Research Report

Understanding the Economic Benefit Associated with Research and Services at the National Institute for Occupational Safety and Health

An Approach and Three Case Studies

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Preface

This report presents and illustrates an approach for estimating economic benefit of research and services at the National Institute for Occupational Safety and Health (NIOSH), using three case studies. Although no set of three case studies can be regarded as fully representative, we selected the cases to represent important variations in NIOSH activities and intended audiences. The report might be of interest to anyone seeking to understand the impacts of research, services, and practice related to worker safety and health. RAND Corporation researchers have published the following related reports:

- Eric Landree, Hirokazu Miyake, and Victoria Greenfield, *Nanomaterial Safety in the Workplace: Pilot Project for Assessing the Impact of the NIOSH Nanotechnology Research Center*, Santa Monica, Calif.: RAND Corporation, RR-1108-NIOSH, 2015
- Valerie L. Williams, Elisa Eiseman, Eric Landree, and David M. Adamson, *Demonstrating and Communicating Research Impact: Preparing NIOSH Programs for External Review*, Santa Monica, Calif.: RAND Corporation, MG-809-NIOSH, 2009.

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RAND Infrastructure Resilience and Environmental Policy

The research reported here was conducted in the RAND Infrastructure Resilience and Environmental Policy program, which performs analyses on urbanization and other stresses. This includes research on infrastructure development; infrastructure financing; energy policy; urban planning and the role of public–private partnerships; transportation policy; climate response, mitigation, and adaptation; environmental sustainability; and water resource management and coastal protection. Program research is supported by government agencies, foundations, and the private sector.

RAND Justice, Infrastructure, and Environment (JIE) conducts research and analysis in civil and criminal justice, infrastructure development and financing, environmental policy, transportation planning and technology, immigration and border protection, public and occupational safety, energy policy, science and innovation policy, space, telecommunications, and trends and implications of artificial intelligence and other computational technologies.

Questions or comments about this report should be sent to the project leader, Benjamin M. Miller (Benjamin_Miller@rand.org). For more information about RAND Infrastructure Resilience and Environmental Policy, see www.rand.org/jie/irep or contact the director at irep@rand.org.

Contents

Tables

Summary

Research impact is often assessed through statistical analysis of scientific publications citing the work or through qualitative assessments by subject-matter experts. However, such assessments seldom estimate the economic benefit associated with particular research investments in terms of lives saved, injuries or illnesses averted, or increases in worker productivity maintained. The National Institute for Occupational Safety and Health (NIOSH) asked the RAND Corporation to develop and illustrate an approach for estimating the economic benefit of NIOSH research, using three case studies. The cases provide concrete illustrations of the ways in which NIOSH research might have an impact on worker health and safety practices and outcomes, as well as some initial estimates of the economic benefit associated with those impacts.

We selected the case studies to illustrate variation in types of NIOSH research and in intended users. The first case study examines research to develop, test, and support implementation of engineering control measures to limit exposure to silica among road construction workers and offers an example of NIOSH's intervention and surveillance research and provision of technical assistance. The second case study involves two NIOSH studies that strengthened the evidence base about the linkage between firefighting activities and increased risk of certain cancers among firefighters and provides an example of etiological and exposure surveillance research, coupled with an intervention study. The third case study involves a NIOSH evaluation of the effectiveness of Ohio's Safety Intervention Grant Program and implementation of safety-oriented engineering controls by employers and illustrates intervention research targeting government organizations. The research in the first and second case studies led to the development of control technologies, and all three case studies involved dissemination and stakeholder engagement efforts that promoted the adoption of risk-reducing technologies and practices.

Assessing the economic benefit of such research requires assigning a dollar value to prevented injuries, illnesses, or deaths using risk-reduction measures derived from the research; determining whether such risk-reduction measures might have occurred without the research in question; and determining whether a particular entity (e.g., NIOSH) made a significant contribution to any resulting benefits. Doing so is fraught with difficulties, including the fact that the benefits of research can occur many years in the future, the absence of natural market price mechanisms for many outcomes, and the difficulty of assessing the contributions of research by any one organization, such as NIOSH, to any observed benefits. The case studies walk the reader through a transparent set of logical steps, marshaling quantitative estimates where possible, and providing transparent discussion about our assumptions where such evidence is not available.

The study employed two common approaches to estimating the economic benefit of avoided injuries, illnesses, and fatalities. The first involves estimating associated medical costs and productivity losses, which is often useful in addressing questions related to budgeting for medical care and other costs. However, where there were gaps in available cost data, we employed a second approach, which expresses benefit in terms of value of a statistical life (VSL) and attempts to take a broader societal perspective than the first approach and value all costs to society, whether "on budget" or not. Given this approach's broader scope, VSL estimates tend to be significantly larger than medical costs. With that in mind, the key findings for each case study are as follows:

- In the silica case, we examined the economic value associated with research conducted in partnership with industry and labor to develop, test, and support implementation of engineering controls to limit road construction workers' exposure to silica dust. Based on the willingness-to-pay and VSL estimates for risk reductions in fatal and nonfatal illnesses, the economic value ranges from $304 million to $1.1 billion on an annualized basis, with a midpoint estimate of $692 million per year. Using a separate medical cost approach, we estimate that NIOSH's activities contributed to $4.9 million in avoided medical and productivity losses on an annualized basis for fatal lung cancers.[1] We did not have sufficient data to monetize benefits for other fatal and nonfatal diseases associated with exposure to crystalline silica in terms of medical cost and productivity losses.
- In the firefighter case study, we examined the economic benefit stemming from two NIOSH research publications that support development of personal protective equipment and other control measures to reduce firefighters' exposure to hazardous materials during and after fires. We estimate that resulting reductions in mortality and morbidity would reduce medical costs and productivity losses by $71 million per year, with a range of $23 million to $93 million, depending on assumptions about reduction in risk and adoption of control measures. VSL estimates are broader, capturing individuals' subjective willingness to pay to avoid the loss of life, health, quality of life, and other factors. Thus, estimates using VSL instead of medical costs and productivity losses are significantly higher. Using VSL, we estimate benefits of approximately $1 billion.
- Finally, in the Ohio safety intervention grant case study, we examined avoided workers' compensation costs, productivity gains, and avoided uncompensated wage losses. We find that, to date, the main benefit of the NIOSH study was the expansion of Ohio's grant program, although the creation of similar, smaller programs in Missouri and Texas has also provided benefits. Our analysis does not consider the total benefits of the NIOSH research in that other states could still be inspired to create similar programs in response to the NIOSH work. More than with the other case studies, the impacts of this work are still developing. Nevertheless, we find evidence that, between 2013 and 2017, NIOSH research has been associated with $4 million to $7 million per year in avoided workers'

[1] Medical and indirect cost estimates for other illnesses, such as other nonmalignant respiratory diseases (including silicosis) and end-stage renal disease, were not available. Thus, this figure underestimates the overall benefits. In our analysis, lung cancers account for approximately four fatalities per year, out of a total of 22 avoided fatal cases and 77 avoided nonfatal cases per year.

compensation costs, $7 million to $11 million in new streams of annual productivity gains per year, and almost $700,000 to more than $16 million in avoided uncompensated wage losses per year.

There are limitations to this analysis. First, given limitations in available data, we found it necessary to make some important assumptions in order to derive estimates of the economic benefit. Where we did this, we explained the logic behind the assumption and, in many cases, conducted sensitivity analyses to clearly show the reader how different assumptions might affect the estimated benefit. Second, the reader should bear in mind that differences in estimated benefit reflect differences not just in effectiveness but also in maturity of the field and the state of prior knowledge. Adjusting our estimates based on such differences among our three case studies was beyond the scope of this study. Third, providing estimates of costs, which are necessary for determining whether benefits are "large enough," was beyond the scope of this analysis.[2] A final caution is that, given the project timeline, we selected the three case studies in part because of data availability. Hence, although the findings might help stimulate discussion, they do not provide a definitive assessment of NIOSH's overall impact.

In spite of these limitations, the value of this analysis lies in illustrating some specific ways in which NIOSH research can produce economic benefits, providing some sense of the likely magnitude of these benefits in dollar terms, and providing an analytical framework on which others can build in future work.

In the future, NIOSH should consider conducting additional case studies to explore other types of research and intended audiences and that account for the costs of producing and implementing research. In addition, it should consider examining cases in which the linkages between its research and safety and health improvements are less clear because there can be important lessons from cases of unrealized impact. Finally, NIOSH should consider ways in which it might start to fill some of the gaps in data and analysis encountered while conducting this economic analysis.

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[2] NIOSH provided us with preliminary, unpublished estimates of NIOSH's (but not NIOSH's partners') costs to produce the research described in this study and indicates that it plans to provide final estimates in a companion piece to this report. Preliminary estimates are $2.2 million for the silica case, $2.4 million for the firefighter case, and $0.5 million for the Ohio safety intervention grant case. Given the project timeline, we were not able to evaluate these estimates systematically.

Acknowledgments

This study could not have been completed without the willingness of National Institute for Occupational Safety and Health staff and stakeholders to give generously of their time. In particular, we thank Regina Pana-Cryan and P. Timothy Bushnell, who helped ensure that we had timely access to key documents and stakeholders. We also thank Philip Armour of RAND and John Mendeloff of RAND and the University of Pittsburgh for providing careful reviews of earlier drafts, Nicholas Burger for helpful advice throughout the project, and Kristin J. Leuschner for writing and editorial assistance.

Abbreviations

BLS	U.S. Bureau of Labor Statistics
BWC	(Ohio) Bureau of Workers' Compensation
CDC	Centers for Disease Control and Prevention
CDC WONDER	Centers for Disease Control and Prevention Wide-Ranging Online Data for Epidemiologic Research
CI	confidence interval
C/P	command and pump operation
CWCS	Center for Workers' Compensation Studies
ESRD	end-stage renal disease
FSRI	Underwriters Laboratories Firefighter Safety Research Institute
FTE	full-time equivalent
FY	fiscal year
GDP	gross domestic product
HI/HO	*Healthy In, Healthy Out*
IAFF	International Association of Fire Fighters
IARC	International Agency for Research on Cancer
IFSI	Illinois Fire Service Institute
MEM	Missouri Employers Mutual
NAPA	National Asphalt Pavement Association
NASI	National Academy of Social Insurance
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
NPRM	notice of proposed rulemaking
OMB	Office of Management and Budget
OSH	occupational safety and health
OSHA	Occupational Safety and Health Administration
PAH	polycyclic aromatic hydrocarbon
PEL	permissible exposure limit
PPE	personal protective equipment
SCBA	self-contained breathing apparatus
TWA	time-weighted average
VSL	value of a statistical life
WTP	willingness to pay

Chapter One. Introduction

The National Institute for Occupational Safety and Health (NIOSH), which is part of the Centers for Disease Control and Prevention (CDC), was established to help ensure safe and healthful working conditions by providing research, information, education, training, and other services in occupational safety and health (OSH) (CDC, 2016a).[1] NIOSH conducts research through ten sector programs and seven cross-sector programs and has 20 "core and specialty programs" that are distributed throughout its various divisions, laboratories, and offices. Research priorities are based on the number of workers at risk for a particular injury or illness, the seriousness of a hazard or problem, and the likelihood that new data or approaches can make a difference (CDC, 2017e). NIOSH not only conducts its own research but also funds research by others and undertakes efforts to translate research findings into workplace practices and policies. It does this by identifying, developing, and testing engineering controls, personal protective equipment (PPE), and other technologies. It also publishes health hazard reviews, distributes guidelines on both risks and remedies, and conducts training.

There are challenges in understanding the benefits associated with this or any agency's research activities. The first is that the benefits of research can occur many years in the future. Also, it is often difficult to determine whether NIOSH made a significant contribution to valued outcomes above and beyond those of other entities. Indeed, much of the institute's work is "coproduced" through partnerships with OSH consultants, universities, insurance company loss control departments, and employers. The research's impact generally occurs when organizations and individuals use the products and services provided by NIOSH, so it might not be visible from an examination of NIOSH's activities alone. A final challenge is that, because NIOSH is a public institute working for the common good, there is often no market price mechanism to allow the easy assessment of the economic benefit of NIOSH's work to society.

Standard methods for assessing the impact or contribution of research efforts to desired outcomes include bibliometrics (i.e., statistical analysis of references to an organization's scientific publications), portfolio assessments involving subject-matter experts (for example, see CDC, 2016c), and case studies that describe the benefits of research in qualitative terms. Such methods can be useful for assessing the overall progress of NIOSH's research and development toward achieving desirable benefits, but they typically are not well suited to estimate the

[1] The main legislative underpinnings of NIOSH are the Federal Coal Mine Health and Safety Act of 1969 (Pub. L. No. 91-173, amended by Pub. L. No. 95-164 in 1977) (also called the Coal Act) and the Occupational Safety and Health Act of 1970 (Pub. L. No. 91-596) (also known as the OSH Act). The Occupational Safety and Health Administration (OSHA), which was also established as part of the OSH Act, is a separate organization in the U.S. Department of Labor that is responsible for developing and enforcing workplace safety and health regulations.

economic value associated with particular research investments in terms of lives saved, injuries or illnesses averted, or worker productivity maintained. Thus, NIOSH asked the RAND Corporation to develop an approach for estimating the economic benefit of its research activities and illustrate its use through three exploratory case studies.

NIOSH's Role in This Study

Before describing the case studies and the approach used to analyze them, we note, in the interest of transparency, NIOSH's role in this study. Given the institute's decisionmaking needs, we conducted the project on a short timeline, with the bulk of the analysis taking place during August, September, and October 2017. For this reason, we needed to focus on examples of research for which data and stakeholders (i.e., for interviews) were readily available, and we needed to rely heavily on NIOSH staff to facilitate access to both. Throughout, we considered suggestions made by NIOSH and incorporated these into the analysis and report, where deemed appropriate. However, we alone developed the methodology and conducted the analysis, and the terms of the contract for this project gave us full editorial authority over the content of the report. We also note that NIOSH decided early on to have a staff member on the project recuse himself from a case study in which he had been personally involved.

In the remainder of this chapter, we describe the selection and analysis of the cases, noting NIOSH's role in this process where relevant.

Selection of the Three Case Studies

The case selection process began with NIOSH providing reports and other documentation to help the RAND team understand the full range of NIOSH research activities. Although NIOSH works on issues related to a wide variety of sectors and outcomes, its research activities can be characterized along two dimensions. The first is defined by *the types of NIOSH activities being performed* (i.e., what is NIOSH doing?) and includes providing technical assistance; conducting etiological research; conducting intervention research; conducting surveillance research; developing research methods and equipment; convening stakeholders; building capacity and training; and developing policy and guidance. The second dimension is defined by *the types of stakeholders who might use the outputs or results from NIOSH's research activities to make improvements in safety and health.* These include workers and employers; equipment manufacturers; finance and insurance organizations; labor unions, associations, and advocacy organizations; training and education organizations; government organizations; and other research organizations.[2]

To narrow the set of possible case studies, NIOSH provided us with a list of research projects or topics related to its construction, personal protective technology, and surveillance programs from which to identify possible case studies. In addition, we reviewed materials related to the National Academies of Sciences, Engineering, and Medicine evidence packages (CDC, 2016c) for the construction and personal protective technology programs to see whether we could identify any additional potential case studies. Given the exploratory nature of the project and its short timeline, we looked for projects that had clear and documented connections between NIOSH activities and any intermediate or end outcomes (i.e., reduction in workplace injuries, illnesses, or fatalities) and, as mentioned above, focused on cases with readily accessible data. Using this information, we and NIOSH jointly identified a list of nine candidate topics for case studies, from which we selected three case studies that, in the judgment of the research team and NIOSH staff, represent some of the key differences along these dimensions. In this section, we briefly describe these cases.

Case Study 1: Supporting Development of Silica Controls in Asphalt Pavement Milling

This case study focuses on NIOSH research conducted in partnership with industry and labor to develop, test, and support implementation of engineering controls to limit road construction workers' exposure to silica. Although silica is harmless in many settings, inhaling respirable-sized particles of crystalline silica can lead to silicosis, lung cancer, and kidney and autoimmune disease (International Agency for Research on Cancer [IARC], 1987). For this analysis, we estimate the economic benefit of ventilation control measures and water sprays developed for asphalt milling machines based on NIOSH research. The case study illustrates NIOSH conducting intervention and surveillance research, providing technical assistance, and convening stakeholders. The recipients of NIOSH intervention and surveillance research findings included construction workers, employers, equipment manufacturers, construction industry associations, other government organizations, and other researchers.

Case Study 2: Building and Disseminating Evidence on Firefighters' Cancer Risk

This case study estimates the economic benefit stemming from two NIOSH research publications that strengthened the evidence base about the linkage between firefighting activities and firefighters' increased risk of contracting certain cancers. Subsequently, stakeholders have taken actions to reduce occupational exposure to remnants of carcinogenic materials burned in

[2] We developed these categories based on NIOSH's strategic goals and objectives (CDC, 2016a) and recent work that RAND had done to develop a logic model for the NIOSH Nanotechnology Research Center (Landree, Miyake, and Greenfield, 2015). We then refined the categories through discussions with NIOSH.

fires through the use of PPE and other control measures, including increasing the use of respirators during postfire overhaul operations—that is, those that begin just after a fire has been brought under control and focus primarily on identifying and eliminating any remaining fire or other hazards. The case study illustrates NIOSH conducting etiological, intervention, and surveillance research and is targeted to workers (i.e., firefighters), employers (e.g., fire departments and fire houses), equipment manufacturers, firefighter associations and advocacy organizations, and other researchers and research organizations.

Case Study 3: Assessing and Disseminating Impacts of Ohio Safety Intervention Grants

This case study focuses on NIOSH research to evaluate the effectiveness of Ohio's Safety Intervention Grant Program, which offers matching funds to employers that agree to implement safety and health engineering control measures to reduce acute accidents, airborne contaminants, and risk factors for work-related musculoskeletal disorders. The case study examines research that was used to justify an expansion of Ohio's program and appears to have encouraged other states to adopt the interventions. It provides an illustration of NIOSH conducting intervention research intended for use by government organizations.

Our Approach to Analyzing the Cases

Attempts to place an economic benefit on research must first estimate the economic benefit of preventing deaths, illnesses, or injuries using risk-reduction measures derived from the research. In this report, we use two common approaches to estimating the economic benefit of avoided injuries, illnesses, and fatalities. The first involves estimating associated medical costs and productivity losses. This approach is widely used in economic valuation, especially for nonfatal conditions, and is often most useful in addressing questions related to budgeting for medical care and other costs. We sought to express all benefits in this study using medical costs and productivity losses. However, where there were gaps in available cost data, we employed a second approach, which expresses benefit in terms of the value of a statistical life (VSL). This approach attempts to take a broader societal perspective than the first approach and to value all costs to society, whether "on budget" or not. In practice, it does this by assessing individuals' subjective willingness to pay (WTP) to avoid the loss of life, health, quality of life, or other harms. The Office of Management and Budget (OMB) mandates the WTP approach for regulatory analysis, and, for many federal agencies, WTP is a standard approach. OMB recommends that rulemaking agencies assume that the value of saving one life is between $1 million and $10 million (OMB, 2003). However, important questions remain about VSL estimates of the value of avoided deaths,[3] and there is less consensus on how to value efforts that prevent injury or illness. Given the broader scope of the VSL approach, VSL estimates tend to be significantly larger than medical costs because they are based on individuals' WTP for small reductions in the probability of dying, while medical costs include actual costs incurred by individuals and, in some cases, third-party insurers. The reader is advised that the use of both approaches adds complexity to the interpretation of the estimated benefits because the two are not comparable. Thus, we periodically remind the reader of these differences as we present the findings.

The second challenge for a study such as this is to determine whether risk-reduction measures might have occurred without the research in question and whether NIOSH research made a significant contribution to any resulting benefits. Here, the analytic approach must often be tailored to the specific case, and there is much less professional consensus about methods.

A third challenge is that data are often lacking for many key parameters of the economic benefit models we estimate. Thus, the case study chapters walk the reader through a transparent set of logical steps, marshaling quantitative estimates where possible, and providing transparent discussion about our assumptions where such evidence is not available. Where possible, given the project timeline, we present sensitivity analyses to illustrate the extent to which estimated benefits depend on such assumptions.

All three case studies draw on document and literature reviews and interviews with key stakeholders (see Appendix A for a list), which informed quantitative spreadsheet models from which we generated estimates of economic benefit. The interviews sought to elicit timelines and to help locate relevant data or records on details of interventions and the adoption of practices. In some instances, the aforementioned gaps in published data meant that we had to ask interviewees to provide expert judgments to inform assumptions made in the quantitative models. One or two members of the NIOSH team attended each interview.

Each case study chapter is organized around the following topics:

- *relevant NIOSH activities and resulting risk control measures:* We created timelines of relevant NIOSH activities. To ascertain which contributions could reasonably be attributed to NIOSH, we also examined how other actors contributed to relevant advancements in knowledge and practice.
- *evidence of adoption:* Next, we assessed the degree to which stakeholders in the relevant industries have adopted control measures derived from NIOSH and other research activities.

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[3] For instance, VSL estimates do not distinguish between traumatic fatalities and those that result from long-term illnesses or other conditions. Although VSL estimates can also depend on individual characteristics, such as age and health status, the available literature on the effects of these characteristics provides inconsistent results.

- *estimated economic benefit of control measures to reduce risk:* Using the analyses described in the previous section, we created quantitative spreadsheet models that
  - identify the worker population that the research activity and related control measures target
  - estimate the number of workers affected by the risk in question
  - estimate the reduction in exposure
  - estimate the number of avoided injuries, illnesses, and fatalities
  - monetize the avoided injuries, illnesses, and fatalities.

Limitations

We emphasize that this is an exploratory effort. In addition to the data gaps and need to make assumptions referenced in the previous section, we note that it is impossible to draw generalizable findings about NIOSH and its broad portfolio of research activities from just three case studies. Thus, although the study sought to quantify some of the possible impacts of NIOSH research, it does not provide a systematic overall evaluation of NIOSH's research investments. Additionally, we note that the benefits of research should ideally be evaluated in the context of the cost of producing it. We initially set out to include estimates of costs as part of this project but found that doing so was impossible given the timeline and budget.

Structure of the Report

The remainder of this report is organized in four chapters. Chapters Two, Three, and Four, respectively, report findings from each of the three case studies. Chapter Five concludes the report by reflecting on key themes across the case studies and offering thoughts regarding the application of this approach for estimating the economic impact of NIOSH's research and services more broadly. We also include two appendixes: Appendix A lists the non-NIOSH stakeholders with whom we spoke, and Appendix B explains how we calculate reductions in risk to firefighters.

Chapter Two. Supporting Development of Silica Controls in Asphalt Pavement Milling

This case study estimates the benefit of NIOSH's efforts to identify and reduce the risk of silica exposure caused by road milling to highway, street, and bridge construction workers.[6] Crystalline silica is an abundant material found in sand, concrete, stone, and other building materials. Although silica is valuable and harmless in many settings, inhaling respirable-sized particles of silica can lead to serious diseases, such as silicosis, lung cancer, and kidney and autoimmune disease (IARC, 1987). Acute silicosis can occur after a few months of exposure to high concentrations of silica dust, while more-common forms of silicosis typically occur after 15 to 20 years of moderate to low exposure (OSHA, 2002).

Workers in construction, maritime, and other industries can be exposed to silica dust during some manufacturing and maintenance procedures (OSHA, 2002). Several road construction tasks, including road milling (Linch, 2002; Rappaport et al., 2003; Valiante et al., 2004), concrete sawing, concrete grinding, concrete breaking, jackhammering, and abrasive blasting (OSHA, undated), are associated with overexposure to crystalline silica (Rappaport et al., 2003).

Since the 1970s, NIOSH has played a critical role in conducting research on silica exposure. In 2003, NIOSH entered into the Silica/Asphalt Milling Machine Partnership with representatives of industry, labor unions, equipment manufacturers, and government to develop and test silica dust control measures for asphalt pavement milling in road construction.

In this chapter, we examine NIOSH's role and assess the economic benefit of the institute's research and related activities. The chapter begins by providing a narrative description of NIOSH's activities related to silica. Next, we summarize evidence on the degree to which these control measures have spread across the highway, street, and bridge construction industries and the effectiveness of these measures in reducing workers' exposure to silica. Finally, we provide estimates of the economic benefit of the illnesses and deaths likely averted by use of these control measures and consider NIOSH's potential role in contributing to these benefits.

Overview of NIOSH's Activities Related to Silica

Although the case study focuses on activities since 2002, these efforts build on three decades of prior NIOSH work on silica-related risk, which, in turn, built on U.S. government studies of silica-related occupational disease beginning in the early 20th century.

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[6] For the purposes of discussion, we use *highway*, *street*, *bridge*, and *road construction* interchangeably.

Earlier NIOSH Work on Silica

NIOSH's prior involvement in silica includes research to establish a comprehensive standard that included a recommended exposure limit for silica, as well as dissemination efforts to raise awareness of exposure and risk among highway workers. In 1974, NIOSH advised having a crystalline silica standard that included a recommended exposure limit for crystalline silica of 50 $\mu g/m^3$ (Center for Disease Control, 1974), which OSHA took into consideration in setting a permissible exposure limit (PEL). In 1978, NIOSH issued *Occupational Health Guideline for Crystalline Silica* (Centers for Disease Control, 1978) as a source of health hazard information for employees, employers, physicians, industrial hygienists, and other occupational health professionals. During the next two decades, mounting evidence linked crystalline silica exposure to other diseases in addition to silicosis, such as lung cancer and kidney disease, including a 1997 review by the World Health Organization's IARC (IARC, 1997a). NIOSH summarized key findings from the research in its hazard review *Health Effects of Occupational Exposure to Respirable Crystalline Silica* (CDC, 2002).

NIOSH also funded extramural research and worked in collaboration with industry and other agencies to reduce occupational exposure to silica. For instance, in 1988, NIOSH began funding the Occupational Health Surveillance Program of the New Jersey Department of Health and Senior Services under the Sentinel Event Notification System for Occupational Risks (SENSOR) Program (New Jersey Department of Health and Senior Services, 2001). In 1999, the New Jersey program joined with other organizations to form a partnership to address growing concerns about silica exposure to road construction workers.[7] A subsequent study using data from this initiative (Valiante et al., 2004) established that a large population of road construction workers were at risk of developing silicosis from exposure to respirable crystalline silica.

During the 1990s, NIOSH helped raise awareness of risks to road construction workers and supported the development of control measures to reduce their exposure. At the request of a partnership that included the National Asphalt Pavement Association (NAPA),[8] NIOSH assisted the five largest asphalt paving machine manufacturers in developing prototype fume control measures for their hot-mix asphalt pavers and then independently evaluated the performance of each prototype (CDC, 1997). In 1996, NIOSH issued engineering control measure guidelines for hot-mix asphalt pavers (updated in 1997), which every highway-class asphalt paving machine

[7] The participants of the New Jersey Silica Partnership included OSHA, NIOSH (Division of Respiratory Disease Studies and Division of Applied Research and Technology), the New Jersey Department of Transportation, the New Jersey Department of Labor, two Laborer's International Union locals, the Laborer's Safety and Health Fund, the New Jersey State Safety Council, Utility and Transportation Contractors Association, several highway construction contractors, and the Occupational Health Surveillance Program of the New Jersey Department of Health and Senior Services.

[8] The partnership included the Asphalt Institute, the Laborers' Health and Safety Fund of North America, and the International Union of Operating Engineers.

manufacturer in the United States subsequently adopted (NIOSH, undated). In 2003, stakeholders from this effort established the Silica/Asphalt Milling Machine Partnership, which is the focus of this case study. Members include NAPA, the International Union of Operating Engineers, the Laborers' International Union of North America, the Association of Equipment Manufacturers, all manufacturers of heavy construction equipment that sell pavement milling machines in the United States, numerous paving contractors, OSHA, the Federal Highway Administration, and NIOSH.

Activities of the Silica/Asphalt Milling Machine Partnership

Table 2.1 shows a timeline of the key silica-focused NIOSH activities and the related events covered in this case study. Note that the table includes only those events covered in the economic analysis. However, in the text that follows, we describe other events that predate "the case." Also, note that the analysis of benefits extends beyond the time period represented in the table.

Table 2.1. Key NIOSH Activities and Related Events: Road Worker Case Study

Year or Period	Event or Activity
2002–2004	NIOSH publishes three studies documenting the risk of silica exposure in asphalt pavement milling.[a]
2003	The Silica/Asphalt Milling Machine Partnership is formed and begins studies on dust control measures.
2004	NIOSH publishes the results of a pilot study evaluating water spray control measures.[b]
2007–2010	NIOSH conducts additional field surveys of water spray control measures.[c]
2011–2012	NIOSH conducts laboratory tracer gas studies on ventilation control measures.[d]
2012	NIOSH conducts field testing of ventilation control measures.[e]
2013	OSHA announces an NPRM for occupational exposure to respirable crystalline silica, proposing a new PEL of 50 μg/m^3.
2014	All major asphalt milling machine manufacturers sign letters of commitment to install dust control measures on half-lane or larger drivable milling machines by January 1, 2017.
2016	OSHA issues its final silica rule.
2017	OSHA proposes to begin enforcement of the final silica rule for the construction sector.

NOTE: NPRM = notice of proposed rulemaking.
[a] Linch, 2002; Rappaport et al., 2003; Valiante et al., 2004.
[b] Echt, Shulman, et al., 2004.
[c] Hammond, Trifonoff, and Shulman, 2011; Blade, Shulman, Cecala, et al., 2011.
[d] Hammond, Mead, et al., 2011; Blade, Shulman, Cecala, et al., 2011; Hammond, Garcia, Henn, et al., 2012; Hammond, Garcia, and Shulman, 2013.
[e] Hammond and Shulman, 2015a, 2015b; Hammond, Shulman, and Echt, 2016.

From 2003 to 2006, the partnership helped facilitate six field surveys on road milling jobs. The first survey (Echt, Shulman, et al., 2004) evaluated water spray control measures for cold milling machines. In a subsequent study, NIOSH published the results of additional field surveys of water spray control measures conducted between 2007 and 2010 (Hammond, Trifonoff, and Shulman, 2011; Blade, Shulman, Cecala, et al., 2011), one of which identified two improvements to engineering dust-emission control measures to reduce respirable dust levels in and around the milling machine (Blade, Shulman, Cecala, et al., 2011). In 2011 and 2012, NIOSH undertook three additional laboratory tracer gas studies on ventilation controls at milling machine manufacturing facilities or contractor-owned facilities, finding tracer gas capture efficiencies of greater than 90 percent (Hammond, Mead, et al., 2011; Blade, Shulman, Cecala, et al., 2011; Hammond, Garcia, Henn, et al., 2012; Hammond, Garcia, and Shulman, 2013).

In 2012, NIOSH began conducting field tests of cold milling machines fitted with ventilation control measures developed by different manufacturers. NIOSH documented the results in three studies (Hammond, Shulman, and Echt, 2016; Hammond and Shulman, 2015a, 2015b), concluding that the evaluated ventilation dust control measures, when implemented with water sprays, are capable of controlling exposure to respirable crystalline silica during typical road construction jobs that use asphalt pavement milling machines.

Evidence of Adoption

OSHA cited NIOSH's research as an important factor motivating a new federal rule regarding worker exposure to silica, the first major revision to its crystalline silica standards in 40 years. OSHA announced an NPRM for occupational exposure to respirable crystalline silica in 2013, concluding, based on available evidence and research, that "workers exposed to respirable crystalline silica are at increased risk of developing silicosis and other non-malignant respiratory diseases, lung cancer, and kidney disease" (OSHA, 2016b, summary). In response to the NPRM, and as a result of the evidence from NIOSH's field surveys through the partnership, all manufacturers of asphalt pavement milling machines sold in the United States signed letters of commitment to install ventilation control measures on all new half-lane or larger drivable machines by January 1, 2017 (NAPA, 2014, Appendix 1).

Following OMB review and public comment, OSHA issued the final rule for occupational exposure to respirable crystalline silica (the silica rule) in 2016 (OSHA, 2016b, pp. 1679, 1741). Under the rule, OSHA developed a comprehensive standard to protect workers from exposure to respirable crystalline silica in the form of quartz, cristobalite, or tridymite for general industry, maritime, and construction and, as NIOSH recommended, set a PEL of 50 $\mu g/m^3$ as an eight-hour time-weighted average (TWA) concentration in all industries covered by the rule. The rule requires employers to keep worker exposure at or below the PEL by using control measures and best practices, including wetting down work operations, using vacuums to capture silica dust from the air at its source, and limiting worker access to high-exposure areas. The rule also requires employers to monitor worker exposure to respirable crystalline silica, develop a written exposure control plan, train workers on silica risks, keep records of workers' silica exposure, and provide and retain records of medical exams. The rule contains a safe harbor (OSHA, 2016b, Table 1) that prescribes engineering and work-practice controls and respiratory protection for 18 construction tasks. Employers that perform the tasks as prescribed are assumed to be in compliance with the PEL. OSHA incorporated large drivable milling machines (half-lane and larger) into Table 1 based in large part on the NIOSH research described here. According to the OSHA website, enforcement of the standards in the construction sector began on September 23, 2017 (OSHA, undated).

NIOSH's field studies have helped manufacturers determine which control measures they can use to meet the new exposure standard. In 2014, following the NIOSH field studies described above, the two largest manufacturers, which account for nearly 80 percent of the market, began installing ventilation controls and water sprays on all new half-lane or larger cold milling machines. The remaining manufacturers signed letters of commitment to OSHA to install ventilation controls on new milling machines by January 1, 2017. Given the replacement rate for cold milling machines, we infer that nearly all large milling machines in the United States will be equipped with modern ventilation controls by 2024.[9] Furthermore, several manufacturers currently sell retrofit kits for older machines at costs ranging from $10,000 to $20,000 (compared with $500,000 for a new machine). Therefore, it is likely that ventilation controls will be installed on the vast majority of cold milling machines several years before 2024.

Approach for Estimating the Economic Benefit of Silica Control Measures

Having described NIOSH activities and documented their likely role in reducing silica-related risks, we now present our analysis of the estimated monetary value of those reductions. To do this, we use the following steps, as described in Chapter One: (1) identify the target population; (2) estimate the number of workers affected; (3) estimate the reduction in exposure; (4) estimate the number of avoided injuries, illnesses, and fatalities; and (5) monetize those avoided injuries, illnesses, and fatalities. The last two steps require further clarification. To estimate the benefit associated with *NIOSH's* activities, we need to characterize the extent to which NIOSH made a significant contribution to reductions in exposure and adoption of safety practices described at the end of the previous section.

The analysis presented in this case study represents the benefits of NIOSH activities to identify and reduce silica exposure among highway, street, and bridge construction workers using asphalt pavement milling machines relative to a baseline *in which no other organization or entity brought about similar changes*. These assumptions are predicated on the fact that NIOSH research and policy recommendations were heavily cited as a key motivation for OSHA to promulgate new industry PELs for silica exposure, which, in turn, prompted voluntary commitments by asphalt pavement milling machine manufacturers to install ventilation control measures and water sprays on their equipment. Manufacturers indicated that they were responding directly to the OSHA rulemaking process and would not have adopted the improved

[9] The average useful life span of a large asphalt milling machine is about ten years, although used machines are often resold to Asian markets after three to five years.

controls otherwise. Furthermore, NIOSH led the design and testing of ventilation control measures with the Silica/Asphalt Milling Machine Partnership.

Thus, to measure the benefit of NIOSH's efforts to identify and reduce the risks of silica exposure from road milling, we first compared the reduction in negative health outcomes associated with observed reductions in exposure levels and *the reduction in health outcomes that might have occurred in an alternative scenario without NIOSH*. In this alternative scenario, we assumed that studies investigated or funded by NIOSH did not occur and that, thus, awareness of the risks of silica exposure during road milling and subsequent responses by industry and policymakers would not have occurred as quickly. Furthermore, in a world without NIOSH, we assume, no other agency would exist to take the lead on engineering and design concepts to develop the ventilation control measures needed to reduce exposure from cold milling machines. Manufacturers would have had to independently develop these controls.

We note that it is likely that awareness of the risks of silica exposure during road milling would have eventually been identified; unbeknownst to each other, both NIOSH and researchers in the Netherlands had separately begun investigating this issue in the late 1990s and early 2000s (TNO, 2000; TNO, 2002; van Daalen, 2002). However, research conducted in the Netherlands was unavailable in English until NIOSH discovered and translated it, beginning in 2005. In the alternative scenario without NIOSH, changes in European regulations and industry behavior might have eventually influenced U.S. regulations and industry, or others might have eventually identified and translated the Dutch research. But this process might have taken decades. In addition to identifying the risk, NIOSH also played a key role in engaging with stakeholders to transform the research into technology and policy changes. Without NIOSH, those changes also might have occurred much more slowly.

Thus, to assess the economic benefit associated with NIOSH's contribution, we estimate an alternative scenario in which industry separately or in coordination with another agency or organization independently developed and installed ventilation control measures and water sprays on milling machines to reduce silica exposure—albeit *15 years later*. In this scenario, we assume that Dutch research on silica exposure would have either directly or indirectly influenced U.S. manufacturers to develop silica dust control measures on milling machines in the future. When the research was eventually translated and reached audiences in the United States, it might have directly influenced OSHA's decision to reduce silica exposure limits. Another channel through which this could have effected change in the United States is that silica researchers in Europe might have influenced local laws regulating occupational exposure, thus eventually triggering European Union liability concerns to encourage manufacturers to adopt ventilation control measures on all of their milling machines.[10]

We present our results for each of the five steps in the rest of this section.

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[10] One of the leading suppliers of road milling equipment in the United States, Wirtgen, is a German company.

Step 1: Identify the Target Population

Because the focus of this case study is NIOSH activities associated with reducing silica exposure through control measures on asphalt pavement milling machines, the primary target population is highway, street, and bridge construction workers using this equipment. The 2012 Economic Census (U.S. Census Bureau, undated) estimates that there are 251,065 highway, street, and bridge construction workers in the United States.[11] The Economic Census, which is conducted every five years, is the most complete official measure of U.S. businesses and the economy.[12]

Step 2: Estimate the Number of Affected Workers

For this analysis, we start with the entire population of road construction workers using portable or mobile milling machines. This population includes workers using large drivable milling machines (half-lane and larger), small drivable milling machines, and walk-behind milling machines and floor grinders. The workers are also divided into different labor categories, including first-line supervisors and managers of construction trade and extraction workers; cement masons and concrete finishers; construction laborers; and paving, surfacing, and tamping equipment operators.

OSHA conducted an analysis of workers at risk for silica exposure for each industry using information from the U.S. Bureau of Labor Statistics' (BLS) Occupational Employment Statistics survey.[13] Informed by OSHA's findings, we estimate that there are 25,706 highway, street, and bridge construction workers using milling machines in the United States. The focus of our analysis is workers using large drivable milling machines. OSHA estimates that these machines account for 10 percent of all road milling equipment, while walk-behind milling machines and floor grinders account for 80 percent and small driven milling machines account for the remaining 10 percent. In addition, we estimate that large drivable machines require an average of three to four workers to operate (one operator and two to three workers to walk alongside or behind the machine), compared with one or two workers for a small drivable machine and one worker for a walk-behind milling machine. This implies that approximately 27 percent of the workforce, or 6,921 workers, are using primarily large drivable milling

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[11] The six-digit North American Industry Classification System code for highway, street, and bridge construction workers is 237300.

[12] The U.S. Census Bureau also reports statistics for businesses in its annual series, County Business Patterns. As of March 2015, the most recent estimate for North American Industry Classification System code 237300 was 260,735 workers. For consistency with other data sources, we rely on data from the 2012 Economic Census. The Economic Census will next be conducted for calendar year 2017.

[13] To be consistent with data from the 2012 Economic Census, we analyzed data from the 2012 BLS Occupational Employment Statistics survey.

machines.[14] We group these workers into two categories: operators and other ground workers (including supervisors). Table 2.2 reports the number of affected workers at risk of silica exposure who will benefit from the adoption of ventilation control measures.

Table 2.2. Number of Affected Highway, Street, and Bridge Construction Workers Using Half-Lane or Larger Milling Machines

Labor Category	Affected Workers
Operators	1,977
Ground workers	4,943
Total	6,921

NOTE: The total is not precisely the sum of the two categories because of rounding.

Step 3: Estimate the Reduction in Exposure

We rely on NIOSH research and field testing to estimate baseline exposure levels and postintervention respirable silica concentrations. We base baseline exposure levels on air samples from three NIOSH studies (Linch, 2002; Rappaport et al., 2003; Valiante et al., 2004).[15] According to NIOSH field testing (Hammond, Shulman, and Echt, 2016; Hammond and Shulman, 2015a, 2015b), ventilation control measures on cold milling machines will reduce the risk of workers' silica exposure significantly, to 6.0 $\mu g/m^3$ and 8.2 $\mu g/m^3$ for operators and ground workers, respectively. These represent more than a 90-percent reduction in silica exposure. Table 2.3 summarizes the measured exposure of highway, street, and bridge construction workers at baseline and after the installation of ventilation control measures and water sprays on cold milling machines.

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[14] This estimate excludes operators of small drivable machines and walk-behind milling machines and floor grinders, as well as all cement masons and concrete finishers, because they are unlikely to use large drivable milling machines.

[15] We focus on samples for asphalt road milling. Informed by conversations with NIOSH staff, we assume that workers are exposed to the documented concentrations for a full eight-hour shift. However, we note that some of the air samples were taken during shifts shorter or longer than eight hours.

Table 2.3. Exposure Profile of Highway, Street, and Bridge Construction Workers Using Milling Machines (Mean Eight-Hour Time-Weighted Average Silica Concentration, in Micrograms per Cubic Meter)

Labor Category	Baseline (Preintervention)	Postintervention (Ventilation Control Measures)	Change in Exposure
Operators	111.6	6.0	–105.7
Ground workers	262.6	8.2	–254.4

NOTE: The total is not precisely the sum of the two categories because of rounding.

Step 4: Estimate the Number of Avoided Injuries, Illnesses, and Fatalities

To estimate the number of avoided injuries, illnesses, and fatalities, we relied on studies cited in OSHA's final economic analysis of the silica rule. First, we estimate the number of excess fatalities due to silica exposure accruing over 60 years without silica controls, based on the lifetime risk models (compared with the probability of a worker dying from non–silica-related causes).[16] Following OSHA's methodology, we estimate the number of excess illnesses over a 45-year working life, from age 20 to age 65, and assume an additional life span of 15 years postretirement. Then, we estimate the number of excess fatalities due to silica exposure after the installation of ventilation control measures and water sprays. We compare the baseline scenario and the postintervention scenario to estimate the reduction in fatal and nonfatal illnesses. Table 2.4 summarizes the estimated number of avoided fatal and nonfatal illnesses associated with reducing exposure levels from baseline to postintervention levels, as described in step 3. For example, the exposure reductions described in Table 2.4 are estimated to reduce ESRD fatalities from 432 cases to 145 cases. Thus, Table 2.4 presents estimates that reduced silica exposure will result in 287 avoided ESRD fatalities over the 45-year period, or an average of six avoided ESRD fatalities per year. Because of limitations in the available literature on the impacts of silica exposure, we did not estimate non–fatal disease instances avoided for lung cancers and ESRD. Therefore, benefits might be underestimated because we did not include some avoided nonfatal illnesses.

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[16] For information on lung cancer, see Attfield and Costello, 2004, and Steenland and Bartell, 2004. For more about nonmalignant respiratory disease, see Park et al., 2002, and 't Mannetje et al., 2002. For information about end-stage renal disease (ESRD), see Steenland, Attfield, and 't Mannetje, 2002.

Table 2.4. Estimated Number of Fatal and Nonfatal Illnesses Avoided Because of Reduction in Silica Exposure over 45 Years

Type of Illness	Reduction in the Rate of Excess Death or Morbidity per 1,000 Operators	Reduction in the Rate of Excess Death or Morbidity per 1,000 Ground Workers	Total Number of Cases Avoided	Annual Number of Cases Avoided
Lung cancers (midpoint estimate)[a]	27.2	95.9	528	12
Nonmalignant respiratory diseases, including silicosis	71.0	159.3	928	21
ESRD	32.6	45.0	287	6
Total fatal illnesses	Not applicable	Not applicable	1,743	39
Total nonfatal silicosis illnesses	396.4	985.5	5,442	121

NOTE: Numbers have been rounded.
[a] For lung cancers, the low-end estimate is 72 total cases (two on an annual basis) and the high-end estimate is 984 total cases (22 on an annual basis).

Step 5: Monetize Avoided Injuries, Illnesses, and Fatalities

As noted in Chapter One, we used two approaches to estimate the economic benefit of NIOSH research. First, for cancer-related deaths, we used the total direct medical costs and productivity losses associated with lung cancer. There is insufficient information available on medical costs and survival rates associated with the other diseases in this case study to monetize these benefits. Therefore, we also use WTP estimates from the available economic literature to monetize benefits associated with all types of avoided fatal and nonfatal illnesses.

To calculate the medical costs of lung cancer, we used data from the National Cancer Institute.[17] These data provide estimates of the medical costs for different types of cancer for both men and women over age 65 in the first year after diagnosis, on a continuing annual basis, and during the final year of life. We adjusted these medical costs according to the gender and age distribution of road construction workers.[18] We inflation-adjusted medical costs to 2016 dollars using BLS's Consumer Price Index for medical care.

To calculate average medical costs for the affected population, we then estimated 20-year survival probabilities for lung cancer. Because survival rates for many cancers have been

[17] See National Cancer Institute, undated, which is based on Mariotto et al., 2011.

[18] We estimate, based on data from BLS, that 96 percent of highway, street, and bridge construction workers are male. We also adjust, based on information in Mariotto et al., 2011, initial-diagnosis costs by a factor of 1.2 and last-year-of-life costs by a factor of 1.5 to account for patterns of care that have been reported to be more aggressive for younger cancer patients. We estimate, based on CDC lung cancer mortality and incidence rates, that 30 percent of diagnoses and 25 percent of fatalities are in people younger than 65.

increasing because of improvements in the quality of medical treatment, we scaled the historical survival rates by the increase in the one-year survival rate for diagnoses made between 2004 and 2013 (the most recent one-year estimate) to estimate the current 20-year survival probability (Howlader et al., 2017).[19] We also assumed, based on the estimated survival probabilities, that the last year of life occurs in year 20 for anyone still alive. Given these survival rates, we estimate that 57 percent of people diagnosed with lung cancer will die within one year of diagnosis. For these cases, we estimate medical costs for only the last year of life. For the 6 percent of people who will die within three years of a lung cancer diagnosis, we estimated medical costs for the first year after diagnosis, continuing annual treatments, and the last year of life. Our estimate of the average lifetime cost of a lung cancer fatality is a weighted average of medical costs by years of treatment and the survival probability for each year after diagnosis.

To account for lost earnings, fringe benefits, and work done outside of the labor force (i.e., home production), we also estimated productivity losses. We derived productivity loss estimates based on the present value of future lifetime production for the affected workforce.[20] The average present value of lost production due to a fatality is based on a weighted average for men and women younger than and older than 65, respectively, according to the distribution of occupational fatalities for these groups and reflecting the average wages of each job category.[21] We then followed the approach in Leigh, 2011, in multiplying estimates of lost production by the morbidity-to-mortality ratios in Rice, Hodgson, and Kopstein, 1985, to estimate the benefits of avoided morbidity.[22] We inflation-adjusted productivity losses to 2016 dollars using the gross domestic product (GDP) implicit price deflator.

To construct an average total lifetime cost for lung cancer fatalities, we combined medical costs and productivity losses. For each avoided fatality, we estimate total medical costs, productivity losses associated with morbidity, and productivity losses associated with mortality. For fatal cases of lung cancer, we estimate average lifetime medical costs of $172,000, plus productivity losses of $113,000 for morbidity and $512,000 for mortality. Thus, we applied medical costs and productivity losses of $798,000 to the estimated number of cancer fatalities

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[19] To estimate survival rates, we used the one- to ten-year survival rates from diagnoses in 2004 and adjusted them by the increase in the one-year survival rate from 2004 to 2013 (approximately 9 percent). Then we used the average year-to-year changes for subsequent years up to year 20 based on diagnoses from 1990 to 1994 to estimate the remaining survival rates.

[20] Using estimates in Grosse, Krueger, and Mvundura, 2009, we applied a 3-percent discount rate to all future production.

[21] Following the discussion in step 2, we estimated that the affected workforce includes equipment operators (29 percent), construction laborers (42 percent), and supervisors (29 percent). In estimating exposure levels, we classified both construction laborers and supervisors as "ground workers."

[22] These estimates do not include the costs associated with overtime and labor replacement costs, such as the cost of training new hires.

avoided.[23] Because of the lack of data on the number of nonfatal cases, we did not estimate costs for nonfatal cases of lung cancer.

Separately, we used WTP estimates to monetize the cost burden for all diseases. Because data on medical costs and survival rates are not available for all diseases, we also used WTP estimates from the available economic literature to monetize benefits. In its final economic analysis of the silica rule, OSHA used the WTP approach, which OMB mandates for regulatory analysis. To monetize the benefits of fatal illnesses avoided, we used a VSL of $9.5 million (in 2016 dollars) (Viscusi and Aldy, 2003).[24] We added the value of avoided morbidity to this estimate and discounted it in the same year. Ideally, this would be captured (and discounted) at the onset of morbidity to reflect the worker's WTP to avoid an illness. This was not feasible, given the insufficiency of data on age of onset and survival probabilities. To monetize the benefits of nonfatal illnesses avoided, we followed OSHA's approach in using a low-end estimate of $68,000 and a high-end estimate of $5.5 million (or approximately 58.3 percent of the value of an avoided fatal illness).[25] Therefore, for nonfatal cases, we used a midpoint estimate of approximately $2.8 million.

We made assumptions about job tenure, cancer latency, and the value of future benefits. Our analysis estimates a stream of benefits over time. Benefits will phase in over several decades because health risks depend on cumulative occupational exposure over a 45-year working lifetime based on occupational tenure in road construction. A worker joining the workforce today would benefit from reduced silica exposure for his or her entire working career; however, current workers would benefit from reduced exposure for a shorter duration depending on age. We assumed that the number of fatalities avoided will gradually increase (in a straight-line projection) from zero in year 1 after the adoption of ventilation control measures and water sprays on large milling machines until reaching a new steady state in year 45—and remaining at the new level in perpetuity. Informed by OSHA's findings, we also estimate a 15-year lag for reductions in lung cancer risk due to a relatively long latency period. We do not estimate a latency period for any other diseases. Given the 15-year latency period for lung cancer, we would not see the full scope of benefits until 60 years after the adoption of ventilation control measures. Specifically, we assumed that the number of lung cancer fatalities avoided will remain at zero for the first 15 years and then rise linearly until year 60. To reflect the social preference

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[23] We rounded these numbers to the nearest thousand.

[24] The U.S. Department of Transportation and the U.S. Department of Health and Human Services currently recommend using a VSL of $9.6 million (in 2016 dollars) for regulatory analyses. Guidance documents from these agencies describe the motivation and methodologies for using WTP estimates to value avoided fatal and nonfatal injuries and illnesses (Moran and Monje, 2016; Centers for Disease Control, 1983). For this analysis, we used OSHA's VSL figure, which predates these guidance documents but is nearly identical.

[25] See discussion in Chapter VII of OSHA's final economic analysis for the silica rule (OSHA, 2016a). The low-end estimate is based on Viscusi and Aldy, 2003, and the high-end estimate is based on Magat, Viscusi, and Huber, 1996.

for the timing of benefits, we applied a discount rate of 3 percent. We also allowed monetized future benefits to increase over time. For the medical cost approach, we assumed that real medical costs would rise over time. In the past 30 years, medical costs have risen 2.4 percent faster than GDP has (Friedman, 2010). For the WTP approach, we assumed that future WTP would rise with real income. Using OSHA's estimates, we also estimate that the VSL would increase by 2 percent per year, assuming a 1.4-average annual increase in real per capita income and an income elasticity of 1.44.[26] Therefore, for both approaches, we estimate that the value of future benefits would increase by approximately 2 percent annually.

Finally, we calculated the net present value of these benefits over 60 years on an annualized basis to estimate the total benefit attributable to NIOSH research activities.[27]

Summary of Assumptions Made in Estimating Benefits

Given gaps in available data, we made several assumptions in estimating benefits:

- The benefit of NIOSH's research is limited to road construction workers using milling machines. If other workers in close proximity to the machines also experience reduced exposure, this analysis could underestimate benefits.
- Ventilation control measures and water sprays have no impact on the productivity or the effectiveness of asphalt pavement milling equipment, so no additional milling equipment will be required to complete projects.
- The magnitude of reductions is representative of different types of ventilation control measures. The effectiveness of dust control measures in this analysis is based on field-testing results for two different manufacturers of cold milling machines. This analysis assumed that the control measures that other manufacturers have developed will be similarly effective to those that NIOSH has tested previously.
- The number and distribution of workers across silica exposure conditions does not change over time. This analysis might overestimate or underestimate benefits depending on any future changes in the composition, size, and activities of the workforce.
- This analysis evaluated two possible future scenarios without NIOSH. Because of time constraints, we did not evaluate additional plausible scenarios. The benefits of NIOSH research could be higher or lower under different alternative scenarios. For example, if OSHA had mandated a new PEL for road construction activities regardless of NIOSH's research, the estimated benefits would be lower than shown in the scenarios described in this report, assuming that manufacturers were willing and able to comply without NIOSH's investment in the design and implementation of ventilation control measures.

[26] See the discussion in Chapter VII of OSHA's final economic analysis for the silica rule (OSHA, 2016a).

[27] The annualized estimates presented in this report indicate that we calculated the present value (the value today) of a future stream of payments in real-dollar terms. This calculation requires a stream of projected future costs, the specific years in which those costs are incurred, and a discount rate. Annualized values, taking into account the discount rate and the number of years in the forecast period, are calculated to provide a comparison across activities with varying time components and forecast periods.

Estimate of the Total Benefit

Tables 2.5 and 2.6 summarize the total estimated annualized benefits from reducing silica exposure among highway, street, and bridge construction workers using asphalt pavement milling machines due to the adoption of ventilation control measures. The results indicate that highway, street, and bridge construction workers using half-lane and larger cold milling machines benefit from significantly reduced exposure to respirable crystalline silica due to the adoption of ventilation control measures. With the WTP and VSL values for risk reductions in fatal and nonfatal illnesses, the economic benefit of this reduced exposure ranges from $304 million to $1.1 billion on an annualized basis, with a midpoint estimate of $692 million per year. Using a separate medical cost approach, we estimate that NIOSH's activities contributed $4.9 million in avoided medical costs and productivity losses on an annualized basis for fatal lung cancers.

Table 2.5 reports the direct medical costs and productivity losses associated with fatal lung cancers avoided due to silica exposure. Because of data limitations, we did not estimate these costs for other diseases.

Table 2.6 reports the monetized benefits associated with the adoption of ventilation control measures using the WTP approach described above. We estimate benefits for three fatal diseases and nonfatal cases of silicosis. Estimates of exposure risk reductions for other nonfatal diseases were unavailable.

Table 2.5. Estimated Annualized Benefits of Avoided Medical Costs and Productivity Losses for Fatal Lung Cancers for Highway, Street, and Bridge Construction Workers Using Milling Machines Due to Reduction in Silica Exposure over a 60-Year Time Horizon

Measure	Baseline 1: No Ventilation Control Measures Developed	Baseline 2: 15-Year Delay in Development of Ventilation Control Measures
Total number of fatal lung cancers avoided	270	149
Annual number of fatal lung cancers avoided	4	2
Annualized benefit of ventilation control measures, in millions of dollars	4.9	2.8

Table 2.6. Estimated Annualized Benefits (Value of a Statistical Life and Willingness to Pay) of Avoided Fatal and Nonfatal Illnesses for Highway, Street, and Bridge Construction Workers Using Milling Machines Due to Reduction in Silica Exposure over a 60-Year Time Horizon

Measure	Baseline 1: No Ventilation Control Measures Developed	Baseline 2: 15-Year Delay in Development of Ventilation Control Measures
Total number of fatal cases avoided	1,296	554
Lung cancer	270	149
Nonmalignant respiratory disease	783	309
ESRD	242	96
Total number of nonfatal cases avoided	4,595	1,814
Annual number of fatal cases avoided	22	9
Annual number of nonfatal cases avoided	77	30
Annualized benefit of ventilation control measures, in millions of dollars	692	312
Lung cancer	90	51
Nonmalignant respiratory disease	221	96
ESRD	72	31
Nonfatal silicosis	310	134

Interpretation of medical cost and productivity loss estimates (Table 2.5) differs from that of WTP estimates (Table 2.6) because the latter estimates seek to capture broader social welfare. Therefore, these approaches are not directly comparable. VSL estimates, for example, tend to be significantly larger than avoided medical costs because they are based on individuals' WTP for small reductions in the probability of dying, while medical costs include actual costs incurred by individuals and, in some cases, third-party insurers.

As noted earlier, it is possible that the controls would have come into place without NIOSH and through eventual access to the Dutch research described above. To quantify the benefits of NIOSH accelerating the adoption of control measures, we estimate health outcomes relative to a baseline of a 15-year delay on the design and implementation of ventilation control measures on milling machines. Both Tables 2.5 and 2.6 report the benefits of ventilation control measures relative to each baseline: one in which no silica controls would be adopted and another in which adoption would be delayed. As the tables show, the estimated benefits would be significantly smaller if NIOSH's activities merely accelerated the installation of ventilation control measures on milling machines by 15 years versus inducing the adoption of controls that would not have occurred without NIOSH's intervention.

Sensitivity Analyses

In this section, we discuss the sensitivity of the results to key assumptions in the analysis regarding the WTP value, baseline exposure levels, and the size of the workforce. First, for the WTP approach, the economic literature and regulatory guidance on VSL values for avoided fatalities is well established. However, the literature on WTP values for avoided nonfatal illnesses is less robust, and there is a wider range of estimates. Therefore, we compared our findings with results using the high-end and low-end WTP estimates for valuing avoided morbidity from OSHA's analysis (we applied these to both fatal and nonfatal cases). In Table 2.6, nonfatal cases of silicosis account for approximately 45 percent of the total benefits.[28] In our sensitivity analyses, nonfatal cases of silicosis account for 58 percent of total benefits using the high-end WTP estimate but just 2 percent of total benefits using the low-end WTP estimate. Given the wide range of estimates, the results are sensitive to the choice of the estimate for valuing avoided morbidity cases.

Second, we estimate the effect of using different baseline exposure levels from NIOSH's reports. Because some of the air samples were taken during shifts shorter or longer than eight hours, it might be reasonable to adjust the air samples to an equivalent eight-hour TWA concentration. On average, the air samples documented in our main analysis are approximately 15- to 20-percent higher than the imputed eight-hour TWA concentrations because many of the samples were taken during shifts shorter than eight hours. Despite this potential discrepancy, we find that the results are not highly sensitive to this assumption. The reduction in the baseline exposure levels is roughly proportional to the reduction in estimated benefits. However, given nonlinearities in the cumulative risk models used in the analysis, this effect could be more pronounced if the differences in measurement were greater.

Third, we evaluated assumptions regarding the size of the affected workforce. Any change in the estimated size of the workforce is directly proportional to the magnitude of the change in estimated benefits. Given uncertainty about the number of half-lane and larger cold milling machines currently being used in the United States, we present an upper-bound estimate reflecting the total number of highway, street, and bridge construction workers using milling equipment—we exclude only cement masons and concrete finishers, who do not use large milling machines. This is likely an overestimation because this number includes workers using small drivable and walk-behind milling machines. Table 2.7 summarizes our results.

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[28] Calculated as avoided cases of nonfatal silicosis ($310 million) in the last row, as a percentage of the total benefits ($692 million).

Table 2.7. Sensitivity Analyses: Road Worker Case Study

Measure	Baseline 1: No Ventilation Control Measures Developed	Sensitivity 1a: High-End WTP Estimate (Morbidity)	Sensitivity 1b: Low-End WTP Estimate (Morbidity)	Sensitivity 2: Lower Eight-Hour TWA Concentration Baseline Samples	Sensitivity 3: Larger Workforce Estimate
Total number of fatal cases avoided	1,296	1,296	1,296	1,037	3,622
Total number of nonfatal cases avoided	4,595	4,595	4,595	4,231	12,823
Annual number of fatal cases avoided	22	22	22	17	60
Annual number of nonfatal cases avoided	77	77	77	71	214
Annualized benefit of ventilation control measures, in millions of dollars	692	1,052	304	589	1,964
Fatal cases	383	440	296	304	1,069
Nonfatal cases	310	612	8	285	864

NOTE: Because of rounding, some numbers might not sum as expected.

Conclusion

NIOSH's research activities in asphalt pavement milling played a major role in advancing the widespread adoption of ventilation control measures. Without NIOSH's contributions, many manufacturers of asphalt pavement milling machines would not have adopted such controls. We estimate that highway, street, and bridge construction workers using half-lane and larger cold milling machines would benefit from significantly reduced exposure to respirable crystalline silica due to the adoption of ventilation control measures and water sprays. With the WTP and VSL estimates for risk reductions in fatal and nonfatal illnesses described earlier in this chapter, the economic benefits range from $304 million to $1.1 billion on an annualized basis, with a midpoint estimate of $692 million per year. Using a separate medical cost approach, we estimate that NIOSH's activities contributed to $4.9 million in avoided medical costs and productivity losses on an annualized basis for fatal lung cancers.[29] We do not have sufficient data to monetize benefits for other fatal and nonfatal diseases on a medical cost basis. These approaches are not directly comparable; rather, policymakers can use them to answer different research questions. The medical cost and productivity loss approach is commonly used in economic valuation from a budgetary perspective, while the WTP approach deals with policy questions from a societal perspective and produces significantly larger estimates.

Given that researchers in other countries were also investigating the risks of occupational exposure to respirable crystalline silica, manufacturers of cold milling machines sold in the United States might have eventually adopted ventilation control measures and water sprays. At a minimum, NIOSH accelerated the dissemination of research and development, as well as the widespread adoption of ventilation control measures, perhaps by decades. Assuming that NIOSH accelerated this process by only 15 years, we estimate that the overall benefits of NIOSH's research would be approximately half as large.

[29] Medical and indirect cost estimates for other illnesses, such as other nonmalignant respiratory diseases, including silicosis, and ESRD, were not available. Thus, this figure underestimates the overall benefits.

Chapter Three. Building and Disseminating Evidence on Firefighters' Cancer Risk

Approximately 1.2 million people in the United States serve their communities as volunteer and career firefighters, about 346,000 of whom are full-time professional career firefighters (Haynes and Stein, 2017). In carrying out their jobs, these men and women can be exposed to a variety of carcinogenic products (including asbestos, arsenic, polycyclic aromatic hydrocarbons [PAHs], benzo[a]pyrene, benzene, and diesel fumes), any of which can lead to an elevated risk of cancer (CDC, 2011). The composition of fires and smoke varies because of fuel sources and fire conditions (e.g., oxygen availability, temperature, confinement), but firefighters can be exposed to a "complex mixture of combustion products and decomposition by-products in the form of heated gases, vapors, and particulate matter" (CDC, 2011, p. 6). These issues have been exacerbated in the past several decades as a growing number of consumer goods are made of plastic and other synthetic materials, which can be much more toxic when burned than their natural counterparts.

Since 2010, NIOSH has played an active role in researching and disseminating information about the link between cancer risk and firefighting, as well as in educating firefighters and their representatives on best practices for minimizing these risks. In this chapter, we examine NIOSH's role in this area and assess the economic benefit of the institute's work. The chapter begins by describing NIOSH research and activities related to the link between cancer risk and firefighting and the ways in which NIOSH's efforts have built on earlier efforts in this domain. Next, we present estimates of the effectiveness of the control measures developed in response to the original studies and the degree to which these measures have been adopted across the sector. Finally, we provide estimates of the economic benefit of the illnesses and deaths likely averted by use of these control measures and consider NIOSH's role in contributing to these outcomes.

Overview of NIOSH's Activities Regarding Cancer Risk to Firefighters

NIOSH's research on cancer risks to firefighters builds on several decades of effort in this area. We begin by briefly reviewing this earlier work and then describe the specific NIOSH contributions that are the focus of this case study.

Earlier Work on Health Risks to Firefighters

Since the 1930s, members of the firefighter community and researchers have been interested in identifying the potential negative health consequences of repeated exposure to burning structures, vehicles, and forest wildland fuels. As understanding about carcinogens grew and cancer became one of the leading causes of death in the United States (CDC, 2017b), researchers began to wonder whether cancer risk was higher among firefighters than among people in other professions. Beginning in the late 1970s, several retrospective cohort mortality studies of firefighters were published.[30] Although they are informative, these studies suffered from small cohort sizes and short time horizons, leading to inconsistent disease risk estimates, especially for cancer deaths, which can occur later in life, even years after exposure to carcinogens. In addition, few of the studies included data on exposure, such as duration of employment, number and type of fires fought, and job duties.

LeMasters et al. conducted a meta-analysis of 32 studies investigating the link between firefighters and cancer (LeMasters et al., 2006). Although the smallness of the cohorts in previous studies limited them, the authors found that firefighters had a probable elevated cancer risk for several types of cancers, including multiple myeloma, non-Hodgkin lymphoma, prostate cancer, and testicular cancer. An additional eight cancers were listed as having a possible association with firefighting. The LeMasters et al. study attracted significant attention from firefighter associations, the National League of Cities, cancer research organizations, and the U.S. Congress. In 2007, IARC convened an expert working group that determined that "occupational exposure as a firefighter is possibly carcinogenic to humans" (IARC, 2007).[31] In April 2009, a National League of Cities report concluded that there was "a lack of substantive scientific evidence currently available to confirm or deny linkages between firefighting and an elevated incidence of cancer" (TriData Division, 2009, p. vi). However, there was widespread agreement among all parties on the need for more research.

NIOSH Research and Related Activities

In 2010, NIOSH researchers began a multiyear study of career firefighters in Chicago, Philadelphia, and San Francisco to investigate the risk of cancer and other causes of death due to job exposure. Covering 29,998 career firefighters employed between 1950 and 2009, the study examined mortality and cancer morbidity patterns, the latter providing a means to quantify increased risk from survivable cancers (such as testicular and prostate), as well as increased risk of non–cancer-related death.[32] NIOSH researchers also collected data to allow estimation of exposure rates, based on the number of runs made and on the use of PPE.[33]

The first results from the study were published online (ahead of print) in 2013 (Daniels, Kubale, et al., 2014). The paper reported no increase in all-cause mortality but did find excess

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[30] See LeMasters et al., 2006, for a review of many of these studies.

[31] These findings were later consolidated in the 2010 publication of IARC Monograph Vol. 98 (IARC, 2010).

[32] Although the study found elevated mortality risk from cirrhosis and falls and other injuries, our case study focuses exclusively on cancer because NIOSH efforts among firefighters have been more focused on the area of cancer prevention.

[33] A run is a response to a call that deploys a vehicle that has been customized for use during firefighting operations.

cancer mortality compared with that in the U.S. population, mainly from digestive and respiratory cancers (see Table 3.3 later in this chapter).[34] The study was the first to document excess malignant mesothelioma among firefighters. There was also some evidence that firefighters younger than age 65 had an increased risk of developing prostate or bladder cancer. In a follow-up analysis, an association between total time spent at fires (fire-hours) and lung cancer and leukemia mortality were found (Daniels, Bertke, et al., 2015). Firefighters with more exposure to fires also had a lower incidence of colorectal and prostate cancers, which the authors suggested came from a "healthy worker survivor effect,"[35] possibly enhanced by medical screening.

The NIOSH publications received significant attention, and the institute continued to explore the specific mechanisms causing the increased cancer risk and control measures to mitigate it (Fent, Eisenberg, Snawder, et al., 2014; Fent, Evans, Booher, et al., 2015; Fent, Alexander, et al., 2017; Fent and Evans, 2011; Horn et al., 2016). It also produced several additional reports to publicize and disseminate its research (e.g., Fent, Evans, and Couch, 2010; Fent, Eisenberg, Evans, et al., 2013; Fent, Musolin, and Methner, 2013). Drawing on these studies and working with industry, NIOSH helped develop recommendations about how firefighters could better protect themselves and what fire departments and equipment manufacturers could do to reduce firefighters' risk of contracting cancer. National firefighter associations developed and published guidelines and procedures instructing firefighters how to avoid contamination during and after fires and how to properly clean and maintain their gear. Several fire service organizations, including Firefighter Safety Through Advanced Research and the Underwriters Laboratories Firefighter Safety Research Institute (FSRI), have also publicized NIOSH findings and new industry safety recommendations and featured research and recommendations on their websites (Horn et al., 2016; Fent, Eisenberg, Snawder, et al., 2014; Firefighter Safety Through Advanced Research, undated; FSRI, 2015b, 2017).

In response to concerns raised in the studies, standard-setting organizations revised or are currently revising their guidelines and standards,[36] and equipment manufacturers developed new products, such as fire-specific skin cleansing wipes, decontamination tools and equipment,

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[34] Many researchers believe that the elevated rates of cancers among firefighters found in this study are actually an underestimate of the cancer risk of firefighting because firefighters tend to be healthier than the average of the population with which they were compared. The 2015 analysis sought to better control for this.

[35] *Healthy worker survivor effect* refers to the phenomenon of a larger concentration of healthy workers left in the workforce when unhealthy people leave work earlier.

[36] NIOSH experts, such as Kenneth Fent and many of his external collaborators, such as Gavin Horn, Denise L. Smith, and Stephen Kerber, have assisted in creating standards, including as members of committees or providing input into National Fire Protection Association (NFPA) Standards 1700 (*Guide for Structural Fire Fighting* [NFPA, proposed]), 1584 (*Standard on the Rehabilitation Process for Members During Emergency Operations and Training Exercises* [NFPA, 2015]), 1971 (*Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* [NFPA, 2018]), and 1851 (*Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* [NFPA, 2014]).

smoke-limiting features on bunker gear, and many new particle-filtering hoods (InterAgency Board for Equipment Standardization and Interoperability, 2016). As an example, in the past two years, the fire service has seen multiple new hoods introduced to the market. Although they are slightly more expensive, these hoods claim to better protect the neck, face, and shoulders of firefighters from exposure to fine particulate matter.[37] To make their findings more accessible to firefighters and fire chiefs, NIOSH researchers and others published articles in commonly read trade journals and gave presentations and workshops at conferences (Fent, Horn, and DeCrane, 2015; Fent, Horn, Kirk, et al., 2015; Jackson et al., 2014; Fent, Evans, Couch, et al., 2012; International Association of Fire Fighters [IAFF], 2016).[38] In September 2017, one of the largest fire service trade magazines, *Firehouse*, published a special supplement highlighting the research of NIOSH and its collaborators, which provided evidence to support many of the exposure reduction recommendations (Illinois Fire Service Institute [IFSI], 2017). Further increasing awareness, the mainstream media began to report on the link between firefighting and cancer (Miller, 2017; Costello, 2017). The increasing awareness led to laws in many states that expanded medical, workers' compensation, and disability coverage for firefighter cancer cases (Hermann and Bui, 2017).[39] Advocates began pushing for more action at the federal level, and, in September 2017, the U.S. House of Representatives passed the Firefighter Cancer Registry Act (H.R. 931, 2017), which tracks cancer cases among firefighters, allowing for more-detailed study of the risks of the job and how to prevent them (National Fallen Firefighters Foundation, 2017; Beilman, 2017). Table 3.1. summarizes key events relevant to the firefighter case study. As with Chapter Two, the table includes only those events covered in the economic analysis. However, in the text below, we describe other events that predate "the case." Also, the analysis of benefits extends beyond the time period represented in the table.

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[37] A particle-filtering hood can cost between $90 and $180, compared with about $40 for more-traditional hoods (see Witmer Public Safety Group, undated, and Walker, 2016).

[38] NIOSH-affiliated researchers have given many presentations, including at the Fire Department Instructor's Conference (a workshop in 2016 and a Big Room session in 2017), the IAFF, the Wellness–Fitness Initiative, and NFPA, as well as creating webinars for *Fire Engineering* and YouTube videos (which have been viewed more than 100,000 times) about reducing exposure. See FSRI, 2015a, 2016.

[39] Thirty-four states have presumptive disability laws (most of which were passed before the NIOSH research), which mandated that, if a firefighter contracted one of the identified cancers (which vary by state), the cancer would be presumed to be work-related, entitling the firefighter to workers' compensation and other benefits. These states are Alabama, Alaska, Arizona, California, Colorado, Idaho, Illinois, Indiana, Iowa, Kansas, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Nebraska, Nevada, New Hampshire, New Mexico, New York, North Dakota, Oklahoma, Oregon, Pennsylvania, Rhode Island, Tennessee, Texas, Utah, Vermont, Virginia, Washington, and Wisconsin. See IAFF, 2016.

Table 3.1. Key NIOSH Activities and Related Events: Firefighter Case Study

Year	Event or Activity
2010	NIOSH begins the largest study of firefighters and cancer conducted to date, including almost 30,000 firefighters.
	The initial NIOSH dermal PAH exposure study for firefighters begins (resulting in a NIOSH report in 2013 and journal articles in 2014 and 2015).
2014	The results of the first NIOSH study are published.[a]
	NIOSH partnership is established with IFSI and FSRI to investigate exposure to chemical carcinogens and other fire service issues.
2015	The results of the second NIOSH study are published.[b]

[a] Daniels, Kubale, et al., 2014.
[b] Daniels, Bertke, et al., 2015.

Evidence of Adoption

In the wake of the NIOSH studies, several fire departments, national fire service organizations, and local fire departments published new exposure reduction guidelines. The most widely cited document compiling a list of these guidelines is *Healthy In, Healthy Out: Best Practices for Reducing Fire Fighter Risk of Exposures to Carcinogens* (HI/HO) (Washington State Council of Fire Fighters, undated), a manual developed with the Kent Fire Department and created with input from NIOSH experts and other researchers. This manual recommends such actions as

- cleaning affected skin of debris with baby cleansing wipes directly after a fire
- continuing to use a breathing apparatus even after a fire has been extinguished
- showering immediately upon returning to the fire station
- establishing command and pump operations upwind of the fire (if possible)
- performing gross on-scene decontamination of gear
- transporting gear in bags or an isolated compartment after a fire
- laundering gear after a fire
- exchanging soiled hoods for clean hoods
- including decontamination as an integrated function of rehab (e.g., cleaning hands prior to nutritional intake)[40]
- paying focused attention to hand cleaning.

In addition, as noted earlier, equipment manufacturers began the process of designing new hoods for firefighters that better protect the head and neck from exposure to chemicals at a fire site, as well as cleaning equipment to rapidly decontaminate skin and PPE on scene. Because of high demand, many new protective products have rapidly transitioned to the fire service market

[40] *Rehab* refers to a period in which (or the location where) the firefighter goes to rest, cool off, be evaluated, and drink and perhaps eat.

in a short time frame, in part because some (e.g., skin cleansing wipes) are inexpensive. Similarly, although respirators have been available since the 1970s for firefighter use, only recently have control measures stressed using them *after* fires by firefighters investigating the scene of the fire and through the *completion* of overhaul. Use of respirators during outside ventilation activities has also recently become a topic of increased conversation, and, with data from the NIOSH studies, this approach is increasingly being implemented in many departments.

Although many fire safety organizations have developed and promoted exposure reduction guidelines to protect their members from an increased risk of cancer, there is currently no precise, quantitative evidence on how widely these standards are being adopted among U.S. fire departments. Some experts with whom we spoke noted that several large fire departments (including departments in Los Angeles County, California; Fairfax County, Virginia; and Phoenix, Arizona) have adopted all or most of the control measures as part of formal protocol. However, we could not find data to indicate how widespread actual use is within those departments.

Approach for Estimating the Economic Benefit of Firefighting Risk Control Measures

Having described NIOSH's activities and documented its likely role in helping to create and publicize new exposure reduction guidelines for firefighters, we now estimate the economic value of the potential risk reductions due to the introduction and adoption of these control measures. To do this, we use the following steps, described in Chapter One: (1) identify the target population; (2) estimate the number of workers affected; (3) estimate the reduction in exposure; (4) estimate the number of avoided injuries, illnesses, and fatalities; and (5) monetize avoided injuries, illnesses, and fatalities.

The last two steps require further clarification. As noted in the previous section, good estimates of the adoption of control measures among firefighters do not exist, and it is likely that the adoption of some recommendations has been more widespread than that of others. Some experts with whom we spoke estimated that this adoption rate could be as high as 85 percent, although this varies by risk-reduction recommendation.[41] Because we lack good estimates of the rate at which departments have adopted control measures among firefighters, in our analysis, we

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[41] Experts believe that the use of self-contained breathing apparatuses (SCBAs) during overhaul has generally become the norm but are less certain of the rate at which departments have adopted the use of SCBAs during ventilation activities. However, there is a strong and established conveyance of research results into practice on cancer protection, and experts believe that the use of SCBAs for ventilation activities should become the norm within the next one to four years. Use of wipes or soap and water to clean the skin right away is another measure that seems to have already become the norm. Experts believe that there is less compliance with the guidance on gross decontamination. Many large departments do appear generally to be laundering the turnout gear with extractors, either in house or contracted out.

assumed a few different levels of adoption and present estimates based on these different assumptions.

In addition, although the relationship between firefighting and cancer is widely accepted among those in the industry and studies to date have shown an association or correlation between cancer and firefighting, it is difficult to establish direct causation. Nonetheless, for the purposes of analysis, we assumed that the excess risk for the cancers analyzed is indeed *caused* by participation in the firefighter occupation (rather than genetics or some other exposure). The strongest evidence to date comes from Daniels, Bertke, et al., 2015, which looked at the incidence of cancer among career firefighters who were more and less exposed to fires, thus accounting for the fact that firefighters might have different characteristics from those in the general population (importantly, smoking prevalence and other lifestyle characteristics were not available in the data for these publications). If firefighting causes cancer, we should expect those who fight more fires to have higher cancer incidence. Daniels, Bertke, et al., 2015, describes a higher incidence of lung cancer among more-exposed firefighters but does not find strong associations with many other types of cancers. Many experts in the field believe that the strongest evidence for a direct link between firefighting and cancer is mesothelioma, which showed a twofold increase in incidence in the original Daniels, Kubale, et al., 2014 study. Although the evidence for a direct link to lung cancer is controversial among researchers, many believe that digestive cancers (e.g., stomach, intestine) are more likely to be directly caused by participation in the firefighting profession.[42] Assessing the validity of the causal relationship between cancer and firefighting is beyond the scope of this paper. In our analyses, we used six cancers (esophagus, intestine, lung, kidney, buccal and pharynx, and mesothelioma) that the Daniels, Kubale, et al., 2014 study found to have significant excess cancer mortality and morbidity among firefighters. However, this list is not comprehensive; as new causal evidence becomes available, cancer types might be added to or deleted from this list.

We also need to characterize the extent to which NIOSH played a significant role in the adoption of safety practices and whether the associated exposure reductions are due to NIOSH rather than to the activities and investments of others. Although the Daniels, Kubale, et al., 2014 study was one of the largest and most-definitive studies of cancer risk among firefighters, several previous studies explored these issues, as did other concurrent large studies in Australia (Glass, Pircher, et al., 2016; Glass, Del Monaco, et al., 2016; Glass, Del Monaco, et al., 2017), Nordic countries (Pukkala et al., 2014), France (Amadeo et al., 2015), and Korea (Ahn, Jeong, and Kim, 2012; Ahn and Jeong, 2015). However, in interviews, industry leaders described the NIOSH publications of Daniels, Kubale, et al., 2014, and Fent, Eisenberg, Evans, et al., 2013 as a turning point in efforts to prevent cancer in firefighters. Because the NIOSH study (Daniels, Kubale, et

[42] This information is based on internal conversations with NIOSH experts in the study of cancer and cancer prevention.

al., 2014) had a large sample and was based in the United States, fire chiefs, firefighters, and policymakers considered it more credible than any of the previous U.S. studies or studies in other countries, where safety standards, construction materials, and other environmental factors can be very different. In addition, NIOSH's experimental studies highlighted exposure pathways that could increase firefighters' risk of cancer, as well as steps that could be implemented to reduce this risk (e.g., Fent, Evans, and Couch, 2010; Fent, Eisenberg, Evans, et al., 2013; Fent, Eisenberg, Snawder, et al., 2014; Fent, Evans, Booher, et al., 2015; Fent, Alexander, et al., 2017). Moreover, those familiar with the industry described a cultural change following NIOSH's work: Where a dirty uniform had earlier been seen as a "badge of courage" or evidence of a positive marker that one was "a real firefighter," this was no longer a widely held belief after the publicizing of the NIOSH results.

Thus, although it is critical to recognize the importance of other research and the pivotal role the partners and stakeholders played in conducting and disseminating the NIOSH research, for this analysis, we assumed that 100 percent of the change in firefighter practices could be attributed in some way to NIOSH's many efforts. However, more research would be needed to determine how best to attribute benefits to individual stakeholders in a highly collaborative effort, such as production of new knowledge.

Steps 1 and 2: Identify the Target Population and Estimate the Number of Affected Workers

Although there are approximately 1.2 million firefighters in the United States, our estimates focus on the roughly 346,000 career firefighters in the country. The Daniels, Kubale, et al., 2014, and Daniels, Bertke, et al., 2015 studies specifically looked at cancer incidence among career firefighters, so these estimates might not apply to firefighters with different occupational roles (e.g., paid on call, paid per call, volunteer) because their risks can be very different. Information from the IAFF indicates that more than 85 percent of the places where people live in the United States are served by career firefighters.[43]

Step 3: Estimate the Reduction in Exposure

Unlike for the case of silica in Chapter Two, there is little research on the extent to which implementation of the new recommendations arising from NIOSH research reduces exposure. One recent NIOSH study showed a 54-percent reduction in PAH exposure to neck skin by using cleansing wipes and an 85-percent reduction in PAH surface contamination from on-scene wet decontamination by using dish soap (Fent, Alexander, et al., 2017). However, there have been no systematic attempts to estimate the overall effect. Fent, a NIOSH researcher who studies

[43] Specifically, the IAFF's website notes that the association's membership of professional firefighters covers "more than 85 percent of the population in communities throughout the United States and Canada." See IAFF, undated.

carcinogenic exposure among firefighters, together with Horn, research director of IFSI (operated by the University of Illinois) used their work in this area and previous research to estimate that, on average, full implementation of the safety recommendations would reduce exposure among full-time firefighters (involved in fire attack or overhaul in the hot zone) by approximately 90 percent.[44] Exposure levels for command and pump-operation (C/P) personnel are estimated to be less than 20 percent of those of firefighters in the hot zone. Fent and Horn estimated that these people would see an approximately 80-percent reduction in exposure by following the exposure reduction recommendations. The confidence intervals (Cis) around these estimates are large, in part because of the unpredictable and variable nature of firefighters' exposure. Appendix B provides additional details about Fent and Horn's estimates. However, it is important to caution that, even with full implementation of current control measures, carcinogenic exposure and biological uptake could continue to occur when contaminants penetrate through or around the spots where various pieces of the turnout gear (PPE) come together.

Estimates of the percentage of firefighters engaged in different activities vary. Firefighters often switch between roles and responsibilities depending on station assignment and might also change roles from response to response. In addition, the activities that a given firefighter performs over his or her career can change dramatically through time. Thus, it is difficult to get a precise measure for a given firefighter's reduction in exposure levels from the control measures. For the purposes of this analysis, we used the estimates from Fent and Horn together with an estimate from Austin, Dussault, and Ecobichon, 2001, about the percentage of people who are engaged in frontline firefighting (in the hot zone) at any given time to estimate total reductions in exposure.[45] Taking a weighted average of the percentage reductions that Fent and Horn suggested, along with the percentage of exposure attributed to the different roles, we estimate that exposure is reduced by between 84 percent and 93 percent when the majority of control measures are put into place. Although the exposure reduction estimates are not precise, point estimates are necessarily used for the economic analyses.

The reader should also note that these percentage reductions in exposure are based on the implementation of the control measures compared with standard practice in the early 2000s. Specifically, we assumed that, in the early 2000s, firefighters did not regularly wear SCBA during overhaul or outside ventilation activities, did not deliberately set up command upwind,

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[44] A large percentage of this reduction would be achieved by the use of SCBA postsuppression and during outside ventilation activities. This is because inhalation is the most direct and expeditious route for chemicals to enter the body. As inhalation exposure is controlled, dermal absorption becomes a more important route of exposure in terms of percentage of total dose.

Hot zone refers to a hazardous material–contaminated area requiring protective gear and decontamination.

[45] See Austin, Dussault, and Ecobichon, 2001. Using these numbers, we estimate that 94.4 percent of exposure is in the frontline firefighter role and that 5.6 percent of exposure is in the C/P personnel and other supporting roles.

did not perform decontamination, and so on. Because the Daniels, Kubale, et al., 2014, and Daniels, Bertke, et al., 2015 studies measure cancer incidence for firefighters employed as early as the 1950s, much of the excess carcinogen exposure measured in the studies might have already been reduced before the early 2000s as control measures improved through time. To the extent that this is true, our estimates of the benefits of NIOSH efforts in this area overestimate the actual benefit because we attribute all reduction in risk to the new guidelines. However, this bias can be counteracted by the increasing prevalence of toxic substances in construction and product manufacturing described earlier. According to NIOSH experts, both trends are important to understanding changing exposure over time, and it is not clear that one outweighs the other. Whereas modern gear and SCBAs provide more-effective protection, modern construction materials likely produce more toxicants. Because of increased safety gear, firefighters might be tempted to move more often and quickly into the interior of structures. NIOSH and its partner organizations are currently doing additional research on fire attack methods, although more research on firefighters' changing risk of carcinogen exposure is also necessary.

Step 4: Estimate the Number of Avoided Injuries, Illnesses, and Fatalities

In estimating the number of avoided cancer cases, we use Daniels, Kubale, et al., 2014 estimates of "excess risk" of cancer among firefighters and Fent and Horn's estimates of reduction in cancer risk from the exposure reduction recommendations. Given uncertainty about the adoption of the control measures, we use an 85-percent adoption rate, but also conduct sensitivity analyses assuming 100-percent adoption and 50-percent adoption.

Step 5: Monetize Avoided Injuries, Illnesses, and Fatalities

We use the total medical costs and productivity losses of cancer together with the total assumed number of cases reduced to provide monetized estimates of the benefit associated with the NIOSH research. As noted above, we provide estimates for six cancers that were identified in the Daniels, Kubale, et al., 2014 study as being associated with firefighters' increased mortality and incidence compared with that of the general public (see Table 3.2). For example, firefighters are 13 percent more likely than members of the general public to get lung cancer.

Table 3.2. Select Cancers Found with Excess Relative Risks to Be More Common Among Firefighters Than in the General Population

Cancer	Standardized Mortality Ratio	Standardized Incidence Ratio (First Cancer)
Buccal or pharynx	1.40 (95% CI: 1.13–1.72; *n* = 94)	1.41 (95% CI: 1.20–1.66; *n* = 148)
Large intestine	1.31 (95% CI: 1.16–1.48; *n* = 264)	1.28 (95% CI: 1.15–1.43; *n* = 335)
Kidney	1.29 (95% CI: 1.05–1.58; *n* = 94)	1.24 (95% CI: 1.04–1.48; *n* = 129)
Lung	1.10 (95% CI: 1.04–1.17; *n* = 1,046)	1.13 (95% CI: 1.04–1.22; *n* = 602)
Malignant mesothelioma	2.00 (95% CI: 1.03–3.49; *n* = 12)	2.00 (95% CI: 1.31–2.93; *n* = 26)
Esophagus	1.39 (95% CI: 1.14–1.67; *n* = 113)	1.71 (95% CI: 1.35–2.13; *n* = 80)

SOURCE: Daniels, Kubale, et al., 2014.
NOTE: These are cancers that had significantly higher mortality and incidence among firefighters than in the general population.

To calculate the medical cost of each type of cancer, we used data from the National Cancer Institute.[46] These data provide estimates of the medical costs for different types of cancer for both men and women over age 65 in the first year after diagnosis, the yearly costs of living with the disease after the first year of diagnosis, and the cost of the final year of life. We adjusted these costs to come up with an *estimated medical cost, by cancer type, for firefighters* by taking into account the gender and age mix of the profession and by estimating costs for people younger than 65.[47] We inflation-adjusted medical costs to 2016 dollars using the Consumer Price Index for medical care.

Next, we estimated 20-year survival probabilities for each of the cancer types to calculate average medical costs for the affected population. Because survival rates for many cancers have been increasing because of improvements in the quality of medical treatment, we scaled the historical survival rates by the increase in the one-year survival rate for diagnoses made between 2004 and 2013 (the most recent one-year estimate) to estimate the current 20-year survival probability (Howlader et al., 2017). We also assumed that the last year of life occurs in year 20 for anyone still alive, based on the estimated survival probabilities. Using these survival

[46] See National Cancer Institute, undated, which is based on Mariotto et al., 2011.

[47] We estimate that 95 percent of firefighters are men (see NFPA, undated). We also adjusted initial-diagnosis costs by a factor of 1.2 and last-year-of-life costs by a factor of 1.5 to account for patterns of care that have been reported to be more aggressive for younger cancer patients, based on information in Mariotto et al., 2011. We assumed that 40 percent of those who are diagnosed with cancer and are living with cancer in a given year are under age 65 and that 30 percent of those who die of cancer are under age 65.

rates, we estimated that 57 percent of people diagnosed with lung cancer will die within one year. For these cases, we estimated medical costs for only the last year of life. For the 6 percent of people who will die within three years of a lung cancer diagnosis, we estimated medical costs for the first year after diagnosis, continuing annual treatments, and the last year of life. Our estimate of the average lifetime cost of a lung cancer fatality is a weighted average of medical costs by years of treatment and the survival probability for each year after diagnosis.

To account for lost earnings, fringe benefits, and work done outside of the labor force (i.e., home production), we also estimated productivity losses. We derived productivity loss estimates based on the present value of future lifetime production for the affected workforce.[48] We then followed the approach in Leigh, 2011, in multiplying estimates of lost production by the morbidity-to-mortality ratios in Rice, Hodgson, and Kopstein, 1985, to estimate the benefits of avoided morbidity.[49] We inflation-adjusted productivity losses to 2016 dollars using the GDP implicit price deflator.

Combining the medical costs and productivity losses (adjusted to the population of firefighters) with the estimated survival rates, we then constructed an average total lifetime cost for each type of cancer. For each avoided fatality, we estimated total medical costs, productivity losses associated with morbidity, and productivity losses associated with mortality. We estimated average lifetime medical costs and productivity losses of $814,963 for fatal cases of lung cancer and $255,695 for nonfatal cases.[50] To come up with an estimated benefit of the NIOSH research, we then applied these costs to the estimated number of firefighters who will not contract cancer due to implementation of the new exposure reduction guidelines.

In a separate analysis, we used WTP estimates to monetize the cost burden for cancers. As an alternative approach and to be consistent with the silica case presented in Chapter Two, we separately report WTP estimates. For fatal illnesses avoided, we used a VSL of $9.5 million (in 2016 dollars) (Viscusi and Aldy, 2003).[51] We added the value of avoided morbidity to this estimate and discounted it in the same year. Ideally, this would be captured (and discounted) at the onset of morbidity to reflect the worker's WTP to avoid an illness. Given insufficient data on age of onset and survival probabilities, this was not feasible. Thus, for nonfatal illnesses avoided,

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[48] We derived the productivity loss estimates from the average population estimates in Grosse, Krueger, and Mvundura, 2009, which also applies a 3-percent discount rate to all future production.

[49] These estimates do not include the costs associated with overtime and labor replacement costs, such as the cost of training new hires.

[50] These are similar to but slightly different from the costs presented for lung cancer in Chapter Two because of differences in the age, gender, and income distribution between firefighters and construction workers.

[51] The U.S. Department of Transportation and the U.S. Department of Health and Human Services currently recommend using a VSL of $9.6 million (in 2016 dollars) for regulatory analyses. Guidance documents from these agencies describe the motivation and methodologies for using WTP estimates to value avoided fatal and nonfatal injuries and illnesses. For this analysis, we used OSHA's VSL figure, which predates these guidance documents but is nearly identical.

we followed OSHA's approach in using a low-end estimate of $68,000 and a high-end estimate of $5.5 million (or approximately 58.3 percent of the value of a fatal illness).[52] Therefore, for nonfatal cases, we used a midpoint estimate of approximately $2.8 million.

To determine the reduction in cancer mortality and incidence for firefighters, we used the increased risk estimates in Daniels, Kubale, et al., 2014 together with data from the CDC Wide-Ranging Online Data for Epidemiologic Research (CDC WONDER) database to calculate the probability of death for each cancer type in the general population and for the population of firefighters.[53] For instance, an average male has about a 5.1-percent chance of dying from lung cancer between the ages of 20 and 84.[54] According to the study, firefighters are 10 percent more likely than members of the general population to die from lung cancer. Therefore, a firefighter has about a 5.6-percent chance of dying from lung cancer between the ages of 20 and 84.

Using the excess mortality for firefighters compared with that for the general population (in the case of lung cancer, this would be 0.5 percent), together with the number of career firefighters in the United States, we could estimate the number of firefighters who die from job-related cancer risk in excess of cancer deaths in the general population. We used the difference between the mortality and incidence rates to estimate the number of firefighters who suffer from the disease but do not die and apply the estimates of nonfatal costs to them. As noted earlier, we do not have rigorous estimates about how many firefighter deaths and illnesses the new exposure reduction guidelines reduce. We used an estimate of 90-percent effectiveness of the exposure reduction recommendations and an 85-percent adoption rate for how widely adopted the control measures are.

We made assumptions about job tenure, cancer latency, and the value of future benefits. Our analysis estimated a stream of benefits over time. Benefits will phase in over several decades because health risks depend on cumulative occupational exposure over a 45-year working lifetime. A worker joining the workforce today would benefit from reduced carcinogen exposure for his or her entire working career; however, current workers would benefit from reduced exposure for a shorter duration depending on age. We assumed that the number of fatalities avoided would gradually increase (in a straight-line projection) from zero in year 1 after the adoption of the new control measures until reaching a new steady state in year 45—and

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[52] See discussion in Chapter VII of OSHA's final economic analysis for the silica rule. The low-end estimate is based on Viscusi and Aldy, 2003, and the high-end estimate is based on Magat, Viscusi, and Huber, 1996.

[53] Data come from the following sources: (1) CDC WONDER, 2016 (data from CDC WONDER, 2017, as compiled from data provided by the 57 vital statistics jurisdictions through the Vital Statistics Cooperative Program); (2) CDC WONDER, undated (c); and (3) CDC WONDER, undated (b). We estimate the probability of death only for people between the ages of 20 and 80.

[54] Calculated from data from the following sources: (1) CDC WONDER, 2016 (data from CDC WONDER, 2017, as compiled from data provided by the 57 vital statistics jurisdictions through the Vital Statistics Cooperative Program) and (2) CDC WONDER, undated (c).

remaining at the new level in perpetuity. Using OSHA's findings, because of a relatively long latency period, we also estimated a 15-year lag for reductions in lung cancer risk. We used an 11-year lag for mesothelioma and four-year lags for all other cancers (Howard, 2013). Given the 15-year latency period for lung cancer, we would not see the full scope of benefits until 60 years after the adoption of control measures. Specifically, we assumed that the number of lung cancer fatalities avoided will remain at zero for the first 15 years and then rise linearly until year 60. To reflect the social preference for the timing of benefits, we applied a discount rate of 3 percent. We also allowed monetized future benefits to increase over time. For the medical cost approach, we assumed that real medical costs would rise over time. In the past 30 years, medical costs have risen 2.4 percent faster than GDP (Friedman, 2010). For the WTP approach, we assumed that future WTP would rise with real income. Using OSHA's estimates, we also estimated that the VSL would increase by 2 percent per year, assuming a 1.4-average annual increase in real per capita income and an income elasticity of 1.44.[55] Therefore, for both approaches, we estimated that the value of future benefits would increase by approximately 2 percent annually.

Finally, to estimate the total benefit attributable to NIOSH research activities, we calculated the net present value of these benefits over 60 years on an annualized basis.[56]

Summary of Assumptions Made in Estimating Benefits

Several assumptions were necessary because of gaps in data and research about many of the key parameters in our model. Some of the important assumptions that we have made (and key areas for future research) include the following:

- We assumed that all the excess cancer risk in firefighters was from their exposure to chemical carcinogens. Shift work, sleep disruption, and even diet could also play a role in their cancer risk.
- We assumed that PAHs and volatile organic compounds reported in the literature are representative of particulate and vapor exposure in general. Because combustion can produce hundreds of compounds, it is likely that many of these compounds are absorbed, metabolized, and excreted differently. Some compounds (including some carcinogens) can be stored in biological tissues, organs, or excreted in feces.
- Because precise estimates do not exist, we used estimates of central tendency as reported in the literature for exposure and exposure reduction where available or professional judgment in deriving our estimates of exposure reduction. Exposure and decontamination efficiency could vary by department or person. Removal efficiency from equipment and

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[55] See discussion in Chapter VII of OSHA's final economic analysis for the silica rule (OSHA, 2016a).

[56] The annualized estimates presented in this report indicate that we calculated the present value (i.e., the value today) of a future stream of payments in real-dollar terms. This calculation requires a stream of projected future costs, the specific years in which those costs are incurred, and a discount rate. We calculated annualized values, taking into account the discount rate and the number of years in the forecast period, to provide a comparison across activities with varying time components and forecast periods.

skin is also likely to vary by type of chemical. For the calculation of benefits, we used point estimates for the reduction in exposure, whereas these point estimates have large Cis.

- Because of a lack of data, we assumed that 85 percent (or 100 percent or 50 percent in the sensitivity analyses) of career firefighters have adopted all the exposure reduction recommendations. This likely varies substantially for each recommendation and each department. In addition, some volunteer departments have adopted some of these recommendations.
- We assumed that 100 percent of the exposure reduction changes in the fire service are attributable in some way to the NIOSH research.
- We did not include volunteer firefighters in the main estimation, although NIOSH research on preventing cancer among firefighters also likely benefits them. We present estimates for the entire population in a sensitivity test; however, some caveats are noted in the "Sensitivity Analyses" section.
- We also did not take into account progress in the adoption of recommendations in the future or potential future improvement in the recommendations. The impacts of recent NIOSH work in this area are ongoing, and adoption and control measure recommendations will likely improve over time.

Estimate of the Total Benefit

Table 3.3 provides annualized benefit estimates for six cancers that the authors of Daniels, Kubale, et al., 2014 found to be associated with firefighting using medical costs and productivity losses. Table 3.4 provides estimates using VSL methodology. As noted, these two methodologies answer very different questions, and VSL estimates are much larger than the medical cost estimates. To illustrate the method described earlier, for lung cancer, we estimated the following using medical costs and productivity losses:

- step 1: 1.2 million firefighters in the United States
- step 2: 346,000 career firefighters in the United States who benefit from the control measures
- step 3: 90-percent reduction in risk for firefighters and 85-percent adoption rate (see also the sensitivity analyses)
- step 4: 1,349 deaths and 993 illnesses
- step 5: total benefits: $16 million annualized.

Table 3.3. Estimated Annualized Benefits of Avoided Fatal and Nonfatal Cancers for Firefighters Due to the Adoption of Control Measures over a 60-Year Time Horizon Using Medical Costs and Productivity Losses

Measure	Estimated Benefits
Total number of fatal cases avoided	4,058
Lung cancer	1,349
Buccal and pharynx cancers	361
Malignant mesothelioma	302
Esophagus cancer	696
Cancer of the large intestine	963
Kidney cancer	386
Total number of nonfatal cases avoided	5,135
Annual number of fatal cases avoided	45
Annual number of nonfatal cases avoided	60
Annualized benefit of control measures, in millions of dollars	71
Lung cancer	16
Buccal and pharynx cancers	10
Malignant mesothelioma	3
Esophagus cancer	14
Cancer of the large intestine	19
Kidney cancer	10

NOTE: We have rounded these numbers, so totals do not sum precisely.

Table 3.4. Estimated Annualized Benefits of Avoided Fatal and Nonfatal Cancers for Firefighters Due to the Adoption of Control Measures over a 60-Year Time Horizon Using Willingness-to-Pay and Value-of-a-Statistical-Life Estimates

Measure	Estimated Benefits
Total number of fatal cases avoided	4,058
Lung cancer	1,349
Buccal and pharynx cancers	361
Malignant mesothelioma	302
Esophagus cancer	696
Cancer of the large intestine	963
Kidney cancer	386
Total number of nonfatal cases avoided	5,135
Annual number of fatal cases avoided	45
Annual number of nonfatal cases avoided	60
Annualized benefit of control measures, in millions of dollars	1,013
Lung cancer	224
Buccal and pharynx cancers	149
Malignant mesothelioma	55
Esophagus cancer	189
Cancer of the large intestine	266
Kidney cancer	130

NOTE: As in the silica case, the results are sensitive to the choice of the WTP estimate for valuing avoided morbidity cases. The total estimated benefits range from a $610 million to $1.4 billion, depending on the choice of the WTP value for avoided morbidity cases. We have rounded these numbers, so totals do not sum precisely.

We estimated that firefighter use of the HI/HO control measures would reduce fatal cancer cases by about 4,000 and nonfatal cases by about 5,000 over 60 years. This reduction in mortality and morbidity would reduce medical costs and productivity losses by $71 million per year. Preventing cancer of the large intestine accounts for the largest share of the reduction in costs, at $19 million, followed by lung cancer ($16 million), esophagus cancer ($14 million), buccal and pharynx cancer ($10 million), kidney cancer ($10 million), and malignant mesothelioma ($3 million). As noted earlier, VSL estimates are broader, capturing individuals' subjective WTP to avoid the loss of life, health, quality of life, and other factors. Thus, estimates using VSL instead of medical costs and productivity losses are significantly higher, ranging from $55 million for mesothelioma to $266 million for cancer of the large intestine. Total estimates using VSL are approximately $1 billion.

Sensitivity Analyses

In this section, we discuss the sensitivity of the medical costs and productivity loss results to two key assumptions in the analysis: the effectiveness of the control measures in preventing cancer and their adoption among career firefighters. We also present a further analysis that estimates the effect of different assumptions about the size of the firefighter workforce. In the main analysis, we assumed that adoption of the control measures would reduce cancer risk by 90 percent and that 85 percent of firefighters adopt the recommendations. In Table 3.5, we test the sensitivity of these assumptions by showing results for 100-percent risk reduction and adoption, as well as for 50-percent risk reduction and adoption.

Table 3.5. Sensitivity Analyses for Medical Costs and Productivity Losses

Measure	Estimated Benefits	Sensitivity 1: 100% Adoption and Risk Reduction	Sensitivity 2: 50% Adoption and Risk Reduction	Sensitivity 3: 1.2 Million Firefighters Affected
Total number of fatal cases avoided	4,058	5,304	1,326	14,074
Total number of nonfatal cases avoided	5,135	6,712	1,678	17,807
Annual number of fatal cases avoided	45	59	15	155
Annual number of nonfatal cases avoided	60	79	20	209
Annualized benefit of control measures, in millions of dollars	71	93	23	248
Lung cancer	16	21	5	54
Buccal and pharynx cancers	10	13	3	35
Malignant mesothelioma	3	4	1	11
Esophagus cancer	14	18	5	48
Cancer of the large intestine	19	24	6	64
Kidney cancer	10	13	3	34

NOTE: Annualized benefits using VSL measures are $1.3 billion for sensitivity 1, $331 million for sensitivity 2, and $3.5 billion for sensitivity 3. We have rounded these numbers, so totals do not sum precisely.

Next, we estimated the effect of assuming a larger career firefighter workforce. Any change in the size of the estimated workforce is directly proportional to the magnitude of the change in estimated benefits. This sensitivity analysis includes the more than 850,000 volunteer firefighters in the country, implicitly assuming that their risk profiles and use of control measures are similar to those of career firefighters. This assumption might not be valid for several reasons. For example, smaller fire departments might not have the same level of resources or capacity for enforcing safety protocols that larger and better-funded departments have, resulting in more exposure to carcinogens and thus increased risk of cancer. On the other hand, rural firefighters likely have fewer fire responses than those in urban areas and therefore have less exposure to fires during their careers. Given the uncertainty of cancer risk and control measure adoption among volunteer firefighters, this estimate likely represents an extreme upper bound by including the total number of firefighters in the country, many of whom likely have lower levels of job-related exposure. Better understanding of cancer risk and adoption of control measures among volunteer firefighters is an important area for future research.

Conclusion

We estimate that firefighters using control measures derived from the studies that Daniels et al. and other NIOSH researchers conducted would benefit from significantly reduced exposure to cancer due to the adoption of control measures that include cleaning affected skin of debris with cleansing wipes directly after a fire, continuing to use a breathing apparatus even after the fire has been extinguished, showering immediately upon returning to the fire station, and establishing command and pump operations upwind of the fire. Specifically, we estimate that such control measures could reduce medical costs and productivity losses for firefighters by approximately $71 million per year, with benefits as high as $93 million and as low as $23 million, depending on assumptions made about the risk reduction caused by the control measures and their adoption among the population of career firefighters. Estimating benefits using VSL instead of medical costs and productivity losses raises benefits to about $1 billion. Moreover, NIOSH's research activities appear to have played a major role in advancing the adoption of the HI/HO recommendations and helping to change firefighter culture to be more focused on safety and cancer prevention.

Chapter Four. Assessing and Disseminating Impacts of Ohio Safety Intervention Grants

Benefit payments under workers' compensation programs totaled $62.3 billion nationally in 2014, with medical benefits and wage loss compensation accounting for roughly $31 billion each. Employers' costs were approximately $1.35 per $100 of covered wages (Baldwin and McLaren, 2016). Thus, reducing the severity or risk of injury provides benefits to insurers, workers, and employers. One way to do this is through investments in engineering controls. The Ohio Bureau of Workers' Compensation (BWC)—the largest of four exclusive state-run workers' compensation systems in the United States—sought to incentivize such purchases through its Safety Intervention Grant Program, which offers matching funds to employers that agree to purchase safety and health engineering controls to reduce acute injuries, airborne contaminants, and risk factors for work-related musculoskeletal disorders.

This case study focuses on a NIOSH research study, published in 2014, that evaluated the effectiveness of BWC's Safety Intervention Grant Program (Wurzelbacher, Bertke, et al., 2014). NIOSH's evaluation found that the program significantly reduced workers' compensation claims and costs. Preliminary results from the study informed BWC's decision to expand the program in 2013, and dissemination of the results promoted the adoption of insurer-supported grant initiatives in other states.

We drew on data from NIOSH's research and related literature, from national statistics, and from three state-run workers' compensation systems to assess the contribution of NIOSH's research and dissemination efforts to the expansion of Ohio's grant program in 2013 and the creation of similar, though smaller, programs in two other states: Texas and Missouri. The first part of the analysis involves our assessment of the extent to which NIOSH played a significant role in these developments. The second part of the chapter estimates the economic benefits associated with the Ohio expansion and the new grant programs in Texas and Missouri relative to a hypothetical alternative scenario in which no expansion or new programs occurred.

Overview of NIOSH's Activities Pertaining to Ohio Safety Intervention Grants

NIOSH's research and dissemination efforts were built on a long-term partnership with BWC. The chapter begins by describing the historical context and then providing more detail on the Ohio evaluation study and related activities. Table 4.1 shows the key activities and events. Like with the earlier chapters, the table includes only those events covered in the economic analysis. However, in the text below, we describe other events that predate "the case." Also, the analysis of benefits extends beyond the time period represented in the table.

Table 4.1. Key NIOSH Activities and Related Events: Ohio Safety Intervention Grant Case Study

Year	Event or Activity
2012	BWC works with NIOSH to evaluate the effectiveness of the grant program.
	NIOSH, along with others, organizes a workshop, "Use of Workers' Compensation Data for Occupational Safety and Health."
2013	BWC quadruples the size of the grant program to reach $15 million annually for Fys 2013 and 2014, based on preliminary results from the NIOSH study.
	NIOSH launches CWCS to support the use of workers' compensation data and systems to improve workplace safety and health.
2014	BWC and CWCS publish Wurzelbacher, Bertke, et al., 2014, on the effectiveness of the grant program.
2015	BWC approves $15 million annually for Fys 2015 and 2016.
	Ohio presents BWC and NIOSH research results at the American Association of State Compensation Insurance Funds conference for state insurers.
2016	After witnessing the success of the Ohio program, Missouri begins a similar safety grant program and Texas pilots one.
2017	Missouri decides to cut the grant size in half in order to double the number of recipients.
	After the pilot program, Texas redesigns its rollout of grants as a first-come-first-served design.
	BWC approves $15 million annually for Fys 2017 and 2018.

NOTE: FY = fiscal year. CWCS = Center for Workers' Compensation Studies.

Ohio Safety Intervention Grants and the NIOSH–BWC Partnership

In July 1999, the Ohio BWC initiated the Safety Intervention Grant Program to provide Ohio employers with matching grants for the purchase of equipment and tools to reduce workers' exposure to workplace hazards. Safety intervention grants are available to all organizations that BWC insures. About 4,000 grants were given out between 1999 and early 2017. BWC also gathers data to study the effectiveness of various safety interventions, identify best practices, and disseminate results to employers (BWC, 2010; CWCS, undated, p. 4). A notable example is the first issue of "Ergonomics Best Practices for the Construction Industry," published in 2004, which documents injury reductions that resulted from the use of adjustable scaffolding, rough-terrain forklifts, and other tools and includes case studies of Ohio companies that used safety intervention grants to purchase different ergonomic aids (Laborers' Health and Safety Fund of North America, 2004). The program requires two years of reporting after the implementation of a grant, along with quarterly reports and a case study prepared by the employer. According to BWC, the reporting structure for grantees ensures continuous engagement of both the employer and employees at affected firms. Currently, employers are eligible for a three-to-one matching grant, up to a maximum award of $40,000 for each eligibility cycle (BWC, undated [b]). The Safety Intervention Grant Program is available to private and public taxing districts that pay into the Ohio state insurance fund and is not available for self-insured employers or state agencies. The state insurance fund provides coverage to about 60 percent of the employees in Ohio, not all of those who are employed in Ohio.

NIOSH Activities in the Ohio Evaluation Study

From 2009 onward, NIOSH became more heavily involved with BWC, and, in 2010, the two formalized a partnership that included the evaluation study that is the focus of this case study. According to an interview with a BWC staff member, the collaboration with NIOSH allowed BWC to obtain, for the first time, credible estimates of workers' compensation claim rates per employee hours worked, the size and industry of employers that the safety intervention grants affected, and other information required to rigorously estimate the effectiveness of the grant program. The report on the study evaluating the Ohio grant program was published in 2014 (Wurzelbacher, Bertke, et al., 2014) and relied on data that BWC collected from 2001 to 2009. In 2013, after seeing the preliminary results of the NIOSH work, BWC quadrupled its annual funding for safety intervention grants to substantially increase the total number of grants available per year (Buehrer, 2013). This allowed an increase in the number of grants (from 126 employers receiving a total of $3.2 million in FY 2012 to an average of 510 employers receiving a total of $13.8 million per year in Fys 2013–2016) and a more generous three-to-one matching-fund ratio. Interviews with a BWC official suggest that, without NIOSH, the program would have been expanded, but maybe not until 2017–2020.

Evidence of Adoption

After establishing the success of the Ohio program, similar programs were launched in Missouri (the Missouri Employers Mutual [MEM] Safety Grant program) and Texas (the safety and wellness grant programs by Texas Mutual Insurance Company). Interviews with representatives from the two states confirmed that NIOSH's evaluation and dissemination efforts—specifically, personal discussions with Ohio BWC staff members, a 2015 presentation at the American Association of State Compensation Insurance Funds conference, and a NIOSH primer on the topic—played a significant role in the decision to adopt the idea. Moreover, Ohio BWC was also heavily involved in providing guidance to the designers of the program in Missouri. For example, the limits on acceptable items that employers can purchase using safety intervention grant funds were copied from Ohio to Missouri.

Missouri began its program in 2016 with 17 safety grants. After three program cycles, MEM decided to cut the grant amount in half in order to double the number of recipients for FY 2018. Over the next three years (2018–2020), MEM plans to award policyholders with at least $1 million in safety grants and potentially more if additional evidence of improved workplace safety is found. The program involves a one-to-one match, and applicants have to buy equipment before MEM reimburses them. Policyholders are also required to report on the success of funded safety initiatives.[57] Grants are available for all policyholders, regardless of premium size.

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[57] Interview with an MEM official, 2017.

Texas Mutual piloted its own grant program in 2016, awarding around $100,000 of safety grants in total. However, the current design of the program differs substantially from those in both Ohio and Missouri. After the pilot, Texas decided to make the application and evaluation process more fluid and manageable and redesigned its full rollout of the grants as a first-come-first-served design rather than an application-based process. There are also no matching funds, only one-time grants. The program was expanded for 2017, with $1 million reserved for safety grants per year. Another $1 million is issued for wellness grants, which we excluded from the analysis in this case study. According to our interviews, it appears that Texas Mutual is committed to continuing to offer both grant types in the future. Table 4.2 summarizes some of the main differences among the programs.

Table 4.2. Primary Differences Among Safety Intervention Grant Programs in Ohio, Missouri, and Texas

State	Year	Application Review Cycle	Policy Requirements	Required Employer Dollars per Grant Dollar	Target High-Risk Industries?	Maximum Grant Size, in Thousands of Dollars
Ohio	2012	Weekly	Policyholder for prior two years	1:2	Yes, via review of applications	40
Ohio	2013	Weekly	Policyholder for prior two years	1:3	Yes, via review of applications	40
Ohio	2014	Weekly	Policyholder for prior two years	1:3	Yes, via review of applications	40
Ohio	2015	Weekly	Policyholder for prior two years	1:3	Yes, via review of applications	40
Ohio	2016	Weekly	Policyholder for prior two years	1:3	Yes, via review of applications	40
Missouri	2016	Twice a year	Policyholder at time of application	1:1	Yes, via review of applications	20
Missouri	2017	Twice a year	Policyholder at time of application	1:1	Yes, via review of applications	20
Missouri	2018	Twice a year	Policyholder at time of application	1:1	Yes, via review of applications	10
Texas	2016	One-time pilot program	Policyholder at time of application	0:1	Yes, via review of applications	1.5
Texas	2017	While funds are available	Policyholder at time of application	0:1	No, first come, first served	1.5

Not counting the spending by employers, since 2012, Ohio has spent an average of $26,800 per grant, $40,000 being the maximum amount.[58] In Missouri, the average award was

[58] Email correspondence with BWC officials, 2017.

approximately $10,000 per grant, with the maximum amount being $20,000 in 2016–2017.[59] Missouri plans to decrease the maximum grant size to $10,000 in 2018 in order to increase the number of grants provided. The grants that Texas Mutual offers are substantially smaller: The average grant size was $1,370, with a maximum amount of $1,500.[60] Table 4.3 shows the number of safety grants issued per state insurer, along with the total sum of the awards per year since 2012.

Table 4.3. Number of Safety Grants per State Since 2012

FY	Ohio Safety Intervention Grants	Ohio Amount Awarded, in Millions of Dollars	Missouri Safety Grants	Missouri Amount Awarded, in Millions of Dollars	Texas Safety Grants	Texas Amount Awarded, in Millions of Dollars
2012	126	3.2	0	0	0	0
2013	491	13.6	0	0	0	0
2014	561	15.4	0	0	0	0
2015	521	14.3	0	0	0	0
2016	479	11.9	17	≈ 0.3 (est.)	73 (est.)	≈ 0.1
2017	n/a	15.0 (est.)	20	≈ 0.4 (est.)	730 (est.)[a]	≈ 1.0
2018	n/a	15.0 (est.)	40 (est.)	≈ 0.4 (est.)	n/a	n/a

NOTE: n/a = data not available.
[a] According to an interview with a Texas Mutual representative, 708 grants were initially provided, but, because not all policyholders spent the maximum award of $1,500, more grants were given out, making the total between 700 and 800.

In addition, several other states have new or forthcoming safety grant programs that were initially flagged in interviews as having been potentially influenced by Ohio's success and the NIOSH study. However, given limited evidence on the links between those programs and the NIOSH study, we decided to exclude these programs from our analysis.

Approach for Estimating the Economic Benefit of Impacts

Employers' specific uses of these safety grants vary by such factors as the state's award process and the size of the grant. However, the general thinking behind the program is that the employer will use these grants to purchase items that will reduce the risk and severity of employee injuries. This avoidance of injury reduces workers' compensation costs paid by the insurer, such as indemnity (partial wage replacement) and medical payouts, as well as administrative costs. These savings can be passed back to employers in the form of lower insurance premiums. Employers also avoid the productivity losses associated with injured

[59] Interview with an MEM official, 2017.

[60] Interview with a Texas Mutual official, 2017.

workers and experience efficiency from any new equipment. Workers and their families benefit from avoiding the cost of injuries, which are rarely fully compensated even under more-generous insurance payments. The avoided injuries also help workers avoid additional long-term wage losses and increased future risk of reinjuring themselves.

Having described NIOSH's activities and documented the institute's likely role in the creation or expansion of various states' workers' compensation safety grants, we next estimated the monetary value of those programs and expansions. To do this, we used the following steps, described in Chapter One: (1) identify the target population; (2) estimate the number of workers affected; (3) estimate the reduction in exposure; (4) estimate the number of avoided injuries, illnesses, and fatalities; and (5) monetize the avoided injuries, illnesses, and fatalities. We used these steps to estimate three categories of benefits associated with the safety grant programs: avoided workers' compensation costs, associated productivity gains, and avoided uncompensated wage losses. We did not account for other categories of benefits, such as a worker's additional utility from avoided injuries beyond avoided wage losses or additional employers being attracted to join the insurance market. Next, we present our approach for each of the five steps.

Throughout, it is important to remember that the analysis sought to estimate the value of NIOSH research. Thus, for the Ohio program, we focused on the *increase* in benefits due to the *expansion* of the program, which was encouraged by the NIOSH evaluation study. Moreover, we also considered the possibility that the program expansion might have occurred without the NIOSH study. According to interviews with personnel in Ohio, however, it seems likely that, without the NIOSH study, BWC would have eventually determined the value of its grant program and expanded it, albeit with perhaps five or more years of delay. Thus, we examined the counterfactual of a five-year delay in the determination of the impact of the BWC program, the subsequent expansion of the program in Ohio, and the creation of similar programs in other states. In Missouri and Texas, the benefit associated with the NIOSH study is the adoption of the idea in the first place. Thus, here we focused on all the benefits flowing from those programs, while, for Ohio, we focused on the difference between pre- and postexpansion benefits.

In the rest of this section, we present our results for each of the five steps.

Steps 1 and 2: Identify the Target Population and Estimate the Number of Affected Workers

The safety grant programs could potentially benefit any employee covered by workers' compensation insurance. Table 4.4 lists the number of covered employees by year for Ohio, Missouri, and Texas. For Ohio, we list the last year of the program preexpansion (2012) to 2016. The program expansion described earlier is clearly seen in the increase in the number of grants from 126 in 2012 to 491 in 2013. For Missouri, we examine the two years that the program has been in existence (2016 and 2017) and forecast the role of changes to the program in 2018. For Texas, we include both 2016, when the program pilot was conducted, and 2017, when the program was under way. Ohio and Missouri attempt to target safety grants at high-risk industries, while Texas, after piloting a targeted application process, instead opted for a first-come-first-served model with lower administrative costs. We used a variety of data sources to estimate the percentage of insured workers, statewide, whom the grant program affects.[61] We used this percentage in later steps to determine the share of total workers' compensation costs associated with employees affected by the grants. These are also provided in Table 4.4.

Table 4.4. Number of Covered Employees, by State and Year

State	Year	Covered Employees in the State	Grants	Average Number of Employees Affected per Grant	Percentage of Employees Affected by the Program
Ohio	2012	4,967,000	126[a]	33	0.08
Ohio	2013	5,033,000	491[a]	33	0.32
Ohio	2014	5,108,000	561[a]	33	0.36
Ohio	2015	5,108,000	521[a]	33	0.33
Ohio	2016	5,252,600[b]	479[a]	33	0.30
Missouri	2016	2,540,000[b]	16	47	0.03
Missouri	2017	2,564,400[b]	20	47	0.04
Missouri	2018	2,588,800[b]	40	47	0.07
Texas	2016	9,165,000[b]	73	40[c]	0.03
Texas	2017	9,327,700[b]	730[d]	40[c]	0.31

[a] For Ohio, we report the number of grants by fiscal year. Thus, for calendar year 2012, we use the number of grants awarded in FY 2012, which corresponds to July of calendar year 2012 to June of calendar year 2013.
[b] Linear extrapolation based on 2010–2015 data.
[c] We estimated this value as the average of the Ohio and Missouri data, which is consistent with Texas Mutual's expectation of an average of less than 50.
[d] This estimate is based on planned spending of $1 million, and the reported average spending of $1,370 per grant in the 2016 pilot.

Steps 3 and 4: Estimate the Reduction in Exposure and the Number of Avoided Insurance Claims

As noted earlier, the underlying idea behind the safety grants is that they reduce workers' exposure to the risk of injury and hence reduce both the number of insurance claims and the cost of claims that occur. For each insurance claim, insurers are liable for both medical costs and a portion of lost wages. Wurzelbacher, Bertke, et al., 2014, estimates that BWC's Safety Intervention Grant Program decreased the number of claims per affected employee by 66 percent

[61] Data for the total number of employees covered by any form of workers' compensation insurance in each state come from 2016 and 2017 reports by the National Academy of Social Insurance (NASI) (Baldwin and McLaren, 2016; McLaren and Baldwin, 2017). BWC, MEM, and Texas Mutual provided data on the number of grants issued in each year and the average number of affected employees per grant. Because we do not have data on the exact number of employees with each grant recipient in each year, we have assumed that these averages are constant across time.

and the geometric mean cost per claim by 30 percent. From this study, we infer that the mean cost per employee declined by 76.2 percent.[62] It is important to note that Wurzelbacher, Bertke, et al., 2014, is based on paid 30-month costs.[63] We assumed that costs incurred more than 30 months after the date of the claim are also reduced by 76.2 percent, on average.[64] Because we assumed that safety grants reduce all costs by 76.2 percent, we look at the total spending in any given year and assume that grants reduce the proportion of costs attributable to workers at grant-receiving employers by 76.2 percent.[65] To do this, we used statewide data on the total medical and wage replacement costs, by year, from Baldwin and McLaren, 2016, and McLaren and Baldwin, 2017, in order to capture costs that insurers incur more than 30 months after the claim is made.[66]

Although 76.2 percent is the estimated reduced cost of claims per full-time equivalent (FTE) employee, for BWC's program, based on 2003–2009 data, there are several reasons that this estimated reduction in the cost per worker might not be the same in other times or in other places. First, each state's safety grants require different match rates. From FY 2000 to FY 2009, the Ohio Safety Intervention Grant Program was a four-to-one match, meaning that an employer had to contribute $1 for every $4 that BWC contributed. In FY 2010, BWC shifted to a two-to-one match, and, in FY 2013, BWC shifted again to a three-to-one match. In theory, an employer should be more willing to purchase an intervention with lower returns for the company if the employer bears less of the burden in purchasing the intervention. There is no clear empirical evidence on how changes in the cost-sharing ratio influence the effectiveness of the purchased interventions, so we did not adjust the reduction in cost per worker to account for different match rates.

Second, the size of the impact likely depends on the total amount of money spent on safety interventions. We assumed that the size of the impact is linearly related to the total amount spent, and we estimated that the average total spending per grant from BWC and employers during the

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[62] If we assume that the percentage decline in mean costs is the same as the percentage decline in geometric mean costs, insurers pay 70 percent of their prior costs for 34 percent of the previous number of claims, meaning that, for employers receiving safety grants, insurers pay only 70% × 34% = 23.8% of their prior costs.

[63] Thirty-month costs are costs paid on the claim as of 30 months after January 1 of the year in which the injury took place. Depending on the date of injury, this measure reflects costs paid 18 to 30 months after the injury.

[64] In other words, these estimates assume that safety grants decrease both the rate of injury and the severity of injury. If the safety grants had no impact on the severity (and, hence, cost) of long-term injuries, this methodology would overestimate avoided medical and indemnity costs. If the safety grants reduce long-term costs by more than they reduce short-term costs, this methodology would underestimate avoided medical and indemnity costs.

[65] This might be an overestimate if a large portion of costs paid in a given year are from claims made prior to the grants being introduced. To the extent that the grants have existed for many years or costs are often paid as a single lump-sum settlement, this bias would be mitigated.

[66] Estimates of total costs can be significantly higher than 30-month costs. See Wurzelbacher, Meyers, et al., 2013.

FY 2000 to FY 2009 study period was $35,000.[67] In other words, we assumed that average total spending per grant by BWC and the employer is half of $35,000, so the estimated reduction in costs per worker is half of 76.2 percent. Again, this assumption could be biased in either direction. On the one hand, there could be diminishing returns to safety spending, so that smaller grants have a higher average impact per dollar. On the other hand, if most of the injury prevention can be driven by larger and more-expensive equipment, larger grants could have a higher impact per dollar.

The total amount spent can vary both because of different matching requirements and different grant sizes. According to data provided by BWC, grant recipients receiving less than the maximum amount of $40,000 tended to have expenses that matched the match requirement. In FY 2012, when the match rate was two to one, most grant recipients spent approximately $1 for every $2 they received. In FY 2013 to FY 2016, when the match rate was three to one, most grant recipients spent approximately $1 for every $3 they received. Those receiving the maximum grant size of $40,000 were more likely to spend money beyond the matching requirement, perhaps to buy a more expensive piece of equipment. When data on employer spending were not available, we assumed that employers exactly follow the matching requirements. This might mean that we likely slightly underestimated total spending in Missouri and Texas.

A third concern is that the 76.2-percent average reduced cost per worker for BWC's program might not translate to Missouri and Texas because of differences in the states' experience ratings, medical compensability, settlement policies, self-insurance rates, and other factors that might result in the cost reductions in Texas and Missouri being different from those in Ohio, even if the safety grants themselves were identically designed. Our analysis did not account for these potential differences; we assumed that the impact would be identical if states had the same safety grant designs.

Finally, a fourth concern is that some of the 76.2-percent reduction in cost could be due not to the grant itself but to selection bias among those firms that apply for grants. Firms might have been spurred to apply following an atypically costly series of workplace injuries, with losses naturally returning to mean levels the following years regardless of the grant. Wurzelbacher, Bertke, et al., 2014, tests for such regression to mean, and indeed the authors found that higher preintervention claims are associated with greater postintervention declines in cost, although they point out that factors other than regression to mean could also cause that pattern. Additionally, the type of firm that applies for grants might also be pursuing workplace safety in other ways.

[67] Average BWC spending per grant is between $25,000 and $27,000. Assuming that average BWC spending was constant and average employer spending was slightly higher than the match requirement gives us the estimated average total spending of $35,000.

Step 5: Monetize the Avoided Productivity and Quality Losses

We used the following steps to estimate avoided losses, or realized gains, in productivity and quality. Because safety grants focus on the prevention of acute injuries rather than of fatal illness and because the policy question at hand is on the return on investment in safety grants, we focused on estimating the avoided losses and realized gains associated with the safety grant, rather than using a VSL approach, such as estimating the utility associated with the avoided loss of quality-adjusted life-years.

To estimate the total avoided indemnity and medical costs, we multiplied the statewide total medical and indemnity costs by the percentage of total state employees affected by the program, as documented in Table 4.4, then by the 76.2-percent estimated cost reduction, and then by the ratio of average spending per grant listed in Table 4.5 relative to the estimated average study-period-per-grant spending of $35,000.[68] This calculation involves an assumption that grant recipients have per-employee costs equal to those of the average insured company in the state. For Ohio and Missouri, this assumption likely means that we underestimated the true avoided losses to the insurer because those states' safety grants are more likely to be awarded to high-risk industries. We estimated administrative costs at 47.7 percent of indemnity costs and 24.8 percent of medical costs, based on Leigh, 2011.

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[68] For example, for Ohio in 2012, this calculation is

$$\begin{pmatrix} (885{,}240{,}000 \text{ of total medical spending}) \\ +(\$1{,}311{,}268{,}000 \text{ of total cash benefits}) \end{pmatrix}$$
$$\times \frac{126 \text{ grants} \times 33 \text{ employees per grant}}{4{,}967{,}000 \text{ insured Ohio employees}}$$
$$\times 0.762$$
$$\times \frac{\$46{,}093}{\$35{,}000}$$
$$= \$1{,}845{,}205.$$

Table 4.5. Average Spending per Grant

State	Year	Average Spending per Grant, in Dollars
Ohio	2012	46,093[a]
Ohio	2013	43,722[a]
Ohio	2014	44,577[a]
Ohio	2015	42,389[a]
Ohio	2016	37,014[a]
Missouri	2016	20,000[b]
Missouri	2017	20,000[b]
Missouri	2018	10,000[c]
Texas	2016	1,370
Texas	2017	1,370[d]

[a] Ohio requests that employers report their total spending. We assumed that employers that have not yet reported spent the same amount as the average employer did.
[b] Based on reported average grant size of $10,000 and a one-to-one match rate.
[c] Based on an intention to halve the average grant size (in order to double the number of grants) and a one-to-one match rate.
[d] We based this estimate on the reported average spending of $1,370 per grant in the 2016 pilot and zero employer spending because Texas does not require an employer match.

We estimated avoided wage losses using two different estimates of the replacement rate. First, we used the statutory wage replacement rate for temporary total disability to estimate the amount of uncompensated wages. If the wage replacement rate is 70 percent, we assumed that total lost wages were indemnity payments divided by 70 percent and that workers absorb the remaining uncovered losses. This is a significant simplification because most states use a relatively complicated wage replacement rate function that contains caps and a replacement rate that varies depending on such factors as the length and severity of the illness or injury. Similarly, we used a simplified wage replacement rate based on each state's initial statutory wage replacement rate for temporary total disability, setting Ohio's wage replacement rate at 72 percent, Missouri's at 67 percent, and Texas's at 75 percent. Similar to the calculation of medical and indemnity costs, we linearly scaled the impact relative to total grant spending, as described earlier.

However, there is literature that suggests that the ultimate uncompensated wage loss that injured workers face can be significantly higher. In addition to any differences attributable to various assumptions about wage replacement rates, such as permanent disability payments being compensated at a lower rate, injured workers have persistently lower future earnings. This might be due to the loss of specific skills, the need to invest time in caring for the injury, or discrimination against workers who claim workers' compensation benefits. The authors of

Seabury et al., 2014, found that, over a ten-year period, people claiming workers' compensation benefits in New Mexico had only 16 percent of their lost income replaced by indemnity benefits.

Thus, for the second calculation of avoided wage losses, we used Seabury et al.'s results to estimate total uncompensated wages in each state,[69] and then applied the reduced number of claims per FTE and reduced cost per claim to that value. As with the other estimates, we then linearly scale the impact relative to total grant spending.

A portion of uncompensated wages might be compensated through other programs, such as federal disability insurance. Because disability insurance and other social insurance programs simply transfer the loss from the injured person to the general taxpayer rather than reducing total losses, we did not include this transfer in the measure of avoided losses. However, we raise this point to highlight that, in addition to individual workers, employers, and state insurers, the broader state and federal taxpayer benefit from this overall risk reduction via reduced claims on other social insurance.

We also included an estimate of productivity gains in our estimate of the total benefit to employers. Employers benefit from avoiding or reducing the severity of employee injuries. Results of a survey (that BWC provided) of 147 employers that benefited from safety grants between 2009 and 2011 suggest that keeping workers healthy provides significant productivity benefits to employers, improves production quality, and reduces absenteeism. Overall, those 147 employers reported jointly saving $3.94 million per year because of the safety grants, or $26,800 per year per employer. To calculate these benefits, we multiplied the number of grants by this average benefit of $26,800 per year, again assuming that the impact scales linearly with spending, although, because we based these benefits on 2009–2011 data, we compared it with an average spending of $45,000.

It is important to note that, unlike the other estimates, which are lump sums, these estimates are annual benefits that presumably last for the life of the purchased engineering control. We do not have enough information to know whether or to what extent these benefits change over time, nor do we know the average life span of purchased engineering controls. Missouri requires that a purchased item have a minimum service life of five years, while Texas allows the purchase of nondurable goods, such as first aid kits.

We conservatively assumed that these benefits reflect reduced absenteeism from both injuries resulting in compensation claims and other absenteeism, such as from medical-only claims. The extent to which the worker or the employer bears the wage-related costs of absenteeism depends on such factors as whether paid sick days are available; we were agnostic as to who bears these losses.

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[69] New Mexico has broadly similar wage replacement rates to those in Ohio, Missouri, and Texas.

Estimate of the Total Benefit

We estimated three categories of benefits associated with the safety grant program: avoided workers' compensation costs, associated productivity gains, and avoided uncompensated wage loss (see Table 4.6). We estimated the benefits of NIOSH research relative to a hypothetical counterfactual in which the Ohio program had a five-year delay before expansion and the Missouri and Texas programs had a five-year delay before being implemented.

Using the statutory wage replacement rate for temporary total disability to estimate the amount of uncompensated wages, we calculated the "low" estimate of worker benefits in Table 4.6. Then, using the Seabury et al., 2014, results to estimate total uncompensated wages in each state and applying the reduced number of claims per FTE and reduced cost per claim to that value, we get the second, "high" estimate of worker benefits in Table 4.6. In the latter case, we estimated reductions in avoided lost wages that are significantly higher than those in the previous case. The estimate of benefits also includes associated productivity gains.

Table 4.6. Overall Estimated Benefits to Insurers, Employers, and Workers, in Dollars

State	Year	Avoided Workers' Compensation Costs	Associated Productivity Gains per Year	Avoided Uncompensated Wage Loss (Low)	Avoided Uncompensated Wage Loss (High)
Ohio	2012	2,521,456	3,459,167	422,762	5,707,290
Ohio	2013	8,681,871	12,786,265	1,413,846	19,086,918
Ohio	2014	9,802,068	14,894,903	1,660,735	22,419,921
Ohio	2015	8,077,631	13,154,024	1,366,712	18,450,617
Ohio	2016	6,340,932	10,560,002	1,087,665	14,683,475
Missouri	2016	162,930	202,509	26,335	276,523
Missouri	2017	193,331	238,246	31,338	329,054
Missouri	2018	194,950	238,246	31,687	332,717
Texas	2016	19,485	59,562	1,961	30,892
Texas	2017	191,543	595,616	19,409	305,695

As is evident in Table 4.6, the annual benefits across all categories are highest in the Ohio program, which is perhaps not surprising given that the program is the largest and most mature of the three programs examined. Postexpansion, avoided workers' compensation costs ranging from approximately $6.3 million to $9.8 million, associated productivity gains from approximately $10.6 million to $14.9 million, and avoided uncompensated wage loss from the lowest estimate of $1.1 million to the highest estimate of $22.4 million. In contrast, similar estimates in Missouri and Texas were considerably lower, reflecting their smaller sizes and the fact that they were at a much earlier stage of development. For instance, avoided workers' compensation costs in Missouri and Texas were in the $100,000–$200,000 range. Table 4.2 reflects some of the differences across the programs. As discussed further below, the benefits of

NIOSH research in a given year, relative to a hypothetical five-year delay, can be viewed as the difference between observed benefits and 2012 benefits for Ohio and, for the Missouri and Texas programs, the total benefit of the first five years.

We also broke out avoided workers' compensation costs into avoided indemnity losses, medical costs, and administrative costs (see Table 4.7). In Ohio, for instance, avoided indemnity costs make up the largest share of avoided costs, while, in Missouri and Texas, avoided medical costs make up the largest share of avoided costs.

Table 4.7. Estimated Avoided Medical, Indemnity, and Administrative Costs, in Dollars

State	Year	Indemnity	Medical	Administrative
Ohio	2012	1,087,103	733,906	700,448
Ohio	2013	3,635,603	2,654,205	2,392,062
Ohio	2014	4,270,461	2,800,500	2,731,107
Ohio	2015	3,514,403	2,313,469	2,249,759
Ohio	2016	2,796,852	1,771,042	1,773,037
Missouri	2016	52,671	68,221	42,038
Missouri	2017	62,677	80,740	49,914
Missouri	2018	63,375	81,211	50,364
Texas	2016	5,884	8,650	4,951
Texas	2017	58,228	84,573	48,743

As noted earlier, to estimate the portion of these program benefits attributed to NIOSH research, we examined a counterfactual scenario in which there was a five-year delay in both the expansion of the Ohio program and the spread of the idea to Missouri and Texas. A benefit of the NIOSH research was that, from 2013 to 2017, the Ohio program was larger than it otherwise would have been in our counterfactual, in which the Ohio program did not expand until 2018. Another benefit is that the Missouri and Texas programs started in 2016 rather than 2021. Table 4.8 presents these estimates of the marginal benefits of this NIOSH research, by year and category, summed across all three states, under the assumption that all three states continue to design their safety grants based on the most-recent information we have available. Recall that the associated productivity gains are estimated values per year that last for an unknown time and decay at an unknown rate, so we cannot simply sum these results across rows.

Table 4.8. Estimated Total Marginal Benefits of NIOSH Research, Assuming a Five-Year Delay in the Ohio Expansion Decision and the Spread to Missouri and Texas, by Category and Year, in Dollars

Year	Avoided Workers' Compensation Costs	Associated Productivity Gains per Year	Avoided Uncompensated Wage Loss (Low)	Avoided Uncompensated Wage Loss (High)
2013	6,160,414	9,327,097	991,084	13,379,629
2014	7,280,612	11,435,736	1,237,973	16,712,632
2015	5,556,175	9,694,857	943,950	12,743,327
2016	4,001,891	7,362,905	693,199	9,283,600
2017	4,457,135	8,833,805	772,550	10,379,085
2018	386,493	833,862	51,097	638,412
2019	214,435	297,808	51,097	363,609
2020	386,493	833,862	51,097	638,412
2021	172,058	536,054	17,448	274,803

These numbers are smaller than those reported earlier because they are the differences between the total benefit of the programs and the benefit that would have occurred without the NIOSH study. The benefits are largest in 2013–2017 because the largest benefit of the NIOSH study to date is the expansion of the Ohio grant program. Because this counterfactual assumes that the Ohio program would have expanded anyway in 2018, the remaining benefits come from the existence of the Missouri and Texas programs, which we assumed would not have begun until 2021. The values in 2021 are smallest because they represent only the difference between the benefit of Texas continuing its safety grant program in that year and the benefit of running its initial pilot in that year. By 2022, our counterfactual assumes, all programs would be operating in essentially the same form that they would have without the NIOSH study.

Conclusion

We estimated that implementation of safety grant programs whose benefits NIOSH quantified can generate a range of benefits for insurers, employers, and workers. We find that, to date, the main benefit of the NIOSH study was the expansion of BWC's Safety Intervention Grant Program, although the creation of similar smaller programs in Missouri and Texas has also provided benefits. The values in Table 4.6 do not represent the total benefits of the NIOSH research because other states might still be inspired to create similar programs in response to the NIOSH work. More than in the other cases, the impacts of this work are still developing. Nevertheless, we find evidence that, between 2013 and 2017, NIOSH research has been associated with $4 million to $7 million per year in avoided workers' compensation costs, $7 million to $11 million of new streams of annual productivity gains per year, and from almost $700,000 to more than $16 million of avoided uncompensated wage losses per year. The reader should note, however, that our analysis did not include other categories of benefits, such as the avoided emotional costs on workers, or other more-general measures of lost utility beyond direct productivity losses. Such benefits are important but are outside of the scope of this analysis.

Chapter Five. Discussion and Conclusions

Summary of Key Findings

To date, there have been few, if any, attempts to assess the economic benefit of investments in research. In part, this is because such assessments are difficult. First, the benefits of research are often indirect and realized in the future. Second, safety and health research often addresses "goods" for which there is no naturally occurring market and thus no mechanisms for setting a "price." Finally, research is often a joint effort involving many individuals and organizations.

This study sought to identify a set of analytic steps for estimating the economic benefit associated with NIOSH research and apply them to three case studies: supporting the development of silica dust ventilation control measures and water sprays for asphalt milling machines, building and disseminating evidence on cancer risk among firefighters, and assessing and disseminating impacts of Ohio's Safety Intervention Grant Program. For each case study, we provided a brief narrative of NIOSH's and other entities' research efforts, reviewed evidence on the effectiveness and adoption of control measures inspired by the research, and used this information to estimate the number of avoid illnesses, injuries, or deaths that could be attributed to the interventions. Finally, we estimated the monetized benefits associated with those avoided illnesses, injuries, and deaths.

We used two common approaches to estimating the economic benefit of avoided injuries, illnesses, and fatalities. The first involves estimating associated medical costs and productivity losses, which is often most useful to those responsible for budgeting for medical care and other costs. However, in several instances, available data did not support such an analysis. Thus, we also used the WTP approach, which assesses individuals' subjective WTP to avoid the loss of life, health, and quality of life. The primary metric used is VSL, and we assumed a VSL of $9.5 million for avoided fatalities (in 2016 dollars). Given its broader scope, VSL estimates tend to be significantly larger than medical costs.

In interpreting findings from the case studies, we must be mindful of the fact that the two approaches to economic valuation answer different types of policy questions, with averted medical costs and productivity losses addressing questions related to on-budget costs and VSL estimates answering questions about the broader societal value of avoided injuries, illnesses, and deaths. Hence, VSL estimates tend to be significantly larger than avoided medical costs and productivity losses. With this in mind, the key findings are as follows:

- In the silica case, we examined the economic value associated with research conducted in partnership with industry and labor to develop, test, and support implementation of engineering controls to limit road construction workers' exposure to silica dust. Based on VSL estimates for risk reductions in fatal and nonfatal illnesses, the economic value ranges from $304 million to $1.1 billion on an annualized basis, with a midpoint estimate of $692 million per year. Using the medical cost and productivity loss (WTP) approach, we estimate that NIOSH's activities contributed to $4.9 million in avoided medical costs and productivity losses on an annualized basis for fatal lung cancers.[70] We did not have sufficient data to monetize benefits for other fatal and nonfatal diseases on a medical cost basis.

- In the firefighter case study, we examined the economic benefit stemming from two NIOSH research publications that support development of PPE and other control measures to reduce exposure during and after fires. We estimated that resulting reductions in mortality and morbidity would lower medical costs and productivity losses by $71 million per year, with a range of $23 million to $93 million, depending on assumptions about reduction in risk and adoption of control measures. Using VSL, we estimated benefits of approximately $1 billion.
- Finally, in the Ohio safety intervention grant case study, we examined avoided workers' compensation costs, productivity gains, and avoided uncompensated wage losses. We find that, to date, the main benefit of the NIOSH study was the expansion of BWC's grant program, although the creation of similar, smaller programs in Missouri and Texas has also provided benefits. The values presented in Chapter Four do not represent the total benefits of the NIOSH research because other states could still be inspired to create similar programs in response to the NIOSH work. Unlike those in the other case studies, the impacts of this work are still developing. Nevertheless, we find evidence that, between 2013 and 2017, NIOSH research has been associated with $4 million to $7 million per year in avoided workers' compensation costs, $7 million to $11 million of new streams of annual productivity gains per year, and from almost $700,000 to more than $16 million of avoided uncompensated wage losses per year.

The reader should exercise care in interpreting differences among the estimated benefits. First, as noted earlier, the results include a mix of avoided medical costs and productive losses and VSL, which address different sorts of questions. However, even if we presented all results using the same metric, one should not automatically conclude that projects with lower estimated economic values are less worthy of public investment than others. First, benefits should ideally be interpreted in light of the costs associated with producing and implementing research findings, which was beyond the scope of this effort.[71] Second, as a general matter, we might expect investments that add to years of previous research to yield greater benefits, other things being equal. Similarly, basic or exploratory research can often have great value even though it is less likely than research in more-mature areas of study to generate quantifiable economic benefits.

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[70] Medical costs and productivity losses for other illnesses, such as other nonmalignant respiratory diseases (including silicosis) and ESRD, were not available. Thus, this figure underestimates the overall benefits. In our analysis, lung cancers account for approximately four fatalities per year out of a total of 22 avoided fatal cases and 77 avoided nonfatal cases per year.

[71] NIOSH provided us with preliminary, unpublished estimates of NIOSH's (but not NIOSH's partners') costs to produce the research described in this report and indicates that it plans to provide final estimates in a companion piece to this report. Preliminary estimates are $2.2 million for the silica case, $2.4 million for the firefighter case, and $0.5 million for the Ohio safety intervention grant case. Given the project timeline, we were not able to evaluate these estimates systematically.

However, even here, it is both possible and desirable to identify and communicate a potential path from research to practice. That said, attempts to incorporate such differences into our analysis were beyond the scope of this project and would require additional research, analysis, and discussion among key stakeholders.

Limitations

Given the inherent difficulties in estimating the economic benefits associated with the research described earlier, these estimates should be regarded as partial but in no way conclusive. In earlier chapters, we described limitations specific to each case; we do not repeat them here. In general, however, we remind the reader of two broad limitations. First, gaps in data and research meant that we had to make some important assumptions in order to derive estimates of economic value. For instance, in the firefighter case, we assumed that 85 percent of career firefighters had adopted the risk-reducing control measures. And in all the case studies, there were uncertainties about attributing reductions in injuries, illnesses, and deaths to research activities. Where assumptions were necessary, we explained the logic behind them, and, where possible given the project timeline, we conducted sensitivity analyses to clearly show the reader how different assumptions might affect the estimated benefits. However, limitations in scope and timeline restricted the number of these analyses that we could conduct.

Second, it is unlikely that one could draw broad generalizations about the research activities of an institute with as broad a reach as NIOSH using three case studies. In addition, given limitations in scope and timeline, the analysis was limited to cases for which data and stakeholders were readily available and for which there were plausible and documented linkages between NIOSH research and safety and health outcomes.

In the end, much of the value of this analysis lies in illustrating some specific ways in which NIOSH research can produce economic benefits, providing some sense of the likely magnitude of these benefits in dollar terms, and providing an analytical framework on which others can build in future work. In the future, NIOSH should consider conducting additional case studies to explore other types of research and intended audiences and that account for the costs of producing and implementing research. In addition, it should consider examining cases in which the linkages between its research and safety and health improvements are less clear. Indeed, there can be important lessons from cases of unrealized impact. Finally, NIOSH should consider ways in which it might start to fill some of the gaps in data and analysis encountered while conducting this economic analysis.

Efforts to assess the economic value of research are in their infancy. We hope that this report represents a useful step toward a better understanding of how this sort of analysis might be done.

Appendix A. Stakeholders Consulted

In this appendix, we identify each of the non-NIOSH stakeholders consulted in developing the analyses for the case studies presented in this report, along with their affiliations.

- Howard Marks, vice president, environment, health, and safety, NAPA
- James Brinkley, director, occupational health and safety, IAFF
- Victor Stagnaro, director, fire service programs, National Fallen Firefighters Foundation
- Beth Gallup, captain, Puget Sound Regional Fire Authority
- Eric Bourquin, vice president, safety services, Texas Mutual Insurance Company
- Brandon Jones, director, safety and risk services, MEM
- Len Welsh, consultant to the president, workplace safety, California State Compensation Insurance Fund
- Ibraheem "Abe" Al-Tarawneh, superintendent, Division of Safety and Hygiene, Ohio BWC.

Appendix B. Calculation of the Reduction in Firefighters' Risk Exposure

There are two basic categories of personnel in the firefighting workforce—firefighters, who engage in fire suppression, outside ventilation, and overhaul, and C/P.[72] The sources and patterns of exposure are different for these two groups. There are at least four personnel in the C/P category at a typical fire—including one command, one pump operator, emergency medical service personnel, and a response intervention team (emergency backup).

Firefighters

Firefighters' carcinogen exposure falls into three broad categories, with the following shares in total excess carcinogen exposure, summarized in Table B.1. The table also provides estimates of the effectiveness of controls associated with the HI/HO recommendations.

[72] Fent and Horn provided this information, which is the basis for the estimation of risk reduction that is expected from implementation of the control measures recommended in HI/HO.

Table B.1. Firefighters' Exposure to Carcinogens

Exposure	Share of Total Excess Carcinogen Exposure, as a Percentage	Effectiveness of HI/HO Recommendations Relative to Traditional Practice[a]
Respiratory exposure to gases, vapors, and particulates during overhaul and during outside ventilation work	80	*Recommendation*: Wear an SCBA. *Estimated effectiveness*: almost 100%
Respiratory exposure to off-gassing of equipment and turnout gear during rehab at the fire scene and during the trip back to the station. Not enough data are available to determine which period of off-gassing is more important. Rate of off-gassing from equipment and gear is higher during rehab, but off-gassing during the trip to the station is in an enclosed space. Station clothing worn under gear can also off-gas.	10 (estimate half during rehab and half during ride back to station)	*Recommendation*: Remove gear and place it away from personnel during rehab, and remove gear and transport it back to station in plastic bags and without placing it in a passenger compartment. Ensure that windows are rolled up, doors are closed, and vents are off during attack. SCBAs should also not be stored in the cabin of the vehicle. *Estimated effectiveness*: during rehab: 70–90% (some will still be inhaled during doffing); during trip to station: 90–100%
Dermal exposure at the fire scene and subsequently until deposits are removed from the skin. There are several ways in which skin is exposed. Note that, when inhalation exposure is controlled, the dermal route becomes a more important route of exposure.	10	*Recommendation*: Complex—see "Additional Information" later in this appendix *Estimated effectiveness*: 25–60%

[a] *Traditional practice* here refers to the practices common in the industry in the early 2000s.

Command and Pump Operation Personnel

C/P personnel's carcinogen exposure also falls into three broad categories, with the following shares in total excess carcinogens, illustrated in Table B.2. Their total exposure is less (estimated at less than 20 percent of firefighters who do not follow HI/HO guidelines) because they do not enter burning structures or get very close to the fire. However, they typically do not wear respiratory protection.

Table B.2. Command and Pump Operation Personnel's Exposure to Carcinogens

Exposure	Share of Total Excess Carcinogen Exposure, as a Percentage	Effectiveness of HI/HO Recommendations Relative to Traditional Practice
Respiratory exposure to gases, vapors, and particulates while working at the command location for the fire	50 (with significant variability to wind direction)	*Recommendation*: Set up the command location upwind of the fire, which is not always feasible. *Estimated effectiveness:* When feasible, effectiveness is 70–90%.
Respiratory exposure to off-gassing of equipment and gear at the fire scene and during the trip back to the station. Not enough data are available to determine which period of off-gassing is more important. Rate of off-gassing from equipment and gear is higher during rehab, but off-gassing during the trip to the station is in an enclosed space. Station clothing worn under gear can also off-gas.	40	*Estimated effectiveness:* during rehab: 70–90%; during trip to station: 90–100%
Dermal exposure would be primarily from existing contamination on gear and equipment.	10	*Recommendation*: Complex—see "Additional Information" after this table *Estimated effectiveness:* 80–90%

Additional Information

Off-Gassing

Most of the volatile organic compounds off-gas within 30 to 40 minutes. Semivolatile compounds are released more slowly, but research has yet to determine the duration and importance of these exposures. For now, off-gassing is judged not to be so important at the station and should take place mainly at the fire scene and during the trip back to the station.

Dermal Exposure

- **General:** Dermal exposure can occur directly through entrance of substances through skin from the air or through penetration of deposits on the skin. The latter can continue until the deposits are removed. Deposit exposure can also result from contact of the skin with contaminated gear, equipment, and other surfaces (cross-transfer). This last source might be more important than deposits directly on the skin because some recent research indicates that, if someone other than the worker removes the gear, the skin is much cleaner. Because exposure of the skin through deposits from the air or from contact with contaminated objects continues until the deposits are removed, the effectiveness of removing the deposits is a function of the time delay between deposit and cleaning.
- **General skin exposure:** The turnout gear protects against skin deposits but not necessarily against gases and vapors. These can be important. For example, small

amounts of benzene vapors are absorbed directly through the skin, and benzene concentrations at fires can be enormous. This could contribute to more-systemic exposure than the deposition or transfer of contaminants to skin. This is the main reason we estimate less reduction in dermal exposure for firefighters than for C/P personnel when implementing the HI/HO recommendations. Although direct uptake of vapors can be difficult to minimize, taking a shower upon returning to the station (hopefully within an hour) could be 60- to 80-percent effective in removing skin deposits. Some deposits will have absorbed into the lower layers of the skin, where showering cannot effectively remove them. Taking a shower soon upon returning to the station is not necessarily a common traditional practice.

- **Neck exposure:** Hoods prevent direct exposure to the skin and skin deposits. HI/HO recommendations are to change hoods on a regular basis. The estimate is that the new and common practice of changing hoods after every fire response could reduce exposure to the neck area by about 85 percent compared with the traditional practice of not changing the hood. Current research is under way to test the effectiveness of "particle-blocking" hoods. These hoods should stop the skin's direct uptake of solid-phase (particulate) carcinogens in the air. Some individual firefighters have started using these hoods, but most departments will probably not do so until NFPA approval and unless the data indicate effectiveness.
- **Hand exposure** (and exposure to other skin touched by hands): Washing hands with soap and water at the fire scene could be 60- to 90-percent effective in removing carcinogens. Use of wipes can remove 40 to 70 percent of carcinogens. Recent tests indicated that wipes were 54-percent effective.
- **Exposure from gear:**
  - Gross decontamination at fire scene: This involves rinsing, scrubbing, and, if possible, use of dish soap or other surfactant to remove the bulk of the loose contaminants. This could be 60- to 80-percent effective.
  - Cleaning of masks, tools, bottles, and other tools and equipment at the station:
    - Using wipes could be 70- to 80-percent effective.
    - Using an ultrasonic cleaner could be 90- to 95-percent effective.
  - Cleaning of turnout gear at the station or by a contractor:
    - This cannot be done without an extractor, which is expected to be 90- to 95-percent effective.
  - Considering the exposure due to the previous two items as a whole, exposure due to lack of cleaning of masks, tools, and such could constitute about 25 percent, and exposure due to lack of cleaning of turnouts could constitute about 75 percent, of the total exposure from gear.
  - Exposure to contaminated gear can also occur while cleaning the gear. Recommendations are to use PPE while cleaning, and this could be 80- to 95-percent effective in reducing exposure during this process.
- **Exposure from contaminated surfaces in the apparatus and the fire station:** Much of this exposure can be reduced through a one-time deep cleaning to remove an accumulation of deposits from over the years. Flame retardant contamination at stations has been documented, but this is a particularly persistent type of compound. The

importance of this exposure is hard to assess, but low-level, long-term exposure cannot be ignored. Going forward, the importance of cleaning the station to reduce exposure might be less significant if the other recommended procedures are followed.

- **Exposure by ingestion:** In Tables B.1 and B.2, we did not include this route of exposure. It can occur during rehab. This is a period in which the firefighter goes to a nearby rehab location to rest, cool off, be evaluated, and to drink and perhaps eat. The recommendation is to wash hands, which is 80- to 95-percent effective. However, this is the same handwashing that is already recommended to reduce exposure to the hands.
- **Exposure to workers other than the firefighting workforce:** Medics and police are often on the scene and can have exposure similar to that of the C/P personnel if they are downwind of the fire.

Rationale for Dermal Exposure Reduction Estimates

Where possible, we based our estimates on numbers reported in the literature. Otherwise, we used professional judgment or made assumptions based on our current understanding of the exposure pathways during fire attack. We also assumed that benzene is representative of other vapor exposures and that PAHs are representative of other solid particulate exposures.

For firefighters, we estimate that 1 percent of benzene vapor can be absorbed directly through skin during interior firefighting. Given concentrations reported in literature, we estimate that 44,341 μg of benzene could surround the firefighter and potentially contact the skin during interior fire attack. Hence, 443 μg of benzene could be absorbed.

We also estimate that 250 μg of PAHs will deposit onto skin via permeation or penetration through turnout gear or cross-transfer during doffing, 10 percent will be absorbed into skin quickly, and 50 percent of the residual will be removed from skin using skin cleansing wipes (more if washing with soap and water). Of the 112 μg remaining on the skin, another 20 percent will be absorbed before showering. Of the 90 μg remaining, 90 percent will be removed via showering. The total absorbed PAHs would be 25 μg + 22 μg + 9 μg = 56 μg. Thus, skin cleaning would remove approximately 80 percent of PAH contamination. However, about 400 μg of benzene would still be absorbed. Hence, the reduction in total carcinogen exposure from skin cleaning might only be about 30 to 40 percent.

Firefighters can also be exposed from wearing or touching previously contaminated gear and equipment. This could contribute another 50 μg of PAH exposure. Routine cleaning of gear and equipment should reduce this exposure by approximately 90 percent. This would add another 5 percent to the total carcinogen reduction for firefighters, bringing the total to around 35 to 45 percent. It is difficult to know whether benzene exposure is more toxic than PAH exposure. Also, given all the assumptions made above, a larger CI is prudent. Thus, a 25- to 60-percent range in reduction from dermal exposure interventions is likely justified for the firefighters.

Note that exposure from wearing contaminated gear would be the primary mechanism for C/P personnel. Thus, routine cleaning of gear and equipment could reduce C/P personnel's skin exposure by 80 to 90 percent.

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