

Potential Impacts of Nanotechnology on Energy Transmission Applications and Needs

Environmental Science Division

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NOTATION

The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) used in this document. Acronyms and abbreviations used only in tables and figures are defined in the respective tables and figures.

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

1G	first generation
2G	second generation
ACCR	aluminum conductor composite reinforced
ACSR	aluminum conductor steel reinforced
CNT	carbon nanotube
CUI	corrosion under insulation
DOE	U.S. Department of Energy
EBP	emergency backup power
EPRI	Electric Power Research Institute, Inc.
ES&H	environmental, safety, and health
HTS	high-temperature superconducting
LED	light-emitting diode
NNI	National Nanotechnology Initiative
QW(s)	quantum wire(s)
ROW(s)	right(s)-of-way
SAM	self-assembled monolayer
SMSs	smart materials and structures
UPI	United Press International
UPS	uninterruptible power supply

UNITS OF MEASURE

°F	degree(s) Fahrenheit
K	Kelvin
kV	kilovolt(s)
kWh	kilowatt-hour(s)
lb	pound(s)
m	meter(s)
nm	nanometer(s)

1 INTRODUCTION

The application of nanotechnologies to energy transmission has the potential to significantly impact both the deployed transmission technologies and the need for additional development. This could be a factor in assessing environmental impacts of right-of-way (ROW) development and use. For example, some nanotechnology applications may produce materials (e.g., cables) that are much stronger per unit volume than existing materials, enabling reduced footprints for construction and maintenance of electricity transmission lines. Other applications, such as more efficient lighting, lighter-weight materials for vehicle construction, and smaller batteries having greater storage capacities may reduce the need for long-distance transport of energy, and possibly reduce the need for extensive future ROW development and many attendant environmental impacts.

This report introduces the field of nanotechnology, describes some of the ways in which processes and products developed with or incorporating nanomaterials differ from traditional processes and products, and identifies some examples of how nanotechnology may be used to reduce potential ROW impacts. Potential environmental, safety, and health impacts are also discussed.

2 WHAT NANOTECHNOLOGY IS

While there are no universally accepted definitions, nanotechnology is generally understood to involve the manipulation of matter on a near-atomic scale to produce new structures, materials, systems, catalysts, and devices that exhibit novel phenomena and properties. Some materials exhibit unique physical, chemical, and biological properties at the nanoscale level (e.g. 1–100 nm; a nanometer [nm] is one billionth of a meter, or the length of 10 atoms). Potential benefits result from miniaturization (e.g., sensors) and from the unique properties of the materials (e.g., high strength). Nanotechnology offers the possibility of introducing technologies that are more efficient and environmentally sound than those used today.

Economists predict a \$1 trillion global market for nanoproducts over the next 10 to 15 years. Products using nanotechnology that are commercially available today include industrial measurement and sensing devices, therapeutic systems, and consumer goods such as wrinkle-free clothing. Research is under way on applications in the fields of energy, agriculture, transportation, medicine, computing, electronics, and manufacturing, among others. Breakthroughs in nanotechnology development could enable fabrication of materials at the molecular scale, giving rise to self-repairing structures, new types of computers, and truly intelligent systems. Before these applications become reality, however, basic research is needed in nanoparticle measurement, behavior, characterization, properties, production techniques, and environmental risks.

2.1 NANOSCALE MATERIALS

Nanoscale materials (or nanomaterials) contain nanoparticles or are developed using nanotechnology. Nanoparticles are commonly considered to be materials that have at least one dimension that is less than 100 nm. Nanoparticles can be distinguished according to their origin. They can occur naturally (e.g., from volcanic eruptions); they can be produced incidentally during other processes (e.g., from fuel combustion); and they can be manufactured intentionally.

Manufactured nanomaterials can be classified according to their method of production. Some are produced “from the top down,” as when a bulk material (e.g., gold, silicate) is reduced to a mass of nanoscale particles. Because of their very small size, these nanoscale metals, metal oxides, powders, and dusts have physical, chemical, magnetic, electrical, mechanical, and other properties that differ from those of the bulk materials from which they are derived. They are found today in sunscreen products (titanium dioxide nanoparticles), solar cells (aluminum oxide nanoparticles), and several other applications in research and commerce.

The second type of manufactured nanoparticles are built “from the bottom up,” atom-by-atom or molecule-by-molecule. Engineered nanoparticles of this type are still relatively difficult and expensive to manufacture, but they have the potential to impact energy development and use, transportation, electronics, manufacturing, and other disciplines. Specific examples of

nanoparticles with the potential to impact energy transmission system development are highlighted in the next section.

2.2 NANOPARTICLES WITH THE POTENTIAL TO IMPACT ENERGY TRANSMISSION SYSTEM DEVELOPMENT

Examples of nanoparticles with the potential to impact energy transmission system development include the following:

- A carbon nanotube (CNT) is a type of fullerene (carbon-only) molecule that is formed when atoms of carbon link together into tubular shapes. CNTs are generally extremely light, strong, and resilient, and some CNTs can be many times more electrically conductive than steel or copper. CNTs are available for industrial applications in bulk quantities, but they currently can cost as much as \$200,000 per pound (Davis 2006).
- Carbon atoms may also link to form spherical nanostructures that can be coated or filled with atoms; these “buckyball” fullerenes are used in mechanical and semiconductor operations.
- Nanodots, or quantum dots, are nanoscale semiconductor crystals having electrical and optical properties that may make for more efficient lighting and solar collection.

A specific type of CNT, the “armchair” CNT, has the potential to greatly impact electrical conductivity and transmission. The armchair CNT is 30 to 100 times stronger than steel, conducts heat better than diamond, and conducts electricity better than any other molecule discovered to date. Some researchers liken CNTs to a new miracle polymer. Richard Smalley, the Nobel Prize winner who discovered fullerenes in 1985, described the potential of the armchair nanotube as follows:

Electrons move down this tube as a coherent quantum particle, much like a photon of light travels down a single-mode optic fiber. Individual armchair tubes can conduct as much as 20 microamps of current. This doesn’t sound like much until you realize that this little molecular wire is only 1 nanometer in diameter. A half-inch-thick cable made of these tubes aligned parallel to each other along the cable would have over 100 trillion conductors packed side-by-side like pipes in a hardware store. If each of these tubes carried only one microamp, only 2% of its capacity, the half-inch-thick cable would be carrying one hundred million amps of current. Fabricating such a cable — we call it the “armchair quantum wire” — is a prime objective of our work (Smalley 2003).

3 ENERGY APPLICATIONS OF NANOTECHNOLOGY

Nanoparticles and nanomanufacturing techniques may impact energy transmission system development and use for many years to come. For example, nanotechnologies may make more efficient use of transportation fuels, possibly slowing the increase in demand for long-distance shipment of liquid fuels. Construction materials made from nanoparticles may be stronger but occupy less volume than today's materials, which may reduce the footprints required for the construction and maintenance of pipelines and electricity transmission lines. Section 3.1 describes some ways in which nanotechnology may accelerate the development of cleaner, more efficient energy sources and uses, which, in turn, may reduce the demand for long-distance transmission of electricity, petroleum distillate fuel, and natural gas. Section 3.2 identifies some more direct applications of nanotechnology, which may improve the construction and operation of ROW infrastructure, thereby potentially reducing its environmental impact.

3.1 GENERAL ENERGY APPLICATIONS

Nanotechnology is being used or considered for use in many applications targeted to provide cleaner, more efficient energy supplies and uses. While many of these applications may not affect energy transmission directly, each has the potential to reduce the need for the electricity, petroleum distillate fuel, or natural gas that would otherwise be moved through energy transmission ROWs. More efficient energy generation and use (and the consequent reduced need to transmit energy over long distances) may decrease the amount of construction, maintenance, repair, and decommissioning activities along the ROWs that would otherwise be needed to meet increased energy demands. Energy-related technologies in which nanotechnology may play a role include:

- Lighting,
- Heating,
- Transportation,
- Renewable energy,
- Energy storage,
- Fuel cells,
- Hydrogen generation and storage, and
- Power Chips™.

Examples of how nanotechnology may be integrated into each of these technology areas are highlighted in the following sections.

3.1.1 Lighting

In the United States, roughly 20% of all electricity is consumed in providing incandescent and fluorescent lighting. Because of their compactness, durability, low heat generation, and electrical efficiency, light-emitting diodes (LEDs) now rival incandescent light sources in many

parts of the visible spectrum and are being used in displays, automobile lights, and traffic lights. Semiconductors used in the preparation of LEDs for lighting are increasingly being built at nanoscale dimensions, and projections indicate that nanotechnology-based lighting advances have the potential to reduce worldwide consumption of energy by more than 10% (NNI 2000). Nanocrystals, also known as quantum dots, are known primarily for their ability to produce distinct colors of light as the size of the individual crystals is varied. In 2005, researchers at Vanderbilt University coated an LED with a thin layer of quantum dots, thereby producing a hybrid LED that yielded warm, white light similar to that of an incandescent lamp. The discovery has implications for using nanotechnology to produce light for residential, commercial, and industrial applications without the heat that accounts for a large portion of the incandescent light bulb's poor energy efficiency (Salisbury 2005).

3.1.2 Heating

Nanotechnology may help accelerate the development of energy-efficient central heating. When added to water, CNTs disperse to form a nanofluid. Researchers have developed nanofluids whose rates of forced convective heat transfer are four times better than the norm by using CNTs. When added to a home's commercial water boiler, such nanofluids could make the central heating device 10% more efficient. The researchers say that the technology is 3 to 5 years away from commercial home use (Pollitt 2006).

3.1.3 Transportation

Nanotechnology may enable more efficient transportation via catalysts in fuels; lighter, stronger materials; and more efficient batteries.

Diesel fuel additives for more efficient combustion. The Envirox™ Fuel Borne Catalyst, developed by Oxonica, Ltd., is an example of a commercially proven product that improves diesel fuel combustion, reducing fuel consumption and harmful exhaust emissions. The additive uses nanoscale (10 nm across) particles of cerium oxide to catalyze the combustion reactions between diesel fuel and air. The small particle size creates a greater surface area for catalyzing the reactions, causes the particles to remain more evenly suspended in the fuel, and allows the additive to be used at concentrations as low as five parts per million, or one-tenth the concentration of previous additives (Fox 2006). Fuel economy benefits of up to 10% have been demonstrated in independently assessed field trials under commercial operating conditions. Additional pilot tests involving a range of vehicles and engines are underway (Oxonica 2006).

Stronger materials. More energy-efficient transportation resulting from the use of high-strength, low-weight materials developed with nanotechnology may reduce the need for transportation fuels that would be shipped via pipeline along a ROW. Nanoparticle-reinforced materials that are as strong as or stronger than today's materials but weigh less will help provide better fuel economy. By using high-strength nanomaterials, parts for automobiles and other modes of transportation could be more than 50% lighter than conventional alternatives. The reduction in weight could cut fuel requirements, thereby potentially reducing the demand for

petroleum fuel (and its attendant pipeline transportation in ROWs). Similarly, new materials developed through nanotechnology will permit the miniaturization of systems and equipment, which may further improve fuel economy.

Batteries and capacitors. More efficient batteries developed by using better electrolytes (composed of nanomaterials) may also reduce the need for transportation fuels. Nanotechnology is being used in lithium-ion and other batteries that are expected to increase the efficiencies of hybrid and electric vehicles. (Section 3.1.5 discusses the use of nanotechnology in batteries.) Nanoscale capacitors made from multiwalled CNTs dramatically boost the amount of surface area, and thus the electrical charge, that each metal electrode in the capacitor can possess. Smaller and more powerful capacitors may facilitate the development of microchips having greatly increased circuit density. Such nanoscale capacitors may also impact the development of compact and cost-effective supercapacitors, which could help reduce the amount of weight in hybrid-electric vehicles, thus improving fuel consumption (UPI 2006).

3.1.4 Renewable Energy

Nanotechnologies may also facilitate the generation of electricity directly from solar, wind, and geothermal sources. Using such energy at or near the source could enable distributed energy production of electricity, thereby minimizing transmission losses and reducing the need for ROW-based transmission of electricity, oil, and gas. Practical energy collectors that are simple and automated may result from cheap nanofabrication (Gillett 2002). Also, more efficient electricity transmission may enable the generation of increased amounts of electricity in remote locations (e.g., nonpopulated areas with abundant renewable energy) to be sent to high-energy-demand areas via nanoenhanced transmission. (Section 3.2.1 discusses nanotechnology applications for electricity transmission.)

Solar photovoltaic technology, which at present relies on crystalline-silicon wafers that are costly to produce, is deployed economically only in limited settings. Less costly quantum dot (nanocrystal) technologies could make important contributions to improving the efficiency of solar energy systems. Examples of some of these potential nanotechnology-enabled improvements are highlighted below:

- High-performance semiconductor nanocrystals (nanodots) that are active over the entire visible spectrum and into the near-infrared have been combined with conductive polymers to create ultrahigh-performance solar cells. The solar cells have improved efficiencies because the nanocrystals harvest a greater portion of the energy spectrum. Solar roofing tiles using quantum dots that are based on metal nanoparticles are expected to be commercialized within the next several years (Strem 2006).
- Highly ordered nanotube arrays have demonstrated remarkable properties when used in solar cells. Researchers explain that the nanotube arrays provide excellent pathways for electron percolation, acting as “electron highways” for directing the photo-generated electrons to locations where they can do useful

work. Research results suggest that highly efficient solar cells could be made simply by increasing the length of the nanotube arrays (Penn State 2006).

- One solar energy company (Konarka Technologies) creates a photoactive nanoscale material that can be printed on a variety of surfaces, including flexible plastics that can be manufactured in rolls. The material can be cut up and used for such applications as roofing and interior wall material, and can even be stitched onto or woven into a soldier's backpack. The product's costs are one-third those of conventional photovoltaics, and the projected capital cost for manufacturing equipment and facilities is about one-fifth that of the prevailing cost for conventional solar cells (McGahn 2006).
- Nanoadditives, including nanoparticles and nanopowders, could be used to enhance the transfer of heat from solar collectors to storage tanks. When added to heat-transfer fluids, the solid nanoparticles conduct heat better than the fluids alone, and they stay suspended longer than larger particles (Strem 2006).

3.1.5 Energy Storage

The ability to store energy locally can reduce the amount of electricity that needs to be transmitted over power lines to meet peak demands. Energy storage could allow downsizing of baseload capacity and is a prerequisite for increasing the penetration of renewable and distributed generation technologies such as wind turbines at reasonable economic and environmental costs. Suitable energy storage is critical to the increased use of renewable energies, particularly solar and wind, because these are inconsistent resources. Nanotechnology may play a role in distributed generation through the development of cost-effective energy storage in batteries, capacitors, and fuel cells. The next generation of storage devices may be optimized by nanoengineered advances and the use of nanoscale catalyst particles (Foster 2006).

Richard Smalley has described a model for storage using nanotechnology (Foster 2006) in which he suggests that by 2050 every house, business, and building would have its own local electrical storage device — an uninterruptible power supply capable of handling all of the needs of the owner for 24 hours. Because such devices would be small and relatively inexpensive, they could be replaced with new models every 5 years or so as technological innovation continues. Today, such a unit, using lead-acid storage batteries and storing 100-kilowatt-hours (kWh) of electrical energy for a typical house, would occupy a small room and cost more than \$10,000. Through advances in nanotechnology, it may be possible to shrink an equivalent unit to the size of a washing machine and drop the cost to less than \$1,000. With these advances, the electrical grid could become exceedingly robust. Such advances could also permit some or all of the primary electrical power on the grid to come from solar and wind energy.

Batteries. CNTs have extraordinarily high surface areas and good electrical conductivity, and their linear geometry makes their surface areas highly accessible to a battery's electrolyte. These properties could enable CNT-based electrodes in batteries to generate increased electricity

output as compared to traditional electrodes. This ability to increase the energy output from a given amount of material means not only that batteries could become more powerful, but also that smaller and lighter batteries could be developed for a wider range of applications. Commercial firms are actually developing such next-generation batteries today. For example, in April 2006, a nanotechnology company (Altairnano) owner testified before Congress about a new nanotechnology battery with potentially broad applications. The battery technology utilizes 25-nm nanostructured lithium titanate spinel (a hard, glassy mineral) as the electrode material in the anode of a rechargeable lithium-ion battery, replacing the graphite electrode typically used in such batteries and contributing to performance and safety issues. The new battery offers vastly faster discharge and charge rates, meaning that the time to recharge the battery can be measured in minutes rather than in hours. The nanostructured materials also increase the useful lifetime of the battery by 10 to 20 times over current lithium batteries and provide battery performance over a broader range of temperatures than currently achievable; over 75% of normal power would be available at temperatures between -40°F and $+152^{\circ}\text{F}$.¹ These types of batteries may enable the U.S. auto industry to “leapfrog” the next generation of hybrid-electric vehicles, thereby accelerating the reduction of the need for petroleum (and for the pipeline transmission of petroleum).

Other commercial applications for these batteries are for uninterruptible power supplies (UPSs) and emergency backup power (EBP). Present-day UPS and EBP systems typically use lead-acid batteries because of their reliability and low initial cost. However, lead-acid batteries must be replaced every 2 to 3 years, and hazardous materials issues surround their manufacture, handling, and maintenance. Lead-acid batteries also lose charge quickly in extreme temperatures ($<32^{\circ}\text{F}$ and $>112^{\circ}\text{F}$) and suffer from power declines and a decreased ability to accept a recharge over time. By comparison, prototype batteries using the nanostructured lithium titanate electrode material show promising improvements. The advanced lithium-ion battery is virtually unaffected by temperature extremes, its charge is fully available immediately, and it can accept a full recharge in a few minutes. It also has a much longer lifetime with no decline in performance, and there are no hazardous materials issues. With these kinds of advantages, UPS and EBP systems could become reliable components of distributed mini-grids (Gotcher 2006).

Capacitors. While batteries, which derive electrical energy from chemical reactions, are effective in storing large amounts of energy, they must be discarded after many charges and discharges. Capacitors, however, store electricity between a pair of metal electrodes. They charge faster and longer than normal batteries, but because their storage capacity is proportional to the surface area of their electrodes, even today’s most powerful capacitors hold 25 times less energy than similarly sized chemical batteries. Researchers, however, have covered capacitor electrodes with millions of nanotubes to increase electrode surface area and thus the amount of energy that they can hold. The researchers claim that the new technology “combines the strength of today’s batteries with the longevity and speed of capacitors and has broad practical possibilities, affecting any device that requires a battery” (Limjoco 2006).

¹ Because conventional lithium-ion batteries cannot charge at temperatures below 32°F and explode at temperatures higher than 208°F , this characteristic would permit the new batteries to be used in physical environments that today cannot be served by lithium-ion batteries because of safety concerns or because they require complex, expensive electronic control circuitry and temperature maintenance.

3.1.6 Fuel Cells

A fuel cell is a device used for electricity generation that is composed of electrodes that convert the energy of a chemical reaction directly into electrical energy, heat, and water. It is similar to a battery, except that it is designed for continuous replenishment of the reactants that become consumed, thereby requiring no recharging. It produces electricity from an external supply of fuel and oxygen, rather than the limited internal energy storage capacity of the battery. Fuel cells come in various sizes and provide useful power in remote locations such as spacecraft and weather stations.

Fuel cells are often considered in the context of hydrogen, because they change hydrogen and oxygen into water, producing electricity and heat in the process but no other by-products. A fuel-cell system running on hydrogen has no major moving parts and can be compact and lightweight. Many believe that in the future, fuel cells will be used to power everything from handheld electronic devices to cars, buildings, and utility power plants. IBM projects that fuel cells in cars will be a “daily fact of life” by 2010, and General Motors estimates that it will have a million fuel-cell cars in production by then (IBM 2004). Such technologies may supply much of the power that would otherwise need to be transported via ROWs (although pipelines may still be needed to transport the natural gas or hydrogen that feeds the fuel cells).

Fuel cells are not new, but the materials’ costs and complex manufacturing processes have limited their development. Nanoengineered materials may help improve fuel cells’ efficiency in several ways; some examples are highlighted below:

- Fuel cells operate by catalyzing the conversion of hydrogen into energy as the hydrogen passes through a catalytic medium. Advanced designs for next-generation fuel cells involve the use of a polymer membrane as the structure through which the hydrogen passes and on which the catalysis occurs. The use of nanoengineered membrane materials may increase the volume of hydrogen conversion and thus result in more energy (McGahn 2006).
- Precious metal nanoparticles of various compositions have been optimized to act as effective electro-catalysts in polymer electrolyte fuel cells and direct methanol fuel cells at both the anode and the cathode sides (Strem 2006).
- A materials design concept used to control and manipulate the structure of a new material on the nanoscale could lead to more powerful fuel cells than currently available and to devices that enable more efficient energy extraction from fossil fuels and carbon-neutral fuels. The new electrode material allows more efficient direct utilization of natural gas or biogas (produced from waste) in fuel cells (Ruiz-Morales et al. 2006).
- CNTs’ high strength and toughness-to-weight characteristics may be important for composite components in fuel cells that are deployed in transport applications where durability is important.

3.1.7 Hydrogen Generation and Storage

The hydrogen economy is a hypothetical future economy in which hydrogen is the primary form of stored energy for mobile applications and load balancing. It is typically discussed as an alternative to today's fossil-fuel economy. Many barriers need to be overcome for the hydrogen economy to become a reality. These include producing the hydrogen (for which adequate sources of electricity are needed), transporting it (including the possible need for additional ROWs), and storing it. Nanotechnology may play a role in helping to meet these challenges. As discussed previously, nanotechnology may help accelerate the use of solar and other renewables to generate electricity. Also, as noted in Section 3.2.1.1, nanowires may increase the efficiency of long-distance electrical energy transmission. Highlighted below are ways in which nanotechnology may help address hydrogen storage problems.

Because hydrogen is the smallest element, it can escape from tanks and pipes more easily than conventional fuels. There are two ways to store hydrogen in materials. One way involves absorption of the hydrogen within the material, and the other is to store the hydrogen in a container. The challenge for absorption is to control the diameter of the nanotube so that the absorption energy of hydrogen on the outside and inside of the tube is high enough to provide the desired storage capacity at an acceptable pressure. If the absorption behavior of the optimized tube is acceptable, the challenge then is to develop a process capable of producing the material at a reasonable cost. Single-walled CNTs are a leading candidate for solving the storage problem for hydrogen-fueled cars and trucks. However, if this approach cannot be carried out, CNTs could still facilitate storage in a container. Small hydrogen-fueled vehicles would have a pressurized tank, and large hydrogen-fueled vehicles, ships, and planes would have a cryogenic liquid hydrogen tank. In this case, CNTs may be used in super-strong composites in the bodies of the vehicles to make them lighter (Smalley 2003).

Additional options might include metal nanoclusters which have been shown to be some of the best catalysts available for reversible hydrogen storage. Core-shell cobalt nanoparticles with tailored chemical compositions can provide protection against corrosive environments. The nanoparticles can easily be removed, leaving a graphite carbon shell. The low-density shell's excellent permeability and electron conductivity make it a candidate for hydrogen storage applications (Strem 2006).

3.1.8 Power Chips™

Numerous nanotechnology applications will likely be developed within the next 20 years, but one example serves to illustrate the potential impact that nanotechnology may have on energy generation, and, in turn, on the reduced need for energy ROWs in the future. "Power Chips" are nanotechnology devices that use thermionics² to convert heat directly into electricity.

² Thermionics is the science that deals with the phenomenon (also known as the Edison effect) in which the flow of electrons from a metal or metal oxide surface, caused by thermal energy, overcomes the electrostatic forces holding electrons to the surface. The effect increases dramatically with increasing temperature, but it is always present at temperatures above absolute zero.

If successful, these small solid-state devices could improve current power generation and waste heat recovery techniques. They are estimated to deliver up to 70 to 80% of the maximum (Carnot) theoretical efficiency for heat pumps (conventional power-generation equipment operates at up to 40% Carnot efficiency). Currently under development, Power Chips contain no moving parts or motors and can be either miniaturized or scaled to very large sizes for use in a variety of applications. More information about this technology is available at <http://www.powerchips.gi/index.shtml>.

3.2 NANOTECHNOLOGY APPLICATIONS HAVING PARTICULAR RELEVANCE TO ENERGY TRANSMISSION TECHNOLOGIES

Numerous nanomaterials and other nano-related applications relevant to electricity transmission and petroleum distillate fuel and gas pipeline transport are in various stages of research, development, and deployment. These applications have the potential to directly or indirectly reduce the environmental impact associated with the construction, operation, and dismantlement of energy transmission technologies. The remainder of this section highlights examples of nanotechnology applications relevant to transmission of electricity via cables and of fossil fuels (i.e., petroleum distillate fuel and natural gas) through pipelines. Potential pitfalls and timeframes have been identified in the literature. In general, however, the potential for practical scale-up of most of the techniques in use today for nanoparticle production is limited by high capital costs, low production rates, the need for exotic and expensive precursor materials, and limited control over nanoparticle physical and chemical homogeneity. Breakthroughs in nanotechnology research may accelerate the development and implementation of these technologies.

3.2.1 Nanotechnology Applications Relevant to Electricity Transmission

3.2.1.1 Wires and Cables

Nanotechnology may help improve the efficiency of electricity transmission wires. Today, aluminum conductor steel reinforced (ACSR) wire is the standard overhead conductor against which alternatives are compared. By 2010, the development of new overhead conductors is expected to increase the capacity of existing ROWs by five times that of ACSR wire at current costs (DOE 2006). The 3M Corporation has developed a nanomaterial-based metal-matrix overhead conductor known as the aluminum conductor composite reinforced (ACCR) wire, which is designed to resist heat sag and provide more than twice the transmission capacity of conventional conductors of similar size. This ACCR wire is currently in use, or has been selected for use, by six major utilities across the country. According to 3M (2006): “Aluminum has been a key ingredient in bare overhead conductors for decades. The difference is that ACCR wire is based on the use of aluminum processed in new ways to create high-performance and reliable overhead conductors that retain strength at high temperatures and are not adversely affected by environmental conditions.” The ACCR wire’s strength and durability derive from its nanocrystalline aluminum oxide fibers, which are embedded in the high-purity 3M aluminum

matrix core wires using a patented process. The constituent materials are chemically inert with respect to each other and can withstand extreme temperatures without chemical reactions or any appreciable loss in strength. The material used in the core of the cable replaces the steel used in conventional cables (3M 2006).

Another example, mentioned in Section 2.2 and still in the research phase, is the use of armchair CNTs — a special kind of single-walled CNT that exhibits extremely high electrical conductivity (more than 10 times greater than copper). Also possessing flexibility, elasticity, and tremendous tensile strength, CNTs have the potential, when woven into wires and cables, to provide electricity transmission lines with substantially improved performance over current power lines (Technology Administration 2003).

Replacing current wires with nanoscale transmission wires, called quantum wires (QWs) or armchair QWs, could revolutionize the electrical grid. The electrical conductivity of QW is higher than that of copper at one-sixth the weight, and QW is twice as strong as steel. A grid made up of such transmission wires would have no line losses or resistance, because the electrons would be forced lengthwise through the tube and could not escape out at other angles. Grid properties would be resistant to temperature changes and would have minimal or no sag. (Reduced sag would allow towers to be placed farther apart, reducing footprint and attendant construction and maintenance impacts.) QW, if spun into noncorrosive polypropylene-like rope, could conceivably be buried “forever” with no fear of corrosion and “no need for shielding of any kind” (Hoffert 2004). Such a grid could have a million times greater capacity than what exists today (assuming the 1-centimeter-diameter aluminum cable carrying about 1,000 to 2,000 amps); even if the capacity were increased by only 0.1%, the amount of enhanced capacity would still be impressive (Davis 2006). The realization of such conducting possibilities depends on developing processes for producing high-quality CNTs in industrial quantities and at reasonable cost, finding ways to manipulate and orient nanotubes into regular arrays, and developing robust testing methods.

Today, QWs made from metallic CNTs are very short — no longer than several centimeters — and are manufactured only in limited quantities. When nanotubes are synthesized, a variety of different configurations appear. (The armchair CNT is the only type that conducts electricity well enough for QWs.) Currently, only 2% of all nanotubes can be used as QWs, and sorting the armchair nanotubes from the rest is nearly impossible. Current processing technologies are not capable of producing nanotubes with controlled and desirable production properties consistently. Until a good solution for separating the “good one from the many other unfavorable configurations is reached for large-volume manufacturing, the impact of nanotubes on power line usage is hypothetical” (Davis 2006).

The National Aeronautics and Space Administration has funded research to produce a 1-meter (m)-long prototype of QW by 2010. It is estimated that at least 5 years will be needed to develop methods to produce QW with high enough purity, in large enough amounts, and cheaply enough to spin continuous fibers into QW (Anderson et al. 2006). CNT manufacturers and government officials express optimism about the successful deployment of CNT in transmission wires, partly because, with a rope of CNTs woven together, it is not necessary for any single fiber to span the entire length of a transmission wire, since quantum tunneling allows electrons to

jump from stand to strand. The president of Raymor Industries (a company specializing in the development and application of CNTs) said in 2006 that “a transmission wire product will be commercially available in the ‘not too distant future’ but as of yet, no single-walled carbon nanotube provider has been able to demonstrate their ability to supply the material in large volumes with reasonable pricing, which is the only path to adaptation of this technology across the power grid” (Davis 2006). Ataf Carim, with the U.S. Department of Energy, said earlier, “While promoting carbon nanotubes to electric utility companies in the near term would be premature, we certainly hope that the promise of such materials for power transmission can be realized in the future” (Davis 2006).

Long-distance transmission of electrical current entails significant losses (about 20%) due to electrical resistance. Superconductors transmit electricity with a small fraction of the losses from conventional conductors, thereby enabling power transmission at higher power densities. Such efficiencies may relieve transmission congestion and lessen the need for transmission equipment. High-temperature superconductors (i.e., substances that become superconducting near liquid nitrogen temperatures [about 77 Kelvin (K)] rather than near liquid helium temperatures [about 4 K]) were discovered in the late 1980s. Noting that transmission constraints have contributed to higher electricity prices and reduced reliability, the 2001 National Energy Policy Report (National Energy Policy Development Group 2001) recommended expanded research and development on transmission reliability and superconductivity.

HTS cables have been demonstrated at full scale at distribution voltages and in lengths up to 100 m. Large-scale use of second-generation HTS wire carrying high-amperage electrical current with virtually no resistance promises dramatic gains in energy efficiency. Other advantages of HTS cables include:

- HTS cables can carry more power at the same voltage than conventional cables, meaning that the need for 500-kilovolt (kV) and higher voltage transmission, which requires expensive power equipment, could be eliminated.
- Because HTS cables are operated at cryogenic temperatures, they have a lower susceptibility to temperature-related faults than overhead lines.
- HTS cables would be sited underground, making them less vulnerable than overhead transmission lines to natural events and unintentional or intentional disruptions.

HTS also has disadvantages. For one, the cost of the HTS wire is currently much higher than that of conventional conductors (such as copper or aluminum) used for electricity transmission and distribution. Also, HTS wires are more susceptible to magnetic fields than their metallic counterparts. If exposed to large magnetic fields such as those found in transmission lines, they would develop resistance, which would heat the ceramic and result in decreased efficiency.

Nanotechnology may be helpful in mitigating some of these challenges, bringing HTS closer to commercial use. For example, American Superconductor Corporation has developed and filed a patent application for a nanotechnology-based manufacturing technique that delivers an immediate 30% increase in the electric current-carrying capability of the company's second-generation (2G) HTS wire. This process disperses nanodots throughout the superconductor coating of the company's 2G HTS wire. The nanodots are ultrasmall particles (typically less than 100 atoms across) of inorganic materials that increase the flow of electrical current through the 2G HTS wire by pinning (immobilizing) magnetic lines of flux in the superconductor (Nanotechwire 2004a). The pinning allows higher amounts of electrical current to flow even in the presence of strong magnetic fields and at relatively high operating temperatures. The 2G HTS wire is being designed as a replacement for today's commercial first-generation (1G) HTS wire at manufacturing costs that are two to five times lower than those of the 1G HTS wire.

3.2.1.2 Other Electrical Transmission Infrastructure

Nanotechnology applications may help improve other components of the electric transmission infrastructure, thereby potentially reducing environmental impacts. The examples below pertain to transformers, substations, and sensors.

Transformers. Fluids containing nanomaterials could provide more efficient coolants in transformers, possibly reducing the footprints, or even the number, of transformers. As noted in Section 3.1.4, nanoparticles increase heat transfer, and solid nanoparticles conduct heat better than liquid. Nanoparticles stay suspended in liquids longer than larger particles, and they have a much greater surface area, which is where heat transfer takes place (Strem 2006). Using nanoparticles in the development of HTS transformers could result in compact units with no flammable liquids, which could help increase siting flexibility.

Substations. Substation batteries are important for load-leveling peak shaving, providing uninterruptible supplies of electricity to power substation switchgear, and for starting backup power systems. Smaller, more efficient batteries (see Section 3.1.5) could reduce the footprints of substations and possibly the number of substations within a ROW.

Sensors. Nanoelectronics have the potential to revolutionize sensors and power-control devices. Nanotechnology-enabled sensors would be self-calibrating and self-diagnosing. They could place trouble calls to technicians whenever problems were predicted or encountered. Such sensors could also allow for the remote monitoring of infrastructure on a real-time basis. Miniature sensors deployed throughout an entire transmission network could provide access to data and information previously unavailable. The real-time energized status of distribution feeders would speed outage restoration, and phase balancing and line loss would be easier to manage, helping to improve the overall operation of the distribution feeder network.

3.2.1.3 Other Materials

Advanced materials using nanomaterials or nanotechnology may extend service life, lower failure rates, and reduce the potential for environmental damage. Two examples of such advanced materials follow.

Smart materials. The Electric Power Research Institute, Inc. (EPRI) has described how nanotechnology may accelerate the development of “smart materials and structures” (SMSs) (EPRI 2003). According to EPRI, SMSs have the unique capability to sense and physically respond to changes in their environment (e.g., temperature, acidity levels, magnetic field). Generally consisting of a sensor, an actuator, and a processor, an SMS device can function autonomously in an almost biological manner. On a transmission line, SMSs could monitor and assess the condition of conductors, breakers, and transformers in real time to avoid outages. SMSs may also enable in situ repair of underground cables. In addition, smart materials may be used to adjust transmission line loads according to real-time thermal measurements. However, to realize such capabilities, more research and development are required to integrate SMSs into components, embed the SMS components into the structure to be controlled, and facilitate communication between smart structure components and the external world. EPRI also notes that nanoscale electronics will most likely be used to make circuits smaller than they are now. Such circuits would be molecular-scale, high-speed, high-capacity electronic circuits. EPRI notes that while basic transistors have been created from organic molecules, the feasibility of building complicated nanoscale electronic or mechanical devices will require solutions to fabrication problems, quantum effects problems, and communication difficulties (EPRI 2003).

Intelligent substations that redirect electrical flow around congestion and take actions determined by simulations will be aided by new power-controller hardware. Smart power controllers employ computer control of the electricity grid’s equivalent of transistors and giant capacitors to divert power from troubling congestion areas to underutilized grid lines. Computers operating these power controllers at every level of the grid would reduce the need to build new generation through better efficiency and safety. However, power-controller hardware is big, heavy, and expensive. Nanomaterials may provide a new generation of power controllers that are cheaper, stronger, and lighter than today’s prototypes (Anderson et al. 2006).

Ceramics. Ceramics are hard and resist heat and chemical attack, but they are also very brittle. Researchers at the University of California at Davis have mixed aluminum oxide with 5% to 10% CNTs and 5% finely milled niobium and processed it to consolidate ceramic powders at lower temperatures than conventional processes. The resulting material has up to five times the fracture toughness (resistance to cracking under stress) of conventional alumina. The material also shows electrical conductivity seven times that of previous ceramics made with nanotubes. It also has interesting thermal properties — conducting heat in one direction, along the alignment of the nanotubes, but reflecting heat at right angles to the nanotubes — making it an attractive material for thermal barrier coatings (Foley 2003).

3.2.2 Nanotechnology Applications Relevant to Pipeline Transmission of Petroleum Distillate Fuel and Natural Gas

Today, most of the identified nanotechnology applications for pipelines involve material coatings (insulation, corrosion, and multipurpose). Other potential applications include nanosensors, which have the potential to minimize environmental damage by identifying potential leaks before they spread, and oil spill remediation with nanomaterials, which may minimize damage should a leak occur. Because the current and expected future applications of nanotechnology for petroleum distillate fuel pipelines are basically the same as those for natural gas pipelines, this section cites examples of general nanotechnology applications for pipelines.

Materials. Advanced materials using nanotechnology may extend service life, reduce failure rates, and limit the potential for environmental damage. Nanocoating metallic surfaces can help achieve superhardening, low friction, and enhanced corrosion protection. Stronger materials may reduce wear, corrosion, and the chances of puncturing associated with third-party damage. Also, because nanomaterials can be stronger per unit volume than conventional materials, the use of pipe materials that contain or are coated with nanomaterials may mean fewer disturbances to the environment during installation, maintenance, and dismantlement. Examples of nanomaterials with applicability to pipelines include:

- *Corrosion inhibitors.* Corrosion under insulation (CUI) is a costly problem that is difficult to detect in pipelines. According to a study by CC Technologies in cooperation with NACE International, the costs associated with direct corrosion on gas and liquid transmission pipelines are \$7 billion per year. Corrosion was the major cause of reportable incidents in North America requiring more than \$1 billion in repairs to one pipeline alone. Nansulate™ is a high-performance thermal insulator that prevents CUI. The translucent characteristic of the coating allows for visual inspection of the substrate without having to remove the coating, making it well-suited for use in gas and liquid transmission pipelines. The coatings utilize nanotechnology to prevent CUI, whereas many of the insulations currently in use actually cause the problem of CUI (Industrial Nanotech, Inc. 2006).
- *Coatings.* Nanostructure coatings have excellent toughness, wear, and adhesion properties. Nanostructure powders have grains less than 100 nm in size, which are agglomerated to form particles large enough to be sprayed using conventional thermal spray methods. These coatings may be used to repair component parts instead of replacing them, resulting in reduced maintenance costs and disturbance. Additionally, the nanostructure coatings may extend the service life of the components because of their improved properties over conventional coatings (Vasanth and Taylor 2002).
- *Insulation.* Aerogels are highly porous solids formed from a gel in which the liquid is replaced with a gas. Containing more than 95% air, they have been dubbed the world's lightest solids. While aerogels were first discovered in 1931, their insulating power was unusable because they were so brittle.

In 2001, Aspen Aerogels commercialized a process to deliver aerogels in flexible blankets, making aerogels easy to use almost anywhere. Using nanotechnology, Aspen now produces the same insulating material in a flexible foam infused with silica nanostructures. Because of the formulation, less insulation can be used to accomplish the same objectives, resulting in smaller pipe diameters (smaller footprint). Also, because heat radiation is a function of surface area, up to 30% less heat is dissipated (Aspen 2006).

- *Multipurpose coatings.* A new class of material known as Quasam™ can be produced as either a thin-film coating or as a bulk material. The material exhibits ultra-low weight combined with the strength, stiffness, hardness, and thermal stability approaching that of natural diamond. The material demonstrates chemical and corrosion resistance, biocompatibility, and electrical conductivity even at a 1-nanometer thickness. It also has the ability to act as a “smart skin,” which provides the ability to measure stress and detect structural damage before an incident. A Quasam coating on an oil pipeline could provide detection of stress buildup before a failure occurs (Nanotechwire 2004b).

Nanosensors. Nanosensors, or sensors made of nanomaterials, can be extremely sensitive, selective, and responsive. As such, they could be smaller and cheaper, and consume less power than conventional sensors. Sensors and controls that are small in size; work safely in the presence of electromagnetic fields, high temperatures, and high pressures; and can be changed cost-effectively may provide the ability to monitor conditions in the infrastructure and monitor for pollutants (vapor or oil losses) continually. Researchers have recently developed sensors made from titania nanotubes coated with a discontinuous layer of palladium. The photocatalytic properties of titania nanotubes are so large — a factor of 100 times greater than any other form of titania — that sensor contaminants are efficiently removed with exposure to ultraviolet light, so that the sensors effectively recover or retain their original sensitivity to hydrogen. Sensors in uncontrolled locations become contaminated by a variety of substances including volatile organic vapors, carbon soot, and oil vapors, as well as dust and pollen. A self-cleaning function capable of oxidizing contaminants would extend sensor lifetime and minimize sensor errors (Science Daily 2004). Nanosensors may also be used to identify approaching vehicles or equipment that may otherwise lead to third-party damage; or, if the pipeline is damaged, provide an immediate indication (e.g., alarm or other notification) so that any potential environmental damage may be mitigated quickly.

Oil spill remediation. A substance that uses nanoparticles and a patented “self-assembled monolayer” (SAM) technology has been developed to absorb about 40 times its weight in oil. Because water is completely rejected by the material, spilled oil can be recovered for use — a substantial benefit in oil spill cleanup efforts. The substance combines materials and surface innovation at the nanoscale level with SAM technology to produce a class of nanostructured hybrid materials that serve as environmental sorbent materials. The system provides the ability to form chemical foundations from which other building blocks can be used to form more complex structures. The interfacial chemistry can be engaged with specific polymer systems to enhance the adhesion properties of a polymer to a solid substrate.

The technology may provide advancements in oil spill recovery and remediation (Lamba 2005). Advances such as this may offer the potential for reduced environmental damage to ROWs and nearby areas, should a leak occur.

4 POTENTIAL ENVIRONMENTAL, SAFETY, AND HEALTH RISKS

Due to their extremely small size and relatively large surface areas, nanomaterials may interact with the environment in ways that differ from more conventional materials. Potentially harmful effects of nanotechnology could result from the nature of the nanoparticles themselves and from products made with them. Environmental, safety, and health (ES&H) risks could occur during research, development, production, use, and end-of-life processes.

The 21st Century Nanotechnology Research and Development Act, signed into law in December 2003, calls for addressing potential environmental and societal concerns associated with nanotechnology. About 10% of the Federal nanotechnology budget is characterized as environmental, but much of this amount is for developing nanotechnologies to address existing environmental problems rather than for investigating potential ES&H effects. Some research has been conducted on the toxicology of nanomaterials, but research on the fate, transport, and transformation; risk characterization, mitigation, and communication; and exposure, bioaccumulation, and personal protection has yet to come. All of the departments and agencies with Federal funding from the National Nanotechnology Initiative have environmental research planned or underway, but industry, nongovernmental organizations, and others have questioned whether the amount of research on the potential ES&H impacts of nanotechnologies is sufficient, given the number of unknowns and the size of the potential nanotechnology market.

There have been relatively few studies on the ES&H risks of engineered nanoparticles. There are also no regulatory requirements to conduct such studies, and little funding is allocated to them. The limited results to date are neither conclusive nor consistent. For example, evidence indicates that nanoparticles in the lungs may cause more severe damage than conventional toxic dusts, but few if any inhalation or exposure studies have been conducted. Nanotechnologies may speed cleanup of soil and water contamination, but in the process may harm local soil ecology. The impacts of large quantities of nanomaterials on the environment or human health have not been studied, and there are no studies on accumulation or other long-term impacts.

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