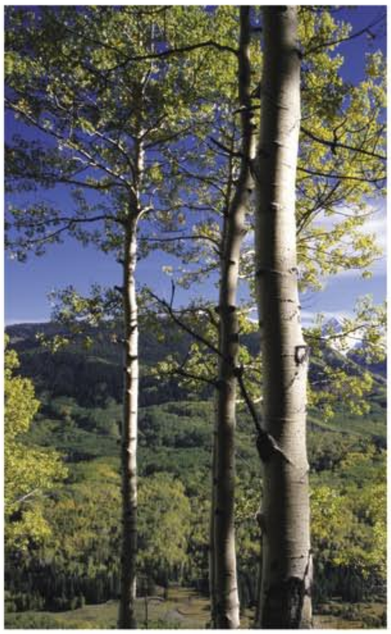
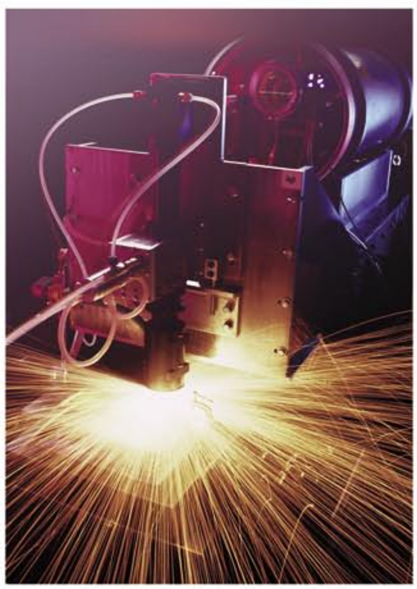
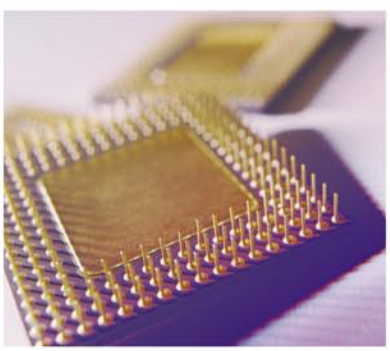
United States
Environmental Protection
Agency

Technology for a Sustainable Environment Grant Program:
A Decade of Innovation



July 2006

Technology for a Sustainable Environment Grant Program:

A Decade of Innovation

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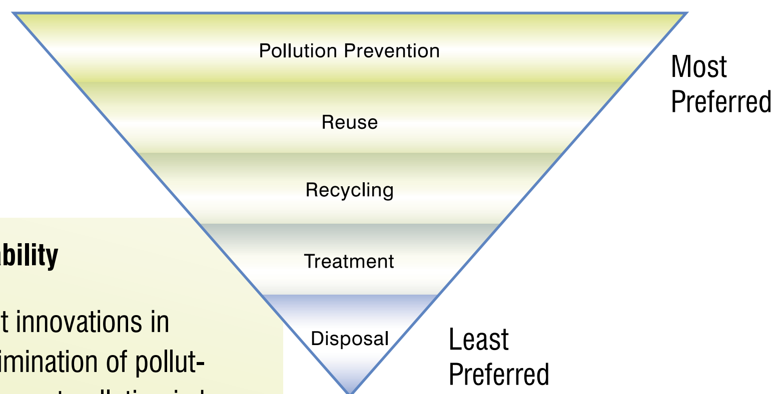
Preface

Sustainability has many definitions, but its underlying concept remains the same: balancing environmental protection and social responsibility with a healthy economy over time.

This concept of sustainability inspires public and private organizations to become better stewards of the environment. Green engineering and chemistry play an important role in creating the options that enable sustainability by developing chemicals, processes, products, and systems that are environmentally preferable, more energy- and resource-efficient, and often more cost-effective.

These fields have grown and matured through the support of the Technology for a Sustainable Environment (TSE) grant program. Established 10 years ago and funded jointly by the U.S. Environmental Protection Agency (EPA) and the National Science Foundation (NSF), the program has invested over $50 million in innovative interdisciplinary research in green chemistry, green engineering, and industrial ecology at universities throughout the U.S. In addition to building fundamental knowledge, this investment has paid off with environmental, economic, and societal benefits. It has led to new practices in industry and reshaped academic curricula.

Pollution Prevention Hierarchy



Pollution Prevention Supports Sustainability

Sustainability cannot be achieved without innovations in pollution prevention—the reduction or elimination of pollutants at the source. The optimal way to prevent pollution is by eliminating the production of waste altogether. When this is not possible, reuse, recycling, and treatment are all better alternatives to direct disposal.

In the success stories presented in this report, Dr. DeSimone's carbon dioxide-based solvents prevent pollution by replacing toxic solvents, Dr. Wool's hurricane-resistant housing made from recycled newspapers reuses waste products, and Dr. Thomas' research into tracking waste aims to increase recycling efficiency.

This report describes the TSE program—its goals, history, benefits, and performance. Seven grant "success stories" are presented to illustrate the breadth of the program and how it has supported researchers with novel ideas and produced groundbreaking results.

Program Overview

The Technology for a Sustainable Environment (TSE) program has fundamentally reshaped the research infrastructure in the fields of chemistry and engineering by promoting green practices, nurturing young scientists and engineers, and supporting new collaborations among established researchers and industry. The program has funded research that develops green chemistry, green engineering, and industrial ecology. The TSE program was designed to cultivate science and engineering that use energy and materials more efficiently, and it promotes the discovery and implementation of innovative and environmentally preferable processes and materials that are functionally equivalent and cost-competitive.

The TSE program was initiated in 1994 when EPA's National Center for Environmental Research (NCER) entered into a partnership with the National Science Foundation (NSF) to fund pollution prevention research. Over the next 10 years, EPA and NSF awarded tens of millions of dollars in the form of grants for fundamental and applied research under the TSE program. The partnership capitalized on both organizations' strengths for soliciting, competitively awarding, and managing high-quality, peer-reviewed environmental research. NSF's focus on basic research has balanced EPA's focus on solutions to environmental problems.

The partnership also brought together a diverse team of EPA and NSF technical staff to shape the program. As a result, the TSE program significantly expanded federal support for innovative research in this area.

> "Green chemistry and engineering are critical components of a comprehensive approach to manufacturing – an approach that considers not just the desired product, but the feedstocks, energy costs, purification procedures, and environmental impact associated with making the product."
>
> — *Arden Bement, Director, National Science Foundation*

Characteristics of the TSE Program

Through 2006, EPA and NSF awarded over $57 million for 205 research projects under the TSE program (NSF, $30.9; EPA, $26.8). Awards averaged approximately $120,000 per year, typically for a period of two to three years. Exhibits 1 and 2 show the number of TSE grants per year and the program's historical funding levels, respectively.

Exhibit 1. Number of TSE Grants Awarded by Year

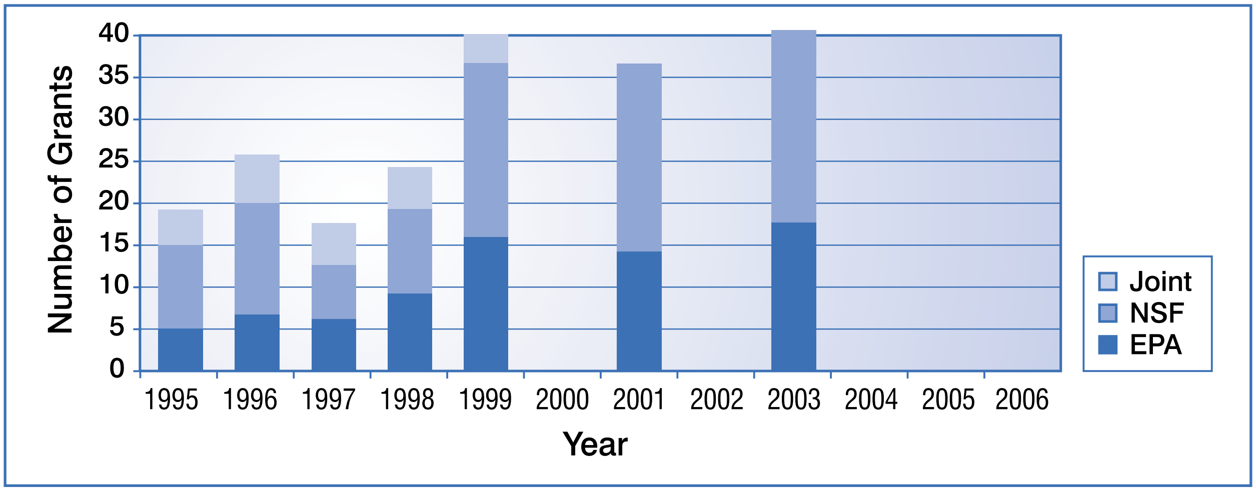
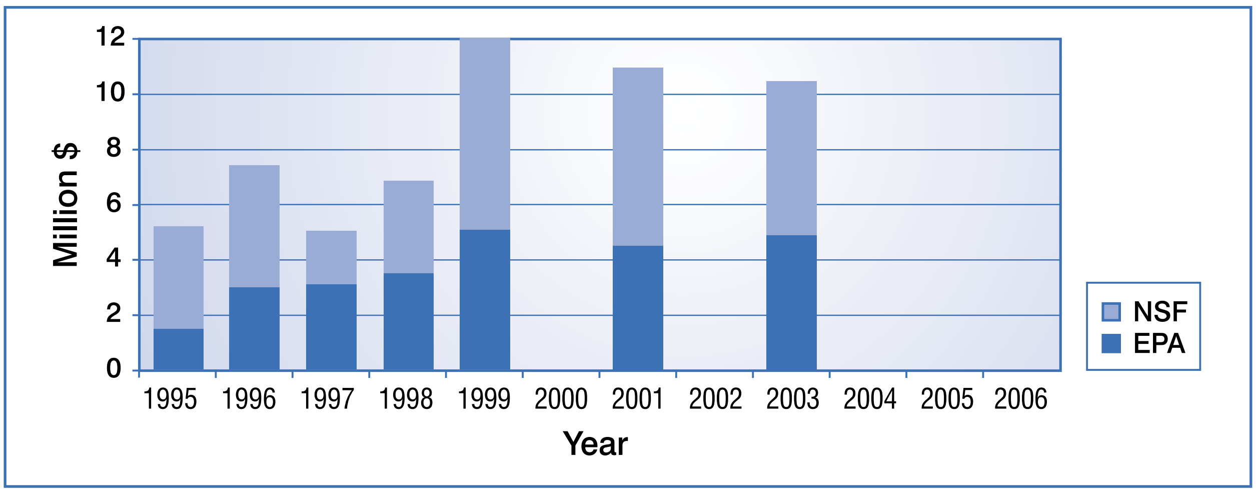


Exhibit 2. TSE Grant Funding Awarded by Year



Funded projects address technological issues of design, synthesis, processing, and the production, use, and ultimate disposal of products. Exhibit 3 provides an overview of the major areas of research funded by TSE grants, with examples of specific grants, although many grants fit under several categories. The program's scope broadened over time such that the number of specific research topics increased, though the major areas remained consistent.

The TSE program encouraged interdisciplinary approaches. Research teams came from a wide range of scientific fields, including environmental sciences, engineering, chemistry, microbiology, materials science, and social sciences. The grants supported pioneering changes in research infrastructure through new collaborations across technical disciplines and organizations. Research and development for a sustainable future often requires analysis

Exhibit 3. TSE Research Areas and Grant Examples

Solvents	Many solvents used throughout the manufacturing industry are highly toxic, and their inadvertent release into the environment can harm the health of wildlife and humans. Dr. Joseph DeSimone's research into alternative carbon dioxide-based solvents is summarized on pages 7-8 of this report.
Process	The electroplating industry creates a very large volume of chemical waste each year. While waste minimization techniques have been available for some time, they have not been well characterized in terms of cost and efficiency. At Wayne State University, Dr. Yinlun Huang is using artificial intelligence techniques to develop an intelligent decision support system that can suggest techniques for waste minimization in electroplating plants of any size. This TSE-funded research has developed four pollution prevention technologies that reduce chemical solvent use and wastewater by 15 percent. Dr. Huang also found that the electroplating industry and local governments were supportive and receptive to these technologies.
Bioengineering	There is a growing need to reduce dependency on fossil fuels with renewable resources, which help diversify the energy portfolio to ensure a constant energy supply even during times of crisis. Dr. Nancy Ho at Purdue University received a TSE grant to further develop a yeast-based ethanol synthesis process. Dr. Ho has genetically engineered or "bioengineered" yeast to more efficiently convert plant material into ethanol, an environmentally friendly alternative transport fuel that can be used directly or blended with gasoline. The use of ethanol has the further advantage of reducing dependency on foreign sources of oil, thus protecting the nation's energy security and reducing the trade deficit caused by importing oil.
Chemical Improvements	The pulp and paper industry uses organic solvents to remove lignin, the color-causing substance in wood, from paper. The use of these solvents can result in the production of toxic dioxins. Dr. Robin Rogers of the University of Alabama-Tuscaloosa received a TSE grant to develop an environmentally benign water-based system for the removal of lignin. Dr. Rogers' new process more efficiently removes color from pulp without the use of organic solvents, thus eliminating the production of dioxins and reducing the sulfur content of paper, making both the process and the product more environmentally friendly.
Green Design and Industrial Ecology	Green design and industrial ecology aim to manage the environmental impact of an industry using a systems approach in which the acquisition, use, and disposal of water, energy, and materials and the relationships among them are documented, evaluated, and optimized. Dr. David Dornfeld at the University of California-Berkeley received a TSE grant to develop a comprehensive tool to assess the environmental impacts of semiconductor manufacturing. The aim of Dr. Dornfeld's research is to find new ways to mitigate negative impacts and to inform environmental decision making with information about environment and health impacts resulting from different industry practices.
Catalysis	Catalysis refers to chemical processes that use catalysts to transform chemicals into other useful products or intermediates. Catalysts facilitate the reactions but are not consumed by them. Research to improve the selectivity and efficiency of catalysts is important to pollution prevention because certain traditional catalysts produce toxic byproducts. The research of Dr. Terry Collins, summarized on pages 12-14, demonstrates how alternative catalysts can be developed to increase efficiency and decrease environmental impacts of manufacturing processes.
Renewable Resources	The use of renewable resources promotes a sustainable production system. New technologies that rely on waste products as a source of raw material help reduce impacts on the environment. Dr. Richard Wool's TSE-sponsored research on high performance composites made from chicken feathers and recycled newspapers is summarized on pages 9-10.
Fuels and Energy	The burning of fossil fuels produces noxious gases such as sulfur oxides, which contribute to acid rain. Conventional sulfur-removal technology is not able to easily reduce fuel sulfur levels to EPA standards. Dr. Chunshan Song and colleagues at Pennsylvania State University received a TSE grant to develop a new process that will efficiently remove the sulfur. The process under development is able to more selectively remove sulfur compounds under ambient temperatures and pressures, thus reducing the cost and energy of sulfur removal.

of technical information and complex phenomena over large spatial and temporal domains.

Multi-disciplinary research teams like the ones funded by the TSE program often find it difficult to obtain funding from narrower scientific research programs. TSE-supported projects tend to be characterized as "on the cutting edge" or "high-risk/high-payoff." With its broader science-societal perspective, the TSE program has supported innovative, problem-solving research.

Geographically, TSE investigators are located in 30 states across the United States, with the highest number of grants in Pennsylvania, Michigan, and Georgia. The distribution of grants is shown in Exhibit 4.

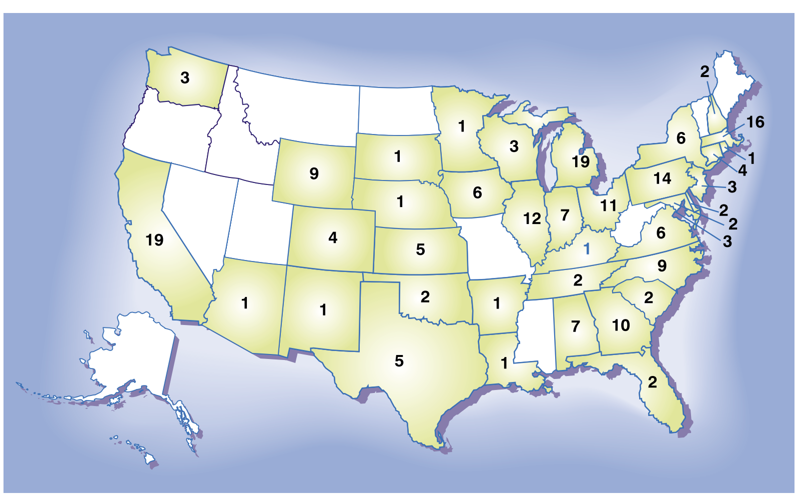
TSE grants were awarded competitively to fund high

> TSE grantees Dr. Richard Wool and Dr. Terry Collins noted that the TSE program's competitiveness and peer review standards results in high quality science that is more likely to achieve buy-in from future industrial partners. "My best research came from my TSE grants," said Dr. Wool.

quality science that meets the research solicitation's goals. The grant applications were evaluated through a rigorous merit review process. The selectivity of the grant program was high, with about 15 percent of the applicants receiving grants in the last two solicitations.

Applicants were encouraged to seek project collaboration with industrial partners on

Exhibit 4. Location of TSE Grantees in the U.S.



fundamental research issues that link basic and applied aspects of pollution prevention. In some cases, state government agencies or other professional organizations also collaborated.

One NSF research priority that has helped shape the TSE program is the focus on training and education of junior scientists and engineers in academia. Projects that provide both graduate and undergraduate students with experience in research, interdisciplinary educational activities, and student teamwork are strongly encouraged.

Benefits

TSE program goals have been focused on improving three interconnected areas: the environment, the economy, and society (see Exhibit 5). Often the TSE-supported research leads to technologies that provide better overall performance at lower costs. In addition to protecting the environment, they require researchers to consider a different set of design constraints, thus stimulating innovation that would not have happened otherwise.

In addition to these benefits, the TSE program has all of the standard indicators of a successful research and technology program, including the following:

Peer reviewed publications that are the main mechanism by which scientific findings and advancements are documented and disseminated to society;

Patents that are an important step in the lifecycle of a new technology leading to licensing agreements and commercialization; and

Industry collaborations that enable a new process to be implemented or a new product to be commercialized more quickly than if there were no formal connection between researcher and industry.

Equally important to the program's success are the student researchers who have contributed significantly to the development of new technologies. Portions of TSE grants funded graduate student research that enabled these individuals to achieve higher degrees, contributing to a more highly educated workforce. Many of them go on to work for industry and government, bringing an awareness of and interest in sustainability.

> "The goals of green chemistry and engineering move us towards innovation and collaboration for the mutual benefit of human health and the environment while furthering economic competitiveness."
>
> — *Dr. Paul Gilman, Former Assistant Administrator for Research and Development and Science Advisor, U.S. Environmental Protection Agency*

Exhibit 5. TSE Program Benefits

Environmental Benefits

- Reduced use of water, especially in manufacturing processes
- Reduced use of energy in manufacturing processes, businesses, and homes
- Reduced use, generation, and release of hazardous chemicals
- Reduced release of greenhouse gas emissions and pollutants to the air
- Reduced release of pollutants to water
- Reduced generation of waste through pollution prevention strategies

Economic Benefits

- Cost savings derived from decreased energy and other resource consumption
- Cost savings associated with reducing hazardous materials procurement, handling, transportation, disposal, and compliance concerns
- Cost savings from reduced liability
- Competitive advantages from improved product/process performance, improved efficiency, and consumer preferences
- New businesses and new jobs
- Lucrative products created from renewable resources produced in the United States

Societal Benefits

- Reduction in public health risks from chemical emissions, releases, and accidents
- Minimization of hazardous materials that require transportation and security efforts
- Safer working environments for industrial employees
- Education and inspiration of new generations of scientists and business leaders who are highly educated and are trained to find sustainable solutions
- Decreased frequency of litigation and associated societal costs

The TSE program has provided many environmental, economic, and societal benefits. In the section that follows, TSE grant “success stories” illustrate in greater detail examples of the program’s benefits and progress made toward sustainability.

TSE Program Success Stories

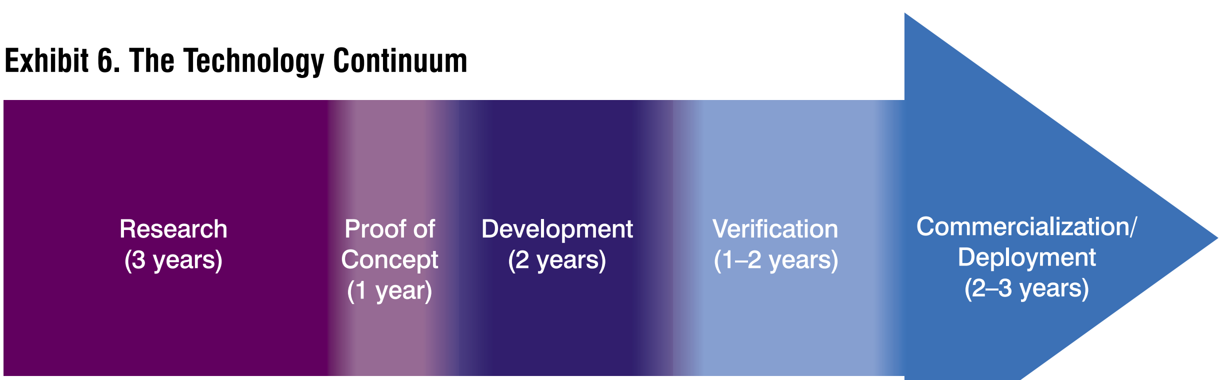
The seven TSE research projects described in this section reflect a wide range of challenges to environmental sustainability that are countered using cutting-edge technologies and practices. These success stories describe research at various stages of completion and at different points in their progression from research and development to commercialization; these stages are depicted in the continuum in Exhibit 6. Several technologies resulting from grants funded in the earliest years of the TSE program have been implemented in industrial applications. Other research projects described here are in earlier stages of the research and development cycle.

Replacing Toxic Solvents with Carbon Dioxide

Organic solvents, such as perchloroethylene (perc), are used in hundreds of industrial processes ranging from manufacturing Teflon to developing film. Some of these solvents are highly toxic or can break down into ozone-depleting gases, and some processes contaminate billions of gallons of wastewater. Given these detrimental environmental impacts, the TSE program funded research to identify alternatives to organic solvent-based processes.

Dr. Joseph DeSimone from the University of North Carolina at Chapel Hill received a TSE grant from EPA in 1997 to develop carbon dioxide-based solvents. His previous research had shown that carbon dioxide (CO_2) in its liquid and supercritical states is an excellent environmentally

Exhibit 6. The Technology Continuum



Research is the first in a series of phases necessary for a new technology to achieve full-scale implementation and realization of its benefits. The rate at which technologies progress to commercialization varies and is dependent on factors beyond the quality of the science. Ten years is the typical timeframe for new pollution prevention technologies to achieve commercialization.[1]

benign alternative solvent to chlorofluorocarbons dissolved in water. Under the TSE grant, Dr. DeSimone and his collaborators developed detergent-like "surfactants" that allow CO_2 to dissolve substances that would not normally be soluble. One of the consumer applications of this research is an alternative dry cleaning solution that replaces perchloroethylene. This detergent system is now used in more than 100 dry cleaning establishments in over 12 states.

RESEARCH HIGHLIGHTS:

- Fourteen articles published
- Several patents for carbon dioxide-based solvents, including those for dry cleaning and circuit board coating
- Four industrial partners: The BOC Group, SCF Consortium, DuPont, Stockhalven
- One start-up company: MiCELL Technologies
- Seven collaborating institutions, including: Georgia Institute of Technology, North Carolina State University, North Carolina A&T University, University of Texas, Austin, the Triangle National Lithography Center, Sandia National Laboratory, Oak Ridge National Laboratory

A follow-up grant to Dr. DeSimone in 2001 allowed him to extend this solvent research into applications for the microelectronics industries. To produce a single computer chip, conventional lithography techniques use one kilogram of organic solvent and aqueous waste. The CO_2-based process that Dr. DeSimone is developing to produce these multi-layer integrated circuits is environmentally benign, ensuring that this and other future manufacturing processes have minimal impact on the environment. The technology also provides solutions to some of the challenges associated with traditional water-based processes, such as achieving film uniformity while spin-coating wafers.

In addition to his TSE research, Dr. Simone co-founded MiCELL Technologies, a start-up company committed to developing and marketing carbon dioxide-based technologies. MiCELL currently owns or has licensing rights to 77 patents in the United States, with an additional eight applications pending.

Dr. DeSimone was appointed the director of the National Science Foundation's Science and Technology Center for Environmentally Responsible Solvents and Processes. In early 2005, he was elected into the National Academy of Arts and Sciences and into the National Academy of Engineering as its youngest member.

ABOUT PERC:

- **136 million kg** used by dry cleaners per year
- **130 million kg** released into the environment each year
- **90%** lost directly to the atmosphere, **10%** enters water supply
- If 50% of dry cleaners switched to CO_2-based solvents, **68 million kg** would be eliminated
- This would **substantially reduce** the exposure to perc via inhalation

From Soybeans, Chicken Feathers, and Newspapers to High-Performance Composites and Resins

Dr. Richard Wool at the University of Delaware is using plant oils and waste products to develop the world's cheapest composites and resins. From tractor parts made with soybean-based plastics to circuit board material produced using chicken feathers, to hurricane-resistant roofing fashioned from recycled newspaper, Dr. Wool has made use of renewable, biologically based materials to create environmentally friendly products. Because of the low cost of plant oil (10 to 15 cents per pound) and natural fibers, these technology breakthroughs are increasing the available options for manufacturers and making sustainable living a reality.

Dr. Wool received a TSE grant from EPA in January 2002 to study fundamental issues pertaining to the cost-effective synthesis and manufacture of plant-based resins and composites. These biologically based materials provide alternatives to petroleum-derived plastics. As a direct result of this research, Dr. Wool helped develop a new universal theory of fracture polymers, applied for five patents, and collaborated with nine industrial partners.

Currently, the John Deere Company uses Dr. Wool's soybean oil plastics to manufacture parts for its tractors, and his chicken feather circuit board material has attracted the interest of Intel. Additionally, Dr. Wool's hurricane-resistant roofing received attention from the news media and architecture societies including *Newsweek*, *Architectural Record*, *and the RIBA Journal* (the magazine of the Royal Institute of British Architects). The roofing is built primarily from recycled newspaper, chicken feathers, and soybean-derived plastics that are processed into a single, specially fitted lightweight roof. Its storm-resistant design could greatly reduce the millions of dollars of damage to homes in regions affected by hurricanes. In addition to the safety factor, its foam-core engineered structure imparts huge thermal energy savings, a benefit to both the environment and consumers. This roofing has the potential to become the country's highest-volume application of bio-based composite materials derived from low-cost, environmentally friendly, renewable resources.

These biologically based composite materials could make a considerable positive impact on the environment. If they are commercialized and produced in large quantities, each pound of plant or beans used would save about a pound

RESEARCH HIGHLIGHTS:

- Twenty-one articles and two books published
- Two patents received and three pending
- Soybean oil plastics used to manufacture parts for tractors
- Using soybean-based plastics could reduce carbon dioxide emissions by 300 billion pounds per year
- Nine industrial partners, including: 3M, Avery Denison, Cytek Corp (formerly UCB Radcure Corp), Diab, Doc Resins, Georgia Pacific, Nike, Rome & Haas, Westvaco
- Four collaborating institutions, including: Colorado State, Howard University, Georgia Tech, Michigan State University
- Ten undergraduate and four graduate students supported
- New course developed on "Green Engineering"

of fossil fuel. In addition, the substitution of 10 billion kilos of soybean-based products for fossil fuel-based plastics would be equivalent to reducing carbon dioxide emissions by 300 billion pounds per year.

This research extends into the classroom, furthering its impact by educating the next generation of green chemistry and engineering researchers. The TSE grant provided partial funding for four graduate and ten undergraduate students to train with Dr. Wool, and many of these students have gone on to careers in environmentally related research. To promote both the growing interest from students and the growing need from industry, Dr. Wool also developed a course on green engineering for undergraduates at the University of Delaware.

RESEARCH HIGHLIGHTS:

- Six articles published
- One intellectual property disclosure
- Three industrial partners, including: Motorola, MOBA Mobile Automation, OxLoc
- Three new employment opportunities with: Intel, New Jersey Congressman Rush Holt, Georgia Tech
- One undergraduate and one graduate student supported

Streamlining Waste Management with Electronic Tags for Trash

Dr. Valerie Thomas at Princeton University received a TSE grant from EPA in 2002 to develop electronic tags that could be used to monitor waste and recycling. Her work aims to increase recycling efficiency by using information technology solutions for identification and sorting.

There is currently no system in place to track non-hazardous waste and recyclables as they move through the waste management system in the United States. Dr. Thomas' research examines the options that are available for implementing such a system, focusing on the feasibility of different technologies such as barcodes, radio frequency identification (RFID) tags, and global positioning system (GPS) transmitters. Such systems potentially could track a product throughout its lifecycle while feeding back important data on product distribution, consumption, use, disposal, and recycling. Identification of products also will make recycling easier and cheaper, allowing a larger recovery of economic value from the waste stream.

Dr. Thomas collaborated with Motorola to develop a working prototype barcode system to aid in recycling Motorola cell phones. With Princeton undergraduate student Steven Saar, Dr. Thomas developed Web-based software that recognizes the scanned barcode on a Motorola phone and provides disassembly instructions for

"My work with Dr. Valerie Thomas has had a profound influence on my current research interests and my future career. I think of Dr. Thomas as my mentor, especially at this juncture in my career where I am exploring my interests and future career after graduate school. She has encouraged me to apply my scientific background to a career in environmental and public policy." [2]

— *Audrey Lee, Ph.D. candidate in Electrical Engineering, Princeton University* that particular model. The software has not been patented in order to promote development of similar waste management systems, but Motorola wrote an intellectual property disclosure naming Dr. Thomas, Saar, and a collaborator at Motorola as the developers of the technology. Saar's work on the barcode-tracking software for Motorola helped secure him a job with Intel after he graduated in 2004. Audrey Lee, a Ph.D. graduate student in electrical engineering, won a Student Paper Award in May 2004 from the Institute for Electronic and Electrical Engineers for a paper she and Dr. Thomas wrote using the findings from the TSE grant. Lee's work with Dr. Thomas on electronic tags allowed her to redirect her thesis toward environmentally relevant issues.

Also as a result of this research, funded almost entirely by the TSE grant, Dr. Thomas was able to win a competitive position working on energy policy as Congressional Science Fellow to New Jersey Congressman Rush Holt and to secure a position at the Georgia Institute of Technology. There, she will continue to develop a practical method of labeling waste and recycling products for use in U.S. towns and cities.

New Technique Reduces Foundry VOC Emissions

Dr. Fred Cannon and his team from the University of Pennsylvania are studying an advanced oxidation (AO) process that can be used to prevent pollution from foundries. Dr. Cannon received a TSE grant from EPA in 2002 to study and improve the AO process based on data from five full-scale foundries where the new technique is in use. The metal casting industry represents a significant manufacturing sector of the U.S. economy, with approximately 3,000 foundries across the country. The AO process is applicable to foundries that use green sand molds, which includes 60 percent of foundries in the U.S. The new process has been shown to greatly reduce the emission of hazardous air pollutants from the foundries where it is installed, including toxic volatile organic compounds (VOCs), benzene, and carbon monoxide.

RESEARCH HIGHLIGHTS:

- Six articles published
- One book published
- Five full-scale foundries employ the new process
- Up to **75 percent reduction** in VOC emissions at the five foundries where process is currently installed
- $10 million savings at one foundry

Dr. Cannon and his team have demonstrated reductions in VOC emissions ranging from 20 to 75 percent at the five foundries where the process is currently installed and predict that it can be improved to consistently reduce up to 80 percent of emissions. Using this as an estimate of potential pollution reduction, this process alone could reduce over 2.5 million pounds of VOCs each year.

In addition to this environmental benefit, the process is more efficient and thus more economically profitable. The AO process has reduced the amount of clay, coal, and sand required for casting by up to 40 percent and decreased the number of casting defects by 35 percent.

Lead-Free Molecular Wires for Household Electronics

Dr. C.P. Wong from the Georgia Institute of Technology received a TSE grant from EPA in December 2003 to develop a substitute for leaded solder, which is used broadly in the electronics industry. Lead is recognized as a carcinogen, a developmental toxicant, a reproductive toxicant, and is suspected to be a neurological toxicant. Its use in household electronics, such as computers, personal digital assistants (PDAs), and cell phones, has attracted scrutiny from regulatory agencies in Europe and Japan.

To date, most substitutes developed for leaded solder have been alloys that combine tin with metals such as silver, gold, copper, bismuth, or antimony. These have the disadvantage of higher manufacturing temperatures (up to 260 degrees Celsius), which necessitates higher energy costs and more expensive circuit board materials. With the assistance of graduate students Grace Yi Li and Kyoung-sik Moon, Dr. Wong is developing electrically conductive adhesives (ECAs) that are much better substitutes for leaded solder.

RESEARCH HIGHLIGHTS:

- Ten articles published, with additional five submitted or in preparation
- Five invention disclosures and two patents pending
- Pursuing licensing of the ECA technology with several companies
- Up to 60 percent energy savings in electronics manufacturing by replacing leaded solder
- Two graduate students trained
- Two companies pursuing licensing of technology: Indium Corporation of America and Ablestik, a National Starch and Chemical Company

In addition to the benefits of reduced lead use, ECAs could simplify electronics manufacture by eliminating several processing steps. Because the ECAs can be cured at lower temperatures—about 150 degrees Celsius and potentially even room temperature—they would produce less thermal stress on components, require less energy, and enable the use of existing circuit board materials.[3] If all of the current tin-lead solder in the U.S. were replaced with ECAs, energy savings for electronics manufacturing could be as much as 60 percent and the short-term consumption of lead potentially could drop by as much as 10 percent.

To overcome one of the main challenges of lead-free ECAs (the lower density of the electrical current, which is not adequate for many power-intensive devices), Dr. Wong and his collaborators developed self-assembled monolayers (SAM). SAM structures are molecular wires made of an organic polymer matrix that provide a direct electrical connection, bypassing resistance normally found at an interface. Georgia Institute of Technology has applied for patents on the SAM and is pursuing licensing of the technology with several companies.

Green Oxidation Catalysis

New and improved catalysts enable important chemical reactions to be conducted under milder conditions, with less energy expenditure, in a shorter time, using less reactive and more environmentally friendly chemicals and solvents. A TSE grant from NSF to **Dr. Terry Collins of Carnegie Mellon University** in 1996 led to the development of environmentally friendly oxidant activators. Dr. Collins won the 1999 Presidential Green Chemistry Challenge Award for this research.

In the paper manufacturing process, the newly developed activators catalyze the oxidizing ability of hydrogen peroxide,

RESEARCH HIGHLIGHTS:

- Eighteen articles published
- Ten U.S. patents received, additional patents received in 25 other countries, and license agreements for commercialization of paper bleaching technology in place
- 23.2 million tons of coal could be saved in energy costs per year with TAML bleaching methods
- One industrial partner: PAPRO New Zealand
- Six collaborating institutions, including: National Energy Technology Laboratory at the Department of Energy, Naval Surface Warfare Center at the Department of Defense, University of Auckland, Osaka City University, GSF Munich, the Pittsburgh Department of Energy

creating water and oxygen as byproducts of the bleaching process. The older methods relied on elemental chlorine-based catalysts and produced toxic dioxins that are known to accumulate and persist in the tissues of humans and animals. One of the alternative methods uses chlorine dioxide, which reduces dioxin emissions significantly but does not eliminate them.

The environmental benefits of the newly developed iron (III)-tetra-amidato macrocyclic ligand (or TAML) activators in paper manufacturing go beyond eliminating dioxin emissions and reducing wastewater production. First, TAML bleaching is more effective, leaving behind only a third of the lignin (the color-causing compound) of traditional bleaching methods. It also works most efficiently at lower temperatures, and the estimated savings from this benefit alone have been calculated at 23.2 million tons of coal per year if 100 percent of paper mills in the U.S. used the TAML activators.[4] This paper bleaching technology has been patented, and license agreements for commercialization already are in place.

TAML oxidant activators also can be used for fuel desulfurization, easily removing more than 85 percent of recalcitrant sulfur compounds in refined fuels. Sulfur is associated with human health impacts, contributes to acid rain, and causes engines to burn less efficiently. The application of these activators in the fuel refining process could lead to cleaner fuels that have higher efficiency.

Potential applications of TAML oxidant activators

- Paper bleaching
- Fuel desulfurization
- Laundry detergents
- Pesticide detoxification
- Drinking water disinfection
- Anthrax decontamination
- Chemical warfare agent decontamination
- Textile mill effluent cleanup

The laundry industry has also benefited from Dr. Collins's activators. TAML-activated peroxide in household bleaches provides the most attractive dye-transfer inhibition and improved stain removal properties. The TAML-peroxide activators used in this process require less water than traditional processes offering both economic and environmental benefits. Dr. Collins and other researchers continue to develop additional uses for the TAML activators including water disinfection, degradation of persistent organic pollutants, and homeland security.

Growing Plastics from Plants

Polylactides (PLAs) are fully biodegradable, completely recyclable plastics derived entirely from a widely available and renewable resource: corn. **Dr. John Dorgan at the Colorado School of Mines** received a TSE grant from EPA in 1998 that helped fund the development of PLAs. Unlike traditional plastics, which are made from non-renewable fossil fuel feedstocks, PLA plastics are produced by the fermentation of corn. This process uses 30 to 50 percent less fossil resources and results in 50 to 70 percent lower carbon dioxide emissions than the typical polyethylene and nylon manufacturing processes for plastics. The production process also uses internal recycling to eliminate waste, preventing pollution at the source and resulting in greater than 95 percent yields.

Dr. Dorgan's TSE grant, which was matched with financial support from Cargill-Dow, funded the research necessary to establish a fundamental scientific understanding of the properties of PLAs. Cargill-Dow now produces 300 million pounds of PLA each year at the word's first global-scale manufacturing facility capable of making commercial-grade plastic resins from an annually renewable resource. The plant in Blair, Nebraska, employs close to 100 people and sells its biodegradable plastics to companies all over the world. Some of the everyday products made from PLA plastics include blister packs, floral wraps, tray inserts, and window films. A number of companies, including Wal-Mart and Del Monte, now use PLA for food packaging.

Dr. Dorgan and his colleagues characterized the basic chain properties of the PLAs, studied the plastic's permeability to gases important to the packaging and food industries, developed a strengthened plastic that combines PLA with a secondary biodegradable plastic, and created a software simulation package which can help facilitate the change-over from the manufacture of traditional plastics to PLA plastics. The research has even led to PLA-based fibers, developed in collaboration with industry, receiving Federal Trade Commission classification as a new generic fiber joining the ranks of cotton, wool, silk, nylon, and polyesters. Seventeen publications and two graduate degree projects in chemical engineering resulted from the research.

RESEARCH HIGHLIGHTS:

- Seventeen articles published
- 30 to 50 percent less fossil fuel resources needed to produce plastics from corn
- 50 to 70 percent reduction in carbon dioxide emissions in corn-based synthesis
- One industrial partner: Cargill-Dow
- 300 million pounds of the newly developed, fully biodegradable, completely recyclable plastics produced each year and distributed world-wide
- Wal-Mart now uses PLA for fresh food packaging
- Two graduate students supported

TSE Program Reach and Relevance

In addition to the successes of the TSE program illustrated in the previous section, other indicators such as program relevance, research awards, and external evaluations contribute to a more complete description of what the program has accomplished. The TSE program is not currently being funded by either agency as results continue to be assessed.

TSE Program Relevance to EPA and NSF Strategic Goals

One measure of the success of the program to date is the extent to which it has supported EPA and NSF strategic goals. The TSE program has supported five of the goals in EPA's *2003-2008 EPA Strategic Plan: Direction for the Future*.[6] The TSE program also has assisted other EPA programs by funding research on innovative technologies for reducing emissions of air toxics from indoor, stationary, and area sources. Some examples are illustrated in Exhibit 7 on the following page.

It has supported three aspects of NSF goals from their *2003-2008 Strategic Plan*[5] that pertain to people, ideas, and tools. TSE grants have provided new opportunities for students to become involved in green science research, promoting the development of a strong community of researchers for the future. Additionally, research funded under the TSE program results in the development of new ideas and tools on the cutting edges of science, engineering, and information technology.

TSE Complements Regional Environmental Protection Programs

TSE's goals and objectives complemented the work of many state and regional environmental protection programs. For example, the Massachusetts Office for Technical Assistance (OTA) for Toxics Use Reduction works with researchers and industry to bring pollution prevention innovations to commercialization. OTA worked with TSE grantee Terry Collins (see pages 12-14) to help develop industry connections, ensuring implementation of his new technology. They provided funding to develop Collins' bench-scale model into a pilot unit that tested the TAML activator bleaching technology on an industrial scale.

And similar to the TSE program, OTA has a strong commitment to both pollution prevention and education. Graduate students funded by OTA grants have worked extensively on developing the TAML bleaching technology, providing key support that are helping bring it to commercialization.

Exhibit 7. How the TSE Program Supports EPA's Strategic Goals	
Goal 1: Clean Air and Global Climate Change	**Supporting the Office of Air and Radiation**
1.1 Healthier Outdoor Air	TSE has funded research in many areas, including solvents and catalysis, that can lead to reductions in emissions of hazardous air pollutants through cleaner alternative manufacturing processes
1.5 Reduce Greenhouse Gas Intensity	Similar to Goal 1.1, the alternative reactions and manufacturing processes being developed by TSE funded researchers offer ways to avoid greenhouse gas emissions, either directly or through reduced energy consumption. Additionally, replacement of petroleum-based feedstocks with bio-based materials reduces CO_2 emissions.
Goal 2: Clean and Safe Water	**Supporting the Office of Water**
2.2.1 Protect the Quality of Rivers, Lakes, and Streams	Alternative manufacturing processes developed with TSE support allow industries to greatly reduce the amount and decrease the concentration of pollutants in wastewater, thus protecting water bodies from pollution.
Goal 3: Land Preservation and Restoration	**Supporting the Office of Solid Waste and Emergency Response**
3.1 Reduce Waste and Increase Recycling	Every research project funded by TSE contributes to waste reduction. Many do so by decreasing the production of waste at the source, while others develop new ways to reuse and recycle waste products.
Goal 4: Healthy Communities and Ecosystems	**Supporting the Office of Prevention, Pesticides, and Toxic Substances**
4.1 Prevent and Reduce Pesticide, Chemical, and Genetically Engineered Biological Organism Risks to Humans, Communities, and Ecosystems	Risks to humans and the environment will be decreased thanks to alternative technologies developed under TSE funding. Environmentally benign chemicals can replace toxic solvents, thus decreasing the risks associated with their acquisition, use, transport, storage, and disposal.
4.3 Protect, Sustain, and Restore the Health of Natural Habitats and Ecosystems	By developing new processes and technologies to minimize the amount of waste and hazardous pollutants produced and released into the environment, TSE-funded researchers contribute to the protection of natural habitats and ecosystems.
Goal 5: Compliance and Environmental Stewardship	**Supporting the Office of Policy, Economics, and Innovation**
5.2 Improve Environmental Performance through Pollution Prevention and Innovation	New green technologies are helping to transform industries traditionally perceived as poor environmental performers into models of green manufacturing.
5.4 Enhance Science and Research Supporting Environmental Policies and Decisions on Compliance, Pollution Prevention, and Environmental Stewardship	TSE-funded research has helped make new low-impact processes and products accessible to industry. The availability of these technologies makes pollution prevention more cost-effective and can strengthen the case for developing new standards that are more protective of the environment.

TSE Research Awards

Another measure that demonstrates the quality of TSE-funded research is the merit awards given to investigators. Prestigious awards won by TSE grantees include the following:

- Presidential Green Chemistry Challenge Academic Award
- Presidential Award for Excellence in Science, Mathematics, and Engineering Mentoring
- Carnegie Science Award for Excellence
- Dreyfus Teacher-Scholar Award
- *Scientific American's* 50 Most Influential Researchers
- R&D 100 Award from *R&D Magazine*

The Presidential Green Chemistry Challenge Academic Award has been won by seven TSE researchers. Sponsored by EPA's Office of Prevention, Pesticides and Toxic Substances, the award recognizes individuals, groups, and organizations for innovations in cleaner, cheaper, smarter chemistry. This award, first granted in 1996, is given annually. As shown in Exhibit 8, TSE grantees have been recognized with academic awards nearly every year since the awards program began.

TSE Evaluation Panel Report

A panel of nine leading scientists from industry, academia, and professional societies met in May 2004 to conduct an independent evaluation of the TSE program. The panel members included highly accomplished senior representatives from the American Institute of Chemical

> "A measure of the quality of investments made through NSF [funding] awards is that nearly all of the academic winners who have received the EPA's Presidential Green Chemistry Challenge Award have been NSF-supported investigators. This award recognizes major contributions to green chemistry and engineering research that have significant societal impact."
>
> — *Arden Bement, Director, National Science Foundation*

Exhibit 8. TSE-funded Investigators Who Have Won the Presidential Green Chemistry Challenge Academic Award[7]

Year	TSE-funded Investigator	Research that Received Award
1997	Joseph M. DeSimone, University of North Carolina at Chapel Hill (EPA)	Design and application of surfactants for carbon dioxide
1998	John W. Frost, Michigan State University (EPA)	Use of microbes as environmentally benign synthetic catalysts
1999	Terry Collins, Carnegie Mellon University (NSF, EPA)	TAML oxidant activators: General activation of hydrogen peroxide for green chemistry
2001	Chao-Jun Li, Tulane University (EPA)	Quasi-nature catalysis: Developing transition metal catalysis in air and water
2002	Eric Beckman, University of Pittsburgh (EPA, NSF)	Design of non-fluorous, highly CO_2-soluble materials
2004	Charles Eckert and Charles Liotta, Georgia Institute of Technology (NSF)	Benign tunable solvents coupling reaction and separation processes
2005	Robin Rogers, University of Alabama (EPA)	A platform strategy using ionic liquids to dissolve and process cellulose for advanced new materials

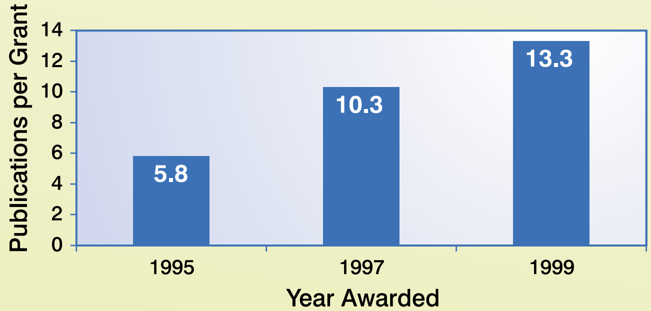
Peer Reviewed Publications from TSE Are Among Those Most Highly Cited

Peer-reviewed publications are the most important means by which credible scientific information is transmitted to and used by other researchers, industry, and government. A random sampling of grantees showed the following:

- As of August 2004, 91 EPA TSE grants produced a total of 372 publications.[8]
- Each grant produces an average of 7.9 publications.
- Approximately 21 percent of these publications were "highly cited publications" according to *ISI Essential Science Indicators* criteria.
- Nearly one-third of the TSE publications were published in "very high-impact" journals—journals that are cited quickly after publication as monitored by *ISI Journal Citation Reports*.

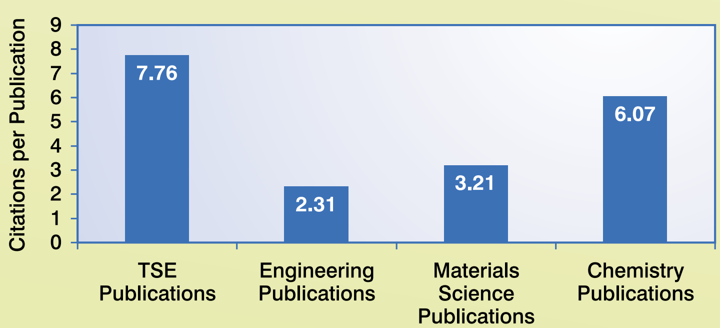
For the three years for which data are available, there is an upward trend in publication rates for the TSE grants. The graph below shows that there was an average of 5.8 publications per grant in 1995, increasing steadily to 13.3 publications per grant in 1999.

Peer-reviewed Publication Rate for TSE Grants by Year Awarded



As shown in the graph, the average citation rate for EPA TSE-funded publications is 7.76 citations per publication, which is above the average citation rates for the fields of engineering and materials science, and comparable to those for the field of chemistry.

Average Citation Rate* for TSE Publications Compared to Individual Fields 1996-2003



*"Citation rate" is the total number of citations from the year of publication to the current year divided by the number of years. It indicates how frequently research articles are subsequently referred to in new research publications.

Engineers, Cameron University, DuPont, Ford Motor Company, Greenpoint Science, the Pacific Northwest National Laboratory, Polytechnic University, the University of Arizona, and the University of California at San Diego. Their expert review was based on historical background materials and presentations by and discussions with the TSE grantees and EPA and NSF officials.[9]

The findings from the evaluation include the following:

- Outputs from TSE research have been of excellent quality, with numerous highly cited publications in highly respected, peer-reviewed journals, and dozens of resulting patents.
- The program's approach has been appropriate and successful in the first years of research.
- EPA and NSF goals are clearly articulated and appropriate.
- Measurable outcomes are being produced, and EPA is developing a mechanism to track these results.

The panel also recommended several strategies to improve the program. These recommendations included holding additional investigator meetings to foster interaction, collaboration, and dissemination of results to industry, EPA regions, states, and the pollution prevention community; and developing formal and informal outreach mechanisms to seek input and feedback about industry needs, program goals, priorities, and outcomes. For example, the TSE program could make presentations to the National Pollution Prevention Roundtable and other similar venues.

Additionally, the panel noted that as the program matures, it is essential to ensure that the goals and desired outcomes are clear and focused. The panel suggested that goals relate more directly to how the program can affect academic researchers, industry, the public, and policy makers in terms of the economy, environment, and society.

> "By fostering a sustainable research community, the TSE program is acting as a catalyst in redefining environmental science and bringing about a paradigm shift toward prevention that will benefit our environment, economy, and quality of life."
>
> — *TSE Evaluation Panel Report*

TSE Program Provides a Foundation

Both EPA and NSF face a very different set of challenges today from those they faced a decade ago. Indeed, the challenges and approaches needed to meet them will change even further over the coming decades. It is important that future research programs anticipate and prepare for these changes. Future programs at both agencies could draw on a broad-scale understanding of technology and technology systems, while still supporting engineering and chemistry foundations. Key areas that could receive greater attention include:

- Identifying gaps and leverage points in technology systems to help achieve sustainability outcomes at the broader systems level.
- Increasing the focus on multi-disciplinary integration – adding to engineering and physical science knowledge by bringing in ideas and experts from other fields in the natural and social sciences.
- Linking research and application by increasing communication and exchange between academia and industry and broadening to wider audiences.

- Understanding and measuring success by tracking long-term direct and indirect benefits from funded grants.

Future research in sustainability could improve understanding technology and technological systems more broadly in time and space. An economy-wide view of materials flow systems can help prioritize opportunities for pollution prevention and the efficient use of materials. This is particularly important for those materials that are potentially harmful to the environment or are used at high volumes. In addition, there is a need for development of the technologies themselves, and also for the broader systems understanding and tools to prioritize and select the technologies. Better understanding the multitude of socioeconomic factors that can influence the development and adoption of new technologies calls for more collaboration across disciplines and between scientist and engineers and decision-makers.

Over the past 15 years, EPA has broadened beyond the traditional command-and-control model of regulation to include other approaches—voluntary, incentive-based, and collaborative—to better achieve environmental results.

Many EPA offices have begun to develop models and strategies for the future that re-examine fundamental approaches to carrying out their missions. For example, a recent Agency report on environmental stewardship sketches a vision that draws from an understanding of the multimedia nature of environmental protection; emphasizes pollution prevention over product lifecycles; emphasizes the substitution of environmentally preferable materials and chemicals; strives to inform the everyday decisions of individuals, companies, and government; and aims for sustainability outcomes. [10]

Sustainability necessarily involves moving toward a shared future, requiring scientists, engineers, and social scientists to interact with each other and the public to refine their research questions and communicate their results. NSF's increasing focus on interdisciplinary research has helped support researchers' important collaborative role. TSE's success thus far has shown NSF's investment in enhancing the quality and productivity of science and engineering to be well-coupled to EPA's goal of protecting the environment.

The TSE grants program has focused on pollution prevention and on funding collaborative research that will lead to applied results, has served EPA well. The program's results to date have contributed to EPA and NSF goals, while its design and focus mesh well with new ways of thinking, new research plans under development, and the new environmental challenges facing our society.

Links to Additional Information

EPA's "Homepage for TSE" web site including a database of grants funded is available at **www.epa.gov/ncer/tse**.

NSF's "Homepage for TSE" is available at **www.nsf.gov/eng/tse/**.

EPA's "Sustainability" web site, at **www.epa.gov/sustainability/**, provides information and links to sustainability planning, practices, scientific tools and technology, progress measures, and new resources and opportunities.

EPA's National Center for Environmental Research "Environmental Research Grant Program Site," located at **www.epa.gov/ncer/**, provides additional access to a database of EPA's TSE STAR grants.

EPA's Office of Prevention, Pesticides and Toxic Substances homepage for the Presidential Green Chemistry Challenge is located at **www.epa.gov/opptintr/greenchemistry/presgcc.html**.

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