MANUFACTURING INSIGHTS
Nanomanufacturing

NARRATION (VO):
MANUFACTURING INSIGHTS, MANUFACTURING ENGINEERING MAGAZINE'S VIDEO SERIES FOR PROCESS IMPROVEMENT. THIS VIDEO HIGHLIGHTS THE CURRENT, NEAR-TERM, AND FUTURE APPLICATIONS OF NANO-MANUFACTURING AND HOW THEY WILL REVOLUTIONIZE THE WAY WE MASS PRODUCE PRODUCTS.

FIRST, WE'LL LOOK AT THE COMPUTATIONAL MODELING AND SIMULATION TOOLS BEING DEVELOPED BY NANOREX FOR THE DESIGN AND ANALYSIS OF PRODUCTIVE NANO-SYSTEMS.

NEXT, WE VISITED NANOINK TO SEE HOW DIP-PEN NANO-LITHOGRAPHY, OR 'DPN', TECHNOLOGY IS USED FOR COMMERCIAL NANO-MANUFACTURING APPLICATIONS.

WE'LL HEAR FROM ZYVEX, THE WORLD'S FIRST MOLECULAR NANOTECHNOLOGY COMPANY DEDICATED TO DESIGNING AND ENGINEERING MOLECULAR ASSEMBLERS AND OTHER NANOSCALE TOOLS.

WE THEN TRAVEL TO NASA'S JOHNSON SPACE CENTER AND GENERAL DYNAMICS TO SEE HOW THE USE OF NANOTECHNOLOGY WILL IMPROVE THE PERFORMANCE CHARACTERISTICS AND DESIGN FUNCTIONALITY OF MATERIALS USED BY THE SPACE AND DEFENSE INDUSTRIES. THIS INCLUDES THE USE OF NANOPARTICLES THAT RESULT IN LIGHTER, STRONGER, SELF-HEALING MATERIALS THAT SIGNIFICANTLY REDUCE THE MASS AND WEIGHT OF PAYLOADS WHILE IMPROVING THEIR ENERGY EFFICIENCY AND THERMAL PROPERTIES.

-- TOUCH TO BLACK –-

NARRATION (VO):
TODAY, THE USE OF NANOTECHNOLOGY HAS BEEN PUT TO PRACTICAL USE FOR A WIDE RANGE OF APPLICATIONS, INCLUDING STAIN RESISTANT CLOTHES, LIGHTER AND STRONGER AUTOMOBILE BUMPERS, NON-CORROSIVE CATALYTIC CONVERTERS, ENHANCED COMPUTER SCREENS, HIGHER-STRENGTH METAL-CUTTING TOOLS, SCRATCH-RESISTANT COATINGS AND CLEAR SUNSCREENS. THOUGH THESE ADVANCES HAVE IMPACTED OUR DAILY LIVES, MANY LEADING RESEARCHERS AND DEVELOPERS WORLDWIDE AGREE THAT IS THE WIDE REACHING EFFECTS OF NANOMANUFACTURING THAT WILL USHER IN THE NEXT INDUSTRIAL REVOLUTION AND REPLACE OUR ENTIRE MANUFACTURING BASE WITH A NEW, PRECISE, LESS EXPENSIVE, AND MORE FLEXIBLE WAY OF MAKING PRODUCTS. YET THE FUTURE OF NANOMANUFACTURING DEPENDS---FIRST AND FOREMOST--- ON CREATING THE TOOLS, INSTRUMENTS, METROLOGICAL DEVICES AND MODELING APPLICATIONS THAT CAN EFFECTIVELY BUILD COMPLEX STRUCTURES WITH ATOMICALLY PRECISE CONTROL.

NANOMANUFACTURING, ALSO KNOW AS MOLECULAR NANOTECHNOLOGY, IS THE PROCESS OF ASSEMBLING COMPLEX STRUCTURES AND PRODUCTS WITH ATOMIC PRECISION. THE IDEA IS TO PRECISELY PLACE EVERY ATOM WITHIN A PRODUCT SO THAT COMPONENTS ARE EXACTLY THE SAME SIZE, TYPE, AND NUMBER OF ATOMS.

NANOMANUFACTURING CAN BE DIVIDED INTO TWO APPROACHES: TOP-DOWN FABRICATION, AND BOTTOM-UP ASSEMBLY.

Mark Sims:
The idea behind top-down fabrication is you start with a machine that makes a smaller machine that makes a smaller machine, and you keep going through that process until you get to the nanoscale. The state of the art in top-down manufacturing in a traditional sense is in the micron range. There is still quite a gap between microscale technology and nanoscale technology. Where the real innovation and excitement is from a Nanomanufacturing perspective is in the bottom up category.

Here we're dealing with synthesizing molecules or components which are made out of atoms, in a variety of techniques—traditional chemical synthesis, more advanced new methods of creating molecules like carbon nanotubes, dendrites, and other structures that have thousands or millions of atoms in them, into these atomically precise products.

NARRATION (VO):
THE HISTORY OF NANOSCALE INSTRUMENTATION AND SCANNING PROBE MICROSCOPY IS RELATIVELY NEW. IN 1981, SCIENTISTS AT IBM RESEARCH IN ZURICH, INVENTED THE SCANNING TUNNELING MICROSCOPE. IN THE FOLLOWING DECADES, A WIDE RANGE OF OTHER MACHINES AND TOOLS HAVE EMERGED, MOST NOTABLY THE ATOMIC FORCE MICROSCOPE OR 'AFM'.

Mark Sims:
I think atomic force microscopes are an example of a technology that's come a long way in a short time. It's an instrument that's able to image a nanoscale surface. An atomic force microscope has a little probe that's a perfect point, it's a crystal. It's used like a person reading Braille. It feels its way back and forth across the surface and creates a three-dimensional image of that surface, so we can actually see what's happening on that surface, what atoms are involved and the configuration of that surface.

NARRATION (VO):
TODAY, COMPANIES AND RESEARCH ORGANIZATIONS ARE USING SOPHISTICATED DESIGN AND ENGINEERING SOFTWARE, DIP-PEN LITHOGRAPHY, NANOMANIPULATORS, ATOMIC FORCE MICROSCOPES, AND OTHER "PICK-AND-SHOVEL" TOOLS TO HELP THEM CONTROL THE PLACEMENT OF CARBON NANOTUBES TO FORM BUILDING BLOCKS FOR LARGER SYSTEMS. THE CHALLENGE IS BUILDING COMPLEX STRUCTURES ATOM-BY-ATOM USING METHODS THAT ARE COST-EFFECTIVE, HIGHLY REPEATABLE, AND REPLICABLE.

-- TOUCH TO BLACK --

NARRATION (VO):
THE USE OF 'CAD' OR COMPUTER AIDED DESIGN SOFTWARE IS AN IMPORTANT STEP IN THE DEVELOPMENTAL PATH OF NANO-MANUFACTURING. NANO-ENGINEER-1, AN OPEN SOURCE PROJECT DEVELOPED BY NANOREX OF BLOOMFIELD HILLS, MICHIGAN, IS ONE OF THE FIRST CAD-BASED MODELING PROGRAMS DEVELOPED EXCLUSIVELY FOR THE DESIGN AND ANALYSIS OF PRODUCTIVE NANOSYSTEMS USED IN NANOMANUFACTURING.

Mark Sims:

Traditional CAD systems that we use today to design cars or airplanes, doesn’t understand, or isn’t capable of designing components and assemblies in atomic detail. They use surfaces to represent continuous materials. At the nanoscale we’re talking about using molecules and individual atoms in certain connectivity arrangements to get a structure that we want into our design. So what we’re doing at Nanorex is developing a molecular engineering package. It’s a computer aided design program that allows you to do molecular modeling, but it includes some of those traditional capabilities and features that you find in any three-dimensional CAD program, like Solid Works or Pro Engineer.

So what we’re trying to do is give engineers a tool that they can design these nanomachines, they can simulate them, and validate the designs ultimately. Even though we may not be able to build them yet, we can at least study them on the computer. We know how to model them, we understand how matter behaves at the nanoscale, and we can simulate all that and tell an engineer is this thing going to work, is it chemically stable, are the components going to work in the way the engineer intended.

NARRATION (VO):
USING AN ANIMATION DEVELOPED BY PIONEER NANOTECHNOLOGIST ERIC DREXLER AND ANIMATOR JOHN BURCH, MARK SIMS EXPLAINS SOME OF THE KEY FEATURES REQUIRED IN THE QUEST TO DESIGN PRODUCTIVE NANOSYSTEMS.

Mark Sims:
What you’re seeing is a beginning to end process, starting with molecules as the starting material. You’re going through the stages of the manufacturing process of how we take those molecules and go step by step to build them up into building blocks, into larger building blocks, and ultimately into full scale products that are atomically precise. One of the earliest manufacturing steps is a process called atomic deposition. What’s happening in that stage is we have these little molecular mills that are grabbing the feed stock molecule, which is an acetylene molecule. It has four atoms, two carbons and two hydrogens. It grabs that atom, it removes the hydrogen atoms, leaving the carbon atoms, and it adds those to a chunk of diamond, a little tiny bit of diamond that is the smallest building block that’s built up layer by layer, two atoms at a time, until it gets to a size where it then can be taken to the next stage of assembly, where they are added together to make a larger building block. Through this process, called convergent assembly, we get to larger and larger products, and eventually you get to your laptop computer made through this multi-stage process of convergent assembly.

A nanofactory is a productive nanosystem of a type; it’s a very large scale nanosystem that can build general purpose products. You could have specialized nanofactories that only, for instance, are capable of building laptop computers. But you might have another nanofactory that’s more general purpose. You could program it to build anything from a wineglass to a screwdriver. It just depends what program you feed it.

NARRATION (VO):
EXPERIENCED MANUFACTURING PROFESSIONALS WILL NOT BE SURPRISED AT THE TYPES OF TOOLS BEING USED IN NANOFACTORIES.

Mark Sims:
Many of the things you're going to see in a nanofactory are going to be the same things you see in a traditional factory, only on a smaller scale. Things like conveyor belts, things like transport mechanisms that carry a component from one place to another. Assembly machines, little robots that are able to join two pieces that plug together. Things like this are going to be things you'll find. There are other things that are a little bit different. As part of molecular manufacturing in the future you're going to have a process called mechanosynthesis, where you're actually directing chemical reactions using mechanical forces, where you're taking a molecule and you're stripping off atoms from it, and then getting it oriented in just the right way to another component, then causing a chemical reaction or a bond to form between those two pieces in just the right way so you end up with the product as you intended. So some of that is different, because you don't have chemical reactions going on in a factory. In a nanofactory you will.

For designing nanomachines you really need a system that combines features from both of these types of programs into a single program. The problem with traditional programs is they don't understand what atoms and molecules are, they only know surfaces and three-dimensional solid geometry, those are the perimeters you work with. With nanosystems we need to design the machines so we know where very atom ends up in that design, in every component. With Nano Engineer 1 you can rapidly design a structure with thousands of atoms in it, that would normally take you hours and hours with a traditional chemistry program. You can do it in literally seconds with our program.

NARRATION (VO):
THERE ARE NUMEROUS BARRIERS TO NANOMANUFACTURING AND OUR ABILITY TO COMMERCIALLY BUILD COMPLEX STRUCTURES ATOM BY ATOM.

Mark Sims
One of the issues is that it's very difficult to do design and simulation of nanomachines. Only now do we have the tools that even allow us to study these kinds of systems and contemplate what the possibilities are. We also have the issue of actually building them. Synthesizing all the components that make up a nanomachine is a big significant challenge. I think there are some breakthroughs that will happen in our lifetime.

-- TOUCH TO BLACK –-

NARRATION (VO):
NANOINK IS A CHICAGO, ILLINOIS-BASED COMPANY COMMERCIALIZING THE DIP PEN NANOLITHOGRAPHY OR DPN METHOD OF NANOMANUFACTURING. THE DPN PROCESS IS USED TO BUILD NANOMETER SCALE STRUCTURES AND PATTERNS BY LITERALLY DRAWING MATERIALS DIRECTLY ONTO A SURFACE. DPN USERS CAN BUILD AT RESOLUTIONS RANGING FROM MANY MICROMETERS DOWN TO 15 NANOMETERS. THIS COMBINATION OF ULTRAHIGH RESOLUTION AND MATERIAL FLEXIBILITY MAKES FOR NUMEROUS COMMERCIAL APPLICATIONS.

Mike Nelson:
Dip pen is a very versatile technology. Probably one of its greatest strengths is the ability to work with a wide variety of materials and substrates. The fact that it can operate at ambient temperature and that

tools and environments for dip pen nanolithography are relatively low cost. This gives it significant advantages as a tool for Nanomanufacturing.

NARRATOR:
DPN IS A TECHNOLOGY THAT CAN BE USED TO FABRICATE STRUCTURES USING SEVERAL DIFFERENT METHODS.

Mike Nelson:
In its most straightforward implementation, DPN can directly write materials using different molecular inks that directly transfer from a tip to a substrate. In another instance, those inks could be resists, so the dip pen could be used in a way similar to photolithography to pattern a resist on a substrate, and then to etch three-dimensional structures. Probably one of the most interesting and powerful ways that you can use dip pen nanolithography is to use it as a templating tool, to put down a substance that can act as a pattern for directed self assembly. This is the approach that's used to fabricate structures in a controllable manner with nanotubes, nanoparticles, and other even biomolecules to produce nanoscale structures.

NARRATOR:
THE INITIAL DIP PEN NANOLITHOGRAPHY EXPERIMENTS WERE ALL CONDUCTED ON COMMERCIALLY AVAILABLE ATOMIC FORCE MICROSCOPE PLATFORMS.

Mike Nelson:
Today simple DPN experiments can still be conducted on a regular bench top AFM system. However, the N-scripter is a dedicated, optimized tool for dip pen nanolithography. It starts with an environmental chamber that provides controlled environment temperature and humidity in which DPN experiments can be conducted. The second thing we did is produce optimized software. The N-scripter is not only a reading tool, a metrology tool, like a conventional AFM, it is also a writing tool, a fabrication tool. So we have added software that allows us to design patterns and then to build patterns reproducibly. To do this we need calibration, we need alignment capabilities. All this is provided via software. The final and probably most important aspect of the N-scripter is the wide range of pen and ink delivery systems that are available with the product. We have moved from single pen systems to linear arrays to parallel arrays of pens with over 55,000 individual cantilevers. This has increased the scale and the magnitude of the types of experiments we can do.

NARRATOR:
NANOINK IS EXPLORING A NUMBER OF NEAR-TERM APPLICATIONS FOR COMMERCIAL DIP PEN NANOLITHOGRAPHY.

Mike Nelson:
Probably our most compelling near term business opportunity relates to our nano encryption technology. NanoInk is helping the pharmaceutical industry prevent counterfeiting and diversion of drugs by fabricating nanoscale structures on individual doses of pharmaceutical products. This technology is now being developed with two of the largest pharmaceutical companies in the world. In addition to nano encryption we are also exploring additive repair for photo masks and thin film transistors on LCD panels.

NARRATOR:
ONE OF THE MOST COMPELLING ATTRIBUTES OF DIP PEN NANOLITHOGRAPHY IS ITS MATERIAL FLEXIBILITY.

Mike Nelson:
Dip pen can be used to pattern, at the nanoscale, a wide variety of biomolecules, including viruses, oligonucleotides, and antibodies. We have recently completed a Phase I effort developing biochips with order of magnitude greater sensitivity than any other published work to detect DNA.

-- TOUCH TO BLACK --

NARRATION (VO):
ZYVEX OF RICHARDSON, TEXAS IS THE FIRST NANOMANUFACTURING COMPANY USING MOLECULAR NANOTECHNOLOGY TO DEVELOP ADAPTABLE, AFFORDABLE, MOLECULARLY PRECISE MANUFACTURING.

James R. Von Ehr II:
The interesting thing about it, the way we understand molecular nanotechnology, is that the factory itself is made with the same technology as the products. That's an important point. If you look at a semiconductor wafer fab, the cost of the manufacturing facility keeps going up exponentially as the cost of the transistor goes down exponentially. The problem is that making better integrated circuits doesn't help make a better factory to make them. But with molecular nanotechnology, since the factory is made out of atoms in precise arrangements, and the factory makes products with atoms in precise arrangements, it can make the next generation factory. That means the factory gets cheaper as we get better at manufacturing. That puts on a double declining learning curve of pricing.

NARRATION (VO):
ZYVEX UNDERSTANDS THAT THERE ARE MANY HURDLES TO DEVELOPING NANOMANUFACTURING PROCESSES.

James R. Von Ehr II:
The first thing we have to do is make some better tools. The tools out there today allow us to reach into the nano world and manipulate atoms and molecules, but they're not really very good, and they are very expensive. So what we started to do is build better tools and more precise tools that let us do this manufacturing better. That's the top down approach, building something macroscopic, something that's big enough to see and hold and work in a machine shop, and make that tool help us to manipulate in the nano world.

NARRATION (VO):
NANOMANIPULATORS ARE FLEXIBLE, COST-EFFECTIVE, MODULAR R&D TOOLS THAT ALLOW SCIENTISTS TO MANIPULATE NANO-SIZE STRUCTURES UNDER A MICROSCOPE.

James R. Von Ehr II:
Now we look at the other half of things, which is the bottom up approach. That is, doing atomic manipulation with larger and larger and more precise assemblies, getting the yields up, understanding from an engineering standpoint how to do atomic precision manufacturing. That is not quite as far along. It's harder to do that because the tools really aren't still quite there. The products we have identified for that, the early products,

do have a high value, and we're actually now putting together a program for doing atomically precise manufacturing that integrates those two, the top down and bottom up. But the top down is an important way to get there.

NARRATOR:
NANO-MANIPULATORS ALLOW FOR INTERCHANGEABILITY OF STRUCTURE CARRIERS. COMBINED WITH INTERCHANGEABLE TOOLS, THEY PROVIDE A WIDE RANGE OF EXPERIMENTAL OPTIONS WITH MESO, MICRO, NANO AND MOLECULAR BASED STRUCTURES.

James R. Von Ehr II:
Our approach to nanotechnology is really not just about making small stuff. A lot of people think that nanotechnology is anything below 100 nanometers in size. To me, that's just making bulk materials, and people have been doing that a long time. The key differentiator at Zyvex is the precision and the hierarchical scale. We want to make atomically precise materials at the very smallest scale, the nanoscale, put those together into larger subassemblies, and build up to the microscale, then put those together in larger assemblies in what we're calling the meso or the millimeter scale, and build larger and larger assemblies, but have atomic precision all the way down to the atoms, and all the way up to large things, things potentially as large as a car or even a house someday. We probably won't design that with atomic precision, but the parts that go in it will be manufactured in high volume and then put together in assemblies.

NARRATION (VO):
USING NANOTECHNOLOGY, ZYVEX HAS ALREADY IMPROVED THE PERFORMANCE CHARACTERISTICS OF MANY PRODUCTS THAT WE USE TODAY.

James R. Von Ehr II:
In our material space, our first really important customer was Easton Sports. They came to us when they saw some of our performance data of the nanotube material, and asked us to help them improve their sporting goods. They always want to be on the leading edge technologically. So we worked with them to put the nanotube material into their bicycle parts to start with. We got a noticeable performance increase by just a very small fraction of nanotubes. They then moved that to their hockey sticks and then to baseball bats.

James R. Von Ehr II:
Since then Aldilla has come up with golf club shafts that use our nanotube material, and they are buying a lot of nanotubes from us to put into the golf club shafts.

NARRATOR:
EARLY ON ZYVEX HAD MANY SKEPTICS ON THEIR NANOMANUFACTURING APPROACH.

James R. Von Ehr II:
The skeptics said if you have one atom at a time in your manufacturing, that's impractical, you can't manufacture large quantities of stuff one atom at a time. Of course that's true. We never had the intention of doing just one at a time, that's why we need the top down. But the top down system is a way of building the system around this chemical reaction, so we actually have a lot of little fingers manipulating molecules in parallel. That will allow us to manufacture commercially viable quantities of products.

-- TOUCH TO BLACK --

NARRATION (VO):
NASA´S JOHNSON SPACE CENTER IN HOUSTON, TEXAS STANDS AT THE FOREFRONT OF NANO-ENABLED SPACE EXPLORATION. USING NANOTECHNOLOGY, NASA IS CREATING BREAKTHROUGHS THAT WILL ULTIMATELY LEAD TO THE DEVELOPMENT OF SPACECRAFT FOR INTERPLANETARY DISCOVERY.

Dr. Arepalli:
NASA is not waiting for nanotechnology to mature. So we are trying to infuse nanotechnology in different areas. That means whether it is power and energy, whether it is communications, we are trying to go with the systems we have, and use nanotechnology to improve their efficiencies, to increase what I call the value for all these systems.

NARRATOR:
CURRENTLY NASA'S JOHNSON SPACE CENTER IS FOCUSING ON THE DEVELOPMENT OF NANO-TECHNOLOGY BASED ON SINGLE-WALL CARBON NANO-TUBES. ADDITIONALLY, THEY ARE FOSTERING WIDESPREAD STUDIES ON NANO-TUBE APPLICATIONS.

Padraig Moloney:
We do grow nanotubes, carbon nanotubes. We're also involved in the growth and production of fullerenes and other types of nanotubes. So we're involved in that sort of fundamental area of production of nanomaterials. Then we also help and encourage industry to standardize, so we always have a reliable supply of materials.

The second tier that we're involved in is actually making nanotechnology useful. This is raw HIPCO, which is high-pressure carbon monoxide produced carbon nanotubes. It's fluffy soot basically. In its raw form it's not very useful, so we have to do a lot of work to take the nanotubes and purify them, and then to also characterize them to understand what we have. Then we have to do things like manipulate them and functionalize nanomaterials, so they can get along with materials that currently exist such as polymers and metals. Raw nanomaterials rarely, as produced, work that well in our current materials, so we have to do a lot of work to manipulate them. Then when you finally take all those qualities together, we can actually start applying them and bringing them together. Like for a fuel cell membrane that I have here. This is a common technology now. It's still not perfected, but basically proton exchange membrane fuel cells are a fairly old technology. What we're trying to do now is apply it now for space use.

NARRATION (VO):
HOWEVER, BECAUSE OF THE PROHIBITIVE COSTS ASSOCIATED WITH PRODUCING LARGE BATCHES OF CARBON NANOTUBES TODAY, WIDE-SCALE COMMERCIALIZATION OF NASA'S RESEARCH CURRENTLY IS RESTRICTED TO SPECIALTY APPLICATIONS.

Dr. Nikolaev:
We are facing here the problem of the chicken and the egg. Nanomaterials so far are very expensive. There are several companies around the world, some

in the United States, Japan and the UK, that work on the manufacture of them on a larger scale, which is supposed to make them less expensive, but so far they are expensive.

NARRATOR:
ORIGINALLY DEVELOPED AT RICE UNIVERSITY, NASA'S LASER LAB IS UTILIZED FOR THE CREATION OF SINGLE-WALL CARBON NANOTUBES.

Dr. Sosa:
Basically as we're doing it we have some spectroscopy and other items to not only make it but try to understand it. So within nine years we further understand how these nanotubes are grown, and from that we can improve upon the process and make other processes.

NARRATION (VO):

OVER THE COURSE OF THE NEXT 25 YEARS, NASA BELIEVES THE GREATEST APPLICATION FOR NANOTECHNOLOGY WILL BE IN AIDING THEIR MISSION TO MARS.

Dr. Arepalli:
If we really have to go there for several months, we need to make sure our systems work very efficiently. Without nanotechnology we'll end up carrying lots of materials with us, it will be very cost prohibitive. Nanotechnology is the only solution for us to go onto the Mars mission.

NARRATION (VO):
NANOTECHNOLOGY CAN ENHANCE SPECIFIC CRITICAL AREAS OF THE MARS MISSION SUCH AS CARBON DIOXIDE AIR SCRUBBERS.

Dr. Arepalli:
Right now the technology uses lithium hydroxide canisters, and they are not reusable. So you have to carry a lot of weight if you are going on a 3-month or 6-month mission. So what we are trying to work on is a recyclable CO2 absorbing medium. It will absorb CO2 and then we will be able to get it out and use it again and again and again. This will only be possible with nanotechnology.

NARRATION (VO):
THE TWO MAJOR HURDLES THAT STAND IN NASA'S WAY OF REACHING MARS ARE ENERGY AND MASS. ON BOTH COUNTS NANOTECHNOLOGY OFFERS POTENTIAL SOLUTIONS.

Padraig Moloney:
Nano is part of the toolbox we're going to use to maybe increase functionality of composites for instance, or reduce weight on battery systems or increase power density on super capacitors or fuel cells. We're applying that nanotechnology across the board, from structures, Power-energy systems, and advance life support. That would be things like CO2 scrubbers or water purification systems. Nano is finding its way in all of our space exploration needs.

NARRATOR (VO):
THOUGH INTERPLANETARY EXPLORATION IS THEIR LONG RANGE GOAL, NASA IS ALSO LOOKING TO NANOTECHNOLOGY TO SOLVE SOME OF THEIR CURRENT SPACE MISSION CHALLENGES.

Dr. Arepalli:
One problem which we had for the last few missions is damage to the tile materials. So we have the means of putting nanomaterials in place which can help cure the materials in space much faster.

NARRATION (VO):
NASA HAS A HISTORY OF IMPLEMENTING PROCESSES THAT ARE AT THE CUTTING EDGE, AND THEN MAKING THEM USEFUL.

Dr. Arepalli:
The way NASA works is to take one of these technologies and push it to the limits. That means we deal with it on a small scale, we deal with only a small number of items that we really need, but they have to be very efficient and work in a very harsh environment. While trying to do that, the technology will come out, the tech transfer for example, to enable us to take this to the market.

NARRATION (VO):
THE SAME NANOTECHNOLOGY BASED INNOVATIONS THAT WILL ENABLE SPACE EXPLORATION HAVE WIDE SCALE COMMERCIAL APPLICATIONS AS WELL.

Padraig Moloney:
One of them is a water filtration system using C60 molecules, or fullarines. That has great commercialization prospects for the hiking and water treatment industries. Also, our CO_2 scrubbers that we're developing will have commercialization possibilities for what they call smokestack applications. With all the emphasis now on energy, an getting energy from coal, industry needs a better way to filter CO_2 out of their emission.

NARRATION (VO):
HOWEVER, SEVERAL PREREQUISITES NEED TO BE ADDRESSED BEFORE INTRODUCING NANO-ENHANCED PRODUCTS TO THE MARKET.

Padraig Moloney:
Just about every nanotechnologist and scientist in the field is thinking about and devoting some of his or her time to make sure the technologies we're developing will be safe and have a consistent effect on the environment around it in the future.

Often the materials you find that have the best possibilities and capabilities are the most expensive to make and the most difficult to manipulate. So there is a lot of fundamental science that still has to take place before you'll see space elevators or cars at a high degree of carbon nanotechnology or other nanotechnology in it.

NARRATION (VO):
A CONCEPT THAT IS MOVING CLOSER TO REALITY, THANKS TO RESEARCH BEING DONE TODAY AT NASA, ARE SPACE ELEVATORS. THESE ELEVATORS ARE DESIGNED TO TRANSPORT MATERIALS FROM A PLANET'S SURFACE INTO SPACE.

DR. SOSA:
If you look at graphite, diamond, they're both carbon, they're just arranged in a different way. Nanotube is arranged in another way. It's actually arranged into a cylindrical fibrous material. This is just plain carbon. But if you take this nanotube and you were to pull it like a rope, like a tug of war, that strength will be 50 times stronger than steel. This blows away anything strength wise, period.

It's the strongest material there is. So if you took this material… You connect to the ground, you get a wire, it goes all the way up to a tether, and you can just orbit. Up until now, people thought it was ludicrous, because it just was not possible. If you use steel, the diameter of that steel cable would be about two miles, huge, you can't do it. But nanotubes have made it to where you can make this cable only a few meters thick. So it's feasible. So people who saw this material said hey, let's look at this further. So now they are actually researching how to do this.

-- TOUCH TO BLACK --

NARRATION (VO):
GENERAL DYNAMICS ADVANCED INFORMATION SYSTEMS LOCATED IN YPSILANTI, MICHIGAN IS ALSO LOOKING AT THE ROLE NANOTECHNOLOGY AND NANOMANUFACTURING WILL PLAY IN THE AEROSPACE AND DEFENSE INDUSTRIES.

Tihamer T. Toth-Fejel:
Like all of us, General Dynamics is interested in the near term material science that's coming out of the NNI programs. We have lots of products, we build aircraft, Gulf Stream commercial aircraft. We would like to make them lighter, get better fuel mileage, safer… same with everything we build. One of the things we're looking at, and the NASA Institute for Advanced Concepts funded us to work on how we can build self-replicating machines at a nanolevel.

NARRATION (VO):
FOR YEARS RESEARCHERS HAVE POINTED TO SELF REPLICATION AS THE KEY TO UNLOCKING NANOTECHNOLOGY'S FULL POTENTIAL.

Tihamer T. Toth-Fejel:
One way to think about it is, let's say you have one relatively simple nanomachine that can make a less complicated version of itself. It's not

quite self replication, but basically it takes an input stream… it's like a machine shop. Using a machine shop you can make an assembly line, so you make an assembly line. What kind of machines do you have there? You have an assembly line of primitive, single use machines that all they can do is make one other different kind of machine shop, like a lathe, a drill and a saw, for example. So you have an entire line of them. Then you take this line, and normally when we think of an assembly line we think of putting pieces on the front end and it gets assembled down the line. What we want is an assembly line that builds things in two dimensions, that builds a plane of devices. That's how we get to a billion devices. You start with one nanomachine; call it a master maker that builds a nanoline. The nanoline builds a membrane. What the membrane does is, it accepts molecular parts that are made using synthetic chemistry, which we can do today, and assembles them into whatever product you want.

Self replication is not the right paradigm. The right paradigm is something like a 3D rapid prototyping printer, where you actually have fairly complex molecular synthetic chemical engineering made parts, kind of like an inkjet printer but more precise from a molecular standpoint. Then it assembles them into whatever you want, just like a 3D printer.

NARRATION (VO):
NANOROBOTICS IS THE TECHNOLOGY OF CREATING ROBOTIC MACHINES AT OR CLOSE TO THE SCALE OF A NANOMETER. NANOROBOTS HAVE POTENTIAL APPLICATIONS IN THE ASSEMBLY AND MAINTENANCE OF SOPHISTICATED SYSTEMS. THEY FUNCTION AT THE ATOMIC OR MOLECULAR LEVEL TO MANUFACTURE DEVICES, MACHINES, OR CIRCUITS THAT CAN ASSEMBLE COPIES OF THEMSELVES.

Tihamer T. Toth-Fejel:
Nanoscale systems can also operate much faster than their larger counterparts because displacements are smaller; this allows mechanical and electrical events to occur in less time at a given speed. A nanorobot, since we haven't built any yet, is a difficult concept. But actually we do have billions of them and trillions of them in existence. Think of a ribosome. It takes data in and it takes parts in, and it outputs something. In the case of a ribosome, it connects amino acids into a polypeptide. The polypeptide then has these weak molecular forces that act on it to make it fold up to become a part, which then is used in other machines or another ribosome. So if you take a ribosome and you feed it the right directions, it will create another ribosome. In simple terms, a nanorobot is something that is made out of atoms, estimates right now are that it would take about a billion atoms, and they're already preassembled into molecules. It would take a string of instructions and manipulate other molecules with it.

What you can do with that depends on what kind of instructions you can give it, what the output envelope of this machine is, it's a productive nanosystem. In a sense it's similar to a computer in the physical world. A computer, as long as you give it the correct data and the correct instructions, it can perform any algorithm. Same with a robot. And we have lots of experience with industrial robots. Well you're going to use the same techniques, only using machines that are much smaller. The big difference is, when you start building machines, there's going to be problems with tolerances, which as an engineer, manufacturing engineers deal with this all the time. You have tolerances and you work within them to build the product you want. With a nanorobot you have the same basic scheme. You have some tolerances, but the interesting thing is the tolerances are no smaller than an atom. The atom will vibrate, but you know how much it's going to vibrate due to thermal noise, and you work within those limits. Ribosomes have been doing that for billions of years, so it's not outside the realm of possibility.

NARRATION (VO):
NANOMANUFACTURING HAS PROFOUND ETHICAL, ENVIRONMENTAL, AND HEALTH IMPLICATIONS.

Tihamer T. Toth-Fejel:
In the far term with nanotechnology, and we're talking here Nanomanufacturing, all of a sudden you have the capability to control things at a molecular level. We will be able to clean up every toxic waste site very inexpensively. We'll be able to clean up pollutants before they ever enter the streams. We'll be able to clean up this planet and make it a garden like it hasn't been for 1000 years.

I'm not too worried about an accidental problem with nanotechnology, or even with molecular manufacturing, despite the fact it's more powerful. One of the things I worry about is a backlash. With nanotechnology, for example, the National Cancer Institute predicts, I think fairly confidently and fairly realistically, that with molecular nanotechnology, in other words the nanoparticles, the functionalized nanoshells, things like that, we'll be able to cure cancer within 15 years. Every year that gets delayed, half a million people die. So there are ethical implications with delaying molecular manufacturing, just as there are ethical implications for jumping ahead too quickly. You're balancing half a million lives, just from cancer, every year that you delay Nanomanufacturing.

-- TOUCH TO BLACK --

NARRATION (VO):
FOR CENTURIES MANUFACTURING METHODS HAVE BECOME LESS EXPENSIVE, INCREASINGLY FLEXIBLE AND MORE PRECISE; HOWEVER, WE WILL SOON APPROACH THE LIMITS OF THESE PROCESSES. BUT NANOMANUFACTURING WILL ENABLE US TO CONTINUE THESE HISTORICAL TRENDS UP TO THE BOUNDARIES IMPOSED BY THE LAWS OF PHYSICS. BY CHANGING THE BASIC BUILDING BLOCKS OF MATERIALS, NANOTECHNOLOGY WILL RADICALLY ALTER THE ESSENCE OF MANUFACTURING FROM A PROCESS OF TRANSFORMATION AND ASSEMBLY TO ONE OF SYNTHESIS OF ADVANCED MATERIALS INTO A FINAL PRODUCT. NANOMANUFACTURING IS POISED TO USHER IN A NEW ERA OF MACHINE SHOP TECHNOLOGIES THAT WILL REVOLUTIONIZE HOW WE CURRENTLY VIEW TOP-DOWN FABRICATION, BOTTOM-UP ASSEMBLY, AND HYBRID MANUFACTURING METHODS. NANOTECHNOLOGY IS UNIQUE BECAUSE IT CAN BE IMPLEMENTED ACROSS AN ENTERPRISE'S VALUE CHAIN, FROM BASIC MATERIALS TO INTERMEDIATE PRODUCTS TO FINAL GOODS. LEADING RESEARCHERS POINT TO SELF REPLICATION AS THE KEY TO UNLOCKING NANOTECHNOLOGY'S FULL POTENTIAL, MOVING IT FROM LABORATORY CURIOSITY TO A ROBUST MANUFACTURING TECHNOLOGY. AS WE HAVE SEEN, NANOMANUFACTURING ON A WIDE SCALE NECESSITATES THE INVENTION OF INNOVATIVE INSTRUMENTS, MEASUREMENT TOOLS, COMPUTATIONAL MODELS, AND STANDARDS TO CHARACTERIZE NANOSCALE MATERIALS AND PROCESSES. ONLY THROUGH SUCH DEVELOPMENTS WILL THE MANUFACTURE OF COMMERCIAL VOLUME PRODUCTS WITH A HIGH

DEGREE OF REPEATABILITY BECOME ECONOMICALLY VIABLE. THE TOOLS OF NANOMANUFACTURING ARE THE GATEWAY TOWARDS REALIZING NANOTECHNOLOGY'S FUTURE.

-- FADE TO BLACK --

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