



Low-Cost α -Alane for Hydrogen Storage

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Project ID #
ST116

Overview

Timeline

Project Start Date: 15 July 2014
Project End Date: 14 July 2017

Percent complete of activities
proposed for FY16: 85%*

* As of 3/26/16

Budget

Total Project Budget: \$1,500,514

- Total Recipient Share: \$301,266
- Total Federal Share: \$1,199,248
- Total DOE Funds Spent*: \$722,566

Barriers

- Low-cost production of α -alane by electrochemical / chemical pathways
- Engineering cost analysis of entire alane synthesis and regeneration process
- Conservation of lithium aluminum hydride electrolyte
- Development of a particle bed reactor

Collaborators

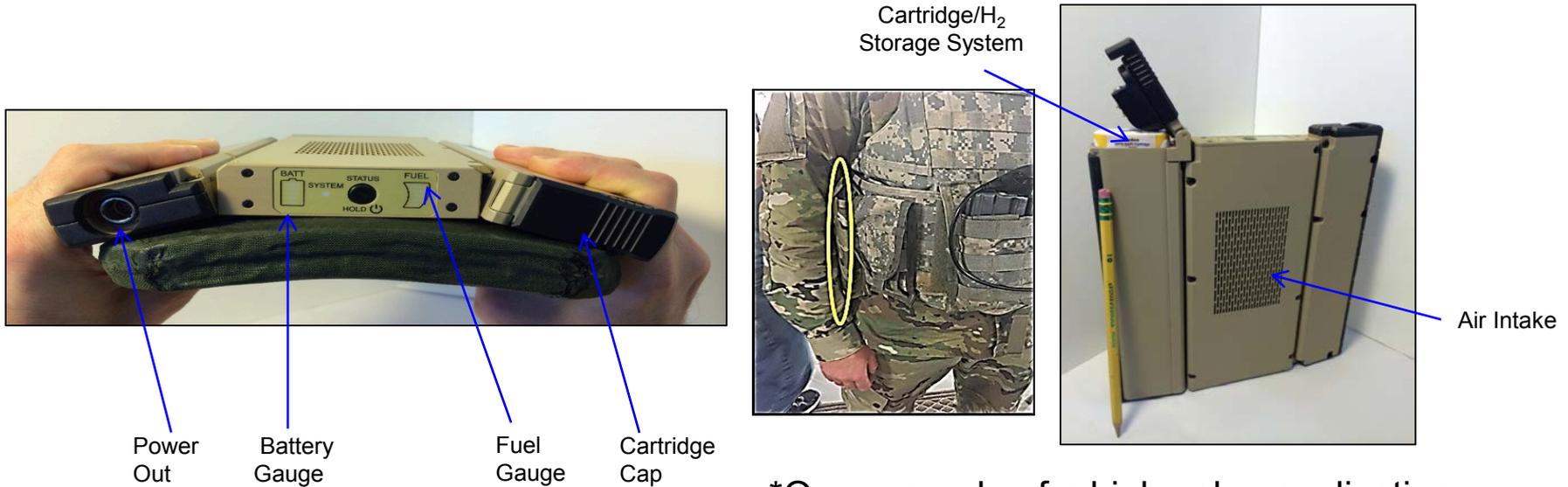
- SRI International (Subcontractor)
- SRNL (CRADA Partner)

Relevance: Project Objectives

Overall: Reduce production cost of α -alane (AlH_3) to meet the DOE 2015 and 2020 hydrogen storage system cost targets for portable low- and medium-power applications. Enables broader applications in consumer electronics (smart phones, tablets, laptops...), back-up power, UAVs, forklifts, and vehicles.

- Perform engineering cost analyses of electrochemical and chemical processes to meet the cost targets for synthesis and regeneration of α -alane throughout the program
- Demonstrate practical *electrochemical process* to synthesize alane adduct building on SRNL's pioneering work that can be transitioned to a large-scale facility
- Develop an electrochemical particle bed design approach that enables increased rate of reaction and a (semi-) continuous process
- Demonstrate recovery of MAlH_4 (M = Li, Na) electrolyte
- Develop an efficient process for recrystallization, passivation and formulation of the alane product

Relevance: Wearable Power System for a Dismounted Soldier (WPS20)*

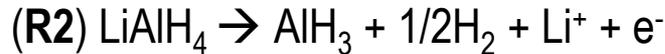


*One example of a high-value application

Features	
Fuel	α -alane (85 grams per cartridge)
Dimensions	7" x 8" x 0.89" with flexibility to conform to a small arms protective insert (SAPI) plate
Power Output	20 W continuous, 35 W peak
Cartridge/H ₂ Storage System Energy Density	1.03 KWh/kg, 1.32 KWh/L (72h at 20W continuous)
System Compatibility	Standards for soldier power distribution manager

Approach: Aluminum Particle Bed Reactor

Background



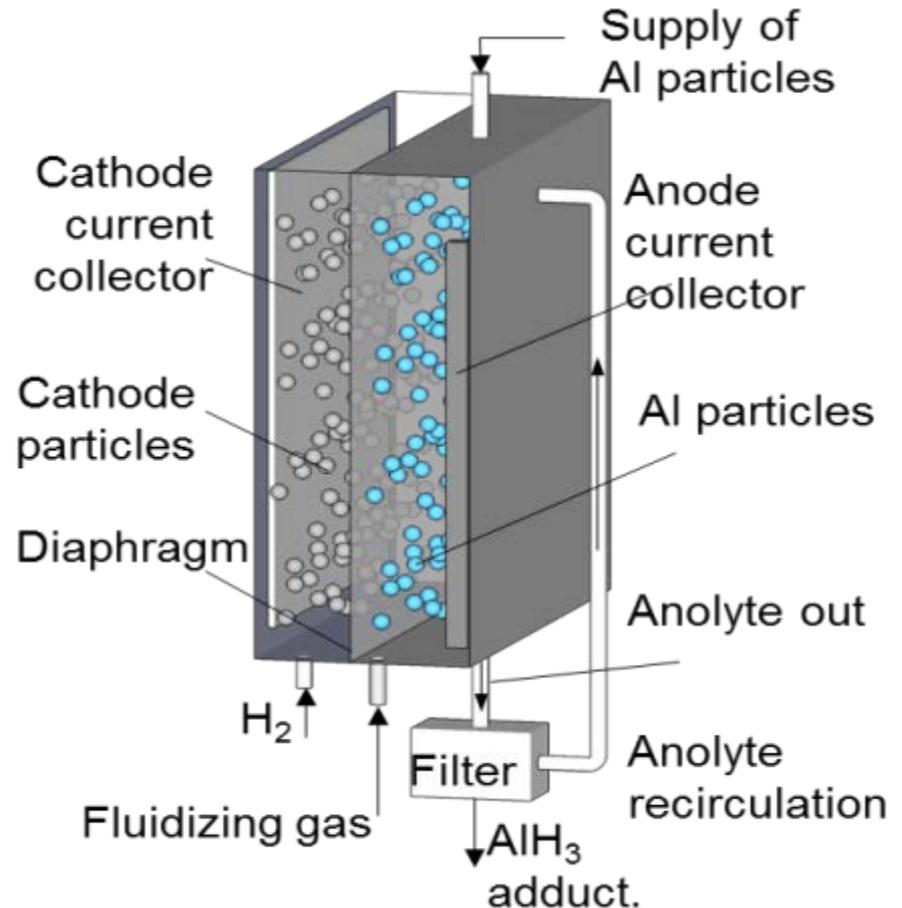
(Anode reactions)

- Electrochemical process developed by SRNL
- Uses NaAlH_4 or LiAlH_4 electrolyte and Al anode

Proposed Particle Bed Reactor

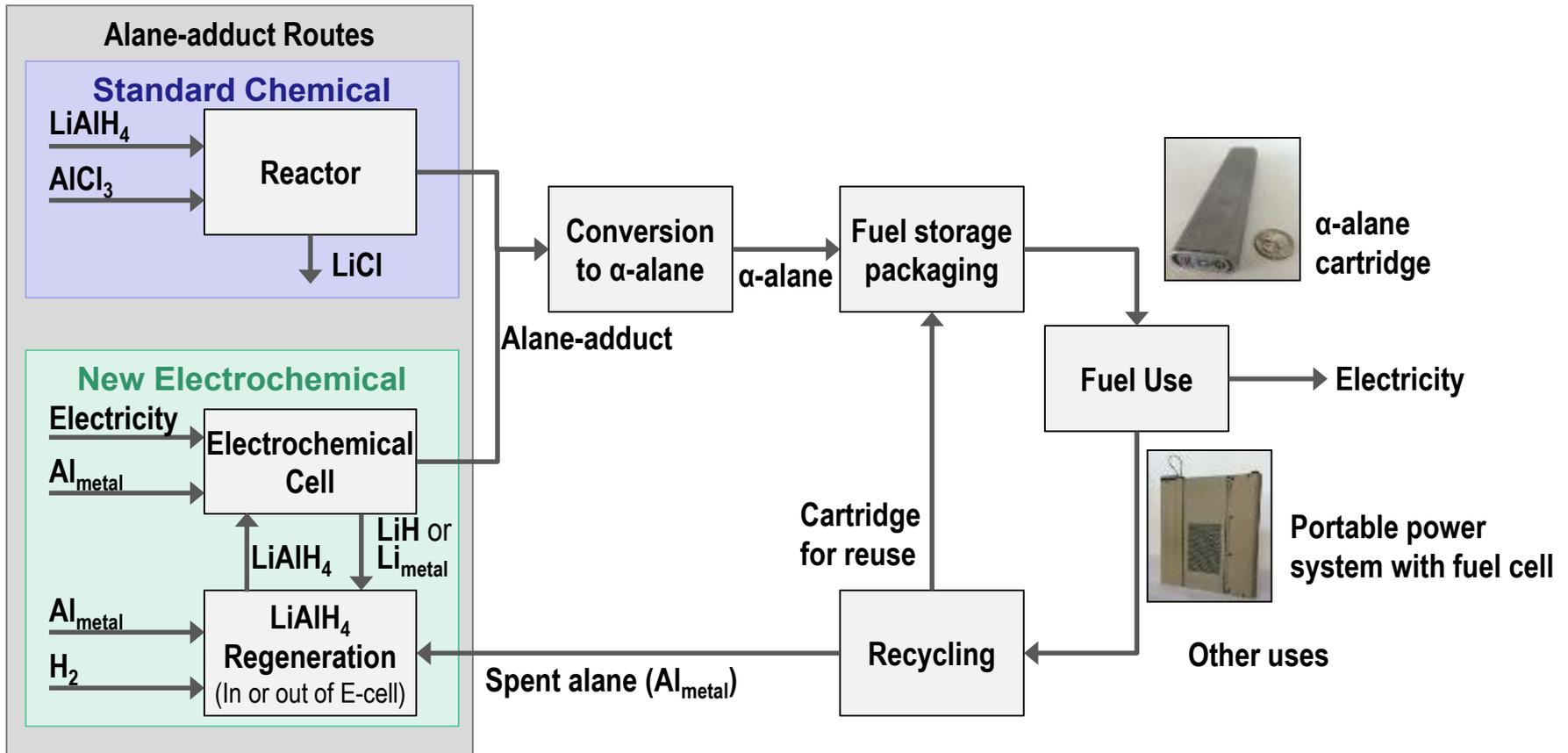
- Bed of conductive particles act as electrodes, ideally both anode and cathode
- High surface to volume enhances kinetics, enabling high current and throughput. Potential for continuous process.
- Regeneration of LiAlH_4 now feasible

Schematic illustration of dual-particle bed reactor



Approach: Electrolysis Process added to Alane Production

Reducing costs in the chemical process is difficult due to feedstock costs. Changing the front end to the electrolysis process for alane adduct production can reduce these costs.



Approach: Process and Economic Modeling Methodology

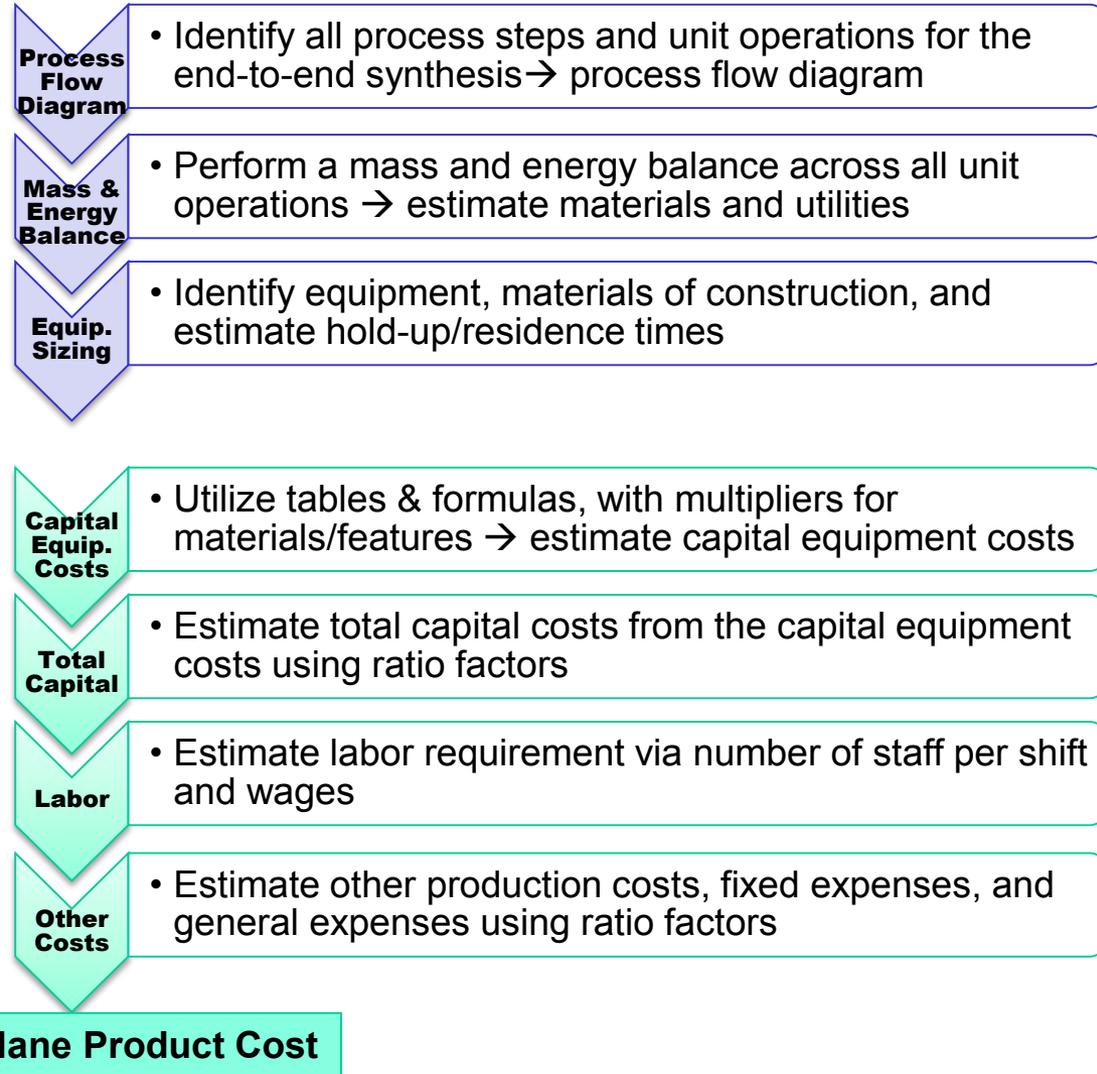
Process Modeling:

- Process flow diagram and mass/energy balance for all unit operations.
- End-to-end process including feedstock preparation, down-stream chemical workup, and materials recycling and regeneration.

Economic Modeling:

- Using methodology laid out by Peters, Timmerhaus, and West¹
- Higher multipliers and ratio factors account for increased costs associated with the safety and air sensitive materials handling requirements of this process compared to a typical chemical process.

Work Flow



Approach: Cost Reduction Compared to the Chemical Synthesis Route to Alane

Electrochemical process reduces alane cost from an improved, consumable aluminum anode to regenerate LiAlH_4 and optimize recycling of unreacted LiAlH_4 .

			Current Cost	Chemical Route (1,2)	Electrochemical Route		
					Baseline (1,3)	Cathode Recycle (1)	Increased Scale to 3,200 MT/yr
Storage System Costs			Pilot Plant	Commercial Scale	(80% AlH_3 from R1)	(80% AlH_3 from R1, 80% LiAlH_4 regenerated)	(80% AlH_3 from R1, 80% LiAlH_4 regenerated)
Alane Fuel Costs	\$/kg alane		3500	112	81	56	29
Cartridge Cost (4)	\$/kg alane		79	53	53	53	44
Total	\$/kg alane		3579	165	134	109	73
Storage System Cost	\$/g H_2		38.91	1.79	1.46	1.18	0.79
DOE Metrics		\$/g H_2	Target Met?				
Low Power	2015	3	N	Y	Y	Y	Y
	2020	1	N	N	N	N	Y
Medium Power	2015	6.7	N	Y	Y	Y	Y
	2020	3.3	N	N	N	Y	Y

Production cost broken down in later slides

1. Chemical and electrochemical route productions costs are for a 320 MT/yr process.
2. Commercial scale estimate provided by Albemarle.
3. Cost of alane entirely from reaction (R2) is \$101, compared to \$81 for 80% from reaction (R1).
4. New cartridge costs based on manufacturer estimates. \$79/kg AlH_3 at small scale production, \$53/kg AlH_3 at 4 M cartridges/year and \$44/kg AlH_3 at 20 M cartridges/year. Further cost savings of 25-33% per cartridge can be realized through recycling, not shown.

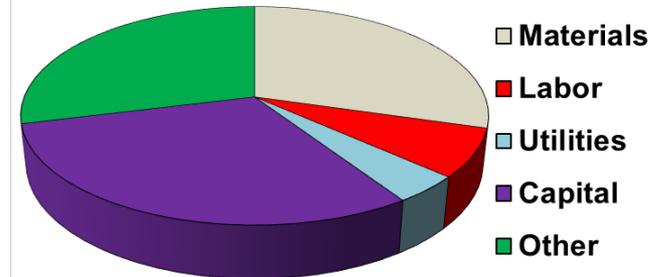
Baseline (Anode Reactions)



Approach: Process and Economic Modeling

Detailed economic model example shows α -alane production cost of \$56 per kg from the electrochemical process in which α -alane is produced from an aluminum anode via an N-ethylmorpholine adduct and LiAlH_4 is regenerated from the cathode by-products.

Production Costs	Basis		\$/kg
Raw materials	Mass balance	\$	16
Labor	Labor estimate	\$	4
Utilities	Energy balance	\$	2
Capital costs (depreciation and financing)	Capital Estimate	\$	17
Other (Maintenance, supplies, plant and admin overhead, etc.)	Various ratio factors	\$	16
Total Product Cost		\$	56



Key Assumptions:

- 320 MT/yr
- 80% AlH_3 is from R1
- 5 V cell potential, incl. ohmic losses
- Current density is 150 mA/cm²
- LiAlH_4 is recovered from cathode by-products with an 80% yield
- N-ethylmorpholine (NEM) adduct is employed
- LiAlH_4 is made from NaAlH_4 (NaAlH_4 supplier cost \$20/kg)
- Fully recover and recycle the solvents, NEM, and LiAlH_4 that persist into downstream processes

Sensitivity Analysis: Largest cost savings from starting material cost and scale of production

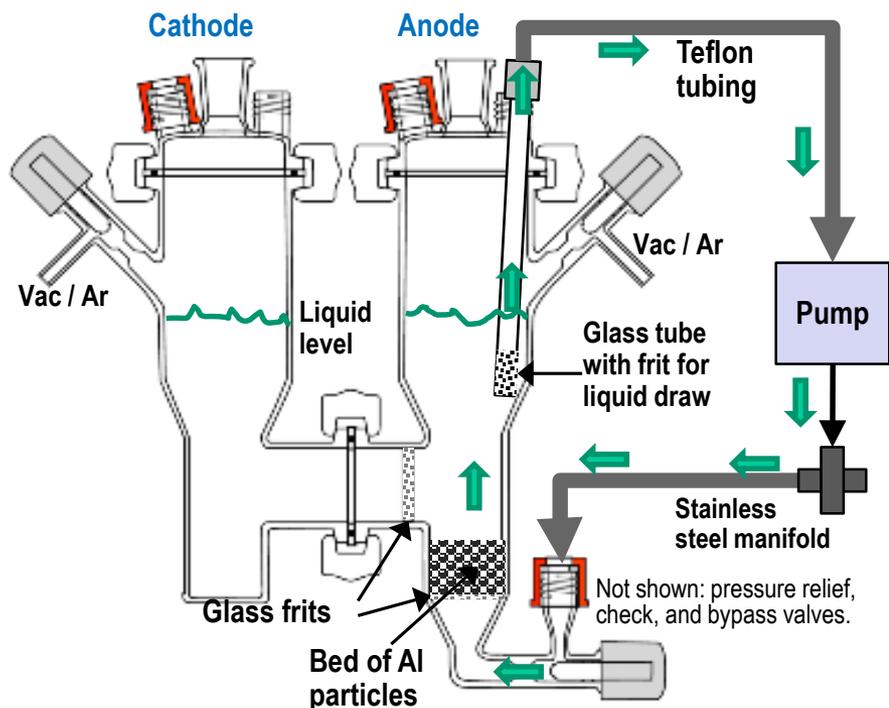
NaAlH_4 Cost (\$/kg)	Product Cost (\$/kg AlH_3)
100	102
20	56
5	47

Potential (V)	Cell Electrical Cost (\$/kg AlH_3)	Product Cost (\$/kg AlH_3)
3	0.23	56
5	0.38	56
10	0.77	56

Annual Production (MT/yr)	Capital Investment (\$M)	Product Cost (\$/kg AlH_3)
320	36	56
3,200	120	29
32,000	720	23

Technical Accomplishments: Particle Bed Fabrication & Operation

- SRI and Prof. Jim Evans (UC Berkeley) settled on a simple particle bed design that utilizes an anode compartment composed of aluminum particles over a porous glass frit fluidized to a variable degree by a reversible and variable flow of electrolyte
- Simple design facilitates rapid assembly and cleanup
- Allows evaluation of different aluminum particles sizes
- Facilitates the evaluation of electrolyte flow rate and flow direction to optimized fluidization vs particle size

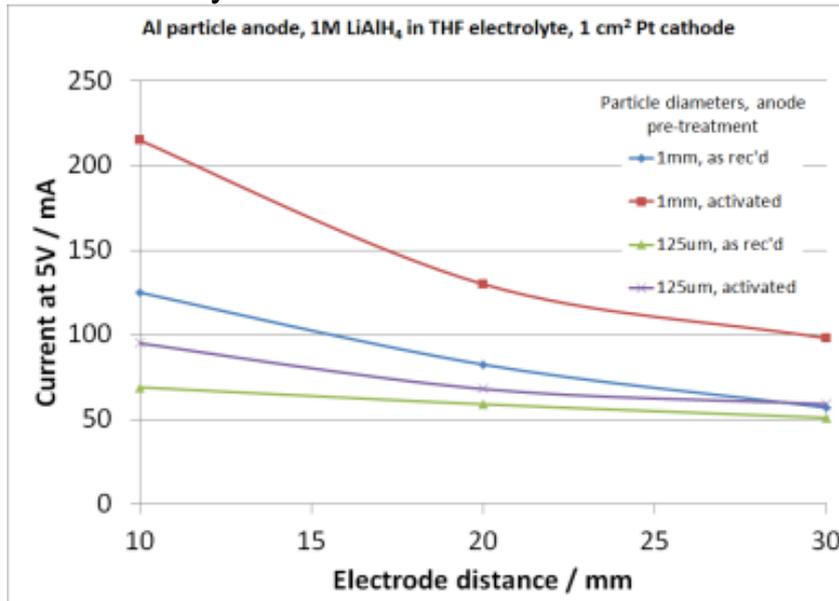
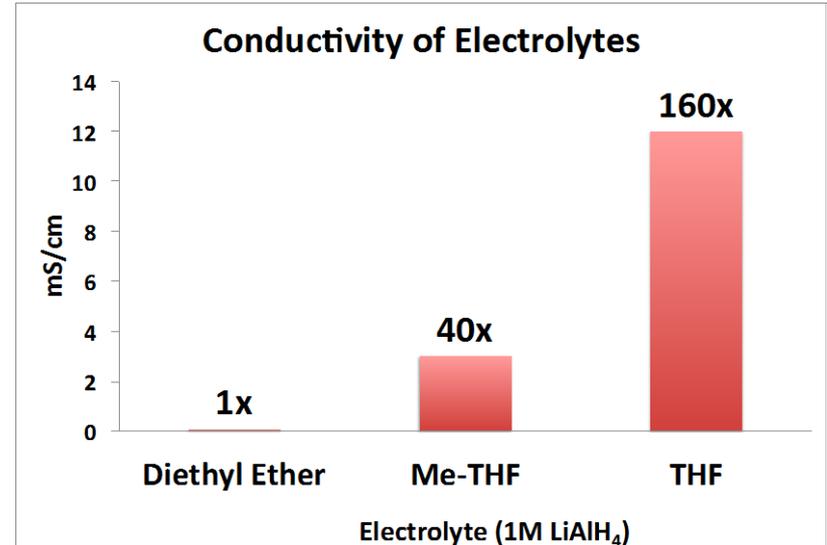


Technical Accomplishments: Understanding Aspects of Cell Design and Operation

Design critical for optimized cell conductance

Choice of electrolytic solvent:

- THF-based electrolytes provide strikingly higher conductivities compared to diethyl ether.
- Conductivity increase linearly with LiAlH_4 concentration.
- Electrolyte additives LiX ($X = \text{Cl}, \text{Br}$ and I), N -ethylmorpholine and glymes to 1M LiAlH_4 in diethyl ether or THF have no significant effect on conductivity.



- As expected, reduction of electrode spacing increases current dramatically.
- Activation of Al particles with 10% aqueous NaOH removes oxides. Up to 70% current increase observed.
- Smaller particles give lower current likely due to higher oxide content. Improve with better activation techniques.

Scaling the Electrochemical Vision

Assumptions:

- For a 320,000 kg/yr (292 days/yr) plant:
→ 46 kg/h (1.6 kmol/h) AlH_3
- Assume 80% of alane is produced from R1:
→ ~33 kA of current required
- Cell contains 1 m² of consumable anode area

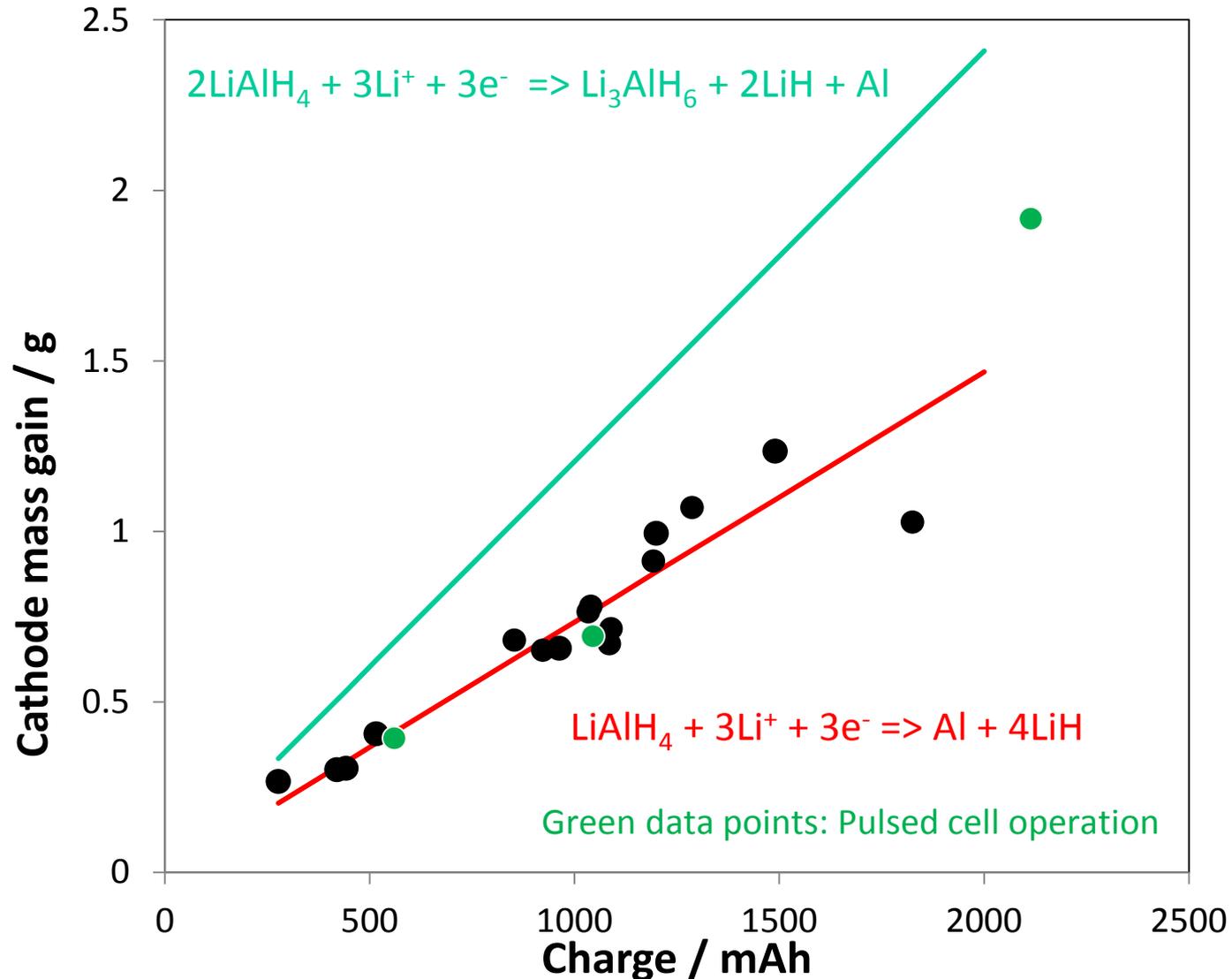
Key design considerations

- Balance needs for minimal (solvent) volume and thermal management;
→ Recirculating electrolyte
- Minimal electrode spacing for high current density
- Optimized current pulse protocol
→ Avoid cathode dendrite formation
→ Maintain practical net anodic current density
→ Facilitate cathode product collection

Current Density (mA/cm ²)	Number of Cells	Alane Production Rate* (kg/h) / cell	Adduct Production Rate** (kg/h) / cell	LiAlH ₄ Consumption Rate (kg/h) / cell	Power Dissipation @ 5V applied*** kW / cell
50	66	0.7	2.4	1.0	2.2
100	33	1.4	4.8	1.9	4.3
200	17	2.8	9.6	3.8	8.6

* Alane content of adduct; ** $\text{AlH}_3 \cdot \text{THF}$ adduct; *** OCV: 0.7 V

Technical Accomplishments: Cathode Reaction Products are Predominantly Al and LiH

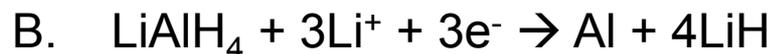


*Pulsed cell parameters based on SRNL work

Technical Accomplishments: Cathodic Processes

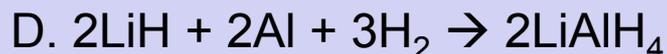
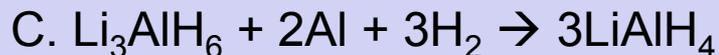
Cathode product composition is sensitive to electrolytic solvent, electrode distance and electrochemical cell operational parameters.

LiAlH_4 may be consumed in various cathode-related reactions:



- Diethyl ether based electrolytes give Li_3AlH_6 complex and Al. Tetrahydrofuran based electrolytes give a mixture of 4LiH and Al (by XRD, IR and Elemental Analysis). We hypothesize that this difference is due to the in-situ conversion of Li_3AlH_6 in more polar solvents.¹ $3\text{Li}_3\text{AlH}_6 \rightarrow \text{Al} + 2\text{LiH} + \text{LiAlH}_4$
- Reverse pulse method deposits identical mass of cathode materials in a laminar configuration that allows reduction in inter-electrode distances. Traps Li_3AlH_6 .

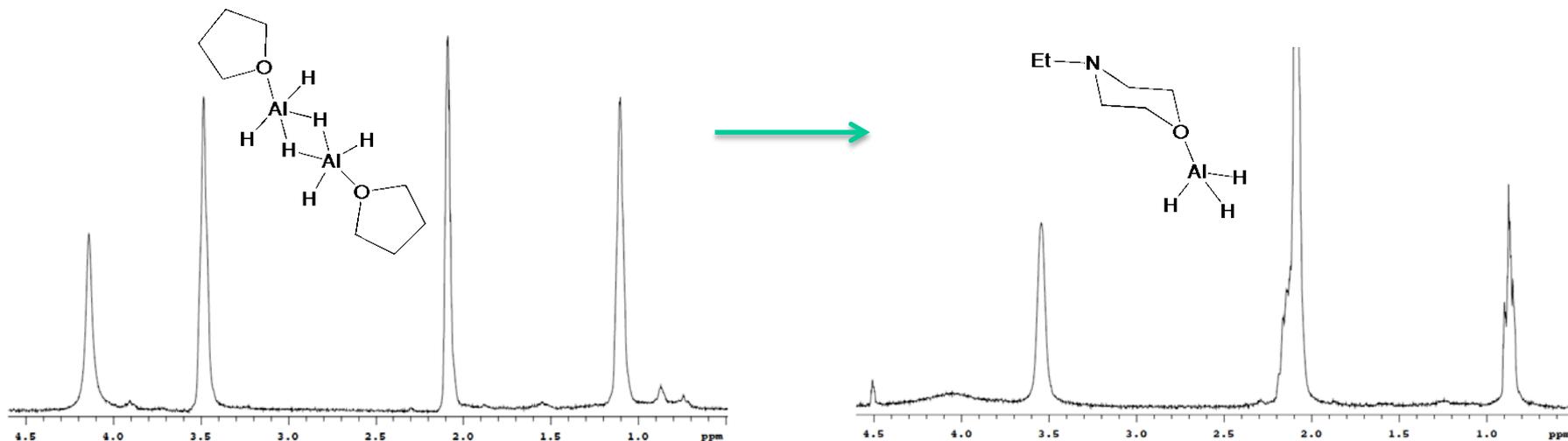
Enables regeneration of electrolyte MAIH_4 from captured cathodic materials (Li_3AlH_6 , LiH and Al)¹



1) Murib, J. H. U.S. Patent 3,649,223, March 4, 1972; Beard Jr., F. M.; Kobetz, P. U.S. Patent 3,355,262, November 28, 1967.

Technical Accomplishments: Successful separation of a useful alane adduct from NaAlH₄/THF based electrolyte.

Verified by ¹H NMR and XRD¹



Alane THF adduct dimer is isolated then converted to the N-ethylmorpholine adduct

We can isolate an adduct from a highly conducting electrolyte (e.g. NaAlH₄/THF) that can reportedly be converted into α -AlH₃. NaAlH₄/THF based electrolyte facilitates isolation of the N-ethylmorpholine (NEM) adduct due to lower energy of solvation (Na⁺ vs. Li⁺). Conversion to α -AlH₃ currently being optimized.

J. Graetz et al reported N-ethylmorpholine adduct can be converted to α -AlH₃¹

1) Chengbao, N.; Yang, L.; Muckerman, J. T.; and Graetz, J., *J. Phys. Chem. C* **2013**, *117*, 14983-14991

Collaborations

Collaborators	Role
<p>Ardica Technologies: Dick Martin (PI) (Receiving DoE project funds)</p>	<p>Development of alane-based hydrogen storage system for portable power</p>
<p>SRI International: Mark Petrie (PI), Steve Crouch-Baker, David Stout, Fran Tanzella (Receiving DoE project funds)</p>	<p>Development of low-cost electrochemical and chemical synthesis production methods for alane production scale-up</p>
<p>SRNL: Ragaiy Zidan (Receiving DoE funds through a related project)</p>	<p>Development of novel methods for the synthesis of low-cost alane</p>
<p>Albemarle: John Parks (Receiving Ardica funds)</p>	<p>Industrial partner for the scale up of alane production. Currently optimizing the chemical route.</p>
<p>UC Berkeley: Prof. James Evans (Receiving Ardica funds)</p>	<p>Expert advisor on fluidized bed design</p>

Remaining Challenges and Barriers

- Minimize cell resistance through cell design; construction, testing of a scalable cell design to increase the rate of alane production
- Regeneration of LiAlH_4 from the products generated on the cathodic side of the cell
- Facile isolation of a stable alane adduct from the electrochemical reaction that is readily converted to alpha alane (e.g. N-ethylmorpholine or triethylamine alane adduct)

Proposed Future Work

1. Design, fabricate, and test a scalable particle bed cell that builds on our experience with the H-cell that optimizes electrode kinetics, enables high-current, and hence high-throughput operation. Collaboration with Prof. Evans (UCB) is critical for this activity. (2016-2017)
2. Deposition of cathode products at high activity and yield for further reaction and regeneration of lithium or sodium aluminum hydride (MAIH_4). Modify pulse methods and fluidization of cathodic bed aluminum particles for deposition/capture of these materials. Improve morphology and optimize conversion to MAIH_4 (2016-2017)
3. Optimize solvent swap methods for complete separation of alane adduct from the concentrated NaAlH_4 based electrolyte. Optimize thermal conversion to α -alane from amine adducts using crystallization aides and heating profiles. (2016-2017)

Project Summary

Evaluate electrochemical/chemical routes to reduce alane synthesis cost

- Full engineering cost analysis of electrochemical and chemical processes to meet DOE metrics
- Initial analysis shows the electrochemical synthesis affords a max. ~50% reduction in alane cost

Maximize electrolyte (LiAlH_4) recovery in electrochemical alane synthesis

- Characterized and modified morphology of materials deposited ($\text{Li}_3\text{AlH}_6 + \text{LiH} + \text{Al}_{(\text{metal})}$) on the cathodic side of the cell
- Strategies include electrolytic solvent, electrode distance and electrochemical cell operational parameters

Optimize particle bed EC reactor (moving or static)

- Designed, constructed and characterized particle bed reactor
- Evaluated reactor as a function of particle size and flow rates
- Continued collaboration with Prof. James Evans for particle bed design

Separation of alane from the concentrated electrolyte

- Partially recovered alane produced in an electrochemical cell using a THF/ NaAlH_4 electrolyte.
- Need to optimize transformation of the alane adduct to the alpha alane product

Technical Back-Up Slides

Model Details – Estimated Materials Requirements

- Estimated from an Excel based mass balance for all steps shown in the flow diagram.
- The quantities are automatically adjusted as the model variables are changed including: total annual production quantity of alane; reaction yields; concentrations; and extents of recycling, recovery, or separation.
- Bulk chemical prices were sourced from chemical manufacturing companies.

Material	Cost		Source	Amounts			Costs	
	\$/kg			kg/hr	kg/yr	kg/kg AlH3	\$/yr	\$/kg AlH3
<u>Reactants & Consumables</u>								
Hydrogen gas	\$	2.00	Cost target from EERE report	4.39	30,741	0.10	61,482	0.19
Aluminum	\$	1.81	Vincent Metals	43.17	302,521	0.95	547,564	1.71
Sodium aluminum hydride	\$	20.00	Albemarle	26.56	186,101	0.58	3,722,013	11.65
Lithium chloride	\$	5.00	Albemarle	20.85	146,103	0.46	730,514	2.29
Hydrochloric acid	\$	0.26	Shijiazuang Xinlonwei	9.78	68,503	0.21	<u>17,811</u>	<u>0.06</u>
						Total	5,079,384	15.89

Notes:

Assumed Operational time 292 days/yr
 Hourly AlH3 production rate 45.6 kg/hr
 Annual AlH3 production rate 319,622 kg/yr
 Hydrogen cost based on anticipated production cost from EERE report

Model Details – Estimated Utilities Requirements

- Estimated from an Excel based energy balance for all steps shown in the flow diagram.
- The heating and cooling requirements are determined by the heat capacities, heat of reactions, and heat of vaporization; all of which are included in the model. The pumping requirements are estimated based on hourly volumetric throughput of the system.
- The other power requirements are only a rough estimate due to the lack of specific equipment detail at this point, however this quantity is almost negligible compared to the other energy requirements.

Unit Operation Name	Power Req'ts MJ/hr	Annual Energy Req'ts kWhr	Annual Energy Cost \$/yr	Cost per kg Alane \$/kg AlH3
Electrochemistry				
Electrochemical cell	617	1,201,738	\$ 122,457	\$ 0.383
Heating				
Alane etherate concentration	465	906,133		
Alane etherate flash	-	-		
Solvent swap evaporation	102	197,843		
Heating for crystallization	61	118,807		
Solvent distillation reboiler	476	927,458		
Wet solvent distillation reboiler	257	499,698		
Ether removal, LiAlH4 regeneration	19	36,724		
Solvent removal, LiAlH4 regeneration	132	257,552		
Heating Total	1,512	2,944,215		
Total with heat integration/recovery	1,512	2,944,215	\$ 300,016	\$ 0.939
Cooling				
Alane etherate concentrate condenser	465	906,133		
Alane etherate flash condenser	-	-		
Solvent swap condenser	102	197,843		
Crystallization condenser	11	21,837		
Post crystallization cooling	63	122,300		
Solvent distillation, ether condenser	10	20,182		
Solvent distillation, toluene condenser	385	749,298		
Alane dryer condenser	41	79,190		
Wet solvent distill, ether condenser	-	-		
Wet solvent distill, toluene condenser	257	499,698		
Solids neutralization	0.01	27		
Ether condenser, LiAlH4 regen. ether removal	18.86	36,724		
Solvent condenser, LiAlH4 regen. solvent removal	5.49	10,694		
Cooling Total	1,358	2,643,926		
Total with heat integration/recovery	1,358	2,643,926	\$ 269,416	\$ 0.843
Pumping (liquid and vacuum)				
Estimate of total pumping	80	155,733	\$ 15,869	\$ 0.050
Other				
Est. of controls, instruments, agitation, heat integration, etc.	100	194,667	\$ 19,837	\$ 0.062
Total energy costs			\$ 727,594	\$ 2.276
Notes:				
Assumed Operational time		292 days/yr		
Hourly AlH3 production rate		45.6 kg/hr		
Annual AlH3 production rate		319,622 kg/yr		
Electricity cost		0.1019 \$/kWhr		

Model Details – Estimated Capital Investment

- Capital equipment sizes are based on the estimated throughput from the mass balance for all process steps shown in the flow diagram
- Purchase costs were determined primarily from literature table cost estimates along with some from vendor estimates. Multipliers were used to adjust the cost for materials of construction and the handling of air sensitive materials.
- The total delivered capital equipment cost is used to determine the total capital cost using ratio factors following the method first proposed by Lang^{1,2}. We used values reported in Peters, Timmerhaus, & West for fluid processing plants.
- Due to the air sensitive materials handling and safety requirements, we used factors for installation, piping, and building costs that were at the higher end of the ranges for chemical plants.

	Approximate Ranges*	Value (%)	Cost (\$)
Direct Costs			
Purchased equipment delivered			4,806,978
Purchased equipment installation	25-55% of purchased	55	2,643,838
Instrumentation and controls (installed)	6-30% of purchased	25	1,201,745
Piping (installed)	10-80% of purchased	80	3,845,582
Electrical (installed)	10-40% of purchased	20	961,396
Buildings (including services)	10-70% of purchased	70	3,364,885
Yard improvements & service facilities	40-100% of	80	3,845,582
Land	4-8% of purchased	4	192,279
Total Direct Costs			\$ 20,862,285
Indirect			
Engineering and supervision	5-30% of direct costs	15	3,129,343
Construction expenses and contractor's fee	6-30% of direct costs	25	5,215,571
Contingency	5-15% of fixed-capital	10	3,245,244
Total Indirect Costs			\$ 11,590,158
Fixed Capital Investment			\$ 32,452,443
Working Capital (15%)	10-20% of total capita	10	3,605,827
Total Capital Investment			\$ 36,058,270

* Ranges from Peters & Timmerhaus for fluid processing.

Annual AIH3 production rate 319,622 kg/yr

1) Lang., H. J., Cost relationships in preliminary cost estimation, Chem. Eng., 54(10):117 (1947). 23

2) Lang., H. J., Simplified approach to preliminary estimates, Chem. Eng., 55(6):112 (1948).

Model Details - Estimated Manufacturing Cost

- The total production cost uses methodology described in Peters, Timmerhaus, and West which provides ranges that are typical for chemical processes.
- In our model, the baseline values for the additional estimates are chosen to be the middle of the ranges; however these are easily adjusted in the model.
- The alane process varies from the approximate ranges in regards to a high raw materials cost (depending on what variables are selected).
- Currently the 'patents and royalties' cost is to be determined, while the 'distribution and selling' and 'research and development' costs are ignored.

	Approximate Ranges (Peters, Timmerhaus, & West)	Value Used	Basis	\$/yr	\$/kg
Manufacturing Costs					
Direct Production Costs					
Raw Materials	(10-50% of total product cost)	Materials table	Mass balance	\$ 5,261,015	\$ 16.46
Operating Labor	(10-20% of total product cost)	Labor Table	Labor est.	\$ 946,080	\$ 2.96
Supervisory and Clerical Labor	(10-25% of operating labor)	Labor Table	Labor est.	\$ 322,368	\$ 1.01
Utilities	(10-20% of total product cost)	Energy Table	Energy balance	\$ 727,594	\$ 2.28
Maintenance and Repairs	(2-10% of fixed-capital investment)	5%	RF of fixed capital	\$ 1,622,622	\$ 5.08
Operating Supplies	(10-20% of maintenance and repairs)	15%	RF of maint. & rep.	\$ 243,393	\$ 0.76
Laboratory Charges	(10-20% of operating labor)	15%	RF of operating labor	\$ 141,912	\$ 0.44
Patents & Royalties	(0-6% of total product costs)	TBD		\$ -	\$ -
Total Direct Costs				\$ 9,264,985	\$ 28.99
Fixed Charges					
Depreciation (Capital Costs)	(10% of fixed capital, 2-3% of building)	10%	Capital Estimate	\$ 3,605,827	\$ 11.28
Local Taxes	(1-4% of fixed capital)	2%	RF of fixed capital	\$ 649,049	\$ 2.03
Insurance	(0.4-1% of fixed capital)	1%	RF of fixed capital	\$ 324,524	\$ 1.02
Total Fixed Charges				\$ 4,579,400	\$ 14.33
Plant Overhead costs	(50-70% of total labor & maint. costs)	60%	RF of labor & maint.	\$ 1,734,642	\$ 5.43
Total Manufacturing Cost	Sum of direct, fixed, and plant overhead.			\$ 15,579,027	\$ 48.74
General Expenses					
Administrative	(15% of total labor & maint. costs)	15%	RF of labor & maint.	\$ 433,661	\$ 1.36
Distribution and Selling	(2-20% of total product cost)	0%		\$ -	\$ -
Research and Development	(2-5% of total product cost)	0%		\$ -	\$ -
Financing	(0-10% of total capital investment)	5%	RF of Capital	\$ 1,802,913	\$ 5.64
Total General Expenses				\$ 2,236,574	\$ 7.00
Total Product Cost	Sum of Manufacturing Costs and General expenses			\$ 17,815,601	\$ 56

RF = Ratio factor

Amount of AlH₃ produced per year

319,622 kg/yr

Ignore distribution and selling costs.

Ignore research and development costs.

Model Details – Cartridge Cost Breakdown

- The cartridge costs are based on vendor and manufacturer estimates for the various cartridge components at two different production scales.
 - As production scale is increased, cost savings are realized through automation
- Estimates are provided for both newly manufactured and recycled cartridges
 - Assumes cartridge canisters, heaters, and insulation are recyclable
 - Recycling costs for emptying, cleaning, and prepping a cartridge is assumed equal to the filling costs.

Values in \$/cartridge	Production Scale Basis	4 M Cartridges/yr		20 M Cartridges/yr	
		New	Recycled	New	Recycled
<u>Recyclable components</u>					
cartridge cans/lids	Aluminum product manufacturer estimate	0.75	NA	0.75	NA
cartridge heater	Heater element vendor estimate	0.50	NA	0.50	NA
insulation	Insulation manufacturer estimate	0.50	NA	0.50	NA
<u>Consumable components</u>					
filters	Filter vendor estimate	0.25	0.25	0.15	0.15
stickers	Vendor estimate	0.15	0.15	0.10	0.10
powder filling	Metal powder products manufacturer estimate	<u>0.75</u>	<u>0.75</u>	<u>0.50</u>	<u>0.50</u>
Components Total		2.90	1.15	2.50	0.75
<u>Labor</u>					
Handling, testing, & overhead	Estimate	1.60	1.60	1.25	1.25
Recycling (empty, clean, & prep)	Assumed equivalent to powder filling costs	<u>NA</u>	<u>0.75</u>	<u>NA</u>	<u>0.50</u>
Labor Total		1.60	2.35	1.25	1.75
TOTAL (\$/CARTRIDGE)		4.50	3.50	3.75	2.50
TOTAL (\$/KG ALANE)		53	41	44	29

Production scale: 4 M cartridges per year, equivalent to 320 MT/yr

Mass of alane per cartridge: 85 g