Catalytically Enhanced Hydrogen Storage Systems

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5/25/05

Project ID: # ST3

Objectives
Technical Barriers and Targets
Budget

I. Determination of the chemical nature and mechanism of action of the species that is responsible for the enhanced kinetics of Ti-doped $NaAlH_4$.

II. Apply insights gained from fundamental studies of Ti-doped $NaAlH_4$ to the design and synthesis of hydrogen storage materials that will meet DOE hydrogen storage system targets.

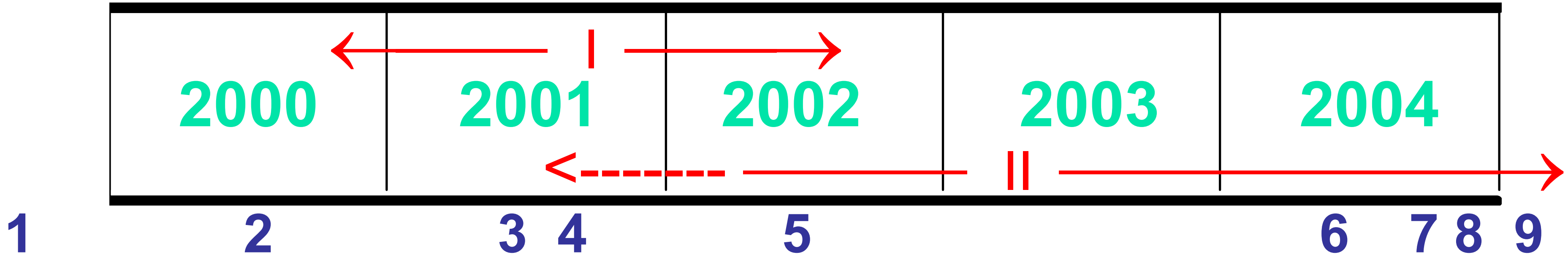
Property	**Units**	**Target**
Hydrogen Density (gravimetric)	wt.% H	6
Energy Efficiency	%	97
Energy Density (volumetric)	W-h/L	1100
Hydrogen Density (volumetric)	kg H_2/m^3	33
Specific Energy	W-h/kg	2000
Cost	\$/kW-h (\$/kg H_2)	5 (167)
Operating Temperature	˚C	-40 - +50
Start-Up Time to Full Flow	sec	15
Hydrogen Loss	scc/hr/L	1.0
Cycle Life	cycles	500
Refueling Time	min	<5
Recoverable Usable Amount	%	90

Total Funding 5/00 - 4/05	
DOE:	1,022,837
UH Cost Share:	238,000
Total:	$1,283,000

FY04 Funding: $271,962

FY05 Funding: 0

Project Timeline



I. Maximization of hydrogen cycling performance of Ti-doped $NaAlH_4$
  - **1**) Mechanically doped $NaAlH_4$ first prepared by Zidan and Jensen in 1998.
  - **2**) DE-FC36-00GO10537 initiated.
  - **3**) Demonstration of hydrogen flow of 1.8 wt/h @ 100 ˚C against 1 atm H_2 pressure.
  - **4**) Demonstration of >4 wt % hydriding of NaH/Al in <4 min
  - **5**) 100 cycle, > 3 wt % capacity test completed.

II. Determination of the fundamental basis of enhanced hydrogen cycling performance
  - **6**) XRD studies of structural and compositional effects of doping and cycling completed.
  - **7**) Electron paramagnetic resonance studies of dopant completed.
  - **8**) Conclusions of EPR and XRD studies verified through electron microscopy and XAFS studies.
  - **9**) Anelastic spectroscopic studies reveal dynamics of point defects involving hydrogen that are generated as a result of doping.

Collaborations

- Dr. Hendrik Brinks, Prof. Bjorn Hauback, Dr. Arnulf Maeland - Institute for Energy Technology, Norway.
- Prof. Klaus Yvon - University of Geneva.
- Dr. Tetsu Kiyobayashi, Dr. Nobuhiro Kuriyama, Dr. Hiroyoyuki Takeshita - National Institute for Advanced Industrial Science and Technology , Osaka, Japan.
- Prof. Sandra Eaton - University of Denver.
- Dr. Carmen Andrei, Prof. Randi Holmestad - Norwegian University of Science and Technology.
- Dr. Job Rijssenbeek, Dr. Yan Gao - G.E. Global Research Center.
- Prof. Rosario Cantelli - University of Rome.
- Dr. Kristin Kumashiro, Dr. Walter Niemczura - Department of Chemistry,University of Hawaii.
- Dr. Terry Udovic - National Institute of Standards and Technology.

Consulting for Other DOE EERE Projects

- UOP - “Discovery of Novel Complex Metal Hydrides for Hydrogen Storage through Molecular Modeling and Combinatorial Methods

- United Technologies - “On-Board Hydrogen Storage Demonstration”

Approach

I. **Maximization of hydrogen cycling performance of Ti-doped $NaAlH_4$**

II. **Determination of the fundamental basis of enhanced hydrogen cycling performance**

<u>Synchrotron X-ray and Neutron Diffraction Studies</u> Influence of doping on structure and composition.

<u>Determination of Equilibrium Hydrogen Plateau Pressures</u> Influence of doping on thermodynamic properties.

<u>Kinetic measurements and modeling</u> Mechanism of hydrogen cycling process.

<u>Electron Paramagnetic Resonance (EPR) Studies</u> Direct characterization of Ti dopants.

Approach

Infrared Spectroscopy, Inelastic Neutron Scattering, and Anelastic Spectroscopy Direct probes of the effects of doping on hydrogen.

III. Design, synthesis, and evaluation of advanced complex hydrides

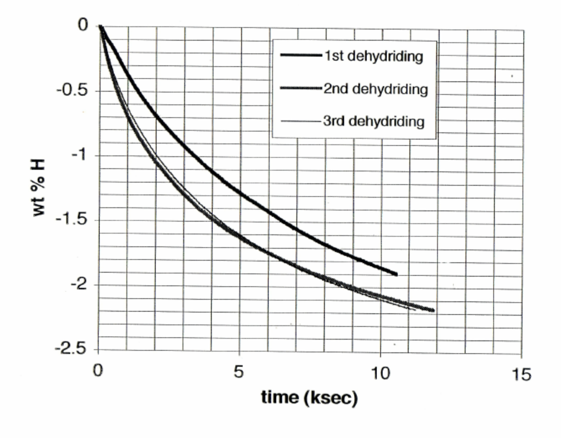
Synthesis and Evaluation of Novel Complex Hydride Systems

Evaluation of “guided design” materials with theoretical hydrogen storage capacity of **>7** wt %.

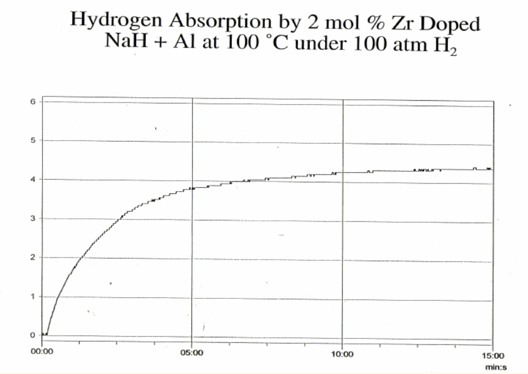
Maximization of hydrogen cycling performance of Ti-doped $NaAlH_4$

Dehydrogenation:

Rate of 1.8 wt % per hour observed at 100 ˚C for 2 mol % Ti doped $NaAlH_4$ to Na_3AlH_6 is adequate to meet the demands of an onboard PEM fuel cell.

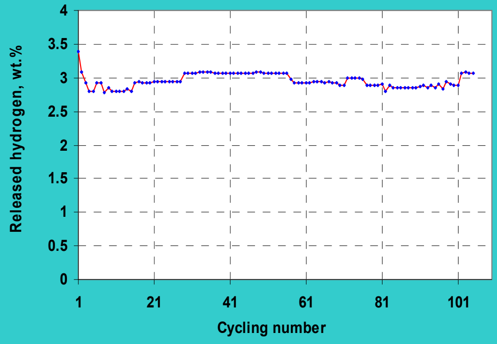


Re-hydrogenation

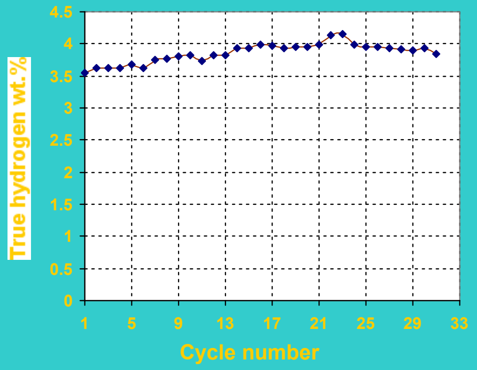

Hydrogen Absorption by 2 mol % Zr Doped NaH + Al at 100 ˚C under 100 atm H_2

Cycling Tests of 2 mol % Ti-doped Na/Al

Desorption: 120 ˚C, 3h. Absorption: 100 atm, 100 ˚C



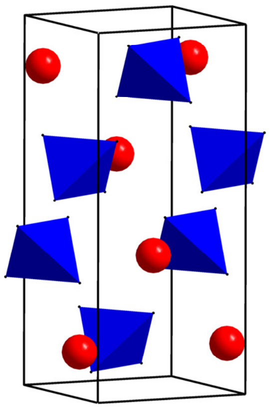
Desorption: 150 ˚C, 3h. Absorption: 100 atm, 100 ˚C



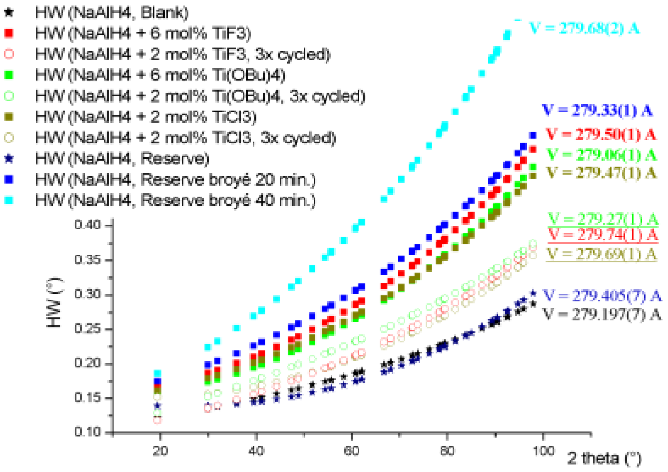
S.S. Srinivasan, H.W. Brinks, B.C. Hauback, D. Sun, C.M. Jensen, *J. Alloys Compd.* **2004**, 377, 283.

Determination of the Fundamental Basis of Enhanced Hydrogen Cycling Performance

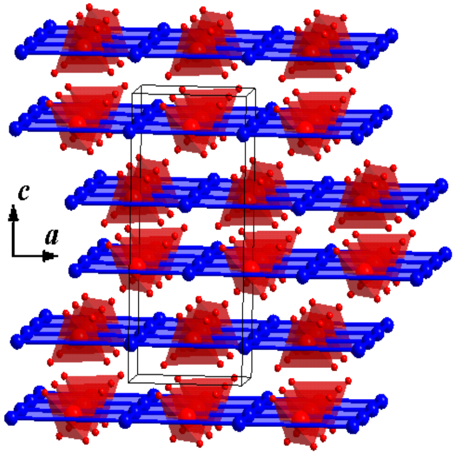
Neutron and X-ray diffraction

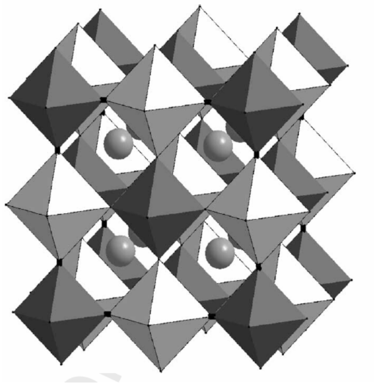


B. Hauback, H. Brinks, C.M. Jensen, K. Murphy, A. Maeland *J. Alloys Compd.* **2003**, ***358***, 142.



Structural representation of $NaAlH_4$





H.W. Brinks, B.C. Hauback, C.M. Jensen, R. Zidan *J. Alloys Compd.* **2005** in press.

Rietveld analysis of X-ray diffraction peak broadening indicates that mechanical milling of the hydride results in distortion of the lattice primarily in the c direction.

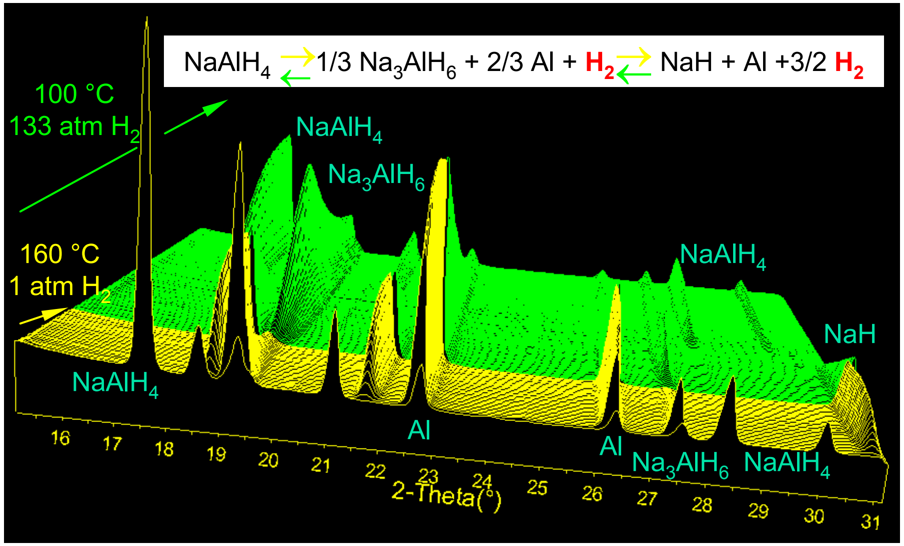
☑ **mechanical milling distorts microstructure.**

S. Gomes, G. Renaudin, H. Hagemann, K. Yvon, M.P. Sulic, and C.M. Jensen *J. Alloys Compds* **2005** *390*, 305.

Determination of the Fundamental Basis of Enhanced Hydrogen Cycling Performance

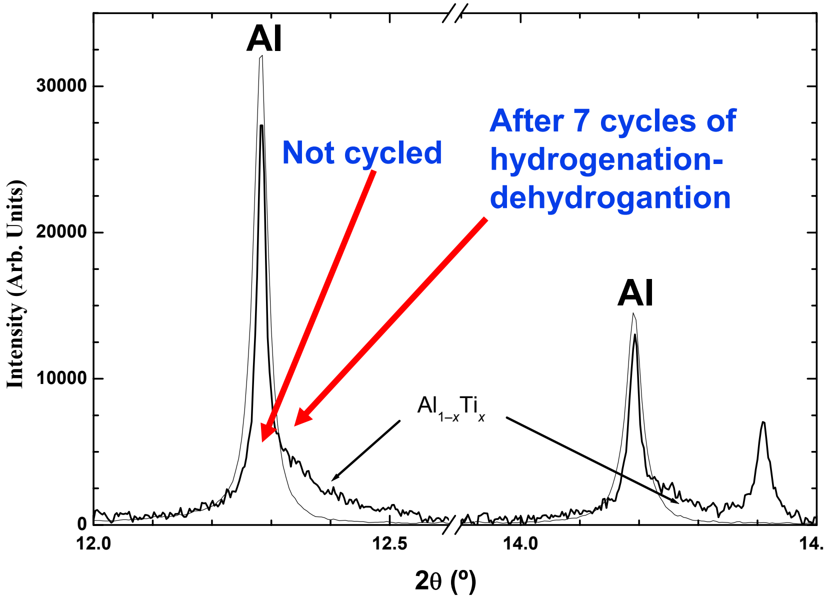
Synchrotron X-ray Diffraction Studies

In situ dehydrogenation/re-hydrogenation



J. Rijsenbeek, Y. Gao C.M. Jensen, S.S. Srinivasan manuscript in preparation.

Cycling introduces shoulders on the Al XRD peaks ⇒ formation of $Al_{0.93}Ti_{0.07}$

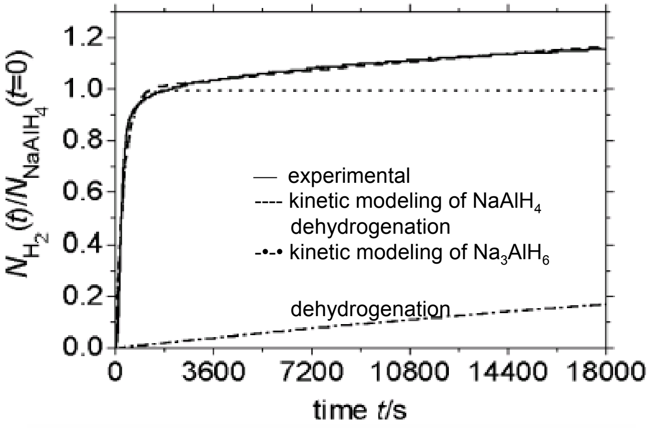


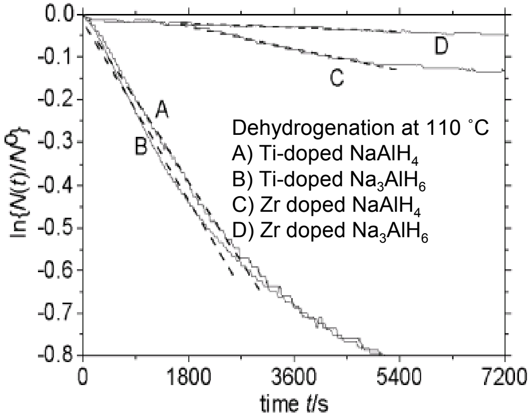
Rietveld refinements indicate that the shoulders correspond to a solid solution of Ti in Al of composition $Al_{0.93}Ti_{0.07}$.

H.W. Brinks, C.M. Jensen, S.S. Srinivasan, B.C. Hauback, D. Blanchard, K. Murphy *J. Alloys Compd.* 2004, 376, 215.

Determination of the Fundamental Basis of Enhanced Hydrogen Cycling Performance

Kinetic Studies

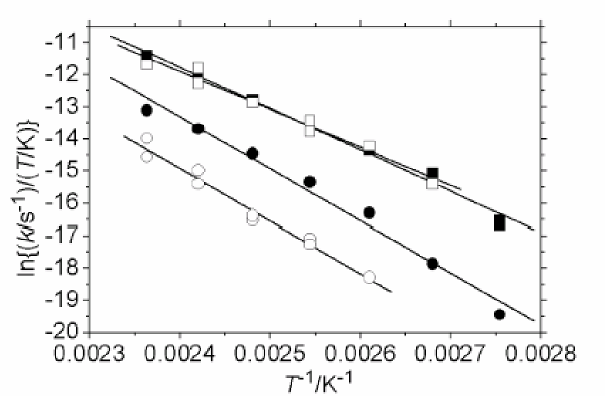




Directly Ti doped Na_3AlH_6 undergoes dehydrogenation at rates equal to that of Ti doped $NaAlH_4$!!

⇒ Dehydrogenation kinetics are not controlled by relative strengths Al-H bonds.

⇒ **Kinetics are limited by processes long range atomic transport phenomenon and location of dopants.**



Eyring plots of rates constants for the dehydrogenation of :A) Ti doped $NaAlH_4$ ■; B) Ti doped Na_3AlH_6 □
C) Zr doped $NaAlH_4$ ●;D) Zr doped Na_3AlH_6 ○

Enthalpies of activation, Δ H (kJ/mol) of Ti and Zr doped $NaAlH_4$ and Na_3AlH_6

	Ti doped	**Zr doped**
$NaAlH_4$	100 ± 7	134 ± 16
Na_3AlH_6	99 ± 13	135 ± 17

T. Kiyobayashi, S.S. Srinivasan, D. Sun, C.M. Jensen, *J. Phys. Chem. A* **2003**, *107*, 7671.

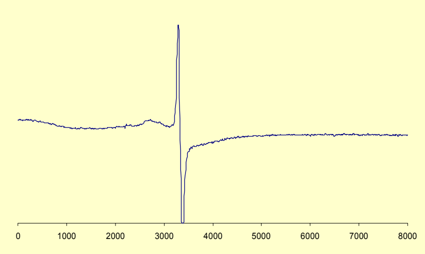
Current Year Results

Electron Paramagnetic Resonance

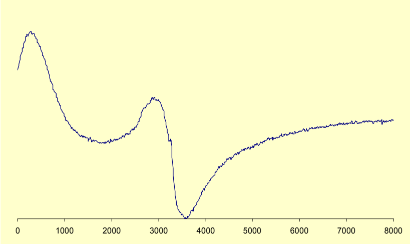
Collaboration with Prof. S. Eaton, University of Denver

$NaAlH_4$ doped with 2.0 mol % of TiF_3

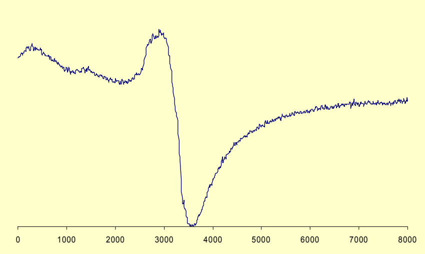
Upon doping The spectrum of is dominated by sharp signal with g = 1.976 and ΔBpp ~ 90 G that is characteristic of spin isolated Ti(III).



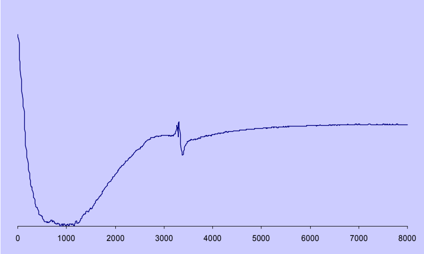
After 5 cycles Instead of the signal with ΔBpp ~ 90 G or ΔBpp ~ 1500 G, the spectrum is dominated by a signal with ΔBpp ~ 650 G. There is also a signal near zero-field.



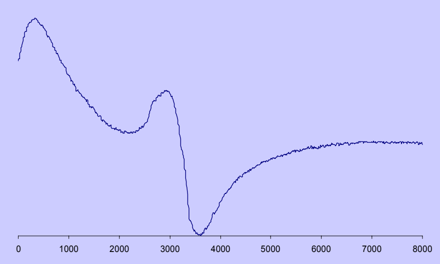
After 10 cycles Only the Ti(0) signal near zero-field has largely disappeared and only the Ti(0) signal at ΔBpp ~ 650 G.



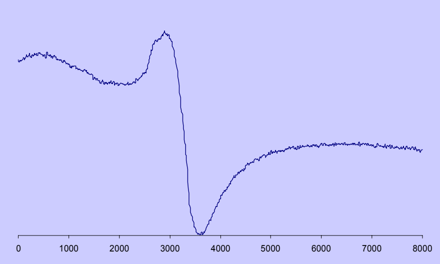
$NaAlH_4$ doped with 2.0 mol % of $TiCl_3$



Upon doping. The spectrum is dominated by a strong signal near zero-field. There is also a small signal with g ~ 1.97 that is quite similar to the Ti(III) signal that is observed in the TiF_3 doped sample.



5 Cycles. There is now a signal with g = 2.01 and ΔBpp ~ 650 G plus a signal near zero-field that is quite different from the original one. This spectrum is very similar to TiF_3 doped sample after 5 cycles.



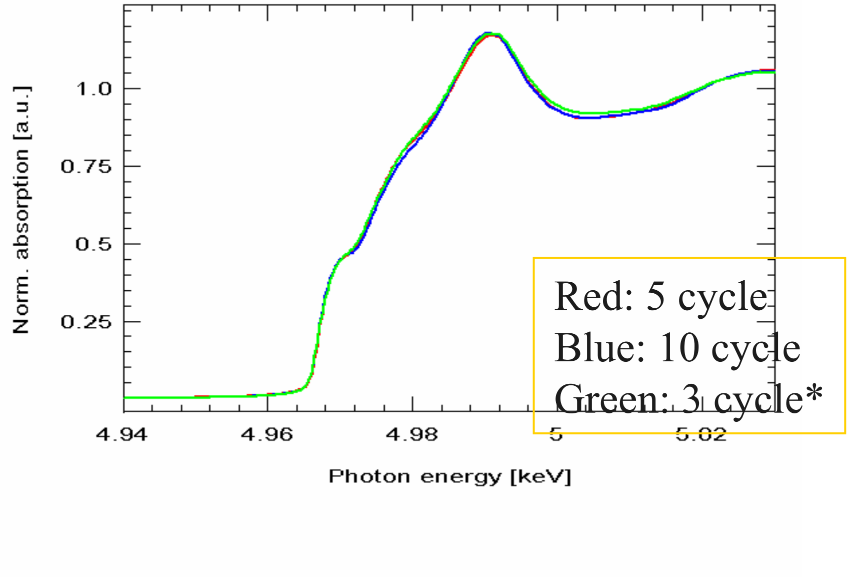
After 10cycles. Only the Ti(0) signal near zero-field has largely disappeared and only the Ti(0) signal at ΔBpp ~ 650 G.

Dominant Ti species changes dramatically on cycling but kinetics do not ⇒ minority Ti species responsible for enhanced kinetics.

Current Year Results

X-ray Absorption Spectroscopy

Collaboration with Dr. J. Rijssenbeek and Dr. Gao,
GE Global Research



Comparison of Ti K-edge XANES for samples doped with 2 mol % TiF_3 and a 3 cycle sample doped with 2 mol % $TiCl_3$ (green). These three samples have identical near-edge features, indicating the same Ti oxidation state.

Agrees with EPR results obtained with cycled samples

XAFS controversy

"Al_3Ti forms immediately on doping with $TiCl_3$ and oxidation state is nearly invariant during hydrogen cycling" - J. Graetz, J.J. Reily, J. Johnson, A.Y. Ingatov, T.A. Tyson *Appl. Phys. Lett.* **2004** *85*, 500.

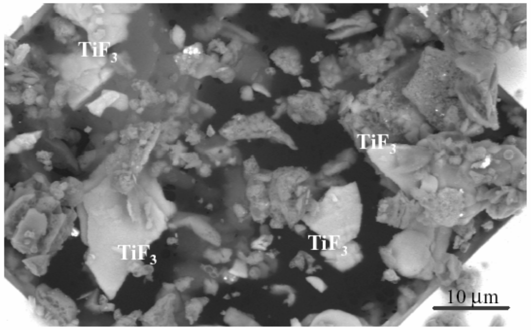
"Ti(0) species are formed immediately on doping and state is nearly invariant during hydrogen cycling with $TiCl_3$. The formation of an alloy with Al or TiH_2 is not supported by EXAFS data." - A. Leon, O. Kircher, J. Rothe, M. Fichtner, *J. Phys. Chem.* **2004** 16372.

$\Rightarrow$ EPR data indicates both maybe correct.

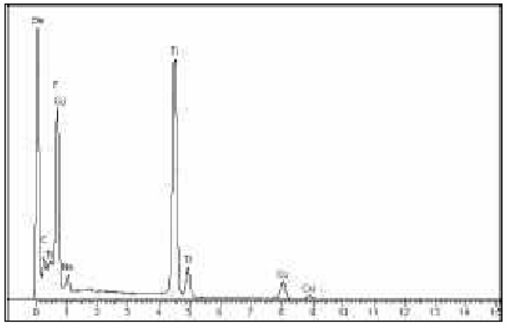
Current Year Results

Tunneling and Scanning Electron Microscopy

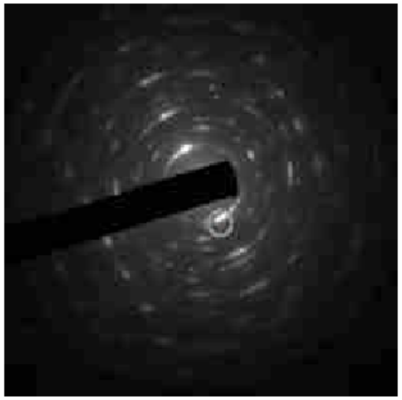
Collaboration with Dr. C. Andrei and Prof. R. Holmstad,
Norwegian University of Science and Technology



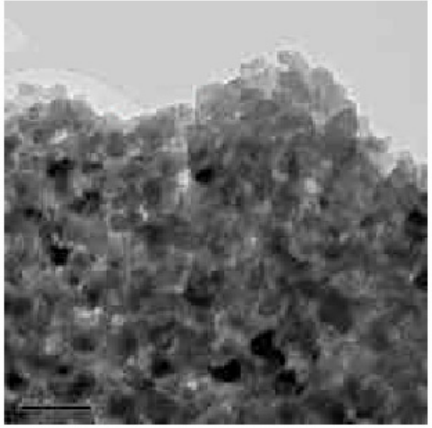
SEM image taken with backscattered electrons (BSE).



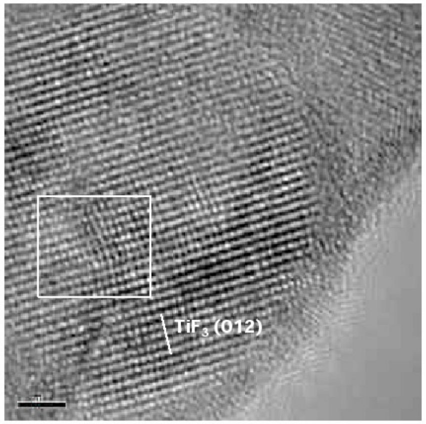
Energy Dispersive X-ray spectrum of a particle observed in uncycled $NaAlH_4$ doped with 2 mol % TiF_3 shows stong Ti and F peaks.



Small Angle Diffraction pattern of a Ti, F rich particle matches TiF_3.



TEM bright field image of a Ti, F rich particle observed in uncycled sample of $NaAlH_4$ doped with 2 mol % TiF_3.



High resolution image of TiF_3 grain. Indicated latttice planes were indexed as TiF_3.

Current Year Results

Tunneling and Scanning Electron Microscopy

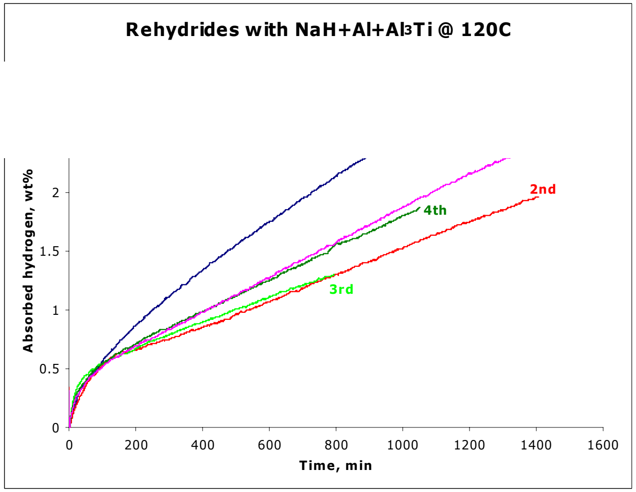
- No correlation between Al and Ti seen in the EDS maps directly after ball milling **but** correlation, suggesting Al-Ti bonding, seen after 15 cycles.

Agrees with findings from synchrotron X-ray, EPR, and XAFS studies

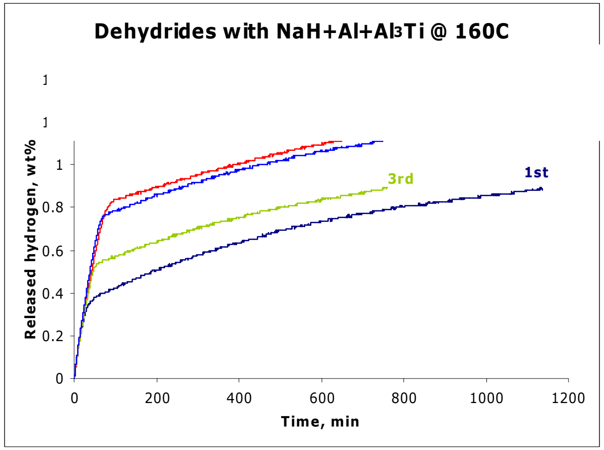
C.M. Andrei, J. Walmsley, H.W. Brinks, R. Holmestad, C.M. Jensen, B.C. Hauback *Appl. Phys. A.* **2005** *80*, 709.

Current Year Results

Doping with Cubic Al_3Ti



Hydrogenation profiles of NaH/Al + 3 mol % Al_3Ti powder mechanically milled for 30 min and charge under 100 atm H_2 at 120 ˚C.



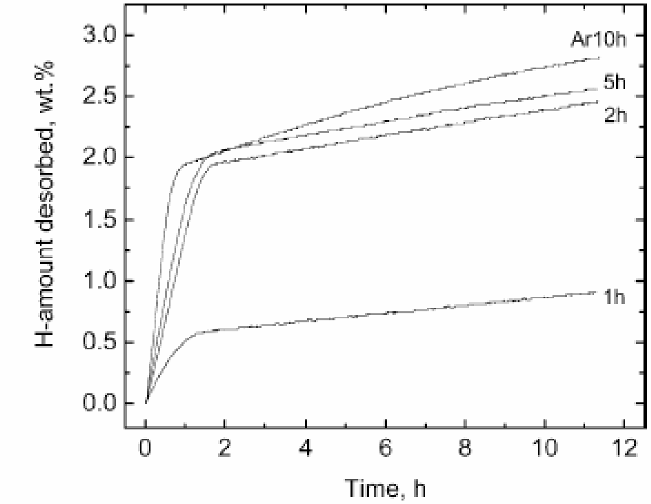
Dehydrogenation profile at 160 ˚C for NaH/Al + 3 mol % Al_3Ti powder mechanically milled for 30 min and charge under 100 atm H_2 for 10 h at 120 ˚C.

Only Minor Kinetic Enhancement of Hydrogen Cycling

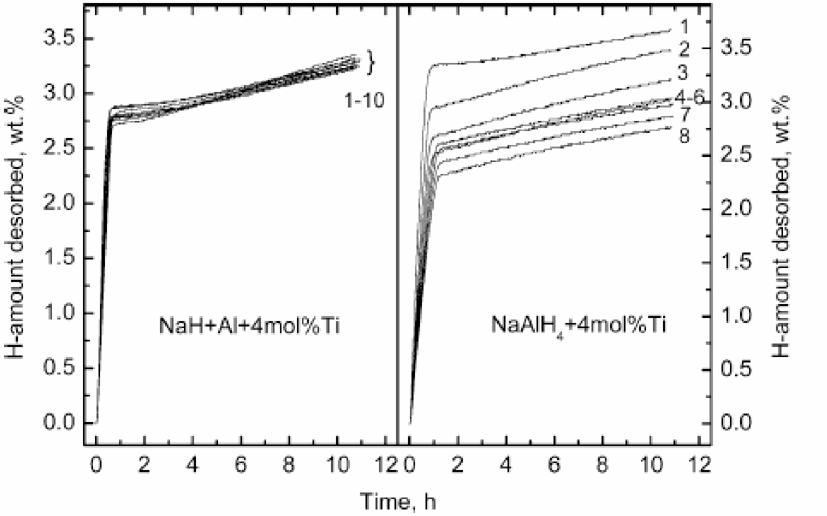
⇒ Al_3Ti is not the active Ti species

Current Year Results

Doping with Off-the-Shelf Ti Powder



First dehydrogenation profiles at 150 ˚C for samples of NaH/Al + 4 mol % Ti powder mechanically milled for different periods.



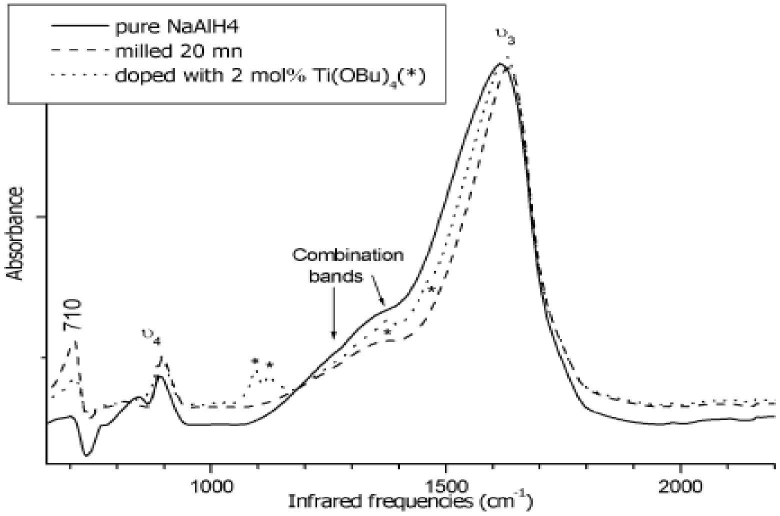
Comparison of the dehydrogenation profiles of NaH/Al + 4 mol % Ti powder and NaAlH4 + 4 mol % Ti both mechanically milled for 10h.

⇒ Ti precursors differ only in the length of milling time required to produce the active Ti species.

P. Wang and C.M. Jensen *J. Phys. Chem. B* **2004,** 107**,** 14157.

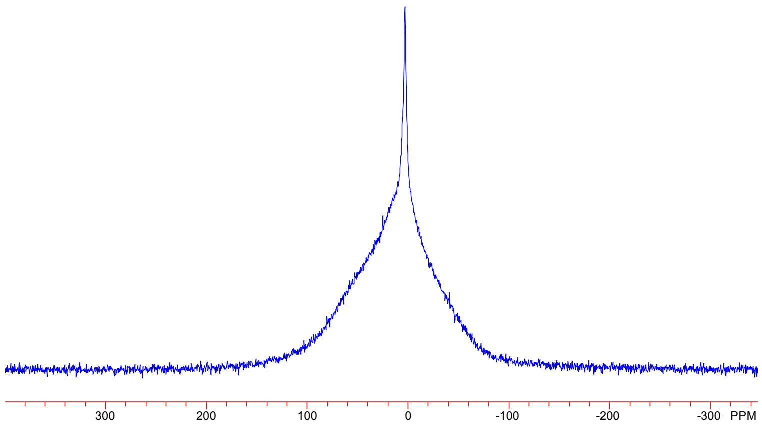
Determination of the Fundamental Basis of Enhanced Hydrogen Cycling Performance

Solid State ^{1}H NMR and Infrared Spectroscopy



IR SPECTROSCOPY
Al-H stretching frequency shifts
⇒ Al bonding is perturbed.

S. Gomes, G. Renaudin, H. Hagemann, K. Yvon, M.P. Sulic, and C.M. Jensen *J. Alloys Compds* **2005** *390*, 305.

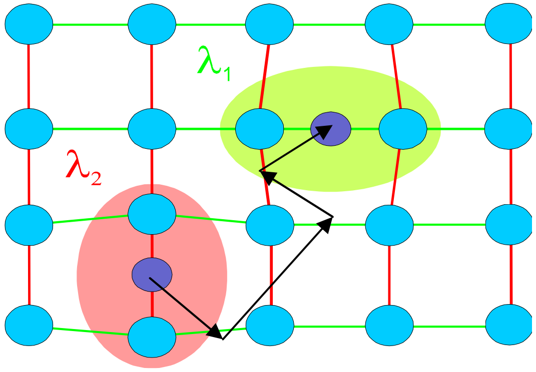


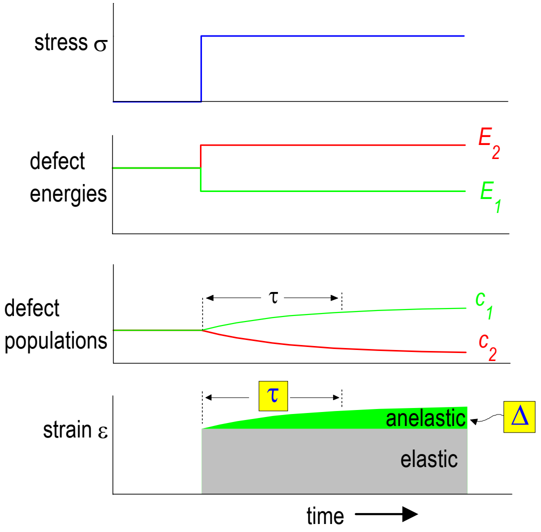
^{1}H NMR SPECTROSCOPY
Narrow Spectral Components:residual solvent, free H_2 and mobile species arising upon doping.

C.M. Jensen, D. Sun, B. Lewandowski, K.K. Kumashiro, W.P. Niemczura, D. Morales-Morales, Z. Wang, Proceedings of the 2001 Hydrogen Program Review, Baltimore, MD. (2001).

⇒ Ti-doping perturbs Al-H bonding and induces a population of highly mobile hydrogen

Anelastic Relaxation





Long range component of the strain due to defects

Elastic dipoles λ (hopping with time τ)

Anelastic strain $\varepsilon^{an} = \lambda_1 n_1 + \lambda_2 n_2$

Stress σ: $dE_i = -\lambda_i \sigma$

Boltzmann distribution:

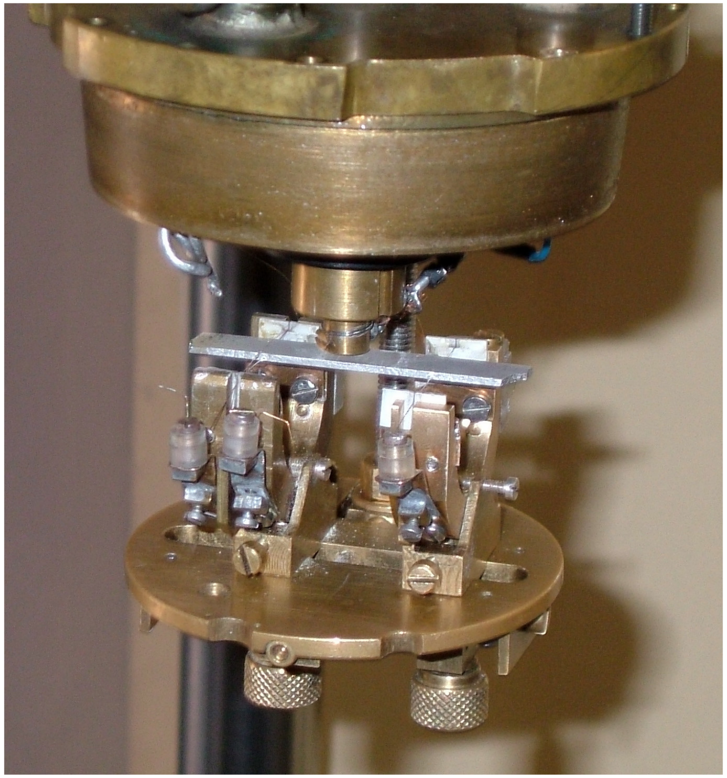
$$n_i = exp\ (-E_i / kT)$$

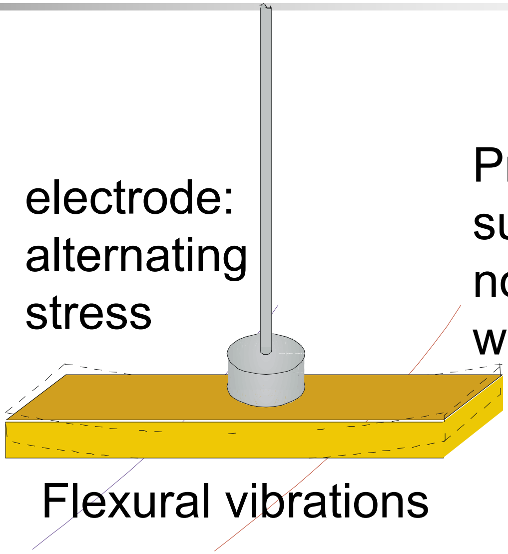
Relaxation strenght:

$$\Delta = \varepsilon^{an} / \varepsilon^{el} \sim (\Delta\lambda)^2 / T$$

Anelastic Relaxation

Prof. R. Cantelli, University of Rome



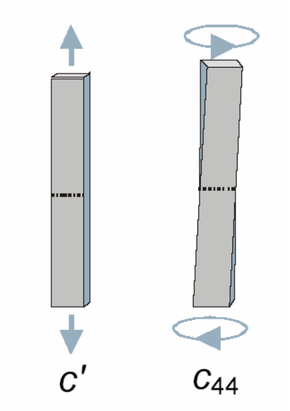


electrode:
alternating
stress

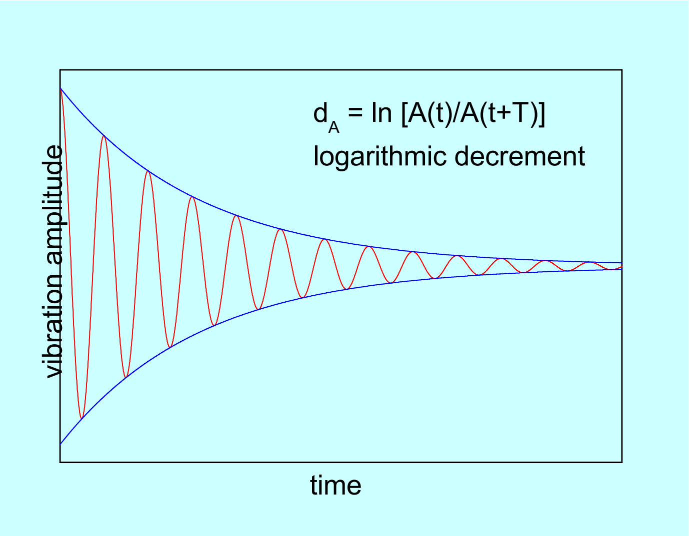
Prismatic Sample suspended on two nodal lines by thin wires

Flexural vibrations

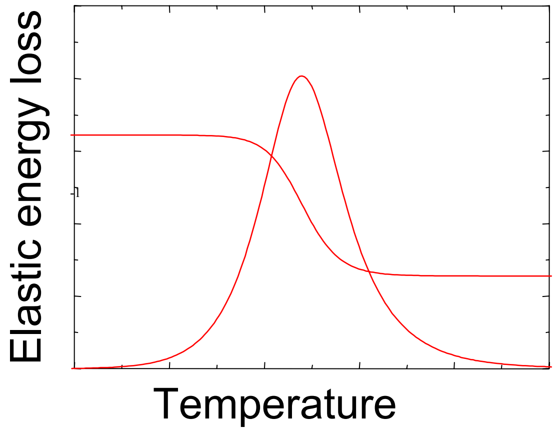
Extensional, torsional vibrations



Relaxation process



- Elastic energy dissipation coeff.: Q^{-1}=M”/M’ from the decay of the vibration amplitude or from width of resonance curve.
- The maximum of the elastic energy loss occurs when the angular vibration frequency is equal to the relaxation rate of the mobile species.

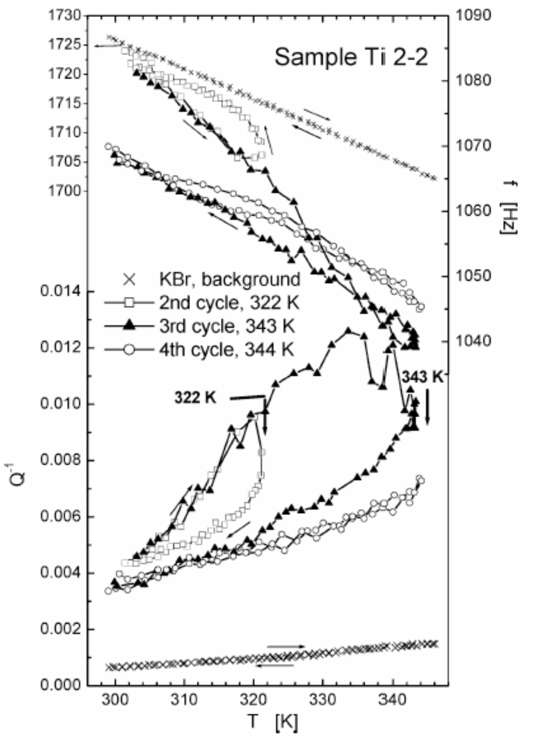


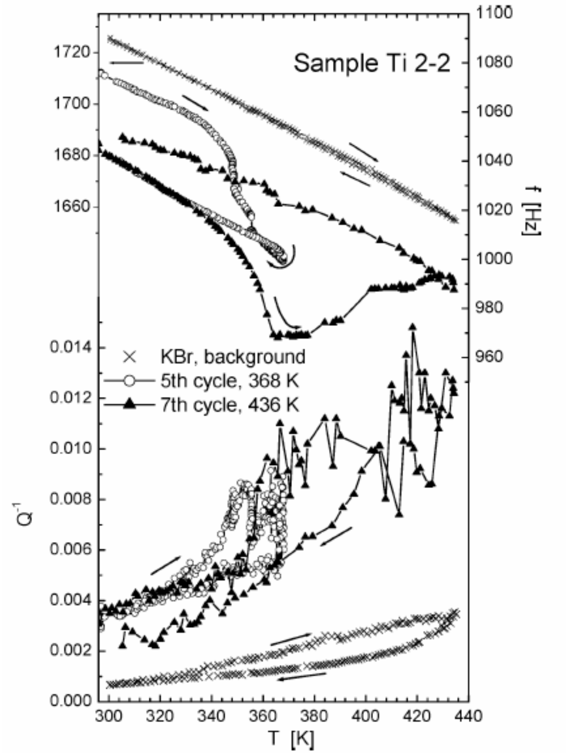
$$Q^{-1} = \frac{M\nu_0(\lambda_1 - \lambda_2)^2 n_1 n_2}{T} \frac{1}{(\omega\tau)^{\alpha} + (\omega\tau)^{-\alpha}}$$

Current Year Results

Anelastic Spectroscopy

Temperature dependence of elastic energy loss and frequency during thermal cycles of $NaAlH_4$ Doped with 2 mol % TiF_3.



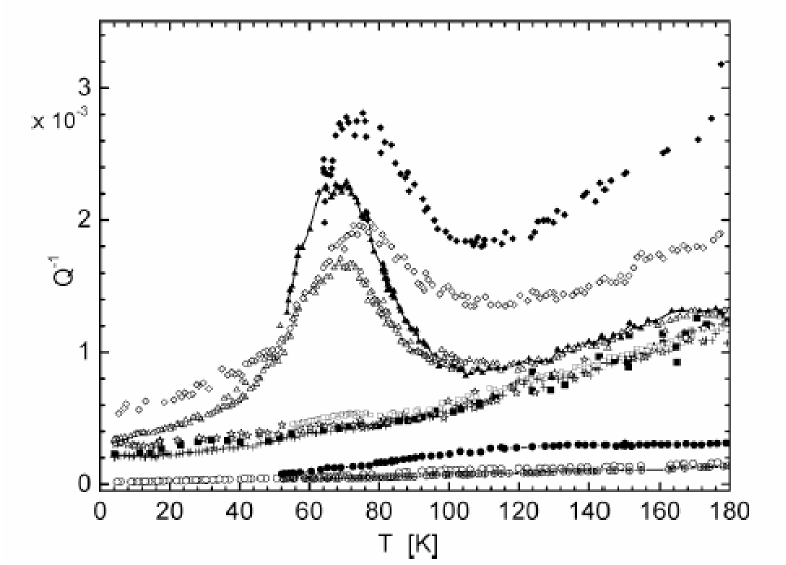


O. Palumbo, R. Cantelli, A. Paolone, C.M. Jensen, S.S. Srinivasan *J. Phys. Chem. B.* **2005** *109*, 1168.

Current Year Results

Anelastic Spectroscopy

Low Temperature Dependence of Elastic Energy Loss



o KBr only
• KBr, H_2 treated
■ undoped
□ undoped, TT
♦ doped, TT, 1.1 Hz
◆ doped, TT, 4.8 Hz
Δ doped, TT, 1.1Hz, aged
✧ doped,TT, 4.8 Hz, aged

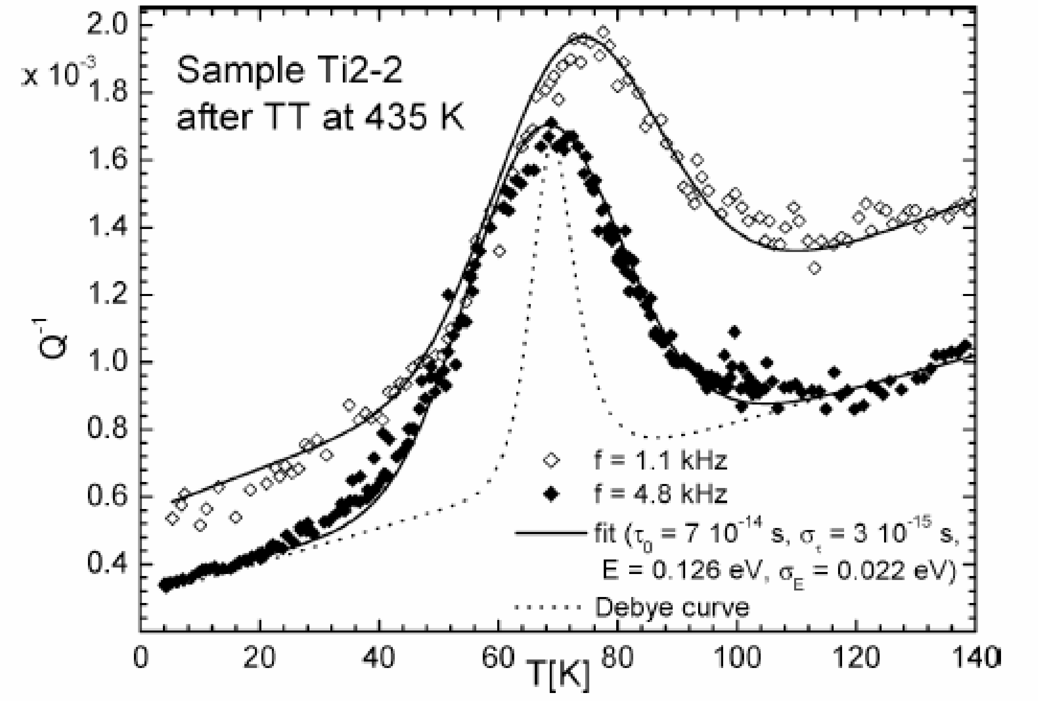
⇒ A point-defect is formed during the dehydrogenation of the Ti-doped hydride that gives rise to a thermally activated relaxation process.

O. Palumbo, R. Cantelli, A. Paolone, C.M. Jensen, S.S. Srinivasan *J. Phys. Chem. B.* **2005**, *109*, 1168.

Current Year Results

Anelastic Spectroscopy

Experimental curve is much broader than predicted for a single Debye process



⇒ At 70 K, the relaxing entities (very likely hydrogen) are strongly interacting and/or highly mobile, performing about **5x10^3 jumps/s** (corresponding to an activation energy of **0.126 eV**).

O. Palumbo, R. Cantelli, A. Paolone, C.M. Jensen, S.S. Srinivasan *J. Phys. Chem. B.* **2005**, *109*, 1168.

Conclusions

- The rate of dehydrogenation of 2 mol % Ti doped $NaAlH_4$ to Na_3AlH_6 at 100 ˚C (1.8 wt % per hour) is adequate to meet the demands of an onboard PEM fuel cell.
- Ti-doped NaH/Al has rapid hydrogenation kinetics (4.0 wt % absorbed in <30 min at 100 ˚C and 100 atm H_2 pressure.
- 2 mol % Ti doped $NaAlH_4$ has a highly stabile hydrogen cycling capacity of 3.0 wt % at 120 ˚C within 3h and 4.0 wt % at 150 ˚C within 3h.
- The kinetic effects resulting from variation in Ti dopant precursor arise from variation in the length of milling time required to produce and position the active Ti species.
- Hydrogen cycling kinetics in Ti-doped $NaAlH_4$ are limited by processes long range atomic transport phenomenon and location of dopants.

Conclusions

- High valent Ti dopant precursors are transformed Ti(0) species during the first few cycles dehydrogenatyion-rehydrogenation.
- The observation that only a relative minor change in the hydrogen cycling kinetics occurs whether the majority of titanium is transformed from Ti(III) to Ti(0) during early cycles of dehydrogenation/rehydrogenation strongly suggests that the enhanced hydrogen cycling kinetics are due to a minority Ti species and that the majority of the Ti is in a resting state.
- Mechanical milling of $NaAlH_4$ not only reduces particle size but also results in distortions microstructure and perturbs Al-H bonding.
- Ti-doping perturbs Al-H bonding and induces a population of highly mobile hydrogen.
- Ti-doping of $NaAlH_4$ induces a thermally activated process the generates point-defects. These entities very likely involve hydrogen and are are highly mobile, performing about $5x10^3$ jumps/s at 70K.

FY04 Review’s Comments

Over 100 comments! ~50/50 positive and negative.
90% of criticism related to 3 questions.

Q1. Why continue to study the alanates?

Q2. Why is the understanding of the fundamental processes involved in hydrogen cycling in the doped alanates so slow in emerging?

Q3. Why weren’t any details given about the 7 wt % material that was mentioned in the presentation?

Responses FY04 Review's Comments

A1. A better understanding of the fundamental basis of the phenomenal enhanced hydrogen cyclic kinetics in Ti-doped alanates would be a great aid to efforts to develop improved hydrogen storage materials based on any complex hydride or related material. The statement is supported by recent reports the Ti-doping enhances the hydrogen cycling kinetics of metal amides and $LiBH_4/MgH_2$.

A2. The complete decomposition and reformation of compounds with strong covalent bonding in the solid state at moderate temperatures was unknown until the discovery of the "Bogdanovic effect" of active Ti species on the reversible $NaAlH_4$ to NaH, Al, and H_2. The establishment of the fundamental basis this phenomenon has required the develop revolutionary fundamental models and wide variety of measurements. This was no small chore. In our efforts alone, we have recruited 15 top scientist from 6 countries (mostly at no additional cost to the DOE) to work on this problem. In the past year comprehensive model in agreement with all the experimental results is beginning to emerge.

A3. Exact compositional detail were withheld to protect priority information. Experimental details were withheld to further emphasize that the results were preliminary and prevent data from being "published" on the web.

Future Directions

Member of the Metal Hydride Center of Excellence

New Project Fundamental Studies of Advanced High-Capacity, Reversible Metal Hydrides

FY05 Budget: \$250,000 (UH - US DOE agreement in place as of 4/20/05)

Objectives

- Characterization of the Active Titanium Species in Ti Doped $NaAlH_4$ and related materials.
- Development of a model of the mechanism of action of the dopants in the dehydrogenation and re-hydrogenation processes in $NaAlH_4$ and related materials.
- Determine if the thermodynamics of the reversible dehydrogenation of alanates and related materials are altered upon doping.
- Prepare “thermodynamically tuned” binary hydrides with improved hydrogen cycling kinetics with the potential to meet the DOE 2010 system gravimetric storage capacity target.

Future Directions

FY05 Work Plan

Task 1. Characterization of Active Ti species

- Complete EPR studies of Ti-doped $NaAlH_4$ (collaboration with University of Denver).
- Complete XAFS studies of Ti-doped $NaAlH_4$ (collaboration with GE Global Research).

Task 2. Elucidation of mechanism of action in dopants

- Anelastic spectroscopy on Ti-doped: $NaAlD_4$ and Na_3AlH_6; Group I and II amides; and $LiBH_4/MgH_2$ (collaboration with University of Rome).
- Position annihilation studies of Ti-doped (collaboration with AIST, Tscuba, Japan).
- NMR studies of Ti-doped revisited.

Task 3. Thermodynamic effects of dopants?

- Differential scanning calorimetry on Ti-doped $NaAlH_4$ (collaboration with University of South Florida).

Future Directions

FY05 Work Plan

Task 4 High Capacity, Thermodynamically Tuned Binary Metal Hydrides

- Determine the effects of doping on the hydrogen cycling kinetics of “thermodynamically tuned” binary hydrides with the potential to meet the DOE 2010 system gravimetric storage capacity target, i.e. $LiBH_4/MgH_2$. (collaboration with HRL, JPL, CalTech, and Stanford University).
- Elucidation of the structural differences of the different phases of AlH_3 through X-ray and neutron diffraction studies. (collaborations with Brookhaven National Laboratory and Institute for Energy Research, Norway).

Future Directions

Beyond FY05

- Apply methods developed for the study and evaluation of doped alanates for the development of advanced complex hydrides and related materials with the potential application in a system that meets the DOE 2010 system storage targets.
- Preparation of advanced complex hydrides and related materials with the potential application in a system that meets the DOE 2010 system storage targets.

2004 Publications

Synchrotron X-ray and Neutron Diffraction Studies of $NaAlH_4$ Containing Ti Additives. H.W. Brinks, C. M. Jensen, S.S. Srinivasan, B.C. Hauback, D. Blanchard, and K. Murphy; *J. Alloys Compd.*2004, *376*, 215.

Structure and Hydrogen Dynamics of Pure and Ti-doped Sodium Alanate. Jorge Iniguez,T. Yildirim, T.J. Udovic, M. Sulic, and C. M. Jensen; *Phys. Rev. B.* 2004 *65,* 235433.

Long Term Cycling Behavior of Titanium Doped $NaAlH_4$ Prepared through Solvent Mediated Milling of NaH and Al with Titanium Dopant Precursors. Sesha S. Srinivasan, Hendrik W. Brinks, Bjorn C. Hauback, Dalin Sun and Craig M. Jensen; *J. Alloys and Compd.* 2004 377, 283.

Method for Preparing Ti-doped $NaAlH_4$ using Ti powder: Observation of Unusual Reversible Dehydrogenation Behavior. Ping Wang and Craig M. Jensen; *J. Alloys and Compd.* 2004 *379*, 99.

Rehydrogenation and Cycling Studies of Dehydrogenated $NaAlH_4$. Dalin Sun, Sesha S.Srinivasan, Guorong Chen and Craig M. Jensen; *J. Alloys and Compd.* 2004, *373*, 265.

Dehydrogenation of Alkanes Catalyzed by an Iridium-Phosphinito PCP Pincer Complex, David Morales-Morales, Rocío Redón, Cathleen Yung, and Craig M. Jensen; *Inorg. Chim. Acta* 2004 *357*, 2953. (invited contribution for topical volume on Rhodium and Iridium Chemistry).

Diffraction Studies of Alanates. H. W. Brinks, B. C. Hauback, D. Blanchard, C. M. Jensen, M. Fichtner, and H. Fjellvåg; *Advanced Materials for Energy Conversion II*, 2004, 153.

Dehydrogenation Process of Titanium and Zirconium Doped Alanates, T. Kiyobayashi, Akita, S.S. Srinivasan, D. Sun, S. Sangawa, C.M. Jensen and N. Kuriyama; *Advanced Materials for Energy Conversion II*, 2004, 157.

2004-05 Publications

Preparation of Ti-doped Sodium Aluminum Hydride from Mechanical Milling of NaH/Al with Off-the-Shelf Ti Power. P. Wang and C.M. Jensen; *J. Phys. Chem. B.* **2004** *108*, 15829.

Point Defect Dynamics and Evolution of Chemical Reactions in Alanates by Anelastic Spectroscopy. Oriele Palumbo, Rosario Cantelli, Annalisa Paolone, Sesha S. Srinivasan, and Craig M. Jensen; *J. Phys. Chem. B.* **2005,** *109*, 1168.

Electron Microscopy Studies of $NaAlH_4$ Doped with TiF_3: Hydrogen Cycling Effects. C.M. Andrei, J. Walmsley, H.W. Brinks, R. Homestad, C.M. Jensen, B.C. Hauback; *Appl. Phys. A*.**2005**, *80*, 709.

Effects of Milling, Doping and Cycling of $NaAlH_4$ Studied by Vibration Spectroscopy and X-ray Diffraction. S. Gomes, G. Renaudin, H. Hagemann, K. Yvon, M.P. Sulic, and C.M. Jensen, *J. Alloys and Compd.* **2005** *390*, 305.

Synthesis and Crystal Structure of Na_2LiAlD_6. H.W. Brinks, B.C. Hauback, C.M. Jensen, and R. Zidan; *J. Alloys and Compd* **2005** in press.

2004 Invited Presentations

3/14/04 “Doped Sodium Aluminum Hydride: Development and Fundamental Studies of a Promising New Hydrogen Storage Material”, Symposium on the Fundamentals of Advanced Materials for Energy Conversion II, 2004 meeting of the Minerals, Metals, and Materials Society, Charlotte, North Carolina.

3/22/04 “Doped Sodium Aluminum Hydride: Development and Fundamental Studies of a Promising New Hydrogen Storage Material”, Session on Perspectives on Hydrogen Storage, annual meeting of the American Physical Soceity, Montreal, Canada.

5/10/04 “Characterization and Mechanistic Studies of the Active Titanium Species in the Reversible Dehydrogenation of Ti-Doped Sodium Aluminum Hydride” Symposium on Hydrogen Storage Materials , 205th meeting of the Electrochemical Society, San Antonio, Texas.

9/4/04 “Mechanistic Studies of the Active Titanium Species in the Reversible Dehydrogenation of Ti Doped Sodium Aluminum Hydride” International Symposium on Metal Hydrogen Systems, Crakow, Poland.

9/14//04 “ Characterization and Mechanistic Studies of the Active Titanium Species in the Reversible Dehydrogenation of Ti-Doped Sodium Aluminum Hydride”, Leiden University, The Netherlands.

9/15/04 “PCP Pincer Complexes as Catalysts for Novel Organic Transformations”, Utrecht University, The Netherlands.

10/18/04 “ Characterization and Mechanistic Studies of the Active Titanium Species in the Reversible Dehydrogenation of Ti-Doped Sodium Aluminum Hydride”, Symposium on the Hydrogen Economy , meeting of the American Society for Materials, Columbus, Ohio.

2004-05 Invited Presentations

11/3/04 "Characterization and Mechanistic Studies of the Active Titanium Species in the Reversible Dehydrogenation of Ti-Doped Sodium Aluminum Hydride Symposium on Hydrogen Absorbing Materials, Fifth Pacific Rim International Conference on Advanced Materials and Processes (PRICM-5), Bejing, China.

11/5/04 "Hydrogen Storage Materials Research in the USA: Update and Prospectus", Nankai University, Tainjin, China.

11/8/04 "Hydrogen Storage Materials Research in the USA: Update and Prospectus", Fudan University, Shanghai, China.

11/30/04 "Doped Sodium Aluminum Hydride: Development and Fundamental Studies of a Promising New Hydrogen Storage Material", Cornell University.

12/1/04 "Characterization and Mechanistic Studies of the Active Titanium Species in the Reversible Dehydrogenation of Ti-Doped Sodium Aluminum Hydride", Symposium on Hydrogen Storage, 2004 Materials Research Society fall meeting, Boston, Massachusetts.

1/12/05 "Characterization and Mechanistic Studies of the Active Titanium Species in the Reversible Dehydrogenation of Ti-Doped Sodium Aluminum Hydride Gordon Research Conference on Hydrocarbon Resources, Ventura, California.

3/23/05 "Anelastic spectrosopic Studies of Point Defect dynamics and Evolution of Chemical Reactions in Alanates. Focus session on Hydrogen Storage: Measurements, American Physical society , Los Angeles, California.

5/29/05 "X-ray and Neutron Diffraction Studies of Ti-doped Sodium Aluminum Hydride, a Promising New Hydrogen Storage Material", Session on "Crystalline Hydrogen Storage Materials",

Hydrogen Safety

The most significant hydrogen hazard associated with this project is: that some of the compounds and mixtures have pyrophoric and/or react violently with water.

Hydrogen Safety

Our approach to deal with this hazard is:

- Methods for the handling, storing, and disposing of all hazardous materials connected with this project are in compliance with EPA and Hawaii Department of Health regulations.
- PI has completed the Hazardous Materials Waste Generator Training course and annual refresher courses of the University of Hawaii Environmental Health and Safety Office.
- All students and postdocs receive intensive training in the safe handling and manipulation of air and moisture sensitive compounds.