

**DRAFT
TOXICOLOGICAL PROFILE FOR
ALUMINUM**

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Agency for Toxic Substances and Disease Registry

September 2006

DISCLAIMER

The use of company or product name(s) is for identification only and does not imply endorsement by the Agency for Toxic Substances and Disease Registry.

This information is distributed solely for the purpose of pre dissemination public comment under applicable information quality guidelines. It has not been formally disseminated by the Agency for Toxic Substances and Disease Registry. It does not represent and should not be construed to represent any agency determination or policy.

UPDATE STATEMENT

A Toxicological Profile for Aluminum was released in 1999. This edition supersedes any previously released draft or final profile.

Toxicological profiles are revised and republished as necessary. For information regarding the update status of previously released profiles, contact ATSDR at:

Agency for Toxic Substances and Disease Registry
Division of Toxicology and Environmental Medicine/Applied Toxicology Branch
1600 Clifton Road NE
Mailstop F-32
Atlanta, Georgia 30333

This page is intentionally blank.

FOREWORD

This toxicological profile is prepared in accordance with guidelines developed by the Agency for Toxic Substances and Disease Registry (ATSDR) and the Environmental Protection Agency (EPA). The original guidelines were published in the *Federal Register* on April 17, 1987. Each profile will be revised and republished as necessary.

The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for the hazardous substance described therein. Each peer-reviewed profile identifies and reviews the key literature that describes a hazardous substance's toxicologic properties. Other pertinent literature is also presented, but is described in less detail than the key studies. The profile is not intended to be an exhaustive document; however, more comprehensive sources of specialty information are referenced.

The focus of the profiles is on health and toxicologic information; therefore, each toxicological profile begins with a public health statement that describes, in nontechnical language, a substance's relevant toxicological properties. Following the public health statement is information concerning levels of significant human exposure and, where known, significant health effects. The adequacy of information to determine a substance's health effects is described in a health effects summary. Data needs that are of significance to protection of public health are identified by ATSDR and EPA.

Each profile includes the following:

- (A) The examination, summary, and interpretation of available toxicologic information and epidemiologic evaluations on a hazardous substance to ascertain the levels of significant human exposure for the substance and the associated acute, subacute, and chronic health effects;
- (B) A determination of whether adequate information on the health effects of each substance is available or in the process of development to determine levels of exposure that present a significant risk to human health of acute, subacute, and chronic health effects; and
- (C) Where appropriate, identification of toxicologic testing needed to identify the types or levels of exposure that may present significant risk of adverse health effects in humans.

The principal audiences for the toxicological profiles are health professionals at the Federal, State, and local levels; interested private sector organizations and groups; and members of the public. We plan to revise these documents in response to public comments and as additional data become available. Therefore, we encourage comments that will make the toxicological profile series of the greatest use.

Comments should be sent to:

Agency for Toxic Substances and Disease Registry
Division of Toxicology and Environmental Medicine
1600 Clifton Road, N.E.
Mail Stop F-32
Atlanta, Georgia 30333

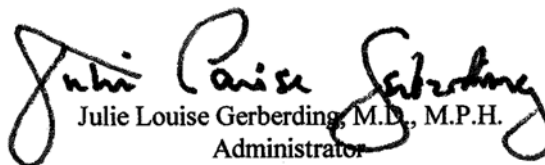
The toxicological profiles are developed in response to the Superfund Amendments and Reauthorization Act (SARA) of 1986 (Public Law 99-499) which amended the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA or Superfund). This public law directed ATSDR to prepare toxicological profiles for hazardous substances most commonly found at facilities on the CERCLA National Priorities List and that pose the most significant potential threat to human health, as determined by ATSDR and the EPA. The availability of the revised priority list of 275 hazardous substances was announced in the *Federal Register* on December 7, 2005 (70 FR 72840). For prior versions of the list of substances, see *Federal Register* notices dated April 17, 1987 (52 FR 12866); October 20, 1988 (53 FR 41280); October 26, 1989 (54 FR 43619); October 17, 1990 (55 FR 42067); October 17, 1991 (56 FR 52166); October 28, 1992 (57 FR 48801); February 28, 1994 (59 FR 9486); April 29, 1996 (61 FR 18744); November 17, 1997 (62 FR 61332); October 21, 1999 (64 FR 56792); October 25, 2001 (66 FR 54014); and November 7, 2003 (68 FR 63098). Section 104(i)(3) of CERCLA, as amended, directs the Administrator of ATSDR to prepare a toxicological profile for each substance on the list.

This profile reflects ATSDR's assessment of all relevant toxicologic testing and information that has been peer-reviewed. Staff of the Centers for Disease Control and Prevention and other Federal scientists have also reviewed the profile. In addition, this profile has been peer-reviewed by a nongovernmental panel and is being made available for public review. Final responsibility for the contents and views expressed in this toxicological profile resides with ATSDR.



Howard Frumkin, M.D., Dr. P.H.
Director

National Center for Environmental Health/
Agency for Toxic Substances and
Disease Registry



Julie Louise Gerberding, M.D., M.P.H.
Administrator

Agency for Toxic Substances and
Disease Registry

QUICK REFERENCE FOR HEALTH CARE PROVIDERS

Toxicological Profiles are a unique compilation of toxicological information on a given hazardous substance. Each profile reflects a comprehensive and extensive evaluation, summary, and interpretation of available toxicologic and epidemiologic information on a substance. Health care providers treating patients potentially exposed to hazardous substances will find the following information helpful for fast answers to often-asked questions.

Primary Chapters/Sections of Interest

Chapter 1: Public Health Statement: The Public Health Statement can be a useful tool for educating patients about possible exposure to a hazardous substance. It explains a substance's relevant toxicologic properties in a nontechnical, question-and-answer format, and it includes a review of the general health effects observed following exposure.

Chapter 2: Relevance to Public Health: The Relevance to Public Health Section evaluates, interprets, and assesses the significance of toxicity data to human health.

Chapter 3: Health Effects: Specific health effects of a given hazardous compound are reported by type of health effect (death, systemic, immunologic, reproductive), by route of exposure, and by length of exposure (acute, intermediate, and chronic). In addition, both human and animal studies are reported in this section.

NOTE: Not all health effects reported in this section are necessarily observed in the clinical setting. Please refer to the Public Health Statement to identify general health effects observed following exposure.

Pediatrics: Four new sections have been added to each Toxicological Profile to address child health issues:

Section 1.6	How Can (Chemical X) Affect Children?
Section 1.7	How Can Families Reduce the Risk of Exposure to (Chemical X)?
Section 3.7	Children's Susceptibility
Section 6.6	Exposures of Children

Other Sections of Interest:

Section 3.8	Biomarkers of Exposure and Effect
Section 3.11	Methods for Reducing Toxic Effects

ATSDR Information Center

Phone: 1-800-CDC-INFO (800-232-4636)	Fax: (770) 488-4178
1-888-232-6348 (TTY)	
E-mail: cdcinfo@cdc.gov	Internet: http://www.atsdr.cdc.gov

The following additional material can be ordered through the ATSDR Information Center:

Case Studies in Environmental Medicine: Taking an Exposure History—The importance of taking an exposure history and how to conduct one are described, and an example of a thorough exposure history is provided. Other case studies of interest include *Reproductive and Developmental*

Hazards; Skin Lesions and Environmental Exposures; Cholinesterase-Inhibiting Pesticide Toxicity; and numerous chemical-specific case studies.

Managing Hazardous Materials Incidents is a three-volume set of recommendations for on-scene (prehospital) and hospital medical management of patients exposed during a hazardous materials incident. Volumes I and II are planning guides to assist first responders and hospital emergency department personnel in planning for incidents that involve hazardous materials. Volume III—*Medical Management Guidelines for Acute Chemical Exposures*—is a guide for health care professionals treating patients exposed to hazardous materials.

Fact Sheets (ToxFAQs) provide answers to frequently asked questions about toxic substances.

Other Agencies and Organizations

The National Center for Environmental Health (NCEH) focuses on preventing or controlling disease, injury, and disability related to the interactions between people and their environment outside the workplace. Contact: NCEH, Mailstop F-29, 4770 Buford Highway, NE, Atlanta, GA 30341-3724 • Phone: 770-488-7000 • FAX: 770-488-7015.

The National Institute for Occupational Safety and Health (NIOSH) conducts research on occupational diseases and injuries, responds to requests for assistance by investigating problems of health and safety in the workplace, recommends standards to the Occupational Safety and Health Administration (OSHA) and the Mine Safety and Health Administration (MSHA), and trains professionals in occupational safety and health. Contact: NIOSH, 200 Independence Avenue, SW, Washington, DC 20201 • Phone: 800-356-4674 or NIOSH Technical Information Branch, Robert A. Taft Laboratory, Mailstop C-19, 4676 Columbia Parkway, Cincinnati, OH 45226-1998 • Phone: 800-35-NIOSH.

The National Institute of Environmental Health Sciences (NIEHS) is the principal federal agency for biomedical research on the effects of chemical, physical, and biologic environmental agents on human health and well-being. Contact: NIEHS, PO Box 12233, 104 T.W. Alexander Drive, Research Triangle Park, NC 27709 • Phone: 919-541-3212.

Referrals

The Association of Occupational and Environmental Clinics (AOEC) has developed a network of clinics in the United States to provide expertise in occupational and environmental issues. Contact: AOEC, 1010 Vermont Avenue, NW, #513, Washington, DC 20005 • Phone: 202-347-4976 • FAX: 202-347-4950 • e-mail: AOEC@AOEC.ORG • Web Page: <http://www.aoec.org/>.

The American College of Occupational and Environmental Medicine (ACOEM) is an association of physicians and other health care providers specializing in the field of occupational and environmental medicine. Contact: ACOEM, 25 Northwest Point Boulevard, Suite 700, Elk Grove Village, IL 60007-1030 • Phone: 847-818-1800 • FAX: 847-818-9266.

CONTRIBUTORS

CHEMICAL MANAGER(S)/AUTHOR(S):

Sam Keith, M.S.

Dennis Jones, D.V.M.

Zemoria Rosemond, B.A.

ATSDR, Division of Toxicology and Environmental Medicine, Atlanta, Georgia

Lisa Ingerman, Ph.D., DABT

Lara Chappell, Ph.D.

Syracuse Research Corporation, North Syracuse, New York

THE PROFILE HAS UNDERGONE THE FOLLOWING ATSDR INTERNAL REVIEWS:

1. Health Effects Review. The Health Effects Review Committee examines the health effects chapter of each profile for consistency and accuracy in interpreting health effects and classifying end points.
2. Minimal Risk Level Review. The Minimal Risk Level Workgroup considers issues relevant to substance-specific Minimal Risk Levels (MRLs), reviews the health effects database of each profile, and makes recommendations for derivation of MRLs.
3. Data Needs Review. The Research Implementation Branch reviews data needs sections to assure consistency across profiles and adherence to instructions in the Guidance.
4. Green Border Review. Green Border review assures the consistency with ATSDR policy.

This page is intentionally blank.

PEER REVIEW

A peer review panel was assembled for aluminum. The panel consisted of the following members:

1. Dr. Jerrold Abraham, Professor of Family Medicine and Pathology, Upstate Medical University, Syracuse, New York,
2. Dr. Michael Aschner, Director, Division of Pediatric Toxicology, Vanderbilt University Medical Center, Nashville, Tennessee, and
3. Dr. Robert Yokel, Professor, Division of Pharmaceutical Sciences, University of Kentucky, College of Pharmacy, Lexington, Kentucky.

These experts collectively have knowledge of aluminum's physical and chemical properties, toxicokinetics, key health end points, mechanisms of action, human and animal exposure, and quantification of risk to humans. All reviewers were selected in conformity with the conditions for peer review specified in Section 104(I)(13) of the Comprehensive Environmental Response, Compensation, and Liability Act, as amended.

Scientists from the Agency for Toxic Substances and Disease Registry (ATSDR) have reviewed the peer reviewers' comments and determined which comments will be included in the profile. A listing of the peer reviewers' comments not incorporated in the profile, with a brief explanation of the rationale for their exclusion, exists as part of the administrative record for this compound.

The citation of the peer review panel should not be understood to imply its approval of the profile's final content. The responsibility for the content of this profile lies with the ATSDR.

This page is intentionally blank.

CONTENTS

DISCLAIMER	ii
UPDATE STATEMENT	iii
FOREWORD	v
QUICK REFERENCE FOR HEALTH CARE PROVIDERS	vii
CONTRIBUTORS	ix
PEER REVIEW	xi
CONTENTS	xiii
LIST OF FIGURES	xvii
LIST OF TABLES	xix
1. PUBLIC HEALTH STATEMENT	1
1.1 WHAT IS ALUMINUM?	1
1.2 WHAT HAPPENS TO ALUMINUM WHEN IT ENTERS THE ENVIRONMENT?	2
1.3 HOW MIGHT I BE EXPOSED TO ALUMINUM?	3
1.4 HOW CAN ALUMINUM ENTER AND LEAVE MY BODY?	5
1.5 HOW CAN ALUMINUM AFFECT MY HEALTH?	5
1.6 HOW CAN ALUMINUM AFFECT CHILDREN?	7
1.7 HOW CAN FAMILIES REDUCE THE RISK OF EXPOSURE TO ALUMINUM?	7
1.8 IS THERE A MEDICAL TEST TO DETERMINE WHETHER I HAVE BEEN EXPOSED TO ALUMINUM?	8
1.9 WHAT RECOMMENDATIONS HAS THE FEDERAL GOVERNMENT MADE TO PROTECT HUMAN HEALTH?	9
1.10 WHERE CAN I GET MORE INFORMATION?	10
2. RELEVANCE TO PUBLIC HEALTH	11
2.1 BACKGROUND AND ENVIRONMENTAL EXPOSURES TO ALUMINUM IN THE UNITED STATES	11
2.2 SUMMARY OF HEALTH EFFECTS	12
2.3 MINIMAL RISK LEVELS (MRLs)	15
3. HEALTH EFFECTS	29
3.1 INTRODUCTION	29
3.2 DISCUSSION OF HEALTH EFFECTS BY ROUTE OF EXPOSURE	29
3.2.1 Inhalation Exposure	30
3.2.1.1 Death	30
3.2.1.2 Systemic Effects	31
3.2.1.3 Immunological and Lymphoreticular Effects	47
3.2.1.4 Neurological Effects	47
3.2.1.5 Reproductive Effects	49
3.2.1.6 Developmental Effects	49
3.2.1.7 Cancer	49
3.2.2 Oral Exposure	51
3.2.2.1 Death	53
3.2.2.2 Systemic Effects	54
3.2.2.3 Immunological and Lymphoreticular Effects	76
3.2.2.4 Neurological Effects	78
3.2.2.5 Reproductive Effects	85

3.2.2.6	Developmental Effects	87
3.2.2.7	Cancer	91
3.2.3	Dermal Exposure	92
3.2.3.1	Death	92
3.2.3.2	Systemic Effects	92
3.2.3.3	Immunological and Lymphoreticular Effects	97
3.2.3.4	Neurological Effects	98
3.2.3.5	Reproductive Effects	98
3.2.3.6	Developmental Effects	98
3.2.3.7	Cancer	98
3.3	GENOTOXICITY	98
3.4	TOXICOKINETICS	99
3.4.1	Absorption	101
3.4.1.1	Inhalation Exposure	101
3.4.1.2	Oral Exposure	102
3.4.1.3	Dermal Exposure	105
3.4.1.4	Other Routes of Exposure	105
3.4.2	Distribution	105
3.4.2.1	Inhalation Exposure	106
3.4.2.2	Oral Exposure	107
3.4.2.3	Dermal Exposure	109
3.4.2.4	Other Routes of Exposure	109
3.4.3	Metabolism	111
3.4.4	Elimination and Excretion	112
3.4.4.1	Inhalation Exposure	112
3.4.4.2	Oral Exposure	113
3.4.4.3	Dermal Exposure	114
3.4.4.4	Other Routes of Exposure	114
3.4.5	Physiologically Based Pharmacokinetic (PBPK)/Pharmacodynamic (PD) Models	114
3.5	MECHANISMS OF ACTION	117
3.5.1	Pharmacokinetic Mechanisms	118
3.5.2	Mechanisms of Toxicity	119
3.5.3	Animal-to-Human Extrapolations	121
3.6	TOXICITIES MEDIATED THROUGH THE NEUROENDOCRINE AXIS	122
3.7	CHILDREN'S SUSCEPTIBILITY	123
3.8	BIOMARKERS OF EXPOSURE AND EFFECT	126
3.8.1	Biomarkers Used to Identify or Quantify Exposure to Aluminum	127
3.8.2	Biomarkers Used to Characterize Effects Caused by Aluminum	128
3.9	INTERACTIONS WITH OTHER CHEMICALS	128
3.10	POPULATIONS THAT ARE UNUSUALLY SUSCEPTIBLE	129
3.11	METHODS FOR REDUCING TOXIC EFFECTS	129
3.11.1	Reducing Peak Absorption Following Exposure	130
3.11.2	Reducing Body Burden	130
3.11.3	Interfering with the Mechanism of Action for Toxic Effects	131
3.12	ADEQUACY OF THE DATABASE	131
3.12.1	Existing Information on Health Effects of Aluminum	132
3.12.2	Identification of Data Needs	132
3.12.3	Ongoing Studies	144

4. CHEMICAL AND PHYSICAL INFORMATION.....	147
4.1 CHEMICAL IDENTITY.....	147
4.2 PHYSICAL AND CHEMICAL PROPERTIES.....	147
5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL.....	159
5.1 PRODUCTION.....	159
5.2 IMPORT/EXPORT.....	168
5.3 USE.....	173
5.4 DISPOSAL.....	175
6. POTENTIAL FOR HUMAN EXPOSURE.....	177
6.1 OVERVIEW.....	177
6.2 RELEASES TO THE ENVIRONMENT.....	180
6.2.1 Air.....	185
6.2.2 Water.....	186
6.2.3 Soil.....	187
6.3 ENVIRONMENTAL FATE.....	188
6.3.1 Transport and Partitioning.....	188
6.3.2 Transformation and Degradation.....	193
6.3.2.1 Air.....	193
6.3.2.2 Water.....	194
6.3.2.3 Sediment and Soil.....	194
6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT.....	195
6.4.1 Air.....	195
6.4.2 Water.....	196
6.4.3 Sediment and Soil.....	200
6.4.4 Other Environmental Media.....	201
6.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE.....	212
6.6 EXPOSURES OF CHILDREN.....	216
6.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES.....	220
6.8 ADEQUACY OF THE DATABASE.....	222
6.8.1 Identification of Data Needs.....	223
6.8.2 Ongoing Studies.....	227
7. ANALYTICAL METHODS.....	229
7.1 BIOLOGICAL MATERIALS.....	229
7.2 ENVIRONMENTAL SAMPLES.....	236
7.3 ADEQUACY OF THE DATABASE.....	240
7.3.1 Identification of Data Needs.....	241
7.3.2 Ongoing Studies.....	243
8. REGULATIONS AND ADVISORIES.....	245
9. REFERENCES.....	251
10. GLOSSARY.....	303

APPENDICES

A. ATSDR MINIMAL RISK LEVELS AND WORKSHEETS A-1

B. USER’S GUIDE..... B-1

C. ACRONYMS, ABBREVIATIONS, AND SYMBOLS..... C-1

D. INDEX D-1

LIST OF FIGURES

3-1. Levels of Significant Exposure to Aluminum and Compounds - Inhalation.....	37
3-2. Levels of Significant Exposure to Aluminum and Compounds - Oral.....	66
3-3. Conceptual Representation of a Physiologically Based Pharmacokinetic (PBPK) Model for a Hypothetical Chemical Substance.....	116
3-4. Existing Information on Health Effects of Aluminum	133
6-1. Frequency of NPL Sites with Aluminum Contamination.....	178

This page is intentionally blank.

LIST OF TABLES

3-1. Levels of Significant Exposure to Aluminum and Compounds - Inhalation.....	32
3-2. Levels of Significant Exposure to Aluminum and Compounds - Oral.....	55
3-3. Levels of Significant Exposure to Aluminum and Compounds - Dermal.....	93
3-4. Genotoxicity of Aluminum <i>In Vitro</i>	100
3-5. Ongoing Studies on Aluminum.....	145
4-1. Chemical Identity of Aluminum and Compounds.....	148
4-2. Physical and Chemical Properties of Aluminum and Compounds.....	153
5-1. U.S. Manufacturers of Aluminum.....	161
5-2. U.S. Producers of Selected Aluminum Compounds.....	162
5-3. Facilities that Produce, Process, or Use Aluminum (Fume or Dust).....	169
5-4. Facilities that Produce, Process, or Use Aluminum Oxide (Fibrous Forms).....	171
6-1. Releases to the Environment from Facilities that Produce, Process, or Use Aluminum (Fume or Dust).....	181
6-2. Releases to the Environment from Facilities that Produce, Process, or Use Aluminum Oxide (Fibrous Forms).....	183
6-3. Aluminum Concentrations Detected in Drinking Water in Various Regions of the United States.....	198
6-4. Estimated Aluminum Concentrations of Selected Foods.....	202
6-5. Dietary Intakes of Aluminum in Children.....	217
6-6. Major Sources of Aluminum in Food by Age-Sex Group.....	218
6-7. Ongoing Studies on Aluminum.....	228
7-1. Analytical Methods for Determining Aluminum in Biological Materials.....	230
7-2. Analytical Methods for Determining Aluminum in Environmental Samples.....	237
7-3. Ongoing Studies on Aluminum.....	244
8-1. Regulations and Guidelines Applicable to Aluminum and Compounds.....	246