NIST Technical Note 1650

U.S. Department of Commerce
National Institute of Standards and Technology

Office of Applied Economics
Building and Fire Research Laboratory
Gaithersburg, Maryland 20899

Benefits and Costs of Research: A Case Study of Improved Service Life Prediction

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Dr. Gary Locke, Secretary

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Dr. Patrick D. Gallagher, Deputy Director

Abstract

The National Institute of Standards and Technology (NIST) is improving its resource allocation process by doing "microstudies" of its research impacts on society. This report is one of a series of microstudies prepared by NIST's Building and Fire Research Laboratory (BFRL).

This report focuses on a critical analysis of the economic impacts of research conducted by BFRL's Service Life Prediction (SLP) Program for High-Performance Polymeric Construction Materials. The SLP Program is an interdisciplinary research effort within BFRL—in collaboration with the private sector, other federal agencies, and other laboratories within NIST—to develop key enabling technologies and advanced measurement technologies needed to deliver high-performance polymeric construction materials to the construction industry. Polymeric materials are used in the construction and building industries in a myriad of applications including protective coatings, sealants and adhesives, siding, roofing, windows, doors, and piping. They can be combined with fibers to form composites that have enhanced properties, enabling them to be used as structural and load-bearing members. Polymers offer many advantages over conventional materials including light weight, corrosion resistance, and ease of processing and installation. This case study of BFRL's SLP-related research, development, and deployment effort illustrates how to apply in practice a series of standardized methods to evaluate and compare the economic impacts of alternative research investments. It is presented in sufficient detail to understand the basis for the economic impact assessment and to reproduce the results.

The results of this study demonstrate that the use of high-performance polymeric construction materials will generate substantial cost savings to materials manufacturers, the owners and managers of commercial buildings, and to other key construction industry stakeholders. The present value of savings nationwide expected from the use of improved SLP products and services is nearly $190 million (measured in 2008 dollars). Furthermore, because of BFRL's involvement, improved SLP products and services are expected to be commercially available on a more-timely basis and in greater quantity. The present value of these cost savings attributable to BFRL is approximately $48 million. These cost savings measure the value of BFRL's contribution for its SLP-related investment costs of approximately $38.5 million. Stated in present value terms, every public dollar invested in BFRL's SLP-related research, development, and deployment effort is expected to generate $1.23 in cost savings to the public.

Keywords

Building economics; building materials; construction; economic analysis; impact evaluation; life-cycle costing; polymeric materials; service life prediction

Preface

This study was conducted by the Office of Applied Economics in the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST). The study is designed to estimate the economic impacts resulting from BFRL research and to estimate the return on BFRL's research investment dollars. The intended audience is the National Institute of Standards and Technology as well as other government and private research groups that are concerned with evaluating how efficiently they allocated their past, present, and future research budgets.

The measurement of economic impacts of research is a major interest of BFRL and of NIST. Managers need to know the impact of their research programs to achieve the maximum social benefits from their limited budgets. The standardized methods for measuring economic impacts employed in this study are essential to support BFRL's effort to evaluate the cost effectiveness of completed and ongoing research projects. As additional experience is gained with the application of these standardized methods, their use will enable BFRL to select the "best" among competing research programs for future funding, to evaluate how cost effective are existing research programs, and to defend or terminate programs on the basis of their economic impact. This need for measurement methods exists across programs in BFRL, in NIST, and in other research laboratories.

Disclaimer

Certain trade names and company products are mentioned in the text in order to adequately specify the technical procedures and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

Disclaimer Regarding Non-Metrics Units

The policy of the National Institute of Standards and Technology is to use metric units in all of its published materials. Because this report is intended for the U.S. construction industry that uses U.S. customary units, it is more practical and less confusing to use U.S. customary units rather than metric units. Measurement values in this report are therefore stated in U.S. customary units first, followed by the corresponding values in metric units within parentheses.

Acknowledgements

The authors wish to thank all those who contributed so many excellent ideas and suggestions for this report. They include Dr. Jonathan Martin, Chief of the Materials and Construction Research Division at NIST's Building and Fire Research Laboratory (BFRL), and Dr. Joannie Chin, manager of BFRL's Service Life Prediction of Nanostructured Polymeric Materials Program, for their technical guidance, suggestions, and support. Special appreciation is extended to Dr. Harold E. Marshall of BFRL's Office of Applied Economics for the thoroughness of his review and for his many insights. Special appreciation is also extended to Dr. Joshua D. Kneifel of BFRL's Office of Applied Economics for his assistance in estimating energy savings from using innovative roofing technologies on low-slope roofs in commercial buildings. Thanks are due to the entire BFRL SLP research team for their assistance in formulating this research effort. And special thanks are due each of the SLP subject matter experts—Drs. Joannie Chin and Li Piin Sung for their guidance on coatings-related issues, Dr. Christopher White for his guidance on sealants and adhesives-related issues, and Dr. Walter Rossiter for his guidance on roofing-related issues. Special thanks are also due to Drs. Jonathan Martin, Joannie Chin, and Christopher White for their assistance in identifying SLP-related benefits and costs. The report has also benefited from the review and technical comments provided by Dr. Nicos S. Martys of BFRL's Materials and Construction Research Division.

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List of Acronyms

Acronym	Definition
AAR	Additions, Alterations and Reconstruction
AHP	Analytical Hierarchy Process
AIRR	Adjusted Internal Rate of return
BFRL	Building and Fire Research Laboboaratory
BSS	Building Science Series
CBECS	Commercial Buildings Energy Consumption Survey
CERL	Construction Engineering Research Laboratory
EPDM	Ethylene-Propylene-Diene Terpolymer
FPL	Forest Products Laboratory
GDP	Gross Domestic Product
HUD	U.S. Department of Housing and Urban Development
M&R	Maintenance and Repair
MARR	Minimum Attractive Rate of Return
NAICS	North American Industrial Classification System
NBS	National Bureau of Standards
NIST	National Institute of Standards and Technology
NRCA	National Roofing Contractors Association
NRCC	National Research Council of Canada
OAE	Office of Applied Economics
OEM	Original Equipment Manufacturers
OMB	Office of Management and Budget
PIC	Polymer Interphase Consortium
PV	Present Value
PVNS	Present Value Net Savings
PVS	Present Value Savings
SERC	Smithsonian Environmental Research Center
SIR	Savings-to-Investment Ratio
SLP	Service Life Prediction
SPHERE	Simulated Photodegradation by High Energy Radiant Exposure
STRS	Scienctific and Technical Research Studies
TV	Terminal Value
USDA	U.S. Department of Agriculture

Executive Summary

The study is designed to estimate the net dollar impacts resulting from BFRL research and to estimate the economic return on BFRL's research investment for its Service Life Prediction (SLP) Program for High-Performance Polymeric Construction Materials. The SLP Program is an interdisciplinary research effort within BFRL—in collaboration with the private sector, other federal agencies, and other laboratories within NIST—to develop key enabling technologies and advanced measurement technologies needed to deliver high-performance polymeric construction materials to the construction industry.

This report on BFRL's SLP-related research, development, and deployment effort illustrates how to apply in practice a series of standardized methods to measure, compare, and evaluate the economic impacts of alternative research investments. It is presented in sufficient detail to understand the basis for the economic impact assessment and to reproduce the results.

The results of this study demonstrate that the use of high-performance polymeric construction materials will generate substantial cost savings to materials manufacturers, the owners and managers of commercial buildings, and to other key construction industry stakeholders. The present value of savings nationwide expected from the use of improved SLP products and services is nearly $190 million (measured in 2008 dollars). Furthermore, because of BFRL's involvement, improved SLP products and services are expected to be commercially available on a more-timely basis and in greater quantity. The present value of these cost savings attributable to BFRL is approximately $48 million. These cost savings measure the value of BFRL's contribution for its SLP-related investment costs of approximately $38.5 million. Stated in terms of the economic return, every public dollar invested in BFRL's SLP-related research, development, and deployment effort is expected to generate $1.23 in cost savings to the public.

Scope of this Study

The economic impact assessment covers a 15-year period from 1994 through 2008. During this period, the focus of BFRL's SLP Program for High-Performance Polymeric Construction Materials was on (1) coatings; (2) sealants and adhesives; and (3) roofing. While these categories of materials are used in all construction industry sectors—industrial, commercial/institutional, infrastructure, and residential—this economic impact assessment, due to data limitations, addresses the commercial/institutional sector only.

The report provides three case studies involving commercial buildings. They are: (1) improved time-to-market for new cool roof technologies; (2) high-performance sealants and adhesives that reduce air infiltration; and (3) high-performance seams for EPDM roofing that reduce warranty repair costs. These three case studies are chosen because the associated benefits are clearly definable and measurable, and they are considered the most substantial. The estimates of benefits and cost savings are based on these three case studies.

The estimated dollar benefits are considered a conservative estimate for two reasons. First, because other types of benefits exist that are less quantifiable in financial terms which are not included in the estimates. One such example is knowledge transfer through scholarly publications. A citation analysis of major SLP publications illustrates the scientific impact of the SLP program and its spillover effects in the research community. For example, the most highly cited article has been cited 109 times. Publications from the SLP program have been cited in a variety of disciplines, including materials science, chemistry, physics, statistics, nanoscience and technology, and civil engineering. The second reason why this economic impact study produces a conservative estimate is that, while improved service life prediction benefits all construction industry sectors, this study focuses only on the commercial sector.

We estimate the part of dollar savings that appears attributable specifically to BFRL's research and development effort. BFRL, through its dual role as a facilitator via industry consortia and as a world-class research institution, hastens the introduction of high-performance polymeric construction materials and expands their base of potential users. This study, in keeping with its conservative approach, suggests a 25/75 split between BFRL's contribution and that of other construction industry stakeholders. This is handled through use of a 0.25 weighting factor for valuing BFRL's contribution.

Methodology for Estimating Costs and Benefits

Two types of analysis were used in this study—a baseline analysis and a sensitivity analysis. In the baseline analysis, all data entering into the benefit, cost, and savings calculations are set at their likely values. In the sensitivity analysis, we change the values of one or more key input variables about which there is uncertainty to measure the impact on project outcomes. A sensitivity analysis complements the baseline analysis by showing how output measures change when selected key sets of data vary about their baseline values.

Three methods, based on ASTM International standard practices, were used to measure the economic performance of the SLP program. These three methods are listed below.

(1) Present Value of Net Savings (PVNS)

> PVNS is used to evaluate investments where there are no significant benefits in terms of revenue or the like, but there are reductions in future costs. PVNS is computed by subtracting the time-adjusted costs of an investment from its time-adjusted savings. If PVNS is positive, the investment is economic; if it is zero,

the investment is as good as the next best investment opportunity; if it is negative, the investment is uneconomical.

(2) Savings-to-Investment Ratio (SIR)

SIR is savings divided by investment costs. A ratio greater than 1.0 indicates an economic investment; a ratio of 1.0 indicates an investment whose benefits or savings just equal its costs; and a ratio less than 1.0 indicates an uneconomic investment.

(3) Adjusted Internal Rate of Return (AIRR)

AIRR is the annual percentage yield from a project over the study period, taking into account reinvestment of interim receipts. An AIRR greater than the minimum attractive rate of return (MARR), set equal to the discount rate, indicates an economic investment; an AIRR equal to the MARR is as good as the next best investment opportunity; an AIRR less than the MARR indicates an uneconomic investment.

U.S. Market for Construction-Related Coatings, Sealants and Adhesives, and Roofing Materials

Polymeric materials are used in the construction and building industries in a myriad of applications including protective coatings, sealants and adhesives, siding, roofing, windows, doors, and piping. They can be combined with fibers to form composites that have enhanced properties, enabling them to be used as structural and load-bearing members. Polymers offer many advantages over conventional materials including light weight, corrosion resistance, and ease of processing and installation.

The U.S. market for construction-related coatings, sealants and adhesives, and low-slope EPDM roofing materials was $17.6 billion in 2008. The market for these materials is summarized in Table ES-1. These values reveal that the economic impacts associated with BFRL's SLP-related research in these areas could be substantial. EPDM roofing materials are specified as being low-slope because EPDM is the single largest roofing material type used for low-slope roofs, and it is not used for steep-slope roofs. Low-sloped roofs are often used on commercial/institutional buildings and industrial facilities.

Table ES-1 U.S. Market for Construction-Related Coatings, Sealants and Adhesives, and Roofing Materials in 2007 and 2008

Type of Material	Millions of Dollars	
	2007	2008
Coatings	10,924.2	10,565.4
Sealants and Adhesives	2,372.3	2,370.8
Low-Slope EPDM Roofing	4,545.2	4,675.6
TOTAL	17,841.7	17,611.9

Baseline Analysis of Economic Impacts

Three case studies were performed to estimate the most measurable benefits of SLP-related research. They are described briefly below.

Improved Time-to-Market for New Cool Roof Technologies

A cool roof reflects a high amount of solar radiation and allows for the rapid remittance of absorbed heat. Cool roofs have been shown to provide significant summertime energy savings. One benefit of improved service life prediction is the faster time-to-market of improved polymeric materials. As improved energy saving technologies are brought to the market sooner, less-efficient products are replaced sooner.

It is assumed that improvements of service life prediction led to early introduction of new, high-performance cool roof coatings beginning in 2005, as opposed to 2008 in the counterfactual scenario. A three-story commercial office building in Los Angeles is used as a model building in the energy simulation. It was estimated that the present value net savings of improved service life prediction on the California cool roof market is $0.82 million. This value was estimated for commercial buildings in California exclusively because California's legislation requires cool roofs to be used in commercial buildings with low-sloped roofs.

High-Performance Sealants and Adhesives that Reduce Air Infiltration

Better performing seals on the exterior façade of a structure reduce energy costs by reducing air and water infiltration into conditioned spaces, and therefore reducing cooling and heating loads as well as reducing water incursion into insulation in the walls. In this case study, a high-performing sealant is compared with a typical sealant. It is assumed that improved service life prediction led to an early introduction of new, high-performance, wet-sealed fenestration beginning in 2004 and expanding into the market place during 2005-2008. A diffusion process was used to estimate the market penetration and resulting value of energy savings.

The present value net savings of improved service life prediction on the heating and cooling of U.S. commercial buildings, from improved window sealants, is estimated to be $10.11 million (2008 dollars).

High-Performance Seams for EPDM Roofing that Reduce Warranty Repair Costs

The reduction in warranty service repair costs is one substantial benefit from better performing EPDM roofing systems. The calculations of these savings are based on "EPDM Roof System Performance: An Update of Historical Warranty Service Costs," authored by James L. Hoff, as well as EPDM roofing statistics from the Census of the Construction Industry and the National Roofing Contractors Association. The total present value of warranty cost savings is estimated to be $178.6 million (2008 dollars).

Cost Savings Nationwide

Total cost savings nationwide from the three case studies are nearly $190 million (2008 dollars). The present value savings attributable to BFRL is $47.4 million (2008 dollars). The investment cost for BFRL's SLP-related research is $38.5 million (2008 dollars). Stated in present value terms, every public dollar invested in BFRL's SLP-related research, development, and deployment effort is expected to generate $1.23 in cost savings to the public. The adjusted internal rate of return of BFRL's investment is estimated to be 8.5 %. Table ES-2 displays these results.

Table ES-2 Summary of Economic Impacts (All Dollar Amounts in 2008 Dollars)

Present Value Cost Savings Nationwide (PVCSN):
Sum from 1994 to 2008 of present value of cost savings nationwide by year
= $189.5 million

Present Value Savings (PVS) Attributable to BFRL:
Sum from 1994 to 2008 of present value of cost savings nationwide by year
= $47.4 million

Present Value Investment Costs (PV Costs) to BFRL:
Sum from 1994 to 2008 of present value of investment cost to BFRL by year
= $38.5 million

Present Value Net Savings (PVNS) Attributable to BFRL:
Difference between present value savings (PVS) attributable to BFRL and present value of investment costs (PV Costs) to BFRL

= $47.4 - $38.5 = $8.8 million

SIR of BFRL Contribution:
Savings-to-Investment Ratio on BFRL investment
= $47.4/$38.5 = 1.23

AIRR of BFRL Contribution:
Adjusted Internal Rate of Return on BFRL investment
$= (1+ 0.07) * 1.23^{1/15} – 1 = 0.085$

Sensitivity Analysis of Economic Impacts

The objective of the sensitivity analysis is to evaluate how uncertainty in the values of the input variables translates into changes in key economic measures. The results of the sensitivity analysis reveal that, on average, the savings outweigh their costs, demonstrated by a present value of net savings (PVNS) of $13.23 million, a savings-to-investment ratio (SIR) of 1.34, and an adjusted internal rate of return (AIRR) of 9 %. Not all simulations produced economic returns, however. The minimum simulated values are -$20.92 million PVNS, 0.46 SIR, and an AIRR of -1 %. The maximum simulated values are $87.76 million PVNS, 3.28 SIR, and an AIRR of 19 %. The results also indicate that the likelihood the true PVNS is greater than 0 is 79 %, that the true SIR is greater than 1.0 is 79 %, and that the true AIRR is greater than 0.07 is 67 %—i.e., there is a 79 % probability that BFRL's SLP-related investments are cost-effective and a 76 % probability that those returns will outperform the 7 % discount rate (0.07).

Suggestions for Further Research

The background research and analysis for this report uncovered additional areas of research. These areas of research are concerned with: (1) the development of standards related to service life prediction; (2) factors affecting the diffusion of new technologies; (3) cool roofs and the heat island effect; and (4) evaluations based on multiattribute decision analysis.

Research Leading to Standards

There is a need for methods for measuring service life prediction (SLP), protocols for evaluating new products before market introduction, protocols for maintaining and servicing new materials and building systems, computer and analytical tools for evaluating SLP, and standard economic methods for evaluating the cost effectiveness of new materials introduction.

Prime topics for standards development include (1) codification of advances in measurement science for coatings and sealants developed in collaboration with the two currently active industry consortia; (2) codification of a protocol for servicing and maintaining EPDM roofs; and (3) a case study of improved sealants for use by manufacturers and customers in choosing sealants to produce and use.

Factors Affecting the Diffusion of New Technologies

Two factors over which a research laboratory exerts some control and which have the potential to reduce uncertainty about new technologies are: (1) the research laboratory’s information dissemination efforts; and (2) the research laboratory’s participation in standards-development organizations. The characteristics of information dissemination are changing dramatically with the advent of the World Wide Web and the increased acceptance of electronic media. This transition needs to be studied to ensure that the information dissemination strategy that emerges is tailored to the needs of the research laboratory’s customer base. For new technologies, acceptance by a standards-making organization should lead both to higher rates of diffusion and to higher levels of adoption. Consequently, research on how a research laboratory’s participation in standards-making organizations affects the rates of diffusion and levels of adoption of new technologies will enable it to improve the efficiency with which it allocates staff and other resources to these activities.

Cool Roofs and the Heat Island Effect

The primary benefit of cool roofs is the reduction in daytime cooling demands in buildings by limiting the amount of heat transfer through a building's roof to interior conditioned spaces. An additional benefit of cool roof technologies is the reduction in the urban heat island effect. The urban heat island effect occurs when the nighttime urban air temperature remains significantly higher than that of neighboring rural areas. Mostly heat, absorbed from the daytime sun, radiating from rooftops and pavement is responsible for the heat island effect. Cool roofs, then, provide a secondary benefit in that they reduce the amount of energy consumption required by evening cooling. Future research could focus on measuring the impact that improvements in service life prediction can have in reducing the urban heat island effect.

Evaluations Based on Multiattribute Decision Analysis

Many research investment alternatives differ in characteristics that decision makers consider important but that are not readily expressed in monetary terms. When non-financial characteristics are important, decision makers need a method that accounts for these characteristics (also called attributes) when choosing among alternative research investments. A class of methods that can accommodate non-monetary benefits and costs is multiattribute decision analysis. The analytical hierarchy process (AHP) is one of a set of multiattribute decision analysis methods that considers non-financial characteristics in addition to common economic evaluation measures when evaluating project alternatives. The AHP and its associated software represent a powerful and versatile management tool. How to apply this management tool most productively in a research environment requires additional research.

1 Introduction

1.1 Background

The pressures of competing in the global marketplace are affecting nearly every U.S. business. Now more than ever, U.S. businesses are finding that they must continually improve their products and services if they are to survive and prosper. Research, with its potential for incremental and breakthrough improvement, is of central importance to most businesses' continuous improvement efforts. A key component of the competitiveness problem is the "inability of American companies (or, more accurately, the U.S.-based portions of what are fast becoming global technology firms) to transform discoveries quickly into high-quality products and into processes for designing, manufacturing, marketing, and distributing such products." [1]

Increasingly, the winners in the competitiveness race are those businesses that most rapidly make use of the fruits of research (e.g., new data, insights, inventions, and prototypes). Efforts underway at the National Institute of Standards and Technology (NIST) and elsewhere in the U.S. focus on speeding up the commercial application of basic and applied research results. The purpose of this report is to respond to the following question: "how do we measure the results of our investments in technology development and application?" [2] A case study approach is used with standardized evaluation methods to measure the economic impacts of investments in three areas of research on high-performance polymeric construction materials.

NIST's research laboratories assist all sectors of U.S. industry through focused research programs. Each laboratory has strong working relationships with industrial, trade, and professional organizations in its areas of technology concentration. The program of NIST's Building and Fire Research Laboratory (BFRL) is guided by a prioritized research agenda developed by experts from the building and fire communities. Its performance prediction and measurement technologies enhance the competitiveness of U.S. industry and public safety. Specifically, BFRL's mission is to promote U.S. innovation and competitiveness by anticipating and meeting the measurement science, standards, and technology needs of the U.S. building and fire safety industries in ways that enhance economic security and improve the quality of life. BFRL studies building

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[1] Reich, Robert W. 1989. "The Quiet Path to Technological Preeminence." *Scientific American* (October): pp. 41-47.

[2] Good, Mary, and Arati Prabhakar. 1994. "Foreword." In Mark Bello and Michael Baum, *Setting Priorities and Measuring Results at the National Institute of Standards and Technology.* Gaithersburg, MD: National Institute of Standards and Technology.

materials; computer-integrated construction practices; fire science and fire safety engineering; and structural, mechanical, and environmental engineering.

BFRL has long recognized the value of measuring the impacts of its research program. Previous studies have shown that even modest research efforts within BFRL are capable of producing significant impacts.[3] One reason for such outcomes is the unique mix of research facilities and skills possessed by BFRL and its staff. Through many years of active collaboration with its various user communities, BFRL's research findings are highly regarded when new building and fire safety technologies are considered for introduction into the U.S. market.

1.2 Purpose

This report is the seventh in a series of impact studies prepared by BFRL.[4] It focuses on a critical analysis of the economic impacts of research conducted by BFRL's Service Life Prediction (SLP) Program for High-Performance Polymeric Construction Materials. The SLP Program is an interdisciplinary research effort within BFRL—in collaboration with

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[3] Marshall, Harold E., and Rosalie T. Ruegg. 1979. *Efficient Allocation of Research Funds: Economic Evaluation Methods with Case Studies in Building Technology.* NBS Special Publication 558. Gaithersburg, MD: National Bureau of Standards.

[4] The first report in the series focuses on two building technology applications: (1) ASHRAE Standard 90-75 for residential energy conservation; and (2) 235 shingles, an improved asphalt shingle for sloped roofing (see Chapman, Robert E., and Sieglinde K. Fuller. 1996. *Benefits and Costs of Research: Two Case Studies in Building Technology*. NISTIR 5840. Gaithersburg, MD: National Institute of Standards and Technology). The second report focuses on a fire technology application: the Fire Safety Evaluation System for health care facilities (see Chapman, Robert E., and Stephen F. Weber. 1996. *Benefits and Costs of Research: A Case Study of the Fire Safety Evaluation System*. NISTIR 5863. Gaithersburg, MD: National Institute of Standards and Technology). The third report focuses on the research, development, deployment, and adoption and use of cybernetic building systems in office buildings (see Chapman, Robert E. 1999. *Benefits and Costs of Research: A Case Study of Cybernetic Building Systems*. NISTIR 6303. Gaithersburg, MD: National Institute of Standards and Technology). The fourth report focuses on the research, development, and deployment, and adoption and use of construction systems integration and automation technologies in industrial facilities (see Chapman, Robert E. 2000. *Benefits and Costs of Research: A Case Study of Construction Systems Integration and Automation Technologies in Industrial Facilities*. NISTIR 6501. Gaithersburg, MD: National Institute of Standards and Technology). The fifth report focuses on the research, development, and deployment, and adoption and use of construction systems integration and automation technologies in commercial buildings (see Chapman, Robert E. 2001. *Benefits and Costs of Research: A Case Study of Construction Systems Integration and Automation Technologies in Commercial Buildings*. NISTIR 6763. Gaithersburg, MD: National Institute of Standards and Technology). The sixth report focuses on a case study of NIST's high performance concrete program (see Helgeson, Jennifer F. 2009. *Benefits and Costs of Research: A Case Study of the NIST High Performance Concrete Program.* NIST Technical Note 1645. Gaithersburg, MD: National Institute of Standards and Technology).

the private sector, other federal agencies, and other laboratories within NIST—to develop key enabling technologies and advanced measurement technologies needed to deliver high-performance polymeric construction materials to the construction industry. Polymeric materials are used in the construction industry in a myriad of applications including protective coatings, sealants and adhesives, siding, roofing, windows, doors, and piping. They can be combined with fibers to form composites that have enhanced properties, enabling them to be used as structural and load-bearing members. Polymers offer many advantages over conventional materials including lightness, corrosion resistance, and ease of processing and installation.

1.3 Scope and Approach

This economic impact assessment covers the period from 1994 through 2008. Therefore, it is an *ex post* or retrospective economic impact assessment. During that period, the focus of BFRL's SLP Program for High-Performance Polymeric Construction Materials was on three categories of materials: (1) coatings; (2) sealants and adhesives; and (3) roofing. SLP products and services in those three categories of materials help all four construction industry sectors—industrial, commercial/institutional, infrastructure, and residential. Although these categories of materials help all four sectors, the data requirements needed to support a rigorous economic impact assessment limited the scope of the economic impact assessment to the commercial/institutional buildings sector. Specifically, this report employs standardized methods to evaluate the expected economic impacts of the adoption and use of SLP products and services in commercial/institutional buildings (e.g., office buildings and educational facilities).

The "case study" approach employed here illustrates how to evaluate and compare the economic impacts of research investments. Standardized methods are used in this report and others in the series to ensure consistency in the measurement of economic impacts. The measurement methods employed here are applicable to other programs in BFRL, in NIST, and in other research laboratories.

The report has nine chapters and an appendix. This first chapter introduces the study. The methodology and the standardized methods employed in the study to measure the economic impacts of BFRL's SLP Program for High-Performance Polymeric Construction Materials are described in Chapter 2. Standardized methods are used to define the key measures of the economic impacts of research investments. A standardized format for summarizing the economic impacts of research investments is also presented.

The body of this report, Chapters 3 through 8, consists of a case study of three categories of SLP-related products and services in commercial/institutional buildings. The approach is to present all SLP-related information in sufficient detail *both to understand* the basis for the economic impact assessment *and to make it possible for the reader to reproduce* the results of the economic impact assessment. The SLP case study is *ex post* (i.e., retrospective) in that it estimates impacts from past research.

This case study estimates the economic impacts to the commercial/institutional buildings sector of the construction industry from BFRL's SLP-related research. Chapter 3 describes BFRL's SLP Program for High-Performance Polymeric Construction Materials. Both the overall SLP research and development effort and the three key areas of research, which are its constituent parts, are described. Chapter 4 provides an overview of the construction industry. The overview provides the context within which the market for SLP products and services is defined. A strategy for measuring SLP-related benefits and costs is presented in Chapter 5. The strategy identifies key stakeholders (e.g., building owners and managers), presents comprehensive lists of SLP-related benefits and costs, and documents the relationships between benefits, costs, and stakeholders. Assumptions about those years over which costs and savings are tabulated, the appropriate discount rate, and the rate and level of adoption of SLP products and services in commercial/institutional buildings are necessary to measure economic impacts. These assumptions, and the supporting data upon which these assumptions are based, are described in Chapter 6. In addition, Chapter 6 develops supporting data for the estimates of the key benefits and costs that are the focus of this *ex post* impact assessment. These "significant few" benefits and costs are well-defined subsets of the comprehensive lists presented in Chapter 5. Estimates of the cost savings from using SLP products and services in commercial/institutional buildings are the focus of Chapter 7. The benefits and cost savings calculated in Chapter 7 are a lower-bound estimate, since our conservative approach included only those which are clearly definable and measurable. In addition, that part of dollar savings that appears attributable specifically to BFRL's research and development effort is estimated. A two-page summary of the SLP case study is given in Section 7.1. Chapter 8 includes a sensitivity analysis to provide the reader with additional background and perspective on the economic impacts of BFRL's SLP Program for High-Performance Polymeric Construction Materials in commercial/institutional buildings. The purpose of the sensitivity analysis is to evaluate the impact of changing the values of a number of key variables whose values are uncertain. Monte Carlo techniques are employed to evaluate how changing the values of these key variables in combination affects the calculated values of the key measures of the economic impacts of SLP products and services in commercial/institutional buildings.

Chapter 9 concludes the report with a summary and suggestions for further research. The appendix is a compilation of stakeholder associations affected by improved service life prediction (e.g., manufacturers of polymeric materials, contractors that install them, and materials-related trade associations and professional societies). The entries are organized along the line of an annotated bibliography. Each entry includes the name of the association, the construction materials involved, the association's website, and a brief description of the association.

2 Methodology for Analyzing Economic Impacts

This chapter focuses on laying out a methodology for conducting and summarizing an economic impact assessment. The methodology is based on two types of analysis, five measures of economic performance, and a format for summarizing the results of an economic impact assessment. The two types of analysis are baseline analysis and sensitivity analysis. They are described in Section 2.1. The five measures of economic performance are present value of net benefits, present value of net savings, benefit-to-cost ratio, savings-to-investment ratio, and adjusted internal rate of return. They are described in Section 2.2. The format for summarizing the results of the economic impact assessment is described in Section 2.3.

2.1 Types of Analysis

2.1.1 Baseline Analysis

The starting point for conducting an economic impact assessment is referred to as the baseline analysis. In the baseline analysis, all data (i.e., all input variables and any functional relationships among these variables) entering into the benefit, cost, and savings calculations are set at their likely values. For selected types of data, the input values are fixed (e.g., a physical constant or a value that is mandated by legislation). The input values associated with these data types are considered to be known with certainty. For other types of data, the likely values reflect the fact that some information associated with these data is uncertain. Consequently, the values of any data subject to uncertainty are set based on some measure of central tendency.[5] Throughout this report, likely value and baseline value are used interchangeably. Baseline data represent a fixed state of analysis based on likely values. For this reason, the results and the analysis of these results are referred to as the baseline analysis. Throughout this report, the term baseline analysis is used to denote a complete analysis in all respects but one; it does not address the effects of uncertainty.

2.1.2 Sensitivity Analysis

Sensitivity analysis measures the impact on project outcomes of changing the values of one or more key input variables about which there is uncertainty. Sensitivity analysis can be performed for any measure of economic performance (e.g., present value of net

[5] Two common measures of central tendency are the mean (e.g., the sum of the individual values of the items divided by the number of items in the sample) and the median (e.g., the middle value in a rank ordering of the individual values of the items in the sample). In most cases in this report, the mean is used as the measure of central tendency. Any case where the median is used as the measure of central tendency is clearly indicated in the text. Consequently, if no explicit reference is made to the measure of central tendency, the measure used is the mean.

benefits, present value of net savings, benefit-to-cost ratio, savings-to-investment ratio, adjusted internal rate of return). Since sensitivity analysis is easy to use and understand, it is widely used in the economic evaluation of government and private-sector applications. Office of Management and Budget *Circular A-94* recommends sensitivity analysis to federal agencies as one technique for treating uncertainty in input variables.[6] Therefore, a sensitivity analysis complements the baseline analysis by evaluating the changes in output measures when selected key sets of data vary about their baseline values. Readers interested in a comprehensive survey on methods for dealing with uncertainty for use in government and private-sector applications are referred to the study by Marshall[7] and the subsequent video[8] and workbook.[9]

2.2 Overview of Evaluation Methods

Several methods of economic evaluation are available to measure the economic performance of a research program, a new technology, a building, a building system, or like investment, over a specified time period. These methods include, but are not limited to, present value of net benefits, present value of net savings, benefit-to-cost ratio, savings-to-investment ratio, and the adjusted internal rate of return. These methods differ in the way in which they are calculated and, to some extent, in their applicability to particular types of investment decisions. The five methods described in this section are based on ASTM International standard practices.[10] Detailed descriptions of each of the standardized methods are given in Chapman and Fuller.[11] Readers interested in an

[6] Executive Office of the President. 1992. *OMB Circular A-94*. Washington, DC: Office of Management and Budget.

[7] Marshall, Harold E. 1988. *Techniques for Treating Uncertainty and Risk in the Economic Evaluation of Building Investments.* NIST Special Publication 757. Gaithersburg, MD: National Institute of Standards and Technology.

[8] Marshall, Harold E. 1992. *Uncertainty and Risk—Part II in the Audiovisual Series on Least-Cost Energy Decisions for Buildings.* Gaithersburg, MD: National Institute of Standards and Technology.

[9] Marshall, Harold E. 1993. *Least-Cost Energy Decisions for Buildings—Part II: Uncertainty and Risk Video Training Workbook*. NISTIR 5178. Gaithersburg, MD: National Institute of Standards and Technology.

[10] ASTM International. Sixth Edition, (2007). *ASTM Standards on Building Economics*. West Conshohocken, PA: ASTM International.

[11] Chapman and Fuller, *Two* Case *Studies in Building Technology*, pp. 27-37.

excellent, in-depth survey covering these as well as other methods are referred to Ruegg and Marshall.[12]

To describe each of the five standardized methods, it is necessary to first introduce and define a series of terms. These terms are used to define each of the standardized methods. Throughout this section the following terms are used as the basis for defining the standardized methods:

$a*$ = the alternative under analysis;

t = a unit of time, where $-t^a$ is the earliest point (i.e., beginning of the study period) before the base year (i.e., t=0) and T is the last point after the base year (i.e., end of the study period);

L = the length of the study period (e.g., $t^a + T$);

B_t^{a*} = the benefits for alternative $a*$ in year t;

I_t^{a*} = the investment costs for alternative $a*$ in year t;

C_t^{a*} = the non-investment costs for alternative $a*$ in year t;

$\underline{\mathbf{C}}_t^{a*}$ = the combined cost for alternative $a*$ in year t (i.e., $\underline{\mathbf{C}}_t^{a*} = I_t^{a*} + C_t^{a*}$);

S_t^{a*} = the savings for alternative $a*$ in year t;

d = the discount rate expressed as a decimal.

Throughout this section the prefix, *PV*, is used to designate dollar denominated quantities in present value terms. The present value is derived by discounting (i.e., using the discount rate) to adjust all benefits, costs, and savings—past, present, and future—to the base year (i.e., t=0). The dollar denominated quantities defined above and their associated present value terms are: the present value of benefits (*PVB*), the present value of investment costs (*PVI*), the present value of non-investment costs (*PVC*), the present value of combined costs ($PV\underline{\mathbf{C}}$), and the present value of savings (*PVS*).

[12] Ruegg, Rosalie T. and Harold E. Marshall. 1990. *Building Economics: Theory and Practice.* New York: Chapman and Hall.

2.2.1 Present Value of Net Benefits and Present Value of Net Savings

The present value of net benefits (PVNB) method is reliable, straightforward, and widely applicable for finding the economically efficient choice among alternatives (e.g., building systems). It measures the amount of net benefits from investing in a given alternative instead of investing in the foregone opportunity (e.g., some other alternative or maintenance of the *status quo*).

PVNB is computed by subtracting the time-adjusted costs of an investment from its time-adjusted benefits. If PVNB is positive, the investment is economic; if it is zero, the investment is as good as the next best investment opportunity; if it is negative, the investment is uneconomical. Emphasis is on economic efficiency because the method is appropriate for evaluating alternatives that compete on benefits, such as revenue or other advantages that are measured in dollars, in addition to costs.

The present value of net savings (PVNS) method is the PVNB method recast to fit the situation where there are no significant benefits in terms of revenue or the like, but there are reductions in future costs (e.g., reductions in the cost of ownership to consumers).[13] By treating savings like revenue benefits, the PVNB method may be reformulated as the PVNS method.

The PVNB for a given alternative, a^*, may be expressed as:

$$\begin{aligned} PVNB^{a^*} &= PVB^{a^*} - PV\underline{\mathbf{C}^{a^*}} \\ &= \sum_{t=-t^a}^{T} \left(B_t^{a^*} - \underline{\mathbf{C}_t^{a^*}} \right) / (1+d)^t \end{aligned} \qquad 2.1$$

If there are no important benefits in terms of revenue or the like, but there are reductions in future costs, then, the PVNS for a given alternative, a^*, may be expressed as:

$$\begin{aligned} PVNS^{a^*} &= PVS^{a^*} - PVI^{a^*} \\ &= \sum_{t=-t^a}^{T} \left(S_t^{a^*} - I_t^{a^*} \right) / (1+d)^t \end{aligned} \qquad 2.2$$

If the decision maker anticipates revenues from the investment, then use the PVNB measure. If the decision maker expects costs to be reduced, then use the PVNS measure.

[13] If there are any benefits, say in the form of revenues or other positive cash flows; add them to the cost savings associated with the alternative under analysis.

The PVNS measure is one of the methods used in the SLP case study (see Chapters 7 and 8).

2.2.2 Benefit-to-Cost Ratio and Savings-to-Investment Ratio

The benefit-to-cost ratio (BCR) and the savings-to-investment ratio (SIR) are numerical ratios whose sizes indicate the economic performance of an investment. The BCR is computed as benefits, net of future non-investment costs, divided by investment costs. The SIR is savings divided by investment costs. The SIR is the BCR method recast to fit the situation where the investment's primary advantage is lower costs. SIR is to BCR as PVNS is to PVNB.

A ratio less than 1.0 indicates an uneconomic investment; a ratio of 1.0 indicates an investment whose benefits or savings just equal its costs; and a ratio greater than 1.0 indicates an economic project. A ratio of, say, 4.75 means that the investor (e.g., the general public for a public-sector research program) can expect to receive $4.75 for every $1.00 invested (e.g., public funds expended), over and above the required rate of return imposed by the discount rate.

The BCR for a given alternative, a^*, may be expressed as:

$$\begin{aligned} BCR^{a^*} &= \left(PVB^{a^*} - PVC^{a^*}\right) / PVI^{a^*} \\ &= \frac{\sum_{t=-t^a}^{T} \left(B_t^{a^*} - C_t^{a^*}\right) / (1+d)^t}{\sum_{t=-t^a}^{T} I_t^{a^*} / (1+d)^t} \end{aligned} \qquad 2.3$$

The SIR for alternative a^* may be expressed as:

$$\begin{aligned} SIR^{a^*} &= PVS^{a^*} / PVI^{a^*} \\ &= \frac{\sum_{t=-t^a}^{T} S_t^{a^*} / (1+d)^t}{\sum_{t=-t^a}^{T} I_t^{a^*} / (1+d)^t} \end{aligned} \qquad 2.4$$

As was the case for the PVNB and PVNS measures, use the BCR if the decision maker anticipates revenues from the investment, and use the SIR if the decision maker anticipates costs to be reduced. The SIR measure is the second method used in the SLP case study (see Chapters 7 and 8).

2.2.3 Adjusted Internal Rate of Return

The adjusted internal rate of return (AIRR) is the annual yield from a project over the study period, taking into account reinvestment of interim receipts. Because the AIRR calculation explicitly includes the reinvestment of all net cash flows, it is instructive to introduce a new term, terminal value (TV). The terminal value of an investment, a^*, is the future value (i.e., the value at the end of the study period) of reinvested net cash flows excluding all investment costs. The terminal value for an investment a^*, is denoted as TV^{a^*}.

The reinvestment rate in the AIRR calculation is equal to the minimum attractive rate of return (MARR), which is assumed to equal the discount rate, d, a constant. When the reinvestment rate is made explicit, all investment costs are easily expressible as a time equivalent initial outlay (i.e., a value at the beginning of the study period) and all non-investment cash flows (e.g., benefits, non-investment costs, savings) as a time equivalent terminal amount. This allows a straightforward comparison of the amount of money that comes out of the investment (i.e., the terminal value) with the amount of money put into the investment (i.e., the time equivalent initial outlay).

The AIRR is defined as the interest rate, r^*, applied to the terminal value, TV^{a^*}, which equates (i.e., discounts) it to the time equivalent value of the initial outlay of investment costs. It is important to note that all investment costs are discounted to a time equivalent initial outlay (i.e., to the beginning of the study period) using the discount rate, d.

Several procedures exist for calculating the AIRR. These procedures are derived and described in detail in the report by Chapman and Fuller.[14] The most convenient procedure for calculating the AIRR is based on its relationship to the BCR (SIR). This procedure results in a closed-form solution for r^*. The AIRR—expressed as a decimal—is that value of r^* for which:

$$\begin{aligned} r^* &= (1+d)(BCR^{a^*})^{\frac{1}{L}} - 1 \\ &= (1+d)(SIR^{a^*})^{\frac{1}{L}} - 1 \end{aligned} \qquad 2.5$$

The AIRR measure is the third method used in the SLP case study (see Chapters 7 and 8).

[14] Chapman and Fuller, *Two Case Studies in Building Technology*, pp. 35-37.

2.2.4 Summary of Methods[15]

The methods presented in the previous sections provide the basis for evaluating the economic performance of research investments. The equations underlying the methods presented earlier are all based on ASTM standard practices. All of the methods are appropriate for evaluating accept or reject type decisions. But among the methods are several distinctions that relate to the type of investment decision the decision maker is facing.

There are four basic types of investment decisions for which an economic analysis is appropriate:

(1) whether to accept or reject a given project;

(2) the most efficient project size/level, system, or design;

(3) the optimal combination of interdependent projects (i.e., the right mix of sizes/levels, systems, and designs for a group of interdependent projects); and

(4) how to prioritize or rank independent projects when the allowable budget can not fund them all.

Each type of investment decision is important in a research environment. First and foremost, decision makers need to know whether or not a particular project or program should be undertaken in the first place. Second, how should a particular research project/program be configured? The third type of decision builds on the second and introduces an important concept, interdependence. Many research projects/programs are multidisciplinary and are analogous to a portfolio. In addition, there may be both economies of scale (e.g., spreading out the use of specialized equipment) and of scope (e.g., packaging of staff talents). Consequently, for a given set of skills, laboratory facilities, candidate projects, and implied interdependencies, the problem becomes how to choose that combination of projects which maximizes PVNB (PVNS). The fourth type of

[15] For a comprehensive treatment of how to choose among economic evaluation methods, see the NIST/BFRL video (Marshall, Harold E. 1995. *Choosing Economic Evaluation Methods—Part III in the Audiovisual Series on Least-Cost Energy Decisions for Buildings*. Gaithersburg, MD: National Institute of Standards and Technology) and workbook (Marshall, Harold E. 1995. *Least-Cost Energy Decisions for Buildings—Part III: Choosing Economic Evaluation Methods Video Training Workbook*. NISTIR 5604. Gaithersburg, MD: National Institute of Standards and Technology).

decision introduces a budget constraint. The key here is how to get the most impact for the given budget amount.

Table 2-1 provides a summary of when it is appropriate to use each of the evaluation methods described earlier. Note that the PVNB (PVNS) method is appropriate in three of the four cases. Only in the presence of a budget constraint is the use of PVNB (PVNS) inappropriate and even in that case it plays an important role in computing the aggregate measure of performance.

Table 2-1 Summary of Appropriateness of Each Standardized Evaluation Method for Each Decision Type

Decision Type	**PVNB** **PVNS**	**BCR** **SIR**	**AIRR**
Accept/Reject	Yes	Yes	Yes
Design/Size	Yes	No	No
Combination (Interdependent)	Yes	No	No
Priority/Ranking (Independent)	No	Yes	Yes

In summary, there are several reasons why multiple measures of economic performance are necessary. First and foremost, managers want to know if a particular research project is economic. Reference to Table 2-1 shows that all of the evaluation methods address this type of decision. Furthermore, these evaluation methods may be used *ex ante* for emerging technologies as well as *ex post* for past research projects. Second, as issues of design, sizing, and packaging combinations of projects become the focus of attention—as often occurs in conjunction with budget reviews—the PVNB (PVNS) method emerges as the principle means for evaluating a project's or program's merits.[16] Finally, the tightening budget picture involves setting priorities. Consequently, decision makers need both measures of magnitude, provided by PVNB (PVNS), and of return, provided by either the BCR (SIR) or the AIRR, to assess economic performance. Multiple measures,

[16] If incremental values of the BCR (SIR) or AIRR are computed, they can be used to make design/size and packaging decisions. See Ruegg and Marshall, *Building Economics*, pp. 54-58 and 85-87.

when used appropriately, ensure consistency in both setting priorities and selecting projects for funding. The results from the SLP case study presented in Chapters 7 and 8 illustrate the importance of multiple measures of economic performance.

2.3 Presentation and Analysis of the Results of an Economic Impact Assessment

The presentation and analysis of the results of an economic impact assessment are central to understanding and accepting its findings. If the presentation is clear and concise, and if the analysis strategy is logical, complete, and carefully spelled out, then the results will stand up under close scrutiny. The purpose of this section is to outline a generic framework for economic impact studies that meets the two previously cited conditions. The generic framework is built upon the following three factors: (1) the significance of the research effort; (2) the analysis strategy; and (3) the calculation of key benefit and cost measures. A specific framework,[17] tailored to BFRL, is given in Exhibit 2-1; it is also used as the basis for summarizing the SLP case study (see Section 7.1).

The discussion that follows relates the three factors for the generic framework referenced above to the specific framework given in Exhibit 2-1. Exposition of the generic framework serves two purposes. First, it provides a means for organizing the way to present material associated with an in-depth economic impact assessment. Second, it provides a vehicle for clearly and concisely presenting the salient results of the analysis. Such a short summary is appropriate for use by senior research managers (e.g., laboratory directors) as the basis for statements on the benefits of the research project or program to the public. A two-page summary of the SLP case study is provided at the beginning of Chapter 7.

2.3.1 Significance of Research Effort

This section of an economic impact assessment sets the stage for the results that follow. The goal at this point is to clearly describe:

(1) why the research is important and how the organization conducting the research became involved; and

(2) why some or all of the changes brought about were due to the research organization's contribution.

Emphasis is placed on providing dollar estimates to define the magnitude of the problem. If any non-financial characteristics are of key importance to senior management, list and

[17] This framework is based on ASTM Standard Guide E 2204 (ASTM International. 2005. *Standard Guide for Summarizing Economic Impacts of Building Related Projects.* E 2204. West Conshohocken, PA: ASTM International.).

describe them briefly. A clear tie into the research organization's mission or vision is included to demonstrate why the organization conducting the research is well qualified and well positioned to participate in the research effort. The section concludes with a statement of the research organization's contribution.

2.3.2 Analysis Strategy

This section of an economic impact assessment focuses on documenting the steps taken to ensure that the analysis strategy is logical and complete. Particular emphasis is placed on summarizing the key assumptions, including any constraints that limited the scope of the study. Responses are provided for key assumptions concerning: (a) the base year for the study; (b) the length of the study period; and (c) the discount rate or minimum acceptable rate of return used.

Special emphasis is placed on documenting the *sources and validity* of any data used to make estimates or projections of key benefit and cost measures. This section establishes an audit trail from the raw data, through data manipulations (e.g., represented by equations and formulae), to the results which describe how to determine:

(1) the present value of **total benefits (savings)** to the nation stemming from all contributors to the research effort under study, any benefits (savings) to users of products (materials, equipment, software, or procedures) stemming from the research effort under study, and any third parties affected positively by either the research effort or the use of products stemming from the research effort;

(2) the present value of **total costs** for all contributors to the research effort under study, any costs to users of products stemming from the research effort under study, and any third parties affected negatively by either the research effort or the use of products stemming from the research effort;

(3) the present value of **net benefits (savings)** to the nation stemming from all contributors to the research effort under study, any users of products stemming from the research effort under study, and any third parties affected by either the research effort or the use of products stemming from the research effort;

Exhibit 2-1 Format for Summarizing the Economic Impacts of BFRL Research Efforts

<table>
<tr>
<td>**1.a Significance of Research Effort:**

Describe why the research is important and how BFRL became involved.

Describe the changes brought about by the BFRL research effort.</td>
<td>**1.b Key Points:**

Highlight two or three key points which convey why this research effort is important.</td>
</tr>
<tr>
<td colspan="2">**2. Analysis Strategy:**

Describe how the present value of ***total benefits (savings)*** *to the nation stemming from all contributions to the research effort was determined.*

Describe how the present value of ***total costs*** *to the nation stemming from all contributors to the research effort was determined.*

Describe how the present value ***net benefits (savings)*** *to the nation was determined.*

Describe how the present value of ***total benefits (savings)*** *attributable to BFRL's research effort was determined.*

Describe how the present value of ***total costs*** *attributable to BFRL's research effort was determined.*

Describe how the present value of ***net benefits (savings)*** *attributable to BFRL's research effort was determined.*

Describe how any ***additional measures*** *were calculated and how BFRL's contribution was determined.*

Summarize key data and assumptions: (a) Base year; (b) Length of study period; (c) Discount rate or minimum acceptable rate of return; (d) Data; and (e) other.</td>
</tr>
<tr>
<td rowspan="2">**3.a Calculation of Benefits, Costs, and Additional Measures:**

Total Benefits (Savings):
Report the present value of the total benefits (savings) attributable to BFRL's research effort.

Total Costs:
Report the present value of the total costs attributable to BFRL's research effort.

Net Benefits (Savings):
Report the present value of net benefits (savings) attributable to BFRL's research effort.

Additional Measures:
Report the values of any additional measures calculated.</td>
<td>**3.b Key Measures:**

Report the calculated value of the Present Value of Net Benefits (PVNB) **or** *the Present Value of Net Savings (PVNS)* attributable to BFRL **and** at least one of the following:
Benefit-to-Cost Ratio (BCR) *or Savings-to-Investment Ratio (SIR)*
Adjusted Internal Rate of Return (AIRR)</td>
</tr>
<tr>
<td>**3.c Traceability**

Cite references to specific ASTM standard practices, ASTM adjuncts, or any other standards, codes, or regulations used.</td>
</tr>
</table>

(4) the present value of **total benefits (savings)** attributable to the research organization's contribution;

(5) the present value of **total costs** attributable to the research organization's contribution;

(6) the present value of **net benefits (savings)** attributable to the research organization's contribution; and

(7) the way in which any **additional measures** were calculated and how the research organization's contribution was determined.

2.3.3 Calculation of Benefits, Costs, and Additional Measures

This section of an economic impact assessment focuses on reporting the calculated values of the key benefit and cost measures, as well as any additional measures that are deemed appropriate, and establishing traceabilty to standardized practices or, where appropriate, to statutory documents or procedures. It consists of three subsections, designated as 3.a, 3.b, and 3.c. Subsection 3.a includes descriptive information as well as calculated values. Subsection 3.b reports calculated values for key summary impact measures. Subsection 3.c is included to ensure traceability to appropriate national standards, codes, or regulations.

In subsection 3.a, report summaries (e.g., using text, mathematical expressions, tables, graphs, comparative statistics) of the following information:

(1) the present value of the total benefits attributable to the research organization's contribution;

(2) the present value of the total costs attributable to the research organization's contribution;

(3) the present value of net benefits attributable to the research organization's contribution; and

(4) the values of any additional measures calculated.

In subsection 3.b, report the calculated value of the present value of net benefits *or the present value of net savings* attributable to the research organization's contribution and at least one of the following:

(a) the benefit-to-cost ratio *or the savings-to-investment ratio*; or

(b) the adjusted internal rate of return.

In subsection 3.c, cite references to specific ASTM standard practices, ASTM adjuncts, or any other standards, codes, or regulations used.

3 Building and Fire Research Laboratory's Service Life Prediction (SLP) Program for High-Performance Polymeric Construction Materials

Polymeric materials are used in the construction and building industries in a myriad of applications including protective coatings, sealants and adhesives, siding, roofing, windows, doors, and piping. They can be combined with fibers to form composites that have enhanced properties, enabling them to be used as structural and load-bearing members. Polymers offer many advantages over conventional materials including light weight, corrosion resistance, and ease of processing and installation.[18]

3.1 Service Life Prediction Methodologies: An Evolutionary Process

Although most building and construction materials are expected to have service lives of several decades, until recently no methods were available for making reliable predictions of service lives either from short-term tests or from science-based first principles. The lack of generally-accepted methods for service life prediction has been a barrier to the most effective selection, use and maintenance of building and construction materials, and has been cited as an important contributor to premature failures. It is also a barrier to innovation since designers are reluctant to specify products for which evidence of performance over time is lacking. The need to reduce costs associated with repairs, replacements, and maintenance, and to assess the service lives of innovative materials without decades of field testing led to the creation of BFRL's research program on service life prediction in 1973.

By 1978, the first of the needed service life prediction standards was in place as ASTM E 632, Standard Practice for Developing Short-Term Accelerated Tests for Prediction of the Service Life of Building Materials and Components. Also in 1978, an international conference on the Durability of Building Materials and Components was held in Ottawa with the National Research Council of Canada (NRCC), NBS, ASTM, and RILEM as sponsors. A keynote paper on "The Measuring of Durability and Durability Prediction" that BFRL researchers Geoffrey Frohnsdorff and Larry Masters[19] presented at the conference suggested that the reliability approach might be brought in to service life predictions of building materials. The 1978 conference became the first in the series of

[18] Some of the material presented in this chapter draws on historical information presented in Wright, Richard N. *Building and Fire Research at NBS/NIST 1975-2000*. Building Science Series 179, National Institute of Standards and Technology, 2003.

[19] Geoffrey J. Frohnsdorff and Larry W. Masters, "The Meaning of Durability and Durability Prediction," *Durability of Building Materials*, (eds., P.J. Sereda and G. G. Litvan), Special Technical Publication, STP 691, American Society of Testing and Materials Philadelphia, PA, pp 17-30.

triennial International Conferences on the Durability of Building Materials and Components (DBMC) sponsored by NRCC, NBS, RILEM and CIB.

When Jonathan Martin joined BFRL's materials research staff in 1978, he introduced the reliability-based approach to service life prediction. The reliability-based methodology,[20] with its rigorous experimental procedure and strong scientific basis, had already had a long history of successful application in the electronics, aerospace, nuclear, and medical fields. In a reliability-based methodology, since weathering factors cannot be controlled, results of field exposure experiments are not the standard of performance; however, they may be an important source of data if the weathering factors can be monitored just as they are in the laboratory. The standard of performance is now based on laboratory experiments that can be made repeatable and reproducible if the sources of experimental error are minimized; with proper design, the experiments can provide data from which service life under any expected condition can be predicted. There is no longer a need to try to design laboratory experiments that simulate outdoor exposures since the laboratory experiments can cover the range of exposure conditions that a product will be exposed to in the field. With the paradigm shift accompanying adoption of the reliability-based methodology, laboratory accelerated aging and fundamental mechanistic experiments are, for all practical purposes, equivalent except for the number of experimental variables under investigation.

3.1.1 Coatings

The industrial significance of BFRL's reliability-based approach was first recognized by the coatings community. In 1994, a research consortium was established. The consortium included several leading coatings manufacturers among its members. Its objective was to apply a reliability-based methodology in estimating the service life of a coating or other polymeric building material subjected to ultraviolet radiation and other weathering factors. Though initially established for a three-year period, the achievements of the consortium were sufficiently encouraging that it was extended for two additional three-year periods. In view of the need to disseminate knowledge of the reliability-based approach, NIST and the Ford Motor Company, initiated a series of international conferences on prediction of service life of coatings, and on polymeric materials in general. The first two conferences were held in 1997[21] and 1999.[22]

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[20] Jonathan W. Martin, S. C. Sauders, F. L. Floyd, and J. P.Wineburg, *Methodologies for Predicting the Service Life of Coating Systems*, Federation Series on Coating Technology, Federation of Societies for Coatings Technology, Philadelphia, PA, 1996.

[21] David R. Bauer and Jonathan W. Martin, Eds., *Service Life Prediction of Organic Coatings: A Systems Approach*, ACS Symposium Series 722, American Chemical Society, Oxford University Press, New York, pp 470, 1999.

The reliability-based methodology requires the sets of data collected from the three primary sources of service life data (field, accelerated laboratory, and fundamental mechanistic studies) to have the same data elements and to be of comparable quality. Data is needed on the initial properties of a material, on changes in the properties of the material as functions of time, and on the weathering factors in the exposure environment as functions of time. Data needed on the exposure environments, whether in the laboratory or field, are usually spectral irradiance, spectral distribution, specimen temperature, and specimen moisture content.

With the need for measurements to improve reliability-based service life predictions, BFRL designed a completely new laboratory exposure device, the NIST SPHERE (Simulated Photodegradation by High Energy Radiant Exposure) to minimize the temporal, spatial, systematic, equipment, and operational sources of error encountered in earlier commercial devices. In the NIST SPHERE,[23] each of the 32 similar ports on the surface of a 2 m diameter integrating sphere opens into the sphere's interior. The interior is illuminated by an intense source of visible and ultraviolet radiation at the top of the NIST SPHERE. The ports provide essentially-identical sources of radiation for exposure chambers attached to the ports through parabolic cone concentrators. Because of the uniformity of the radiation within the NIST SPHERE, monitoring the radiation emitted from a single port is equivalent to monitoring the radiation emitted from every port. Conditions within any of the exposure chambers can be controlled for spectral radiation, temperature, and relative humidity, and for almost any other factor of interest (e.g., mechanical loads). Large numbers of small specimens can be exposed in each of the chambers, and the specimens can be easily removed for analysis to determine the degree of degradation. The ability to provide a variety of precisely-controlled exposures of large numbers of specimens greatly increases the power and practicality of applying the reliability-based approach to prediction of service lives under any specified conditions. One of the early findings from the reliability-based experiments was the unexpectedly strong dependence of rate of photodegradation on the moisture content within a coating.[24]

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[22] Jonathan W. Martin and David R. Bauer, Eds., *Service Life Prediction: Methodologies and Metrologies*, ACS Symposium Series 805, American Chemical Society, Oxford University Press, New York pp 516, 2001.

[23] Joannie Chin, E. E. Byrd, Edward N. Embree, and Jonathan W. Marin, "Integrating Sphere Sources or UV Exposure: A Novel Approach to the Artificial UV Weathering of Coatings, Plastics, and Composites," *Service Life Prediction Methodology and Metrologies*, (eds., Jonathan W. Martin and D. R. Bauer), American Chemical Society Symposium Series 805, Oxford Press, New York, p 144, 2001.

[24] Tinh Nguyen, Jonathan W. Martin, E. E. Byrd, and Edward N. Embree, "Effects of Relative Humidity on Photodegradation of Acrylic Melamine – A Quantitative Study," *Proceedings of the Polymeric Materials Science and Engineering Division*, American Chemical Society, 83, 118, 2000.

The need for high-quality field data for use with data from the NIST SPHERE in predicting the service lives of materials in the field was accompanied by a need for access to strategically-located, well-instrumented, field exposure sites. The establishment of eight such sites at widely-spaced locations within the U.S. was carried out as a cooperative project among four Federal Agencies with overlapping interests – NIST, the Smithsonian Environmental Research Center (SERC), the USDA UV-B Network Program, and the Forest Products Laboratory (FPL) at Madison, WI.[25] With the establishment of these sites, NIST has put in place all the necessary components for development and demonstration of its world-class capability to apply the reliability approach to the prediction of the service lives of polymeric building materials including paints and coatings, building joint sealants, and composites.

3.1.2 Sealants and Adhesives

Polymeric sealant materials represent an essential component of modern construction. They serve in the weatherproofing of buildings and structures by preventing unwanted moisture intrusion and subsequent water damage and by limiting energy loss in joints surrounding doors and fenestration. The ability of a sealant to perform its function over its lifetime, however, is affected by both its properties and exposure history. When exposed outdoors, sealants undergo chemical, physical, and mechanical degradation caused by ultraviolet radiation in addition to temperature- and moisture-induced cyclic displacements of a sealant joint in response to diurnal, seasonal, and annual variations in the weather.

Historically, the durability of a sealant has been assessed from results obtained from prescriptive standards, which were developed over the last 60 years and were not designed and never intended for obtaining fundamental understanding of the failure modes of a sealant joint and, indeed, they only provide qualitative assessments of the performance of a sealant. The lack of fundamental understanding of sealant failure modes has made it impossible to accurately and precisely predict the service life of a sealant.

As a replacement for the prescriptive methodology, BFRL researchers implemented a reliability-based methodology for linking field and laboratory exposure results for sealants. This methodology is scientifically rigorous and has been successfully applied in predicting the service live performance of wide variety of products used in the electronics, medical, and aerospace industries. In this methodology, controlled experiments are designed for the laboratory, while field experiments mainly provide

[25] Lawrence J. Kaetzel, "Data Management and a Spectral Solar UV Network," *Service Life Prediction Methodology and Metrologies*, (Eds., Jonathan W. Martin and D. R. Bauer) American Chemical Society Symposium Series 805, Oxford Press, New York, p 89, 2001.

valuable information regarding the dominant failure modes and expected service lives for specimens exposed in a specified location. Since much of this research was carried out in conjunction with a NIST/industry sealants consortium, details are given in Section 3.2.2.

3.1.3 Roofing Materials

In 1969, C.W. Griffin[26] wrote that "the volume of built-up roofing annually installed in the United States totals 2 billion square feet…Probably 10 to 15 percent of the roofs…fail prematurely." Statements such as Griffin's made it evident that the U.S. membrane roofing industry urgently needed to improve the performance of its products. One of the major problems of the era was poor characterization of the engineering properties of built-up-roofing (BUR) membranes.

Consequently, specifications detailing the performance requirements for completed BUR membranes were non-existent. In contrast, prescriptive specifications indicating the type and number of reinforcing plies, and the type and amount of bitumen were the norm. A common result was that installed membranes had inadequate properties to perform satisfactorily.

This situation changed dramatically, when in 1974, BFRL researchers Robert Mathey and William Cullen published Building Science Series (BSS) 55, Preliminary Performance Criteria for Bituminous Membrane Roofing.[27] For the first time, the U.S. membrane roofing industry had guidance for selecting membranes based on their performance properties. Mathey and Cullen identified 20 performance attributes considered important to the satisfactory performance of BUR membranes, and they suggested performance criteria for 10 of these attributes. The performance concept, applied to BUR membranes, was widely embraced by the industry. Specifiers selected membranes on the basis of their conformance to the criteria, manufacturers promoted (where appropriate) existing products, and developed new products, meeting the criteria. Consultants investigating performance problems with in place membranes compared properties with the BSS 55 recommendations. Roofing contractors were perhaps the most vocal group of supporters and, in this regard, the National Roofing Contractors Association (NRCA) Manual incorporated recommendations that installed membranes have performance properties in accordance with BSS 55 criteria.

The impact of BSS 55 has been long lasting. For example, at an NRCA annual convention in the late 1980's, the Owens-Corning Company made a presentation on the history and performance of BUR systems in the U.S. The development of BSS 55 was

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[26] C. W. Griffin, *Manual of Built-Up Roof Systems*, McGraw-Hill, New York, NY, p 1, 1970.

[27] Robert G. Mathey and W. C. Cullen, *Preliminary Performance Criteria for Bituminous Membrane Roofing*, Building Science Series 55, National Bureau of Standards, 1974.

recognized as a significant milestone in the industry's history, and a major driving force behind the significant improvements in BUR performance that occurred over the 15 year period after the report's publication.

Another major issue that faced the BUR industry in the early 1970's centered on restrictive requirements that severely limited the temperature to which asphalt could be heated during installation of built-up membranes. One consequence was that asphalt was often applied at temperatures too low for proper flow. Improper flow results in excessively thick, non-uniform asphalt layers that may contain voids and that may be inadequately adhered to membrane reinforcing felts. As a solution to this asphalt heating problem, industry task groups proposed the Equiviscous Temperature concept. According to this concept, asphalt was to be applied at a temperature at which it would flow sufficiently to achieve well-adhered, uniformly thin, void-free layers between membrane plies. In support of the industry efforts, BFRL researchers Walter Rossiter and Robert Mathey authored BSS 92, The Viscosities of Roofing Asphalts at Application Temperature.[28] BSS 92, which described a combined laboratory and field study, was a cornerstone of the technical foundation for the Equiviscous Temperature Concept. In the laboratory, the viscosities of 20 typical roofing asphalts were measured over their application temperatures, and compared with softening points and penetrations. These data demonstrated that different asphalts had different viscosity-temperature relationships, and that asphalt application temperatures should be determined on the basis of viscosity. In the field, BUR membrane samples were prepared using typical roofing asphalts heated at different temperatures encompassing the range of application temperatures encountered in practice. These BUR samples were analyzed to relate the quality of the asphalt application to the application temperature and, in turn, the viscosity at application. Soon after publication of BSS 92, the industry adopted the Equiviscous Temperature Concept which remains in use today.

As noted above in the quote from Griffin, at the beginning of the 1970s built-up roofing had a monopoly on the U.S. membrane market. However, the monopoly was soon to be broken. Because of the all-too-frequent problems with BUR membranes in the early 1970s, many owners, architects, specifiers, and others responsible for roof system selection were eager to find alternative membrane materials. In response, material suppliers emerged who provided, at competitive costs, alternative systems based on elastomeric and thermoplastic polymeric membranes, and polymer-modified bituminous membranes. The growth in use of these products was explosive. Although their use was almost non-existent in the mid-1970s, by the end of the 1980s they accounted for about 70 percent of the membranes installed in the U.S. – a figure that has remained reasonably

[28] Walter J. Rossiter and Robert G. Mathey, *The Viscosities of Roofing Asphalts and Application Temperatures*, Building Science Series 92, National Bureau of Standards, 1976.

constant through today. However, the growth in use was not problem free. These membranes had been introduced into the market without consensus standards to assist in their proper selection and use. Research was needed to understand better the performance of these systems, to develop solutions to the problems that were arising, and to contribute to the technical bases of the much needed consensus standards.

Of the new membrane materials that entered the market in the mid-1970s EPDM (ethylene-propylene-diene terpolymer) rubber, manufactured as preformed single-ply sheets ready for field installation, experienced the most rapid growth. By the mid-1980s, it accounted for about 35 percent of the membrane market. EPDM is rather chemically inert rubber, which makes it attractive for outdoor use as a membrane material. However, this chemical inertness becomes a limitation when bonding adjacent sheets in the field to form the seams of a waterproofing membrane. At the time, these seams were typically fabricated with contact-type, polymer-based, liquid adhesives. In the mid-1980s, unsatisfactory seam performance accounted for about 50 percent of the EPDM membrane problems reported to the NRCA in surveys of member contractors. BFRL initiated research to elucidate the factors affecting performance and to develop solutions for improved performance.

Reports from NRCA in the late 1980s indicated that many seam defects developed within the first three years of service. In these cases, disbonded seams were seen to be located at buckles and ripples in the EPDM membrane. BFRL researchers reasoned that many of these early failures were related to the rheological behavior of the adhesive and not to chemically-induced deterioration. Consequently, BFRL research staff began studies to elucidate the major factors affecting the capability of seams to sustain loading. They developed creep-rupture test protocols, suitable to EPDM seams, in which joint specimens were stressed under constant load and the time over which they sustained the load was recorded. The better performing seams had longer times-to-failure. The factors investigated included material parameters such as the adhesive and its applied thickness, mechanical parameters such as the magnitude and type (i.e., peel and shear) of load, environmental parameters such as temperature, moisture and ozone, and application parameters such as the cleanness of the EPDM rubber surface.

Initial creep-rupture experiments and major findings were described in BSS 169, Strength and Creep-Rupture Properties of Adhesive-Bonded EPDM Joints Stressed in Peel.[29] Chief among the findings was that the thickness of the adhesive layer was an extremely important parameter affecting performance, as time-to-failure increased exponentially with adhesive thickness. Additionally, the cleanness of the EPDM rubber at the time of

[29] Jonathan W. Martin, Edward Embree, Paul E. Stutzman, and J. A. Lechner, *Strength and Creep-Rupture Properties of Adhesive-Bonded EPDM Joints Stressed in Peel*, Building Science Series 169, National Institute of Standards and Technology, 1990.

the adhesive application was also shown to be significant. Although industry had always required that EPDM rubber was to be thoroughly cleaned before adhesive application, until BSS 169, the importance influence of adhesive thickness on seam performance had been given little attention by practitioners. BFRL observations from field inspections showed, for example, that the thickness of adhesive layers often was less than EPDM manufacturers' recommendations. Although the relationship between adhesive thickness and seam performance was surprising to many, its implications were taken seriously. In 1991, the NRCA published,[30] with BFRL assistance, a feature article entitled, "Is Your Adhesive Layer Thick Enough?" to alert contractors to the importance of adhesive thickness. At least one EPDM membrane manufacturer made available wet-film thickness gages to help ensure that the amount of applied adhesive was within prescribed limits.

BSS 169 demonstrated the importance of creep-rupture tests in evaluating seam performance. In 1993, ASTM issued Standard Test Method D 5405, Conducting Time-to-Failure (Creep-Rupture) Tests of Joints Fabricated from Nonbituminous Organic Roof Membrane Material. This test method is based on BFRL seam research, and provides a comprehensive procedure for investigating factors affecting seam performance under loading conditions that may lead to failure in the field.

Since 1993 when ASTM D 5405 was issued, experience has shown that the performance of both butyl-based, liquid-adhesive-bonded and performed-tape-bonded seams of EPDM roofing membranes has been satisfactory. At the time of publication of this current report, adhesive tapes dominate the EPDM seam market. The availability of D 5405 coupled with NIST's consortium-based research on tap-bonded seams was among the important contributors leading to the acceptance of tape adhesives. The tape seam consortium and its major findings are summarized in Section 3.2.3.

3.2 Critical Role of Industrial Consortia

Since the early 1990's, BFRL has launched four industry consortia concerned with service life prediction of polymeric materials: two on coatings, one on sealants, and one on the performance of tape-bonded seams for EPDM roofing membranes. Two of the four consortia are still active, an indication of the value of BFRL's research to key industry stakeholders.

3.2.1 Service Life Prediction of Polymer Coatings Consortium

The industrial significance of BFRL's reliability-based approach was first recognized by the coatings community. In 1994, a research consortium – the Coatings Service Life

[30] Jonathan W. Martin, Walter J. Rossiter, Jr., and Edward Embree, "Is Your Adhesive Layer Thick Enough?" *Professional Roofing*, Vol. 21, No. 5, pp 30-37, May 1991.

Performance Consortium involving industry, government and academe – was established. The consortium included several leading coatings manufacturers among its members. Its objective was to apply a reliability-based methodology in estimating the service life of a coating or other polymeric building material subjected to ultraviolet radiation and other weathering factors. Though initially established for a three-year period, the achievements of the consortium were sufficiently encouraging that it was extended for two additional three-year periods.

In order to implement the reliability-based methodology, a laboratory exposure device was needed that had higher reproducibility and repeatability than the available commercial devices. To this end, BFRL researchers designed and constructed a novel analytical laboratory exposure device in which the primary environmental weathering factors (e.g., temperature, moisture, and spectral ultraviolet irradiance) can be independently, precisely, and accurately monitored and controlled over long exposure periods. This device, now known as SPHERE (Simulated Photodegradation via High Energy Radiant Exposure, possessed an irradiance exposure uniformity of greater than 95 %, irradiance levels approaching 22 suns, and capability for extremely precise temperature and relative humidity control in the specimen chambers. Model acrylic and epoxy coatings were exposed on SPHERE and in outdoor test racks to generate data that ultimately validated the reliability-based service life prediction models.

In view of the need to disseminate knowledge of the reliability-based approach, NIST and the Ford Motor Company, initiated a series of international conferences, sponsored by the American Chemical Society, on prediction of service life of coatings, and on polymeric materials in general. To date, four international conferences have been held on service life predictions in organic coatings. In these four conferences, between 65 to 85 attendees participated, representing government laboratories and agencies, private laboratories, coating manufacturers, suppliers to coating manufacturers, coating end-users, universities, and other stakeholders from the U.S. and several other countries. These international conferences provide a forum in which the current state of knowledge and industry needs are identified, and what needs to bridge the knowledge gap is brainstormed.

A book was published as a result of each of these four conferences. These books are compilation of conference papers, and they provide a summary of the conference, documenting scientific advances and attendees' perspectives on directions and strategies for moving forward. The first conference was held in Breckenridge, Colorado in 1997. In this conference, discussions centered around framing the problem. Better quantification of weather, better laboratory testing, and the construction and use of verified materials databases in the coatings industry were some of the issues identified as needs of the industry.[31]

The second conference was held in Monterey, California in November of 1999. An attendee commented that this conference "reports on the transition of service life prediction in coatings from an art to a science and finally to an engineering tool." [32] While much progress has been made, more research remains to be done. One important topic area is to establish the relationships between in-service exposure tests and laboratory exposure tests so that results from outdoor exposure tests can be reproduced in the laboratory. There is also a need to characterize coatings and their degradation processes. Models are critical for using short-term experimental results to predict long-term performance. Papers presented at the conference address these three broad topic areas.

The third conference took place in Sedona, Arizona in February of 2004. Advances in replicating field exposure in the laboratory setting and in linking field exposure to laboratory simulated exposure were reported, as well as advances in informatics, regarding high-throughput and combinatorial analyses, data collection, and data storage formats.[33] Discussion topics also included attributes of an ideal methodology for service life predictions, approaches to implement advances in knowledge, and legal issues regarding limited warranties on coatings. There was a stronger sense of community, with participants wishing to form working sub-groups on a number of topics to accelerate progress.

The fourth conference was held in Key Largo, Florida in December of 2006. Much progress has been reported, as in previous conferences. Using the reliability-based methodology, a single model derived from laboratory data with a minimal set of assumptions was shown to link laboratory and field exposure results and can subsequently be used to predict material performance.[34] This pioneering work was a significant contribution to service life prediction. In this conference, there was a stronger

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[31] David R. Bauer and Jonathan W. Martin, Eds., *Service Life Prediction of Organic Coatings: A Systems Approach*, ACS Symposium Series 722, American Chemical Society, Oxford University Press, New York. 1999.

[32] Jonathan W. Martin and David R. Bauer, Eds., *Service Life Prediction: Methodologies and Metrologies*, ACS Symposium Series 805, American Chemical Society, Oxford University Press, New York. 2001.

[33] Jonathan W. Martin, Rose A. Ryntz, and Ray A. Dickie, Eds., *Service Life Prediction: Challenging the Status Quo*, Federation of Societies for Coatings Technology. 2005.

[34] Jonathan W. Martin, Rose A. Ryntz, Joannie Chin, and Ray A. Dickie, Eds., *Service Life Prediction of Polymeric Materials: Global Perspectives*, Federation of Societies for Coatings Technology. 2009.

sense of community with individuals collaborating on larger projects. There was a lot of motivation for moving forward.

Following on the success of the Coatings Service Life Performance Consortium, BFRL's research emphasis shifted to the interface region or interphase, the area where the molecules of two materials interact with each other. The interphase is vital to the durability and performance of particle-filled materials, paints on plastics and metals, and fiber-reinforced composites. Recognizing the complexity and importance of the interface/interphase (including film/air interface) on the performance and service life of polymeric systems, NIST and key industry stakeholders held a series of meetings and sponsored two workshops in 1997 and 1999 to address the problems on "Characterization and Modeling of the Interface/Interphase of Polymeric Materials and Systems." As a result of these workshops and further discussions with industry, the Polymer Interphase Consortium (PIC) was formed in December 2000.

The main objective of PIC is to develop methodologies and metrologies for testing, characterization, and modeling of surface and interphase of polymeric coatings and plastics. The consortium is organized around three phases: Phase I (January 18, 2001 – September 30, 2004); Phase II (October 1, 2004 – March 31, 2008); and Phase III (started on January 1, 2009).

There were three projects in Phase I: (1) mechanical characterization of polymer surfaces; (2) effects of shear flow and thermal gradients; and (3) interphase characterization. The three projects were carefully chosen for the first phase consortium study to address the immediate research needs identified by the industry.

There were three projects in Phase II: (1) methodologies for scratch testing and relating scratch morphology to appearance properties of polymeric coatings and plastics; (2) surface nanomechanical characterization of polymeric coatings and plastics through instrumented indentation; and (3) application and development of photon-based imaging techniques for characterization of the chemical and morphological microstructure of polymeric materials and interfaces. Materials of interest for Phase II included automotive clear coat systems, impact modified thermoplastics, and polymer blend architectural coatings.

Phase III has been renamed as PSI (Polymer Surface/Interface). Prior to the start of Phase III, a NIST/PIC Workshop was held on January 16, 2008. Discussions with prospective industrial partners on areas of interest in the field of polymer surfaces, interfaces, and interphases research took place during the workshop. Based on inputs from interested industrial partners, BFRL shaped and refined its research plans to develop new methods for chemical, optical, and mechanical characterization of polymer interfaces. In particular, BFRL is interested in combining these technologies to relate material properties to performance. The new focus projects are: (1) mechanical properties and failure at the surface and interface of polymeric coatings and nanocomposites; and (2) methodologies for characterizing optical properties and scratch resistance assessment for polymeric coatings, plastics, and nanocomposites.

3.2.2 Sealants Service Life Prediction Consortium

In 2000, NIST/BFRL was asked by representatives of the sealants industry to establish a NIST/industry consortium to address their need for a predictive service life methodology. The industry representatives also expressed their willingness to put both their financial and intellectual resources behind this effort. Given this commitment, the Sealants Service Life Prediction Consortium was established in late 2001. The consortium included ten industrial members, accounting for a significant portion of the world's sealant production capacity, along with two other federal agencies (the Department of Housing and Urban Development (HUD) and USDA's Forest Products Laboratory in Madison, WI). In 2009, the consortium is still active and highly engaged with NIST, and possesses all but one of its original members.

From its inception, the consortium has focused on developing performance based standards. The three consortium research objectives are:

- Generating repeatable and reproducible exposure results, in the laboratory and in the field,
- Gaining a fundamental understanding of sealant failure modes and mechanisms, and
- Linking field and laboratory exposure results.

The SPHERE weathering device developed in the Coatings Service Life Prediction Consortium was extended by BFRL researchers to have capability for mechanical loading. This device has allowed researchers to study the quantitative relationship between the failure mechanisms causing a sealant to degrade and the environmental factors causing this degradation. More importantly, this device has consistently been able to generate repeatable and reproducible exposure results. White has also designed and constructed several novel field exposure devices. These devices have been constructed to subject sealant specimens to exactly the same stress regimes, to monitor outdoor weathering variables, and to measure displacement of the sealant joint with the same degree of precision and accuracy as in the laboratory experiments.

Using the custom-designed laboratory and outdoor testing devices, White's team discovered that the dominant factor affecting a sealant's long-term performance is the temporal physical displacement of the sealant in response to changes in the weather and the properties of the material. In both the laboratory and outdoor experiments, White's team accurately and precisely measured temporal changes in a sealant's strain behavior as a function of its viscoelastic properties, cure history, and environmental conditions. White and his team have been able to demonstrate, for a model sealant material, that accelerated degradation data obtained in the laboratory could be used to predict behavior of the same sealant exposed on an outdoor testing device. This achievement subsequently enabled White and his team to establish the linkage between field and laboratory exposure results via a mechanistic model having a strong basis in viscoelastic theory.

Upon demonstration of this capability, two industrial members have incorporated the NIST-developed sealant instruments and testing methodology into their product development process. The first performance-based ASTM standard, Test Method for Viscoelastic Characterization of Sealant Using Stress Relaxation, is currently being balloted and it is anticipated that this standard will be adopted in 2009. Knowledge gained through BFRL's sealant-related research has benefited industry by: (1) significantly reducing sealant life-cycle costs and increasing material reliability; (2) reducing the need for expensive, time-consuming outdoor weathering measurements as a condition for consumer acceptance of commercial sealant products; and (3) enabling manufacturers to assign accurate warranties on sealants that are supported by robust scientific data.

3.2.3 EPDM Seam Consortium

As BFRL was completing its study on liquid adhesives and ASTM Test Method D 5405 was under development, EPDM roofing manufacturers introduced a new generation of adhesives based on preformed, polymer-based, tape adhesives. The introduction of tape adhesives was received with little enthusiasm by many practitioners, as they had become confident of the liquid adhesives being used at the time. On the other hand, proponents believed that tape adhesives had advantages over liquid adhesives such as enhanced seam performance, lessened environmental impact because they were solvent-free, and lower seam fabrication costs. In 1994, the EPDM industry formed a consortium with BFRL to conduct laboratory and field research to further the understanding of this innovative EPDM seam-adhesive technology. The initial consortium was comprised of three EPDM membrane material manufacturers, two tape adhesive manufacturers, two industry associations, and the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL). The objectives of the consortium were to:

- Compare the creep-rupture performance of tape-bonded and liquid-adhesive-bonded seams of EPDM membranes, and
- Recommend a test protocol for evaluating creep-rupture performance of such seams.

The result of the tape-bond seam consortium studies were published in BSS 175,[35] BSS 176[36] and BSS 177.[37] Among the key findings, it was shown that tape-bonded seams had times-to-failure that were, in most cases, comparable to or greater than, those of the liquid-adhesive-bonded seams. Moreover, the times-to-failure of tape-bonded specimens prepared with primed, clean EPDM rubber was not affected by the application temperatures and pressures investigated. This finding was significant because application temperatures and pressures are difficult to control in practice. Also, tape-bonded seams prepared with properly cleaned and primed EPDM rubber had longer times-to-failure than those fabricated without adequate cleaning and priming of the EPDM. This result, although not unexpected, emphasized to contractors in particular that proper application is a critical parameter affecting tape-bonded seam performance.

The consortium study hastened the acceptance of the innovative EPDM tape-bonded seam technology. In 1998, the NRCA marked the study conclusion in summarizing key findings and acclaimed its success in stating that "laboratory and field studies confirm the viability of tape-bonded seams."[38] Additionally, the second study objective was successfully met, as the results provided the technical basis for ASTM Standard Practice D 6383, Time-to-Failure (Creep-Rupture) of Adhesive Joints Fabricated from EPDM Roof Membrane Material. Among its benefits, this Standard Practice allows for evaluating the creep-rupture performance of newly developed adhesives for fabricating EPDM seams. The significance of this Standard Practice was made clear as the consortium study was concluding. At that time, two new tape adhesives for EPDM seams entered the market, which doubled the number available when the consortium study began.

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[35] Walter J. Rossiter, Jr., M. G. Vangel, E. Embree, K. M. Kraft, and James F. Seiler, Jr., *Performance of Tape-Bonded Seams of EPDM Membranes: Comparison of the Creep-Rupture Response of Tape-Bonded and Liquid-Adhesive-Bonded Seams*, Building Science Series 175, National Institute of Standards and Technology, 1996.

[36] Walter J. Rossiter, Jr., M. G. Vangel, K. M. Kraft, and James J. Filliben, *Performance of Tape-Bonded Seams of EPDM Membranes: Effect of Material and Application Factors on Creep-Rupture Response*, Building Science Series 176, National Institute of Standards and Technology, 1997.

[37] Walter J. Rossiter, Jr., M. G. Vangel, and K. M. Kraft, *Performance of Tape-Bonded Seams of EPDM Membranes: Factors Affecting the Creep-Rupture Response of Tape-Bonded and Liquid-Adhesive-Bonded Seams*, Building Science Series 177, National Institute of Standards and Technology, 1998.

[38] T. L. Smith, "EPDM Research Results," *Professional Roofing*, Vol. 28, No. 8, pp 20-22, August 1998.

4 Market for Polymeric Construction Materials

The construction industry is a key component of the U.S. economy and is vital to its continued growth. Investment in plant and facilities, in the form of construction activity, provides the basis for the production of products and the delivery of services. Investment in infrastructure promotes the smooth flow of goods and services and the movement of individuals. Investment in housing accommodates new households and allows existing households to expand or improve their housing. Clearly, construction activities affect nearly every aspect of the U.S. economy.[39]

This chapter provides a snapshot of the U.S. construction industry. As such, it provides the context within which the scope and size of the market for polymeric construction materials is defined. The chapter contains three sections.

Section 4.1 presents information on the value of construction put in place to show the size of the construction industry and each of its four sectors. The four sectors, which taken together define the construction industry, are residential, commercial/institutional, industrial, and infrastructure. Data from the seven-year period 2002 through 2008 are used to highlight the magnitude of construction-related investments in each sector. Data from 2008 are then used to establish the relative shares of construction-related investments for each sector.

Section 4.2 uses information on the construction supply chain to highlight the critical importance of materials, components, and systems.

Section 4.3 places special emphasis on identifying and detailing the key characteristics of the market for polymeric construction materials. The focus is on the markets for coatings, sealants and adhesives, and roofing materials. Ways in which these key characteristics affect the calculation of service life prediction-related benefits and costs are discussed in Chapter 6.

4.1 Value of Construction Put in Place

This section provides information on a key indicator of construction activity; the value of construction put in place. Data published by the U.S. Census Bureau are used to establish the composition of construction expenditures by type of construction/function (e.g., non-residential/office building). These expenditures are then assigned to the four key construction industry sectors. The reference document used throughout this section is the Current Construction Reports series C30 publication *Value of Construction Put in*

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[39] Readers interested in learning more about construction statistics, their sources and interpretation, are referred to the document by Rogers (Rogers, R. Mark. 1994. *Handbook of Key Economic Indicators*. Burr Ridge, IL: Irwin Professional Publishing).

Place.[40] A brief description of the "C30 report" follows. Special attention is given to the organization of the data in the C30 report and how these data map into the four key construction industry sectors. The section concludes with tabular and graphical summaries of the value of construction put in place.

Construction expenditures data are published monthly in the Current Construction Reports series C30 publication *Value of Construction Put in Place*. Construction expenditures refer to actual construction rather than planned or just initiated activity. It is noteworthy that the C30 report covers both private residential and non-residential construction activities and public sector construction activities.

The value of construction put in place is a measure of the value of construction installed or erected at a site during a given period. For an individual project, this includes: (1) cost of materials installed or erected; (2) cost of labor and a proportionate share of construction equipment rental; (3) contractor's profit; (4) cost of architectural and engineering work; (5) miscellaneous overhead and office costs chargeable to the project on the owner's books; and (6) interest and taxes paid during construction. Expenses do not include the cost of land nor do they include maintenance and repairs to existing structures or service facilities.

The C30 data are compiled via survey and through indirect estimation. In the context of the C30 survey, construction includes the following: (1) new buildings and structures; (2) additions, alterations, conversions, expansions, reconstruction, renovations, rehabilitations, and major replacements (e.g., the complete replacement of a roof or a heating system); (3) mechanical and electrical installations (e.g., plumbing, heating, electrical work, and other similar building services); (4) site preparation and outside construction of fixed structures or facilities (e.g., sidewalks, highways and streets, water supply lines, sewers, and similar facilities which are built into or fixed to the land); (5) installation of boilers, overhead hoists and cranes, and blast furnaces; (6) fixed, largely site-fabricated equipment not housed in a building (e.g., petroleum refineries and chemical plants); and (7) cost and installation of construction materials placed inside a building and used to support production machinery (e.g., concrete platforms, overhead steel girders, and pipes).

The data presented in the C30 report are summarized in Tables 4-1 and 4-2. To facilitate comparisons between this report and the C30 report, Tables 4-1 and 4-2 use the same row and column headings as are used in the C30 report. Tables 4-1 and 4-2 record annual values for the years 2002 through 2008. Table 4-1 records annual values in millions of

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[40] US Department of Commerce. 2009. *Current Construction Reports: Value of Construction Put in Place*. ***C30***. Washington, DC: U.S. Census Bureau.

constant 2008 dollars. Table 4-2 records annual values in millions of current dollars.[41] Reference to Table 4-1 reveals that total construction expenditures in real terms increased gradually from 2002 to 2006 and then declined in 2007 and 2008. When the effects of inflation are included, the rates of change are more pronounced. Table 4-2 shows total construction expenditures in current dollars.

Tables 4-1 and 4-2 are organized to allow for in-depth analyses of the components/ subcomponents of total construction expenditures. To facilitate such analyses, the data presented in Tables 4-1 and 4-2 are initially divided into two parts: (1) private construction; and (2) public construction.

Private construction contains two major components—residential buildings and non-residential buildings—plus a number of subcomponents. Both the two major components and the subcomponents are shown as headings in the first column of Tables 4-1 and 4-2.

The residential buildings component includes new private housing and improvements. New private housing includes new houses, apartments, condominiums, and town houses. New private housing units are classified as "1 unit" or "2 or more units." The value of improvements put in place are a direct measure of the value of residential additions and alterations activities.

The non-residential buildings component includes industrial, office buildings, hotels and motels, and "other commercial" (e.g., shopping centers, banks, service stations, warehouses, and other categories). Also falling under the non-residential buildings component are religious, educational, hospital and institutional, and "miscellaneous" non-residential buildings.

[41] Inflation reduces the purchasing power of the dollar over time; deflation increases it. When amounts are stated in actual prices as of the year in which they occur, they are said to be in ***current dollars***. Current dollars are dollars of any one year's purchasing power, inclusive of inflation/deflation. That is, they reflect changes in purchasing power of the dollar from year to year. In contrast, ***constant dollars*** are dollars of uniform purchasing power, exclusive of inflation/deflation. Constant dollars indicate what the same good or service would cost at different times if there were no change in the general price level to change the purchasing power of the dollar. For additional information on conducting economic analyses using either constant dollars or current dollars, see Fuller, Sieglinde K., and Stephen R. Petersen. 1996. *Life-Cycle Costing Manual for the Federal Energy Management Program*. NIST Handbook 135. Gaithersburg, MD: National Institute of Standards and Technology.

Table 4-1 Value of Construction Put in Place in Millions of Constant 2008 Dollars

Type of Construction	Millions of Constant Dollars (2008)						
	2002	2003	2004	2005	2006	2007	2008
Total Construction	1,014,728	1,043,163	1,130,154	1,215,644	1,246,914	1,194,869	1,072,132
Total Private Construction	759,287	790,267	879,195	957,501	974,170	894,697	766,170
Residential	474,763	521,917	607,385	674,571	655,447	512,184	350,078
New Housing Units	357,651	404,502	475,856	530,052	500,665	367,740	229,934
New single family	318,214	363,412	430,329	477,911	444,273	316,902	185,776
New multi-family	39,437	41,090	45,527	52,141	56,392	50,839	44,158
Improvements	117,112	117,415	131,529	144,519	154,782	144,444	120,144
Nonresidential	284,524	268,351	271,811	282,930	318,723	382,513	416,092
Lodging	12,527	11,619	13,657	13,963	18,822	28,536	35,379
Office	42,242	35,781	37,475	41,094	48,785	55,881	57,084
Commercial	70,620	67,288	72,028	73,404	78,355	89,155	81,495
Health Care	26,854	28,337	29,944	31,414	34,192	36,954	39,101
Educational	15,689	15,708	14,476	14,098	14,780	17,332	18,585
Religious	9,975	10,015	9,293	8,505	8,266	7,811	7,097
Public Safety	260	216	329	450	447	618	650
Amusement and Recreation	8,950	9,105	9,611	8,276	9,960	10,584	10,316
Transportation	8,106	7,685	7,797	7,854	9,242	9,355	9,896
Communication	22,002	16,915	17,630	20,776	23,695	28,543	25,496
Power	39,025	39,338	31,184	28,998	33,282	49,184	68,702
Sewage and Waste Disposal	294	325	377	265	326	424	548
Water Supply	475	460	462	359	509	536	696
Manufacturing	27,220	25,080	26,975	32,947	37,471	47,042	60,784
Other	286	476	573	528	591	558	263
Total Public Construction	255,441	252,896	250,958	258,143	272,744	300,172	305,962
Residential	6,300	6,103	6,278	6,182	6,496	7,499	7,330
Nonresidential	249,141	246,792	244,681	251,961	266,248	292,674	298,632
Office	10,750	10,343	10,856	9,356	9,085	11,884	13,222
Commercial	4,203	4,709	4,402	4,033	3,572	3,974	3,447
Health care	5,626	5,982	6,738	6,543	6,895	8,493	8,598
Educational	72,709	71,251	70,152	73,751	75,921	83,142	85,496
Public safety	9,108	8,163	7,671	7,613	7,850	9,975	12,286
Amusement and recreation	11,790	10,608	9,418	8,520	10,367	11,442	11,172
Transportation	22,747	21,228	20,766	19,764	20,623	23,746	24,057
Power	5,022	9,163	9,158	10,099	9,174	12,398	11,457
Highway and street	68,636	66,667	66,442	70,323	76,431	79,176	81,592
Sewage and waste disposal	19,138	19,078	20,058	21,637	24,436	25,403	24,596
Water supply	14,415	14,159	13,922	15,106	15,467	15,869	16,255
Conservation and development	4,208	4,322	4,410	4,765	5,390	5,353	5,350
Other	790	1,120	688	450	1,037	1,818	1,104

Source: Census C30 Report. Individual entries may not sum to totals due to independent rounding.

Table 4-2 Value of Construction Put in Place in Millions of Current Dollars

Type of Construction	Millions of Current Dollars						
	2002	2003	2004	2005	2006	2007	2008
Total Construction	847,873	891,497	991,561	1,102,703	1,167,554	1,150,688	1,072,132
Total Private Construction	634,435	675,370	771,378	868,543	912,169	861,615	766,170
Residential	396,696	446,035	532,900	611,899	613,731	493,246	350,078
New Housing Units	298,841	345,691	417,501	480,807	468,800	354,143	229,934
New single family	265,889	310,575	377,557	433,510	415,997	305,184	185,776
New multi-family	32,952	35,116	39,944	47,297	52,803	48,959	44,158
Improvements	97,855	100,344	115,399	131,092	144,931	139,103	120,144
Nonresidential	237,739	229,335	238,478	256,644	298,438	368,369	416,092
Lodging	10,467	9,930	11,982	12,666	17,624	27,481	35,379
Office	35,296	30,579	32,879	37,276	45,680	53,815	57,084
Commercial	59,008	57,505	63,195	66,584	73,368	85,858	81,495
Health Care	22,438	24,217	26,272	28,495	32,016	35,588	39,101
Educational	13,109	13,424	12,701	12,788	13,839	16,691	18,585
Religious	8,335	8,559	8,153	7,715	7,740	7,522	7,097
Public Safety	217	185	289	408	419	595	650
Amusement and Recreation	7,478	7,781	8,432	7,507	9,326	10,193	10,316
Transportation	6,773	6,568	6,841	7,124	8,654	9,009	9,896
Communication	18,384	14,456	15,468	18,846	22,187	27,488	25,496
Power	32,608	33,619	27,360	26,304	31,164	47,365	68,702
Sewage and Waste Disposal	246	278	331	240	305	408	548
Water Supply	397	393	405	326	477	516	696
Manufacturing	22,744	21,434	23,667	29,886	35,086	45,303	60,784
Other	239	407	503	479	553	537	263
Total Public Construction	213,438	216,127	220,183	234,160	255,385	289,073	305,962
Residential	5,264	5,216	5,508	5,608	6,083	7,222	7,330
Nonresidential	208,174	210,911	214,675	228,552	249,303	281,852	298,632
Office	8,982	8,839	9,525	8,487	8,507	11,445	13,222
Commercial	3,512	4,024	3,862	3,658	3,345	3,827	3,447
Health care	4,701	5,112	5,912	5,935	6,456	8,179	8,598
Educational	60,753	60,892	61,549	66,899	71,089	80,068	85,496
Public safety	7,610	6,976	6,730	6,906	7,350	9,606	12,286
Amusement and recreation	9,851	9,066	8,263	7,728	9,707	11,019	11,172
Transportation	19,007	18,142	18,219	17,928	19,310	22,868	24,057
Power	4,196	7,831	8,035	9,161	8,590	11,940	11,457
Highway and street	57,350	56,974	58,294	63,790	71,567	76,248	81,592
Sewage and waste disposal	15,991	16,304	17,598	19,627	22,881	24,464	24,596
Water supply	12,045	12,100	12,215	13,703	14,483	15,282	16,255
Conservation and development	3,516	3,694	3,869	4,322	5,047	5,155	5,350
Other	660	957	604	408	971	1,751	1,104

Source: Census C30 Report. Individual entries may not sum to totals due to independent rounding.

Rounding out the private construction component are farm non-residential, public utilities, and "all other private." These are generally of a non-residential nature, but are not part of non-residential buildings. Farm non-residential construction includes structures such as barns, storage houses, and fences. Land improvements such as leveling, terracing, ponds, and roads are also a part of this subcomponent. Privately owned public utilities construction is categorized by industry rather than function of the building or structure. This subcomponent includes expenditures made by utilities for telecommunications, railroads, petroleum pipelines, electric light and power, and natural gas. "All other private" includes privately owned streets and bridges, sewer and water facilities, airfields, and similar construction.

For public construction, there are two major components—building and non-building. Both the two major components and the various subcomponents are shown as headings in the first column of Tables 4-1 and 4-2. The building component contains subcomponents similar to those for private construction, with educational buildings being the largest subcomponent. Expenditures for the non-building component overwhelmingly consist of outlays for highways and streets, with sewer systems being a distant second subcomponent.

To get the sector totals, each subcomponent was assigned to a sector and summed. The sector assignments are identical to those used in Chapman and Rennison.[42] The sector totals and the overall total are recorded in Tables 4-3 and 4-4. Reference to the tables reveals that sector totals vary considerably, with residential normally being the largest and industrial the smallest.

Table 4-3 Value of Construction Put in Place: Sector Totals and Sum Total in Millions of Constant 2008 Dollars

Type of Construction	Millions of Constant Dollars						
	2002	2003	2004	2005	2006	2007	2008
Residential	481,063	528,020	613,663	680,753	661,944	519,684	357,408
Commercial/Institutional	301,784	290,052	296,490	301,233	327,855	377,068	384,394
Industrial	27,438	25,167	27,136	33,117	37,913	47,475	61,269
Infrastructure	204,443	199,924	192,868	200,543	219,204	250,642	269,062
TOTAL	1,014,728	1,043,163	1,130,154	1,215,644	1,246,914	1,194,869	1,072,132

Source: Census C30 Report. Note that due to rounding the values entered in the "Total" row in Table 4-3 differ slightly from the values entered in the "Total Construction" row in Table 4-1.

[42] Chapman, Robert E., and Roderick Rennison. 1998. *An Approach for Measuring Reductions in Operations, Maintenance, and Energy Costs: Baseline Measures of Construction Industry Practices for the National Construction Goals*. NISTIR 6185. Gaithersburg, MD: National Institute of Standards and Technology.

Table 4-4 Value of Construction Put in Place: Sector Totals and Sum Total in Millions of Current Dollars

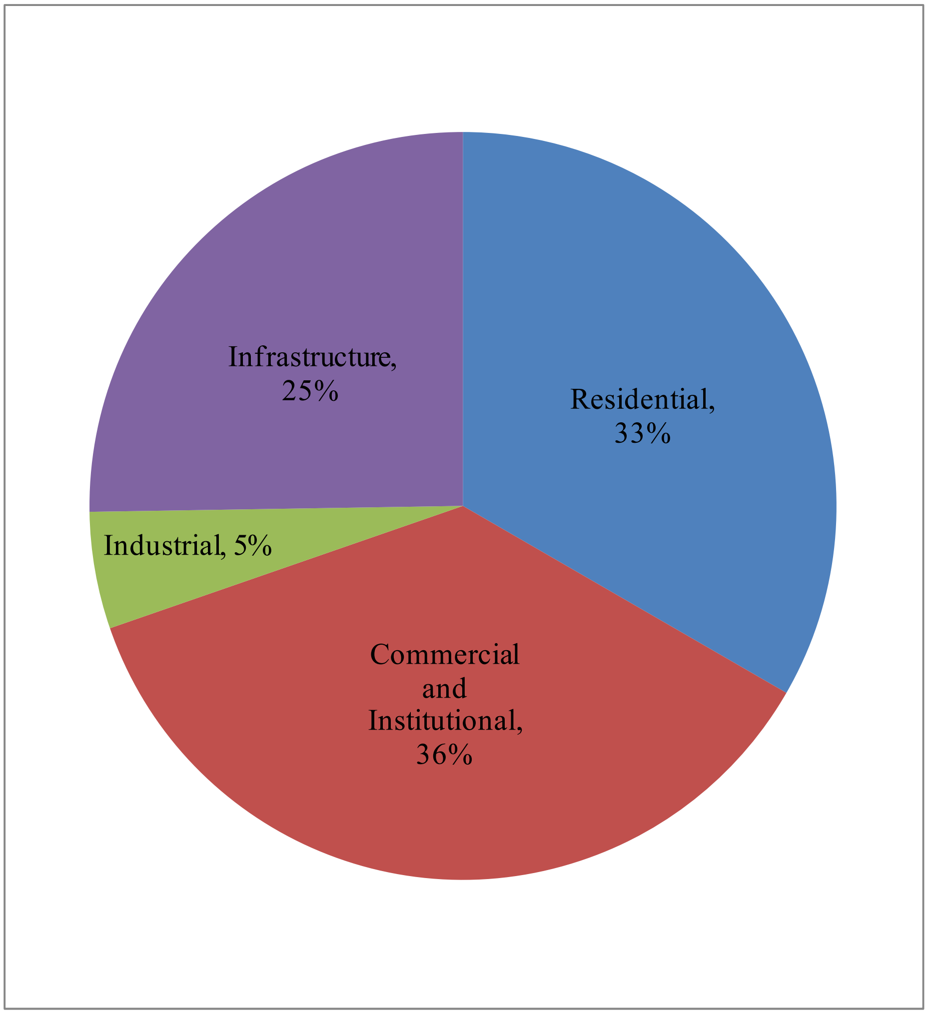
Type of Construction	Millions of Current Dollars						
	2002	2003	2004	2005	2006	2007	2008
Residential	401,960	451,251	538,408	617,507	619,814	500,468	357,408
Commercial/Institutional	252,161	247,881	260,131	273,247	306,989	363,126	384,394
Industrial	22,926	21,508	23,808	30,040	35,500	45,720	61,269
Infrastructure	170,826	170,857	169,216	181,911	205,253	241,374	269,062
TOTAL	847,873	891,497	991,561	1,102,703	1,167,554	1,150,688	1,072,132

Source: Census C30 Report. Note that due to rounding the values entered in the "Total" row in Table 4-4 differ slightly from the values entered in the "Total Construction" row in Table 4-2.

Reference to Table 4-3 reveals that the commercial/institutional, industrial, and infrastructure sectors grew more or less consistently in real terms over the entire seven-year period. In real terms, expenditures in the commercial sector grew from $301.8 billion in 2002 to $384.4 billion in 2008, an increase of almost 30 %. Real expenditures for two of the four sectors, industrial and infrastructure, were essentially constant between 2002 and 2005 and then increased sharply between 2006 and 2008. Real expenditures for the industrial sector grew from $27.4 billion in 2002 to $61.3 billion in 2008, an increase of almost 125 %. Over the 2002 to 2008 period, real expenditures for infrastructure increased by slightly more than 30 %. Real expenditures for the residential sector exhibited a cyclical pattern that highlights the magnitude of the current housing crisis. Real expenditures for the residential sector first increased sharply—from $481.1 billion in 2002 to $680.8 billion in 2005—declined gradually in 2006 (to $661.9 billion), and then fell precipitously in 2007 (to $519.7 billion) and 2008 (to $357.4 billion).

The data contained in Tables 4-3 and 4-4 provide the basis for calculating each sector's relative share of total construction expenditures. Each sector's relative share of total construction expenditures is shown graphically in pie chart form in Figure 4-1. It was constructed using 2008 data from Table 4-4 (i.e., current dollar expenditures). Reference to Figure 4-1 reveals that in 2008 the commercial sector accounted for 36 % of total construction expenditures, followed by the residential sector with 33 % of total construction expenditures. Over the longer term, the commercial sector's relative share of total construction expenditures is usually exceeded by the residential sector, which normally constitutes about 45 % of the total. However, due to the current housing crisis, their relative shares are reversed. Historically, the commercial sector's relative share tends to exceed the combined total for the industrial and public works sectors.

Figure 4-1 2008 Breakdown of $1072 Billion Construction Market



4.2 Overview of the Construction Industry Supply Chain

A total industry supply chain for construction gives a more complete representation of construction work in the United States. Complete data is not gathered on an annual basis; however, there is sufficient data in the 1997 and 2002 Census of the Construction Industry reports to extrapolate construction data that is gathered on an annual basis. Using the Census Bureau's C30 annual figures for construction put in place along with Census data from 1997 and 2002, one can calculate values for five components of the construction industry: facility design; facility construction; renovation; maintenance and repair; and a value for materials, components, supplies, and fuels. Other components of the construction supply chain include contents and furnishings, operation and use, demolition, losses. Each of these components is labeled in Figure 4-2, which records both the linkages between supply chain components and their estimated values.

In 2008, the construction industry's contribution to gross domestic product (GDP) was $582 billion (see Figure 4-2), or 4.1 % of GDP.[43] In 2008, the value of construction put in place was $1 072 billion ($750 billion for new construction, $323 billion for additions, alterations, and reconstruction (AAR)).[44] Reference to Table 4-3 reveals that the value of construction put in place declined by 6.8 % from 2007 to 2008. This decline was caused by a 34.3 % decline in new residential construction and a 13.6 % decline in residential renovations (see Table 4-1). The total of these two declines resulted in a -28.6 % change in the value of residential construction put in place. The remaining sectors of construction, commercial/institutional, industrial, and infrastructure, grew by 5.9 %, 34.0 %, and 11.5 % respectively. Overall, new construction declined by 9.4 % while renovations declined by 0.2 %.

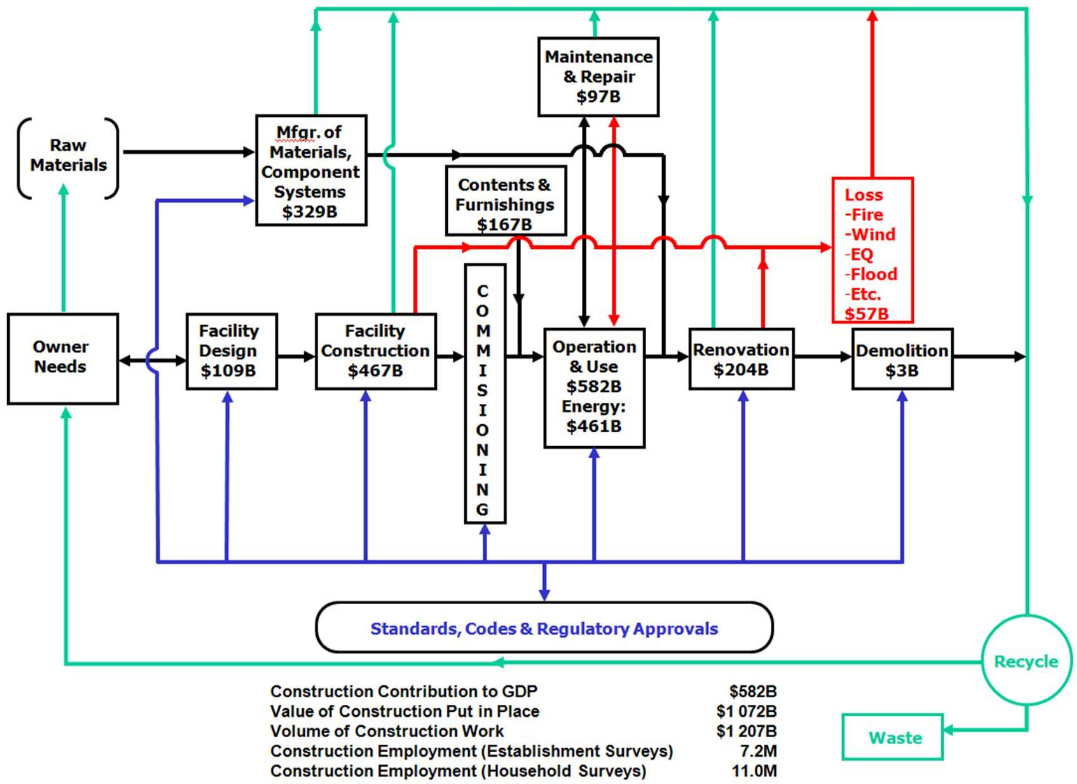
Maintenance and repair activities are an integral part of the construction industry. Expenditures for maintenance and repair (M&R) amounted to $134 billion in 2008.[45] Thus, the total volume of construction work in 2008—equal to the value of construction put in place plus expenditures for maintenance and repair—was $1 207 billion. It is important to note that expenditures for maintenance and repairs declined by 9.4 % from 2007 to 2008.

[43] Bureau of Economic Analysis. "Gross-Domestic-Product-(GDP)-by-Industry Data." *Industry Economic Accounts* (Washington, DC: Bureau of Economic Analysis), http://www.bea.gov/bea/dn2/gdpbyind_data.htm (accessed July 2009).

[44] United States Census Bureau: Manufacturing and Construction Division. "Annual Value of Construction Put in Place." *Current Construction Report (CCR) C30* (Washington, DC: United States Census Bureau, July 3, 2007), http://www.census.gov/const/C30/total.pdf (accessed July 2009).

[45] The value for maintenance and repair is calculated by using the ratio of maintenance and repair to new construction put in place from the 1997 census and multiplying it by the current value for new construction put in place.

Figure 4-2 Impacts of Construction Industry Supply Chain in 2008



Approximately 30 % of the volume of construction work—$329 billion—was due to the demand for manufactured products (materials, components, and systems).[46] Note that expenditures for manufactured products are derived as percentages of expenditures for facility design services, new construction, AAR, and M&R. Thus, expenditures on manufactured products are tied to the volume of construction work done. Consequently, these expenditures decreased by 7.1 % from 2007 to 2008.

Figure 4-2 is organized so that expenditures are not double counted. Since expenditures for manufactured products (materials, components, and systems) are derived as percentages of expenditures for facility design services, new construction, AAR, and M&R, the values for the latter items are reduced by the appropriate percentage. Facility design services is also a derived calculation; it is derived based on data from the 2002 Census of the Construction Industry for architectural services, surveying services, and engineering services. The total thus derived for facility design services is allocated

[46] The value of manufactured products, materials, components, and systems is calculated using ratios from the 2002 census. United States Census Bureau. *2002 Economic Census: Construction Subject Series, Industry General Summary: 2002*. EC02-23SG-1 (Washington, DC: U.S. Census Bureau, October 2005).

according to the percentage shares between the value of new construction and AAR put in place, also from the 2002 Census of the Construction Industry.

Four components recorded in Figure 4-2 are of particular importance in understanding how the double counting of expenditures is avoided; they are: (1) facility design; (2) facility construction; (3) renovation; and (4) maintenance and repair. The value of facility design recorded in Figure 4-2, \$109 billion, equals the sum of architectural services (\$32.0 billion), surveying services (\$5.4 billion), and engineering services (\$73.7 billion) for a total of \$111.2 billion[47] less manufactured products associated with these services (\$2.2 billion). The value for facility construction in Figure 4-2, \$467 billion, equals the value of new construction put in place (\$749.7 billion) less new construction-related facility design services (\$79.7 billion) and new construction-related manufactured products (\$202.7 billion). The value for renovation recorded in Figure 4-2, \$204 billion, equals the value of AAR (\$323.4 billion) less AAR-related facility design services (\$31.6 billion) and AAR-related manufactured products (\$87.5 billion). The value for maintenance and repair recorded in Figure 4-2, \$97 billion, equals M&R expenditures (\$133.6 billion) less M&R-related manufactured products (\$36.4 billion). Thus, the value of manufactured products (materials, components, and systems) recorded in Figure 4-2, \$329 billion, equals the sum of manufactured products associated with: (1) facility design services (\$2.2 billion); (2) new construction (\$202.7 billion); (3) AAR (\$87.5 billion); and (4) M&R (\$36.4 billion).

The large value of manufactured products that appear in the construction industry supply chain is noteworthy because polymeric construction materials are a subset of this total. A more detailed breakdown of the market for polymeric materials within the construction industry supply chain is presented in Section 4.3.

Construction also has a major impact on U.S. employment. In 2008, 11.0 million persons were employed in the construction industry.[48] This translates into 7.6 % of the total U.S. workforce. During the 2007 to 2008 period, the construction industry shed 882 000 jobs representing 7.4 % of all construction jobs, according to the Current Population Survey. This loss was the most severe among all industries in terms of percent lost and number of jobs lost. No other industry exceeded a loss of more than 3 % of employment or more than 400 000 jobs.

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[47] The value of facility design services is allocated according to the percentage shares between the value of new construction and AAR put in place. Thus, \$79.7 billion is for new construction-related facility design services and \$31.6 billion is for AAR-related facility design services.

[48] United States Bureau of Labor Statistics. "Household Data: Employed Persons in Nonagricultural Industries by Sex and Class of Worker." *Current Population Survey* (Washington, DC: Bureau of Labor Statistics), http://www.bls.gov/cps/cpsaat16.pdf (accessed July 2009).

The composition of the construction workforce differs from much of the U.S. workforce due to the large number of self-employed workers (sole proprietorships and partnerships). Within the construction industry, there are 1.8 million self-employed workers. In contrast, manufacturing, which employs 15.9 million workers, has only 308 thousand self-employed workers.[49] The large number of self-employed workers both reduces the size of the average firm and increases fragmentation within the construction industry. Both factors complicate the adoption of new technologies and practices.

4.3 Market Snapshot: Coatings, Sealants and Adhesives, and Roofing Materials

The U.S. market for coatings, sealants and adhesives, and roofing materials was valued at $57.9 billion in 2008. Roofing materials led the way with $26.8 billion, followed by coatings with $20.5 billion, and sealants and adhesives with $10.6 billion. These figures are reported in Table 4-5, which includes values for both 2007 and 2008. It is important to note that the figures in Table 4-5 are for the entire U.S. market and, as such, contain expenditures for materials that are associated with industries other than construction.

Table 4-5 U.S. Market for Coatings, Sealants and Adhesives, and Roofing Materials: 2007 and 2008

Type of Material	Millions of Dollars	
	2007	2008
Coatings	21,157.6	20,471.5
Sealants and Adhesives	10,344.3	10,604.4
Roofing	26,094.0	26,842.9
TOTAL	57,595.9	57,918.8

The values reported in Table 4-5 are broken down in a series of subsequent tables that enable us to allocate the appropriate amounts to construction-related activities and, in the case of roofing materials, to tie them to a specific polymeric material. These breakouts are facilitated through reference to U.S. Census Bureau publications, including the 2002 Census of the Construction Industry. Three Census data series are of special importance in developing estimates for construction-related expenditures for coatings, sealants and adhesives, and roofing materials. These series are associated with North American Industrial Classification System (NAICS) codes for coatings 325510, for sealants 325520 and adhesives, and for roofing materials 238160. The industry series reports for

[49] *Ibid*.

coatings,[50] sealants and adhesives,[51] and roofing materials[52] are comprehensive treatments of each industry and are recommended to readers interested in learning more about the key statistics associated with these industries.

The U.S. Census Bureau organizes the market for coatings around four broad product areas: (1) architectural coatings; (2) OEM (original equipment manufacturers) product coatings; (3) special purpose coatings; and (4) miscellaneous allied paint products. The overall U.S. market values for 2007 and 2008 for each product area are reported in Table 4-6. Consequently, some of the values recorded in Table 4-6 may include manufactured products (e.g., automotive paints/coatings).

Table 4-6 U.S. Market for Coatings in 2007 and 2008: Overall

Product Description: Overall	Millions of Dollars	
	2007	2008
Architectural Coatings	9,065.2	8,669.0
OEM Product Coatings	5,960.0	5,662.5
Special Purpose Coatings	4,597.2	4,604.8
Miscellaneous Allied Paint Products	1,535.2	1,535.2
TOTAL	21,157.6	20,471.5

Each of the four broad product areas were analyzed, using the detailed Census data classifications, to determine which portion of the total dollar value was construction-related. The construction-related part of the U.S. market for coatings is reported in Table 4-7 for each of the four broad product areas and in total.

Architectural coatings are coatings for on-site application to interior or exterior surfaces of residential, commercial/institutional, or industrial buildings. These are protective and decorative finishes applied at ambient temperatures, for ordinary use and exposure. These coatings are all construction-related. OEM coatings are coatings formulated specifically for original equipment manufacturers to meet conditions of application and product requirements, and applied to such products during the manufacturing process. A

[50] U.S. Census Bureau. *Paint and Coating Manufacturing: 2002, 2002 Economic Census*. EC02-311-325510, Economics and Statistics Administration, February 2005.

[51] U.S. Census Bureau. *Adhesives Manufacturing: 2002, 2002 Economic Census*. EC02-311-325520, Economics and Statistics Administration, December 2004.

[52] U.S. Census Bureau. *Roofing Contractors: 2002, 2002 Economic Census*. EC02-231-238160, Economics and Statistics Administration, December 2004.

small portion of these coatings are construction-related (e.g., metal building product finishes). Special purpose coatings may also be stock type or shelf goods, but differ from general architectural coatings by the fact that they are formulated for special applications and/or special environmental conditions such as extreme temperatures. Miscellaneous allied paint products include paint and varnish removers, thinners for lacquers and other solvent-based paint products, pigment dispersions, and other miscellaneous allied paint products, including brush cleaners, ink vehicles, putty and glazing compounds.

Table 4-7 U.S. Market for Coatings in 2007 and 2008: Construction-Related

Product Description: Construction-Related	Millions of Dollars	
	2007	2008
Architectural Coatings	9,065.2	8,669.0
OEM Product Coatings	616.9	656.2
Special Purpose Coatings	1,242.1	1,240.2
Miscellaneous Allied Paint Products	0.0	0.0
TOTAL	10,924.2	10,565.4

According to the Adhesive and Sealant Council, Inc., the U.S. consumes nearly 30 % of global adhesive and sealant products.[53] Table 4-8 demonstrates that the U.S. market for adhesives is significantly larger than the market for sealants—$9.0 billion versus $1.6 billion. The U.S. market for adhesives and sealants is slightly in excess of $10.6 billion. Data published by the Adhesive and Sealant Council shows that the U.S. market for adhesives is dominated by demands related to paper, board, and related products. These demands amount to 57.0 % of the total.[54] The demand for construction-related adhesives is second, amounting to 16.6 % of the total,[55] which translates into nearly $1.5 billion in 2008 (see Table 4-9). The U.S. market for sealants is dominated by demands related to construction. These demands amount to 59.7 % of the total,[56] which translates into nearly $900 million in 2008 (see Table 4-9).

[53] The Adhesive and Sealant Council, Inc. *2007-2010 North American Market Study for Adhesives and Sealants with a Global View*, 2008 Edition, The Adhesive and Sealant Council, Inc., 2008.

[54] *Ibid.*, p. 42.

[55] *Ibid.*

[56] *Ibid.* p. 65.

Table 4-8 U.S. Market for Adhesives and Sealants in 2007 and 2008: Overall

Product Description: Overall	Millions of Dollars	
	2007	2008
Adhesives	8,827.3	9,048.0
Sealants	1,517.0	1,556.4
TOTAL	10,344.3	10,604.4

Table 4-9 U.S. Market for Adhesives and Sealants in 2007 and 2008: Construction-Related

Product Description: Construction-Related	Millions of Dollars	
	2007	2008
Adhesives	1,503.1	1,479.1
Sealants	869.2	891.8
TOTAL	2,372.3	2,370.8

The U.S. market for roofing materials is divided into two parts: low-slope roofing and steep-slope roofing. Roof slope is considered a primary factor in roof design. The slope of a roof has an effect on the interior volume of a building, the drainage, the style, and the materials used. The slope of a roof is often referred to as the pitch. A roof that is nearly level or slightly pitched is called low-slope roof. Low-sloped roofs are often used on commercial/institutional buildings and industrial facilities. A steep-slope roof has a higher pitch and is often associated with residential construction as well as some commercial/institutional buildings.

In addition to the data published by the U.S. Census, the National Roofing Contractors Association (NRCA) publishes an annual market survey of its members.[57] The NRCA classifies data two ways: by low-slope versus steep-slope and by new construction versus reroofing. Table 4-10 provides the breakout by low-slope roofing and steep-slope roofing. Note that the value for low-slope roofing—$17.9 billion—is significantly higher than for steep-slope roofing—$9.0 billion. Although most roofing materials are polymeric, there are also non-polymeric materials used for roofing (e.g., metal). In addition, since EPDM is the single largest roofing material type for low-slope roofs—

[57] National Roofing Contractors Association. *Annual Market Survey: 2006-2007*. National Roofing Contractors Association, 2007.

26.9 % of new construction and 24.3 % of reroofing[58]—and NIST has had an active research program on tape-bonded seams for EPDM roofing, the focus in Table 4-11 is on low-slope EPDM roofing. Reference to Table 4-11 shows that low-slope EPDM roofing accounted for $4.7 billion of expenditures in 2008.

Table 4-10 U.S. Market for Roofing Materials in 2007 and 2008: Overall

Type of Roofing	Millions of Dollars	
	2007	2008
Low-Slope Roofing	17,368.2	17,866.6
Steep-Slope Roofing	8,725.8	8,976.3
TOTAL	26,094.0	26,842.9

Table 4-11 U.S. Market for Roofing Materials in 2007 and 2008: Low-Slope EPDM Roofing

Low-Slope EPDM Roofing	Millions of Dollars	
	2007	2008
New Construction	3,349.4	3,445.5
Reroofing	1,195.8	1,230.1
TOTAL	4,545.2	4,675.6

Given the individual breakouts for coatings, sealants and adhesives, and roofing materials reported in Tables 4-7, 4-9, and 4-11, we can create a table summarizing the market for polymeric construction materials. These values, recorded in Table 4-12, reveal that the market for polymeric construction materials is $17.6 billion. Thus, the economic impacts associated with BFRL's SLP-related research in these areas could be substantial.

[58] Ibid., p.2.

Table 4-12 U.S. Market for Coatings, Sealants and Adhesives, and Roofing Materials in 2007 and 2008: Construction-Related

Type of Material	Millions of Dollars	
	2007	2008
Coatings	10,924.2	10,565.4
Sealants and Adhesives	2,372.3	2,370.8
Low-Slope EPDM Roofing	4,545.2	4,675.6
TOTAL	17,841.7	17,611.9

5 Strategy for Identifying, Collecting, and Measuring SLP-Related Benefits and Costs

The material covered in this report was developed by the Office of Applied Economics (OAE) project team and subject matter experts. The analysis strategy is believed to be comprehensive and to encompass all stakeholder groups. The process began by reviewing previous research studies and using discussions with subject matter experts to create a list of key stakeholders that was later refined by the OAE project team. The stakeholder list was then classified into a hierarchy that includes “Building Owners and Managers;” “Codes, Standards, and Support Services;” “Construction and Associated Support Services;” “Manufacturing and Associated Support Services;” “Professional and Financial Services;” and “Other.” The OAE project team and subject matter experts examined and critiqued the list to ensure its accuracy and completeness. Following the identification of stakeholders, the OAE project team identified the various benefits and costs associated with improved service life of polymeric materials. Benefits and costs were then “assigned” to one or more of the stakeholder groups.

5.1 Identification of Key Stakeholders

Individual stakeholders are affected differently by improved service life prediction (SLP) of polymeric materials. Therefore, it is useful to identify individual stakeholders and then classify them into stakeholder groups. This classification hierarchy makes it easier to understand and identify how the benefits and costs of developing improved service life prediction of polymeric materials relate to individual stakeholders and stakeholder groups.

Because stakeholders evaluate benefits and costs of improved service life prediction purely from their “stakeholder” viewpoint, it is important to identify both individual perspectives and aggregate perspectives. Individual stakeholder perspectives are important because they are impacted by improved service life prediction in a variety of ways. An example of an individual stakeholder would be building managers. Individual stakeholders are classified into stakeholder groups that perform similar functions in society. For example, “Building Owners and Managers” is the stakeholder group that contains the following individual stakeholders: “Building Managers,” “Building Owners,” and “Facility Operations” (see Table 5-1). These groups are important in understanding how sectors of the economy are affected by improved service life prediction.

Tables 5-1 and 5-2 identify individual stakeholders and the corresponding stakeholder group(s) used in the assessment of SLP-related benefits and costs. Both tables provide the same information, but are organized in different ways.

Table 5-1 is a two-tiered hierarchy of stakeholders; it lists stakeholder groups with their corresponding individual stakeholders. It shows how the stakeholder groups are aggregated. In Table 5-1, the six stakeholder groups are listed in a ***bold-italics*** typeface. The individual stakeholders are listed in alphabetical order beneath each stakeholder group heading.

Table 5-2 is arranged as a checklist; it assigns each of the individual stakeholders to their corresponding stakeholder group(s). Table 5-2 lists the individual stakeholders in alphabetical order to facilitate cross-referencing of individual stakeholders and stakeholder groups. Note that an individual stakeholder may be associated with more than one stakeholder group. For example, the group "Building Owners" is part of three stakeholder groups: "Building Owners and Managers," "Construction and Associated Support Services," and "Professional and Financial Services."

5.2 Classification of SLP-Related Benefits

Stakeholders invest in new service life prediction methods or purchase high-performance polymeric materials/products because they anticipate receiving, in present value terms, benefits (cost savings) in excess of the costs (benefit reductions) associated with these investments. Examples of SLP-related benefits are increased revenue, increased product quality, and lower maintenance costs. Table 5-3 lists all SLP-related benefits (cost savings).

Table 5-3 is organized as a two-tiered hierarchy. It represents the culmination of the OAE efforts to produce a consensus of SLP-related benefits.

The first tier of the hierarchy classifies SLP-related benefits (cost savings) listed in alphabetical order. The benefits listed are considered to be exhaustive and self-evident. An example of a first tier element is "***Greater availability of products with new features***."

The second tier, listed in alphabetical order as a series of bullets, lists more specific benefits within each first tier element. An example of a second tier element is "Products coming available sooner to meet customer needs," which is under the first tier element "***Greater availability of products with new features***."

Table 5-1 Hierarchy of SLP Stakeholders by Groups and Classes of Individual SLP Stakeholders

Building Owners and Managers
Building Managers
Building Owners
Facility Operations

Codes, Standards, and Support Services
Building Permitting and Inspection
Code Officials
Code Organizations
Construction Materials/Product Manufacturers
Professional Societies
Product Certification Services
Product Evaluation Services
Research Organizations
Standards Organizations
Trade Associations

Construction and Associated Support Services
Building Owners
Building Permitting and Inspection
Code Officials
Construction Workers
Customer Service Operations
General Contractors
Maintenance and Repair Services
Salvage Operations
Specialty Trade Contractors
Trade Associations
Warranty Services
Wholesale/Retail Trade/Supply

Manufacturing and Associated Support Services
Construction Materials/Product Manufacturers
Customer Service Operations
Materials/Product Marketing
Materials/Product Research and Development
Materials/Product Sales and Distribution
Professional Societies
Research Organizations
Test Equipment Manufacturers
Testing Laboratories
Testing Services
Trade Associations
Warranty Services

Professional and Financial Services
Architects and Design Consultants
Building Owners
Conditions Assessment Services
Engineering Consultants
Financial Institutions
Insurance Companies
Investment Banking Services
Legal Services
Real Estate Services
Warranty Services

Other
Building Occupants
Special Interest Groups
Third Parties

Table 5-2 Assignment of Classes of Individual SLP Stakeholders to SLP Stakeholder Groups

Individual Stakeholder Class	Stakeholder Group					
	Building Owners & Managers	Codes, Standards, & Support Services	Construction & Associated Support Services	Manufacturing & Associated Support Services	Professional & Financial Services	Other
Architects and Design Consultants					✓	
Building Managers	✓					
Building Occupants						✓
Building Owners	✓		✓		✓	
Building Permitting and Inspection		✓	✓			
Code Officials		✓	✓			
Code Organizations		✓				
Condition Assessment Services					✓	
Construction Materials/Product Manufacturers		✓		✓		
Construction Workers			✓			
Customer Service Operations			✓	✓		
Engineering Consultants					✓	
Facility Operations	✓					
Financial Institutions					✓	
General Contractors			✓			
Insurance Companies					✓	
Investment Banking Services					✓	
Legal Services					✓	
Maintenance and Repair Services			✓			

Table 5-2 Assignment of Classes of Individual SLP Stakeholders to SLP Stakeholder Groups (Continued)

Individual Stakeholder Class	Stakeholder Group					
	Building Owners & Managers	**Codes, Standards, & Support Services**	**Construction & Associated Support Services**	**Manufacturing & Associated Support Services**	**Professional & Financial Services**	**Other**
Materials/Product Marketing				✓		
Materials/Product Research and Development				✓		
Materials/Product Sales and Distribution				✓		
Product Certification Services		✓				
Product Evaluation Services		✓				
Professional Societies		✓		✓		
Real Estate Services					✓	
Research Organizations		✓		✓		
Salvage Operations			✓			
Special Interest Groups						✓
Specialty Trade Contractors			✓			
Standards Organizations		✓				
Test Equipment Manufacturers				✓		
Testing Laboratories				✓		
Testing Services				✓		
Third Parties						✓
Trade Associations		✓	✓	✓		
Warranty Services			✓	✓	✓	
Wholesale/Retail Trade/Supply			✓			

Table 5-3 SLP-Related Benefits (or Cost Savings) for All Stakeholders

Benefits from standard tools made possible with advanced SLP

- Published standards facilitate application of advanced SLP, thereby magnifying the benefits and generating them more quickly
- SLP research provides the technical underpinnings for standards for government and industry use

Greater availability of products with new features

- Customized to meet specific needs
- Opportunities for increasing market share
- Perception of company as a market leader
- Products coming available sooner to meet customer needs

Increased opportunities for innovation

- Improved company capability and flexibility for new product opportunities
- Opportunities for developing new products outside of existing product areas
- Opportunities for increasing market share
- Perception of company as a market leader

Increased sales/revenue for high quality polymer producers

- Increased knowledge of product vis-à-vis non-polymeric materials
- Increased potential for longer warranty
- Opportunities for increasing market share and sales/revenue due to innovative products or products with new features
- Reduced information uncertainty
- Upselling encouraged by demonstrated lower life-cycle costs of high-quality products

Increased sales opportunities from new services

- Provide SLP-related services to clients

Increased satisfaction to customers

- Higher perception of quality
- Reduced performance uncertainty
- Reduced potential for a “lemons market”

Lower maintenance/replacement costs

- Better estimates of service life (cost variability)
- Increased service life (total cost)

Table 5-3 SLP-Related Benefits (or Cost Savings) for All Stakeholders (Continued)

Potential for health benefits

- Better service life prediction
- Increased resistance to pathogens
- Safer manufacturing, storage, and installation processes
- Slower degradation

Reduce costs of damage caused by polymer product failure

- Better service life prediction (more likely to perform scheduled replacement)
- Reduction in litigation-related costs

Reduced risk associated with the introduction of new products

- Increased availability of investment capital
- Reduced research and development costs
- Reduction in litigation-related costs

Reduced time to market

- Earlier introduction of products with new features
- Earlier revenue stream
- Reduced research and development costs

Reduced waste and pollution

- Environmental awareness
- Environmental stewardship

Reduction in costs of code compliance

- Easier introduction of new polymer products (better understanding of polymers)
- Science based methods promote uniformity in demonstrating code compliance

Reduction in energy costs and associated carbon footprint

- Better materials/sealants reduce air infiltration
- Reduced energy consumption diminishes carbon footprint

Reductions in material costs from overengineering

- Less costly inputs required with better understanding of their performance
- Less quantity of material required with better understanding of material

Reduction in warranty costs

- Better service life prediction
- Lower holding costs associated with a given warranty
- Reductions in litigation-related costs

Summary of First Tier Benefits and Cost Savings

Benefits from "standard" tools made possible with advanced SLP: Improved service life prediction tools, be they standard methods of measurement, protocols for how to predict service life, or computer programs/instruments for predicting, provide the technical underpinnings necessary for the development of standards for guiding government and industry service life prediction. Published standards by a recognized organization facilitates the widespread application of advanced SLP, thereby magnifying the benefits of better service life prediction and generating them more quickly.

Greater availability of products with new features: Improved understanding of degradation factors affecting polymeric materials leads to improved service life prediction. This increase in knowledge helps producers develop products with new features that meet the specific needs of consumers.

Increased opportunities for innovation: The increase in knowledge from better service life prediction results in increased opportunities for innovation. Producers will be better able to produce new products that fit the needs of consumers and demonstrate that these products perform better for their individual needs.

Increased sales opportunities from new services: Having service life prediction tools, protocols, and standards will provide new sales opportunities to companies that assist product developers in the formulation of new or improved products. For example, a company producing chemicals could provide consulting services to companies producing sealants, roofing adhesives, or paints that would help them predict the service life performance of alternative product designs.

Increased sales/revenue for high quality polymer producers: Without service life prediction there is information uncertainty where consumers are not equipped to distinguish between high quality products and low quality products. The result is that consumers are less willing to pay the premium for high quality products, leaving producers with little incentive to produce high quality products. This situation can result in production of only low quality polymeric materials, which is often referred to as a "lemons market." Improved service life prediction reduces information uncertainty and distinguishes low-quality products from high-quality products that consumers are willing to pay for.

Increased satisfaction to customers: Improved service life prediction reduces information uncertainty and allows customers to identify high-quality products; it also reduces the potential for a "lemons market." Customers are more satisfied with their selected products because they perform in the manner that they expect. Additionally, improved service life prediction allows consumers to better predict when a product will require replacement, enabling them to schedule replacements rather than replace the product on an emergency basis.

Lower maintenance/replacement costs: The increased knowledge from better service life prediction results in greater ability for producers to make products that last longer. Also, with the ability to demonstrate this increase in quality, consumers are more willing to pay for high-quality, long-lasting products, which may have higher first costs but lower life-cycle cost from significantly reduced future costs of maintenance and repairs.

Potential for health benefits: Increased product performance due to better service life prediction results in slower degradation, reducing the potential for pathogens and other health hazards caused by product failure from water intrusion. In addition, improved service life prediction allows the consumer to better predict when a product will require replacement, enabling them to schedule replacements rather than doing them on an emergency basis.

Reduced costs of damage caused by polymer product failure: Improved service life prediction allows the consumer to more accurately predict when a product will require replacement. With this knowledge, the consumer can replace the product before it fails and causes further damage.

Reduced risk associated with the introduction of new products: The increase in knowledge from better service life prediction results in increased investment opportunities for innovation and facilitates the introduction of new products. Improved products provide a more stable income to producers and investors, and creates an environment of growth that reduces financial risk to both producers and investors.

Reduced time to market: With a better understanding of polymeric materials and improved service life prediction, producers are able to deliver new products to the market in less time. This reduction in the "product development cycle" brings revenue earlier than before.

Reduced waste and pollution: The increase in knowledge from better service life prediction creates opportunities for innovation and eventually better performing products. These products result in less waste from untimely product failure and replacement.

Reduction in costs of code compliance: With more accurate estimates of service life, inspectors can more easily identify code compliant products. Service life prediction also allows producers to more easily demonstrate code compliance by using science-based methods.

Reduction in energy costs and associated carbon footprint: Better performing materials resulting from improved service life prediction will reduce air and water infiltration into conditioned spaces, thereby reducing cooling and heating loads as well as reducing water incursion into insulation in the walls. Maintaining a tighter envelope reduces the energy requirements for maintaining a target comfort level in a building and thereby reduces the carbon footprint from fuel use of that building. In addition, decreased water incursion will preserve the insulation performance, thereby saving more energy and reducing the carbon footprint from what would occur with wet insulation. For example, longer-lasting and better performing sealants on a building façade will decrease air and moisture penetration and thereby reduce energy consumption and associated carbon emissions.

Reduction in material costs from overengineering: Improved understanding of material performance enables designers to better predict how a new product will perform, thereby enabling them to more finely tune the mix of inputs to achieve a desired level of final product or system performance. Furthermore, this improved understanding also helps designers select the most cost-effective inputs that can be relied upon to meet product standards.

Reduction in warranty costs: Improved service life prediction allows producers to more accurately predict when a product will fail. With this knowledge, producers can offer a warranty that is consistent with the life of the product. That is, improved service life prediction reduces the risk of early product failure; therefore, producers and other stakeholders spend less on replacing failed products that are under warranty.

5.3 Classification of SLP-Related Costs

Costs are at the heart of any investments in new materials, products, or production processes. SLP-related cost increases are experienced by those within the polymer industry and by many outside of it. They include research costs, product development costs, production costs, dissemination costs, and installation costs. In addition, a particular producer or supplier may experience benefit reductions due to reduced sales of some of their more "traditional" products or services. SLP-related costs are summarized in Table 5-4, and are also organized in two tiers.

The first tier of the hierarchy classifies SLP-related costs, and is listed in alphabetical order. The list is considered to be exhaustive and self-evident. An example of a first tier cost increase is "***Decreased sales/revenue to producers of competing materials***."

The second tier lists more specific cost increases within each first tier element. The second tier elements are listed in alphabetical order as a series of bullets under the first tier element. An example of a second tier element is "Increased consumer preference for high quality polymer products," which is under the first tier "***Decreased sales/revenue to producers of competing materials***."

Table 5-4 SLP-Related Cost Increases (or Benefit Reductions) for All Stakeholders

Decreased sales/revenue to producers of competing materials
- Increased consumer preference for high quality polymer products
- Reduced market share for supplies and services of competing materials

Development of new standards
- Switch from field-based studies to science-based methods
- Costs of participating in standards development organizations/committees

Increased cost of product testing
- Costs associated with use of specialized test equipment
- Costs associated with specialized training for testing services personnel

Increased risk exposure due to introduction of "niche" products
- Niche markets may be too small to recover costs
- Niche markets may be very sensitive to changes in consumer behavior (taste, preferences, and perceptions)

New technology introduction costs
- Increased costs of adapting new technologies, products, equipment, and practices to industry use
- Increased marketing, advertising, and distribution costs by products/equipment manufacturers
- Increased risk exposure and uncertainty due to new technologies, products, equipment, or practices
- Increased training costs

Potential for health and environmental risks
- New products and practices introduce unknown environmental and health risks

Summary of First Tier Cost Increases and Benefit Reductions

Decreased sales/revenue to producers of competing materials: Improved service life prediction reduces information uncertainty and produces a perception of higher quality for polymer products, making them more competitive vis-à-vis other materials.

Development of new standards: Improved service life prediction allows producers to more easily demonstrate code compliance through science-based methods; however, these methods require the development of new standards and costs are incurred through participation in standards development organizations and committees.

Increased cost of product testing: New methods of testing require new equipment and training for standards organizations, code organizations, producers, and testing laboratories.

Increased risk exposure due to introduction of niche products: Improved service life prediction results in a better understanding of polymeric products. This increase in knowledge helps producers develop products for specialized niche markets, but increases financial risk due to localized demand for these products.

New technology introduction costs: Improved service life prediction results in a better understanding of polymeric products. While this increase in knowledge helps producers develop new products, it requires investment in equipment, training, and marketing.

Potential for health and environmental risk: Improved service life prediction may result in new products and processes that introduce unknown environmental and health risks.

5.4 How SLP-Related Benefits and Costs Accrue to Stakeholders

Thus far, the assessment of SLP-related impacts has been from a societal point of view; that is, it includes benefits and costs of multiple stakeholder groups. This approach is appropriate for studying the impact of improved service life prediction on the economy, but does not classify benefits and costs by individual stakeholders. Tables 5-5 and 5-6 classify the benefits and costs into their respective stakeholder groups. Table 5-5 lists key types of benefits by stakeholder group; Table 5-6 lists key types of costs by stakeholder group. The benefits and costs were drawn from Tables 5-3 and 5-4 while the stakeholder groups were drawn from Tables 5-1 and 5-2.

Tables 5-5 and 5-6 serve three purposes. First, the list of stakeholder groups and the list of the different types of benefits and costs define the potential data categories required for the analysis. Second, they promote a priority-setting process for identifying the type of data needed for each benefit or cost; that is, Tables 5-5 and 5-6 narrow the scope of the data that needs to be collected for each stakeholder. For example, "*Greater availability of products with new features*" benefits the following stakeholder groups: building owners and managers; construction and associated support services; professional and financial services; and other. Finally, Tables 5-5 and 5-6 associate each stakeholder with their individual benefits and costs of improved service life prediction of polymeric materials. This aids stakeholders in understanding the effect that improved service life prediction will have on them. Some stakeholder groups benefit strongly; these are distinguished with a check plus (✓+). Others benefit directly from the listed type of benefit but not as strongly; these are distinguished with a check (✓). Other stakeholders benefit indirectly from the listed benefit; these are distinguished with a check minus (✓-). Cost increases are designated in a similar manner (see Table 5-6).

Table 5-5 Types of SLP-Related Benefits (or Cost Savings) Classified by Stakeholder Group

Type of Benefit or Cost Saving	Stakeholder Group					
	Building Owners & Managers	Codes, Standards, & Support Services	Construction & Associated Support Services	Manufacturing & Associated Support Services	Professional & Financial Services	Other
Benefits from standards made possible with advanced SLP	✓	✓+	✓	✓+	✓+	✓
Greater availability of products with new features	✓+		✓		✓	✓
Increased opportunities for innovation				✓+	✓-	
Increased sales/revenue for high quality polymer producers			✓	✓+	✓	
Increased sales opportunities from new services	✓		✓	✓+	✓+	
Increased satisfaction to customers	✓+		✓-		✓-	✓+
Lower maintenance/replacement costs	✓+		✓-		✓-	✓+
Potential for health benefits	✓+	✓-	✓	✓	✓-	✓+
Reduce costs of damage caused by polymer product failure	✓+	✓	✓	✓	✓	✓+
Reduced risk associated with the introduction of new products				✓+	✓	
Reduced time to market	✓		✓	✓+	✓	✓
Reduced waste and pollution	✓	✓-	✓	✓	✓	✓
Reduction in costs of code compliance	✓	✓+	✓	✓+	✓	✓
Reduction in energy costs and associated carbon footprint	✓+		✓	✓	✓	✓+
Reduction in material costs from overengineering	✓		✓	✓+	✓	
Reduction in warranty costs	✓		✓	✓+	✓	✓

Table 5-6 Types of SLP-Related Cost Increases (or Benefit Reductions) Classified by Stakeholder Group

Type of Cost Increase or Benefit Reduction	Stakeholder Group					
	Building Owners & Managers	Codes, Standards, & Support Services	Construction & Associated Support Services	Manufacturing & Associated Support Services	Professional & Financial Services	Other
Decreased sales/revenue to producers of competing materials			✓	✓+	✓-	
Development of new standards		✓+	✓	✓+	✓	
Increased cost of product testing		✓		✓+		
Increased risk exposure due to introduction of "niche" product			✓-	✓+	✓-	
New technology introduction costs	✓-	✓	✓+	✓+	✓	✓-
Potential for health and environmental risk	✓	✓-	✓	✓	✓-	✓

6 Data and Assumptions for the SLP Economic Impact Assessment

This chapter describes the data and assumptions used to evaluate the economic impacts expected from the adoption and use of SLP products and services. The goal of this chapter is fourfold. First, it establishes the sources and validity of the data used in the SLP economic impact assessment. Second, it defines the base case and the SLP alternative. Third, it derives estimated values for key input parameters. Fourth, it documents the process by which key assumptions were established, including how the values of key parameters were set. The values of the key input parameters and assumptions provide the basis for the estimated values of benefits and costs presented in Chapters 7 and 8.

6.1 Data Sources

Establishing the sources and validity of the data used in the SLP economic impact assessment is essential if readers are to be able to follow the analysis, gain insights useful for their own applications, and reproduce our results. This section describes the strategy for gaining input from key stakeholders and the findings from their inputs. The material presented in this section is intended to establish an audit trail which readers can follow to gain access to the same information used in the SLP economic impact assessment.

6.1.1 Strategy for Obtaining Stakeholder Input

The project team in consultation with the NIST Legal Office decided that the best way to announce our research effort to the public was through a broadcast email with a link to a web page on the BFRL web site. The content of the broadcast email and the web page were developed in consultation with subject matter experts and then cleared by the NIST Legal Office for distribution.

A mailing list composed of present and past consortium members, participants in major materials-related workshops and conferences, and other interested parties in academe and professional societies was compiled. The final list consisted of nearly 1000 email addresses. The broadcast email was sent on March 31, 2009; it included both links to the web page for additional information and an email address where comments could be sent to the project team. The broadcast email requested that comments be submitted by May 1, 2009. Among the comments received were a number that gave permission for project team members to contact them for a follow-up discussion.

The web page provided background information on the scope of the research project, the intended benefits of the research project, how the project team would measure economic impacts, and the purpose of the announcement. Each component of the background information posted on the web page is described briefly in the text which follows.

Scope and Purpose of the NIST Research Project

This research project, to be completed in September 2009, examines three industries—roofing, sealants and adhesives, and coatings—and estimates economic impacts from NIST's SLP research on those materials.

Intended Benefits of this Research:

- Construction industry stakeholders will have economic tools and metrics to help them make more cost-effective choices among construction materials and products, which can raise profits to businesses and reduce the life-cycle costs of construction to consumers of building services.

- Research organizations—both in the private and public sectors— will have new tools to help them in allocating research budgets more efficiently, thereby increasing budget impacts per dollar spent.

To Measure Economic Impacts, We Need to Know Specifically:

- How important improved SLP is to stakeholders' bottom lines; i.e., in reducing costs, raising sales revenues, and increasing profits; and

- How improved SLP helps stakeholders reduce uncertainty in product development, establish warranty terms, decide on new product innovation, estimate product failure, and reduce time to market.

The Purpose of this Announcement is to:

- Notify key stakeholders—product manufacturers, building owners and managers, and professional services related to codes and standards, construction support, consulting, and finance—of this NIST ongoing research, and to

- Invite stakeholders to identify potential benefits from improved SLP from the perspective of their product and profession, and how SLP impacts their business decisions, such as in establishing warranties.

As a follow-up to the announcement, the research team talked to numerous industry stakeholders. The intent was to make sure that all benefits and costs associated with improved service life prediction in their respective sectors were being identified in our analysis. Section 6.1.2 describes some of the benefits or reductions in costs that they felt were particularly significant in their industries.

Another purpose of the follow-up discussions was to identify specific examples for which adequate documentation existed to support a series of case studies. Although many excellent topics were suggested, the project team felt that there were only three examples that had sufficient documentation to support a rigorous case study analysis. All three of these case studies involve commercial buildings. These case studies are: (1) improved time-to-market for new cool roof technologies; (2) high-performance sealants and adhesives that reduce air infiltration; and (3) high-performance seams for EPDM roofing that reduce warranty repair costs. Details on how the case study analyses were developed are presented in Section 6.3.1.

6.1.2 Summary of Major Findings

Although SLP-related benefits and costs were discussed in some detail in Chapter 5, the discussions with key stakeholder representatives provided a more in-depth and focused assessment. These findings are presented under the general topic areas of coatings, sealants and adhesives, and roofing materials.

Coatings

As noted in Section 4.3 the construction-related market for coatings includes architectural coatings, OEM product coatings, and special purpose coatings. Most industry people agreed that better service life prediction reduces time to market. Three areas, however, were highlighted as being of special importance.

Greater availability of products with new features: Improved service life prediction results in a better understanding of polymeric products. This increase in knowledge helps producers develop products with new features that meet the specific needs of consumers.

Increased sales opportunities from new services: Having service life prediction tools, protocols, and standards will provide new sales opportunities to companies that assist product developers in the formulation of new or improved products. For example, a company producing chemicals could provide consulting services to companies producing coatings that would help them predict the service life performance of alternative product designs.

Reduction in energy costs and associated carbon footprint: Better performing materials resulting from improved service life prediction will increase solar reflectance, reducing solar heat gain, thereby reducing cooling loads. Reducing solar heat gain reduces the energy requirements for maintaining a target cooling comfort level in a building and thereby reduces the carbon footprint from electricity use in that building.

Sealants and Adhesives

The industry has companies that sell such products as caulk, glues, and adhesives mainly to large quantity users constructing big buildings as well as companies that sell through retailers to homeowners. Most industry people agreed that better service life prediction reduces time to market. Reducing the time to measure service life to just a month, for example, was estimated by one industry person to save a year of trial and error testing. Another, on the other hand, said improved SLP would have to cut the time to one-sixth or one-seventh for the testing time to be worthwhile, because you still have to run field tests to make sure the product can be used successfully and that appliers are willing to use it.

Several benefits stood out. The first was overengineering. Improved understanding of material performance through improved SLP enables designers to better predict how a new product will perform, thereby enabling them to more finely tune the mix of inputs to achieve a desired level of final product or system performance. Furthermore, this improved understanding also helps designers select the most cost-effective inputs that can be relied upon to meet product standards. One industry person predicted a 5 % to10 % decrease in raw material costs if overengineering could be contained.

A second benefit is the reduced energy costs from better performing seals on the exterior façade of a structure from reduced air and water infiltration into conditioned spaces, thereby reducing cooling and heating loads as well as reducing water incursion into insulation in the walls. Thus maintaining with better seals a tighter envelope reduces the energy requirements for maintaining a target comfort level in a conditioned space. This in turn delivers a second benefit—a reduction in the carbon footprint from reduced energy consumption in that structure. In addition, decreased water incursion from better seals will preserve the insulation performance, thereby saving more energy and reducing the carbon footprint further than what would occur with wet insulation. As an example, longer-lasting and better performing sealants on a high-rise building façade can decrease air and moisture penetration sufficiently over time to reduce significantly energy consumption and associated carbon emissions.

One industry spokesperson spoke of a third benefit that would be important to their company, namely, upselling. If architects or engineers are planning and building for an occupying tenant, they can justify and specify high first-cost materials on cost-effective grounds by pointing out to the tenant that the life-cycle cost of the higher-price material will save money over the long run of the tenant's occupancy. Better service life prediction enables the manufacturer of sealants or adhesives in this case to make a life-cycle case for better long-term performance and superior cost effectiveness over competing lower first-cost products. The potential benefits that accrue to the manufacturer then are greater market share with higher-price, greater profit margin products.

Roofing Materials

NIST initiated an industry-government consortium of roofing stakeholders to compare the performance of tape-bonded and liquid-adhesive-bonded seams of EPDM membranes used in roofing and to recommend a test protocol and criteria for evaluating the performance of such seams. Participants included EPDM manufacturers Carlisle, Firestone, and Genflex; tape-system manufacturers Adco and Ashland; the trade associations National Roofing Contractors Association and the Roof Consultants Institute; CERL; and roofing consultants, designers, and appliers. Members of this consortium team were asked what benefits they felt were brought about by the improved service life prediction research.

There were three generations of EPDM sealing methods.[59] The first two—adhesive-bonded and adhesive-tape-bonding—resulted in numerous failures. The third generation system, replacing adhesive with a double-stick splice tape, was a major improvement for performance.

A prime benefit from the consortium was demonstrating the viability of tape-bonded seams such that installers, designers, and customers believed that the tape would work and last. This confidence encouraged more usage and greatly decreased the number of flawed systems entering the market. Thus a related benefit from the tape-bonded seam was the savings from reduced repair callbacks. One consultant estimated that the introduction of tape decreased by 95 % the trouble-shooting costs incurred for investigation of system failures. And seam failures were 75 % to 85 % of those callbacks. Replacing adhesive-bonded seams with double-stick butyl tape resulted in 2 to 3 times fewer labor errors in installing EPDM systems.

An expected increase in warranty cost savings was a third benefit arising from better predictability of lifetime system performance. A major change in warranty periods resulted, with 20-30 year warranties being added to an initial warranty offering of 10-15 years.

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[59] The three generations are described briefly below. The first generation was composed of two phases: (1a) early liquid adhesive-bonded based primarily on chloroprene adhesive. This adhesive had problems but not so numerous that EPDM was driven from the market; it was used until a replacement became available; and (1b) early preformed tape bonded. This adhesive had numerous failures to the extent that these tapes disappeared; these failures contributed to the distrust expressed by many practitioners when tapes were re-introduced in the late 1980s and early 1990s. The second generation was liquid adhesives based on liquid butyl-based adhesives. These were successful and accepted to the extent that they were the benchmark of performance. The third generation consisted of a "second" generation of pre-formed tapes. These were the subject of the NIST-industry consortium; they are now the major adhesive used by the industry. The "second" generation of liquid adhesive is still available for use when tapes are not appropriate.

A fourth benefit from better service life prediction is a reduction in overengineering costs. Better understanding of performance results not only in lower-cost material combinations, but different protocols for application that may reduce costs of installation as well as life-cycle costs of maintenance and repair.

An unrealized, but potential benefit, cited by consortium members was the cost savings that could result from a "standard guide" that codified the protocol used by the consortium in evaluating the succeeding generations of seam-sealing approaches to installing EPDM systems. If manufacturers had such a protocol for testing new products before putting them in the market, specifiers could confirm that manufacturers had followed the protocol and would feel confident in specifying tested products for applications. Furthermore, owners/builders would feel confident in the performance of the systems they buy. One consortium member pointed out that if the consortium studies had been performed on the first and second generation EPDM systems prior to their market introduction, the industry could have avoided significant failed systems costs.

6.2 Defining the Base Case and the SLP Alternative

The purpose of this section is to define the base case and the SLP alternative to the base case. This "definition step" is done to draw two key distinctions between the base case and the SLP alternative (i.e., the two configurations). These distinctions are important because they facilitate the estimation of the benefits and costs covered in Section 6.3.

It is anticipated that SLP products and services will be employed in both the construction of new commercial and residential buildings and for the renovation of existing commercial and residential buildings. Verification that the SLP products and services employed are performing "as stipulated" is done as part of a formal project execution process. If the SLP alternative is not chosen, the same process applies for commercial and residential buildings employing the base case. Thus, for new commercial and residential buildings, either the base case or the SLP alternative is employed during "grass roots" construction. Similarly, for existing commercial and residential buildings, either the base case or the SLP alternative is employed while the facility is undergoing renovation.

Both the base case and the SLP alternative (i.e., both configurations) have features against which costs, savings, and performance are measured. These features include the materials, components, and systems required for design, construction, and facility operations. It is important to recognize that both configurations must meet all facility-related performance requirements. This "performance requirement" constraint is needed to ensure that both configurations are reliable, serviceable, safe, and at a minimum, neutral with regard to design aesthetics.[60] The performance requirement applies both to either configuration employed during the construction of a new commercial or residential building and to either configuration employed during the renovation of an existing commercial or residential building.

Throughout the remainder of this report, the term base case is used to represent the configuration that maintains the status quo (i.e., the "continued" use of field testing and exposure). The SLP alternative is that collection of products and services (i.e., configuration) that provides equivalent or enhanced performance for all features of the base case while satisfying the definition of a reliability-based methodology that is based on laboratory experiments that are repeatable and reproducible.

6.3 Estimating Significant SLP-Related Benefits and Costs

This section develops estimates of the key benefits and costs that are the focus of the SLP economic impact assessment. These benefits and costs are well-defined subsets of the comprehensive lists of benefits and costs presented in Chapter 5.

It is important to recognize that every effort has been made to capture and record any cost-related information affecting the users of SLP products and services. Similarly, considerable effort went into documenting and estimating BFRL's SLP-related investments. Relatively less effort went into estimating the full range of SLP-related benefits and cost savings. We focused on what we judged the most substantial and measurable benefits, which we termed the "significant few" benefits. Thus, the return on BFRL's SLP-related investments is expected to be very conservative (i.e., the values presented in this report are lower bounds on the potential range of economic returns on BFRL's SLP-related investments).

6.3.1 Benefits and Cost Savings

The enhanced performance of the SLP alternative vis-à-vis the base case produces three types of benefits and cost savings in commercial buildings. These benefits and cost savings are: (1) improved time-to-market for new cool roof technologies; (2) high-performance sealants and adhesives that reduce air infiltration; and (3) high-performance seams for EPDM roofing that reduce warranty repair costs.

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[60] For more information on how to specify performance requirements, see Chapter 2 of Fuller and Petersen (Fuller, Sieglinde K., and Stephen R. Petersen. 1996. *Life-Cycle Costing Manual for the Federal Energy Management Program*. NIST Handbook 135. Gaithersburg, MD: National Institute of Standards and Technology).

6.3.1.1 Improved Time-to-Market for New Cool Roof Technologies

In 2005, the use of cool roofs on low-slope non-residential buildings became part of California's energy code (Title 24 Building Energy Efficiency Standards). A cool roof both reflects a high amount of solar radiation, as well as allows for the rapid emittance of absorbed heat. Cool roofs have been shown to provide significant summertime energy savings as they stay 50° F to 60° F (28° C to 33° C) cooler than traditional roofs (California Energy Commission 2009).[61]

The California cool roof energy standard applies to all new construction of low-sloped (2:12 or less) nonresidential buildings with heated or cooled space (conditioned space). Types of buildings subject to the standard include: assembly, office, educational (through 12th grade), factory, hazardous facilities, mercantile, storage facilities, and utility facilities.[62] Institutions (e.g., hospitals, prisons) are exempt from the standard, as are buildings with steep slopes, high-rise residential, unconditioned buildings, and hotels and motels. This standard also applies to many reroofing projects on similar buildings. To meet the cool roof standard, the roofing product must produce an initial emittance of at least 0.75 and an initial reflectance of at least 0.70.[63]

Improvements in service life prediction techniques can have two effects on the cool roof coatings market: (1) to increase the speed of development of new cool roof technologies; and (2) to provide new (accelerated) test methods. Thus, a benefit of improved service life prediction is the faster time-to-market of improved polymeric materials, which will induce greater near-term energy savings. As improved energy saving technologies are brought to market sooner, less efficient products are replaced.

Using EnergyPlus, a Department of Energy energy simulation program, a counterfactual analysis of the energy savings in California from improved service life prediction of cool roof coatings is conducted. This counterfactual analysis presupposes improvements in service life prediction led to early introduction of new, high-performance cool roof coatings beginning in 2005. The net energy savings from applying a high-performance cool roof coating to a three-story commercial office building in Los Angeles is simulated

[61] California Energy Commission. 2005. "Q and A on COOLS ROOFS." Downloaded from: http://www.energy.ca.gov/2005publications/CEC-400-2005-053/CEC-400-2005-053.PDF. Last accessed by authors on September 2, 2009.

[62] *Ibid.*

[63] *Ibid.*

in EnergyPlus and then the economic effect is estimated statewide for net energy savings in California, following a procedure developed in Levinson and Akbari.[64]

The prototypical three-story office building used in the analysis has a flat roof with an area of 6663 ft^2 (619 m^2) and a combined floor area of 19 999 ft^2 (1858 m^2). Table 6-1 presents the characteristics of the office building used in the analysis. The HVAC is programmed to cool to 24° C (75° F) and heat to 21° C (70° F) during 'in-use' operating times, while the HVAC is programmed to cool to 30° C (86° F) and heat to 15.6° C (60° F) during 'off-use' times. During the cooling period, the HVAC system operates between 6AM to 10PM on weekdays and 6AM to 6PM on Saturdays. The building is closed on Sundays. During the heating period, the HVAC system operates between 6AM to 7PM on weekdays and 6AM to 5PM on Saturdays.

The introduction of a high-performance cool roof coating is compared to a cool roof coating that meets the minimum California cool roof standard. The high-performance cool roof coating is based on the characteristics (i.e., solar resistance and thermal emittance) of some of the best performing Energy Star qualified reflective roofing products currently available. The solar resistance is set at 0.92 and the thermal emittance is set at 0.87. Using the typical meteorological daily weather data, the EnergyPlus energy simulation estimates that the high-performance coating would decrease electricity usage by 0.39 kWh/ft^2 (4.20 kWh/m^2) and would increased natural gas usage by 0.00021 therms/ft^2 (0.00226 therms/m^2). The heating penalty is caused by reducing the solar heating during the heating period (e.g., wintertime). Net savings averaged \$0.05/ft^2 (\$0.54/m^2) of conditioned floor area (area cooled), based on energy pricing in California over the 2005 to 2007 period (see Table 6-2). Average electricity and natural gas prices was derived from Energy Information Administration data (*1990 - 2007 Retail Sales of Electricity by State by Sector by Provider (EIA-861)*; *1990 - 2007 Revenue from Retail Sales of Electricity by State by Sector by Provider (EIA-861)*; *Average Price of Natural Gas Sold to Commercial Consumers, by State, 2007-2009*).

[64] Levinson, R., and H. Akbari. 2009. "Potential benefits of cool roofs on commercial buildings: conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants." Energy Efficiency. Published Online 14 March 2009.

Table 6-1 Characteristics of the prototypical three-story office building used in the EnergyPlus energy simulations

Geometry	**Office Building**
Roof Area (ft^2)	6663
Floor Area (ft^2)	19,999
Roof Insulation (continuous insulation)	R-20
Wall Insulation (continuous insulation)	R-7.6
Cooling Equipment	Unitary system with DX coils
Cooling Energy Efficiency Ratio (BTU/[h*W])	10.24
Heating Equipment	Gas-fired heating coil
Heating Efficiency (%)	80
Operating Hours	
Cooling	Weekdays 6A-10P; Saturday 6A-6P
Heating	Weekdays 6A-7P; Saturday 6A-5P
Cool Roof Technology #1 (CA Min. Standard)	
Solar Reflectance	0.70
Thermal Emittance	0.75
Cool Roof Technology #2 (Best Available)	
Solar Reflectance	0.92
Thermal Emittance	0.87

Table 6-2 Nominal energy prices and estimated net energy savings (California)

Year	**Electricity ($/kWh)**	**Natural Gas ($/therm)**	**Net Savings ($/ft^2)***
2005	0.125	1.04	0.048
2006	0.135	1.01	0.052
2007	0.134	0.99	0.051

* Based on a cooling energy savings of 0.390 kWh/ft^2 and a heating energy penalty of 0.00072 therm/ft^2.

Levinson and Akbari present a method for interpolating net energy savings (due to cool roof use) estimated from individual building energy simulations to statewide areas.[65] The method requires calculating the net energy savings per conditioned square-foot (see Table 6-2) and multiplying it with the amount of statewide conditioned roof area (see Table 6-3). The estimated conditioned roof area for three commercial building types (education, mercantile, office) is presented in Table 6-3. Table 6-3 also breaks out conditioned roof area out into new construction and pre-existing. In this analysis, 67 % of all commercial conditioned roof area is assumed to be associated with low slope buildings (NRCA 2006).[66] Also, it is assumed that all new low-slope construction requires cool roofs, as well as 5 % of the pre-existing low-slope building stock (reroofing projects).

Table 6-3 Estimated conditioned roof area (ft^2)

Building Type	New Construction	Pre-Existing Buildings
Education	13,247,952	462,836,836
Mercantile	28,223,299	309,767,974
Office	1,620,615	422,600,113

It is assumed that the high-performance coating is introduced to the market three years ahead of schedule due to the benefits provided by improved service life prediction. All new cool roof technologies require licensing from the Cool Roof Rating Council (CRRC). The licensing process requires product samples to be weathered for three years. Therefore, the benefits of improved service life prediction are quantified as the net energy savings afforded to owners and operators of low sloped commercial buildings (focusing on education, mercantile, and office) due to the early introduction of the new improved technology. Without improved service life predictions, the new (high-performance) technology is assumed to be introduced in 2008. Benefits accrue, then, with early introduction in 2005, 2006, or 2007 because the high-performance technology provides greater efficiency than other lower-performance technologies meeting only the minimum California standard.

6.3.1.2 Reduced Air Infiltration: High-Performance Sealants and Adhesives

The energy impact from the introduction of high-performance window sealants is measured as the difference in commercial energy consumption between a building using the high-performance sealant and a building using a typical sealant. Differences occur

[65] *Ibid.*

[66] National Roofing Contractors Association. Annual Market Survey: 2006-2007. *Op. cit.*

due to variation in their air infiltration rates. Based on Carbary *et al.*,[67] a typical fenestration product produces an infiltration rate of 5.5 $m^3/m^2/hr$, whereas a high-performing fenestration product that uses a structural sealant to attach glass to framing allows almost none. Benefits of reduced air infiltration include energy savings due to reduced cooling demands during the summertime and reduced heating demands during the wintertime. The counterfactual analysis presented in this section presupposes improvements in service life prediction led to early introduction of new, high-performance, wet-sealed fenestration beginning in 2004 and expanded into the marketplace in the follow years (2005 to 2008). Improvements in service life prediction techniques speed the development of new window sealant technologies. This induces greater near-term energy savings, as improved energy saving technologies (better sealants) are brought to market sooner, thus replacing less efficient products (established sealants).

Three energy models are used to estimate the annual energy savings throughout the U.S. due to improved fenestration systems from the use of a new high-performance sealant. The energy models, based on Carbary *et al.,* estimate the effects that differences in glazing systems have on energy consumption. Their energy models were location-based, meaning energy consumption was estimated for different regions of the world—Madrid, Hong Kong, Minneapolis, and Tampere—for the same prototypical building design: a 9-story, 58 125 ft^2 [5400 m^2] commercial building. Based on the energy numbers reported in Carbary *et al.* for low E^3 (high performance) windows, square-foot electricity (kWh/ft^2) and natural gas (kWh/ft^2), we computed savings, as well as net (combined) energy cost savings (see Table 6-4), for the nine census divisions in the United States. The Pacific and Mountain divisions are computed based on the Carbary *et al.* Madrid model; West North Central, East North Central, Middle Atlantic, and New England divisions are computed based on the Carbary *et al.* Minneapolis model; and the South Atlantic, East South Central, and West South Central are computed based on the Carbary *et al.* Hong Kong model.[68]

Average electricity and natural gas prices were derived from Energy Information Administration data (*1990 - 2007 Retail Sales of Electricity by State by Sector by Provider (EIA-861)*; *1990 - 2007 Revenue from Retail Sales of Electricity by State by Sector by Provider (EIA-861)*; *Average Price of Natural Gas Sold to Commercial Consumers, by State, 2007-2009*) (see Table 6-5).

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[67] Carbary, LD, V. Hayez, A. Wolf, and M. Bhandari. 2009. Comparisons of thermal performance and energy consumption of facades used in commercial buildings. GPD 2009 Proceedings. Tampere, Finland.

[68] *Ibid*.

Table 6-4 Energy and cost savings ($2008)

Census Division	Energy Model*	Energy Savings*		Cost Savings ($/ft^2)				
		Cooling (kWh/ft^2)	Heating (therms/ft^2)	2004	2005	2006	2007	2008
Pacific	Madrid	-0.010	0.024	0.02	0.03	0.03	0.02	0.03
Mountain	Madrid	-0.010	0.024	0.02	0.02	0.03	0.02	0.02
West North Central	Minneapolis	0.019	0.065	0.06	0.07	0.08	0.07	0.07
East North Central	Minneapolis	0.019	0.065	0.06	0.08	0.08	0.07	0.08
Middle Atlantic	Minneapolis	0.019	0.065	0.08	0.09	0.09	0.08	0.06
New England	Minneapolis	0.019	0.065	0.09	0.10	0.10	0.10	0.10
South Atlantic	Hong Kong	0.134	0.008	0.02	0.02	0.02	0.02	0.02
East South Central	Hong Kong	0.134	0.008	0.02	0.02	0.02	0.02	0.02
West South Central	Hong Kong	0.134	0.008	0.02	0.02	0.02	0.02	0.02

*Based on Carbary *et al.* 2009.

Table 6-5 Energy prices ($2008) from 2004 to 2008

Census Division	Electricity Prices ($/kWh)					Natural Gas Prices ($/therms)				
	2004	2005	2006	2007	2008*	2004	2005	2006	2007	2008
Pacific	0.12	0.12	0.13	0.12	0.12	0.95	1.11	1.10	1.07	1.10
Mountain	0.08	0.08	0.08	0.08	0.08	0.87	1.01	1.11	0.98	0.97
West North Central	0.07	0.07	0.07	0.07	0.07	0.98	1.14	1.14	1.05	1.07
East North Central	0.09	0.09	0.09	0.09	0.09	0.97	1.15	1.17	1.07	1.15
Middle Atlantic	0.15	0.15	0.16	0.16	0.16	1.15	1.27	1.32	1.22	0.93
New England	0.14	0.15	0.18	0.19	0.19	1.33	1.46	1.55	1.44	1.44
South Atlantic	0.08	0.08	0.09	0.10	0.10	1.18	1.38	1.42	1.29	1.29
East South Central	0.08	0.08	0.08	0.08	0.08	1.09	1.34	1.40	1.23	1.33
West South Central	0.09	0.09	0.10	0.10	0.10	0.96	1.13	1.11	1.02	1.12

*2008 prices not available—assumed equal to 2007.

The energy savings vary from -0.010 kWh/ft^2 (-0.108 kWh/m^2) to 0.134 kWh/ft^2 (1.442 kWh/m^2) for electricity and 0.008 therms/ft^2 (0.086 therms/m^2) to 0.065 therms/ft^2 (0.700 therms/m^2) for natural gas (see Table 6-4). The energy savings translate into unit cost savings of \$0.02/ft^2 (\$0.22/m^2) to \$0.10/ft^2 (\$1.08/m^2) over the 2004 to 2008 study period (see Table 6-4).

Total energy savings (see Section 7.1) are computed by multiplying the annual square-foot cost savings with the total amount of conditioned area in commercial buildings (see Table 6-6) in each of the census divisions, and summing these values over all years and census divisions. A diffusion process is used to estimate the market penetration of the high-performance sealant into new and existing commercial buildings from 2004 to 2008.

Table 6-6 Estimated conditioned roof area (ft^2)

Census Division	New Construction	Existing Buildings
Pacific	4,387,572,704	166,344,241
Mountain	1,999,208,673	11,724,000
West North Central	1,881,893,907	-
East North Central	5,466,207,612	86,607,100
Middle Atlantic	4,800,925,612	37,749,270
New England	1,543,479,190	32,340,380
South Atlantic	7,013,856,425	26,988,454
East South Central	1,499,880,324	-
West South Central	4,225,714,304	92,857,610

6.3.1.3 Reduction in Warranty Repair Costs: High-Performance Seams for EPDM Roofing

NIST initiated an industry-government consortium of roofing stakeholders (1) to compare the performance of tape-bonded and liquid-adhesive-bonded seams of EPDM membranes used in roofing and (2) to recommend a test protocol and criteria for evaluating the performance of such seams. Participants included EPDM manufacturers; tape-system manufacturers; trade associations; and roofing consultants, designers, and appliers. Members of this consortium team were asked in 2009 what benefits they felt were brought about by the improved service life prediction that resulted from consortium activities. They responded with multiple benefits: decreased costs from substituting fewer or less expensive materials (less overengineering); increased confidence of installers, designers, and customers that the new system would work and last; reduced repair costs from callbacks to fix leaks; decreased warranty repair costs arising from better predictability of lifetime system performance; and longer warranty periods—for example, 10 to 15 year warranties being replaced with 25 to 35 year warranties.

This section examines one of those benefits—the reduction in warranty service repair costs. Although it is only one of the expected benefits from better performing EPDM roofing systems, it is substantial and has been documented. So while not all benefits or savings from improved EPDM systems are calculated, we can provide a lower-bound estimate of the savings based on actual records of warranty service costs. Our source is "EPDM Roof System Performance: An Update of Historical Warranty Service Costs," authored by James L. Hoff and published in RCI Interface in September 2003.[69] The database underlying this study covers over three billion square feet of EPDM roofs on over 150,000 roofs installed between 1982 and 2003. Each roof in the database has a material and workmanship warranty, the majority being 10 years in length. The date, cost, and type of service repairs are given for the entire warranty period. As of 2003, there were service repair data available for at least 10 years on all roofs installed in 1993 or before.

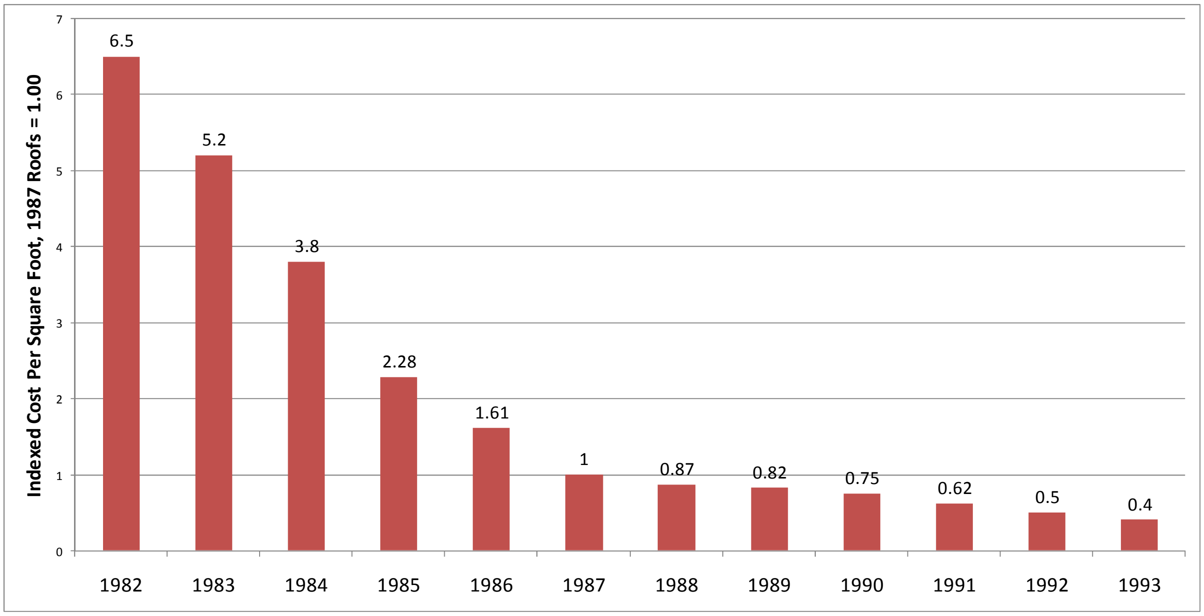
Since the historical warranty costs are exclusively the manufacturer's service call costs, this data might underestimate total repair costs; that is, owners sometimes incur additional repair/maintenance costs beyond what is covered in the warranty. For comparison purposes, the costs are presented in $\$/ft^2$. To preserve confidentiality of manufacturers' actual costs, the service costs described in Hoff's study are normalized and indexed to a baseline year, in this case 1987, with a cost index of 1.0 cost/ft^2. The 10-year stream of indexed warranty service cost data for any given installation year was adjusted for the time value of money using the U.S. National GDP Deflator as calculated by the U.S. Bureau of Labor Statistics.

Figure 6-1 shows, as of July 2003, the change in total warranty service costs, by installation year, from 1982 to 1993, where the height of each bar in the figure represents, for that year's installed EPDM roofs, the cumulative, time adjusted, indexed cost per square foot of the 10 years of warranty service. From 1982 to 1987, unit warranty service costs dropped 85 % ((6.5 - 1.0)/6.5). And although the curve flattens out from 1987 to 1993, the warranty service costs still drop another 60 % ((1.0 - 0.4)/1.0). From such

[69] James L. Hoff. 2003. An Update of Historical Warranty Service Costs. *RCI Interface* September, 29-32. http://www.rci-online.org/interface/2003-09-hoff.pdf (accessed September 2009).

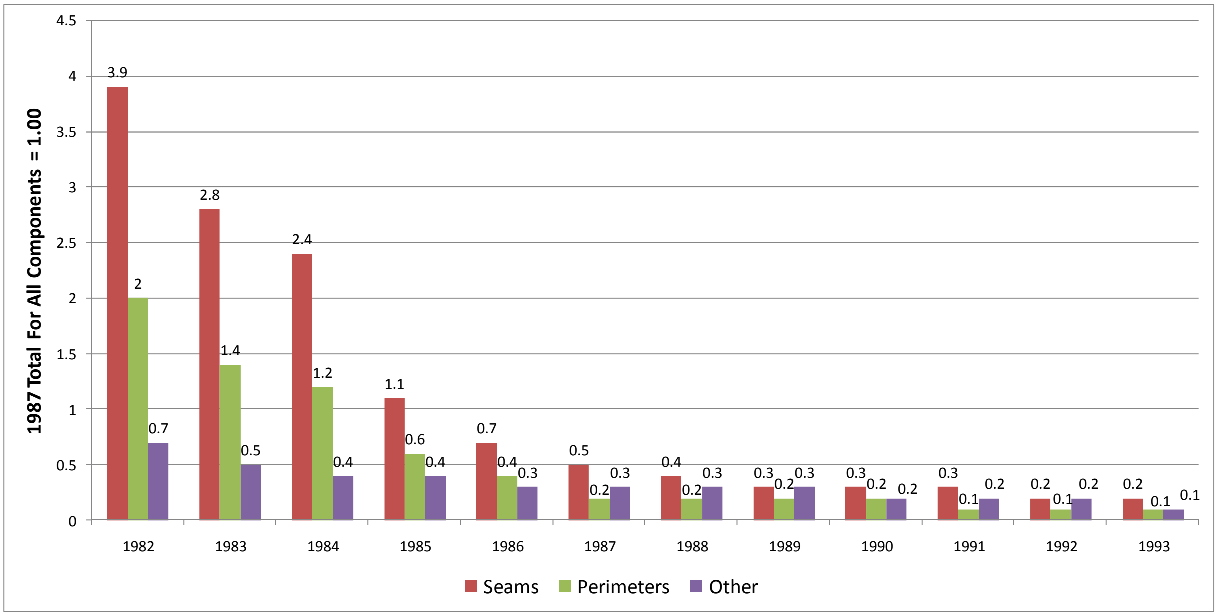
significant drops in warranty costs from 1982 to 1987, Hoff suggests that technological changes must have occurred. This could have taken place in roof materials, application technique, or design.

Figure 6-1 EPDM Warranty Service Costs: First Ten Years of Service



Hoff's article provides further insight as to just what component of the roofing was responsible for most of the service costs. Figure 6-2 shows the indexed cost per square foot of warranty service costs by key components of EPDM roofing. Field seams were by far the most significant cost driver, and perimeter flashings were second. And each of these decreased in 10-year unit costs between 1982 and 1987—87 % ((3.9 - 0.5)/3.9 = .87) for seams, and 90 % ((2.0 - 0.2)/2.0 + .9) for flashings.

Figure 6-2 EPDM Warranty Service Costs by Key Component: First Ten Years of Service—Indexed Cost per Square Foot



The Hoff article shows dramatic reductions in warranty service costs over the 20 years from 1982 to 2003. His explanation for this reduction is the introduction of several technologies by the roofing manufacturer. Table 6-7 presents the new technologies by the years that they were introduced. Hoff maintains that these were significant in driving down the warranty service costs.

Table 6-7 Technologies Introduced in EPDM Roofing Systems

Year Introduced	Technology
1985-1986	Butyl-based splice adhesive replaces neoprene-based adhesive
1985-1986	EPDM-based wall flashings replace neoprene-based flashings
1987-1988	Tape laminates replace adhesive seams at roof edges and battens
1988-1989	Metal battens and screw fasteners replace wood nailers and nails
1991-1992	Reinforced perimeter fastening strips introduced
1992-1993	Seam tape with high-solids primer replaces seam adhesive

The implications for service life prediction are that NIST's EPDM-related research contributed to the technologies in Table 6-7, thereby expediting the drop in EPDM warranty service costs.

Hoff's article provides a final insight that enables us to develop estimates of the reductions in warranty service costs. Figure 6-3 shows the first ten-year warranty service costs for 1985 through 1993 as a percentage of the original installed costs.

Figure 6-3 EPDM Warranty Service Costs as a Percentage of Original Installed Cost: First Ten Years of Service

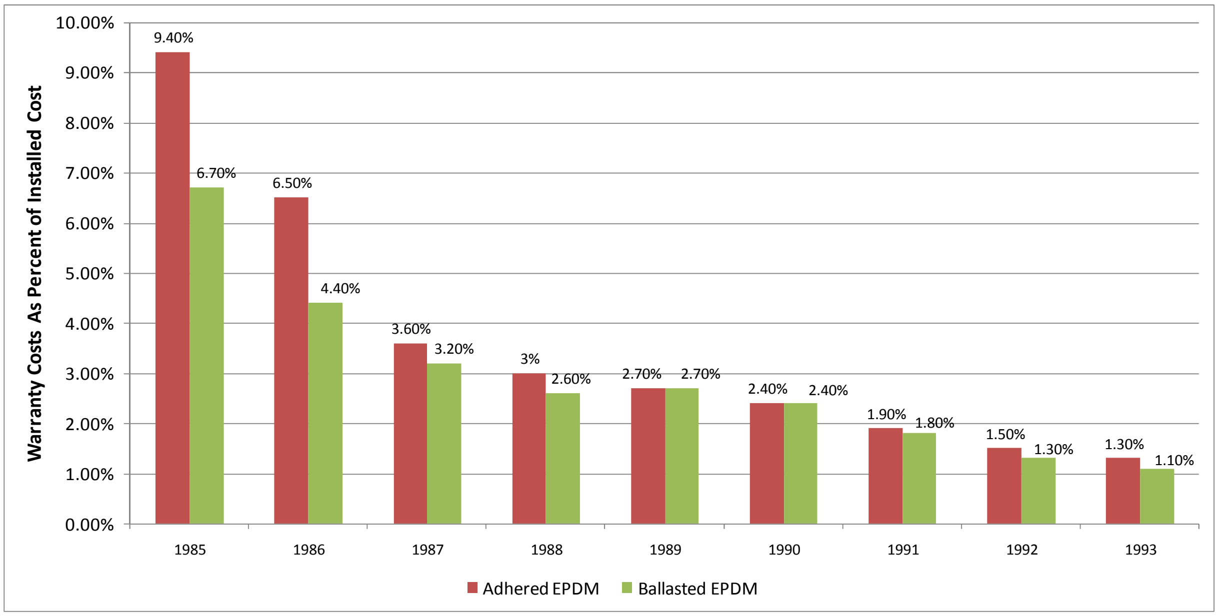


Table 6-8 shows the estimated installed costs for EPDM roofs over the nine-year period, 1985 through 1993, reported in Hoff's article. These data, once linked with information contained in Figures 6-1, 6-2, and 6-3, enable us to estimate EPDM-related warranty service costs for the first ten years of service. These costs can then be annualized and used to estimate the year-by-year reductions in EPDM warranty service costs due to technological improvements. The procedure for estimating year-by-year reduction in EPDM warranty service costs due to technological improvements in described in detail in Section 7.2.

Table 6-8 Estimated Installed Costs for EPDM Roofs: 1985 to 1993

Year	Installed Costs in Millions of Dollars
1985	1554.7
1986	1688.3
1987	1836.2
1988	1931.7
1989	1898.0
1990	2097.8
1991	2094.7
1992	2143.0
1993	2330.8

Source: Census of the Construction Industry (1982, 1987, 1992, 1997) and National Roofing Contractor Association[70]

6.3.2 Cost Increases and Benefit Reductions

Two types of cost increases—new-technology introduction costs and increased research and development costs—are central to this economic impact assessment. The first type of costs, new-technology introduction costs, may result in higher costs to commercial building owners and managers and to contractors. Understanding the types of costs that affect commercial building owners, managers, and contractors is necessary in order to estimate annual values of net savings on a national level. These estimates affect not only the present value of net savings nationwide, but the estimated return on BFRL's SLP-related investments as well. The second type of costs, increased research and development costs, focuses only on BFRL's SLP-related investments.

6.3.2.1 New-Technology Introduction Costs

If commercial building owners, managers, and contractors employ the SLP alternative rather than the base case, they can expect to bear new-technology introduction costs (see Table 5-6). Ehlen and Marshall[71] define new-technology introduction costs as those costs covering the activities that bring the material/product from the research laboratory to full field implementation. New-technology introduction costs include the extra time and labor to design, test, monitor, and use the new technology. Ehlen's and Marshall's research on new-technology introduction costs is particularly relevant for this economic

[70] Cullen, William C. 1993. *Project Pinpoint Analysis: Ten-Year Performance Experience of Commercial Roofing 1983-1992*. Rosemont, IL: National Roofing Contractors Association.

[71] Ehlen, Mark A., and Harold E. Marshall. 1996. *The Economics of New-Technology Materials: A Case Study of FRP Bridge Decking*. NISTIR 5864. Gaithersburg, MD: National Institute of Standards and Technology.

impact assessment because they demonstrate that new-technology introduction costs disappear once the designer is satisfied with the technology's performance, the technology enters full implementation, and its application has become routine.[72]

Interactions with industry stakeholders suggest that better engineered products are capable of delivering equivalent or superior performance at a comparable cost. Thus, new-technology introduction costs are not expected to be a major factor in the adoption and use of the SLP alternative.

6.3.2.2 Increased Research and Development Costs

BFRL's SLP program has three distinct research and development costs associated with it. The first is the annual Scientific and Technical Research Studies (STRS) allocation. This allocation comes from NIST appropriated funds and is used to support the core research functions of the SLP program. The second and third categories of costs are referred to as leveraged research and development funds. These funds come from two sources: (1) consortia fees and (2) other federal agency contract research funds. Leveraged research and development funds are important to BFRL's SLP program for two reasons. First, they allow BFRL researchers to broaden the scope of their STRS base by adding a market-oriented element to their research projects. This helps in transferring their research findings into practice. Second, these leveraged funds are a recognition that BFRL researchers in the SLP program are working on the right things that will ultimately provide significant value to construction industry stakeholders. Thus, in one sense, the receipt of leveraged research and development funds is akin to a beneficial industry impact. Given the conservative approach taken in this analysis, however, we include leveraged research and development funds as a cost that must be balanced against the three types of benefits and cost savings in commercial buildings referenced in Section 6.3.1.

Table 6-9 records for NIST the three types of SLP-related research and development expenditures by funding source for the period of 1994 to 2008. The NIST STRS allocations are first reported. Leveraged research and development funds are then recorded by source (i.e., consortia and other federal agency) and in total. The year-by-year total is recorded in the last column. Although individual sources of R&D funds have varied considerably over time, Table 6-9 shows that the trend for the total has been mostly upwards.

[72] *Ibid.* p. 15.

Table 6-9 SLP-Related Research and Development Expenditures

Year	NIST (In $K)	Leveraged Research and Development Funds (In $K)			TOTAL (In $K)
		Consortia	Other Agency	Total	
1994	455.0	29.4	1046.8	1076.2	1531.2
1995	760.4	83.0	1136.0	1219.0	1979.4
1996	953.8	172.9	629.3	802.2	1756.0
1997	996.9	145.1	382.1	527.2	1524.1
1998	919.3	223.3	602.7	826.0	1745.3
1999	1046.6	422.0	551.0	973.0	2019.6
2000	1080.8	150.6	1296.5	1447.1	2527.9
2001	1431.7	149.4	780.1	929.5	2361.2
2002	1858.1	93.3	1059.4	1152.7	3010.8
2003	2072.2	374.6	782.4	1157.0	3229.2
2004	1597.1	87.9	1345.3	1433.2	3030.3
2005	2125.1	238.9	1130.0	1368.9	3494.0
2006	1917.3	206.2	1666.3	1872.5	3789.8
2007	2031.2	172.0	1275.8	1447.8	3479.0
2008	1901.3	9.5	2851.6	2861.1	4762.4

6.4 Key Assumptions and Analysis Issues

A clear statement of the assumed values of key sets of parameters underlying the analysis is vital to understanding how the analysis was conducted. The assumptions covered in this section focus on the setting of the assumed values of the following key sets of parameters: (1) the base year; (2) the starting and ending points in the study period; (3) the discount rate; (4) the process by which SLP products and services diffuse into the marketplace; and (5) the process by which BFRL's contribution is measured. The assumed values of these five key sets of parameters figure prominently in evaluating the economic impacts of SLP products and services. Documenting the assumptions and the rationale behind the setting of the assumed values of these key sets of parameters is necessary to ensure that: (1) all costs and savings are discounted to an equivalent time basis for purpose of comparison; and (2) readers can follow the flow of the analysis, gain insights useful for their own applications, and reproduce our results.

The base year establishes the anchor point for all cost and savings calculations. The starting and ending points in the study period define both the scope of the study period—those years over which costs and savings are tabulated—and the length of the study period. Because cash flows, both costs and savings, are distributed throughout the study period, the choice of the discount rate is of central importance to the analysis. The diffusion process is the critical link between potential cost savings (see Subsection 6.3.1) and cost savings nationwide (see Section 7.2). The model of the diffusion process presented in Subsection 6.4.4 provides the basis for calculating year-by-year savings following the introduction of SLP products and services. Because BFRL's SLP-related research is expected to speed up the introduction of SLP products and services into the commercial marketplace, a process for evaluating the "value" of BFRL's contribution is needed. This process is described in Subsection 6.4.6.

In addition to the five key sets of parameters used to make explicit the assumptions of the economic impact assessment, there are issues linking the baseline analysis to the sensitivity analysis. These "analysis issues" are concerned with the discount rate, the diffusion process, measuring BFRL's contribution, and dealing with uncertainty. The first three analysis issues provide the necessary "direct" linkage between the baseline analysis and the sensitivity analysis. They are crucial in measuring how variations about the baseline input values affect the economic outcome measures. The last analysis issue, dealing with uncertainty, is the core concept in structuring the sensitivity analysis. This analysis issue is discussed in Subsection 6.4.5.

6.4.1 Base Year for Computing Benefits and Costs

The base year for computing all SLP-related costs and savings is 2008. There are two reasons, one primary and one secondary, why 2008 was selected as the base year.

First, by using 2008 as the base year, this economic impact study maintains its *ex post* (i.e., retrospective) nature while still being rooted in the present.

Second, 2008 is a year for which authoritative and comprehensive construction industry cost data are available. Thus, cost conversions for previous years may be accomplished through the use of a well-defined cost index to equate them to constant 2008 dollars.

6.4.2 Length of the Study Period

The study period begins in 1994 and ends in 2008. Thus, the length of the study period is 15 years. Any costs and/or savings that occur after 2008 are not included. Two factors were instrumental in determining the beginning and end of the study period. First, 1994 is the year in which the first polymer coating consortium and the EPDM seam consortium were formed. Thus, 1994 marks the start of formal collaborations between BFRL's SLP program and key industry stakeholders. Second, the 15-year period 1994 to 2008 represents a period of intense industry collaboration and key breakthroughs in the validation and acceptance of reliability-based service life prediction.

6.4.3 Discount Rate

The baseline analysis for the SLP economic impact assessment uses a real rate of 7 % to convert dollar amounts to present values. This rate is specified in Section 8.b of OMB Circular A-94[73] as the rate for all benefit-cost analyses of public investments and regulatory programs that provide benefits or incur costs to the general public. The use of a 7 % real discount rate also facilitates comparisons of the results of the SLP baseline analysis with the results of the baseline analyses of the previous economic impact assessments.

OMB recommends that separate analyses be used to evaluate the sensitivity of key economic measures to variations in the discount rate.[74] The sensitivity analysis presented in Chapter 8 evaluates the implications of raising the discount rate to 10 % or lowering the discount rate to 4 %. The 4 % to 10 % range of values for the real discount rate was chosen to bracket the historical values of real treasury interest rates. These rates are periodically updated by OMB and published in Appendix C of OMB Circular A-94; they apply to government lease-purchase and cost-effectiveness analyses. Although these rates do not apply to regulatory analyses or benefit-cost analyses of public investments, they provide a useful frame of reference for establishing minimum and maximum values for the real discount rate. All values of the discount rate used in this report are real rates, since constant dollar estimates of benefits and costs are used.

6.4.4 Diffusion Process

Facts and data are essential components in any rigorous analysis. Factual information on the market for polymeric construction materials was tabulated from published sources (see Section 4.2). These data provide the basis for estimating the "potential" benefits and cost savings associated with the use of the SLP products and services in commercial buildings (see Subsection 6.3.1). However, to develop realistic estimates of cost savings nationwide, it is also necessary to generate estimated values for the annual proportion of commercial buildings employing SLP products and services for new construction activities and for additions and alterations. To generate estimates of cost savings nationwide, information on potential benefits and cost savings and on cost increases and benefit reductions (e.g., new-technology introduction costs) must be coupled with a model of the diffusion process. Much of the discussion in this subsection and in Section 7.2 of the next chapter is aimed at establishing an audit trail for how the values of the key

[73] Executive Office of the President. 1992. *OMB Circular A-94*. *Op. cit.*

[74] *Ibid*., p. 7.

parameters of the diffusion process were established and employed in the economic impact assessment. The focus of this subsection is on how the diffusion process is modeled (i.e., the form of the model and its key parameter values). Section 7.2 focuses on how the diffusion model is employed in the economic impact assessment.

An economy is not affected in any material way by a new technology until the use or ownership of that technology is widespread. This spread of a new technology is a topic usually referred to as technological diffusion. It is modeled via a diffusion process. The underlying basis for the study of technological diffusion is to rationalize why, if a new technology is superior, it is not taken up immediately by all potential users.

The empirical analysis of diffusion processes is a vast and complex subject. Although a full treatment of the topic is beyond the scope of this report, four factors affecting the diffusion process are worth noting. Readers interested in thorough treatments of this important subject, including case studies, are referred to the books by Stoneman[75] and Mansfield.[76]

First, new technology and its adoption involve uncertainty. Thus, the attitude of decision makers to uncertainty needs to be considered. The degree of uncertainty may be related to the level of use of the new technology and to how learning proceeds.

Second, how learning proceeds affects the diffusion process in a number of ways. It can involve learning about the existence of a new technology or learning about its true characteristics. For example, firms might learn about how to use the new technology to produce new or current products at lower cost. For a given initial state of knowledge, the faster that learning occurs, the higher the rate of diffusion.

Third, during a diffusion process, how learning proceeds may not be the only factor changing. The good itself may be improving. This improvement may have a double-edged effect on diffusion: a direct effect, stimulating greater use; and an indirect effect, whereby expectations of future advances may lead to the postponement of adoption.

Fourth, to a large degree the adoption decision for the firm will be related to expected profitability, which in turn will be dependent upon a number of factors. Thus differences between firms will be important, as may be the behavior of the industry supplying any new goods. The market structure of the user and supplying industries (i.e., situations involving imperfect competition) are also important.

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[75] Stoneman, Paul. 1983. *The Economic Analysis of Technological Change*. New York: Oxford University Press.

[76] Mansfield, Edwin. 1995. *Innovation, Technology and the Economy: Selected Essays of Edwin Mansfield*. 2 vols. Economists of the Twentieth Century Series. Aldershot, UK: Elgar.

The most widely accepted model of technology diffusion was developed by Edwin Mansfield. Consequently, the Mansfield model is employed in the SLP economic impact assessment. The Mansfield model estimates the proportion of potential users who have adopted the new technology by time t. The mathematical representation of the model is

$$P(t) = \left[1 + e^{(\alpha - \beta\, t)}\right]^{-1}$$

where

P(t)	=	the proportion of potential users who have adopted the new technology by time t,
e	=	Euler's number, the base of the natural system of logarithms,
α	=	the location parameter, and
β	=	the shape parameter ($\beta > 0$).

A plot of P(t) produces an S-shaped logistics curve, which is asymptotic to 0 as the value of t gets small and to 1 as the value of t gets large. Because the diffusion of a new technology may not achieve 100 % penetration of the marketplace, P(t) must be modified to reflect the level at which the potential market is saturated. The version of the Mansfield model employed in this report uses a subscript η to designate the market saturation level. The mathematical representation of the model is

$$P_\eta(t) = \eta\left[1 + e^{(\alpha - \beta\, t)}\right]^{-1}$$

where

$P_\eta(t)$	=	the proportion of potential users who have adopted the new technology by time t,
η	=	the market saturation level,
e	=	Euler's number, the base of the natural system of logarithms,
α	=	the location parameter, and
β	=	the shape parameter ($\beta > 0$).

An extensive review of the economics literature on the diffusion process produced candidate values for α and β. Readers interested in case studies based on the Mansfield model that are useful in specifying values for α and β are referred to Mansfield's collection of articles.[77] An additional factor used to specify the values of α and β is the length of time it takes for $P_\eta(t)$ to reach 50 % of its potential market. Due to the relationship between the Mansfield model and the logistics distribution, the value at which $P_\eta(t)$ reaches 50 % of its potential market has a closed-form relationship based solely on the values of α and β. If we assume $t = 1$ is the time at which the technology is first introduced, then α/β is the number of years it takes that technology to reach 50 % of its potential market. In order to get a meaningful value of t, it is necessary to constrain α to be positive (i.e., $\alpha > 0$).

The values of the ratio α/β vary from 4 years to 16 years in a wide range of articles published in the economics literature (see Mansfield,[78] Mansfield et al,[79] and Simon[80]). Consequently, this report uses a value of 8 for the ratio α/β as its baseline value. The corresponding baseline values for α and β are 4.0 and 0.5, respectively.

The estimated value for η was set equal to 0.4 for new commercial building construction and 0.25 for renovations. Thus, the baseline value for η is 0.4. This means that SLP products and services will eventually be employed in new projects totaling 40 % of the value of construction put in place for eligible commercial buildings. The estimated value for η for this class of commercial buildings is based on data contained in the 2003 Commercial Buildings Energy Consumption Survey (CBECS).[81] Specifically, the value of η is set to approximate the average proportion of floorspace in commercial buildings employing an energy management and control system[82] (EMCS). This technology was selected because it is mature (i.e., its use is sufficiently widespread to "approximate" market saturation).

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[77] Mansfield, *Innovation, Technology and the Economy*, Vol. II, pp. 3-83.

[78] *Ibid*., pp. 63-72.

[79] Mansfield, Edwin, John Rapoport, Anthony Romeo, Edmond Villani, Samuel Wagner, and Frank Husic. 1977. *The Production and Application of New Industrial Technology*. New York: W. W. Norton & Company, Inc.

[80] Simon, P. 1975. *Models of Process Diffusion and Entry in the U.S. Chemical Industry*. Ph.D. dissertation, University of Pennsylvania.

[81] Energy Information Administration. Commercial Buildings Energy Consumption Survey. http://www.eia.doe.gov/emeu/cbecs/contents.html (accessed September 2009).

[82] An EMCS is an energy management feature that uses mini/micro-computers, instrumentation, control equipment, and software to manage a building's use of energy for heating, ventilation, air conditioning, lighting, and/or business-related processes. These systems can also manage fire control, safety, and security.

The specification of the baseline values of the diffusion model is not complete until a time of first use is made explicit. As noted earlier, the time of first use corresponds to the value at which t = 1. The baseline value for the time of first use is 2005.

The values of α and β specify the rate of adoption of SLP products and services in commercial buildings, whereas the value of η specifies the size of the potential market for these products and services. Consequently, once the time of first use is made explicit, it becomes possible to estimate the annual proportion of construction-related expenditures in the commercial sector covered by SLP products and services. Table 6-10 records the values for $P_{\eta}(t)$, expressed as a percentage, for both new commercial building construction and renovations of existing commercial buildings. Note that t = 5 corresponds to the year 2008. Reference to Table 6-10 indicates that the diffusion of the products introduced in 2004 begin to rise rapidly in years 6 though 10. Thus, the benefits and cost savings estimated in Chapters 7 and 8 are very conservative lower-bound estimates of the impact of the SLP program on construction industry stakeholders, since they do not include benefits and cost savings accruing after 2008.

Table 6-10 Baseline Case of Pη(t) for New Construction (η = 0.4) and Renovation (η = 0.25)

t	New	Existing
1	1.1725	0.7328
2	1.8970	1.1856
3	3.0343	1.8965
4	4.7681	2.9801
5	7.2970	4.5606
6	10.7577	6.7235
7	15.1016	9.4385
8	20.0000	12.5000
9	24.8984	15.5615
10	29.2423	18.2765
11	32.7030	20.4394
12	35.2319	22.0199
13	36.9657	23.1035
14	38.1030	23.8144
15	38.8275	24.2672
16	39.2806	24.5503

The diffusion model, as specified above and used in the baseline analysis, is plotted in a graphical form in Figure 6-6 and Figure 6-7. Figure 6-6 covers 2004 through 2008. Figure 6-7 covers 2004 through 2019. The trace of $P_{\eta}(t)$ is shown as two solid lines in Figures 6-6 and 6-7; one for new construction and one for renovation. The vertical axis of Figures 6-6 and 6-7 records the values of $P_{\eta}(t)$ expressed as a percent. The values on the vertical axis ranges from 0 to ηx100. The horizontal axis of Figures 6-6 and 6-7 records the values of t and the years for which the value of $P_\eta(t)$ is calculated. Recall that in the baseline analysis t = 1 corresponds to the year 2004. Note that the years shown on the horizontal axis extend past the end of the study period. This is done to show that $P_\eta(t)$ does not approach the market saturation level, η, until well after the study period is over. Thus, substantial cost savings due to the use of SLP products and services will continue to accrue well after the end of the study period. Once again, this leads to the conclusion that the estimated savings nationwide are a lower-bound estimate.

Figure 6-6 Baseline Case of Pη(t) by t(year): 2004 to 2008

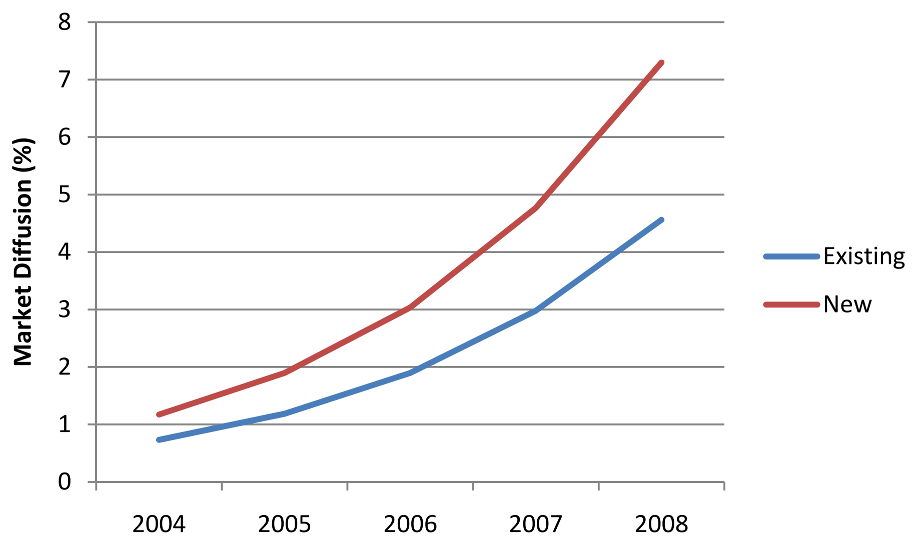
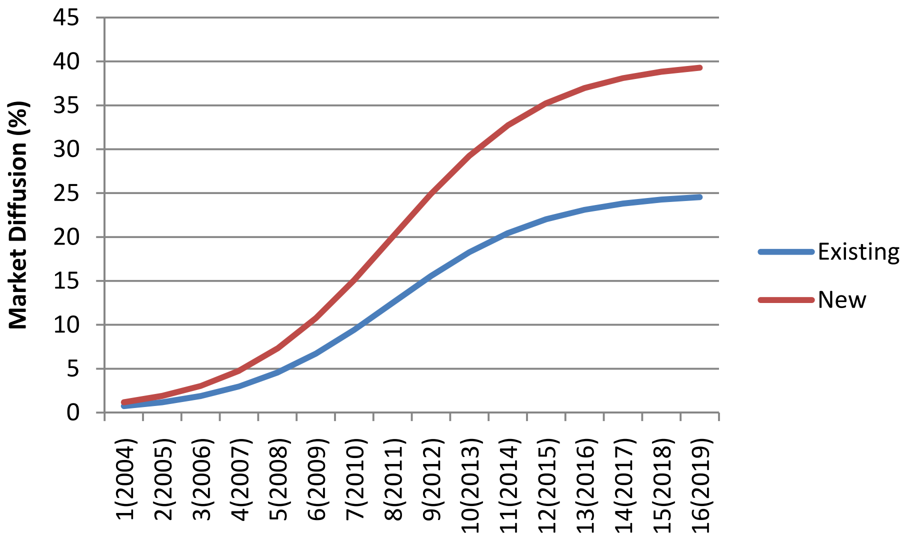


Figure 6-7 Baseline Case of $P\eta(t)$ by t(year): 2004 to 2019



Much of the sensitivity analysis is concerned with the diffusion model (see Chapter 8). As such, ranges of values were specified for α, β, η, and the time of first use. The ranges for α and β were selected based on values of α and β published in the economics literature and their implications for the values of the ratio α/β also published in the economics literature. The range of values for α used in the sensitivity analysis is a low of 3 and a high of 5 (i.e., $3 \leq \alpha \leq 5$). The range of values for β used in the sensitivity analysis is a low of 0.4 and a high of 0.6 (i.e., $0.4 \leq \beta \leq 0.6$). These ranges of values for α and β result in ranges for the ratios α/β which are consistent with the values published in the economics literature (i.e., $5.0 \leq \alpha/\beta \leq 12.5$). The range of values for η is based on information published in the 2003 CBECS.[83] For new commercial buildings these values range from a low of 30 % to a high of 50 % (i.e., $0.3 \leq \eta \leq 0.5$). For existing commercial buildings these values range from a low of 15 % to a high of 35 % (i.e., $0.15 \leq \eta \leq 0.35$).

6.4.5 Dealing with Uncertainty

Uncertainty enters into a benefit-cost analysis in three main ways. First, the value of cash flows (i.e., benefits, costs, and savings) may not be known with certainty. For example, a new technology may not be well understood by many potential users, implying that their benefits of adopting the technology may be subject to considerable variability. Consequently, decision makers are presented with a range of potential benefit values (e.g., high, moderate, and low). As the technology becomes better known, this range of values may be reduced (i.e., uncertainty, in the form of benefit variability, is being

[83] Energy Information Administration. Commercial Buildings Energy Consumption Survey. *Op. cit.*

reduced with time as new information becomes available). In addition, variations in the discount rate affect the present value of any cash flows which do not occur in the base year.

Second, the timing of cash flows may not be known with certainty. In the case of a new technology, the process by which the technology diffuses to firms and households may take many time paths.[84] For example, one time path might imply slow adoption at first followed by a period of rapid adoption. Such might be the case if, shortly after introduction, the technology were adopted as a standard. Alternatively, the new technology might enjoy a brief period of rapid adoption followed by a relatively long period of slow adoption. Such might be the case if, after introducing the new technology, there were a series of product improvements that caused many potential users to adopt a "wait and see" attitude.

Third, the value, timing, and magnitude of cash flows may not be known with certainty. This "composite" source of uncertainty is more complex than the two cases just discussed. It includes two issues related to the time path overlaid by variability in benefits, costs, and savings. The two time path issues are related to the rate of adoption over the time path and the level of adoption that prevails when the market reaches saturation. Although the introduction of a new technology can be expected to result in variability of benefits, costs, and savings for users which adopt it (i.e., there is some uncertainty about the values of these cash flows and, via the discount rate, their present values), the case at hand is more complex. Variations in the rate of adoption are the principal sources of variability in the timing of cash flows. Variations in the level of adoption enter as factors affecting both the values and the magnitudes of cash flows. This is because the level of adoption comes into play as a multiplicative factor applied to any given time path. While different rates of adoption affect the timings of cash flows, different adoption levels affect the values (i.e., due to its being overlaid by the variability in benefits, costs, and savings) and magnitudes (i.e., due to its affect on the size of the potential market) of these cash flows. Consider the case of the direct benefits to users from adopting a new technology. Other things being equal, higher levels of adoption result in larger benefit streams and higher variability (i.e., a wider range of values) of those benefit streams across all time paths than do lower levels of adoption.

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[84] The time paths by which a new technology may diffuse have several characteristics that are important. First, there is a *time of first use* (i.e., when the technology is introduced to the market place). If the time of first use is considered fixed, then it is the same for all that technology's time paths. Second, for each time path, there is a *rate of adoption*; the rate of adoption affects the slope of the time path. It is important to recognize that the slope of the time path need not be the same at different points on the time path. Finally, there is a *level of adoption* that prevails when the market reaches saturation.

6.4.6 Measuring BFRL's Contribution

This section describes the process used to measure the "value" of BFRL's contribution to the development of SLP products and services for use in commercial buildings. It begins with a review of the nature of BFRL's contribution.

BFRL's contribution serves two vital roles. One is that of a facilitator, and the other is that of world-class research organization providing the scientific basis for key SLP enabling technologies. Both roles are crucial if commercial products and services are to be developed in a timely manner. Because of BFRL's leadership role in research and participation in key industry-focused activities (e.g., industry consortia, workshops and conferences, standard development organizations, and other technology transfer activities), high-performance polymeric construction materials are expected to be commercially available both in a more-timely manner and in greater quantity.

This review of the nature of BFRL's contribution makes it clear that BFRL is a catalyst in the development of SLP products and services. Does this mean that SLP products and services would not be developed without BFRL's participation? The answer to that question is an unequivocal "No." Eventually, SLP products and services would become commercially available. Would they have the same capabilities? The answer to that question is a qualified "Probably not." The reasoning stems from the fact that the nature of BFRL's dual role is one that few organizations can fill. Consider the case of an enabling technology. Few if any vendors will invest in enabling technologies, since they can not adequately recapture their investment. In fact, other vendors might be able to employ the enabling technology to develop their own proprietary products. BFRL and NIST do not have this problem, since a key part of their mission is to promote competitiveness through the development of enabling technologies. A similar reasoning holds for BFRL's role as a facilitator. Thus, BFRL's contribution both serves to speed up the introduction of SLP products and services and to result in products and services with better understood properties and, in all likelihood, better capabilities. The remainder of this section focuses on how to measure the value of BFRL's contribution.

BFRL's dual role as a facilitator via industry consortia and a world-class research institution hastens the introduction of high-performance polymeric construction materials and expands their base of potential users. Although BFRL is a key player, it is anticipated that the bulk of the costs savings are attributable to materials manufacturers and professional services within the construction industry. Thus, this study, in keeping with its conservative approach, suggests a 25/75 split between BFRL's contribution and that of other construction industry stakeholders. Such an accounting framework may be handled through use of a 0.25 weighting factor for BFRL's contribution.

7 Baseline Analysis of Economic Impacts

The baseline analysis presented in this chapter is the reference point for the SLP economic impact assessment. Recall that in the baseline analysis, all data entering into the calculations are set at their likely values (see Section 2.1.1). Throughout this report, likely value and baseline value are used interchangeably. Thus, the baseline values represent a fixed state of analysis. The term baseline analysis is used to denote a complete analysis in all respects but one; it does not address the effects of uncertainty. Sensitivity analysis measures the impact on project outcomes of changing the values of one or more key variables about which there is uncertainty. Sensitivity analysis is the subject of Chapter 8. The results of the baseline analysis portion of the SLP economic impact assessment are presented for two basic cases (see Exhibit 7-1). First, are the cost savings nationwide achievable through the use of high-performance polymeric construction materials in commercial buildings. Second, are the cost savings attributable to BFRL and the return on BFRL's SLP-related investment costs. Key economic measures show the present value of savings (PVS), the present value of net savings (PVNS), the savings-to-investment ratio (SIR), and the adjusted internal rate of return (AIRR) that are attributable to BFRL's SLP-related research, development, and deployment efforts (see Chapter 3).

The results of the baseline analysis demonstrate that the use of three categories of high-performance polymeric construction materials in commercial buildings will generate substantial cost savings to commercial building owners and managers and to materials manufacturers and contractors engaged in the construction of those buildings. The present value of savings nationwide expected from the use of these three categories is nearly $190 million (measured in 2008 dollars). Furthermore, because of BFRL's involvement, these three categories of high-performance polymeric construction materials for use in commercial buildings are expected to be commercially available in a more-timely manner and in greater quantity. Consequently, a portion of the estimated cost savings accruing to commercial building owners and managers, materials manufacturers, and to contractors over the period 2005 through 2008 would have been foregone without BFRL's involvement. The present value of these cost savings is approximately $48 million. These cost savings measure the value of BFRL's contribution for its SLP-related investment costs of approximately $38.5 million. Stated in present value terms, every public dollar invested in BFRL's SLP-related research, development, and deployment efforts between 1994 and 2008 is expected to have generated $1.23 in cost savings to the public (i.e., an SIR of 1.23). The annual percentage yield (AIRR) from BFRL's SLP-related investments over the study period is 8.5 percent.

Exhibit 7-1 Summary of Economic Impacts of BFRL Research on Improved Service Life Prediction

<table>
<tr>
<td>
1.a Significance of Research Effort:

Improved service life prediction (SLP) of polymeric construction materials is especially beneficial to materials manufacturers in reducing product development cycle time, in positioning their products in the marketplace, and in determining suitable warranty terms. Owners and managers of commercial and residential buildings benefit from improved SLP by having available the facts and data that help them make economically efficient choices among construction materials and products. Finally, improved SLP produces new sales opportunities to firms that assist product developers in the formulation of new or improved products.

BFRL's dual role as a facilitator via industry consortia and a world-class research institution hastens the introduction of high-performance polymeric construction materials and expands their base of potential users. Although BFRL is a key player, it is anticipated that the bulk of the costs savings are attributable to materials manufacturers and professional services within the construction industry. This study, in keeping with its conservative approach, suggests a 25/75 split between BFRL's contribution and that of other construction industry stakeholders. Such an accounting framework is handled through use of a 0.25 weighting factor for valuing BFRL's contribution.
</td>
<td>
1.b Key Points:

• BFRL's reliability-based approach allows repeatable results to be produced in several months rather than in years.

• BFRL is uniquely positioned to collaborate with industry on the development of SLP products and services.

• BFRL's leadership role in research and participation in industry-focused activities is expected to result in cost-effective SLP products being available sooner and in greater quantity.
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2. Analysis Strategy: How Key Measures are Estimated

The objective of the study is to (1) evaluate, for the period 1994 through 20008, the net cost savings due to the adoption and use of SLP products and services in commercial buildings, and (2) estimate BFRL's contribution to these net cost savings. The approach is to estimate in 2008 present value (PV) dollars:
Present Value Cost Savings Nationwide in commercial buildings that employ SLP products and services. PV cost savings nationwide are estimated for each year from 1994 to 2008 and summed.
Present Value Savings (PVS) attributable to BFRL by including the savings only for those years that accrued due to BFRL's participation (i.e., 1994 to 2008).
Present Value Net Savings (PVNS) attributable to BFRL by subtracting from BFRL PVS the present value of BFRL's investment costs (PV Costs). A PVNS >0 indicates an economically worthwhile project.
Two additional measures are also estimated:
Savings-to-Investment Ratio (SIR) attributable to BFRL by taking the ratio of BFRL PVS to BFRL PV costs. A ratio >1 indicates an economically worthwhile project.
Adjusted Internal Rate of Return (AIRR), the annual rate of return over the study period on BFRL's investment. An AIRR > the discount rate indicates that the project is economically worthwhile.
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Exhibit 7-1 Summary of Economic Impacts of BFRL Research on Improved Service Life Prediction (continued)

2. Analysis Strategy: Data and Assumptions

- The period over which costs and savings are measured begins in 1994 and ends in 2008. Hence the length of the study period is 15 years.
- The base year is 2008, and all amounts are calculated in PV 2008 dollars.
- The discount rate is 7 percent (real), which is the discount rate currently in effect for government projects.
- Estimates of cost savings associated with the adoption and use of SLP products and services are based on construction industry data and information provided by industry experts.

3.a Calculation of Savings, Costs, and Additional Measures

Savings and Costs

Present Value Cost Savings Nationwide (PVCSN):
Sum from 1994 to 2008 of present value of cost savings nationwide by year

= $189.5 million

Present Value Savings (PVS) Attributable to BFRL:
Sum from 1994 to 2008 of present value of cost savings nationwide by year

= $47.4 million

Present Value Investment Costs (PV Costs) to BFRL:
Sum from 1994 to 2008 of present value of investment cost to BFRL by year

= $38.5 million

Present Value Net Savings (PVNS) Attributable to BFRL:
Difference between present value savings (PVS) attributable to BFRL and present value of investment costs (PV Costs) to BFRL

= $47.4 - $38.5 = $8.8 million

Additional Measures

SIR of BFRL Contribution:
Savings-to-Investment Ratio on BFRL investment

= $47.4/$38.5 = 1.23

AIRR of BFRL Contribution:
Adjusted Internal Rate of Return on BFRL investment

$= (1+ 0.07) * 1.23^{1/15} - 1 = 0.085$

3.b Key Results:

2008 Dollars
($ amounts in millions)

Cost Savings Nationwide:

$189.5

Savings and Costs Attributable to BFRL:

PVS	**$47.4**
PV Costs	**$38.5**
PVNS	**$8.8**
SIR	**1.23**
AIRR	**8.5%**

3.c Traceability:

ASTM *Discount Factor Tables* (PVCSN and PVS)

ASTM E 917 (PV Costs)

ASTM E 1074 (PVNS)

ASTM E 964 (SIR)

ASTM E 1057 (AIRR)

7.1 BFRL Summary Impact Statement

Exhibit 7-1 is a summary impact statement, covering the background, approach, and results of the baseline analysis. Exhibit 7-1 utilizes the framework, based on ASTM standard guide E 2204, introduced in Chapter 2 (see Exhibit 2-1).

7.2 Cost Savings Nationwide

This section combines four types of information presented in Sections 6.3 and 6.4 to generate a baseline estimate of cost savings nationwide. These four types of information are related to: (1) research investment costs; (2) improved time-to-market for new cool roof technologies; (3) high-performance sealants and adhesives that reduce air infiltration; and (4) high-performance seams for EPDM roofing that reduce warranty repair costs. These four types of information are combined via three sets of calculations to estimate "annual" cost savings to the nation. Estimates are produced for each year from 1994 to 2008. Each year's cost savings is then converted to a present value and summed to get the present value of cost savings nationwide. The present value of cost savings nationwide is a key indicator of the merits of employing high-performance polymeric construction materials in commercial buildings.

The results of the baseline analysis show that research investment costs are approximately \$75 million, cost savings nationwide are nearly \$190 million, and net cost savings nationwide are approximately \$115 million (all three figures are expressed in present value 2008 dollars). Each set of calculations used to produce the estimate of cost savings nationwide is summarized through a table and described in the text that follows.

Research Investment Costs

Research investment costs—NIST STRS, consortia fees, and other federal agency contract research funds—are drawn from the last column of Table 6-9 and inserted into column (2) of Table 7-1. These figures are in current year dollars and must first be converted to 2008 constant dollars. The conversion factors are contained in column (3). Multiplying the year-by-year current dollar values by the conversion factor produces the year-by-year values in 2008 constant dollars. These figures are recorded in column (4) of Table 7-1. The 2008 constant dollar values are then converted into 2008 present value dollars (the year-by-year product of columns (4) and (5) to get the values in column (6)) and summed to get the value for research investment costs (RI), of \$74.8 million. The following formula documents the process used in Table 7-1:

$$RI = \sum_{t}^{T} RI_t * (1 + R)^{T-t}$$

where *RI* is the total research investment (in present value 2008 dollars), *R* is the discount rate, *t* indexes time, *T* is the study length.

Table 7-1 Summary of Combined Research Investments: 1994 to 2008

Year	Annual Dollar Amount (In Millions of Current Dollars)	Conversion Factor by Year (Current Dollars to 2008 Dollars)	Investment Costs by Year (in Millions of 2008 Dollars)	Single Present Value Factor by Year	Present Value of Investment Costs by Year (In Millions of 2008 Dollars)
Col. (1)	Col. (2)	Col. (3)	Col. (4) (2)x(3)	Col. (5)	Col. (6) (4)x(5)
1994	1.531	1.453	2.225	2.579	5.737
1995	1.979	1.413	2.796	2.410	6.739
1996	1.756	1.372	2.410	2.252	5.427
1997	1.524	1.341	2.045	2.105	4.304
1998	1.745	1.321	2.305	1.967	4.535
1999	2.020	1.292	2.610	1.838	4.797
2000	2.528	1.250	3.161	1.718	5.430
2001	2.361	1.216	2.871	1.606	4.610
2002	3.011	1.197	3.603	1.501	5.409
2003	3.229	1.170	3.779	1.403	5.301
2004	3.030	1.140	3.454	1.311	4.528
2005	3.494	1.102	3.852	1.225	4.719
2006	3.790	1.068	4.047	1.145	4.634
2007	3.479	1.038	3.613	1.070	3.865
2008	4.762	1.000	4.762	1.000	4.762
				TOTAL	**74.797**

Improved Time-to-Market of New Cool Roof Technologies

The baseline analysis of the net energy savings due to the early introduction of high-performance cool roof coatings is estimated as:

$$NES^{CR} = \sum_{i}^{I} \sum_{t_0-s}^{t_0-S} \sum_{j}^{J} (ES * P^{E}_{t_0-s} - EP * P^{NG}_{t_0-s}) * CRA_{i,j} * MP * LS * ECB_i * (1+R)^s$$

where NES^{CR} is the present value of the net energy savings due to cool roof use (in \$2008), *ES* is the cool roof-induced cooling savings in kWh/ft^2, *ES* is the cool roof-induced heating penalty in therms/ft^2, P^E is the price of electricity in \$/kWh, P^{NG} is the price of natural gas in \$/therms, *CRA* is the conditioned roof area, *MP* is the proportion of market penetration by the cool roof product, *LS* is the proportion of all commercial buildings that have low slope roofs, *ECB* is the proportion of commercial buildings eligible for a cool roof, *R* is the discount rate, *i* indexes building status (new construction, pre-existing; *I*=2), *j* indexes building type (office, educational, mercantile; *J*=3), *s* is the number of years early that high-performance cool roof coatings were introduced to the market due to improved service life prediction (*s*=1, 2, 3; *S*=3), and t_0 is the base year of the analysis (2008).

The baseline present value net benefits of improved service life prediction on the California cool roof market is estimated at \$824 555. The net benefits account for the heating penalty that may occur during cool winter months when solar heating would reduce natural gas demand. The cooling energy savings was estimated at 0.39 kWh/ft^2 (4.20 kWh/m^2) and the heating penalty was estimated at 0.00072 therms/ft^2 (0.00226 therms/m^2). Net savings averaged \$0.05/ft^2 (\$0.54/m^2) of conditioned floor area. Again, this is a counterfactual analysis that estimates the energy savings that would have been realized had improvements in service life prediction led to the early introduction of new, high-performance cool roof coatings beginning as early as 2005. The base year for the study is 2008, and the analysis is based on a 2-year early introduction (beginning in 2006), 7 % discount rate, 10 % market penetration rate, with all new commercial (office, educational, and mercantile) low-sloped roofs required to use cool roofing materials along with 5 % of the reroofing market. The benefits accrue about equally between 2006 and 2007, with 39 % of the energy savings occurring in educational buildings. Office buildings experience 35 % of the energy savings and mercantile buildings experience 26 %. Differences in energy savings across the commercial buildings types in California are due to the relative difference in total statewide conditioned floor area.

Table 7-2 summarizes the various stages in the calculations represented by the formula recorded above, including the year-by-year values.

Table 7-2 Summary of Cool Roof-Related Savings: 1994 to 2008

Year	Annual Dollar Amount of Energy Cost Savings (In Millions of Current Dollars)	Conversion Factor by Year (Current Dollars to 2008 Dollars)	Annual Energy Cost Savings by Year (in Millions of 2008 Dollars)	Single Present Value Factor by Year	Present Value of Annual Energy Cost Savings by Year (In Millions of 2008 Dollars)
Col. (1)	Col. (2)	Col. (3)	Col. (4) (2)x(3)	Col. (5)	Col. (6) (4)x(5)
1994	0.00	1.453	0.00	2.579	0.00
1995	0.00	1.413	0.00	2.410	0.00
1996	0.00	1.372	0.00	2.252	0.00
1997	0.00	1.341	0.00	2.105	0.00
1998	0.00	1.321	0.00	1.967	0.00
1999	0.00	1.292	0.00	1.838	0.00
2000	0.00	1.250	0.00	1.718	0.00
2001	0.00	1.216	0.00	1.606	0.00
2002	0.00	1.197	0.00	1.501	0.00
2003	0.00	1.170	0.00	1.403	0.00
2004	0.00	1.140	0.00	1.311	0.00
2005	0.00	1.102	0.00	1.225	0.00
2006	0.35	1.068	0.38	1.145	0.43
2007	0.35	1.038	0.37	1.070	0.39
2008	0.00	1.000	0.00	1.000	0.00
				TOTAL	**0.82**

Improved Time-to-Market of New Wet-Sealed Fenestration Systems

The baseline analysis of the net energy savings due to the early introduction of high-performance wet sealed fenestration is estimated as:

$$NES^{WS} = \sum_{i}^{I}\sum_{c}^{C}\sum_{t}^{T}\sum_{j}^{J}(ES^{NG} * P^{E}_{c,t} + ES^{NG} * P^{NG}_{c,t}) * CRA_{i,j} * LS * ECB_i * (\eta_i * [1 + e^{(\alpha-\beta t)}]^{-1}) * (1 + R)^{T-t}$$

where NES^{WS} is the present value of the net energy savings due to the use of wet-sealed fenestration (in \$2008), *ES* is the sealant-induced cooling savings in kWh/ft^2, *ES* is the sealant-induced heating savings in therms/ft^2, P^E is the price of electricity in \$/kWh, P^{NG} is the price of natural gas in \$/therms, *CRA* is the conditioned roof area, *LS* is the proportion of all commercial buildings that have low slope roofs, *ECB* is the proportion of commercial buildings eligible for wet sealed fenestration, η is the market saturation level, *e* is base of the natural system of logarithms, α is a location parameter, β is a shape parameter, *R* is the discount rate, *i* indexes building status (new construction, pre-existing; *I*=2), *c* indexes the census division (Pacific, Mountain, West North Central, East North Central, Middle Atlantic, New England, South Atlantic, East South Central, West South Central; *C*=9), *t* indexes time (*T* is the total number of study period years; *T*=5), *j* indexes building type (office, educational, mercantile; *J*=3).

The baseline present value net benefits of improved service life prediction on the heating and cooling of U.S. commercial building, from improved window sealants, is estimated at \$10 015 039. The net benefits account for year-around energy savings due to the reduced infiltration of outside air. Both electricity and natural gas consumption are affected. Less infiltration in summertime reduces the cooling load, while less infiltration in the wintertime reduces the heating demand. Again, this is a counterfactual analysis that estimates the energy savings that would have been realized had improvements in service life prediction led to the early introduction of new, high-performance wet sealed fenestration systems beginning as early as 2004. The base year for the study is 2008. The analysis is based on a 7 % discount rate and separate market diffusion models for new and existing commercial buildings.

The diffusion process (see Section 6.4.4) occurs within the eligible market segment (i.e., 22 % of all new and 5 % of all existing commercial buildings). The five-year diffusion processes are reported in Figure 6-6. The market penetration of high performance window sealants used in existing commercial construction begins near 1 % and steadily increases to 4.5 % of the eligible market segment in 2008. The market penetration related to new commercial buildings also begins around 1 % and steadily increases to

7.3 % of the eligible market segment in 2008. The majority of diffusion growth occurs after 2008, however. Figure 6-7 shows the percent market diffusion during the study period and beyond. In 2019, high-performance sealants are shown to comprise 39 % of new construction and 25 % of existing commercial buildings.

Table 7-3 summarizes the various stages in the calculations represented by the formula recorded above, including the year-by-year values.

Table 7-3 Summary of Savings from High-Performance Sealants and Adhesives: 1994 to 2008

Year	Annual Dollar Amount of Energy Cost Savings (In Millions of Current Dollars)	Conversion Factor by Year (Current Dollars to 2008 Dollars)	Annual Energy Cost Savings by Year (in Millions of 2008 Dollars)	Single Present Value Factor by Year	Present Value of Annual Energy Cost Savings by Year (In Millions of 2008 Dollars)
Col. (1)	Col. (2)	Col. (3)	Col. (4) (2)x(3)	Col. (5)	Col. (6) (4)x(5)
1994	0.00	1.453	0.00	2.579	0.00
1995	0.00	1.413	0.00	2.410	0.00
1996	0.00	1.372	0.00	2.252	0.00
1997	0.00	1.341	0.00	2.105	0.00
1998	0.00	1.321	0.00	1.967	0.00
1999	0.00	1.292	0.00	1.838	0.00
2000	0.00	1.250	0.00	1.718	0.00
2001	0.00	1.216	0.00	1.606	0.00
2002	0.00	1.197	0.00	1.501	0.00
2003	0.00	1.170	0.00	1.403	0.00
2004	0.48	1.140	0.54	1.311	0.71
2005	0.98	1.102	1.08	1.225	1.32
2006	1.55	1.068	1.66	1.145	1.90
2007	2.33	1.038	2.42	1.070	2.59
2008	3.59	1.000	3.59	1.000	3.59
				TOTAL	**10.11**

High-Performance Seams for EPDM Roofing that Reduce Warranty Repair Costs

The baseline analysis of the savings in warranty repair costs for high-performance seams for EPDM roofing is estimated as:

$$Z = \sum_{t=t_0+1}^{T} \sum_{i=t-t_0}^{t_0} A_i * B_i * \frac{C_i}{D_i} * E_i * F * (1+R)^{T-i}$$

where

$$E_i = \frac{B_i - B_{t_0}}{B_i}$$

and

$$F = \frac{R(1+R)^{10}}{(1+R)^{10} - 1}$$

where Z is the present value of warranty cost savings in 2008 dollars, A is the installed costs of EPDM roofing in millions of dollars (see Table 6-8), B is the ten-year warranty cost as a percent of installed cost (see Figure 6-3), C is the ten-year warranty service cost for seams (see Figure 6-2), D is the ten-year indexed cost per square foot (see Figure 6-1), E is the estimated proportion of ten-year warranty service costs for seams that can be averted due to improvements in technology, F is the uniform capital recovery factor that converts estimated ten-year savings in warranty repair costs into a uniform annual stream of savings over a ten-year period, R is the discount rate, t and i index time. In this analysis $t_0 = 9$ and $T = 24$.

To illustrate the conversion process, consider the year 1985. Table 6-8 reports the installed cost of EPDM roofs in 1985 was \$1.55 billion. Figure 6-3 reports the ten-year warranty service costs as a percentage of original installed cost in 1985 as 6.7 %. Thus, the estimated ten-year warranty service costs for 1985 is \$104.2 million. The seam warranty portion is 48.2 % (seam indexed cost per square foot for 1985 of 1.1 (see Figure 6-2) divided by the indexed cost per square foot for 1985 of 2.28 (see Figure 6-1)). Thus, the estimated ten-year seam-related warranty service costs for 1985 is \$50.3 million. The estimated proportion of ten-year warranty service costs for seams that can be averted due to improvements in technology is the difference between the value for B_i, in the case of 1985 6.7 %, and the value B_i for 1993, which is 1.1 %, divided by B_i, in this case 6.7 %. Thus, the estimated ten-year seam-related warranty service cost savings amounts to \$42.0 million. Multiplying this amount by the uniform capital recovery factor for a ten-year period with a 7 % discount rate produces an annual seam-related warranty service cost savings estimate of \$5.98 million. The \$18.46 million figure in column (2) of Table 7-4 is the sum of the annual seam-related warranty service cost savings estimates for the years 1985 through 1993. Table 7-4 summarizes the various stages in the calculations represented by the formula recorded above, including the year-by-year values.

Table 7-4 Summary of EPDM Seam-Related Warranty Repair Savings: 1994 to 2008

Year	Annual Dollar Amount of Warranty Cost Savings (In Millions of Current Dollars)	Conversion Factor by Year (Current Dollars to 2008 Dollars)	Annual Warranty Cost Savings by Year (In Millions of 2008 Dollars)	Single Present Value Factor by Year	Present Value of Annual Warranty Cost Savings by Year (In Millions of 2008 Dollars)
Col. (1)	Col. (2)	Col. (3)	Col. (4) (2)x(3)	Col. (5)	Col. (6) (4)x(5)
1994	18.46	1.453	26.82	2.579	69.18
1995	12.48	1.413	17.63	2.410	42.50
1996	9.03	1.372	12.39	2.252	27.91
1997	6.29	1.341	8.43	2.105	17.75
1998	4.39	1.321	5.80	1.967	11.41
1999	2.81	1.292	3.63	1.838	6.67
2000	1.25	1.250	1.57	1.718	2.69
2001	0.24	1.216	0.30	1.606	0.48
2002	0.00	1.197	0.00	1.501	0.00
2003	0.00	1.170	0.00	1.403	0.00
2004	0.00	1.140	0.00	1.311	0.00
2005	0.00	1.102	0.00	1.225	0.00
2006	0.00	1.068	0.00	1.145	0.00
2007	0.00	1.038	0.00	1.070	0.00
2008	0.00	1.000	0.00	1.000	0.00
				TOTAL	**178.59**

Present Value of Cost Savings Nationwide

Table 7-5 summarizes how baseline cost savings by category and in total are calculated. The years for which cost savings are calculated are listed in Column (1) of Table 7-5. The years run from 1994 until 2008 (i.e., the entire study period). The table records information on three cost savings: (1) cool roof-related savings; (2) high-performance sealant-related savings; and (3) EPDM seam-related warranty repair savings. Annual values for each category of cost savings are recorded in Column (2) for cool roofs, Column (3) for sealants, and Column (4) for EPDM roofing. It is important to note that the cost savings reported in Table 7-5 are lower-bound estimates, since our conservative approach included only those which are clearly definable and measurable.

In addition to annual cost savings by category, Table 7-5 also contains total cost savings by year. These cost savings are recorded in Column (5). Total cost savings for each year equal the sum of each category's cost savings for that year. Total cost savings are denominated in millions of 2008 present value dollars. Because the entries in Column (5) are in present value terms, they can be summed to get the present value of cost savings nationwide, which is $189.5 million.

Table 7-5 Baseline Cost Savings by Category and in Total in Millions of Present Value 2008 Dollars: 1994 to 2008

Year	Annual Cost Savings By Category (In Millions of 2008 Dollars)			Present Value of Cost Savings by Year (In Millions of 2008 Dollars)
	Cool Roof-Related Savings	High-Performance Sealant-Related Savings	EPDM Seam-Related Warranty Repair Savings	
Col. (1)	Col. (2)	Col. (3)	Col. (4)	Col. (5) (2)+(3)+(4)
1994	0.00	0.00	69.18	69.18
1995	0.00	0.00	42.50	42.50
1996	0.00	0.00	27.91	27.91
1997	0.00	0.00	17.75	17.75
1998	0.00	0.00	11.41	11.41
1999	0.00	0.00	6.67	6.67
2000	0.00	0.00	2.69	2.69
2001	0.00	0.00	0.48	0.48
2002	0.00	0.00	0.00	0.00
2003	0.00	0.00	0.00	0.00
2004	0.00	0.71	0.00	0.71
2005	0.00	1.32	0.00	1.32
2006	0.43	1.90	0.00	2.33
2007	0.39	2.59	0.00	2.98
2008	0.00	3.59	0.00	3.59
			TOTAL	**189.53**

Present Value of Net Cost Savings Nationwide

Table 7-6 summarizes how the present values of net cost savings nationwide by year and in total are calculated. The years for which present values are calculated are listed in Column (1) of Table 7-6. The years run from 1994 until 2008 (i.e., the entire study period). Column (2) of Table 7-6 contains total cost savings by year in millions of 2008 dollars. The total cost savings for each year is transferred from the respective row of Column (5) of Table 7-5. The additional research investment cost to BFRL and its collaborators for each year is recorded in Column (3) of Table 7-6; these values are drawn from Column (6) of Table 7-1. The difference between total cost savings and the additional research costs equals net cost savings. Column (4) of Table 7-6 records net present value of net cost savings for each year in millions of 2008 dollars.

Because the entries in Column (4) are in present value terms, they can be summed to get total cost savings nationwide over the entire study period. Total cost savings nationwide resulting from the three sets of baseline analysis calculations are nearly $114.7 million (in present value 2008 dollars); see the bottom of Column (4) in Table 7-6.

Reference to Table 7-6 demonstrates the magnitude of the savings to the nation from using three types of SLP products and services in the commercial sector. These cost savings nationwide also provide a basis for measuring the value of BFRL’s contribution.

Table 7-6 Baseline Computation of Net Present Value of Cost Savings Nationwide in Millions of 2008 Dollars: 1994 to 2008

Year	Present Value of Total Cost Savings by Year (In Millions of Dollars)	Present Value of Research Investment Costs (In Millions of Dollars)	Present Value of Net Savings Nationwide (In Millions of Dollars)
Col. (1)	Col. (2)	Col. (3)	Col. (4) (2)-(3)
1994	69.18	5.74	63.44
1995	42.50	6.74	35.76
1996	27.91	5.43	22.49
1997	17.75	4.30	13.45
1998	11.41	4.53	6.87
1999	6.67	4.80	1.87
2000	2.69	5.43	-2.74
2001	0.48	4.61	-4.13
2002	0.00	5.41	-5.41
2003	0.00	5.30	-5.30
2004	0.71	4.53	-3.81
2005	1.32	4.72	-3.39
2006	2.33	4.63	-2.31
2007	2.98	3.87	-0.88
2008	3.59	4.76	-1.17
		TOTAL	**114.73**

7.3 Measuring the Value of BFRL's Contribution and the Return on BFRL's SLP-Related Investments

Measuring the value of BFRL's contribution to the development of high-performance polymeric construction materials and the return on its SLP-related investments is the focus of this section. Information on BFRL's SLP-related research, development, and deployment efforts—in terms of its dollar investments—over the 15-year period from 1994 to 2008 are first presented. These figures demonstrate not only a significant, up-front research commitment by BFRL, but also a continued effort as high-performance polymeric construction materials move into the commercial marketplace. Next, the proportion of year-by-year cost savings attributable to BFRL is addressed. Because of BFRL's leadership role in research and participation in key industry-focused activities (e.g., industry consortia, workshops and conferences, and other technology transfer activities), high-performance polymeric construction materials are expected to be commercially available both in a more-timely manner and in greater quantity with better performance per customer dollar spent. Finally, measures of economic impact summarize the importance of BFRL's contribution to the development of high-performance polymeric construction materials for use in commercial and residential buildings. These measures include the present value of savings (PVS), the present value of net savings (PVNS), the savings-to-investment ratio (SIR), and the adjusted internal rate of return (AIRR).

Table 7-7 summarizes information on BFRL's SLP-related investments. Column 1 of the table records the year in which SLP-related investments were made. Column 2 records the value (in millions of current dollars) by year of investment for each year between 1994 and 2008. For example, in 1994 the investment was \$455,000 (in 1994 dollars), in 1995 the investment was \$760,000 (in 1995 dollars), and in 1996 the investment was \$954,000 (in 1996 dollars). Because the values for 1994 through 2008 in Column 2 are in current dollars by year, it is necessary to convert them to constant 2008 dollars and then convert them to present value (i.e., time equivalent) dollars. This involves a two-step process. First, each year's current dollar investment is converted to a "real" investment in 2008 constant dollars through application of the Consumer Price Index (CPI). The conversion factors, for each year, are shown in Column 3 of Table 7-7. The constant 2008 dollar values (in millions of dollars) are the year-by-year products of the entries in Column 2 and Column 3. These values are shown in Column 4. The values in Column 4 are converted into present value terms through the use of a single present value factor, based on a real discount rate of 7 percent. The value of each year's single present value factor is given in Column 5. The present values in millions of 2008 dollars are recorded in Column 6; they are the year-by-year products of the entries in Column 4 and Column 5.

Table 7-7 Summary of BFRL Research Investments: 1994 to 2008

Year	Annual Dollar Amount (In Millions of Current Dollars)	Conversion Factor by Year (Current Dollars to 2008 Dollars)	Investment Costs by Year (in Millions of 2008 Dollars)	Single Present Value Factor by Year	Present Value of Investment Costs by Year (In Millions of 2008 Dollars)
Col. (1)	Col. (2)	Col. (3)	Col. (4) (2)x(3)	Col. (5)	Col. (6) (4)x(5)
1994	0.455	1.453	0.661	2.579	1.705
1995	0.760	1.413	1.074	2.410	2.589
1996	0.954	1.372	1.309	2.252	2.947
1997	0.997	1.341	1.337	2.105	2.815
1998	0.919	1.321	1.214	1.967	2.388
1999	1.047	1.292	1.353	1.838	2.486
2000	1.081	1.250	1.351	1.718	2.322
2001	1.432	1.216	1.741	1.606	2.795
2002	1.858	1.197	2.224	1.501	3.338
2003	2.072	1.170	2.425	1.403	3.402
2004	1.597	1.140	1.820	1.311	2.386
2005	2.125	1.102	2.343	1.225	2.870
2006	1.917	1.068	2.048	1.145	2.345
2007	2.031	1.038	2.109	1.070	2.257
2008	1.901	1.000	1.901	1.000	1.901
				TOTAL	**38.546**

Because entries in Column 6 are in present value terms, they can be summed to get the present value of BFRL's SLP-related investments. The present value of BFRL's SLP-related investments, PV Costs, totals $38.546 million; this value is recorded at the bottom of Column 6.

Table 7-8 provides the information needed to calculate the present value of savings attributable to BFRL. The years for which present values are calculated are listed in Column 1 of Table 7-8. The years run from 1994 until 2008 (i.e., the entire study period). The present value of cost savings nationwide by year is recorded in Column 2 of Table 7-8. The present value of cost savings nationwide for each year is transferred from the respective row of Column 6 of Table 7-4. BFRL's dual role as a facilitator via industry consortia and a world-class research institution hastens the introduction of high-performance polymeric construction materials and expands their base of potential users. Although BFRL is a key player, it is anticipated that the bulk of the costs savings are attributable to materials manufacturers and professional services within the construction industry. This study, in keeping with its conservative approach, suggests a 25/75 split between BFRL's contribution and that of other construction industry stakeholders. Such an accounting framework may be handled through use of a 0.25 weighting factor for BFRL's contribution. The year-by-year values of the BFRL baseline weighting factor are given in Column 3 of Table 7-8. The present value of savings attributable to BFRL is the product of each year's present value of cost savings nationwide in Column 2 and the value of the BFRL baseline weighting factor in Column 3. The present value of savings attributable to BFRL on a year-by-year basis is given in Column 4 of Table 7-8.

Because entries in Column 4 are in present value terms, they can be summed to get the present value of savings attributable to BFRL. The present value of savings attributable to BFRL, PVS, totals $47.381 million; this value is recorded at the bottom of Column 6.

Given the values of PV Costs and PVS attributable to BFRL, it is now possible to derive the three economic impact measures. These measures are: (1) present value of net savings (PVNS) attributable to BFRL; (2) the savings-to-investment ratio (SIR) on BFRL's SLP-related investments; and (3) the adjusted internal rate of return (AIRR) on BFRL's SLP-related investments. Multiple measures are particularly useful because they each provide a different perspective—PVNS is a magnitude, the SIR is a ratio, and the AIRR is a rate of return.

Table 7-8 Estimated Cost Savings in Millions of Present Value 2008 Dollars Attributable to BFRL: 1994 to 2008

Year	Present Value of Total Cost Savings Nationwide by Year (In Millions of Dollars)	BFRL Baseline Weighting Factor	Present Value of Cost Savings by Year Attributable to BFRL (In Millions of Dollars)
Col. (1)	Col. (2)	Col. (3)	Col. (4) (2)x(3)
1994	69.18	0.25	17.29
1995	42.50	0.25	10.62
1996	27.91	0.25	6.98
1997	17.75	0.25	4.44
1998	11.41	0.25	2.85
1999	6.67	0.25	1.67
2000	2.69	0.25	0.67
2001	0.48	0.25	0.12
2002	0.00	0.25	0.00
2003	0.00	0.25	0.00
2004	0.71	0.25	0.18
2005	1.32	0.25	0.33
2006	2.33	0.25	0.58
2007	2.98	0.25	0.75
2008	3.59	0.25	0.90
		TOTAL	**47.38**

The PVNS attributable to BFRL, expressed in millions of present value 2008 dollars and based on the approach outlined in Section 2.2.1, is equal to:

$$\begin{aligned} \text{PVNS} &= \text{PVS} - \text{PV Costs} \\ &= \$47.381 - \$38.546 \\ &= \$8.835 \text{ million} \end{aligned}$$

Utilizing the approach outlined in Section 2.2.2, the SIR on BFRL's SLP-related investments is equal to:

$$\begin{aligned} \text{SIR} &= \text{PVS} / (\text{PV Costs}) \\ &= \$47.381 / \$38.546 \\ &= 1.23 \end{aligned}$$

Utilizing the approach outlined in Section 2.2.3, the AIRR on BFRL's SLP-related investments is equal to:

$$\begin{aligned} \text{AIRR} &= (1 + 0.07) * 1.23^{1/15} - 1 \\ &= 0.085 \\ &= 8.5\ \% \end{aligned}$$

The values of the economic impact measures derived in Chapter 7 are the baseline values that appear in Section 3.b of Exhibit 7-1. These values also figure in the sensitivity analysis, which is the subject of the next chapter.

7.4 Knowledge Transfer: A Key Non-Monetary Benefit

The topic of knowledge transfer has figured prominently in two recently completed economic impact studies.[85, 86] These studies have noted that technical papers published in

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[85] Alan C. O'Connor, Howard J. Walls, Dallas W. Wood, and Albert N. Link, *Retrospective Economic Impact Assessment of the NIST Combinatorial Methods Center*, NIST Planning Report 09-1, National Institute of Standards and Technology, 2009.

[86] Jennifer F. Helgeson, *Benefits and Costs of Research: A Case Study of the NIST High Performance Concrete Program*, NIST Technical Note 1645, National Institute of Standards and Technology, 2009.

peer-reviewed literature facilitated the transfer of knowledge generated by applied research and strategic basic research into the public domain for use by the entire materials science community. This section provides a review of a core set of technical papers and reports statistics on the frequency and types of citations. The papers are organized around three themes: (1) polymer science; (2) applied chemistry, materials science, and coatings and films; and (3) miscellaneous journal articles and books.

7.4.1 Citation Analysis of Major SLP Publications

We compiled a list of major publications from the SLP program and performed a citation analysis using the Web of Science academic database. These publications are categorized into three groups by topic. These three groups are (1) Polymer Science, (2) Applied Chemistry, Materials Science, and Coatings and Films, and (3) Miscellaneous. The following discussions focus on each of these three groups in turn.

7.4.1.1 Polymer Science

Five articles are categorized under this topic. Table 7-9 shows the publication information for these five articles along with the number of citations. Collectively, these articles have been cited 197 times. The paper that generated the most citations, under this topic and also under the overall SLP program, was Raghavan *et al.* (2000a), with 109 citations. Raghavan *et al.* (2000a) used atomic force microscopy (AFM) to characterize microstructure of model coating materials, at the nanometer scale. This paper is academic in nature and focuses on the nano metrology using AFM, which is important for probing early-stage degradation. AFM traditionally has been used to study morphology of materials. This paper shows that two techniques of AFM, phase imagining and nano scale indentation, can be used to study properties of materials. This paper shows that observations at the nanometer scale can be reconciled with macro scale observations. In addition to applications in the study of degradation, AFM is widely used in other areas of research. This wide applicability, the innovative approach of the paper, and the prestige of the journal are reasons for the high citation count of this paper.

Table 7-9 List of Publications in Polymer Science (Articles) with the Highest Numbers of Citations

Publication Information	Number of Citations
Raghavan, D; Gu, X; Nguyen, T; VanLandingham, M; Karim, A. 2000. Mapping polymer heterogeneity using atomic force microscopy phase imaging and nanoscale indentation. *MACROMOLECULES* 33 (7): 2573-2583.	109
Chin, JW; Nguyen, T; Aouadi, K. 1999. Sorption and diffusion of water, salt water, and concrete pore solution in composite matrices. *JOURNAL OF APPLIED POLYMER SCIENCE* 71 (3): 483-492.	38
Gu, X; Raghavan, D; Nguyen, T; VanLandingham, MR; Yebassa, D. 2001. Characterization of polyester degradation using tapping mode atomic force microscopy: exposure to alkaline solution at room temperature. *POLYMER DEGRADATION AND STABILITY* 74 (1): 139-149.	23
Martin, JW; Chin, JW; Byrd, WE; Embree, E; Kraft, KM. 1999. An integrating sphere-based ultraviolet exposure chamber design for the photodegradation of polymeric materials. *POLYMER DEGRADATION AND STABILITY* 63 (2): 297-304.	15
Signor, AW; VanLandingham, MR; Chin, JW. 2003. Effects of ultraviolet radiation exposure on vinyl ester resins: characterization of chemical, physical and mechanical damage. *POLYMER DEGRADATION AND STABILITY* 79 (2): 359-368.	12

Note: Citation counts obtained through Web of Science academic database, August, 2009.

The SLP program aims to study the long-term performance of polymer coatings, particularly upon exposure to aggressive environments. Polymeric materials are advantageous in building and construction for many of their desirable qualities, including corrosion and fatigue resistance, high strength-to-weight ratio, and relative chemical inertness. For instance, fiber-reinforced polymer composites have been promoted to enhance the structural integrity of materials and serve as a solution to the deterioration of bridges.[87] However, the outdoor environment also can be destructive to these materials. Moisture, acidic or alkaline environment, temperature fluctuations, and ultraviolet radiation are elements of the outdoor environment that can influence the integrity of polymeric materials. The second most cited paper under this topic, Chin *et al.*, 1999, studies the sorption and transport of water, salt water, and a simulated concrete pore solution using model polymeric materials that are widely used commercially in structural composites. This paper has been cited 38 times.

[87] Chin, J.W., T. Nguyen, K. Aouadi. 1999. Sorption and Diffusion of Water, Salt Water, and Concrete Pore Solution in Composite Matrices. *Journal of Applied Polymer Science* 71(3): 483-492.

A major contribution of the SLP program is the development of the integrating sphere technology which is a controlled experimental environment used to mimic long-term weathering. This new approach represents a shift in paradigm, compared to traditional methods, in the study of how weathering influences the degradation of polymeric materials. In particular, it utilizes "total effective dosage" as the metric for ultraviolet radiation exposure,[88] which facilitates reproducibility and comparability of experiments. Upon weathering exposure, chemical, physical, and mechanical properties of the materials are examined. Martin *et al.* (1999) discusses the integrating sphere technology for the study of ultraviolet exposure of polymeric materials. Signor *et al.* (2003) studies the properties of vinyl ester resins upon exposure to ultraviolet radiation. Gu *et al.* (2001) studies polyester degradation upon exposure to alkaline solution.

Note that many factors affect the number of citations in addition to quality of the publications. For instance, certain journals require subscriptions for accessing their articles, while others do not. Articles that can easily be accessed are likely to be read more and therefore cited more, all else being equal. Book chapters and books are less often available online, unlike many articles. Therefore, book chapters and books may be likely to have lower citation counts than articles in general. Many of the end users of the SLP program are industry practitioners, who read and write in trade journals, which are not included in academic databases, such as Web of Science. Additionally, citation counts depend on the number of researchers working in the same topic area. The study of long-term performance of materials is a relatively small field. Consequently, research articles in this area are likely to experience lower citation counts. While academic citations are useful indicators of impact, these numbers may be underestimates of knowledge contribution or knowledge transfer.

Figure 7-1 shows the yearly citations for each of these five articles in polymer science.

[88] Chin, J.W., T. Nguyen, X.H. Gu, E. Byrd, and J. Martin. 2006. "Accelerated UV Weathering of Polymeric Systems: Recent Innovations and New Perspectives." *JCT CoatingsTech*, 3(2): 20-26.

Figure 7-1 Yearly Citation Analysis for Major Publications in Polymer Science

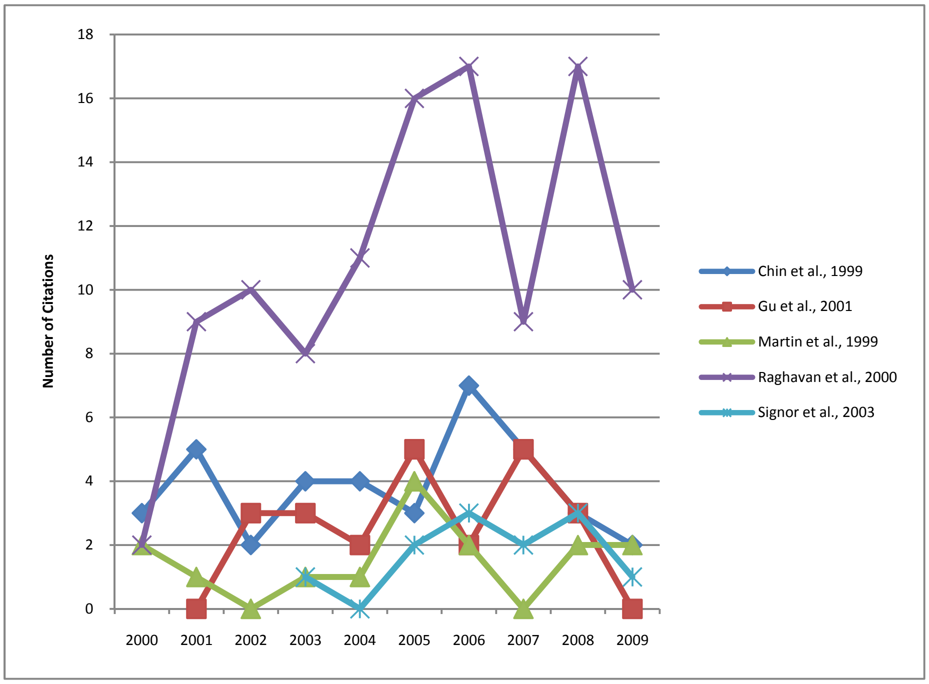

Table 7-10 shows the number of citations by subject areas for these five articles. Note that numbers of citations by subject areas do not necessarily add up to the total number of citations. One reason is that articles that cite the publications of interest may not be in the journals subscribed to by the NIST Library, in which case, attributes of these articles, such as year published or subject areas, are not retrievable. The second reason is that an article may be classified under multiple subject areas. Overall, these five articles in polymer science have the largest impact in polymer science. These articles have been cited by publications in polymer science 79 times. The other prominent subject areas of impact are materials science (with 60 citations), chemistry (with 57 citations), engineering (with 19 citations), and physics (with 18 citations).

Table 7-10 Number of Citations by Subject Areas for Major Publications in Polymer Science

	Chin et al., 1999	Gu et al., 2001	Martin et al., 1999	Raghavan et al., 2000	Signor et al., 2003	Total
Biochemistry & molecular biology				7	1	8
Biodiversity conservation			1			1
Biophysics					1	1
Construction & building technology	3					3
Chemistry, applied					4	4
Chemistry, physical		1	1	31	2	35
Chemistry, applied		8	2	4		14
Chemistry, organic				4		4
Ecology			1			1
Engineering, chemical	2	1	2	5		10
Engineering, civil	5				1	6
Engineering, electrical & electronic	2					2
Engineering, multidisciplinary					1	1
Instruments & instrumentation			1			1
Materials science, biomaterials				3		3
Materials science, characterization & testing			1		1	2
Materials science, coatings & films		8	3		4	15
Materials science, composites	12				2	14
Materials science, multidisciplinary	8	3		15		26
Mechanics	5					5
Multidisciplinary sciences		1				1
Nanoscience & nanotechnology	3					3
Nuclear science & technology		1				1
Physics, applied	3		1	6		10
Physics, atomic, molecular & chemical		1				1
Physics, condensed matter				7		7
Polymer science	17	8	6	46	2	79

7.4.1.2 Applied Chemistry, Materials Science, and Coatings & Films

Four papers are classified under the Applied Chemistry, Materials Science, and Coatings & Films category. All four papers on this topic are proceedings papers. Table 7-11 lists these publications with the number of citations. These four papers collectively have been cited for 67 times. The most cited article was Nguyen *et al.* (1996) with 39 citations.

This paper studies the water layer at the organic coating/substrate interface. A technique was developed to measure the thickness of the water layer at the interface. This technique can also be used to study water transport through a coating adhered to a substrate. Data on the water and its transport properties allow the study of failures of organic coatings and are important for developing models on service life prediction of these materials.

The second most cited article under this category, Martin *et al.* (2003), is a literature review of the reciprocity law experiments in polymeric photodegradation. Reciprocity law experiments are experiments designed to test whether laboratory-based high radiant influx can be mapped to particular levels of solar radiation. This review article concludes that the Schwarzschild law, which is a generalization of the reciprocity law, tends to model adequately the photoresponse as a function of radiant flux for most materials and systems. This article contends that it appears feasible to translate laboratory-based high radiant influx to an equivalent level of solar radiation and that it may be practical to accelerate the weathering process of polymeric materials using high levels of radiant flux.

The third most cited paper in this category is Chin *et al.* (2005). This paper has been cited 10 times, and was the First Place 2004 Roon Award Competition Paper. The Roon Award is administered by the Federation of Societies for Coatings Technology (FSCT). The purpose of the Roon Foundation Awards is "to recognize the best technical papers directly related to the protective coatings industry, presented by individuals associated with the organic coatings industry."[89] Chin *et al.* (2005) is a significant contribution to the literature and is a follow-up study of Martin *et al.* (2003). Using the NIST integrating sphere, Chin *et al.* (2005) validated the reciprocity law for coating materials under radiation exposure. Furthermore, they demonstrated that high radiant influx generated in the laboratory setting can be extrapolated to levels of solar radiation. The authors show that the photoresponse of a material is dependent only on the total energy the material has been exposed to.

Chin *et al.* (2006) reviews the advantages of accelerated laboratory weathering experiments over the traditional approach based on outdoor exposure. One major advantage of accelerated laboratory experiments is the speed at which results can be obtained. Additionally, laboratory weathering experiments are designed to cover the range of expected outdoor exposure, which is an improvement over the traditional method, which is based on the actual history of weather. The authors propose the use of "total effective dosage" as the metric for ultraviolet exposure. Based on total effective

[89] http://www.coatingstech.org/index.cfm?event=FsctAwards#Roon

dosage, predictions can be made on the extent of damage. Additionally, data obtained in the laboratory can be compared with data obtained through outdoor exposure.

Table 7-11 List of Publications in Applied Chemistry, Materials Science, Coatings & Films (Proceedings Papers) with the Highest Numbers of Citations

Publication Information	Number of Citations
Nguyen, T; Byrd, E; Bentz, D; Lin, CJ. 1996. In situ measurement of water at the organic coating substrate interface. *PROGRESS IN ORGANIC COATINGS* 27 (1-4): 181-193.	39
Martin, JW; Chin, JW; Nguyen, T. 2003. Reciprocity law experiments in polymeric photodegradation: a critical review. *PROGRESS IN ORGANIC COATINGS* 47 (3-4): 292-311.	16
Chin, J; Nguyen, T; Byrd, E; Martin, J. 2005. Validation of the reciprocity law for coating photodegradation. *JCT RESEARCH* 2 (7): 499-508.	10
Chin, JW; Nguyen, T; Gu, XH; Byrd, E; Martin, J. 2006. Accelerated UV weathering of polymeric systems: Recent innovations and new perspectives. *JCT COATINGSTECH* 3 (2): 20-26.	2

Note: Citation counts obtained through Web of Science academic database, August, 2009.

Figure 7-2 shows the yearly citations for each of these four articles in this category.

Table 7-12 shows the number of citations by subject area. These four publications were cited most by publications in materials science (with 27 citations), followed by chemistry (with 15 citations), and polymer science (with 9 citations). Interestingly, Nguyen *et al.* (1996) has been cited 7 times by articles in dentistry, oral surgery, and medicine. Citations by articles in seemingly unrelated subject areas suggest spillover benefits of the SLP program outside of intended stakeholder groups.

Figure 7-2 Yearly Citation Analysis for Major Publications in Applied Chemistry, Materials Science, and Coatings & Films

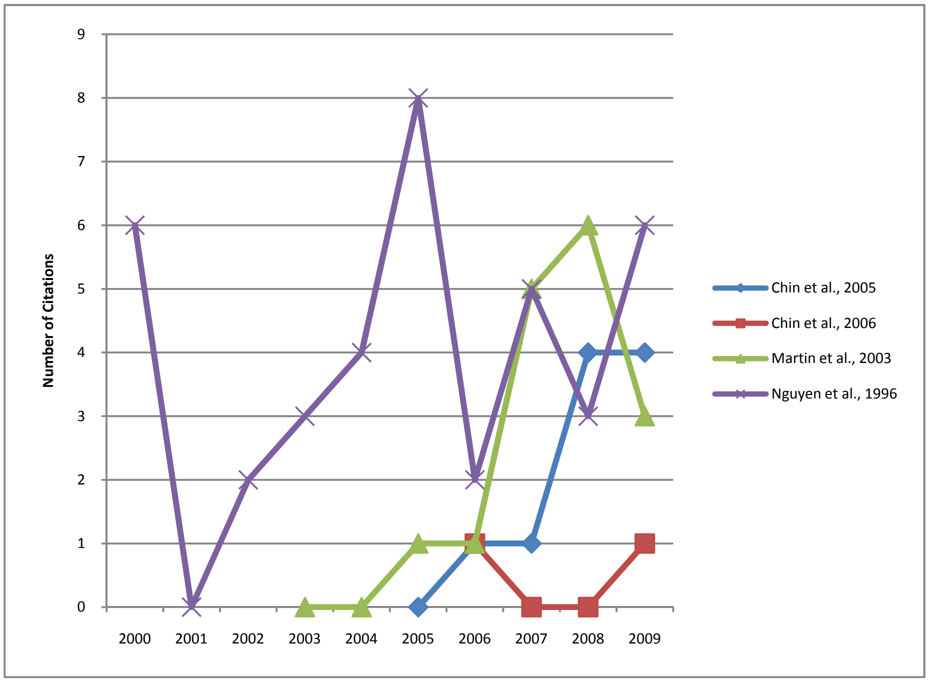

Table 7-12 Number of Citations by Subject Areas for Major Publications in Applied Chemistry, Materials Science, and Coatings & Films

	Chin et al., 2005	Chin et al., 2006	Martin et al., 2003	Nguyen et al., 1996	Total
Biochemistry & molecular biology			2		2
Biophysics			4		4
Chemistry, applied	4			9	13
Chemistry, physical			1	1	2
Dentistry, oral surgery & medicine				7	7
Electrochemistry				4	4
Engineering, biomedical			1		1
Engineering, chemical				8	8
Environmental sciences		1			1
Materials science, coatings & films	4			11	15
Materials science, multidisciplinary				12	12
Mathematics, applied		1			1
Mechanics				5	5
Metallurgy & metallurgical engineering				2	2
Microbiology			1		1
Operations research & management science		1			1
Optics			1		1
Physics, applied			1	1	2
Polymer science	3		6		9
Radiology, nuclear medicine & medical imaging			1		1

7.4.1.3 Miscellaneous Category

Publications in this group include three journal articles and two books. The most highly cited publication in this category is Raghavan *et al.* (2000b) with 46 citations. This paper is similar in nature to Raghavan *et al.* (2000a). These two papers are both focused on nano-scale characterization of polymeric materials using atomic force microscopy. One reason for the high citation counts may be due to the wide applicability of this approach.

The second most highly cited publication in this category is Chin *et al.* (1997), with 34 citations. Chin *et al.* (1997) studied how exposure to a variety of environmental conditions affects the properties of polymeric materials. The goal of this paper is similar to Chin *et al.* (1999), discussed previously. Fiber-reinforced plastic (FRP) materials have the potential to enhance the structural integrity of construction materials, such as concrete. Both Chin *et al.* (1997) and Chin *et al.* (1999) seek to understand how FRP materials perform under environmental exposure. Chin *et al.* (1997) examined the strength, thermal properties, and surface morphology of resins commonly used in construction upon exposure to UV radiation, moisture, alkaline, and saline environment.

Two books are listed in Table 7-13. These two books are compilations of proceedings papers from earlier consortium symposiums. To date, four biannual International Symposium on Service Life Prediction have been held, and research articles and review articles have been compiled for each of these symposiums. The two more recent books are titled "Service Life Prediction: Challenging the Status Quo" edited by Jonathan W. Martin, Rose A. Ryntz, and Ray A. Dickie (2005) and "Service Life Prediction of Polymeric Materials: Global Perspectives" edited by Jonathan W. Martin, Rose A. Ryntz, Joannie Chin, and Ray A. Dickie (2009).

Finally, Chin *et al.* (2004) describes the components and qualities of the NIST SPHERE (Simulated Photodegradation via High Energy Radiant Exposure). This integrating sphere is a device that has the capability of uniformly irradiating multiple samples with UV energy while simultaneously keeping these samples under a range of precisely and independently controlled temperature and relative humidity conditions. This technology reduces systematic errors associated with previous laboratory setups for weathering experiments and represents a major contribution to the study of service life prediction.

Figure 7-3 shows the yearly citation counts for each of these publications.

Table 7-13 List of Publications in Miscellaneous Categories (Articles and Books) with the Highest Numbers of Citations

Publication Information	Number of Citations
Raghavan, D; VanLandingham, M; Gu, X; Nguyen, T. 2000. Characterization of heterogeneous regions in polymer systems using tapping mode and force mode atomic force microscopy. *LANGMUIR* 16 (24): 9448-9459.	46
Chin, JW; Nguyen, T; Aouadi, K. 1997. Effects of environmental exposure on fiber-reinforced plastic (FRP) materials used in construction. *JOURNAL OF COMPOSITES TECHNOLOGY & RESEARCH* 19 (4): 205-213.	34
Bauer, D.R. and Martin, J.W. (1999) Service Life Prediction of Organic Coatings: A Systems Approach, American Chemical Society Symposium Series 722, Oxford Press, New York, New York.	20
Martin, J.W. and Bauer, D.R. (2001) Service Life Prediction: Methodology and Metrologies, American Chemical Society Symposium Series 805, Oxford Press, New York, New York.	4
Chin, J; Byrd, E; Embree, N; Garver, J; Dickens, B; Finn, T; Martin, J. 2004. Accelerated UV weathering device based on integrating sphere technology. *REVIEW OF SCIENTIFIC INSTRUMENTS* 75 (11): 4951-4959.	3

Note: Citation counts obtained through Web of Science academic database, August, 2009.

Figure 7-3 Yearly Citation Analysis for Major Publications in the Miscellaneous Category

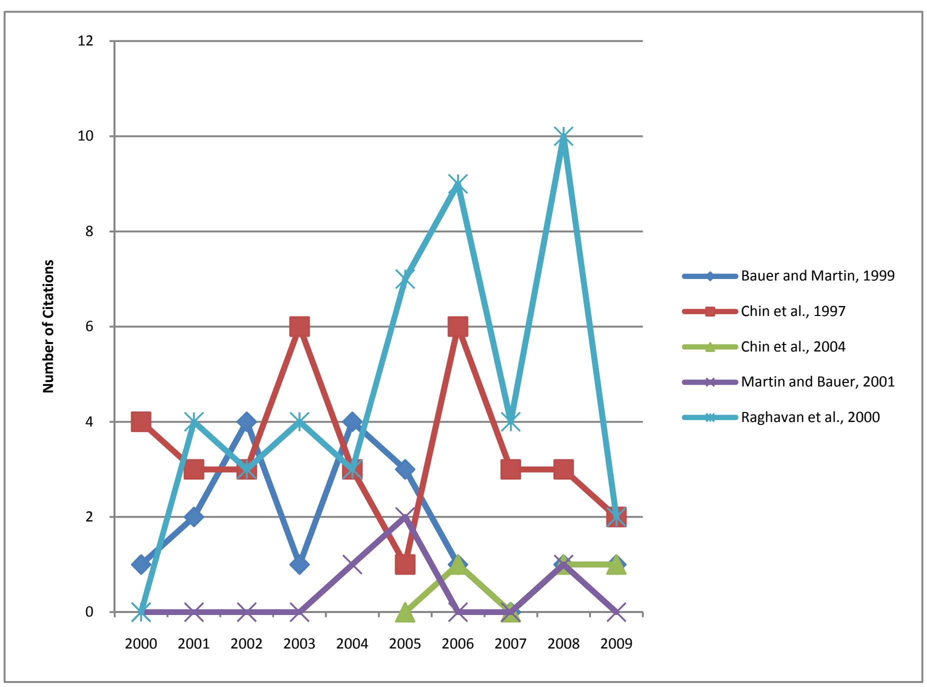

Table 7-14 lists the number of citations by subject areas for these five publications. The subject area with the most publications that cite the five publicaitons of interest is materials science (with 51 citations), followed by chemistry (with 34 citations), polymer science (with 30 citations), and physics (with 13 citations). Noteably, 12 citations came from building materials research, construction & building technology, and civil engineering.

Table 7-14 Number of Citations by Subject Areas for Major Publications in the Miscellaneous Category

	Bauer and Martin, 1999	Chin et al., 1997	Chin et al., 2004	Martin and Bauer, 2001	Raghavan et al., 2000	Total
Biochemistry & molecular biology					3	3
Building materials research	2					2
Chemistry, analytical	1					1
Chemistry, applied	7		1	2		10
Chemistry, multidisciplinary		1			7	8
Chemistry, physical					15	15
Construction & building technology		2				2
Engineering, civil		8				8
Engineering, chemical					3	3
Engineering, multidisciplinary		2				2
Materials science, characterization & testing	1	7				8
Materials science, coatings & films	7		1	2	3	13
Materials science, composites		16				16
Materials science, multidisciplinary		3		1	10	14
Mechanics		4				4
Nanoscience & nanotechnology					6	6
Physics, applied					6	6
Physics, condensed matter					7	7
Polymer science	5	9	1	1	14	30
Statistics & probability	2					2

8 Sensitivity Analysis of Economic Impacts

The SLP economic impact assessment described in this report was carried out in two stages. In the first stage, a baseline analysis was performed. The data and assumptions underlying the baseline analysis were described in Chapter 6; the results of the baseline analysis were presented in Chapter 7.

In this second stage, nine variables are varied in combination according to an experimental design. The sensitivity analysis uses the same data and assumptions as the baseline analysis for its starting point. Information on how the deviations about the baseline values for each of the nine input variables are specified. The sensitivity analysis described in this chapter is based on Latin Hypercube techniques. The objective of the sensitivity analysis is to evaluate how uncertainty in the values of each of the nine input variables translates into changes in each of three key economic measures. The three economic measures are: (1) the present value of net savings due to BFRL's SLP-related investment costs; (2) the savings-to-investment ratio on BFRL's SLP-related investments; and (3) the adjusted internal rate of return on BFRL's SLP-related investments. These measures are particularly helpful in understanding BFRL's contribution, because each measure provides a different perspective. The first, the present value of net savings (PVNS) due to BFRL, is a magnitude measure; it shows a net dollar value to the public net of BFRL's SLP-related investments. The second, the savings-to-investment ratio (SIR) on BFRL's SLP-related investments, is a multiplier; it shows, in present value terms, how many dollars the public receives for each public dollar spent. The third, the adjusted internal rate of return (AIRR) on BFRL's SLP-related investments, is a rate of return; it shows the return on the public monies going into the development of SLP products and services throughout the 15-year study period.

8.1 Methodology

Because the values of many variables that enter into the SLP economic impact assessment are not known with certainty, it is advisable to select a small set of variables whose impact is likely to be substantial and subject them to a sensitivity analysis. Variations in the values of these input variables translate into the value of each outcome (e.g., the SIR) in such a manner that the impacts of uncertainty can be measured quantitatively.

Sensitivity analysis may be divided into two polar cases: (1) deterministic; and (2) probabilistic. Deterministic sensitivity analyses are the most straightforward. Their advantage is that they are easy to apply and the results are easy to explain and understand. Their disadvantage is that they do not produce results that can be tied to probabilistic levels of significance (i.e., the probability that the SIR is less than 1.0).

For example, a deterministic sensitivity analysis might use as inputs a pessimistic value, a value based on a measure of central tendency (e.g., mean or median), and an optimistic value for the variable of interest. Then an analysis could be performed to see how each outcome (e.g., the SIR) changes as each of the three chosen values for the selected input is considered in turn, while all other input variables are maintained at their baseline values. A deterministic sensitivity analysis can also be performed on different combinations of input variables. That is, several variables are altered at once and then an outcome measure is computed. This is the approach used in two of the previous economic impact assessments.[90]

In a probabilistic sensitivity analysis, a small set of key input variables is varied either singly or in combination according to an experimental design. In most cases, probabilistic sensitivity analyses are based on Monte Carlo or Latin Hypercube techniques. The major advantage of probabilistic sensitivity analysis is that it permits the effects of uncertainty to be rigorously analyzed. For example, not only the expected value of each economic measure can be computed but also the variability of that value. In addition, probabilistic levels of significance can be attached to the computed values of each economic measure. The disadvantage of a probabilistic sensitivity analysis is that it requires many calculations carried out according to an experimental design, and is therefore practical only when used with a computer.

The approach selected for this study makes use of works by McKay, Conover, and Beckman[91] and by Harris;[92] it is based on the method of model sampling. Model sampling provides the basis for many probabilistic sensitivity analyses. Model sampling is a procedure for sampling from a stochastic process to determine, through multiple trials, the characteristics of a probability distribution. This approach was used in two of the previous economic impact assessments.[93]

[90] See Chapman and Fuller, *Two Case Studies in Building Technology*, and Chapman and Weber, *A Case Study of the Fire Safety Evaluation System*.

[91] McKay, M. C., W. H. Conover, and R.J. Beckman. 1979. "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code." *Technometrics* (Vol. 21): pp. 239-245.

[92] Harris, Carl M. 1984. *Issues in Sensitivity and Statistical Analysis of Large-Scale, Computer-Based Models*. NBS GCR 84-466. Gaithersburg, MD: National Bureau of Standards.

[93] See Chapman, *A Case Study of Cybernetic Building Systems*, and Chapman, *A Case Study of Construction Systems Integration and Automation Technologies in Industrial Facilities*.

The method of model sampling was implemented through application of the *Crystal Ball* software product.[94] This software product is an add-in for spreadsheets. For the case at hand, selected columns of the spreadsheet were associated with one or more of the nine input variables. The *Crystal Ball* software product allows the user to specify a unique probability distribution for each input variable. Specification of the experimental design involves defining which variables are to be simulated and the number of simulations. Throughout this sensitivity analysis, 10 000 simulations were run for each combination of input variables under analysis. When the *Crystal Ball* software product is executed, it randomly samples from the parent probability distribution for each input variable of interest (i.e., the input variable(s) specified by the experimental design). In this analysis, a Latin Hypercube sampling approach is used to ensure at least some sampling from the tails of the distributions. Latin Hypercube sampling trades the randomness created by Monte Carlo sampling for sampling evenness. This yields better predictions (greater representativeness).

In reality, the exact nature of the parent probability distribution for each input variable is unknown. Estimates of the parameters (e.g., mean and variance) of the parent probability distribution can be made and uncertainty can be reduced by investigation and research. However, uncertainty can never be eliminated completely. The true specification of the parent probability distribution can only be known after SLP products and services have been operating in the marketplace for an extended period of time. Therefore, to implement the procedure without undue attention to the characterization of the parent probability distribution, it was decided to focus on only three probability distributions. These probability distributions are: (1) the triangular; (2) the uniform; and (3) the discrete or multinomial. Readers interested in learning more about these probability distributions, including variate relationships, estimation procedures, and random number generation, are referred to Evans, Hastings, and Peacock.[95]

One reason for using these three probability distributions is that they are all defined over a finite interval. Furthermore, the specification of each probability distribution is accomplished with as few as two data points. The triangular distribution is widely used in simulation modeling; its specification requires three data points, the minimum value, the most-likely value, and the maximum value. The triangular distribution is used whenever the range of input values is continuous and a clustering about some central value is expected. The uniform distribution is also widely used in simulation modeling; its specification requires only two data points, the minimum value and the maximum

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[94] Crystal Ball. 2007. *Crystal Ball 7.3 User Manual*. Denver, CO: Decisioneering, Inc.

[95] Evans, Merran, Nicholas Hastings, and Brian Peacock. 1993. *Statistical Distributions*. New York, NY: John Wiley & Sons, Inc.

value. In addition, all values between the minimum and maximum are equally likely. The uniform distribution is used whenever the range of input values is continuous but no *a priori* reason can be given for expecting clustering about some central value. The discrete distribution is used whenever the range of input values is discrete.

8.2 Sensitivity Analysis of Benefits Estimation

8.2.1 Improved Time-to-Market of New Cool Roof Technologies

In the baseline analysis, the present value benefits of improved service life prediction (SLP) for the California cool roof market was estimated to be $824 555. The baseline analysis assumed a 7 % discount rate, 10 % market saturation by the high-performance cool roof technology, a SLP-induced improved time-to-market of 2 years (i.e., the technology was introduced in 2006 instead of 2008), 5 % of the pre-existing low-slope commercial building stock is reroofed annually, and that 67 % of all commercial buildings (conditioned roof area) are low-sloped. The discount rate, market penetration, and improved time-to-market parameters contain some degree of uncertainty. In this uncertainty analysis, the discount rate follows a uniform distribution and varies between 4 % and 10 %, the percent of market penetration follows a triangular distribution with a minimum value of 5 % and a maximum value of 20 %, and the SLP-induced improved time-to-market follows a triangular distribution with a minimum of a 1 year improvement and a maximum of a 3 year improvement (see Table 8-1). Thus given the degree of uncertainty, the actual benefits resulting from an improved SLP in the cool roofing market is somewhere between $189 890 and $2 684 550.

Using Latin Hypercube sampling, the distribution of these three uncertainty parameters were sampled 10 000 times (trials). This produced 10 000 net energy savings estimates.[96] The results are shown in Table 8-2. The mean net energy savings is $966 264, with a median value of $894 386. The minimum value is estimated at $197 968 and the maximum value estimated is at $2 647 909.

[96] The “net” in net energy savings refer to the difference of cooling energy savings from cool roof technologies and the associated increase in heating energy costs.

Table 8-1 Assumptions for Cool Roof Latin Hypercube Simulation

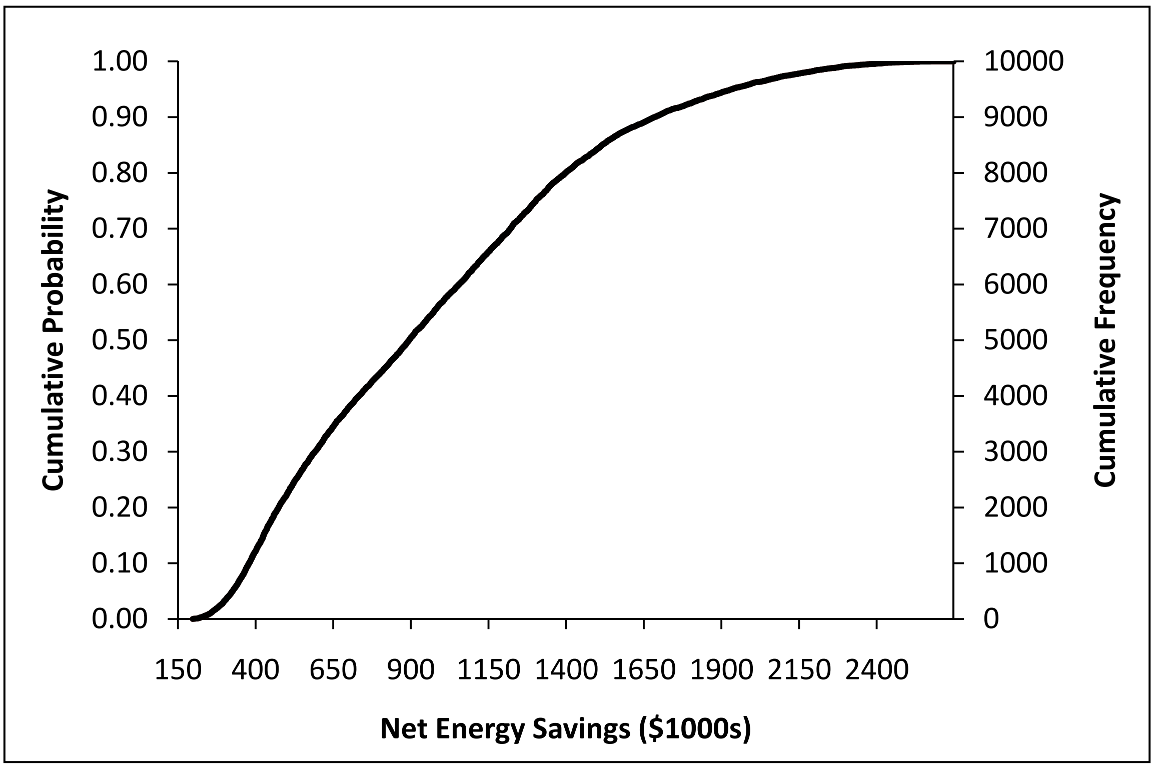
Variable Name	Probability Distribution	Setting and Value		
		Most-Likely	Minimum	Maximum
Discount Rate	Uniform	0.07	0.04	0.10
% Market Penetration	Triangular	10	5	20
SLP-Improved Time to Market	Discrete Uniform	2	1	3
% Annual Reroof		5		
% Low Slope Roofs		66.52		

Table 8-2 Summary Statistics of the Latin Hypercube Simulation

Summary Statistics	**Value**
Trials	10,000
Mean	$966,264
Median	$894,386
Minimum	$197,968
Maximum	$2,647,909
Standard Deviation	$505,563
Mean Standard Error	$5,056

Figure 8-1 plots the net energy savings against the cumulative probability and the cumulative frequency (one on each vertical axis). Figure 8-1 shows the proportion (frequency) of simulated trials that produced a net energy savings below each value. For instance, the net energy savings was below \$1 150 000 in about 67 % of the simulated trials (and that 33 % of the simulated trials resulted in a net energy savings greater than \$1 150 000). Of the three uncertainty parameters, improved time-to-market causes 76.1 % of the observed variation in the net energy savings estimates, with market penetration contributing 23.6 % and the discount rate contributing 0.3 % (results not shown). Thus, reducing the time-to-market is the single most important factor in producing energy savings in the cool roof market.

Figure 8-1 The Simulated Cumulative Probability and Frequency of the Net Energy Savings Due to Improvements in Cool Roof Technology



8.2.2 Improved Time-to-Market of New Wet-Sealed Fenestration Systems

In the baseline analysis the present value benefits of improved service life prediction (SLP) due to the early introduction of high-performance, wet-sealed fenestration was estimated to be \$10 015 039. The baseline analysis assumed a 7 % discount rate and used two diffusion processes for new and existing commercial buildings applied to 22 % of the eligible new buildings and 5 % of the eligible existing building stock. A SLP-induced improved time-to-market allowed early introduction of the high-performance window sealant to the commercial building stock, beginning in 2004. The discount rate and diffusion process (discussed in Chapter 6) parameters contain some degree of uncertainty. In this uncertainty analysis the discount rate follows a uniform distribution and varies between 4 % and 10 %; the market saturation level for new buildings follows a triangular distribution with a minimum value of 30 % and a maximum value of 50 %; the market saturation level for existing buildings follows a triangular distribution with a minimum value of 25 % and a maximum value of 35 %; the location parameter follows a uniform distribution with a minimum value of 3.0 with a maximum value of 5.0; and the shape parameter follows a triangular distribution with a minimum value of 0.4 with a maximum value of 0.6 (see Table 8-3).

Table 8-3 Assumptions for Wet-Sealed Fenestration Latin Hypercube Simulation

Variable Name	Probability Distribution	Setting and Value		
		Most-Likely	Minimum	Maximum
Discount Rate	Uniform	0.07	0.04	0.10
% Market Saturation				
New	Triangular	40	30	50
Existing	Triangular	25	15	35
Location Parameter	Uniform	4	3	5
Shape Parameter	Triangular	0.5	0.4	0.6

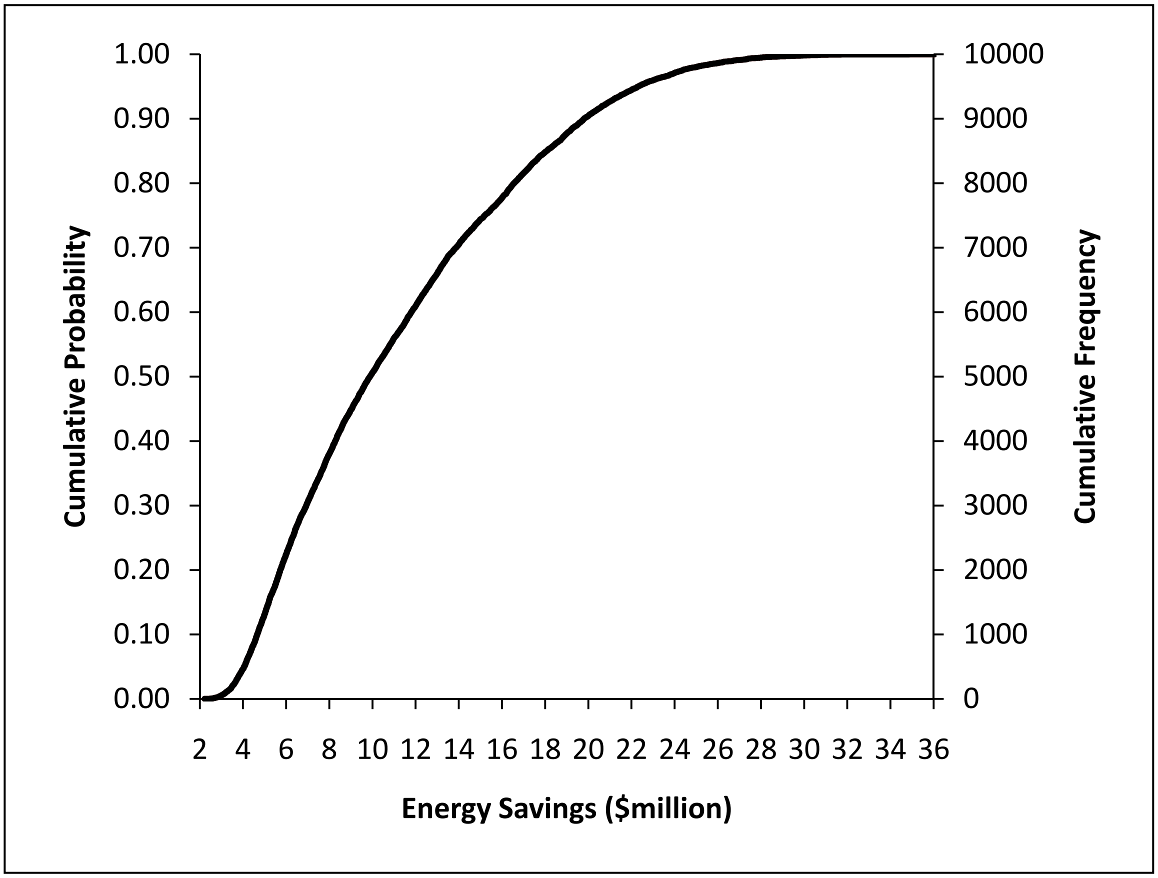
Given the degree of uncertainty, the actual benefits resulting from an improved SLP in the sealant market is somewhere between $1 653 293 and $41 778 580. Using Latin Hypercube sampling, the distribution of the uncertainty parameters were sampled 10 000 times (trials). This produced 10 000 energy savings estimates. The results are shown in Table 8-4. The mean energy savings is $11 201 661, with a median value of $9 877 728. The minimum value is estimated at $2 219 811 and the maximum value estimated is at $36 049 535. Figure 8-2 plots the energy savings against the cumulative probability and the cumulative frequency (one on each vertical axis).

Table 8-4 Summary Statistics of the Wet-Sealed Fenestration Latin Hypercube Simulation

Summary Statistics	Value
Trials	10,000
Mean	$11,201,661
Median	$9,877,728
Minimum	$2,219,811
Maximum	$36,049,535
Standard Deviation	$5,872,866
Mean Standard Error	$58,729

Figure 8-2 shows the proportion (frequency) of simulated trials that produced an energy savings below each value. For instance, the energy savings was below $14 million in about 70 % of the simulated trials (and that 30 % of the simulated trials resulted in an energy savings greater than $14 million). Of the uncertainty parameters, the location parameter causes 88.5 % of the observed variation in the energy savings estimates, with existing market saturation contributing 6.9 %, the shape parameter contributing 4.4 %, the discount rate contributing 0.1 %, and new market saturation contributing <0.1 % of the variation in energy savings (results not shown). Thus, increasing the diffusion of new technologies to market is the single most important factor in producing energy savings in the sealant window market.

Figure 8-2 The Simulated Cumulative Probability and Frequency of the Energy Savings Due to Improvements in Wet Sealant Fenestration



8.2.3 EPDM Warranty Repair Cost Savings

In the baseline analysis the present value benefits of improved service life prediction (SLP) for the EPDM market was estimated to be \$178.6 million. The baseline analysis assumed a 7 % discount rate. There is uncertainty surrounding the discount rate and the exact size of the benefits. In this uncertainty analysis the discount rate follows a uniform distribution and varies between 4 % and 10 %, and the 'true' (nominal) benefit is assumed to be 0.5 to 1.5 times the estimated ('multiplier') (see Table 8-5). Thus given the degree of uncertainty, the actual present value benefits resulting from improved SLP in the EPDM market is somewhere between \$62.5 million and \$379.9 million.

Table 8-5 Assumptions for the EPDM Latin Hypercube Simulation

Variable Name	Probability Distribution	Setting and Value		
		Most-Likely	Minimum	Maximum
Discount Rate	Uniform	0.07	0.04	0.10
Multiplier	Triangular	1	0.5	1.5

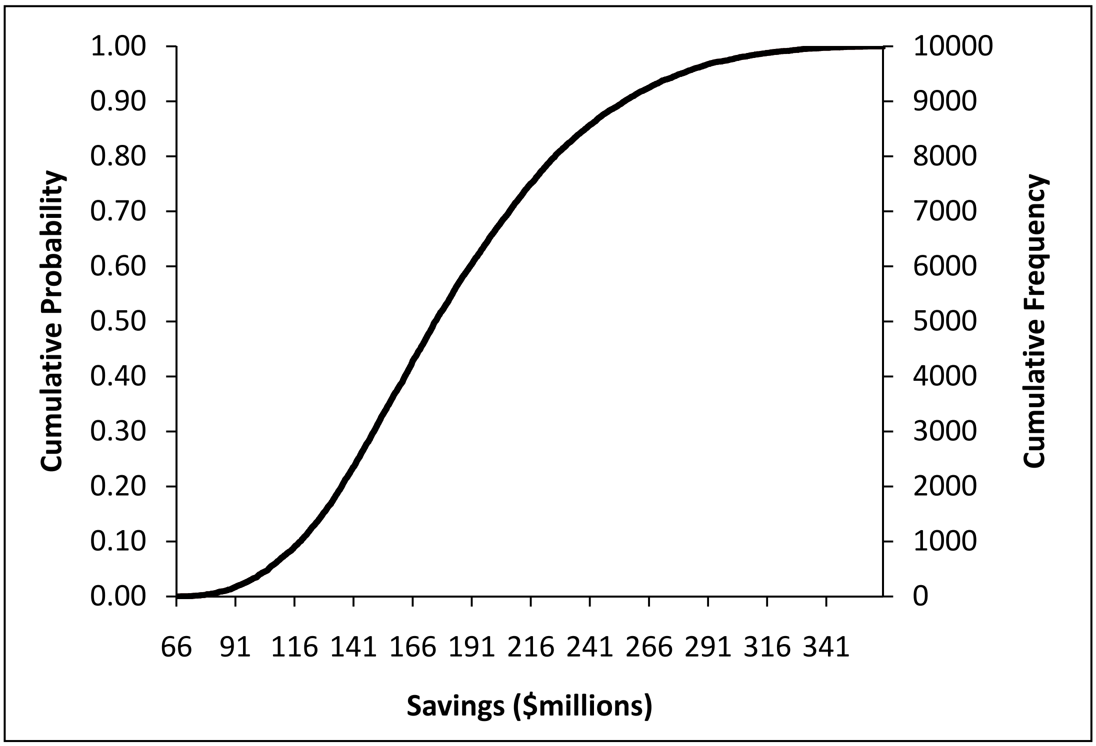
Using Latin Hypercube sampling, the distribution of the two uncertainty parameters were sampled 10 000 times (trials). This produced 10 000 benefit estimates. The results are shown in Table 8-6. The mean benefit is \$182.0 million, with a median value of \$175.6 million. The minimum value is estimated at \$65.6 million and the maximum value estimated is at \$365.3 million.

Table 8-6 Summary Statistics of the EPDM Latin Hypercube Simulation

Summary Statistics	Value
Trials	10,000
Mean	\$182 020 472
Median	\$175 553 613
Minimum	\$65 630 800
Maximum	\$365 270 871
Standard Deviation	\$52 741 715
Mean Standard Error	\$527 417

Figure 8-3 plots the net energy savings against the cumulative probability and the cumulative frequency (one on each vertical axis). Figure 8-3 shows the proportion (frequency) of simulated trials that produced a savings below each value. For instance, the savings was below $191 million in about 62 % of the simulated trials (and that 38 % of the simulated trials resulted in a savings greater than $191 million). Of the two uncertainty parameters, changes in the discount rate causes 50.3 % of the observed variation in the savings estimates, with the multiplier contributing to 49.7 % (results not shown).

Figure 8-3 The Simulated Cumulative Probability and Frequency of the Savings Due to Improvements in EPDM



8.3 Sensitivity Analysis of Economic Impact

Table 8-7 summarizes the results of a Latin Hypercube simulation in which the total SLP-related benefits are compared with the BFRL's SLP-related investments. All eight of the uncertainty variables (described above), along with an additional variable, which approximates the share (proportion) of SLP-induced benefits attributable to BFRL's investments, are varied in combination. The share of SLP-induced benefits attributable to BFRL's investments follows a triangular distribution with a minimum of 0.20, the most-likely value of 0.25, and a maximum of 0.35.

Table 8-7 Summary Statistics of the Latin Hypercube Simulation Due to Changes in All of the Uncertainty Input Variables

	Statistical Measure						
Economic Measure	Minimum	25%	50%	75%	Maximum	Mean	Standard Deviation
PVNS	-20.92	1.67	11.31	22.68	87.76	13.23	15.44
SIR	0.46	1.04	1.29	1.59	3.28	1.34	0.40
AIRR	-0.01	0.06	0.09	0.12	0.19	0.09	0.04

The results show that, on average, the benefits outweigh their costs, demonstrated by a present value of net savings (PVNS) of $13.23 million, a savings to investment ratio (SIR) (i.e., benefit-cost ratio) of 1.34, and an adjusted internal rate of return (AIRR) of 9 %. Not all simulations produced economic returns, however. The minimum simulated values are -$20.92 million PVNS, 0.46 SIR, and a -1 % AIRR. The simulated PVNS, SIR, and AIRR distributions are not symmetric, as the maximum values are much farther from the means than are the minimums. (In addition, note the means are larger than the medians [50 % percentile]). The maximum simulated values are $87.76 million PVNS, 3.28 SIR, and a 19 % AIRR.

Figures 8-4, 8-5, and 8-6 plot the PVNS, SIR, and AIRR, respectively, against the cumulative probability and the cumulative frequency generated from the Latin Hypercube simulations. From these plots, it is apparent that the likelihood the true PVNS is greater than 0 is 79 %, that the true SIR is greater than 1.0 is 79 %, and that the true AIRR is greater than 0.07 is 67 %—i.e., there is a 79 % probability that BFRL's SLP-related investments are cost-effective and a 67 % probability that those returns will outperform the discount rate (0.07). The uncertainty parameters that have the greatest influence on

PVNS, SIR, and AIRR are the discount rate and the EPDM benefits multiplier (results not shown). If, when holding the other parameters constant, the discount rate is greater than 0.051, the share (proportion) of SLP-induced benefits attributable to BFRL's investments is greater than 0.21, or the EPDM benefits multiplier is greater than 0.9, the BFRL's SLP-related investments are cost-effective (results not shown).

Figure 8-4 Present Value of Net Savings Attributable to BFRL ($2008)

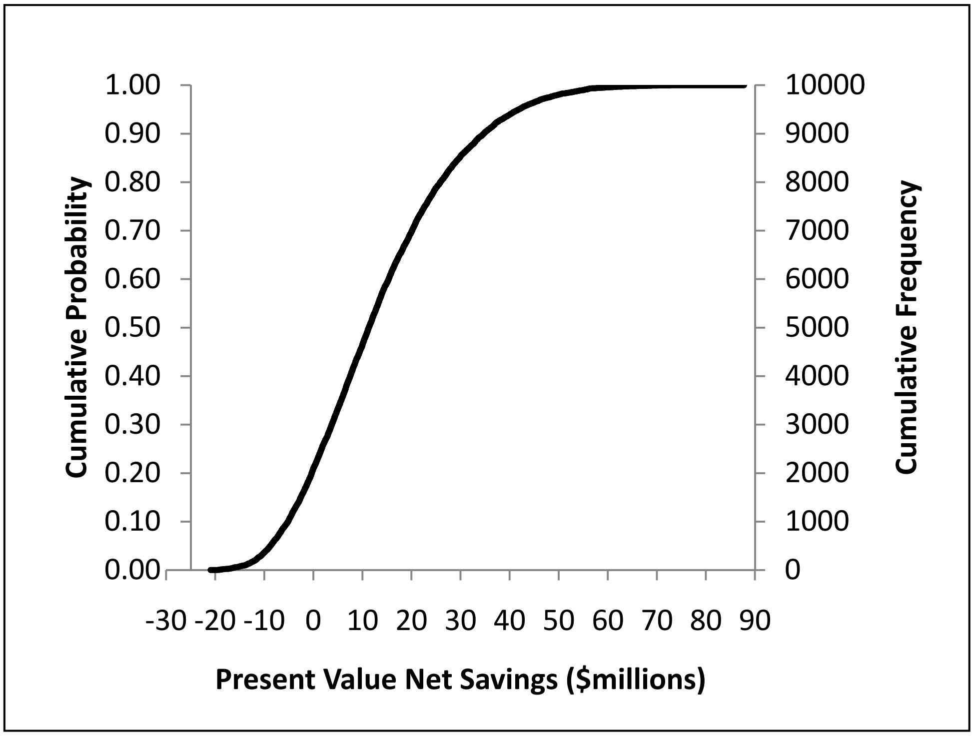


Figure 8-5 Savings to Investment Ratio on BFRL's Research and Development Investment

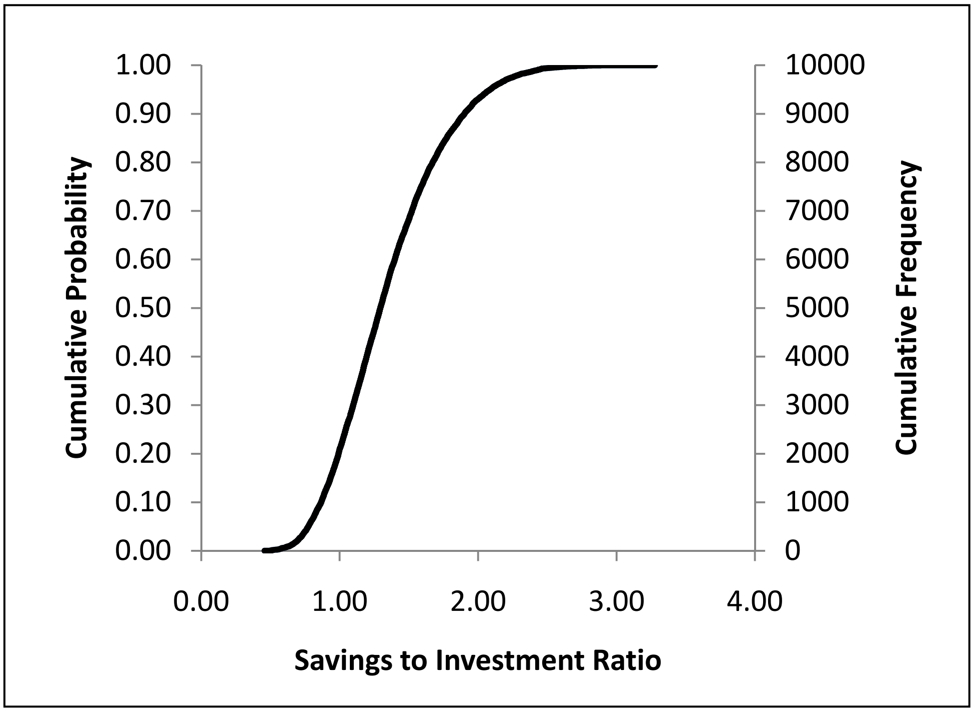
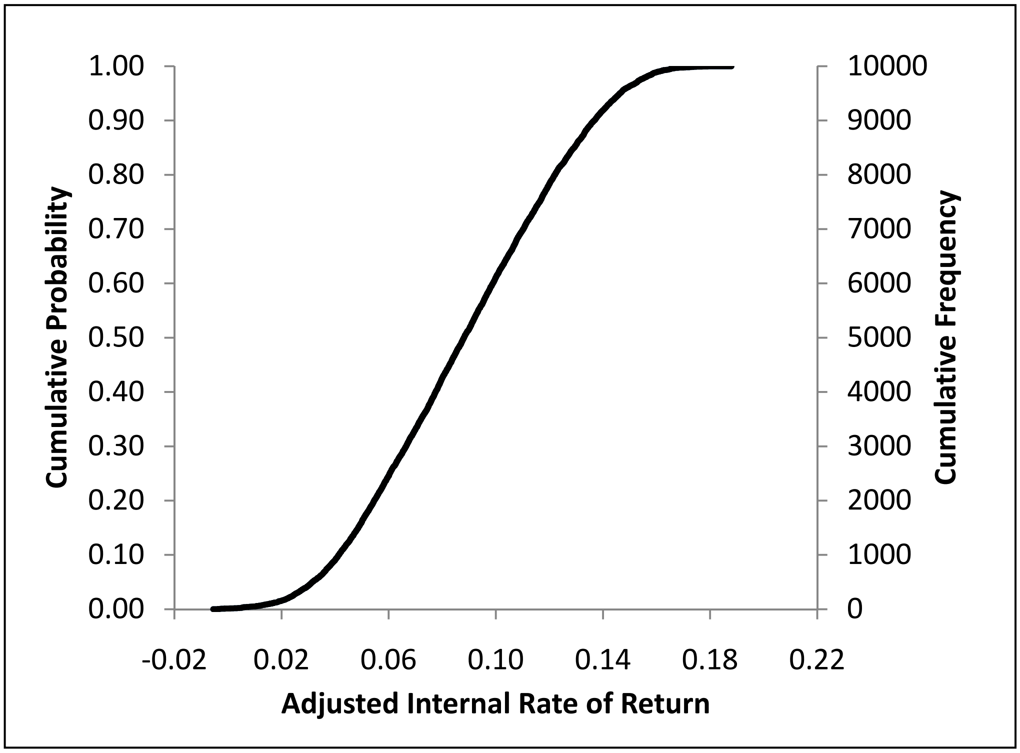


Figure 8-6 Adjusted Internal Rate of Return on BFRL's Research and Development Investment



9 Summary and Suggestions for Further Research

9.1 Summary

A formal resource allocation process for funding research is needed in both the public and private sectors. Research managers need guidelines for research planning so that they can maximize the payoffs from their limited resources. Furthermore, quantitative descriptions of research impacts have become a basic requirement in many organizations for evaluating budget requests.

There are several reasons for measuring the economic impacts of a federal laboratory's research program. First, economic impact studies are a management tool; they help set priorities and point to new research opportunities. Second, as federal laboratories become more customer oriented, by revealing the "voice of the customer," such studies will strengthen the ties to industry and identify opportunities for leveraging federal research investments. Finally, changing requirements will affect how federal research funds are allocated. Increasingly, federal agencies and laboratories are encouraged to demonstrate that their research efforts complement those of industry and that they are having a positive impact on society.

NIST, a scientific research agency of the U.S. Department of Commerce, is improving its resource allocation process by doing "microstudies" of its research impacts on society. This report is the seventh in a series of impact studies prepared by BFRL.[97] It focuses on

[97] The first report in the series focuses on two building technology applications: (1) ASHRAE Standard 90-75 for residential energy conservation; and (2) 235 shingles, an improved asphalt shingle for sloped roofing (see Chapman, Robert E., and Sieglinde K. Fuller. 1996. *Benefits and Costs of Research: Two Case Studies in Building Technology*. NISTIR 5840. Gaithersburg, MD: National Institute of Standards and Technology). The second report focuses on a fire technology application: the Fire Safety Evaluation System for health care facilities (see Chapman, Robert E., and Stephen F. Weber. 1996. *Benefits and Costs of Research: A Case Study of the Fire Safety Evaluation System*. NISTIR 5863. Gaithersburg, MD: National Institute of Standards and Technology). The third report focuses on the research, development, deployment, and adoption and use of cybernetic building systems in office buildings (see Chapman, Robert E. 1999. *Benefits and Costs of Research: A Case Study of Cybernetic Building Systems*. NISTIR 6303. Gaithersburg, MD: National Institute of Standards and Technology). The fourth report focuses on the research, development, and deployment, and adoption and use of construction systems integration and automation technologies in industrial facilities (see Chapman, Robert E. 2000. *Benefits and Costs of Research: A Case Study of Construction Systems Integration and Automation Technologies in Industrial Facilities*. NISTIR 6501. Gaithersburg, MD: National Institute of Standards and Technology). The fifth report focuses on the research, development, and deployment, and adoption and use of construction systems integration and automation technologies in commercial buildings (see Chapman, Robert E. 2001. *Benefits and Costs of Research: A Case Study of Construction Systems Integration and Automation Technologies in Commercial Buildings*. NISTIR 6763. Gaithersburg, MD: National Institute of Standards and Technology). The sixth report focuses on a case study of NIST's high performance concrete program (see Helgeson, Jennifer F. 2009. *Benefits and Costs of Research: A Case Study of the NIST High Performance*

a critical analysis of the economic impacts of research conducted by BFRL's Service Life Prediction (SLP) Program for High-Performance Polymeric Construction Materials. The SLP Program is an interdisciplinary research effort within BFRL—in collaboration with the private sector, other federal agencies, and other laboratories within NIST—to develop key enabling technologies and advanced measurement technologies needed to deliver high-performance polymeric construction materials to the construction industry. Polymeric materials are used in the construction industry in a myriad of applications including protective coatings, sealants and adhesives, siding, roofing, windows, doors, and piping. They can be combined with fibers to form composites that have enhanced properties, enabling them to be used as structural and load-bearing members. Polymers offer many advantages over conventional materials including lightness, corrosion resistance, and ease of processing and installation.

This case study of BFRL's SLP-related research, development, and deployment effort illustrates how to apply in practice a series of standardized methods, referred to as economic measures, to evaluate and compare the economic impacts of alternative research investments. It is presented in sufficient detail to understand the basis for the economic impact assessment and to reproduce the results. It is based on past research efforts.

Although many excellent topics were uncovered, the project team felt that there were only three categories of high-performance polymeric construction materials that had sufficient documentation to support a rigorous case study analysis. All three of these categories involve commercial buildings. These categories are: (1) improved time-to-market for new cool roof technologies; (2) high-performance sealants and adhesives that reduce air infiltration; and (3) high-performance seams for EPDM roofing that reduce warranty repair costs.

The SLP economic impact assessment was carried out in two stages. In the first stage, a baseline analysis was performed. In the baseline analysis, all input variables used to calculate the economic measures are set at their likely values. It is important to recognize that the term baseline analysis is used to denote a complete analysis in all respects but one; it does not address the effects of uncertainty. In the second stage, eleven input variables were varied both singly and in combination according to an experimental design. Monte Carlo simulations are employed to evaluate how changing the value of these variables affects the calculated values of the economic measures.

Concrete Program. NIST Technical Note 1645. Gaithersburg, MD: National Institute of Standards and Technology).

The results of the baseline analysis demonstrate that the use of three categories of high-performance polymeric construction materials in commercial buildings will generate substantial cost savings to commercial building owners and managers and to materials manufacturers and contractors engaged in the construction of those buildings. The present value of savings nationwide expected from the use of these three categories is nearly $190 million (measured in 2008 dollars). Furthermore, because of BFRL's involvement, these three categories of high-performance polymeric construction materials are expected to be commercially available in a more-timely manner at a higher level of quality/performance, at lower life-cycle cost, and in greater quantity. Consequently, a portion of the estimated cost savings accruing to commercial building owners and managers, materials manufacturers, and to contractors over the period 1994 through 2008 would have been foregone without BFRL involvement. The present value of these cost savings is approximately $48 million. These cost savings measure the value of BFRL's contribution for its SLP-related investment costs of approximately $38.5 million. Stated in present value terms, every public dollar invested in BFRL's SLP-related research, development, and deployment efforts is expected to generate $1.23 in cost savings to the public (i.e., an SIR of 1.23). The annual percentage yield (AIRR) from BFRL's SLP-related investments over the study period is 8.5 percent.

In the second stage, nine variables are varied in combination according to an experimental design. The sensitivity analysis uses the same data and assumptions as the baseline analysis for its starting point. Information is presented on how the deviations about the baseline values for each of the nine input variables are specified. The sensitivity analysis is based on Latin Hypercube techniques. The objective of the sensitivity analysis is to evaluate how uncertainty in the values of each of the nine input variables translates into changes in each of three key economic measures. The three economic measures evaluated in the sensitivity analysis are: (1) the present value of net savings due to BFRL's SLP-related investment costs; (2) the savings-to-investment ratio on BFRL's SLP-related investments; and (3) the adjusted internal rate of return on BFRL's SLP-related investments. These measures are particularly helpful in understanding BFRL's contribution, because each measure provides a different perspective. The first, the present value of net savings (PVNS) due to BFRL, is a magnitude measure; it shows a net dollar value to the public net of BFRL's SLP-related investments. The second, the savings-to-investment ratio (SIR) on BFRL's SLP-related investments, is a multiplier; it shows, in present value terms, how many dollars the public receives for each public dollar spent. The third, the adjusted internal rate of return (AIRR) on BFRL's SLP-related investments, is a rate of return; it shows the return on the public monies going into the development of SLP products and services throughout the 15-year study period.

The results of the sensitivity analysis show that, on average, the benefits outweigh the costs, demonstrated by a present value of net savings (PVNS) of $13.23 million, a savings to investment ratio (SIR) of 1.34, and an adjusted internal rate of return (AIRR) of 9.0 %. Not all simulations produced economic returns, however. The minimum simulated values are -$20.92 million PVNS, 0.46 SIR, and a -1.0 % AIRR. The simulation PVNS, SIR, and AIRR distributions are not symmetric, as the maximum values are much farther from the means than are the minimums. In addition, the means are larger than the medians (50 % percentile). The maximum simulated values are $87.76 million PVNS, 3.28 SIR, and a 19 % AIRR.

9.2 Suggestions for Further Research

The background work for this report uncovered additional areas of research that might be of value to government agencies and other institutions that are concerned with an efficient allocation of their research budgets. These areas of research are concerned with: (1) the development of standards related to service life prediction; (2) factors affecting the diffusion of new technologies; (3) cool roofs and the heat island effect; and (4) evaluations based on multiattribute decision analysis.

9.2.1 Research Leading to Standards

In service life prediction, one area dependent on future research is the development of standards. There is a need for methods for measuring service life prediction (SLP), protocols for evaluating new products before market introduction, protocols for maintaining and servicing new materials and building systems, computer and analytical tools for evaluating SLP, and standard economic methods for evaluating the cost effectiveness of new materials introduction. Using the types of standards published by ASTM, International as a guide, the following types of standards could be developed: guides, practices, test methods, terminologies, classifications, and adjuncts (including software, audiovisuals, spreadsheets, and other supporting materials). Research is needed to develop the underlying technical content, measurement methods, and tools to support the standards as well as expert contributions to the production of the standards themselves (including shepherding them through the standards approval process). Standards research is recommended in the following areas based on interactions with SLP stakeholders in the preparation of this report.

Measurement Standards for Deploying Improved Service Life Prediction Techniques

The SLP research team has established the scientific basis for the linkage between field and laboratory exposure results via a mechanistic model. This achievement represents a potential watershed both for future for SLP-related research and for the development of a suite of SLP-related standards. Prime topics for standards development include codification of advances in measurement science for coatings and sealants developed in collaboration with the two currently active industry consortia. A leading indicator of the potential for such a suite of SLP-related standards is the first performance-based ASTM Standard Test Method for Viscoelastic Characterization of Sealant Using Stress Relaxation. This standard is currently being balloted, and it is anticipated that it will be adopted in 2009. Knowledge gained through BFRL's sealant-related research, which is embodied in the draft standard, will benefit industry by: (1) significantly reducing sealant life-cycle costs and increasing material reliability; (2) reducing the need for expensive, time-consuming outdoor weathering measurements as a condition for consumer acceptance of commercial sealant products; and (3) enabling manufacturers to assign accurate warranties on sealants that are supported by robust scientific data. It is anticipated that other SLP-related standards will convey similar benefits to materials manufacturers, the owners and managers of industrial facilities and commercial/ residential buildings, the contractors that construct those facilities/buildings, and other key construction industry stakeholders.

The first step is to develop a roadmap for producing such a suite of SLP-related standards. The roadmap would include information on standards committees, their membership, the standards they have produced, their current standards-development activities, and a recommended strategy/ sequence for introducing any proposed SLP-related standards to those committees. The second step is to introduce the standards to the standards committees and shepherd them through the standardization process to final publication.

Standard Guide for EPDM Roof Maintenance

A major challenge to long-term satisfactory performance of EPDM roofs is appropriate maintenance. Even when installed well, thin-membrane EPDM roofs are subject to damage, and unless maintained, will prematurely fail. Management process models that help owners determine when and how to maintain roofs will help assure that roofs will have a long, useful life. Membranes can last much longer than seams, so seams have to be restored to keep the roof system performing properly. If owners had a defined protocol for servicing and maintaining their EPDM roofs, they could benefit from lower life-cycle costs of providing the roof; decreased costs of repairs and replacements; reduced loss of building use due to leaks; and reduced tenant dissatisfaction/inconvenience from using a building under repair.

The first step is research to develop management process models that would provide a protocol for maintaining an EPDM roof system over its expected useful life. The second step is to introduce the protocol to a standards committee and shepherd it through the standardization process to final publication as a standard guide.

Case Study of Improved Sealants for Use by Manufacturers and Customers in Choosing Sealants to Produce and Use.

Both manufacturers and customers are concerned about the life-cycle cost effectiveness of new, improved, but sometimes more expensive sealants being produced. The manufacturers want to be able to provide new sealants that are cost-effective and the customers want to choose sealants that are the most economical over their time horizon.

The required work would be to develop a case study of a representative problem requiring a choice between competing sealants/adhesives using the ASTM E 917 Life-Cycle Cost Standard Practice as a basis for the calculations, to incorporate the case study into an appendix of the E 917 standard, and then to shepherd it through the balloting process.

9.2.2 Factors Affecting the Diffusion of New Technologies

Reliable estimates of the data input values for the standardized evaluation methods cannot be made without some relatively sound basis for predicting the rate of diffusion and the ultimate level of adoption of a new technology. The rate of diffusion and the ultimate level of adoption of a new technology depend on many factors. Uncertainty about how a new technology will perform affects both its rate of diffusion and its ultimate level of adoption.

Two factors over which a research laboratory exerts some control and which have the potential to reduce uncertainty about new technologies are: (1) the research laboratory's information dissemination efforts; and (2) the research laboratory's participation in standards-making organizations. Additional research on these two factors is warranted for a number of reasons. First, the characteristics of information are changing dramatically. With the advent of the World Wide Web and the increased acceptance of electronic media, the fruits of research may be quickly and widely disseminated. The reliance on printed reports sent to a targeted audience as the sole vehicle for communication is being eclipsed by other means of information dissemination. This transition needs to be studied to ensure that the information dissemination strategy that emerges is tailored to the needs of the research laboratory's customer base. Second, research results in the form of technical reports often provide the basis for standards. Consequently, information dissemination efforts may be used to leverage private-sector activities aimed at standardization. Finally, standards are an important means for disseminating information on expected levels of performance and for measuring key performance characteristics (e.g., through the use of standard practices, specifications, and test methods). For new technologies, acceptance by a standards-making organization should lead both to higher rates of diffusion and to higher levels of adoption. Consequently, research on how a research laboratory's participation in standards-making organizations affects the rates of diffusion and levels of adoption of new technologies will enable it to improve the efficiency with which it allocates staff and other resources to these activities.

9.2.3 Cool Roofs and the Heat Island Effect

The primary benefit of cool roofs is the reduction in daytime cooling demands in buildings by limiting the amount of heat transfer through a building's roof to interior conditioned space. An additional benefit of cool roof technologies is the reduction in the urban heat island effect. The urban heat island effect occurs when the nighttime urban air temperature remains significantly higher than that of neighboring rural areas. Research has shown this effect can result in temperatures differentials as high as 22° F (12° C) depending on nighttime conditions.[98] Mostly heat, absorbed from the daytime sun, radiating from rooftops and pavement is responsible for the heat island effect. Cool roofs, then, provide a secondary benefit in that they reduce the amount of energy consumption required by evening cooling.[99] An additional consideration is the role of urban geometry, which is the spatial relationship (dimensions and spacing) of buildings that can produce urban canyons or configurations of buildings that limit nighttime cooling.[100] Future research could focus on measuring the impact improvements in service life prediction can have in reducing the urban heat island effect. Further, the interaction between urban geometry and cool roofs could be studied as well. For instance, how well do cool roofs reduce the urban heat island effect given a particular urban geometry, and do alternative geometries exist that enhance their effect? Because of spatial considerations, it may be that cooling the roof of one structure benefits the energy demands of neighboring, non-cooled roof buildings. If so, this demonstrates a third, albeit indirect, benefit of cool roof technologies.

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[98] Oke, T.R. 1987. *Boundary Layer Climates*. New York: Routledge. As cited in EPA 2009a.

[99] Environmental Protection Agency (EPA). 2009. Reducing Urban Heat Islands: Compendium of Strategies, *Urban Heat Island Basics*. Available at: http://www.epa.gov/heatislands/resources/pdf/CoolRoofsCompendium.pdf. Accessed by authors September 21, 2009.

[100] Environmental Protection Agency (EPA). 2009. Reducing Urban Heat Islands: Compendium of Strategies, *Urban Heat Island Basics*. Available at: http://www.epa.gov/heatislands/resources/pdf/BasicsCompendium.pdf. Accessed by authors September 21, 2009.

9.2.4 Evaluations Based on Multiattribute Decision Analysis

Many research investment alternatives differ in characteristics that decision makers consider important but that are not readily expressed in monetary terms. Because the standardized evaluation methods employed in this report consider only monetary benefits and monetary costs associated with alternative research investments, their application does not reflect the importance of these non-financial characteristics to the decision maker. When non-financial characteristics are important, decision makers need a method that accounts for these characteristics (also called attributes) when choosing among alternative research investments. A class of methods that can accommodate non-monetary benefits and costs is multiattribute decision analysis.[101]

The analytical hierarchy process (AHP) is one of a set of multiattribute decision analysis methods that considers non-financial characteristics in addition to common economic evaluation measures when evaluating project alternatives. The AHP has several important strengths: (1) it is well-known and well-reviewed in the literature; (2) it includes an efficient attribute weighting process; (3) it incorporates hierarchical descriptions of attributes; (4) its use is facilitated by available software; and (5) it has been accepted by ASTM as a standard practice for investments related to buildings and building systems.[102]

The AHP and its associated software represent a powerful and versatile management tool. How to apply this management tool most productively in a research environment suggests additional research. Specifically, how will the AHP be used to assess fit to mission, to set priorities, or to evaluate performance against some other management goal? If such research is conducted, the AHP-based tool which emerges will provide a format for: (1) efficiently and reliably screening and selecting among alternative research investments (e.g., by embedding information on research benefits and costs, information on fit to mission, and on research priorities) and (2) selecting research projects for in-depth analyses, either of the *ex ante* or *ex post* type of evaluation.

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[101] For more information on multiattribute decision analysis, see Norris, Gregory A., and Harold E. Marshall. 1995. *Multiattribute Decision Analysis Method for Evaluating Buildings and Building Systems.* NISTIR 5663. Gaithersburg, MD: National Institute of Standards and Technology.

[102] American Society for Testing and Materials. 2007. *Standard Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems*. E 1765. West Conshohocken, PA: American Society for Testing and Materials.

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Appendix A: Service Life Prediction Stakeholder Associations

This appendix is an annotation of stakeholder associations of polymeric materials that will be affected by improved service life prediction. Each entry includes the name of the association, the construction materials involved, the association's website, and a brief description of the association. Construction materials include sealants and adhesives, coatings, roofing, and miscellaneous. Information given in the brief description strongly correlates with stated missions and goals so that it accurately reflects the association's purpose. In some instances, parallel phrasing is drawn from the associations website to keep descriptions as close as possible to those stated by the organization. The summaries below also contain information on membership, organization, and activities of the association. If an association creates standards or certifications it is noted in the summary.

Associations were identified by product focus of the organization. For many of the associations listed, polymeric materials are the primary focus for the organization; however, this is not always true. Some associations focus on a broad topic such as roofing or flooring with subtopics that include polymeric materials. Although this annotation of stakeholder associations cannot encompass every stakeholder in polymeric materials, it does identify many of the prominent stakeholders.

American Architectural Manufacturers Association
Construction Materials: Sealants and Adhesives, Coatings, Roofing, Miscellaneous
Website: **http://www.aamanet.org/**
The American Architectural Manufacturers Association (AAMA) is a professional society that strives to address common issues in the architectural manufacturing industry. It brings together window, door, skylight, curtain wall, and storefront manufacturing companies of various sizes. The AAMA ensures quality standards by providing information on components of windows, doors, and other products that are tested and found to be in compliance with applicable specifications. The association is organized into eight industry-related product councils and five material councils. It works to bring codes and specifications in line with the current needs of the architectural community and the consumer. Information on codes, specifications, and compliance is disseminated through marketing committees, marketing programs, conferences, and publications targeted to industry professionals as well as consumers.

American Composites Manufacturing
Construction Materials: Sealants and Adhesives, Coatings, Roofing, Miscellaneous
Website: **http://www.acmanet.org/**
This professional society provides a forum for the composites industry to address common issues of composite manufacturing. Building and construction are among a number of uses for composites that the American Composites Manufacturing Association

(ACMA) focuses their attention. The organization promotes education and information dissemination through scholarships, grants, publications, and an annual composites show. Regulatory influence is done by working with policy makers and promoting dialogue about composites; this includes sponsoring the Congressional Composites Caucus. The ACMA's *Composites Manufacturing* magazine brings to light developments in the composites industry and promotes the growth of composites into new industries. There are a number of committees within the organization focusing on five topics: education and information, regulations and legislation, market expansion, submarkets, and operations. The ACMA also provides certification through its Certified Composites Technician Program.

Adhesion Society
Construction Materials: Sealants and Adhesives
Website: http://www.adhesionsociety.org/
The Adhesion Society is a professional society that promotes the advancement and dissemination of adhesion science and technology, through education and training, and provides recognition of accomplishments to the greater international adhesion community. The society was formed to provide a multidisciplinary forum to discuss adhesion issues. Membership includes participants from industry and academia, and has co-hosted meetings with other international adhesion societies. Current membership stands around 500. The society's annual meeting is structured around three topical divisions-Particle Adhesion Division, Pressure Sensitive Adhesion Division, Structural Adhesives Division-although the society's interest in adhesion science remains broader. The society publishes proceedings of a short-course, *Adhesion Science and Technology,* which provides participants with an introduction and overview of important topics in the field of adhesion.

Adhesives and Sealants Council
Construction Materials: Sealants and Adhesives
Website: http://www.ascouncil.org/
The Adhesives and Sealants Council is a professional society that promotes growth in the adhesives and sealants industry, disseminates information to the industry, delivers educational programs, and serves as an advocate in government affairs. In order to promote growth, the council conducts research on identifying industries that could potentially increase their use of adhesives and sealants. Information and research are disseminated through conventions, reports, and courses. As a part of the council, the Education Foundation Committee provides support for research and graduate courses at universities across the nation. There are 120 companies that are members of the Adhesives and Sealants Council.

American Floor Covering Alliance
Construction Materials: Coatings, Miscellaneous
Website: http://www.americanfloor.org/
The American Floor Covering Alliance (AFA) is a professional society that was formed to promote the floor covering industry. AFA is a not for profit association and promotes the industry's products and services and educates the members and others through seminars, press releases, and trade shows. The AFA promotes the business of its members and promotes the growth of the floor covering industry as a whole. The association is financially supported by membership dues and trade shows. The association is governed by a board of directors elected from within the membership.

American Plastics Council
Construction Materials: Coatings, Roofing, Miscellaneous
Website: http://www.americanplasticscouncil.org/s_apc/index.asp
The Plastics Division of the American Chemistry Council (ACC) is a professional society that represents manufacturers of plastic resins. It advocates opportunities for plastics and promotes their economic, environmental and societal benefits. To accomplish their mission they demonstrate the benefits of plastic products and the contributions of the plastics industry to the society it serves. The council focuses on four key plastics markets: Packaging and Consumer Products, Building and Construction, Automotive, and Electrical and Electronics. Their work on building and construction includes both residential and non-residential structures with a recent focus on green buildings. These plastics are used in roofing, walls, windows, piping, decks, and other building components.

Asphalt Institute
Construction Materials: Roofing
Website: http://www.asphaltinstitute.org/
This professional society promotes the use and development of petroleum asphalt through research, marketing, and education. Its members represent 90 % of the liquid asphalt industry in North America and it has a network of field engineers that provide technical support to member companies. There are a number of technical topic areas that the Asphalt Institute focuses on, one is roofing technical issues. The institute provides AASHTO accredited laboratory services for roofing asphalt proficiency. The institute also has an education program that includes several seminars while they also seasonally distribute an asphalt magazine for information dissemination.

Asphalt Roofing Manufacturers Association
Construction Materials: Roofing
Website: http://www.asphaltroofing.org/
This trade association advances the asphalt roofing industry through R&D support and promoting asphalt roofing to the greater public. This association represents 95 % of the

nation's manufacturers of bituminous-based roofing products and supports both asphalt roofing manufacturing companies and raw material suppliers. This type of roofing is used on both residential and non-residential structures. The organization provides a number of publications and information on asphalt roofing through their website. The information that the association gathers is provided to building and code officials along with regulatory agencies.

Association of the Wall and Ceiling Industry
Construction Materials: Roofing
Website: http://www.awci.org/
The Association of the Wall and Ceiling Industry (AWCI) represents acoustics systems, ceiling systems, drywall systems, exterior insulation and finishing systems, fireproofing, flooring systems, insulation, and stucco contractors, suppliers and manufacturers and those in allied trades. The association's membership includes 2200 companies and organizations related to the wall and ceiling industry. The mission of AWCI is to provide services and undertake activities that enhance the members' ability to operate a successful business. The AWCI Convention and INTEX Expo along with training programs, publications, and seminars provide a number of outlets for information dissemination.

Ceilings and Interior Systems Construction Association
Construction Materials: Coatings
Website: http://www.cisca.org
The Ceilings & Interior Systems Construction Association (CISCA) is an international trade association founded for the advancement of the interior commercial construction industry. CISCA's mission is to provide education and a forum for communication and interaction among its members. CISCA membership includes over 600 contractors, distributors, manufacturers and their representatives. Volunteer committees within the association include topics on membership, education, publications, technology, manufacturers advisory, distributors advisory, and strategic planning. Publications of CISCA include *Interior Construction* magazine, the Ceilings Systems Handbook, and other topical publications. CISCA's Annual Convention and INTEX Expo are primary outlets for information dissemination.

Center for the Polyurethanes Industry
Construction Materials: Sealants and Adhesives
Website: http://www.polyurethane.org/s_api/index.asp
The Center for the Polyurethanes Industry (CPI) is a professional society that promotes the sustainable growth of the polyurethane industry. The center has areas of focus on the environment, health, safety, energy efficiency, and standards relating to the polyurethane industry. Each of these topics has environmental subtopics that focus on green building and sustainability. The center disseminates information through education, publications, and the annual Polyurethane Conference. Its members include U.S. producers or

distributors of chemicals and equipment used to make polyurethane or manufacturers of polyurethane products.

Composite Panel Association
Construction Materials: Coatings, Roofing
Website: http://www.pbmdf.com/
The Composite Panel Association (CPA) is a professional society that is a North American trade association for producers of particleboard (PB), medium density fiberboard (MDF), hardboard (HB) and other compatible products. It is dedicated to increasing the acceptance and use of composite panel products and educating users about their benefits. CPA represents the composite panel industry on technical, environmental, quality assurance and product acceptance issues. Current membership includes 37 of the leading US and Canadian producers of composite panels, collectively representing over 95 percent of total North American manufacturing capacity. The CPA accredited laboratories conduct product testing along with third-party certification programs.

Construction and Agricultural Film Manufacturers Association
Construction Materials: Coatings, Roofing
Website: http://www.cafma.org/
This organization is a national trade association for polyethylene sheeting products used in construction, agriculture, and industry. These products are used as protection from the elements and as a vapor barrier in buildings. The CAFMA SEAL appears on products that are regularly inspected under its certification program that includes random, in plant tests. CAFMA'S independent professional inspector's field test polyethylene film to ensure that products meet or exceed established standards for length, width, gauge, and weight. Tests are unannounced and performed at each manufacturing site. Only products that pass the test may display the CAFMA SEAL.

EIFS Industry Members Association (EIMA)
Construction Materials: Coatings, Roofing
Website: http://www.eima.com/
The EIFS Industry Members Association (EIMA) is a national technical trade association comprised of more than 400 manufacturers, suppliers, distributors and applicators involved in the exterior insulation and finish systems (EIFS) industry. EIFS are multi-layered exterior wall systems for residential and non-residential buildings. EIMA's mission is the advancement and growth of the EIFS Industry through standards development, education, and communication. Various standards on EIFS provided on their website outline standard installation and development of these exterior wall systems.

EPS Molders Association (EPSMA)
Construction Materials: Miscellaneous
Website: **http://www.epsmolders.org/**
EPS Molders Association is a professional society that promotes the advancement and growth of innovative building technologies relating to expanded polystyrene (EPS). They strive to provide the construction industry with the latest information on EPS products. The association has two stated goals: educate and inform building professionals on the use of EPS products and affect EPS markets by informing the public about its uses and applications. EPS has become a product often used in green building practices. It can be used as insulation in walls, roofs, and foundations in addition to being a component in structural insulated panels, insulated concrete forms, and exterior and insulating form systems. It has also been utilized in other applications such as flotation devices, cold storage, and geofoam. In addition to their website, the association hosts an annual expo for the purpose of disseminating information.

Fiberglass Tank and Pipe Institute
Construction Materials: Miscellaneous
Website: **http://www.fiberglasstankandpipe.com/**
This professional society aims to advance the fiberglass reinforced thermoset plastic industry by promoting the use of all fiberglass products in the tank and piping marketplace. The institute provides information on standards and regulations related to fiberglass tanks in addition to organizing studies, collecting data, and disseminating information to the government and industry. Many of the publications produced by the institute are available on their website.

Floor Covering Installation Contractors Association
Construction Materials: Coatings, Miscellaneous
Website: **https://www.fcica.com/**
The Floor Covering Installation Contractors Association's mission is to help train, inform, and unite floor covering professionals throughout the nation. They provide access to other members through committees and meetings while also disseminating information through a conference and convention. Floor covering installation training is available through the association as well as technical assistance and guides.

Flooring Installation Association of North America
Construction Materials: Coatings and Miscellaneous
Website: **http://www.fiana.org/html/Home.htm**
Floor Installation Association of North America (FIANA) is a professional society whose members are manufacturers and distributors located in Canada and the United States. The objective of the association is to provide "professionalism through education" and is currently developing a training program for sales, marketing, and product knowledge.

The annual FIANA Convention and Trade Show provides an outlet for information dissemination.

Geosynthetic Materials Association
Construction Materials: Miscellaneous
Website: http://www.gmanow.com/
This professional society serves as a resource for information on geosynthetics, which are polymeric products often used for separation, reinforcement, filtration, drainage, and containment. The associations activities are focused on five areas: engineering support, business development, education, government\industry relations, and geosynthetic industry recognition. It works with government agencies and private industry to educate the public on geosynthetics and engineering applications. The organizations Geosynthetics magazine provides an outlet for information dissemination for the industry as does the *Geosynthetics* conference that the association hosts.

Insulation Contractors Association of America
Construction Materials: Miscellaneous
Website: http://www.insulate.org/
The Insulation Contractors Association of America (ICAA) is a professional society that supports insulation contractors. The association provides an opportunity for contractors to advance the insulation industry through information dissemination in committees and other specialized workshops. Additionally, each year the ICAA hosts a convention and a trade show.

Manufactured Housing Research Alliance
Construction Materials: Sealants and Adhesives, Coatings, Roofing, Miscellaneous
Website: http://www.mhrahome.org/pages/home.htm
The Manufactured Housing Research Alliance (MHRA) is an organization with the mission of developing new technologies to enhance the quality and performance of the nation's manufactured and modular homes. MHRA's research supports the industry by developing new methods for using factory built homes in housing applications by solving technical challenges and by supporting innovations in home design, construction, and installation. To carry out its mission, MHRA develops, tests, and promotes better methods and materials for designing, manufacturing, and marketing factory built homes. These activities include research, new product development, training and educational programs, testing programs and demonstrations, commercialization efforts, workshops, conferences and other events. Some of the current projects of MHRA include conducting research on construction and manufacturing technologies, energy efficiency, health and safety, expansion of the market, and installation practices.

National Floor Safety Institute
Construction Materials: Coatings, Miscellaneous
Website: http://www.nfsi.org/
The National Floor Safety Institute (NFSI) was founded in 1997 with the mission to aid in the prevention of slip-and-fall accidents through education, training and research. The NFSI is led by a Board of fifteen Directors representing product manufacturers, insurance underwriters, trade associations, and independent consultants. NFSI product certification

National Paints and Coatings Association | Federation of Societies for Coatings Technology
Construction Materials: Coatings and Sealants
Website: http://www.coatingstech.org/
The Federation of Societies for Coatings Technology (FSCT) provides educational, development, and networking opportunities relating to the coatings industry. Currently the members are by individual rather than by company; however, the FSCT is currently merging with the National Paints and Coatings Association which has membership by both organization and individual. The FSCT is made up of 26 constituent societies located in the U.S., Canada, Mexico, and the United Kingdom. It hosts the International Coatings Expo (ICE), the CoatingsTech Conference, and topic specific conferences including virtual learning conferences. The *Journal of Coatings Technology and Research* along *with JCT CoatingsTech* provide outlets for information dissemination. The NPCA has a number of programs to promote and advance the paint and coatings industry. These include health, safety, environmental, and security related programs as well as strategy programs. The American Coatings Conference and show along with various virtual conferences and topic specific conferences hosted by the NPCA provides an outlet for information dissemination.

National Roofing Contractors Association
Construction Materials: Roofing
Website: http://www.nrca.net/
The National Roofing Contractors Association (NRCA) is a professional trade association that supports the roofing industry. It gathers information on the roofing industry and practices to distribute to industry producers and distributers along with consumers and code officials. The NRCA's mission is to "inform and assist" the roofing industry, act as an advocate, and aid in serving customers. There are 4000 members in the NRCA. The NRCA sponsors the annual *International Roofing Expo*, which provides an outlet for information dissemination.

North American Association of Floor Covering Distributors
Construction Materials: Miscellaneous
Website: **http://www.nafcd.org/**
The National Association of Floor Covering Distributors (NAFCD) was organized to promote trade and commerce for wholesale distributors or manufacturers of floor covering products; these include tile products, carpet, cushion/padding, rugs, ceramic tile, installation accessories, wood flooring, rubber flooring, and high pressure laminates. As a professional society, NAFCD disseminates information through educational services and by hosting an annual meeting. The association focuses on four main topics: leadership, networking, education, and trends.

North American Insulation Manufacturers Association
Construction Materials: Miscellaneous
Website: **http://www.naima.org/**
The North American Insulation Manufacturers Association (NAIMA) is a trade association of North American (United States, Canada and Mexico) manufacturers of fiber glass, rock wool, and slag wool insulation products. NAIMA members represent the vast majority of these types of products. The organization and its predecessor associations have been committed to rendering services to all segments of the construction industry. The organization communicates current and new issues on energy efficiency and sustainable development. Product committees include air handling, residential and commercial insulation, commercial and industrial, and metal buildings.

Paint and Decorating Retailers Association
Construction Materials: Coatings
Website: **http://www.pdra.org/index.php**
The Paint and Decorating Retailers Association (PDRA) supports independent paint and decorating dealers while advancing the relationships between dealers and suppliers. PDRA provides members with information, sales, training, and business operations programs. The association often has product-specific, sales-oriented seminars for product dealers. It also offers general courses such as the PDRA Coatings Specialist, Managing Your Business for Success, Certified Faux Consultant, and Industrial Paint and Coatings Consultant courses. These courses along with the PDRA monthly trade magazine provide an outlet for information dissemination.

Plastics Pipe Institute
Construction Materials: Miscellaneous
Website: **http://www.plasticpipe.org/index01.php**
The Plastics Pipe Institute (PPI) is an association dedicated to the advocacy and advancement of polyethylene pipe; the mission of the institute is to make plastics the material of choice for all piping applications. Topics of focus include water systems, drainage, fuel gas, conduit, and plumbing and heating applications. PPI members share a

common interest in broadening market opportunities that make effective use of plastics piping for water and gas distribution, sewer and wastewater, oil and gas production, industrial and mining uses, power and communications, and duct and irrigation. The PPI semi-annual meeting provides an outlet information dissemination along with reports it has developed on design, operation, and manufacture of polyethylene pipes.

Polyisocyanurate Insulation Manufacturers Association
Construction Materials: Roofing, Miscellaneous
Website: http://www.polyiso.org/
The Polyisocyanurate Insulation Manufacturers Association (PIMA) is a national trade association that represents polyiso insulation manufacturers and suppliers. Polyiso is a closed-cell, rigid foam board insulation used primarily on the roofs of offices, health facilities, warehouses, retail facilities, industrial manufacturing facilities, and educational institutions. Because of its high thermal performance in the home building market, it is promoted for energy-aware homebuilders and consumers. PIMA plays a role in education, product development, and relevant legislation along with disseminating information through meetings and publications.

Polyurethane Foam Association
Construction Materials: Miscellaneous
Website: http://www.pfa.org/
The Polyurethane Foam Association (PFA) educates customers and other groups about flexible polyurethane foam (FPF) and promotes its use in manufactured and industrial products. This includes providing facts on environmental, health and safety issues related to FPF to members of the organization, flexible polyurethane foam users, regulatory officials, business leaders and the media. PFA also provides its members and their customers with technical information on the performance of FPF in consumer and industrial products. Information dissemination is achieved through bi-annual meetings along with various publications and education materials.

PVC Pipe Association
Construction Materials: Miscellaneous
Website: http://www.uni-bell.org/
Uni-Bell is a professional society that provides considerable time and resources to the engineering, regulatory, public health and standardization communities within the PVC pipe industry. Uni-Bell provides pipe designers and installers with research regarding pipe deflection, ultraviolet aging, tapping, cyclic surge performance, in-service durability, safety, and many other topics of interest to the user community. Uni-Bell is an active entity in the development of PVC pipe standards and specifications through its technical literature and research. One such document is the Uni-Bell Handbook of PVC Pipe: Design and Construction, which is an extensive text on PVC pipes and fittings. Uni-Bell's

professional service offers an electronic version of the Handbook, design software, and instructional videos.

Resilient Floor Covering Institute
Construction Materials: Miscellaneous
Website: http://www.rfci.com/
The Resilient Floor Covering Institute (RFCI) is an industry trade association of North American manufacturers who produce resilient flooring products. Associate members of RFCI supply raw materials to the resilient flooring industry and manufacture installation and maintenance products. The institute was established to support the interests of the total resilient floor covering industry and the people who use its products. Objectives include: Promoting the use of resilient floor covering as a product category; Monitoring and responding to federal, state and local legislation and regulations that affect the industry and its products; Developing guidelines for products, installation, maintenance and related subjects to ensure the continued quality of resilient products; and Providing technical information and data on the resilient flooring industry.

Roof Coatings Manufacturers Association
Construction Materials: Roofing
Website: http://www.roofcoatings.org/
The Roof Coatings Manufacturers Association is a national trade association representing manufacturers of cold-applied coatings and cements used for roofing and waterproofing; it also represents the suppliers of products, equipment, and services for the industry. Cold-applied roofing system generally refers to solvent-borne bituminous adhesives and multiple plies of reinforcement. Founded in 1983, RCMA advances product technology to ensure an ongoing supply of quality energy-efficient materials meet the needs of contractors, consumers and the environment. Topical publications and meetings are frequently organized for information dessimination. RCMA currently has more than 70 member companies.

RCI, Inc.
Construction Materials: Roofing
Website: http://www.rci-online.org
RCI, Inc., formally known as the Roof Consultants Institute (RCI), "is an international association of professional consultants, architects, and engineers that specialize in the specification and design of roofing, waterproofing and building envelope systems." The mission of RCI, Inc. is to ensure the credibility of the roofing, waterproofing, and building envelope consulting professions. The membership of RCI, Inc. includes over 2500 individuals. The association often hosts educational programs on a number of topics and has developed a technical library for the purpose of information dissemination. RCI, Inc. also provides certifications as a Registered Roof Consultant, Registered Waterproofing Consultant, and Registered Roof Observer.

Sealant Waterproofing and Restoration Institute
Construction Materials: Sealants and Adhesives, Coatings
Website: http://www.swrionline.org/
The Sealant, Waterproofing and Restoration Institute (SWRI) is a trade organization with more than 230 commercial contractors, manufacturers and consultants. It provides a forum for information dissemination for those engaged in "the application, design and manufacture of sealant, waterproofing and restoration products." A bi-annual technical meeting hosted by SWRI along with a number of online publications and resources provides additional outlets for information sharing. Participants receive an opportunity to learn about trends, new products, exchange ideas, and discuss new methods of application. The SWRI validation program provides reassurance of the performance of sealant and coating products through laboratory tests.

Society of Protective Coatings
Construction Materials: Coatings
Website: http://www.sspc.org/
The Society of Protective Coatings (SSPC) is a professional association that is focused on the protection and preservation of concrete, steel, and other industrial and marine structures and surfaces through the use of high-performance industrial coatings. SSPC provides information on surface preparation, coating selection, coating application, environmental regulations, and health and safety issues that affect the protective coatings industry. The association develops coating standards, publications, training and certification courses, and online publications. A number of web resources provided on their website provide assistance to members and non-members. Meetings and conferences hosted by SSPC provide an outlet for information dissemination. The association has 7221 individual members, 740 organizational members, and 33 staff members.

Vinyl Siding Institute
Construction Materials: Miscellaneous
Website: http://www.vinylsiding.org/
The Vinyl Siding Institute (VSI) is a trade association for vinyl and polymeric siding manufacturers and suppliers. It provides a vinyl siding product certification program as well as an installer certification program. Certified products and installers can be accessed through the VSI website. Other resources on the association's website provide information on installation and product details.

World Floor Covering Association
Construction Materials: Miscellaneous
Website: http://www.wfca.org/
The World Floor Covering Association (WFCA) is a professional association that provides consumers with information, service, and support. The association includes

members of carpet, hardwood, laminates, ceramics, porcelain, vinyl, cork, and stone floor producers and distributors. The WFCA provides information on the different types of floors along with information on green flooring solutions.