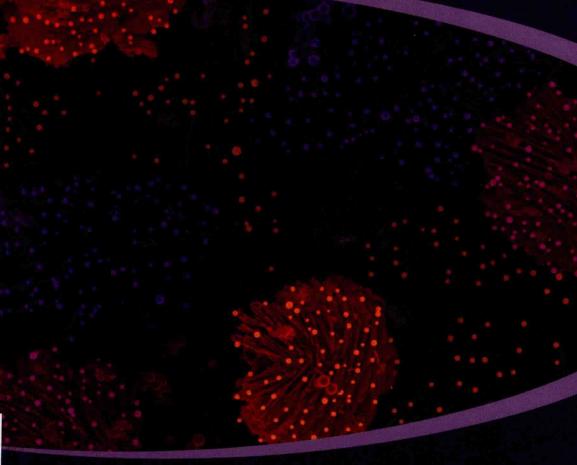
Exposure Assessment and Safety Considerations for Working with

IGINEERED NANOPARTICLES



MICHAEL J. ELLENBECKER • CANDACE SU-JUNG TSAI

WILEY

EXPOSURE ASSESSMENT AND SAFETY CONSIDERATIONS FOR WORKING WITH ENGINEERED NANOPARTICLES

MICHAEL J. ELLENBECKER, Sc.D., CIH

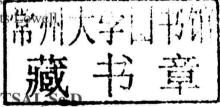
Professor Emeritus of Occupational and Environmental Hygiene Director, Massachusetts Toxics use Reduction Institute

Department of Work Environment

College of Health Sciences

University of Massachusetts
One University Avenue

Lowell, MA, USA



CANDACE SU-JUNG TS

West Lafayette, IN, USA

Assistant Professor of Occupational/Environmental Health and Hygiene School of Health Sciences
College of Health and Human Sciences
Purdue University
Delon and Elizabeth Hampton Hall of Civil Engineering
550 Stadium Mall Drive



Copyright © 2015 by John Wiley & Sons, Inc. All rights reserved

Published by John Wiley & Sons, Inc., Hoboken, New Jersey Published simultaneously in Canada

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at http://www.wiley.com/go/permissions.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Ellenbecker, Michael J.

Exposure assessment and safety considerations for working with engineered nanoparticles / Michael J. Ellenbecker, Sc.D., CIH, Professor Emeritus of Occupational and Environmental Hygiene, Director, Massachusetts Toxics use Reduction Institute, Department of Work Environment, College of Health Sciences, University of Massachusetts Lowell, Su-Jung (Candace) Tsai, Sc.D., Assistant Professor of Occupational/Environmental Health and Hygiene, School of Health Sciences, College of Health and Human Sciences, Purdue University.

pages cm

Includes bibliographical references and index.

ISBN 978-0-470-46706-0 (cloth)

- 1. Nanotechnology-Safety measures. 2. Nanostructured materials industry-Employees-
- Health and hygiene. 3. Nanotechnology-Health aspects.

4. Nanoparticles—Toxicology. 5. Industrial hygiene. I. Tsai, Su-Jung. II. Title. T174.7.E454 2015

363.17'9-dc23

2014029773

Cover image credit:

Image courtesy of Argonne National Laboratories

Image title: Fireworks over Night Sky

Image was taken by Vilas Pol and Natalie Fitzgerald

Description of image:

A dramatic fireworks display over a night sky is demonstrated. Golden yellow lights pournward along with colorful and radiant clusters of pink, purple and orange. The viewer's perspective is that of looking up at the fireworks coming down to the earth in a shower of light. Originally, it's a scanning electron micrograph of photo-luminescentlanthanum hydroxycarbonate superstructure, prepared in critical autogenic reactions. The U.S. Department of Energy's Argonne National Laboratory, 2011

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

EXPOSURE ASSESSMENT AND SAFETY CONSIDERATIONS FOR WORKING WITH ENGINEERED NANOPARTICLES

Dedication

I (ME) dedicate this book to my wife, Marlene Goldman, for her understanding throughout the long process of research and writing leading to its publication. I greatly appreciate her support. I also dedicate it to our daughters, Anne and Heidi, and our five grandchildren, in the hope that the safe application of nanotechnology will bring them a better world.

I (CT) dedicate this book to my husband, Chunyuan Chen, and children, Xenia and Steven, for their understanding and encouragement while I spent the time doing the research followed by the writing. I appreciate my parents' support of my career. Being in the forefront conducting research on this important topic, I hope that nanotechnology will bring a bright future to the next generation with a safe environment for everyone.

PREFACE

The field of nanotechnology is expanding rapidly, with new discoveries being announced almost daily in fields ranging from the fairly mundane (e.g., advanced composite materials) to the exotic (e.g., targeted anticancer drug delivery). As with any new technology, however, excitement over the likely benefits to society must be balanced with attention to any potential adverse effects that may arise. For nanotechnology, there is growing evidence that at least some of the new engineered nanomaterials may have adverse health and safety aspects that must be addressed in order to ensure that they are used in a safe and effective manner.

Hence this book. We the authors, occupational hygienists, have been performing research into the occupational and environmental health and safety aspects of nanotechnology since 2003. Here we have attempted to present our view of the current state of this rapidly advancing field. The primary audience for the book is health and safety professionals who find that they have to develop a working knowledge of this new field. Given our backgrounds, the book's primary focus is on occupational exposures, and we have attempted to give attention to environmental exposures. It is our hope that the reader will be able to use the information from this book to apply the occupational hygiene model of anticipation, recognition, evaluation, and control to nanotechnology development.

We would like to acknowledge the contributions of Rick Reibstein of the Massachusetts Office of Technical Assistance and Technology, who provided valuable information and insight to Chapter 11. We also acknowledge the support received from the National Institute for Occupational Safety and Health (NIOSH) and the National Science Foundation (NSF) funded Center for High-rate Nanomanufacturing, which supported much of our research as reported in the book's case studies.

CONTENTS

Pr	Preface		
1	Inti	1	
	1.1	Why A Book on Nanotechnology Health and Safety?	1
	1.2	Some Scenarios	3
	1.3	Organization of the Material	5
	1.4	Our Approach to Nanoparticle Health and Safety	5
	Ref	erences	7
2	Wh	at is a Nanoparticle?	8
	2.1	Nanotechnology, Nanomaterials, and Nanoparticles	9
		2.1.1 Nanotechnology	9
		2.1.2 Nanomaterial	9
		2.1.3 Nanoparticle	9
	2.2	Naturally Occurring Nanoparticles	10
		Industrial Nanoparticles	12
	2.4	Engineered Nanoparticles	14
		2.4.1 Carbon Nanotubes	15
		2.4.2 Fullerenes	17
		2.4.3 Quantum Dots	17
	2.5	Emerging Uses for Engineered Nanoparticles	19
	2.6	Other Useful Definitions	20
		2.6.1 Aerosol	20
		2.6.2 Particle Inertia	21
		2.6.3 Brownian Motion	22

VIII CONTENTS

		- THE PART OF	Particle Diameter Agglomerate versus Aggregate ary	23 24 25 26
3	Why	y are w	e Concerned? The Unique Properties of Nanoparticles	28
	3.1		e-to-Volume Ratio	28
		Particl		30
			e Concentration	32
	3.4		Metrics: Particle Number, Surface Area, Morphology, urface Properties	33
	3.5		eations for the Occupational and Environmental Health	55
	5.5		ts of Nanoparticles	33
			Respiratory Deposition	33
		3.5.2	Skin Penetration	34
	3.6		eations for Physical Risks	35
			Introduction	35
			Current Status	35 36
	27	Sumn	Conclusions	37
		erences		37
				20
4	Rou	ites of	Exposure for Engineered Nanoparticles	39
		Introd		39
	4.2		eered Nanoparticle Exposure through Inhalation	40
			Human Respiratory System	40 43
	12		Particle Deposition in the Respiratory System eered Nanoparticle Exposure Through Dermal Contact	46
	4.4		neered Nanoparticle Exposure Through Ingestion	48
	4.5	_	location of Nanoparticles from the Lung	48
		Sumn		49
	Ref	erences	S	49
5	Cui	rrent K	Knowledge on the Toxicity of Nanoparticles	51
	5.1	Introd	luction	51
	5.2	The T	oxicity of Industrial Nanoparticles	52
	5.3	Nano	particle Toxicity: General Concepts	53
		5.3.1	1	53
		5.3.2		53
	1990 50 12		on Nanotubes	54 56
		Fulle		58
			tum Dots I-Based Nanoparticles	58
		Sumr		59
		ference		60

CC	ONTE	NTS	ix		
6	Sou	arces of Exposure	63		
	6.1	Overview of Occupational Exposures	63		
		Occupational Exposures in Research Facilities	64		
		Occupational Exposures in Manufacturing Facilities	65		
	0.4	Exposure Potential for ENPs in Different Physical States 6.4.1 Dry Powders	66		
		6.4.2 Liquid Suspensions	66 69		
		6.4.3 ENPs Bound to a Solid	72		
	6.5	Environmental Exposures to Engineered Nanoparticles	73		
		6.5.1 Environmental Releases	73		
		6.5.2 Exposures Through a Product's Life Cycle	74		
	Ref	erences	76		
7	Eva	duation of Exposures to Engineered Nanoparticles	79		
	7.1	Current Knowledge Concerning Exposure to Engineered			
		Nanoparticles	79		
	7.2	Exposure to Engineered Nanoparticles by Inhalation	81		
		7.2.1 Mass Sampling	81		
		7.2.2 Surface Area Measurement	83		
		7.2.3 Number Concentration Measurement	84		
		7.2.4 Conversion between Number, Surface Area, and Mass Concentrations	98		
		7.2.5 Particle Characterization	99		
	7.3	Dermal Exposures to Engineered Nanoparticles	102		
	7.4	Evaluation of Exposures in Aquatic Environments	102		
		7.4.1 Introduction	104		
		7.4.2 Sample Collection	104		
		7.4.3 Measurement Methods	105		
		7.4.4 Exposure Characterization in Aquatic Environments	107		
	Ref	erences	108		
8	Exp	re Characterization 112			
	8.1	Exposure Characterization Steps	113		
		8.1.1 Standard Occupational Hygiene Models	113		
		8.1.2 Exposure Characterization for Nanomaterials	113		
	8.2	Exposure Measurement Strategies	120		
		8.2.1 Single-Location Measurement	120		
		8.2.2 Multiple-Location Measurement	120		
		8.2.3 Near-Field and Far-Field Measurement	121		
	8.3	8.2.4 Dynamic Personal Sampling Measurement	122		
		Data Analysis and Interpretation Statistical Analysis of Data	123 124		
	0.1	Junion I mary 515 of Data	124		

8.4.1 Pearson Correlation

8.4.2 *T*-test

124

125

X CONTENTS

	8.5	Practica	l Aspects of Aerosol Sampling and Microscopy Techniques	127
		8.5.1	Aerosol Sampling Techniques	127
		8.5.2	Microscopy Techniques	128
	8.6	Practica	l Applications and Limitations	128
		8.6.1	Particle Losses	128
		8.6.2	Concentration Measurement versus Particle Samples	130
	8.7	Typical	Production Processes	130
		8.7.1	Synthesis of Carbon Nanotubes	130
		8.7.2	Composite Manufacture	131
	8.8	Case Str	udy: Manual Handling of Nanoparticles	133
		8.8.1	Materials and Conditions	134
		8.8.2	Particle Handling	134
		8.8.3	Measurements	134
		8.8.4	Aerosol Particle Characterization	136
		8.8.5	Results	137
		8.8.6	Discussion	144
		8.8.7	The Challenge and Brainstorming	145
		8.8.8	Study Questions	145
	8.9	Case St	udy: Synthesis of Carbon Nanotubes	146
		8.9.1	Materials and Synthesis	146
		8.9.2	Measurement	147
		8.9.3	Results	148
		8.9.4	The Challenge and Brainstorming	155
		8.9.5	Study Questions	156
	8.10		tudy: Exposure From Twin Screw Extrusion	
		Compo	unding	156
		8.10.1	Materials and Production Process	157
		8.10.2	Measurements	158
		8.10.3	Results	158
		8.10.4	The Challenge and Brainstorming	162
		8.10.5	Study Questions	163
	Refe	rences		164
9	Con	trol of O	ccupational Exposures to Engineered Nanoparticles	166
	9.1	Contro	1 of Airborne Exposures	166
	2.1	9.1.1	General	166
		9.1.2		169
		9.1.3	Alternatives to Conventional Fume Hoods	178
	9.2		l of Dermal Exposures	181
	,	9.2.1	General	181
		9.2.2	Clothing and Personal Protective Equipment	181
	9.3		istrative Controls and Good Work Practices	182
	- 10	9.3.1	Housekeeping	183
		9.3.2	Work Practices	183
		9.3.3		183

CONTENTS

	9.4	Respira	atory Protection	185
		9.4.1	General Considerations	185
		9.4.2	Respirator Designs	186
	9.5	Case S	tudy: Comparison of the Performance of	
		Various	s Fume Hoods	195
		9.5.1	Materials and Hoods	195
		9.5.2	Measurements	198
		9.5.3	Results	198
		9.5.4	The Challenge and Brainstorming	206
		9.5.5	Study Questions	206
	9.6	Case S	tudy: Performance of Nontraditional Fume Hoods	206
		9.6.1	Materials and Hoods	207
		9.6.2	Measurements	207
		9.6.3	Results	207
		9.6.4	The Challenge and Brainstorming	214
		9.6.5	Study Questions	215
	Refer	rences		215
10	Cont	rol of Eı	nvironmental Exposures	219
	10.1		•	
	10.1		l of Air Emissions	219
		10.1.1	Factors Affecting Air Cleaner Performance	220
	10.2	10.1.2	San	220
	10.2		of Water Emissions	228
	10.3		articles in Solid Waste	232233
	10.5			234
	10.0		Materials and Process	234
				235
		10.6.3	The Challenge and Brainstorming Study Questions	246
	Refer		Study Questions	246
	KCICI	chees		247
11	The I	Regulato	ry Environment for Engineered Nanomaterials	249
	11.1	Occupa	tional Health Regulations	250
		11.1.1	Occupational Health Regulations in the European Union	250
		11.1.2	US Occupational Health Regulations	252
		11.1.3	Summary: Occupational Exposure Regulations	256
	11.2	Enviror	nmental Regulations	257
		11.2.1	US Environmental Regulations	257
		11.2.2	Environmental Regulations in the European Union	261
	11.3	Compar	ison of Nanotechnology Regulation under TSCA and REACH	263
		11.3.1	The Precautionary Principle and the Burden of Proof	263
		11.3.2	Differences in Handling New and Existing Chemicals	264
		11.3.3	Volume-Based Thresholds and Exemptions	265

XII CONTENTS

	11.5	1.4 Private Law 1.5 Conclusions References		265 266 266
12	Futur	re Direct	tions in Engineered Nanoparticle Health and Safety	269
	12.1	Where	we are Today	269
		12.1.1	Research Efforts in the United States	269
		12.1.2	Research Efforts in Europe	273
		12.1.3	to our a second and the second and t	273
	12.2	Human	Health Effects Studies	276
	12.3	Exposu	re Assessment	276
		12.3.1	Future Needs in Exposure Assessment Techniques	276
		12.3.2	The Development of Occupational Exposure Limits	278
	12.4	Optima	l Approaches to Control Exposures	279
		12.4.1		279
		12.4.2	Control Banding	280
		12.4.3	Respiratory Protection	280
		12.4.4	Safe Work Practices	281
		12.4.5	Air Pollution Control of Nanoparticles	281
		12.4.6	Water Pollution Control of Nanoparticles	281
		12.4.7	Nanoparticles in Waste Streams	282
	12.5	The Fu	ture of Regulation	282
	12.6	Conclu		282
	Refe	rences		283
Ind	lex			285

INTRODUCTION

1.1 WHY A BOOK ON NANOTECHNOLOGY HEALTH AND SAFETY?

Asbestos, once hailed as a "miracle" material for its insulating properties, has been an occupational and environmental health disaster. Many thousands of people, mostly workers but also members of the general population, have developed serious illnesses, including asbestosis, lung and colon cancer, and mesothelioma, and many have died as a result of their exposure. The reader may ask, "why start a book on nanoparticle health and safety with a discussion of asbestos, which most definitely is not a nanoparticle?" The answer leads us to our purpose in writing this book, at this time.

The authors have been to many nanoparticle health and safety meetings over the past several years. A constant theme at those meetings, both in the formal presentations and also in the informal discussions among the scientists in attendance, is "we have to prevent the next asbestos." Starting in the 1920s, exposure to asbestos from its mining, milling, and incorporation into products such as textiles was associated with severe lung disease that came to be called asbestosis; other hazards from asbestos exposure, such as lung cancer and mesothelioma, were not discovered until years later. In addition, the risks to workers using products containing asbestos and to individuals in the general population took some time to be appreciated.

Today, engineered nanoparticles represent a miracle new material (actually, a range of materials, as discussed later), just as asbestos was a miracle new material

2 INTRODUCTION

early in the last century. And, as with asbestos, there are early indications that there may be adverse health effects associated with at least some of these new materials; in fact, carbon nanotubes may have similar health effects as asbestos (see Section 5.4). The extent of the risk to workers and the general public is not known at this time. The answer to the question posed above leads to another question, that is, have we learned our lessons from asbestos and other similar occupational and environmental health disasters, so that we can develop the exciting new field of nanotechnology while protecting the health of workers and the general population, and prevent any adverse effects to the environment?

We believe that the answer to this question is "yes." The nanotechnology industry is still in its infancy, meaning that proactive steps can be taken to further its development in a safe, sustainable manner. Andrew Maynard and colleagues summarized the risks and opportunities in their 2006 *Nature* article as follows (Maynard et al., 2006):

The spectre of possible harm—whether real or imagined—is threatening to slow the development of nanotechnology unless sound, independent and authoritative information is developed on what the risks are, and how to avoid them. In what may be unprecedented pre-emptive action in the face of a new technology, governments, industries and research organizations around the world are beginning to address how the benefits of emerging nanotechnologies can be realized while minimizing potential risks.

This book has been written in an attempt to contribute to the minimizing of the potential risks of nanotechnology. In occupational and environmental health, we have a very simple model that guides our work, that is, exposure to a material or physical agent may lead to an adverse health effect in the exposed population. Although we have included a brief review of the current state of nanoparticle toxicology in Chapter 5, in order to put the need for exposure assessment and control in their proper context, this is a book about the exposure side of our model. In considering exposure, the two most important aspects are to *evaluate* the magnitude of the exposure and, in those cases where the exposure is judged to be excessive, take steps to *control* the exposure. These are the two major topics covered in this book.

It is important to emphasize that this book pays relatively little attention to the *judgment* step just mentioned. In most cases, environmental health professionals make the decision as to whether a measured exposure is excessive by comparison to standards, such as published occupational exposure limits. These standards, in turn, are established based on results of toxicology and epidemiology studies that quantify the risk of exposure for a certain material. The difficulty with engineered nanomaterials, as discussed in Chapter 5, is that at this time there is insufficient information to set such standards. The consensus among occupational and environmental health scientists studying engineered nanoparticles is that until sufficient toxicology and epidemiology information is available for any given material, the precautionary approach must be followed in order to minimize the risk to workers, the general public, and the environment. This concept is further discussed in Section 1.4.

SOME SCENARIOS 3

In the occupational environment, exposure assessment and control are the purview of industrial hygiene or, more widely used today, occupational hygiene; regarding the general environment, the equivalent field might be called "environmental hygiene," although this term is not widely used. In any case, the subject of this book is the current state of knowledge concerning the occupational and environmental hygiene aspects of nanotechnology. It is fair to say, however, that most of the focus in on occupational hygiene, and there are two reasons for this. First is the fact that the authors are occupational hygienists, so most of our experience and expertise, such as it is, falls within this field. The second reason is perhaps more important, which is that in a new and growing industry such as nanotechnology, most of the significant exposures will be to those workers who are doing research with and manufacturing nanomaterials. Consequently, most of the concerns and attention of the research community to date has been focused on nanotechnology workers, rather than the general public. As nanotechnology-enabled products become more widely used, we can expect more of the focus to shift to their environmental impact.

1.2 SOME SCENARIOS

Some scenarios may help to put the need for nanoparticle health and safety in its proper context. These scenarios are all fictional but based more or less on real situations now being encountered in the nanotechnology field.

- A small company specializes in the manufacture of relatively small quantities of high-quality powders in the micrometer size range for specialized niche markets. The company is too small to employ a person with health and safety training. The company president wishes to modify their production equipment to produce powders in the nanometer size range but has read of general concerns about the safety of nanoparticles. He asks his production manager to find out whether manufacturing nanopowders will present any new hazards to their workers.
- A university laboratory is conducting research on the use of carbon nanotubes (CNTs) as a new form of digital storage device. As part of this research, the laboratory technician must transfer small quantities of dry bulk CNTs from a 2 L jar to a beaker, weigh them on a balance, and disperse them in a solvent. These steps are now done on a laboratory bench, and the technician is concerned that she may be breathing in some CNTs that are being released from the powder.
- A plastics manufacturing company has recently begun pilot-scale testing of a new composite material, consisting of polyester reinforced with 2% by mass of alumina nanoparticles. The composite is produced in a twin-screw extruder. The polymer pellets are dumped into one hopper and the nanoalumina in another; they are fed by gravity into the throat of the extruder, where the pellets are melted by high temperature and pressure and mixed with the nanoalumina to form the nanocomposite. The extruder operator has noticed some of the alumina powder on various work surfaces around the hopper and is concerned that this may not be completely safe.

4 INTRODUCTION

• A company uses the nanocomposite material produced above to make tennis racket frames. The pellets are fed into an injection molding machine which produces the tennis racket shape. However, extraneous material has to be cut off the frame with a saw and the frame must be sanded smooth. The plant occupational hygienist is concerned that these operations may release nanoparticles. In addition, the tennis racket manufacturer labels the product "contains nanomaterials for added strength" and is receiving anxious questions from consumers on their web site.

- An occupational hygienist working in the health and safety office at a large research university conducted a university-wide survey which found that more than 50 laboratories across the university claimed to be doing research with some type of nanoparticle. Many of the respondents stated that they did not know what practices should be followed when working with nanoparticles; the occupational hygienist decided that the university needed a policy on good work practices but he did not know how he would gather the information to develop such a policy.
- A research laboratory recently purchased a chemical vapor deposition furnace for making CNTs. While the furnace is a closed system during CNT production, at the end of a run, it must be opened and the CNT material must be scraped from the furnace walls into a drum. This process creates visible dust, which has caused the operator some anxiety.
- A research laboratory was working with quantum dots suspended in a solvent. During normal operations, the laboratory director was fairly confident that no nanoparticle exposure was occurring, since the particles were in liquid suspension. One day, however, a technician dropped a beaker containing the nanoparticle suspension, and the beaker shattered when it hit the floor. Since the laboratory had no emergency response plan in place, the laboratory director was unsure what steps to take to clean up the spill. She decided to evacuate all personnel from the lab, waited until the solvent had completely evaporated, swept up the broken glass and placed it in the lab's broken glass receptacle. The workers were then allowed back in the lab.

These scenarios share certain characteristics, that is,

- Uncertainty as to the adverse health effects, if any, associated with using a nanomaterial;
- Uncertainty as to the level of worker exposure, if any, from using a nanomaterial; and
- Uncertainty as to what steps (control methods) should be taken to ensure that worker exposures are controlled to an acceptable level.

This text does not address the first point above but is meant to address the other two. We hope to provide the reader with the latest information concerning techniques to evaluate and control occupational and environmental exposures to nanoparticles.

1.3 ORGANIZATION OF THE MATERIAL

The remainder of the book generally follows the basic occupational hygiene model for addressing a possible worker exposure, which is the four-step process of anticipation, recognition, evaluation, and control. We start in Chapter 2 with a presentation on the terms used in this field—the definition of a nanoparticle, the different types of nanoparticles, and so on. In the anticipation phase, we attempt to identify possible problems of concern. Chapter 3 discusses the unique properties of nanoparticles that may make them more toxic than larger particles of the same material, and Chapter 4 describes the various pathways by which a nanoparticle might enter the body. We then move to the recognition phase in Chapter 5 with an overview of the current knowledge on engineered nanoparticle toxicity, followed by a discussion of possible sources of exposure in Chapter 6.

We then move to the main topics of this book, evaluation, and control. Chapter 7 reviews the current state of instruments and methods available to evaluate exposures to engineered nanoparticles, and Chapter 8 reviews in detail how those tools are used to perform an engineered nanoparticle exposure characterization. Included in Chapter 8 are three detailed case studies arising from work in our laboratory that illustrate the practical application of the exposure assessment methodology. Chapters 9 and 10 are concerned with solutions—methods to control occupational and environmental exposures that an exposure assessment found to be problematic. Again, the basic techniques are supplemented by case studies from our research.

We end the book by considering important policy issues facing the nanotechnology health and safety community. Chapter 11 discusses the current state of health and safety regulations, both in the United States and internationally, and Chapter 12 concludes with our thoughts and recommendations for needed next steps if we are to continue to make progress toward our goal of preventing occupational injuries and disease related to nanotechnology.

1.4 OUR APPROACH TO NANOPARTICLE HEALTH AND SAFETY

We will return to this topic at the end of Chapter 12, but we believe that it is important for the reader to understand the basic philosophy behind our approach to nanoparticle health and safety, since it informs all of the topics covered throughout the text. At the time of this writing in 2014, much is not known about the toxicology of engineered nanoparticles, but enough is known to certainly raise concerns. Likewise, we know that workers and the general public have the potential to be exposed to engineered nanoparticles. Therefore, we believe that a precautionary approach must be followed—specifically, we believe that until toxicology and/or epidemiology tell us differently, all reasonable steps should be taken to minimize exposures to engineered nanoparticles. In order to accomplish this, exposures must first be measured and, where exposures are found to be measurably above background levels, steps must be taken to reduce those exposures.