JV TASK 121 – ELECTROCHEMICAL SYNTHESIS OF NITROGEN FERTILIZERS

Final Report

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ABSTRACT

An electrolytic renewable nitrogen fertilizer process that utilizes wind-generated electricity, N_2 extracted from air, and syngas produced via the gasification of biomass to produce nitrogen fertilizer ammonia was developed at the University of North Dakota Energy & Environmental Research Center. This novel process provides an important way to directly utilize biosyngas generated mainly via the biomass gasification in place of the high-purity hydrogen which is required for Haber Bosch-based production of the fertilizer for the production of the widely used nitrogen fertilizers. Our preliminary economic projection shows that the economic competitiveness of the electrochemical nitrogen fertilizer process strongly depends upon the cost of hydrogen gas and the cost of electricity. It is therefore expected the cost of nitrogen fertilizer production could be considerably decreased owing to the direct use of cost-effective “hydrogen-equivalent” biosyngas compared to the high-purity hydrogen. The technical feasibility of the electrolytic process has been proven via studying ammonia production using humidified carbon monoxide as the hydrogen-equivalent vs. the high-purity hydrogen. Process optimization efforts have been focused on the development of catalysts for ammonia formation, electrolytic membrane systems, and membrane–electrode assemblies. The status of the electrochemical ammonia process is characterized by a current efficiency of 43% using humidified carbon monoxide as a feedstock to the anode chamber and a current efficiency of 56% using high-purity hydrogen as the anode gas feedstock. Further optimization of the electrolytic process for higher current efficiency and decreased energy consumption is ongoing at the EERC.

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EXECUTIVE SUMMARY

The fast-growing renewable energy industry is strongly reliant on nitrogen fertilizer. Commercial production of nitrogen fertilizers is based on the Haber Bosch process, which involves the heterogeneous reaction of nitrogen and hydrogen on an iron-based catalyst at high pressure (100–300 atm) and high temperature (400°~500°C). Key limitations of the Haber Bosch process for smaller-scale fertilizer production are the requirements of expensive high-purity hydrogen and large-scale production. Using biomass-derived syngas to replace high-purity hydrogen derived from natural gas offers the potential to compete with imported fertilizer and, simultaneously, develop a new domestic fertilizer industry that is based on smaller-scale, widely distributed production.

Since 2004, the National Alternative Fuels Laboratory (NAFL) of the Energy & Environmental Research Center (EERC) has been pursuing development of commercial electrochemical processes for producing ammonia, urea, and ammonium nitrate fertilizers from nitric oxide (NO) recovered from coal combustion emissions. High current efficiency for the nitrogen fertilizer was obtained using NO as a nitrogen source at ambient temperature and atmospheric pressure. However, NAFL's electrochemical processes of nitrogen fertilizers are strongly dependent upon the recovery of NO from flue gases which hinders their commercialization. The initially proposed scope of work for this project included working with Cansolv Technologies Inc. of Montreal, Quebec, Canada, to optimize a Cansolv-developed process for extracting oxides of nitrogen (NO_x) from utility coal combustion emissions. The purpose of this proposed work was to ensure availability of NO_x for use as the nitrogen input to an EERC-developed electrolytic process for production of ammonium nitrate fertilizer. Although a good-faith effort was made to establish a working partnership between the EERC and Cansolv that would allow EERC optimization of the Cansolv process, the effort has been unsuccessful to date, due primarily to 1) a long-term, serious medical condition sustained by the Cansolv principal responsible for setting up the partnership and 2) lack of Cansolv personnel resources to take over responsibility for the partnership because of heavy commitment to ongoing work in other areas.

In response to the lack of a clear, commercially viable path forward on the NO_x-based ammonium nitrate process, the EERC adjusted the project scope of work to focus on optimization of electrolytic processes for nitrogen fertilizer production that utilize air-separated elemental nitrogen (N_2), rather than NO_x, as the nitrogen input. A key advantage of these electrolytic processes is that they can directly utilize syngas generated via biomass gasification rather than the high-purity hydrogen required for Haber Bosch-based production of the fertilizer. Because the electrolytic processes can use a syngas comprising any combination of carbon monoxide and hydrogen, the cost of this "hydrogen-equivalent" input is significantly lower than the cost of the high-purity hydrogen required for the Haber Bosch process.

An electrochemical process that utilizes wind-generated electricity, N_2 extracted from air, and syngas produced via the gasification of biomass to produce nitrogen fertilizer ammonia was

proven technically feasible. This feasibility demonstration provides an important way to directly utilize syngas generated via biomass gasification rather than the high-purity hydrogen required for Haber Bosch-based production of the fertilizer for the production of the widely used nitrogen fertilizers. Process optimization efforts have been focused on the development of catalysts for the ammonia formation, electrolytic membrane systems, and membrane–electrode assemblies. An optimized electrolytic process is characterized by a current efficiency of 43% using humidified carbon monoxide as a feedstock to the anode chamber and a current efficiency of 56% using high-purity hydrogen as the anode gas feedstock. The EERC will further optimize the electrolytic process for higher current efficiency and decreased energy consumption and pursue the commercialization of the electrolytic nitrogen fertilizer process.

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INTRODUCTION

Industrial production of nitrogen fertilizers ammonia and urea are mainly based on the Haber process, which involves the heterogeneous reaction of nitrogen and hydrogen on an iron-based catalyst at high pressure (150–300 atm) and high temperature (400°–500°C) to produce ammonia. The equilibrium conversion of hydrogen gas and nitrogen gas to ammonia in the Haber process is generally only on the order of 10%–15%. Such low conversion efficiencies give rise to cost-intensive, large-scale chemical plants and costly operating conditions required to commercially produce hundreds-to-thousands-of-tons-per-day of ammonia in an ammonia synthesis plant. Urea is commercially produced via the reaction of carbon dioxide and ammonia at high pressure (100–200 atm) and high temperature (180°–185°C) to form ammonium carbamate, which is subsequently dehydrated into urea and water. Therefore, it is of industrial interest to develop simplified approaches for the production of nitrogen fertilizers, especially at small to middle scales. A one-step process that can convert carbon, nitrogen, and/or hydrogen sources to nitrogen fertilizers at decreased pressure and/or temperature has the potential to meet such requirements of small- to middle-scale production of high-nitrogen fertilizers.

The most obvious advantages of electrochemical processes over the traditional processes mentioned above include 1) decreased process complexity since a one-step process is likely, 2) simplified operation conditions since electrochemical reaction could be run even at room temperature and atmospheric pressure, and 3) decreased system volume and size.

Only recently has the feasibility of using electrochemical processes for ammonia synthesis been demonstrated. Most of the electrochemical processes for the synthesis of ammonia reported to date have involved the cathodic reduction of nitrogen gas at the cathode of an electrochemical cell. Both aqueous-based and organic solvent-based electrolyte solutions have been used at ambient temperature and atmospheric pressure. In these liquid electrolyte solution-based investigations, the source of hydrogen required for the formation of ammonia is provided by the electrochemical decomposition of water or an organic solvent, such as ethanol, at the anodes of the electrochemical cells.

Tsuneto et al. (1953) disclosed the use of an ambient-temperature electrochemical process utilizing an organic solvent-based electrolyte solution that contained lithium perchlorate as the electrolyte where ammonia gas was formed, with a current efficiency of 8% on flowing nitrogen gas at atmospheric pressure over either a titanium metal or silver metal cathode. On using a copper metal cathode and an electrochemical cell temperature of 50°C, a current efficiency of 48% for the production of ammonia was obtained on flowing nitrogen gas at a pressure of 50 atm over the cathode.

Marnellos and Stoukides (1998) developed a cathodic electrochemical process for the synthesis of ammonia that avoids the use of aqueous-based or organic solvent-based electrolyte solutions. With this process, electrosynthesis of ammonia takes place at the surface of a porous metal cathode attached to one side of a strontia–ceria–ytterbia peroskite solid-state proton (H+)

conductor. The electrochemical process is operated at atmospheric pressure and 570°C, which is a similar temperature to that used in the Haber–Bosch catalytic process. At this operating temperature and at atmospheric pressure, greater than 78% of the electrochemically supplied hydrogen from the anode that was transported through the solid electrolyte to the cathode was converted into ammonia. However, the process is limited by slow electrochemical reaction rates due to low proton fluxes through the solid electrolyte at 570°C. Increasing the temperature to obtain higher proton fluxes would also increase the rate of thermal decomposition of ammonia. A major drawback of these cathodic electrochemical processes is that the competing hydrogen gas evolution reaction takes place more readily than the formation of ammonia since recombination of adsorbed hydrogen atoms with each other is more likely to occur than reaction between adsorbed hydrogen atoms and adsorbed nitrogen molecules because of the high bond strength (~1000 kJ mol-1 at 25°C) of the N≡N triple bond of a nitrogen molecule.

More recently an anodic electrochemical process for the synthesis of ammonia was disclosed. This new anodic electrochemical process overcomes many of the limitations of the earlier discussed cathodic electrochemical processes. The anodic process uses molten salts selected from those having melting points that range from room temperature to greater than 400°C and containing a dissolved nitride ion-containing salt, such as lithium nitride (Li_3N), as the electrolyte. In the electrochemical reaction, N_2 is reduced to nitride ions (N_3-) at the cathode–molten salt electrolyte interface. Because of the applied electrical potential between the cathode and the anode, nitride ions migrate from the cathode–molten salt electrolyte interface to the anode–molten salt electrolyte interface. At the anode, nitride ions are oxidized to produce adsorbed nitrogen atoms (Nads). Adsorbed nitrogen atoms react with either adsorbed hydrogen molecules, or more likely with adsorbed hydrogen atoms, on the surface of the anode to produce ammonia gas molecules. With this process, a current efficiency of over 50% was obtained for the production of ammonia. There remains a need for an improved method of producing ammonia.

The feasibility of using electrochemical processes for urea synthesis at ambient temperature and atmospheric pressure has been demonstrated by Shibata et al. In this process, urea was produced from the reaction of carbon dioxide, nitrite or a nitrate as nitrogen source, and hydrogen gas. In an aqueous electrolyte using potassium bicarbonate ($KHCO_3$), the current efficiency for the urea formation strongly depends on electrode potential, nitrogen source, and electrocatalysts at the cathode sides. A maximum current efficiency of around 55% was obtained via simultaneous reduction of CO_2 and potassium nitrite (KNO_2) at −1.0 V at a cadmium electrode. The use of nitrate to replace nitrite source decreases the current efficiency. The maximum current efficiency was approximately 37% for the urea formation via simultaneous reduction of carbon dioxide and potassium nitrate (KNO_3) in the same electrolyte at −1.75 V at a gas diffusion electrode with zinc catalysts. However, Shibata's process holds several disadvantages for industrial use. The high cost of nitrite and nitrate as the source of nitrogen and the requirement of more hydrogen input compared to the Haber process decrease the commercialization potential of Shibata's process.

Since 2004, the National Alternative Fuels Laboratory® (NAFL®) of the Energy & Environmental Research Center (EERC) has been pursuing development of commercial electrochemical processes for producing ammonia, urea, and ammonium nitrate fertilizers from nitric oxide (NO) recovered from coal combustion emissions. High current efficiency for the nitrogen fertilizer was obtained using NO as the nitrogen source at ambient temperature and atmospheric pressure. However, NAFL's electrochemical processes of nitrogen fertilizers are strongly dependent upon the recovery of NO from flue gases which hinders their commercialization. The initially proposed scope of work for this project included working with Cansolv Technologies Inc., of Montreal, Quebec, Canada, to optimize a Cansolv-developed process for extracting oxides of nitrogen (NO_x) from utility coal combustion emissions. The purpose of this proposed work was to ensure the availability of NO_x for use as the nitrogen input to an EERC-developed electrolytic process for production of ammonium nitrate fertilizer. Although a good-faith effort was made to establish a working partnership between the EERC and Cansolv that would allow EERC optimization of the Cansolv process, the effort has been unsuccessful to date, primarily due to 1) a serious long-term medical condition sustained by the Cansolv principal responsible for setting up the partnership and 2) lack of Cansolv personnel resources to take over responsibility for the partnership because of heavy commitment to ongoing work in other areas.

In response to the lack of a clear, commercially viable path forward on the NO_x-based ammonium nitrate process, the EERC adjusted the project scope of work to focus on optimization of electrolytic processes for nitrogen fertilizer production that utilize air-separated elemental nitrogen (N_2) rather than NO_x as the nitrogen input. A key advantage of these electrolytic processes is that they can directly utilize syngas generated via coal or biomass gasification rather than the high-purity hydrogen required for Haber–Bosch-based production of the fertilizer. The principle of the ammonia electrolytic process is shown schematically in Figure 1. Because the electrolytic processes can use a syngas comprising any combination of carbon monoxide and hydrogen, the cost of this "hydrogen-equivalent" input is significantly lower than the cost of the high-purity hydrogen required for the Haber–Bosch process.

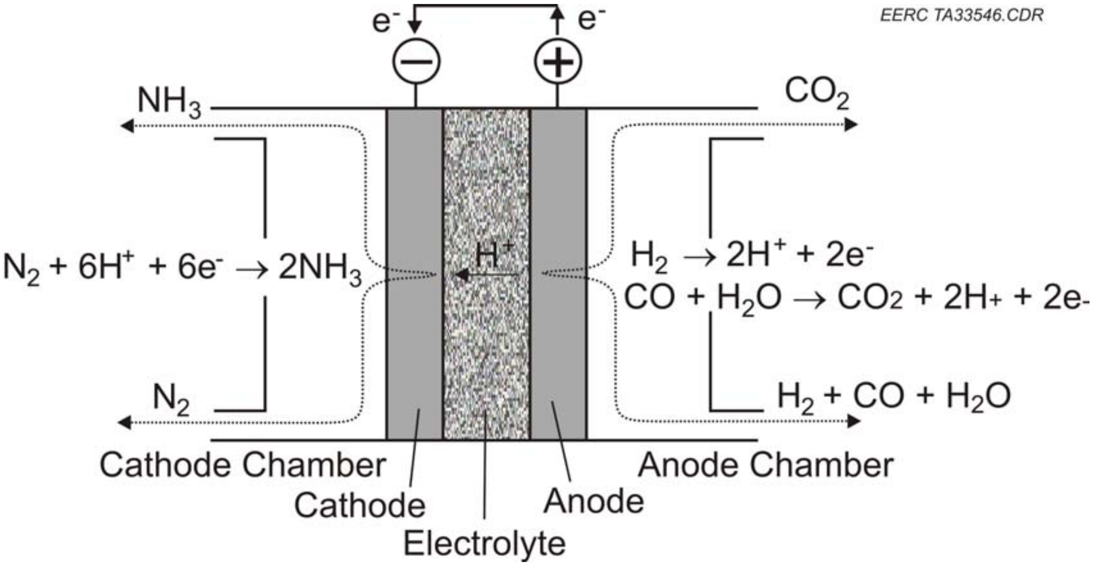

Figure 1. Schematic of an electrochemical hydrogenation process of N_2 using simulated syngas as a hydrogen source.

GOALS AND OBJECTIVES

The overall goal of the proposed research was to optimize an electrochemical process that utilizes inputs of electricity, N_2 extracted from air, and syngas produced via the gasification of coal or biomass to produce nitrogen fertilizers, with a primary focus on ammonia. Specific objectives included:

- Optimizing the electrolytic fertilizer production process via the development of high-efficiency catalysts, electrolytic membrane components and membrane–electrode assemblies (MEA) in a single-cell electrolyzer, and evaluation of process inputs and conditions.

- Identifying technical and economic challenges associated with the electrolytic process, and developing strategies to overcome the challenges.

- Evaluating the commercial potential of the process.

EXPERIMENTAL

Electrolysis Cell and Preparative Electrolysis

The electrolysis cell was composed of two high-alumina ceramic tubes separated by an MEA, as shown in Figure 2. During preparative electrolysis, N_2 gas of 99.99% purity was passed through the cathode chamber and the outlet gas, which is a mixture of reaction products, and

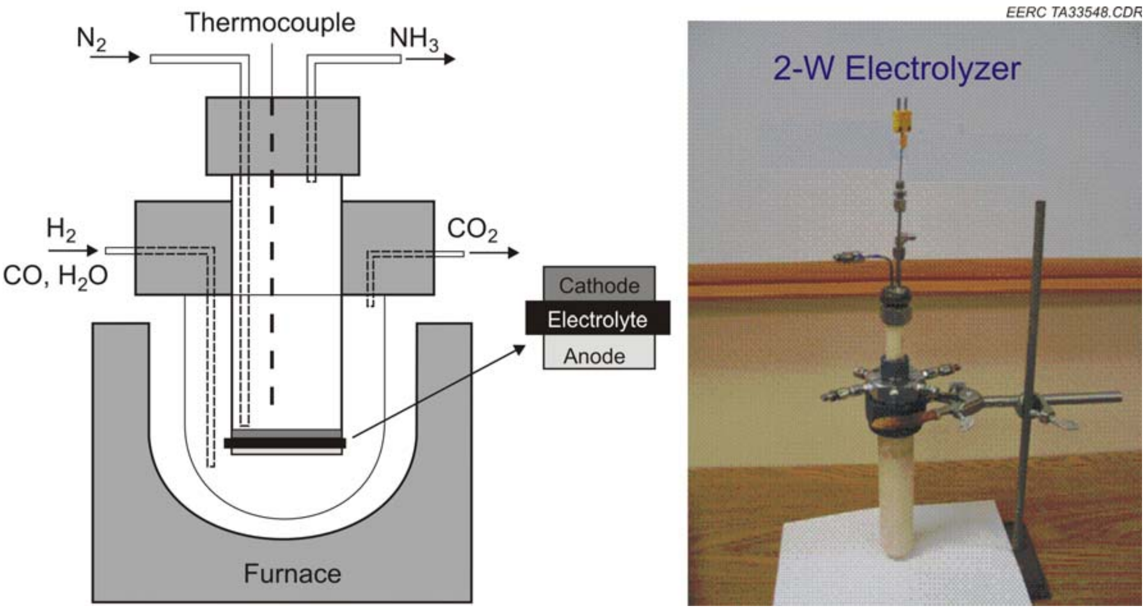

Figure 2. Schematic diagram (left) and image (right) of electrolysis cell.

unreacted N_2 was purged through a solution of 0.5 M sulfuric acid and was then vented. High-purity hydrogen or a mixture of water vapor and high-purity carbon monoxide used as a hydrogen resource is introduced to the anode chamber. All current-controlled or potential-controlled electrolysis was performed using an Autolab general purpose electrochemical system (Ecochemie, Netherlands).

Evaluation of Cathode Catalysts

It is commonly accepted that the dissociative adsorption of N≡N on catalyst surfaces is the rate-limiting step for both cathodic hydrogenation of N_2 and thermal hydrogenation of N_2. In this research, initial evaluation of cathode catalysts was based on a thermal catalysis approach, which is shown schematically in Figure 3. During each measurement, 0.1–0.3 g catalyst was placed in a continuous-flow microreactor with a volume of 1 mL and secured in place using quartz wool. A mixture of hydrogen and nitrogen in a molar ratio of 3:1 was passed through the reactor at GHSV = 7200 h-1, and the product ammonia in the outlet gas was captured using a solution of 0.5 M sulfuric acid.

Analysis of Products

The product ammonia in the outlet gas was captured using a solution of 100 mL 0.5 M sulfuric acid and analyzed by an ammonium ion-selective electrode (Cole-Parmer Instrument Company). Current efficiency was calculated from the ratio of the theoretical charge required by the formation of measured product to the total charge input, assuming the electron number transferred per molecules corresponding to the formation of ammonia is 3.

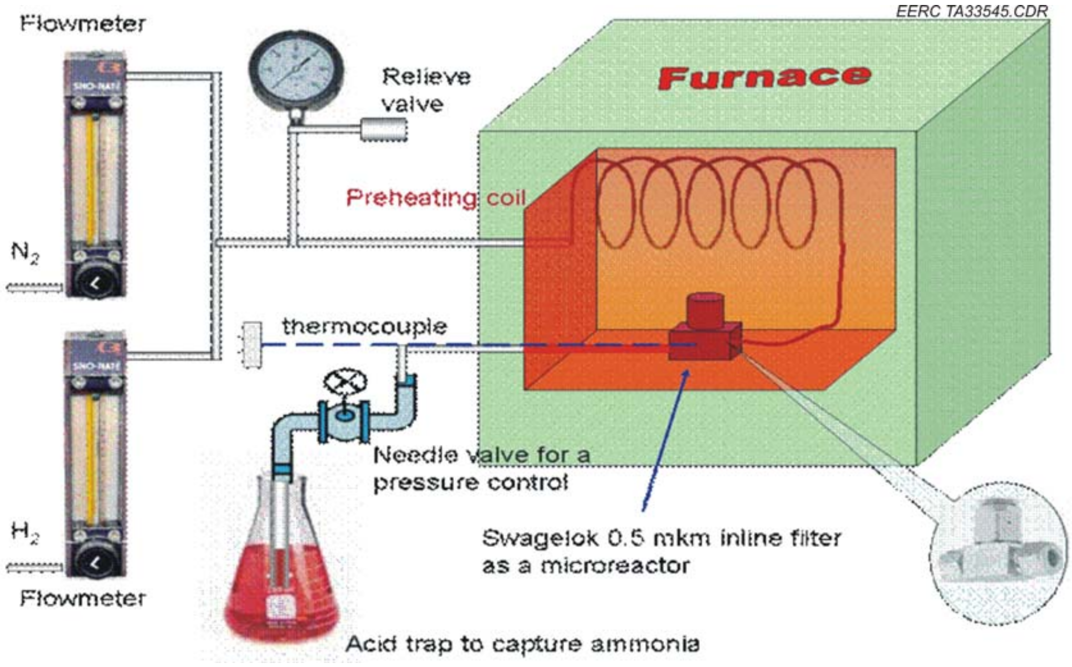

Figure 3. Schematic diagrams for fast evaluation of ammonia production catalysts.

RESULTS AND DISCUSSION

Development of Ammonia Production Catalysts

At the cathode, the hydrogenation of N_2 is the target reaction and hydrogen evolution is the main competitive reaction. To achieve high current efficiency of ammonia, promising catalysts should possess high activity for ammonia formation and high overpotential for hydrogen evolution reaction. Traditionally an iron-based catalyst with magnetite has been widely used in the industrial process of ammonia synthesis. But the use of this class of catalyst requires critical operating conditions including high pressure and high temperature. Taking into account tendencies to lower the applied pressure and reduce energy consumption, it is of urgent importance to develop new catalyst systems that can work at lower pressure and/or lower temperature at no cost of activity. This proposed research was to develop a non-iron-based catalyst system for the electrolytic ammonia process. Our research efforts have been focused on the following:

1) Evaluating a range of single elemental and bimetallic non-iron-based catalysts for the ammonia process, then identifying promising candidates

2) Investigating high-surface metal oxides and carbon materials as electronically conductive supports

3) Optimizing surface promoters based on alkaline metal salts to improve catalyst activities

4) Improving the dispersion of catalysts on the supports by developing new approaches and optimizing preparation conditions

5) Optimizing reaction conditions including temperature, pressure, and reactant inputs

Figure 4 shows that the introduction of surface promoters and the use of support are very effective for the development of highly efficient catalysts for ammonia production. Compared to unsupported catalyst (A), the surface modification of A with promoter (B) could increase the activity by around 40. Further substantial increase in activity is achieved by the combined efforts of the introduction of the promoter and use of catalyst support (C). One example is that the activity is increased by a factor of around 1540 by comparing A + B + C1 to A.

Development of Electrolyzer Components

Important for the electrolytic process of nitrogen fertilizers is the development of components including anode, cathode, and electrolyte membranes and their integration. At the anode side, single-metal-based catalysts have been evaluated as the catalytic system since they have demonstrated high activity and stability for the electrochemical oxidation of H_2 and CO in the temperature range of our interest. At the cathode side, the catalyst system used is a composite of a single metallic element, surface promoter, and conductive support. Because there is no

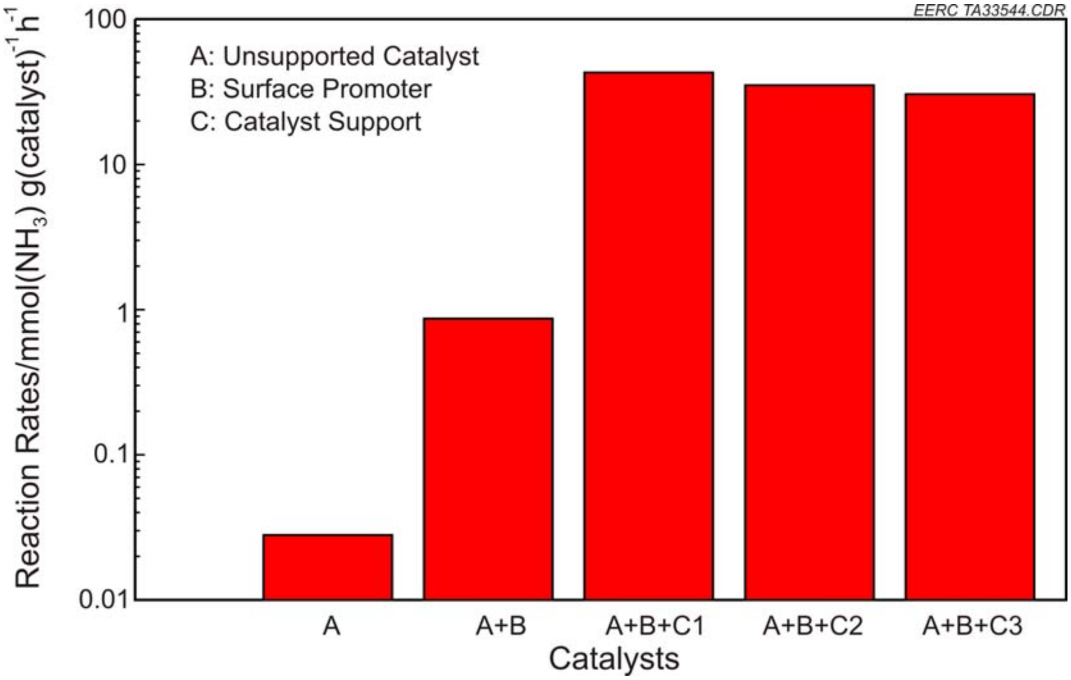

Figure 4. Comparison of catalytic activity of five catalysts toward ammonia production at 400°C and 15 psi. A: unsupported catalyst; B: surface promoter; C: catalyst support.

suitable solid electrolyte membrane materials available in the temperature range of our interest, our initial efforts have been focused on the evaluation of salt-based electrolyte systems fixed in a ceramic matrix. For the preparation of a thin-film ceramic matrix, we have used a tape-casting approach that normally includes highly dispersed ceramic powder in flowing vehicles and casting of the resultant ceramic paste onto a smooth substrate. We have examined the chemical stability of a couple of ceramic powders and have identified one stable ceramic powder for the preparation of a thin-film matrix. Flexible and uniform ceramic tapes have successfully been prepared upon the optimization of formula and casting procedure. Similarly, we have successfully prepared electronically conductive tapes using metallic powders in place of ceramic powders. The ceramic and conductive tapes could be punched or cut into shape for further treatment. Figure 5 shows the images of tape stripes, disks, and patches of conductive elements (dark gray) and ceramic elements (white).

Further treatment of both ceramic and conductive tapes mainly refers to the firing of the tapes without deformation by controlling heating rate, firing temperature, and firing atmosphere. Porous electrode discs and a porous ceramic disc with good mechanical strength have been prepared and evaluated. At the cathode side, we have used the porous electrode as a substrate to support cathode catalysts newly developed. At the anode side, the porous electrode prepared via tape casting is directly used as the cathode. The porous ceramic tape sandwiched between the cathode and anode is evaluated after the firing treatment and the introduction of the electrolyte component. We have examined gas permeability of MEA based on the change of open-circuit potential (OCP) by introducing H_2 through the anode chamber and O_2 through the cathode

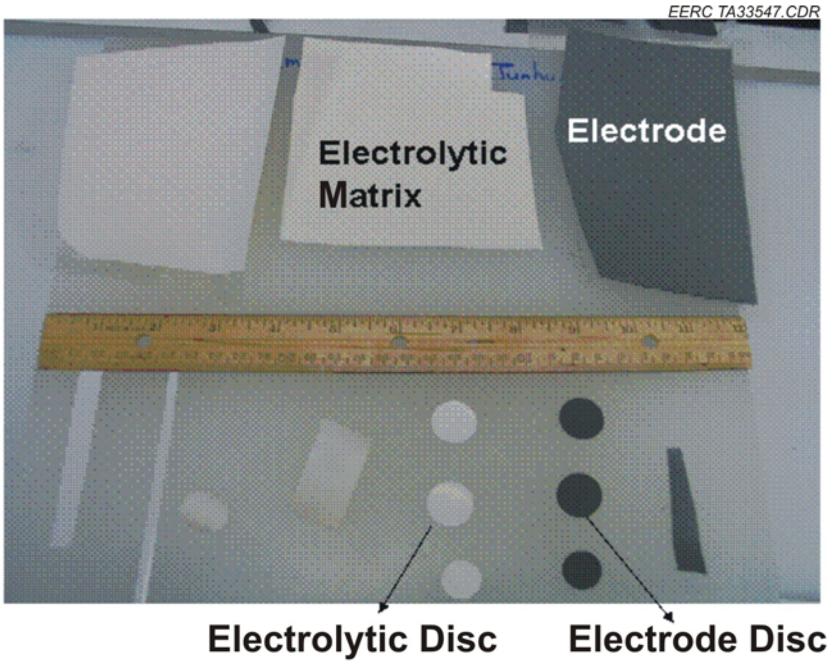

Figure 5. Images of ceramic (white) and conductive (dark gray) tapes prepared using a tape-casting method.

chamber. The OCP value is measured as being around 1.08 V, very close to 1.18 V of a theoretical value under the same conditions. This means that the electrolyte component could satisfactorily fill in all pores of the ceramic matrix, and the MEA has acceptable gas impermeability.

Preparative Electrolysis and Process Optimization

Process optimization work has been focused on improving process efficiency and decreasing energy consumption for ammonia production via the following efforts:

- Evaluating supported and unsupported catalyst systems for the electrolytic ammonia process, which demonstrated high activity toward the thermal hydrogenation of N_2.
- Examining different electrolyte systems.
- Assessing the impact of reaction temperature, reaction pressure, reactant feed rate, and electrolysis mode on process efficiency and energy consumption.

Key results of the process optimization work are shown in Figure 6. For the purpose of comparison, the results obtained using humidified carbon monoxide and hydrogen as the anode feedstock are included. It is clearly seen that the current efficiency for the ammonia formation using the humidified carbon monoxide is comparable to that using hydrogen under the same

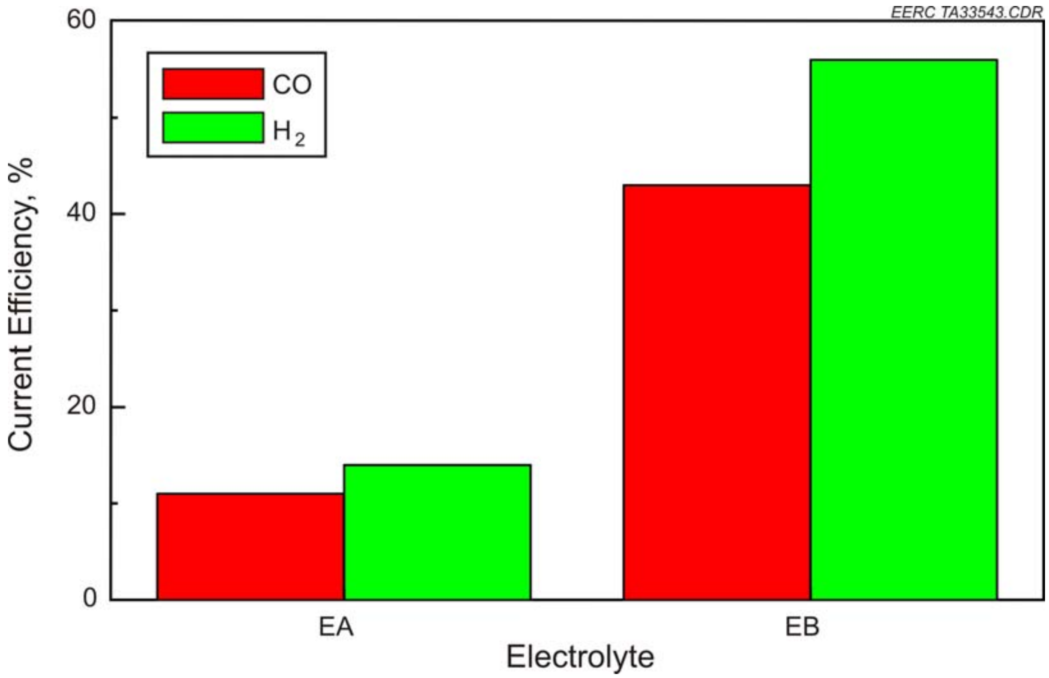

Figure 6. Comparison of currency efficiencies for the cathodic formation of ammonia with EA and EB as electrolyte components, respectively. All electrolysis was run for 3600 in a constant-current mode at 400°C and 1 atm, with N_2 purging through the cathode chamber.

conditions, although the former is a little lower. When the electrolyte component EA is used, the current efficiency is around 11%. This value could be increased to around 43% as the electrolyte component EA is replaced by another electrolyte component EB. We have examined the possibility of using solid-proton conductors based on doped metallic oxides for the ammonia process. But high resistance of the resultant proton membranes in the temperature range of our interest prevents their application to the electrolytic ammonia process. Different classes of proton conductors will be further examined in our lab.

CONCLUSIONS

An electrochemical process that utilizes inputs of electricity, N_2 extracted from air, and syngas produced via the gasification of coal or biomass to produce nitrogen fertilizer ammonia was proven technically feasible. This feasibility demonstration provides an important way to directly utilize syngas generated via coal or biomass gasification rather than the high-purity hydrogen required for Haber–Bosch-based production of the fertilizer for the production of the widely used nitrogen fertilizers. Because the electrolytic processes can use a syngas comprising any combination of carbon monoxide and hydrogen, the cost of this “hydrogen-equivalent” input is significantly lower than the cost of the high-purity hydrogen. The status of the electrochemical ammonia process developed at the EERC is characterized by a current efficiency of 43% using humidified carbon monoxide as a feedstock to the anode chamber and a current efficiency of 56% using high-purity hydrogen as the anode gas feedstock. The economic competitiveness of the electrochemical urea process strongly depends upon the cost of hydrogen gas and the cost of electricity, as described in Appendix A. Further optimization of the electrolytic process for higher current efficiency and decreasing energy consumption continues in our laboratory at the EERC.

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APPENDIX A

PRELIMINARY ECONOMIC ANALYSIS OF ELECTROCHEMICAL NITROGEN FERTILIZER PRODUCTION USING ELEMENTAL NITROGEN

PRELIMINARY ECONOMIC ANALYSIS OF ELECTROCHEMICAL NITROGEN FERTILIZER PRODUCTION USING ELEMENTAL NITROGEN

Preliminary estimates were developed for the cost of producing nitrogen fertilizers via two electrochemical processes. Both processes are conducted at atmospheric pressure and an intermediate temperature of 200°–400°C and utilize inputs of elemental nitrogen and syngas. Cost projection were conducted for the electrochemical production of 1) ammonia from N_2 and syngas and 2) urea from N_2 and syngas.

As shown in Tables A-1–A-2, based on these preliminary estimates, both urea and ammonia production processes using syngas as the hydrogen source offer potential market viability, primarily because the direct use of syngas considerably decreases the cost of hydrogen input. Assuming an electricity cost of $0.05 per kilowatt-hour (kWh), the projected cost for electrochemical ammonia production is $565/ton, using $8/MMBtu versus the market price of around $650/ton in March 2008. Similarly, the projected cost of electrochemical urea production is $404/ton using syngas of $8/MMBtu in cost, versus the market price of $475/ton in March 2008. The production cost could be further decreased to around $351/ton with $4/MMBtu syngas as the hydrogen source.

Table A-1. Cost Projection for Per-Ton Ammonia Electrochemical Production from N_2 and Syngas (urea production reaction: N_2 + $3CO + 3H_2O > 2NH_3 + 3CO_2$)

Syngas Price	$8/MMBtu[1]	$4/MMBtu
Electricity Price	$0.05/kWh[2]	$0.05/kWh
Cost of Electricity[3]	$322	$322
Cost of Syngas Input	$190	$95
Capital Cost	$21	$21
O&M Cost	$20	$20
Cost of N_2	$12	$12
Total Cost	$565	$470
Market Price Differential[4]	$85	$180

[1] Million Btu.
[2] Kilowatt-hour.
[3] Electricity consumption of 6450 kWh/ton anhydrous ammonia.
[4] March 2008 ammonia market price of $650/ton minus total cost.

Table A-2. Cost Projection for Per-Ton Urea Electrochemical Production from N_2 and Syngas (Urea Production Reaction: $N_2 + 3CO + 2H_2O > CO[NH_2]2 + 2CO_2$)

Syngas Price	\$8/MMBtu	\$4/MMBtu
Electricity Price	\$0.05/kWh	\$0.05/kWh
Cost of Electricity[1]	\$245	\$245
Cost of Syngas Input	\$106	\$53
Capital Cost[2]	\$21	\$21
O&M Cost	\$20	\$20
Cost of N_2	\$12	\$12
Total Cost	\$404	\$351
Market Price Differential[3]	\$71	\$124

[1] Electricity consumption of \$4900 kWh/ton urea.

[2] Based on capital cost for comparably sized water electrolysis system.

[3] March 2008 urea price of \$475/ton minus total production cost.