Contents

1 Introduction *1*
1.1 History/Background *1*
1.2 Tanks and Storage *4*

2 Hydrogen – Fundamentals *11*
2.1 Hydrogen Phase Diagram *13*
2.2 Hydrogen in Comparison with Other Fuels *14*
2.3 Hydrogen Production *16*
2.3.1 Reforming Processes in Combination with Fossil Fuels (Coal, Natural Gas, and Mineral Oil) *18*
2.3.1.1 Steam Reforming of Natural Gas *19*
2.3.1.2 Partial Oxidation and Autothermal Reforming of Hydrocarbons *20*
2.3.1.3 HyPr-RING Method to Produce Hydrogen from Hydrocarbons *21*
2.3.1.4 Plasma-Assisted Production of Hydrogen from Hydrocarbons *23*
2.3.1.5 Coal Gasification *25*
2.3.2 Water-Splitting Processes (Hydrogen from Water) *27*
2.3.2.1 Electrolysis of Water with Electricity from Renewable and Nonrenewable Energy Sources (Low-Temperature Water Splitting) *27*
2.3.2.2 Different Types of Electrolyzers *33*
2.3.2.3 High-Temperature Water Splitting in Combination with High-Temperature Nuclear Energy and Solar Energy *42*
2.3.3 Hydrogen from Biomass *45*
2.3.3.1 Thermochemical Processes *47*
2.3.3.2 Biological Processes *47*
2.3.4 Hydrogen from Aluminum *50*
2.3.5 Outlook *51*
2.4 Hydrogen Storage Safety Aspects *53*
2.4.1 Hydrogen Properties Related to Safety *55*
2.4.2 Selected Incidents with Hydrogen *61*
2.4.3 Human Health Impact *62*
2.4.4 Sensors *63*
2.4.5 Regulations, Codes, and Standards (RCS) *63*

2.4.6 Safety Aspects in the Hydrogen Chain from Production to the User *65*
2.4.6.1 Hydrogen Production *66*
2.4.6.2 Hydrogen Refuelling Stations *67*
2.4.6.3 Storage/Transportation (Compressed/Liquid/Metal Hydride) *68*
2.4.6.4 Garage for Repairing Cars *70*
2.4.7 Safety Aspects of Hydrogen Vehicles *70*
2.4.8 Safe Removal of Hydrogen *73*
References *73*

3 Hydrogen Application: Infrastructural Requirements *81*
3.1 Transportation *81*
3.2 Filling Stations *86*
3.3 Distribution *87*
3.4 Military *89*
3.5 Portables *92*
3.6 Infrastructure Requirements *93*
References *96*
Further Reading *96*

4 Storage of Pure Hydrogen in Different States *97*
4.1 Purification of Hydrogen *97*
4.2 Compressed Hydrogen *98*
4.2.1 Properties *98*
4.2.2 Compression *98*
4.2.2.1 Mechanical Compressors *100*
4.2.2.2 Nonmechanical Compressor *101*
4.2.3 Materials *106*
4.2.3.1 Hydrogen Embrittlement *106*
4.2.3.2 Hydrogen Attack *107*
4.2.3.3 Hydrogen Permeation *107*
4.2.3.4 Used Structural Materials *108*
4.2.3.5 Used Materials for Sealing and Liners *109*
4.2.3.6 High Pressure Metal Hydride Storage Tank *109*
4.2.4 Sensors, Instrumentation *110*
4.2.5 Tank Filling *110*
4.2.6 Applications *111*
4.2.6.1 Storage in Underground *111*
4.2.6.2 Road and Rail Transportation *112*
4.2.6.3 Vehicles *112*
4.3 Liquid/Slush Hydrogen *114*
4.3.1 Properties *114*
4.3.2 Ortho Para Conversion *114*
4.3.3 Liquefaction *116*

4.3.3.1 Linde Process *116*
4.3.3.2 Claude Process *117*
4.3.3.3 Collins Process *117*
4.3.3.4 Joule–Brayton Cycle *118*
4.3.3.5 Magnetic Liquefaction *118*
4.3.3.6 Thermoacoustic Liquefaction *120*
4.3.4 Hydrogen Slush *120*
4.3.5 Boil-Off *121*
4.3.5.1 Zero Boil-Off Solutions *122*
4.3.6 Materials *123*
4.3.6.1 Tank Material *123*
4.3.6.2 Insulation *123*
4.3.6.3 Braze Materials *124*
4.3.7 Sensors, Instrumentation *124*
4.3.8 Applications *125*
4.3.8.1 Storage *125*
4.3.8.2 Sea Transportation *126*
4.3.8.3 Road and Rail Transportation *126*
4.3.8.4 Vehicles *127*
4.3.8.5 Aircraft *130*
4.3.8.6 Rockets *131*
4.3.8.7 Solar Power Plants *131*
4.4 Metal Hydrides *131*
4.4.1 Classical Metal Hydrides *135*
4.4.1.1 Intermetallic Hydrides (Heavy Metal Hydrides) *135*
4.4.1.2 Magnesium-Based Hydrides *137*
4.4.2 Light Metal Complex Hydrides *139*
4.4.2.1 Alanates *139*
4.4.2.2 Amides-Imides (Li_3N–Li_2NH–$LiNH_2$) *143*
4.4.2.3 Borohydrides *146*
4.4.3 Application *149*
4.4.4 Outlook *163*
References *166*

5 Chemical Storage *171*
5.1 Introduction *171*
5.2 Materials and Properties *172*
5.3 Hydrogen Storage in Hydrocarbons *173*
5.4 Hydrocarbons as Hydrogen Carrier *177*
5.5 Application: Automotive *178*
5.6 Ammonia *181*
5.6.1 Properties *181*
5.6.2 Application Areas of Ammonia *182*
5.6.3 Production *184*
5.6.3.1 Production from Nitrogen and Hydrogen *184*

5.6.3.2 Production from Silicon Nitride *184*
5.6.4 Methods for Storing Ammonia *185*
5.6.4.1 Liquid Dry Ammonia *185*
5.6.4.2 Solid-State Ammonia Storage *185*
5.6.5 Use of Ammonia as Fuel in High-Temperature Fuel Cells *186*
5.6.6 Hydrogen from Ammonia *187*
5.6.6.1 Ammonia Electrolysis *187*
5.6.6.2 Catalytic Decomposition *187*
5.6.7 Hydrogen from Ammonia and Metal Hydride *189*
5.6.8 Energetic Consideration *190*
5.7 Borohydrides *191*
5.7.1 Sodium Borohydride *191*
5.7.1.1 Direct Use of Sodium Borohydride as Fuel in a PEM-Based Fuel Cell *191*
5.7.1.2 Hydrogen Generation by Hydrolytic Release *192*
5.7.2 Ammonia Borane *193*
References *194*

6 Hydrogen Storage Options: Comparison *197*
6.1 Economic Considerations/Costs *197*
6.2 Safety Aspects *200*
6.2.1 Safety Rules and Regulations *200*
6.2.2 Safety Equipment *205*
6.3 Environmental Considerations: Waste, Hazardous Materials *209*
6.4 Dimension Considerations *212*
6.5 Sociological Considerations *216*
6.6 Comparison with Other Energy Storage System *218*
References *222*

7 Novel Materials *225*
7.1 Silicon and Hydropolysilane (HPS) *225*
7.2 Carbon-Based Materials – General *228*
7.2.1 Carbon Nanotubes (CNT), Activated Carbon (AC), Graphite Nanofibers *229*
7.2.2 Other High-Surface Area Materials *233*
7.2.3 Zeolites *234*
7.2.4 Metal-Organic Frameworks (MOFs) *235*
7.2.5 Covalent Organic Frameworks (COF) *236*
7.3 Microspheres *239*
7.3.1 Methods for Discharging *244*
7.3.2 Resume *245*
References *246*

Index *249*