

3-23-2015

Study of Ammonia Borane and its Derivatives: Influence of Nanoconfinements and Pressures

Yongzhou Sun

Florida International University, ysun004@fiu.edu

DOI: 10.25148/etd.FI15032164

Follow this and additional works at: <https://digitalcommons.fiu.edu/etd>

 Part of the [Materials Science and Engineering Commons](#)

Recommended Citation

Sun, Yongzhou, "Study of Ammonia Borane and its Derivatives: Influence of Nanoconfinements and Pressures" (2015). *FIU Electronic Theses and Dissertations*. 1830.

<https://digitalcommons.fiu.edu/etd/1830>

This work is brought to you for free and open access by the University Graduate School at FIU Digital Commons. It has been accepted for inclusion in FIU Electronic Theses and Dissertations by an authorized administrator of FIU Digital Commons. For more information, please contact dcc@fiu.edu.

FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

STUDY OF AMMONIA BORANE AND ITS DERIVATIVES: INFLUENCE OF
NANOCONFINEMENTS AND PRESSURES

A dissertation submitted in partial fulfillment of the

requirements for the degree of

DOCTOR OF PHILOSOPHY

in

MATERIALS SCIENCE AND ENGINEERING

by

Yongzhou Sun

2015

To: Dean Amir Mirmiran
College of Engineering and Computing

This dissertation, written by Yongzhou Sun, and entitled Study of Ammonia Borane and its Derivatives: Influence of Nanoconfinements and Pressures, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

Surendra K. Saxena

W. Kinzy Jones

Arvind Agarwal

Wenzhi Li

Jiuhua Chen, Major Professor

Date of Defense: March 23, 2015

The dissertation of Yongzhou Sun is approved.

Dean Amir Mirmiran
College of Engineering and Computing

Dean Lakshmi N. Reddi
University Graduate School

Florida International University, 2015

DEDICATION

I dedicate this dissertation to my wife and my parents. Without their support and love, the completion of this work would have been impossible.

ACKNOWLEDGMENTS

First of all, I wish to thank my Major Professor Dr. Jiuhua Chen for his advices, support and guidance throughout the dissertation period. I greatly acknowledge him for the opportunities availed to me during my dissertation such as to work in national synchrotron facilities and to attend many national and international conferences. Those experiences molded me towards different aspects of my goal and helped me to expand my knowledge.

I would like to thank my dissertation committee members, Dr. Surendra K. Saxena, Dr. W. Kinzy Jones, Dr. Arvind Agarwal, and Dr. Wenzhi Li, for their suggestions and encouragement for this endeavor. I greatly appreciate Dr. Vadym Drozd for his guidance and also his help during different stages of the experiments. I thank Dr. Andriy Durygin for making me friendly with the instrument. I also acknowledge Dr. Shu Huang, Dr. Shah Najiba, Dr. Jennifer Girard, Dr. H el ene Couvy Craig, Dr. Selva Vennila Raju, Dr. Bin Yang, and Dr. Fangli Chi for their help and useful discussions about the hydride research. I always remember the efforts of Dr. Wenge Yang, Dr. Zhenxian Liu, Dr. Zhiqiang Chen, and Dr. Xingguo Hong for technique support and discussions. The MoFs samples were synthesized in Dr. Shilun Qiu's group, Jilin University. I would like to thank my family and all my colleagues in CeSMEC for their support and help.

This research was partially supported by COMPRES, the Consortium for Materials Properties Research in Earth Sciences under NSF Cooperative Agreement EAR 11-57758. This dissertation used the National Synchrotron Light Source (Synchrotron FTIR from U2A and X-Ray from X17C), Brookhaven National Laboratory, which was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences,

under Contract No. DE-AC02-98CH10886. This work was supported by the Department of Energy DOE under Award Number DE-FG02-07ER46461, the Dissertation Year Fellowship of Florida International University, and the EFree, Energy Frontier Research Center funded by DOE-BES under Award Number DESC000105.

ABSTRACT OF THE DISSERTATION
STUDY OF AMMONIA BORANE AND ITS DERIVATIVES: INFLUENCE OF
NANOCONFINEMENTS AND PRESSURES

by

Yongzhou Sun

Florida International University, 2015

Miami, Florida

Professor Jihua Chen, Major Professor

Recently, ammonia borane has increasingly attracted researchers' attention because of its merging applications, such as organic synthesis, boron nitride compounds synthesis, and hydrogen storage. This dissertation presents the results from several studies related to ammonia borane.

The pressure-induced tetragonal to orthorhombic phase transition in ammonia borane was studied in a diamond anvil cell using *in situ* Raman spectroscopy. We found a positive Clapeyron-slope for this phase transformation in the experiment, which implies that the phase transition from tetragonal to orthorhombic is exothermic. The result of this study indicates that the rehydrogenation of the orthorhombic phase is expected to be easier than that of the tetragonal phase due to its lower enthalpy.

The high pressure behavior of ammonia borane after thermal decomposition was studied at high pressures up to 10 GPa. The sample of ammonia borane was first decomposed at ~140 degree Celcius and ~0.7 GPa and then compressed step wise in an isolated sample chamber of a diamond anvil cell for Raman spectroscopy measurement. We did not observe the characteristic shift of Raman mode under high pressure due to

dihydrogen bonding, indicating that the dihydrogen bonding disappears in the decomposed ammonia borane. Although no chemical rehydrogenation was detected in this study, the decomposed ammonia borane could store extra hydrogen by physical absorption.

The effect of nanoconfinement on ammonia borane at high pressures and different temperatures was studied. Ammonia borane was mixed with a type of mesoporous silica, SBA-15, and restricted within a small space of nanometer scale. The nano-scale ammonia borane was decomposed at ~125 degree Celcius and rehydrogenated after applying high pressures up to ~13 GPa at room temperature. The successful rehydrogenation of decomposed nano-scale ammonia borane gives guidance to further investigations on hydrogen storage.

In addition, the high pressure behavior of lithium amidoborane, one derivative of ammonia borane, was studied at different temperatures. Lithium amidoborane (LAB) was decomposed and recompressed in a diamond anvil cell. After applying high pressures on the decomposed lithium amidoborane, its recovery peaks were discovered by Raman spectroscopy. This result suggests that the decomposition of LAB is reversible at high pressures.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION.....	1
1.1 Introduction to ammonia borane and its derivatives.....	1
1.2 Background for ammonia borane used as hydrogen storage materials	2
1.3 Hypotheses.....	8
1.4 Specific Statement of Research Questions/Objectives	9
CHAPTER 2 LITERATURE REVIEW	11
2.1 Fundamentals of ammonia borane.....	11
2.2 Challenges on ammonia borane.....	12
2.3 Ammonia Borane Under High Pressure	16
2.3.1 Pressure influence on ammonia borane physic-sorption of hydrogen.....	16
2.3.2 Pressure dependence of phase stability	17
2.4 Nanoconfined ammonia borane.....	20
2.5 Derivatives of NH ₃ BH ₃ : metal amidoboranes	24
CHAPTER 3 EXPERIMENTS	26
3.1 High Pressure Tools.....	26
3.1.2 Temperature control.....	30
3.1.3 Pressure measurement.....	31
3.2 Raman Spectroscopy	32
3.3 in situ X-ray Diffraction	32
3.4 IR Measurement.....	38
CHAPTER 4 PHASE BOUNDARY OF PRESSURE-INDUCED <i>I4mm</i> TO <i>Cmc2₁</i> TRANSITION IN AMMONIA BORANE AT ELEVATED TEMPERATURES.....	42
4.1 Introduction.....	43
4.2 Experiment.....	44
4.3 Result and discussions	52
4.4 Conclusion	68
CHAPTER 5 BEHAVIOR OF DECOMPOSED AMMONIA BORANE AT HIGH PRESSURE	69
5.1 Introduction.....	70
5.2 Experiment.....	71
5.3 Result and discussions	76
5.4 Conclusion	82
CHAPTER 6 REHYDROGENATION OF NANO-SCALE AMMONIA BORANE....	83
6.1 Introduction.....	83
6.2 Experiment and results	86
6.2.1 Materials and Methods.....	86
6.2.2 High Pressure studies of neat ammonia borane and nano-scale ammonia borane in SBA-15.....	88

6.2.3 High pressure studies of nano-scale ammonia borane in other nanoscaffolds.....	93
6.2.4 Rehydrogenation of neat ammonia borane and nano-scale ammonia borane in SBA-15.....	97
6.3 Conclusions.....	101
CHAPTER 7 HIGH PRESSURE STUDY ON DECOMPOSITION AND REHYDROGENATION OF LITHIUM AMIDOBORANE.....	105
7.1 Introduction.....	105
7.2 Materials and Methods	109
7.2.1 Rehydrogenation of neat ammonia borane.....	110
7.2.2 Rehydrogenation of lithium amidoborane.....	112
7.3 Conclusions.....	118
8 SUMMARY AND FUTURE WORK.....	119
8.1 Summary.....	119
8.2 Future Scope of this Work	119
REFERENCES	121
VITA.....	131

LIST OF TABLES

TABLE	PAGE
Table 1 Selected Raman modes of ammonia borane	15
Table 2 Comparison of Nanoscaffolds	23
Table 3 Advantages and Disadvantages of Raman spectroscopy	33
Table 4 Angle Dispersive Diffraction Experiments at X17C of NSLS	38
Table 5 Comparison of Raman, infrared, and near infrared spectroscopy	41
Table 6 Advantages and Barriers of Ammonia Borane	43

LIST OF FIGURES

FIGURE	PAGE
Figure 1 The impending oil crisis and need of renewable energy	5
Figure 2 Volume of 4 kg of hydrogen compacted in different ways relative to the size of a car	6
Figure 3 Stored hydrogen per mass and per volume: comparison of metal hydrides, carbon nanotubes, petrol and other hydrocarbons	7
Figure 4 Questions and Objectives	8
Figure 5 Two barriers of ammonia borane and solutions for on-board hydrogen storage: 1, non-reversibility. 2, low kinetics	9
Figure 6 H ₂ release measurements from ammonia borane	14
Figure 7 Extra hydrogen taken by ammonia borane	16
Figure 8 Raman spectra showing PIB-H ₂ complex	17
Figure 9 Evidence of Di-hydrogen bonding in Ammonia borane	19
Figure 10 3D structure image views of the (001) faces of (a) JUC-32-Y and (b) AB/JUC-32-Y	22
Figure 11 Ammonia–borane (Lewis acid–base) interactions present on the surface of COF-10	22
Figure 12 Plots of the equivalents of H ₂ liberated upon heating LAB, SAB, and AB	25
Figure 13 Schematics of the core of a diamond anvil cell	26
Figure 14 Drilling machines	28
Figure 15 Experiment setups	30
Figure 16 Raman spectroscopy setup with <i>in situ</i> ruby pressure measurement system at CeSMEC	34
Figure 17 The National Synchrotrons Light Sources (NSLS), Brookhaven National Laboratory (BNL), Brookhaven, New York	34
Figure 18 Brookhaven National Laboratory (BNL), Brookhaven, New York	35

Figure 19 X-ray diffractometer in CeSMEC	35
Figure 20 X17C in NSLS, BNL.....	37
Figure 21 Position of Beamline X17C and U2A, in NSLS, BNL	39
Figure 22 Raman spectra of ammonia borane at different pressures with pressure medium.	51
Figure 23 Synchrotron XRD patterns of ammonia borane at room temperature and high pressures.....	54
Figure 24 Raman spectra of ammonia borane at different pressures without pressure medium	60
Figure 25 Phase boundary between I4mm and Cmc21 phases of ammonia borane by Raman spectroscopy	61
Figure 26 Raman spectra of ammonia borane during decomposition at ambient pressure	67
Figure 28 Raman spectra of ammonia borane as pressure increases from bottom to top	75
Figure 29 Raman spectra of Ploy-amidoborane and Poly-imidoborane (without H ₂) during compression (from bottom up) and decompression	80
Figure 30 Pressure dependence of the N-H stretching mode from PAB, PIB and ammonia borane.....	81
Figure 31 Comparison of ammonia borane and ammonia borane confined in Nanoscaffolds	91
Figure 32 Evolution of ammonia borane in SBA-15 Raman spectra with pressure.....	92
Figure 33 <i>in situ</i> IR spectra of ammonia borane in MCM-41.....	95
Figure 34 High pressure <i>in situ</i> IR spectra of ammonia borane in MoFs.....	96
Figure 35 Raman Spectra of neat ammonia borane in Diamond Anvil Cell during decomposition and rehydrogenation.....	97
Figure 36 Raman Spectra of neat ammonia borane in Diamond Anvil Cell during decomposition and rehydrogenation.....	98
Figure 37 <i>in situ</i> IR spectra of ammonia borane before and after decomposition.....	102

Figure 38 Raman spectra of Ammonia Borane mixed with SBA-15 (SiAB) measured in-situ at different temperatures and pressures	103
Figure 39 Microscopic figures of ammonia borane captured by CCD during the decomposition and rehydrogenation	104
Figure 40 Microscopic figures of nano-scale ammonia borane in SBA-15 captured by CCD during the decomposition and rehydrogenation	104
Figure 41 Raman Spectra of neat ammonia borane in Diamond Anvil Cell during decomposition and rehydrogenation	111
Figure 42 Raman Spectra of neat ammonia borane in Diamond Anvil Cell during decomposition and rehydrogenation	113
Figure 43 Raman spectra of LAB during dehydrogenation and rehydrogenation.....	115
Figure 44 Raman spectra of LAB during dehydrogenation and rehydrogenation (without H ₂)	116

ABBREVIATIONS

ANL	Argonne National Laboratory
APS	Advanced Photon Source
AMERI	Advanced Materials Engineering Research Institute
CeSMEC	Center for the Study of Matters at Extreme Conditions
EC	Engineering Center
FIU	Florida International University
BNL	Brookhaven National Laboratory
NLSL	National Synchrotron Light Source
PEM	Proton exchange membrane
DAC	Diamond Anvil Cell
DSC	Differential Scanning Calorimetry
TGA	Thermogravimetric Analysis
LAB	lithium amidoborane (LiNH_2BH_3)
AB	Sodium amidoborane (NaNH_2BH_3)
SBA-15	Santa Barbara amorphous-15 (Hexagonally p6mm mesoporous silica)
MCM-41	Mobil crystalline materials-41
XRD	x-ray diffraction
P	pressure
T	temperature
asym.	asymmetric
sym.	symmetric
def.	deformation

str.	stretching
V	volume
S	entropy
atm.	atmospheric
PAB	poly-amidoborane
PIB	poly-imidoborane
EDXD	Energy dispersive X-ray detector
CCD	Charge-coupled device
EDM	electronic discharge machine
COMPRES	Consortium for Materials Properties Research in Earth Sciences
NSF	National Science Foundation
DADB	ionic dimer diammoniate of diborane
SMAB	$\text{NaNH}(\text{Me})\text{BH}_3$
PMAB	$\text{KNH}(\text{Me})\text{BH}_3$
PBAB	$\text{KNH}(\text{}^t\text{Bu})\text{BH}_3$
TEOS	Tetraethylorthosilicate

NOMENCLATURE

°C	degree Celcius
K	Kelvin
cm ⁻¹	per centimeter
Å	Angstrom
wt%	weight percent
Pa	Pascal
kPa	Kilopascal
MPa	Megapascal
GPa	Gigapascal
nm	nanometer
µm	micrometer
km	kilometer
L	liter
g	gram
kg	kilogram
W	watt
mW	miliwatt
kW	kilowatts
kV	kilovolts
keV	kiloelectron-volts
mA	miliampere
\bar{M}_w	molecular weight

CHAPTER 1 INTRODUCTION

1.1 Introduction to ammonia borane and its derivatives

Recently, ammonia borane (AB) [1] [2] attracts more and more attention for its multiple applications, such as organic synthesis[3], boron nitride compounds synthesis[4], and hydrogen storage[5-7]. Ammonia borane has been extensively studied by high pressures [8-10], Infrared (IR), Raman spectroscopy [8, 11-22], x-ray[23-26], nuclear magnetic resonance (NMR)[27-30], computations [25, 31-34], neutron scattering or diffraction[32, 35-37], anelastic spectroscopy[38], and other methods.

At ambient conditions, ammonia borane [1, 2, 6] (NH_3BH_3) is a stable, non-reactive, inflammable, colorless solid boron-nitrogen-hydride compound. It also has much higher volumetric hydrogen density than that of liquid hydrogen[6]. Therefore, ammonia borane is considered as a good hydrogen carrier. Ammonia borane transforms from an orthorhombic structure to a tetragonal structure at ~ 225 K [28, 35, 38-43]. Close contact of B-H \cdots H-N (in the range 1.7-2.2 Å) [37] of two adjacent ammonia borane molecules promotes a dihydrogen bond[14, 15]. X-ray diffraction (XRD) studies [23-25] discovered a first order phase transition at 1.3 GPa and a second order phase transition at 5GPa. A new phase at 4 GPa and 450 K was also discovered [24].

Nano scale ammonia borane could be synthesized by confining neat ammonia borane into mesoporous silica (such as SBA-15 and MCM-41), Metal-Organic Frameworks(MOFs) [44], poly(methyl acrylate) (PMA) [45], mesoporous carbon [46], and other nanoscaffolds. These nanoconfinements decrease dehydrogenation temperature from 114 °C to 60-80 °C, and also significantly decreased the amount of undesired by-products, such as borazine, released from the decomposition for fuel cell or battery

applications. Kim, et al [47] found that the nano-phase ammonia borane confined in mesoporous silica MCM-41 did not undergo the structural phase transition from orthorhombic to tetragonal at ~ 225 K that was observed in bulk ammonia borane. This result was confirmed by an anelastic spectroscopy and differential scanning calorimetric (DSC) investigation[42]. Additionally, the derivatives of ammonia borane [48-50], such as lithium amidoborane (LAB) and sodium amidoborane (SAB), were reported to have lower decomposition temperatures, less undesired volatile products, and higher hydrogen releasing rate.

1.2 Background for ammonia borane used as hydrogen storage materials

Global energy consumption keeps rising exponentially due to the economy expansion and population growth. The oil, coal, natural gas, and other non-renewable fossil fuels won't be able to meet the growth of energy demand in the long term. On the other hand, emissions of carbon dioxide from these conventional energy consumptions significantly bring side-effects to human-beings, such as air pollution, global warming, and etc. Seeking the replacements of traditional energy becomes a very important task that attracts more and more scientific interests.

As shown in figure 1, due to the above considerations, the renewable energies, such as hydropower, nuclear, solar, wind, geothermic energy, and etc., become more and more popular in global energy consumptions. There have been many breakthroughs as science and technologies, such as fuel cells, solar cell, and high capacity lion batteries, advance. Some of these new energy carriers are being experimentally placed into automobiles as replacements for traditional energies. These techniques of the new energies show better performance than that of traditional energies, such environmentally friendly, clean, low-

cost, non-toxic, high efficiency, and, most importantly, renewable. Even though some of these new technologies are very attractive for commercial applications, there are still barriers that prevent these new technologies from being applied practically. For example, the capacities and life-times of the new batteries could not meet the expectations, or the cost of high quality batteries is too high to be taken into commercial applications; the working conditions of solar cell automobiles rely on the weather and geographic positions, which are limited and unpredictable. In spite of the many advantages of these cutting edge technologies, automobiles, such as bus, passenger cars, trucks, boats, and other vessels, are still mainly using traditional fuel products as energy sources.

Other than the previous methods, the fuel cells have their own advantages: an optimum car with a combustion engine travels 400 km and burns about 24 kg of petrol; but only 8 kg of hydrogen are needed for the combustion engine version or 4 kg of hydrogen for an electric car with a fuel cell to cover the same distance [7]. Nowadays, fuel cell becomes a very popular future automobile engine candidate.

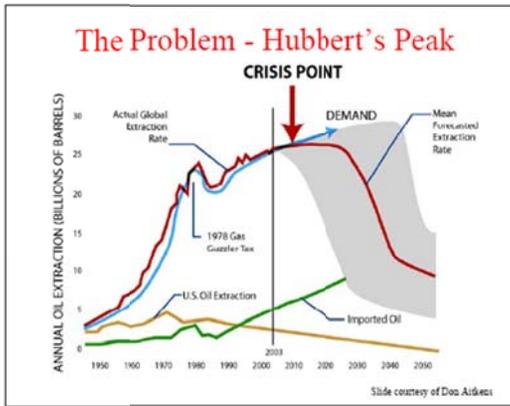
Showing in figure 1 (right hand side), a single fuel cell consists of an electrolyte and two catalyst-coated electrodes (a porous anode and cathode) [51]. The product of the reaction is nothing but water. Therefore, fuel cell is also called Zero Emission Cell. The fuel cell could be varied by sizes and types to make sure they are suited to be applied in every aspects of daily life: plants, communities, automobiles, and etc.

As we know, the fuel cell starts to be applied into stationary units, since there will be no problem for storage and transportation of the fuel cell energy sources, which are mainly hydrogen. However, in terms of automobiles, the storage and transportation

become one of the most significant barriers that prevent the fuel cells from practical and commercial application.

There are many advantages to using hydrogen: non-toxicity, high energy density, easy to be synthesized or extracted, environmentally-friendly, and etc. However, hydrogen has a very low melting point at 13.99 K (~ 259.16 °C, ~ 434.49 °F) and low boiling point at 20.271 K (~ 252.879 °C, ~ 423.182 °F). In addition, hydrogen has a very low density 0.08988 g/L (at 0 °C, 101.325 kPa) [52, 53]. Therefore, it is extremely difficult to transport or storage with traditional gas storage methods, such as high pressure gas tanks or low temperature liquid tanks. In reality, even if we storage the hydrogen in low temperature liquid tank, the density doesn't meet the commercial expectations, either: the density of liquid hydrogen is only ~ 0.07 g·cm⁻³ and density of solid hydrogen is only 0.0763 g·cm⁻³[53] .

On the other hand, hydrogen is highly flammable and highly explosive with the existence of oxygen, which is much more dangerous than most of the traditional energies. Therefore, even if we successfully put a desired amount of hydrogen into a small enough volume by traditional high pressure or liquid tanks, it is not convincing considering the safety terms. In addition, we should also consider the variable conditions and unexpected issues during the transportations: accidents, temperature verifications, extreme weathers, and so on.



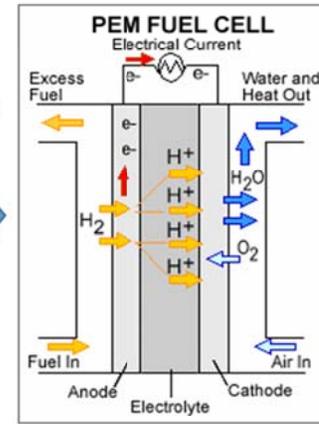
The impending oil crisis- Hubbert's Peak
(Basu, Sumit; PhD. Thesis, 2010)

Renewable
Energy

- Biofuel
- Biomass
- Geothermal
- Hydroelectricity
- Solar energy
- Tidal power
- Wave power
- Wind power



Energy
Storage



U.S. Department of Energy, Technical Plan:
Fuel Cells, 2007

Figure 1 The impending oil crisis and need of renewable energy

Regarding these aspects, it is required to find a safe, high efficient, economic, commercially available, and robust way for hydrogen storage. Louis Schlapbach et al.'s group [7] gave us a good comparison of different ways of hydrogen storage, which is shown in figure 2. As previously mentioned, an electric car with a fuel cell burns 4 kg of hydrogen to travel a standard refuel distance, ~ 400 km. The volume of different ways to store 4 kg hydrogen was calculated as shown in figure 2. The high pressure tanked hydrogen is not acceptable due to its extremely high volume. It is very difficult and costly to create the low temperature conditions for liquid storage, too. Additionally, even though it has a much smaller volume than that of the high pressure hydrogen storage method, the volume is still larger than automobile transportation requirement. On the other hand, storing hydrogen into solid materials shows much better performance than that of high pressure or liquid hydrogen storage method, regarding the volumetric density.

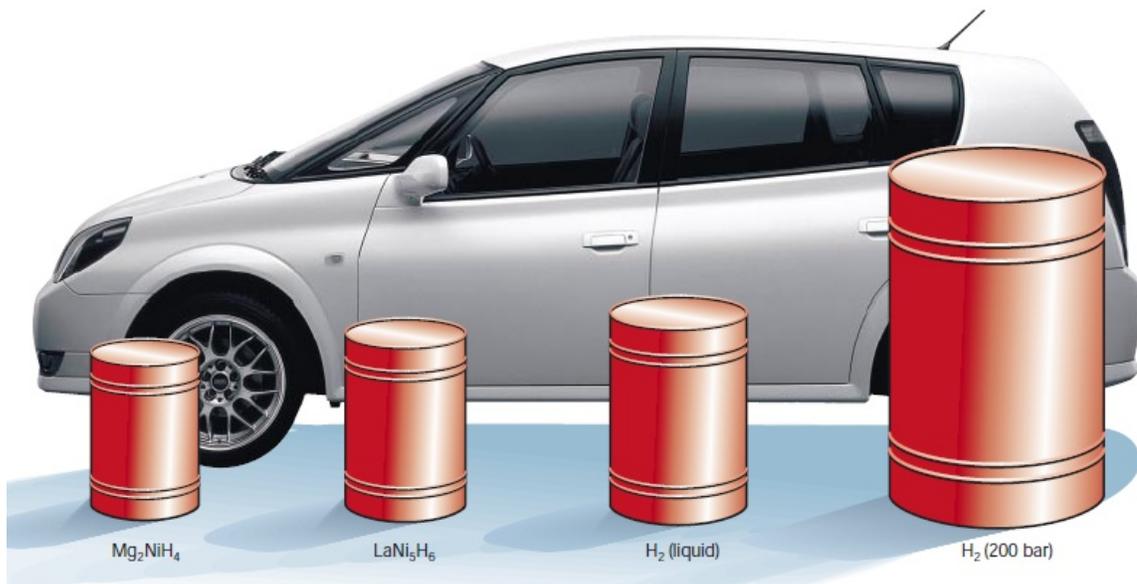


Figure 2 Volume of 4 kg of hydrogen compacted in different ways relative to the size of a car [7]

The hydrogen infrastructures and transportation needs good hydrogen storage materials with high volumetric densities, mass percentages, and mild releasing conditions,

because of the economy and safety issues. As shown in figure 3, ammonia borane [1, 2, 39] could be a very good candidate for hydrogen storage due to its 19.6 wt% hydrogen content, which exceeds the ultimate target of hydrogen storage content for light-duty vehicles (7.5 % by weight) of the US Department of Energy [4, 54].

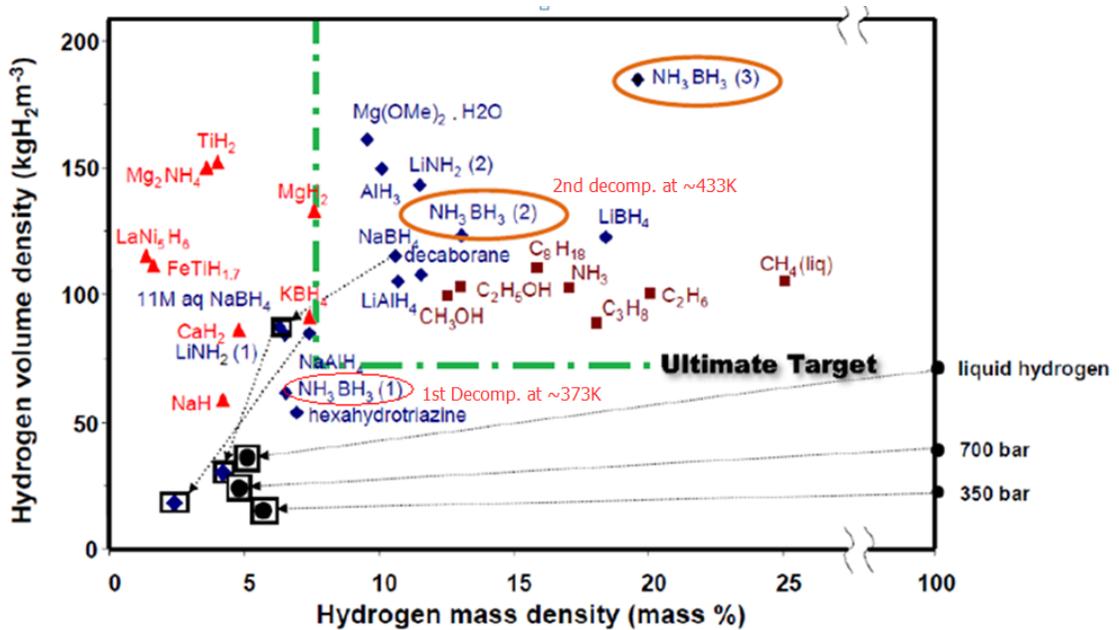
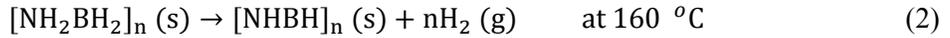
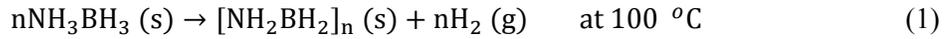


Figure 3 Stored hydrogen per mass and per volume: comparison of metal hydrides, carbon nanotubes, petrol and other hydrocarbons

(modified from reference [55])

The first two decompositions, shown by equation (1) and (2), which take place at mild conditions, are favorable for on board applications such as proton exchange membrane (PEM) fuel cells. Total of 13 wt % hydrogen is released from the first two decompositions, exceeding DOE's ultimate target of hydrogen storage capacity (7.5 wt%)

H) [54]. The third decomposition take place at much higher temperature ($>1000^{\circ}\text{C}$)[4], therefore this decomposition is not usually considered for hydrogen storage.

1.3 Hypotheses

Pressure will play a reverse role for decomposition and it is expected to change the behavior of ammonia borane. Nanoconfinements or catalysts are expected to reduce the energy barrier of ammonia borane dramatically during decomposition or recompression [56-59]. Ammonia borane that is confined by other nanoconfinement materials, such as metal-organic frameworks (MOFs), multi walled carbon nanotubes (MWCNTs), and MCM-41, is expected to have different catalytic effects and different behavior under pressures, such as a possible rehydrogenation and storing extra hydrogen. Additionally, the derivatives of ammonia borane, such as LAB and sodium amidoborane, have been proven to have lower decomposition temperatures and higher discharge rates. They are expected to be thermodynamically and kinetically more favorable for better performances during decompositions or compressions under different pressures and temperatures.

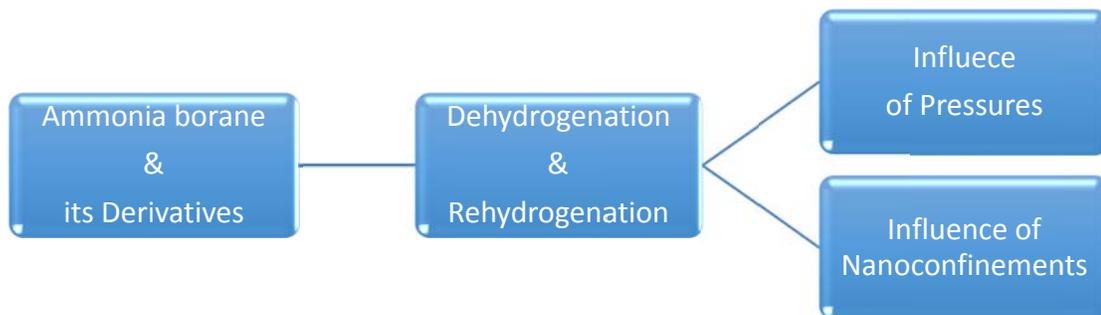


Figure 4 Questions and Objectives

The problems of dehydrogenation and rehydrogenation on ammonia borane and its derivatives will be discussed or addressed by different ways