that both firms outsource.

4. The fourth is the cause of 90% of small business failure, the failure to manage cash. Due to the long period between proof of concept and adoption of the technology, nanotechnology firms face a numbing drain of their cash. The ability to develop a product or technology and get to breakeven with equity capital is essential. Due to the capital intensive requirements of nanotechnology, funding is even an issue with NASA.

- The literature points out that managing knowledge can become a significant source of competitive advantage, especially for companies involved in rapidly changing environments such as nanotechnology (Iansiti 1995, Kasvi et al. 2003). Understandably, companies are more interested in reaching breakeven than spending resources on building a knowledge management system, however, an effective system can reduce overhead by making their development process more efficient. Moreover, waiting until the firm reaches breakeven before attempting to develop a management system can create a culture that will not fully utilize such a system. Companies should begin with the idea of accounting for their knowledge, and as they develop, they should use their lessons learned to further refine a system of development. While concentration should be given to making money, having the team aware of the opportunities available with knowledge management should remain important. And, as always, it starts with top management.

- The literature also points out that not very many companies actively manage knowledge (Kasvi et al. 2003). The companies interviewed use meetings as the primary method of exchanging knowledge. Documents that are created are shared in meeting, emails, and public directories. All the organizations studied count on the interests of their employees to scan the horizon for possible opportunities or threats. The main source used to learn about industry developments is the attendance of conferences and scanning the scientific literature is second. Proactively managing knowledge was the main finding from the literature that the interviewees did not practice in their firms.
- The only unique managerial issue identified for the development of nanotechnology products is that it requires a multidisciplinary and highly educated team. This issue requires managers to facilitate communication between team members and ensure progress is being made.

VI. RECOMMENDATIONS & FUTURE RESEARCH

The following are recommendations that have evolved from this research:

- Use the consortium method when practical and keep the management team as small as possible in order to keep overhead low.
- A multidisciplinary team must be involved in the development of nanotechnology products.
- Outsource activities to keep fixed costs low.
- Standardize the IP process to make it efficient and a part of business practice.
- Focus on the problems that need to be solved, not the uniqueness of the science.
- Develop surrogate measures to keep control of quality real time and low cost.
- Develop the firm's business and documentation processes on the principles of knowledge management, including a systems-focused approach, iterative problem solving, flexibility, and project management.
- Ensure that the products being manufactured are safe for production, consumption, and disposal.
- A balance should be maintained between scientific and business interests in the organization.
- Management needs to be held responsible for the ethical decisions they make.

- Leadership should be a "dynamic" entity that circulates throughout the multidisciplinary team. Project managers should not consider that they are the "static" leader, but inspire different leaders in the team through quality management.

The following are areas of future research. The author thinks that successfully researching and implementing the following issues can give a firm a distinct competitive advantage.

- The further refinement project management tools and techniques developed specifically for the innovation process and work in conjunction with a knowledge management system.
- Researching and developing a knowledge management database that offers the attributes discussed in the Knowledge Management section of this thesis.

A final note: caution should be taken with regards to the ideas of a knowledge management system. Is it just another management trend and will it soon be on the wayside? Being that none of the companies interviewed used, or even saw the need for a sophisticated knowledge management system, is it needed? Would the resources required to build such a system outweigh the benefits that the system would give?

APPENDIX: INTERVIEW QUESTIONNAIRE

Date: ____________________

Company: ________________

Name: ___________________

Title: ____________________ Education: _______________

What products do they have currently on the market?

What are their core technologies?

What approaches to nanotechnology do they use? (Bottom up, top down)

What types of metrology equipment do you use?

What are their prospective products?

Business structure? (LLP, Inc.)

Year Began Operations?

Is it OK if I record this interview?

Would you like a transcript of this interview?

To begin, What are some of the challenges that you face, personally, with in working in the nanotechnology field?

Generally, for a company that is working in a challenging field, like nanotechnology, what do you think are some of the most important issues to deal with?

At the stage your company is in right now, what are the biggest obstacles it faces?

<u>Development</u>

How has your company generated new ideas for products?

How have you assessed the feasibility of new products?

<u>Integration</u>

The literature suggests that in uncertain technological environments, a focused integration team should be used during the product development process. This team should use iterative problem solving skills and knowledge management techniques to remain flexible and increase competence. This approach to product development requires a high level of communication between the phases of development, both upstream and downstream and even into production.

Do you think this statement is relevant to your company? *Please explain:*

If Yes, *What steps has your company taken to communicate between the phases?*

If No, *What aspects do you disagree with? (Is it that your company is not working in an uncertain environment or is it that this is not the most productive/competitive way to develop products?)*

Are there Standard Operations Procedures (SOPs) regarding the product development process?

Knowledge Management

What sources do you use to learn about developments in nanotechnology?

The literature suggests that managing the accumulation of knowledge has become a real source of competitive advantage for companies.

How does your company document/manage knowledge that is created inside the organization?

How does your company document/manage knowledge from outside the organization?

When Knowledge is created, how is it disseminated to individuals/teams inside the organization?

With the rapid development of nanoscience, How does your company monitor the horizon? How do you ensure there are no products/technologies on the horizon that may make your products inferior?

How does your company adapt in response to new information?

Project Management

Does your company use project managers?

Traditional Project Management tools (Gantt Chart, WBS, Baseline Budgets) are based on managing projects that use known technologies (computers, construction equipment). Project managers traditionally work with definable processes that have known deliverables and milestones.

Would you say that the Project Management skills required in your company are traditional in nature?   Please explain.

Outsourcing

What business functions, if any, do you outsource?

How do you manage those outsourcing activities?

End Well

Are there any questions you would like to ask me?

Thank you for your Time!

REFERENCES

Alderman, Neil Thwaites, A. "Project-level influences on the management and organization of product development in engineering." *International Journal of Innovation Management.* 5,4 (December 2001) 517

Anonymous 1. "Nanotechnology scientists call for risks to be identified" *Professional Engineering.* 16,20 (Nov 2003) 13

Anonymous 2. (October 25, 2003) "Science and technology: Pipe dreams; Nanotechnology" *The Economist.* 369, 8347. 98

Anonymous 3. (September 3, 2003) "Darts technique to pinpoint dimensions of nanoparticles." *Professional Engineering.* 16,15 48

Anonymous 4. (March 2003) "Nanotechnology faces GM-style backlash." *IEE Review.* 49, 3 12

Anonymous 5. (July 17, 2003) "Tough lessons from the field." *Nature.* 424, 6946. 248

Anonymous 6. (July 17, 2003) "Don't belive the hype." *Nature.* 424, 6946. 237

Brumfiel, G. (July 17, 2003) "A little knowledge…" *Nature.* 424, 6946. 246

Bucher, P., Birkenmeier, B., Brodbeck, H., Escher, J. P. (2003) "Management principles for evaluating and introducing disruptive technologies: the case of nanotechnology in Switzerland" *R&D Management.* 33, no 2 149-163

Challener, C. (Apr 28, 2003) "Who's doing what in nanotechnology." *Chemical Market Reporter.* 263, 17 FR4.

Christensen, C. M. (2000) *The Innovator's Dilemma.* New York, NY. HarperBusiness.

Clifford G. F., Larson, E. W. (2003) *Project Management: The Managerial Process.* New York, New York. McGraw

Compano, R., Hullmann, A. (2002) "Forecasting the development of nanotechnology with the help of science and technology indicators." *Nanotechnology.* 13. 243.

Draman, R. H. (December 2003) "The living Generator: An approach to aligning the growth of technology and jobs. Part two: A systems-based model for business. WHY it's needed and how it works." *Nano Express* Vol. 3, (December 2003). http://www.txstate.edu/nac/nanoexpress.htmlx

Dubie, D. (August 11, 2003 "Q&A: Research exec helps IBM bring projects to reality." *Network World.* 20, 32.) 21

Evans, E., Smithson, R., Adams, L., Stacy, S. (March 20, 2003) "Catching the Next Wave in the Corridor" *IC² Institute: The University of Texas at Austin.* Prepared for: The Corridor NanoBioTech Summit.

Fowler, A. (2003) "How to build effective teams." *People Management*, 1, 40

Ghosh, A. (December 2002) "Nanotechnology and Manufacturing". *Chemical Processing*, 65, 12. 8.

Hill, P. D. (December 2003) "White-Collar Outsourcing: Derailment of U.S. Dominion?" *Nano Express* Vol. 3, (December 2003) http://www.txstate.edu/nac/nanoexpress.htmlx

Hirschler, Ben. (January 9, 2004) "Scientists warn on potential nanotech health risk." *Science – Reuters.* http://story.news.yahoo.com/news?tmpl=story&cid=570&e=16&u=/nm/science_nanotech_health_dc. (January 9, 2004)

Hunger, D., Wheelen, T. (2003) *Essentials of Strategic Management 3rd edition.* New Jersey, USA. Prentice Hall.

Hurd, J. (December 2003) "Master New York Chefs Serve up latest molecular accomplishments – and review U.S. position in global technology race." *Nano Express* Vol. 2, (December 2003). http://www.txstate.edu/nac/nanoexpress.htmlx

Iansiti, M. (Fall 1995) "Shooting the rapids: managing product development in turbulent environments" *California Management Review.* 38, 1. 37

Iansiti, M. (Febuary 2000) "How the incumbent can win: Managing technological transitions in the semiconductor industry." *Management Science.* 46, 2. 169

Iansiti, M. (May-June 1993) "Real-world R&D: jumping the product generation gap" *Harvard Business Review.* 71, 3. 138

Kasvi, J., Vartiainen, M., Hailikari, M. (2003) "Managing knowledge and knowledge competences in projects and project organizations." *International Journal of Project Management.* 21 (2003) 571

Kordzik, K. (December 16, 2002) "Intellectual Property: Small new world." *The National Law Journal.* reprinted

Kreitner, R., Kinicki, A. (2004) *Organizational Behavior Sixth Edition.* New York, NY. McGraw-Hill.

Krishnan V., Ulrich K.T. (January 2003) "Product Development Decisions: A Review of the Literature." *Management Science.* 47, no1 1-21

Kuo, W. "Redefining our relevance." *Industrial Engineer.* 35, 5 (May 2003) 41

Ladendorf, K. (December 3, 2003) "Austin nanotech firm raises $30 million, third largest venture deal this year" *Austin American-Statesman.* http://www.statesman.com/business/content/auto/epaper/editions/tuesday/business_f3cc64… (December 3, 2003)

Larsen, Henrick, Holt. (2002) "Oticon: Unorthodox project–based management and careers in a "Spaghetti Organization." *Human Resource Planning.* 25, 4. 30

Lloyd S.M., Lave L.B. (2003) "Life Cycle Economic and environmental implications of using nanocomposites in automobiles." *Environmental Science and Technology.* 37, 15. 3458-3456

McKee, M. (Summer 2003) "Si Diamond Technology, Inc." *Term Project for Management 5313-Administrative Policy at Southwest Texas State University.*

Mnyusiwalla, A., Darr, A., Singer, P. A. (2003) "Mind the gap: science and ethics in nanotechnology" *Nanotechnology.* 14. R9

Nano.gov 1 (January 11, 2004) http://www.nano.gov/html/about/funding.html

Nano.gov 2 (January 11, 2004) http://www.nano.gov/html/about/history.html

Nano.gov 3 (January 11, 2004) http://www.nano.gov/html/about/home_about.html

Nano.gov 4 (January 11, 2004) http://www.nano.gov/html/about/nnco.html

Nano.gov 5 (January 11, 2004) http://www.nano.gov/html/about/nnibudget.html

Nano.gov 6 (January 13, 2004) http://www.nano.gov/html/facts/appsprod.htm

Nano.gov 7 (January 13, 2004) http://www.nano.gov/html/facts/society.html

Nano.gov 8 (January 13, 2004) http://www.nano.gov/html/facts/whatIsNano.html

Newberger, B. (December 2003) "Intellectual property and nanotechnology" *Nano Express* Vol. 2,. http://www.txstate.edu/nac/nanoexpress.htmlx

Peters, L. (April 2003) "Nanotechnology – Conception to Commercialization" *Semiconductor*

International. 26, 4. 19

Pullin, J. (June 2003) "Goo and Evil." *Professional Engineering.* 16, 10. 29

Rashba, D., Gamota, D. (2003) "Anticipatory standards and the commercialization of nanotechnology." *Journal of Nanoparticle Research* 5: 401-407

Ratner, M., Ratner D. (2003) *Nanotechnology A Gentle Introduction to the Next Big Idea.* Upper Saddle River, New Jersey: Pretence Hall PTR, 2003.

Roco M.C. (2003) "Broader societal issues of nanotechnology." *Journal of Nanoparticle Research.* 5. 181-189

Roco, M.C. (2002) "Coherence and Divergence of Megatrends in science and engineering" *Journal of Nanoparticle Research.* 4. 9-19

Rutledge, C.O. (Fall, 2002) "The Rho Chi Lecture: Stories from a life of learning." *American Journal of Pharmaceutical Education.* 66. 329

Satava, R. M. (Oct. 2002) "Disruptive Visions: Moral and ethical challenges from advanced technology and issues for the new generation of surgeons." *Surgical Endoscopy and Other Interventional Techniques.* 16, 10. 1403-1408.

Schmidt, K. F. (January 12, 2004) "Natures helping hands." *U.S. News and World Report.* 46

Serov I. N., Zhabrev, V. H., Margolin, V. I. (2003) "Problems of nanotechnology in modern materials science." *Glass Physics and Chemistry.* 29, 2. 169-178.

Shock, C. (July 7, 2003) Winstead Nanotechnology Colloquium Series Austin, Texas offices of Winstead Sechrest & Minick

Soderlund, J. (2002) "Managing complex development projects: arenas, knowledge processes and time." *R&D Management.* 32, 5. 419

Temponi, C. (1997) "The Impact of General System Theory in Evolving Organizations." *Journal of Advances in Systems Science & Applications.* Special Issue 415-423.

Thayer, A. M. (September 1, 2003) "Venture capitalists are cautious toward nanotech." *Chemical & Engineering News.* 81, 35. 20

Tsuruoka, D. (September 30,2003) "Nanotech Boom Expected to Force Legal Scrambling" http://story.news.yahoo.com/news?tmpl-story&cid=1471&ncid=1471&e=4&u=/ibd/2003

Vartiainen, M., Hakonen, M., Simola, A., Kokko, A., Rantamaki, T. (1999) Learning project model and Transfer of Experiences. In: Proceedings of the 6th International Product Development Conference, Cambridge, UK; 1085-1095.

Vink D.L.N (2001) "A deeper Level of Quantum Mechanics" *Physics Essays.* 14, 2. 132-143

Yaniv, Z. (December 2003) "Definitions of nanotechnology and short term commercialization opportunities in the Austin – San Antonio corridor" *Nano Express* Vol. 1,. http://www.txstate.edu/nac/nanoexpress.htmlx

Yaniv, Z. (December 2003) "The ultimate pot of gold: The patent portfolio" *Nano Express* Vol. 2,. http://www.txstate.edu/nac/nanoexpress.htmlx

Zhao, Y., Ming N. (June 2002) "The Implementation of Innovation and Resource Allocation with Nanotechnology" *Journal of Wuhan University of Technology.* 17, 2. 99-101

Primary Research Interviews:

Dr. Mary Pat Moyer. (April 8, 2004) CEO of Incell and Teksa, Discussed Risk Assessment and Business Feasibility in the nano/bio product development

Dr. Gary Beall, Texas State University Chemistry Professor, Thesis Committee Member. Discussed a variety of nanoparticle applications, technology issues in business environments, and team member composition for successful technology development.

Dr. Cecilia Temponi, Texas State University Professor of Management, Thesis Committee Chair. Discussed system theory and how it is applied to managerial processes.

Dr. Denny Hamill. (August 12, 2004) Vice President of Business Development, Nanotechnologies Inc. Interview for primary research.

Dr. Zvi Yaniv. (August 18, 2004) President and CEO Applied Nanotech, Interview for primary research

Dr. Leonard Yowell. (October 13, 2004) NASA, Nanomaterials Team Lead.. Interview for primary research

VITA

Ryan Klepetko was born December 29, 1974 in Kadina Air Force Base, Okinawa, Japan. He grew up in San Antonio, Texas, where in 1992 received his GED. After attending San Antonio Community College for two years he transferred to Texas State University-San Marcos in 1995. He received his Bachelor of Science and Technology in December of 1998 in Industrial Technology, Manufacturing Technology. After graduation he worked in several different technical, engineering, and managerial positions until the fall of 2002 when he returned to Texas State University-San Marcos to begin work on his Master of Business Administration degree.

Permanent Address: 515 River Springs
Seguin, TX 78155

This thesis was typed by Ryan Klepetko.