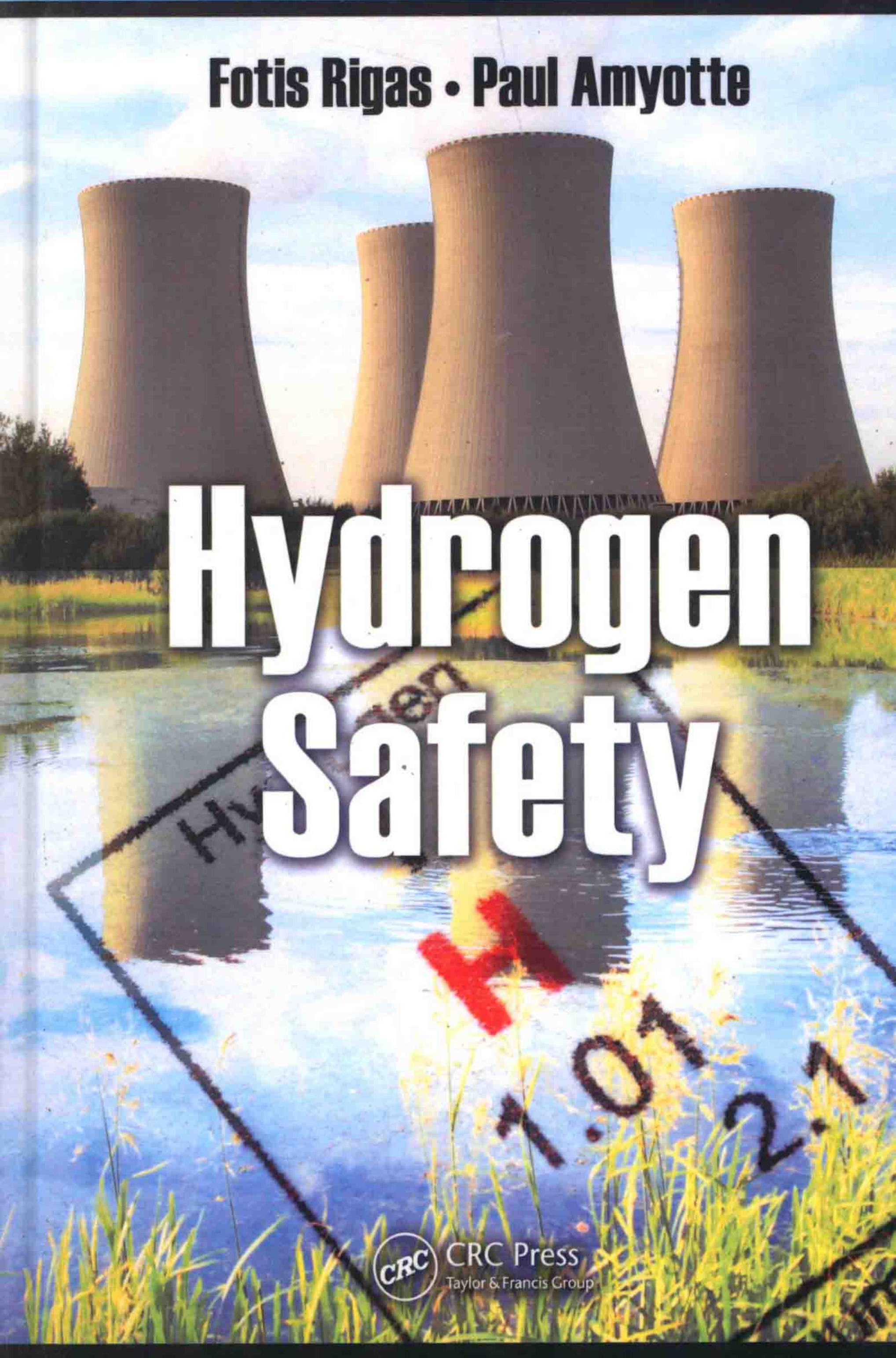
GREEN CHEMISTRY AND CHEMICAL ENGINEERING

Fotis Rigas • Paul Amyotte

Hydrogen Safety



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Hydrogen Safety

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Series Preface

The subjects and disciplines of chemistry and chemical engineering have encountered a new landmark in the way of thinking about developing and designing chemical products and processes. This revolutionary philosophy, termed *green chemistry and chemical engineering*, focuses on the designs of products and processes that are conducive to reducing or eliminating the use and/or generation of hazardous substances. In dealing with hazardous or potentially hazardous substances, there may be some overlaps and interrelationships between environmental chemistry and green chemistry. Whereas environmental chemistry is the chemistry of the natural environment and the pollutant chemicals in nature, green chemistry proactively aims to reduce and prevent pollution at its very source. In essence, the philosophies of green chemistry and chemical engineering tend to focus more on industrial application and practice rather than academic principles and phenomenological science. However, as both a chemistry and chemical engineering philosophy, green chemistry and chemical engineering derive from and build on organic chemistry, inorganic chemistry, polymer chemistry, fuel chemistry, biochemistry, analytical chemistry, physical chemistry, environmental chemistry, thermodynamics, chemical reaction engineering, transport phenomena, chemical process design, separation technology, automatic process control, and more. In short, green chemistry and chemical engineering are the rigorous use of chemistry and chemical engineering for pollution prevention and environmental protection.

The Pollution Prevention Act of 1990 in the United States established a national policy to prevent or reduce pollution at its source whenever feasible. And adhering to the spirit of this policy, the Environmental Protection Agency (EPA) launched its Green Chemistry Program in order to promote innovative chemical technologies that reduce or eliminate the use or generation of hazardous substances in the design, manufacture, and use of chemical products. Global efforts in green chemistry and chemical engineering have recently gained a substantial amount of support from the international communities of science, engineering, academia, industry, and government in all phases and aspects.

Some of the successful examples and key technological developments include the use of supercritical carbon dioxide as a green solvent in separation technologies; application of supercritical water oxidation for destruction of harmful substances; process integration with carbon dioxide sequestration steps; solvent-free synthesis of chemicals and polymeric materials; exploitation of biologically degradable materials; use of aqueous hydrogen peroxide for efficient oxidation; development of hydrogen proton exchange membrane (PEM) fuel cells for a variety of power generation needs; advanced biofuel productions; devulcanization of spent tire rubber; avoidance of the use of chemicals and processes causing generation of volatile organic compounds (VOCs); replacement of traditional petrochemical processes by microorganism-based bioengineering processes; replacement of chlorofluorocarbons (CFCs) with nonhazardous alternatives; advances in design of energy-efficient processes; use of clean, alternative, and renewable energy sources in manufacturing; and much more. This list, even though it is only a partial compilation, is undoubtedly growing exponentially.

This book series on Green Chemistry and Chemical Engineering by CRC Press/Taylor & Francis is designed to meet the new challenges of the twenty-first century in the chemistry and chemical engineering disciplines by publishing books and monographs based on cutting-edge research and development to the effect of reducing adverse impacts on the environment by chemical enterprise. In achieving this, the series will detail the development of alternative sustainable technologies that will minimize the hazard and maximize the efficiency of any chemical choice. The series aims at delivering the readers in academia and industry with an authoritative information source in the field of green chemistry and chemical engineering. The publisher and its series editor are fully aware of the rapidly evolving nature of the subject and its long-lasting impact on the quality of human life in both the present and future. As such, the team is committed to making this series the most comprehensive and accurate literary source in the field of green chemistry and chemical engineering.

Sunggyu Lee

Preface

This book on the safe handling and use of hydrogen is intended as much to provoke thought and dialogue as to provide practical guidance. We of course hope that readers will find the information we present to be helpful in their endeavors to bring the envisaged hydrogen economy into reality. But we also hope that important areas of safety research, often viewed as being nontechnological, will be welcomed into the discussion of hydrogen safety along with the more familiar technological topics.

The book is organized to first address questions associated with the hazards of hydrogen and the ensuing risk in its use within industry and by the public. What are the properties of hydrogen that can render it a hazardous substance? How have these hazards historically resulted in undesired incidents? How might these hazards arise in the storage of hydrogen and with its use in vehicular transportation?

We then turn to the issues of inherently safer design and, in accordance with the previous comment on so-called nontechnological topics, safety management systems and safety culture. The European Commission (EC) Network of Excellence for Hydrogen Safety, *HySafe*, is singled out for separate coverage, as are various case studies associated with hydrogen and constructional materials. We conclude with a brief look at future research requirements and current legal requirements for hydrogen safety.

Our approach, then, has been to attempt a balanced view of hydrogen safety. Such a perspective comes not only from our respective areas of expertise, but also a collective belief that the safety of any material or activity is most effectively addressed through a combination of the physical sciences and engineering principles together with the management and social sciences. Non-hydrogen-related industries have undergone painful experiences in this regard; there should be no need for industrial applications involving hydrogen to experience the same difficulties.

Coauthor Fotis Rigas would like to acknowledge and thank his family, and especially his wife, Betty, for their (almost) uncomplaining and enduring patience during his long-drawn-out academic activities. He also wishes to express his gratitude to Ms. Allison Shatkin, senior editor in Materials Science and Chemical Engineering of CRC Press/Taylor & Francis, for entrusting him and coauthor Paul Amyotte with the task of writing this book.

Coauthor Paul Amyotte would like to acknowledge and thank his family for their loving support in all his professional undertakings. He is especially grateful to his wife, Peggy. He also extends gratitude to Dalhousie University, and in particular Dr. Joshua Leon, dean of Engineering, for his recent appointment as C. D. Howe Chair in Engineering.

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Fotis Rigas is an associate professor of Chemical Engineering at National Technical University of Athens in Greece and has been a Visiting Professor at National Autonomous University of Mexico. His current research and academic activities are in the areas of process safety and bioremediation of contaminated sites. He has published or presented over 150 papers in the fields of his activities and is a reviewer of papers in 34 international journals.

Paul Amyotte is a professor of Chemical Engineering and the C. D. Howe Chair in Engineering at Dalhousie University in Canada. His research and practice interests are in the areas of inherent safety, process safety, and dust explosion prevention and mitigation. He has published or presented over 200 papers in the field of industrial safety and is the editor of the *Journal of Loss Prevention in the Process Industries.*

List of Acronyms

ADNR (inland waterways)	Regulation for the Carriage of Dangerous Substances on the Rhine (EU)
ADR (road)	Accord Européen Relatif au Transport International des Marchandises Dangereuses par Route - European Agreement Concerning the International Carriage of Dangerous Goods by Road
AIChE	American Institute of Chemical Engineers
ALARP	As Low As Reasonably Practicable Principle
ATEX	Appareils destinés à être utilisés en ATmosphères EXplosives (EU Directive)
BAMs	Bulk Amorphous Materials
BLEVE	Boiling Liquid Expanding Vapor Explosion
CCPA	Canadian Chemical Producers' Association
CCPS	Center for Chemical Process Safety
CEI	Dow Chemical Exposure Index
CFCs	Chlorofluorocarbons
CFD	Computational Fluid Dynamics
CL	Checklist
CNG	Compressed Natural Gas
COD	Code of Practice
CPU	Central Processing Unit
CSB	Chemical Safety Board (USA)
CSChE	Canadian Society for Chemical Engineering
CVCE	Confined Vapor Cloud Explosion
DDT	Deflagration-to-Detonation Transition
DGR	IATA Dangerous Goods Regulations
DNR	Department of Naval Research
DOE	United States Department of Energy
EIGA	European Industrial Gases Association
EPR	European Pressure Reactor
ETA	Event Tree Analysis
FDS	Fire Dynamics Simulator Code
F&EI	Dow Fire and Explosion Index
FMCSA	Federal Motor Carrier Safety Administration
FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis

FVM	Finite Volume Method
GH_2	Compressed Hydrogen Gas
HAZOP	Hazard and Operability Analysis
HIAD	European Hydrogen Incident and Accident Database
HRAM	Hydrogen Risk Assessment Method
HSE	Health and Safety Executive
HTHA	High-Temperature Hydrogen Attack
IATA	International Air Transport Association
IChemE	Institution of Chemical Engineers (UK)
IEA	International Energy Agency
IGC	Industrial Gases Council
IMO (sea)	International Maritime Organization
ISD	Inherently Safer Design
ISO	International Standards Organization
ITER	International Thermonuclear Experimental Reactor
LBLOCA	Large Break Loss of Coolant Accident
LDL	Lower Detonability Limit
LFL	Low Flammability Limit
LH_2	Liquid Hydrogen
LLNL	Lawrence Livermore National Laboratory
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MH	Metal Hydride
MHIDAS	Major Hazard Incident Database Service
MIACC	Major Industrial Accidents Council of Canada)
MIC	Methyl Isocyanate
MIL-STD 882	Military Standard 882
MOC	Management of Change
MOFs	Metal-Organic Frameworks
MVFRI	Motor Vehicle Fire Research Institute
NASA	National Aeronautics and Space Administration
NBP	Normal Boiling Point
NFPA	National Fire Protection Association
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NRA	National Railway Authority
NTP	Normal Temperature and Pressure
NWC	Naval Weapons Center
OHA	Operating Hazard Analysis
OHSAS	Occupational Health and Safety Assessment Series

OSHA	U.S. Occupational Safety and Health Administration
PAR	Passive Auto-Catalytic Recombiners
PED	European Pressure Equipment Directive
PHA	Preliminary Hazard Analysis
PRD	Pressure Relief Devices
PSM	Process Safety Management
QRA	Quantitative Risk Assessment
RID (rail)	Règlement Concernant le Transport International Ferroviaire des Marchandises Dangereuses – Regulation Concerning the Transport of Dangerous Goods by International Railway
RRR	Relative Risk Ranking
SHHSV	Stationary High-pressure Hydrogen Storage Vessel
SRB	Solid Rocket Boosters
SST	Shear Stress Transport Models
STP	Standard Temperature and Pressure
SUV	Suburban Utility Vehicle
SwRI	Southwest Research Institute
TNT	Trinitrotoluene
TPED	Transportable Pressure Equipment Directive
TRD	Thermal Relief Device
UFL	Upper Flammability Limit
UDL	Upper Detonability Limit
UN ECE	United Nations' Economic Commission for Europe
UVCE	Unconfined Vapor Cloud Explosion
WI	What-If Analysis

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