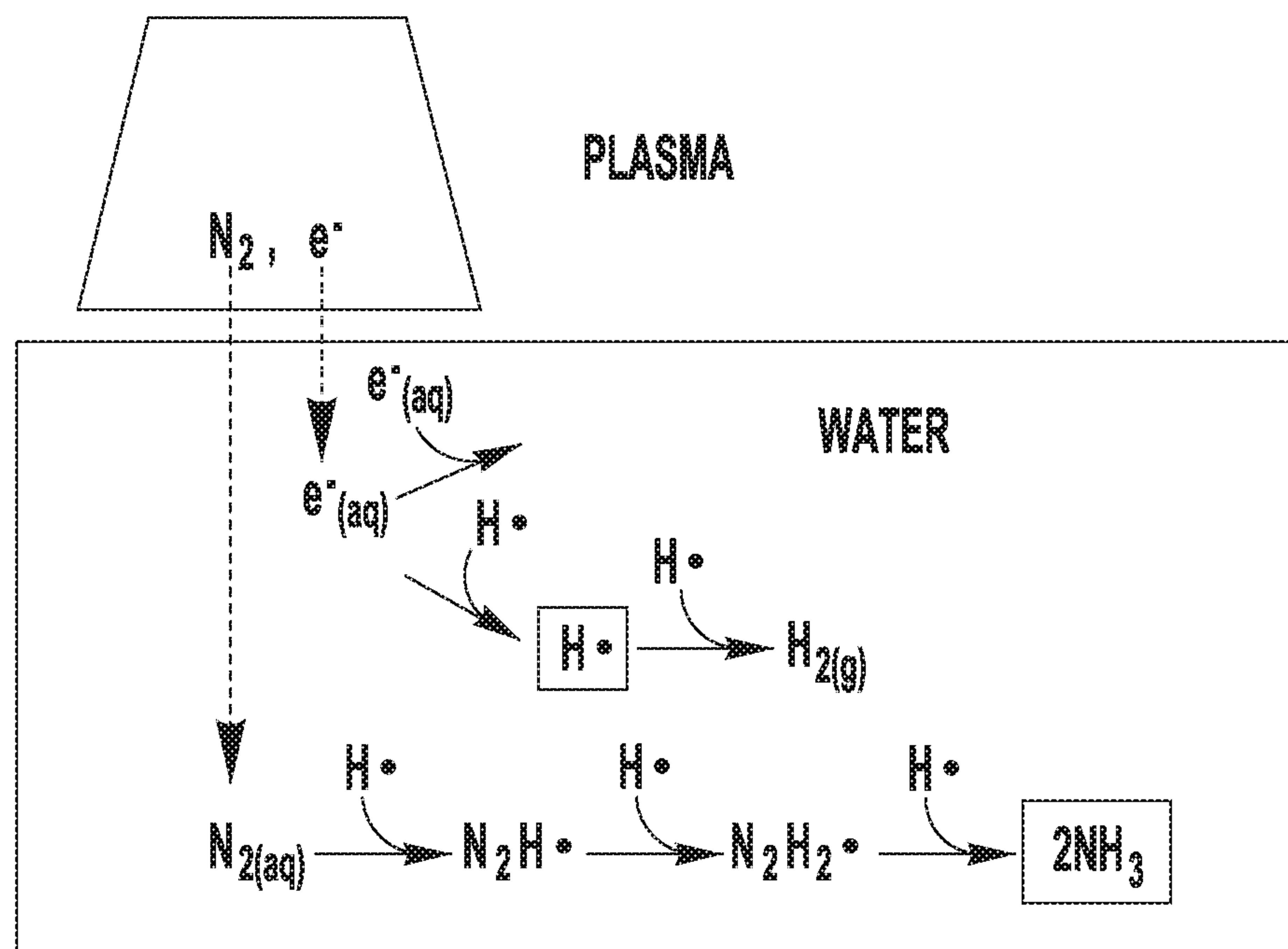




US 20230286820A1

(19) **United States**(12) **Patent Application Publication****Renner et al.**(10) **Pub. No.: US 2023/0286820 A1**(43) **Pub. Date: Sep. 14, 2023**(54) **AMMONIA SYNTHESIS USING PLASMA-PRODUCED ELECTRONS***C25B 11/061* (2006.01)
C25B 11/081 (2006.01)(71) Applicant: **Case Western Reserve University,**
Cleveland, OH (US)(52) **U.S. Cl.**
CPC *C01C 1/0494* (2013.01); *C25B 1/04*
(2013.01); *C25B 11/02* (2013.01); *C25B 11/061*
(2021.01); *C25B 11/081* (2021.01);
C25B 15/02 (2013.01)(72) Inventors: **Julie Renner,** Cleveland, OH (US); **R.**
Mohan Sankaran, Cleveland, OH (US)(21) Appl. No.: **18/321,404**(22) Filed: **May 22, 2023****Related U.S. Application Data**(62) Division of application No. 16/363,548, filed on Mar.
25, 2019, now Pat. No. 11,679,988.(60) Provisional application No. 62/647,021, filed on Mar.
23, 2018.**Publication Classification**(51) **Int. Cl.**
C01C 1/04 (2006.01)
C25B 1/04 (2006.01)
C25B 11/02 (2006.01)(57) **ABSTRACT**

A method of ammonia synthesis is described that includes contacting a nitrogen gas-containing plasma with an aqueous solution, thereby forming ammonia from the nitrogen gas and water. The nitrogen gas-containing plasma is present in an electrochemical cell. The electrochemical cell includes a container including an acidic liquid electrolyte. The electrochemical cell also includes a source of nitrogen gas, a metal electrode at least partially immersed in the electrolyte, a metal tube electrode spaced apart from a surface of the electrolyte by a predetermined spacing. The electrochemical cell is configured to provide a plasma spanning the predetermined space from the metal tube electrode to contact the surface of the electrolyte when power is applied to the metal tube electrode.



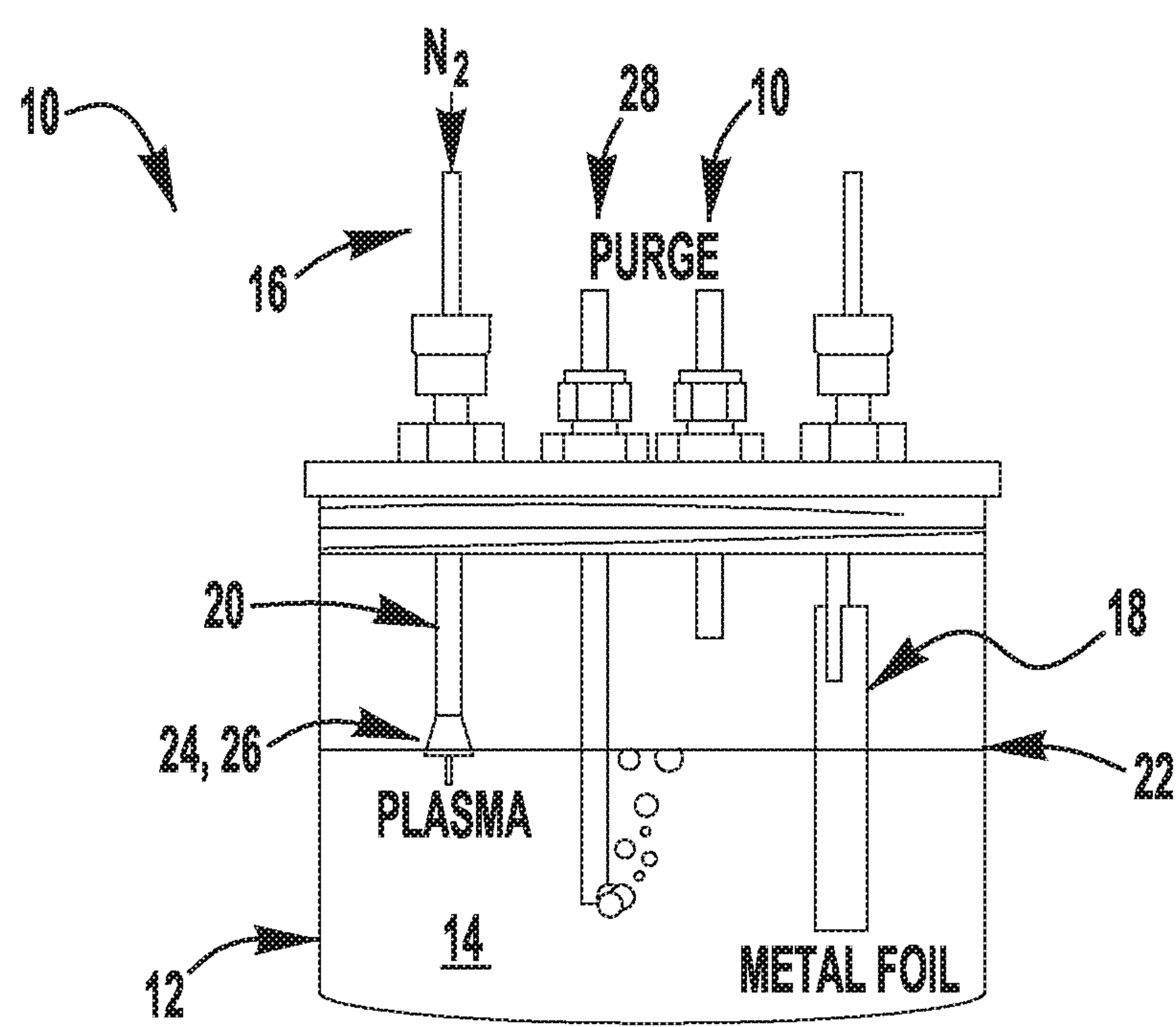


FIG. 1

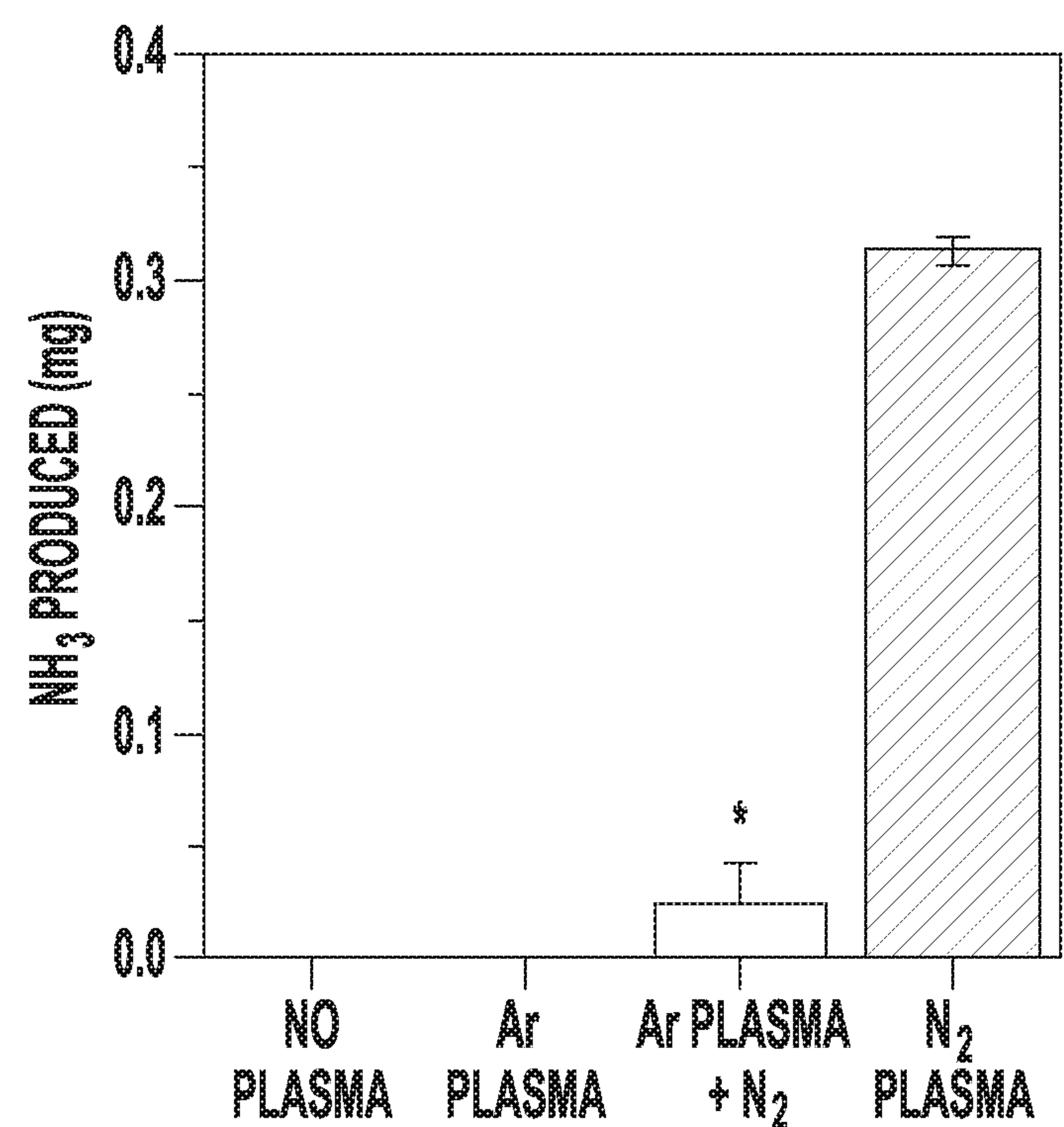


FIG. 2

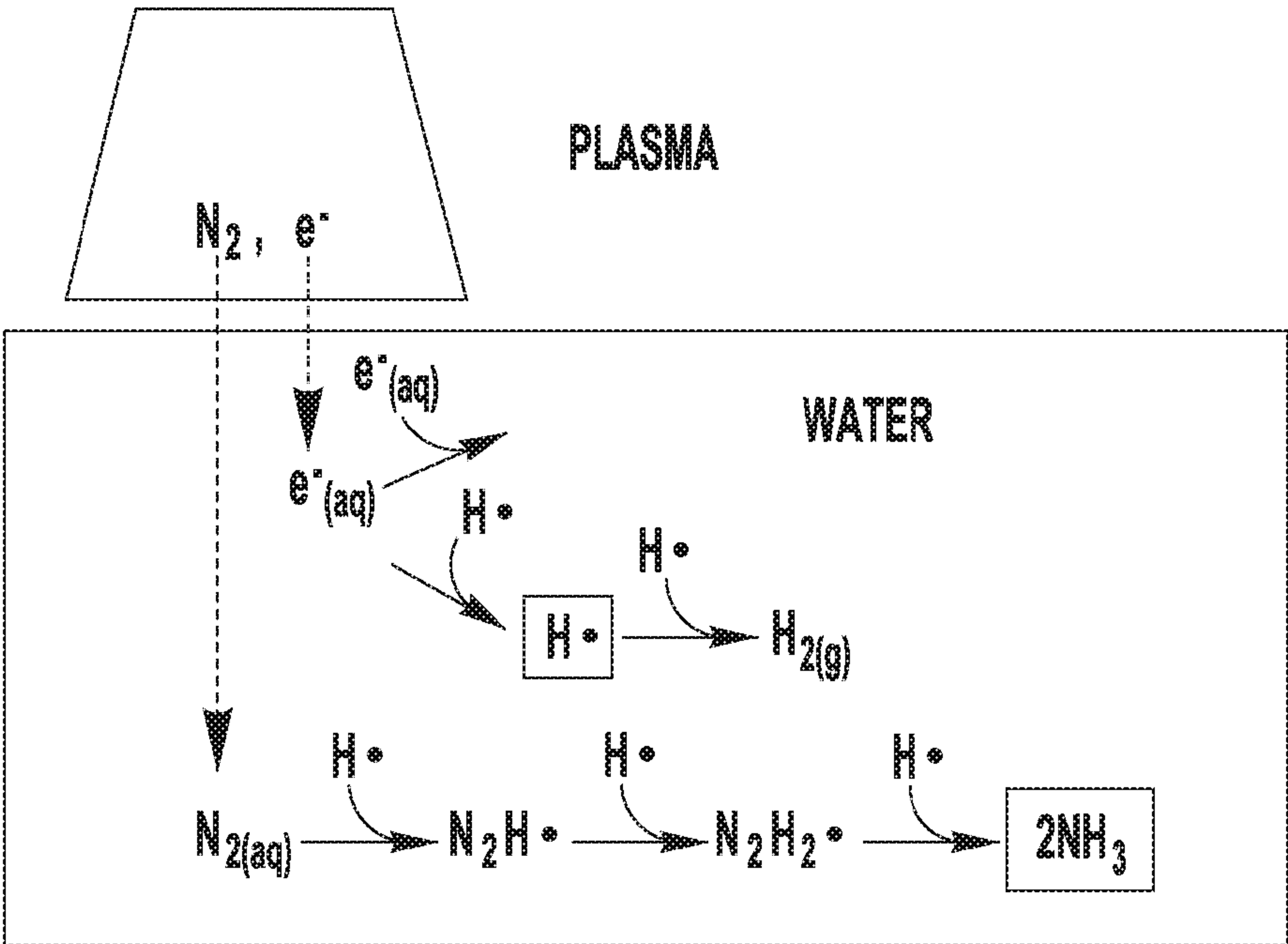


FIG. 3

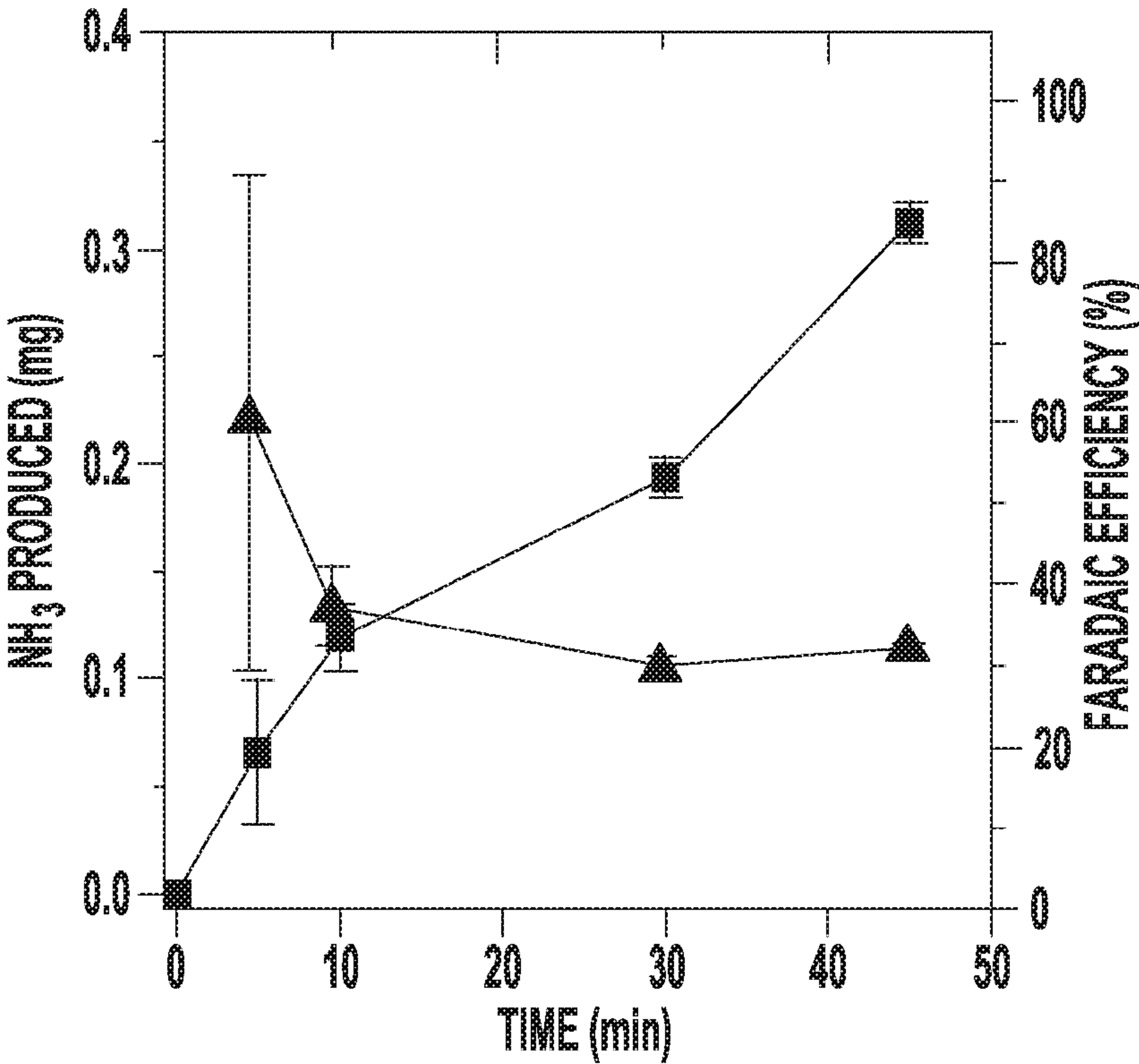


FIG. 4

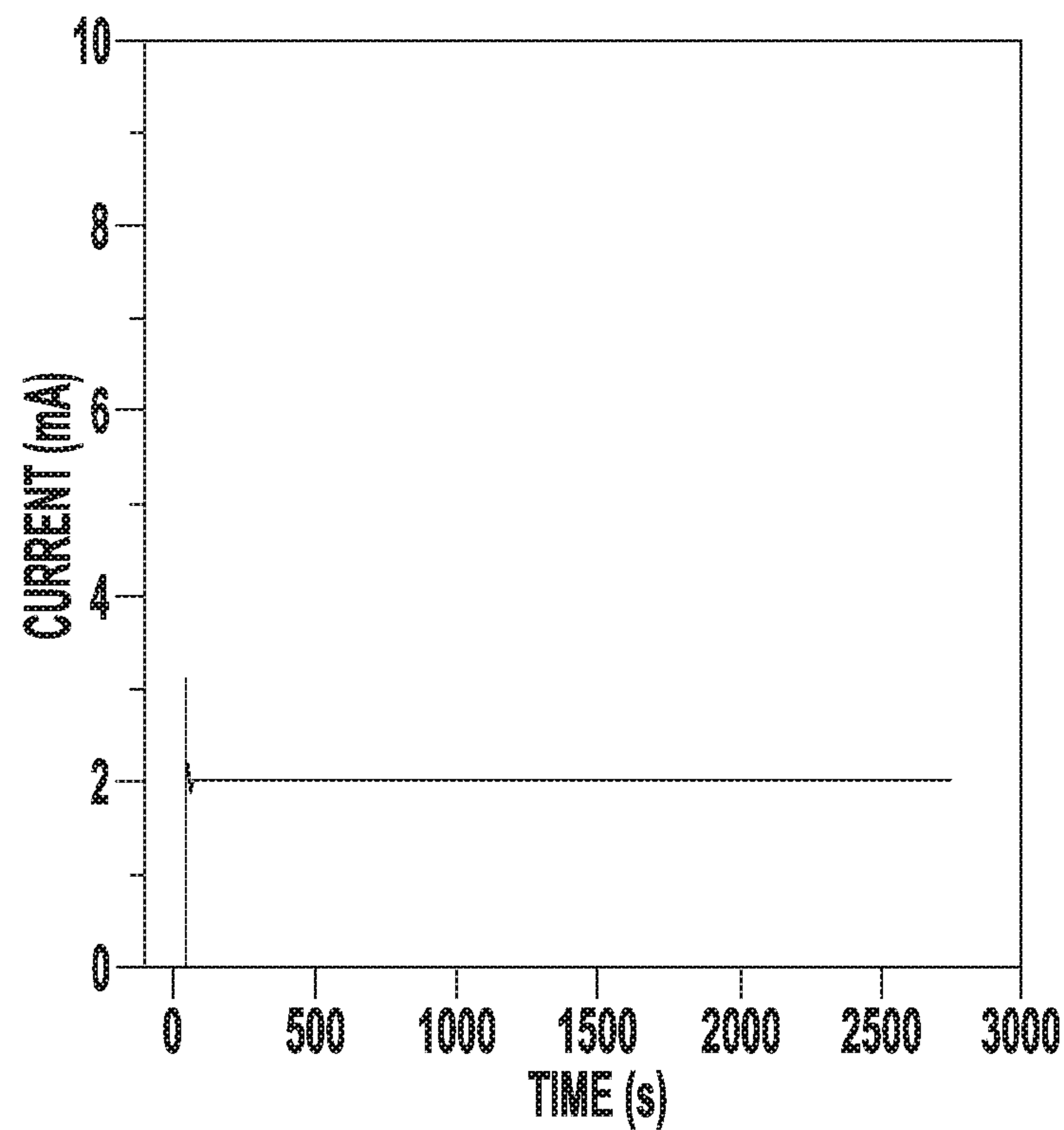


FIG. 5

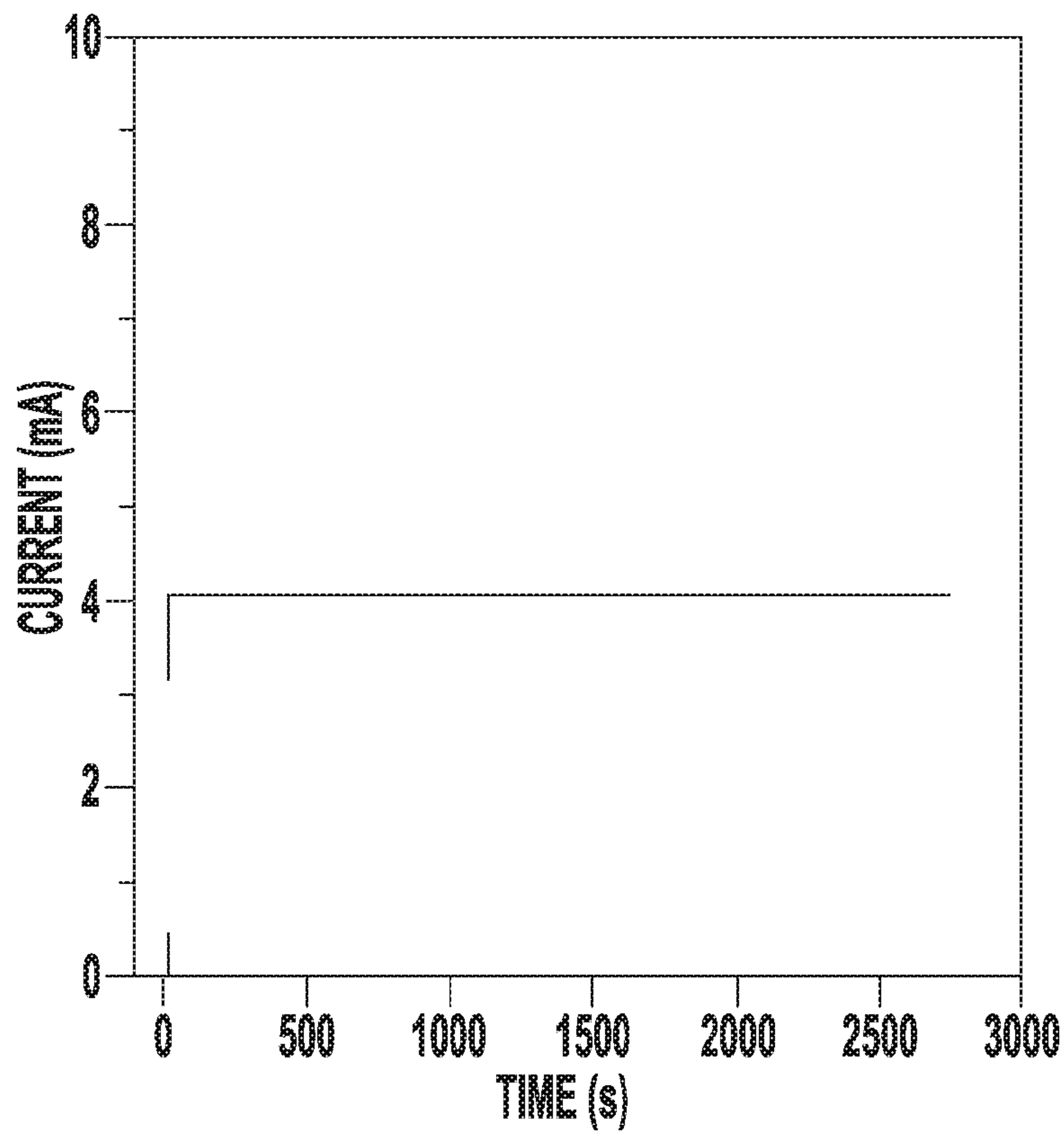


FIG. 6

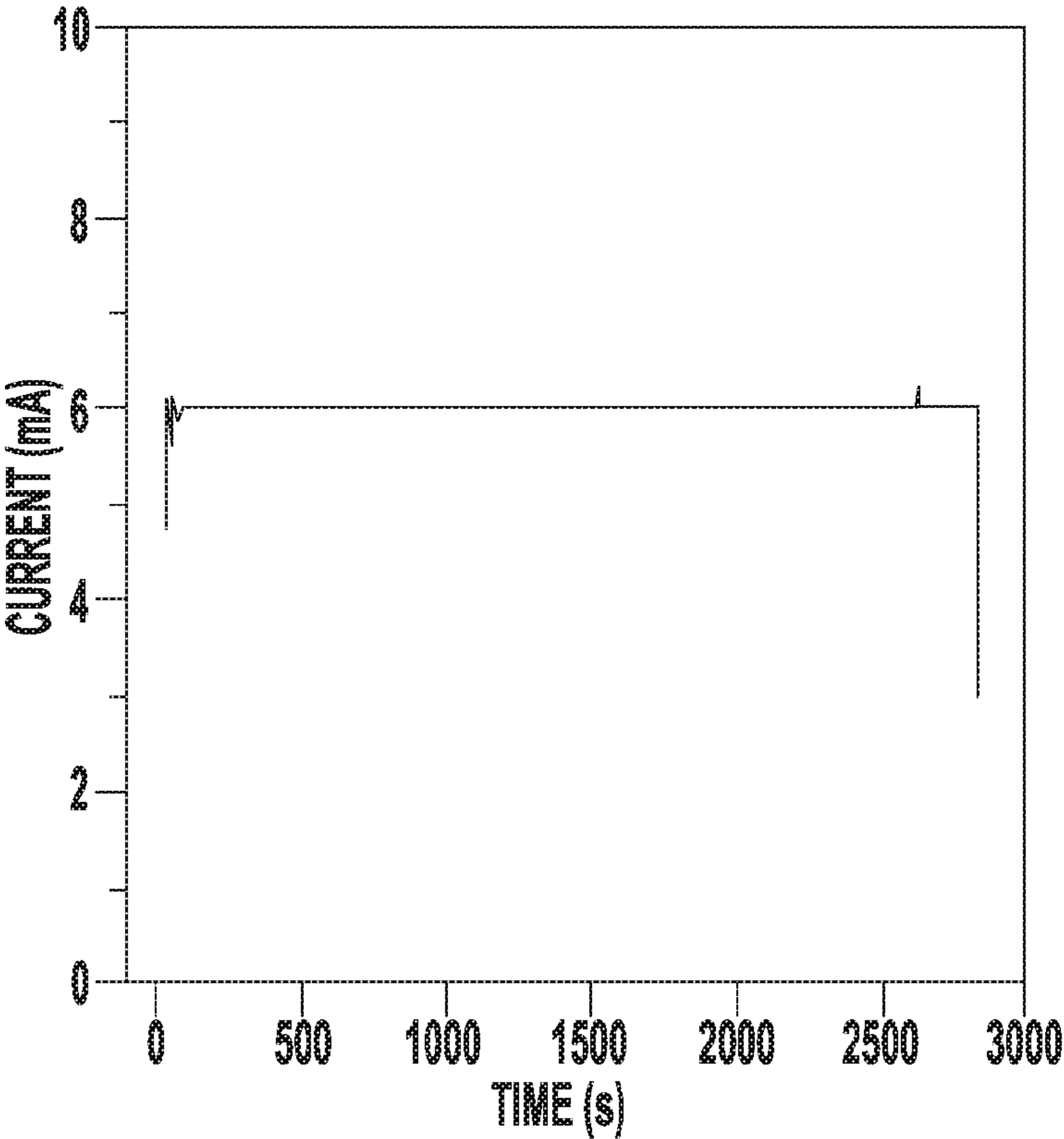


FIG. 7

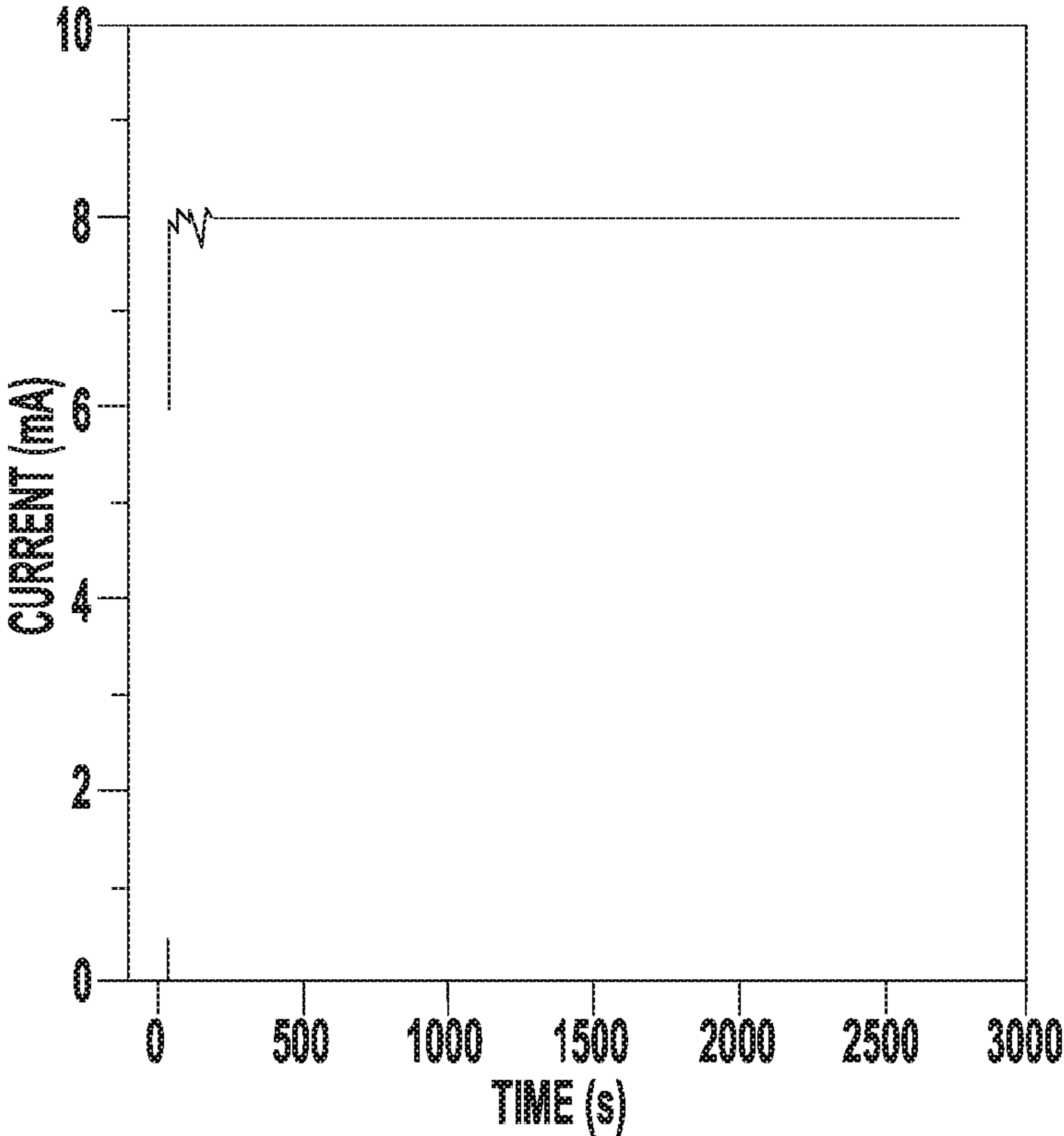


FIG. 8

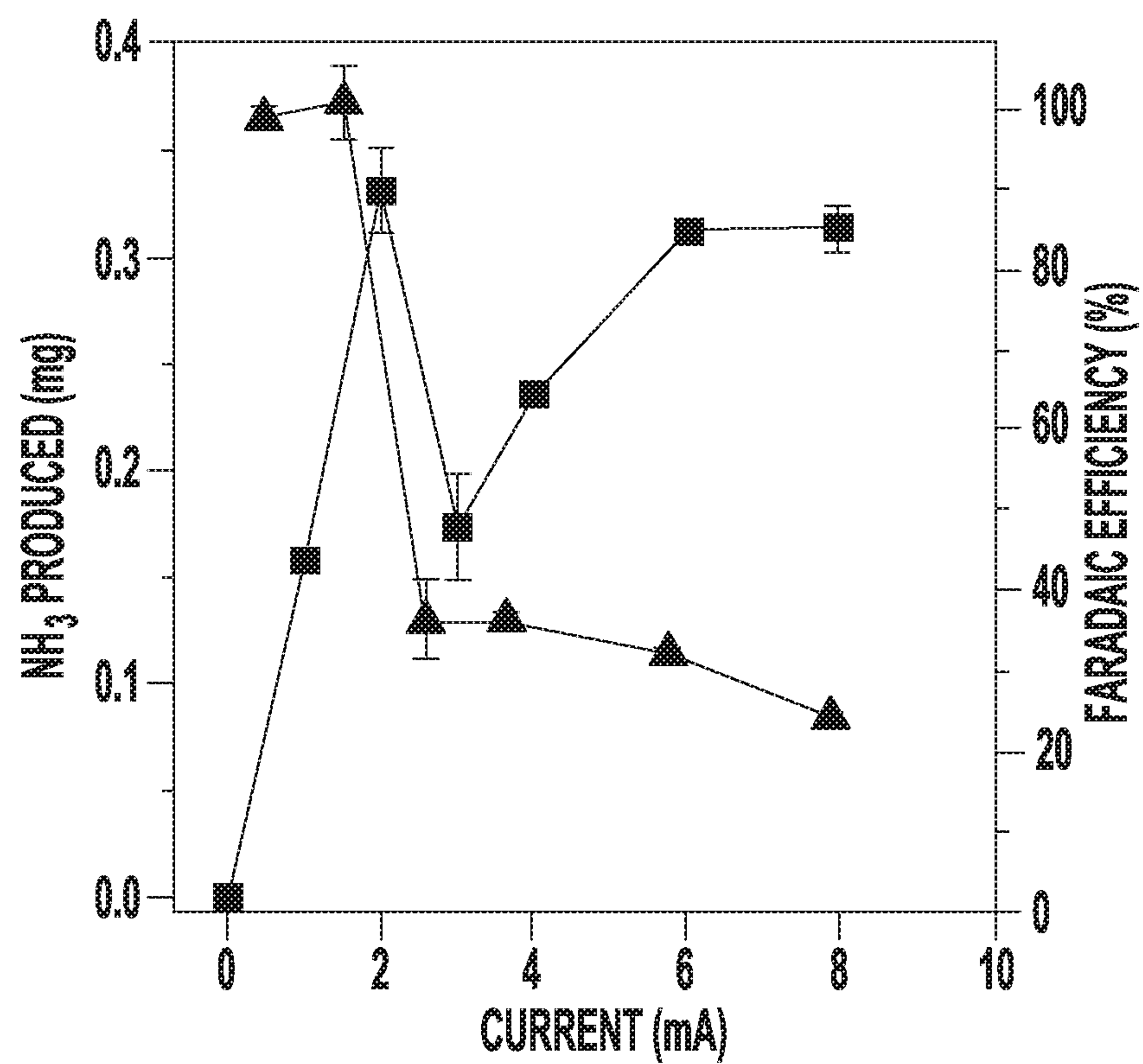


FIG. 9

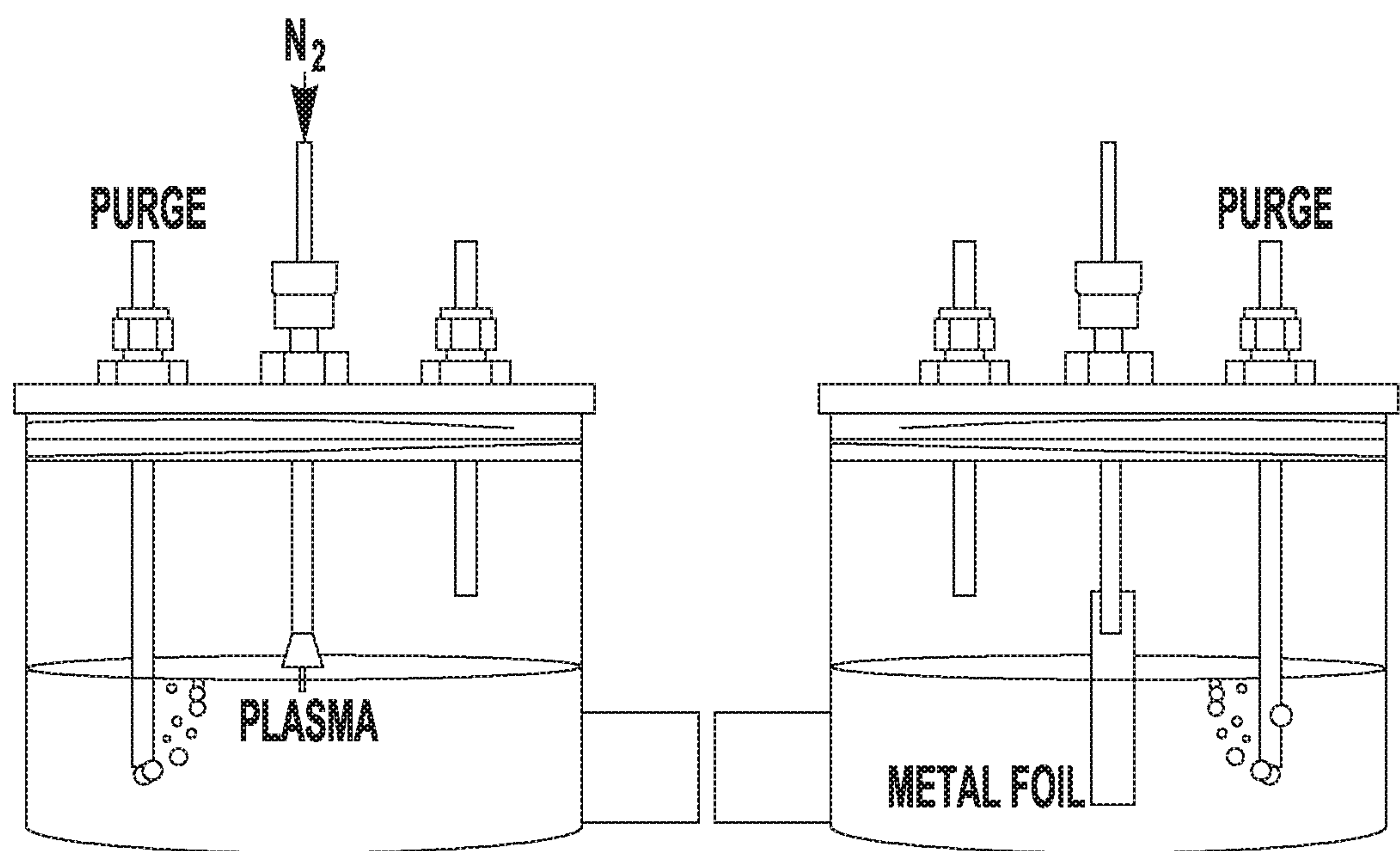


FIG. 10

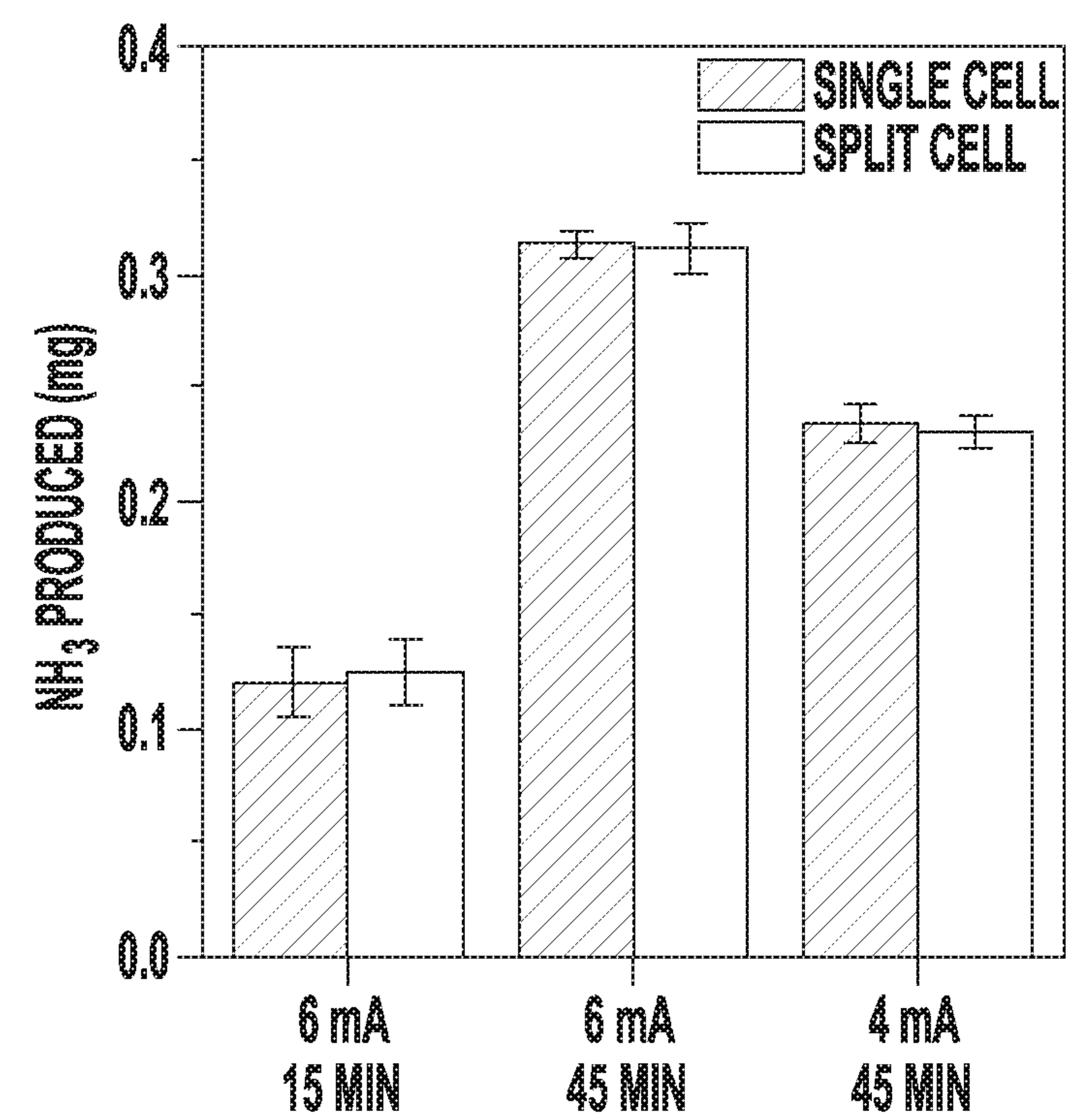


FIG. 11

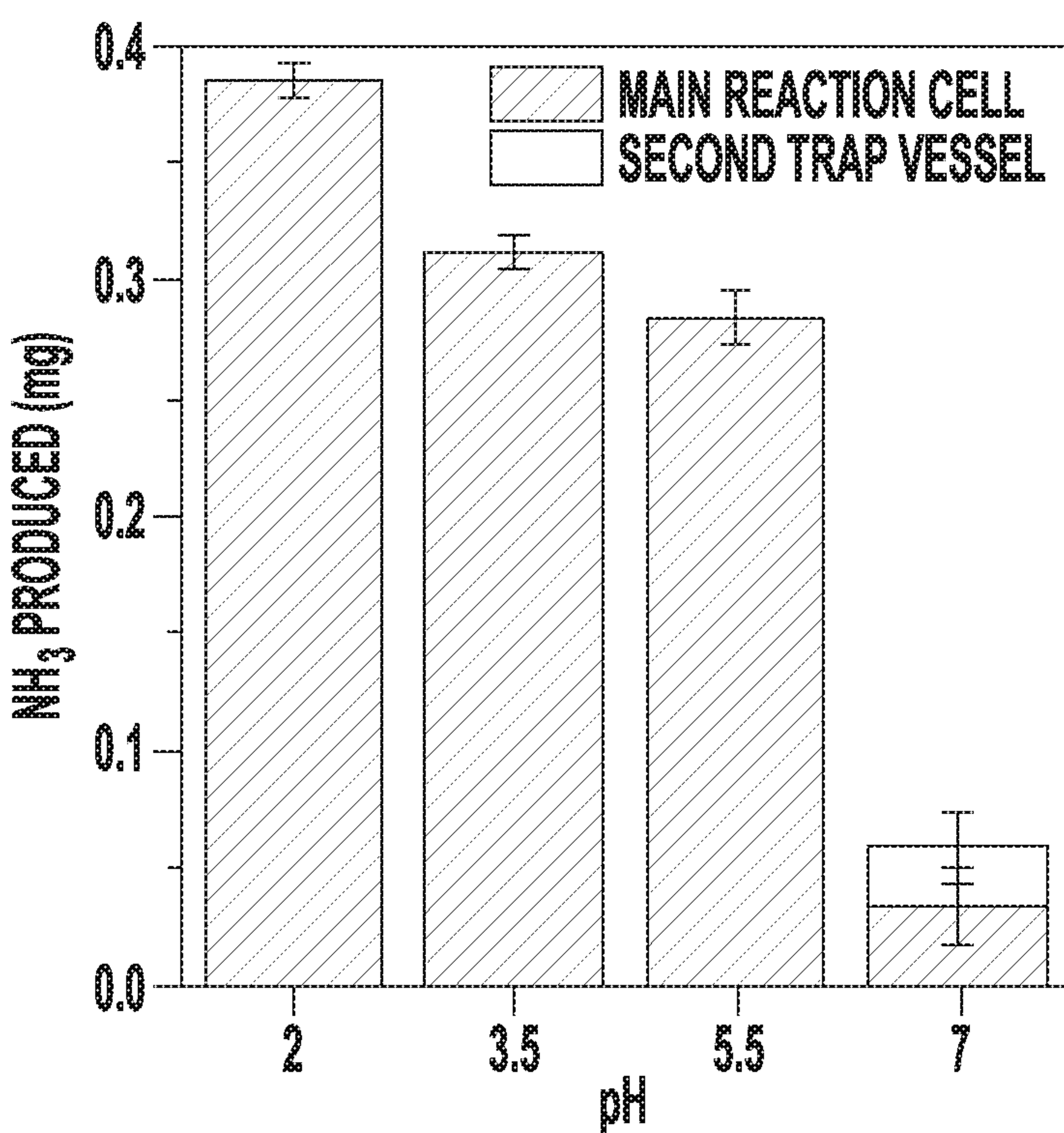


FIG. 12

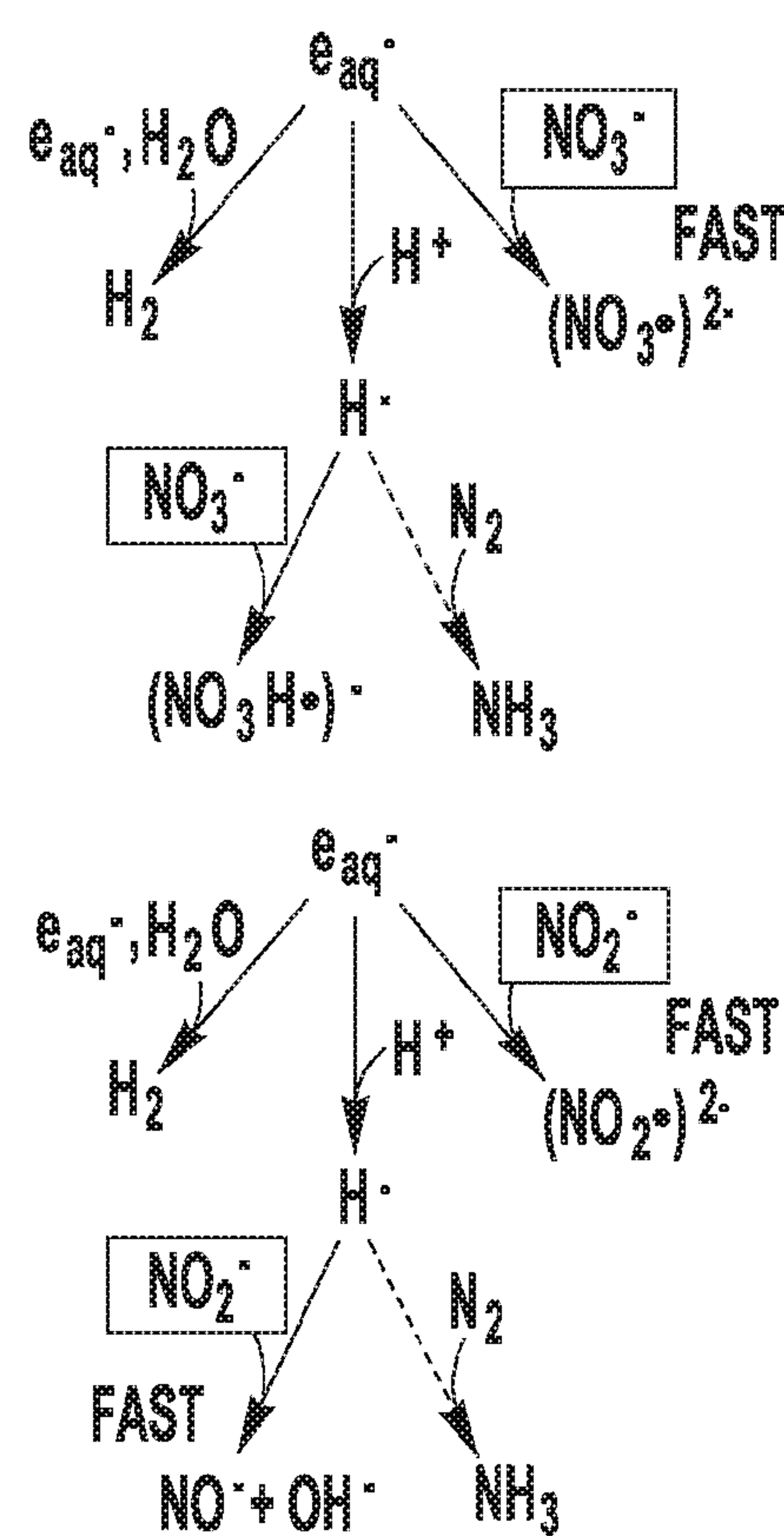


FIG. 13

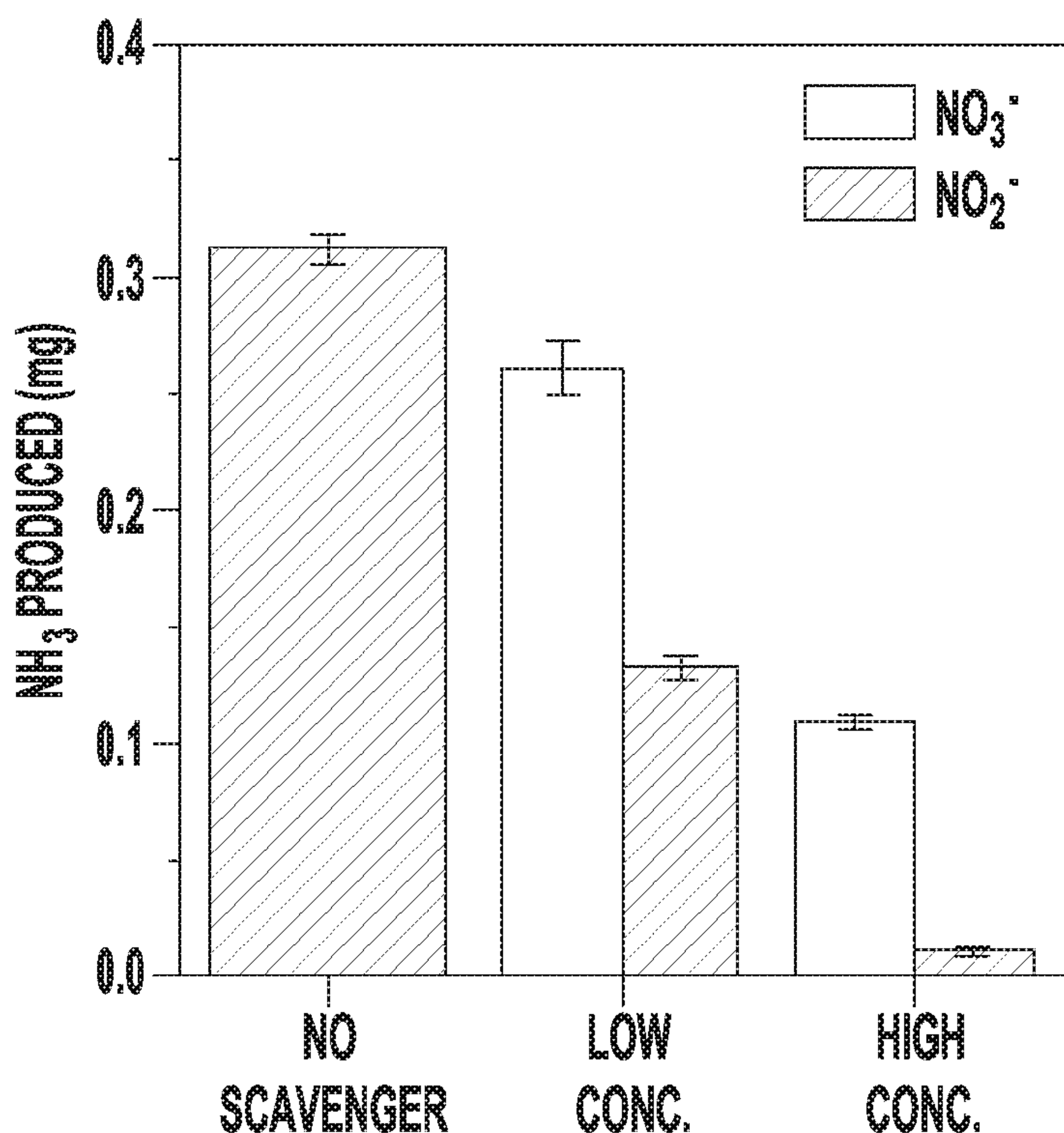


FIG. 14

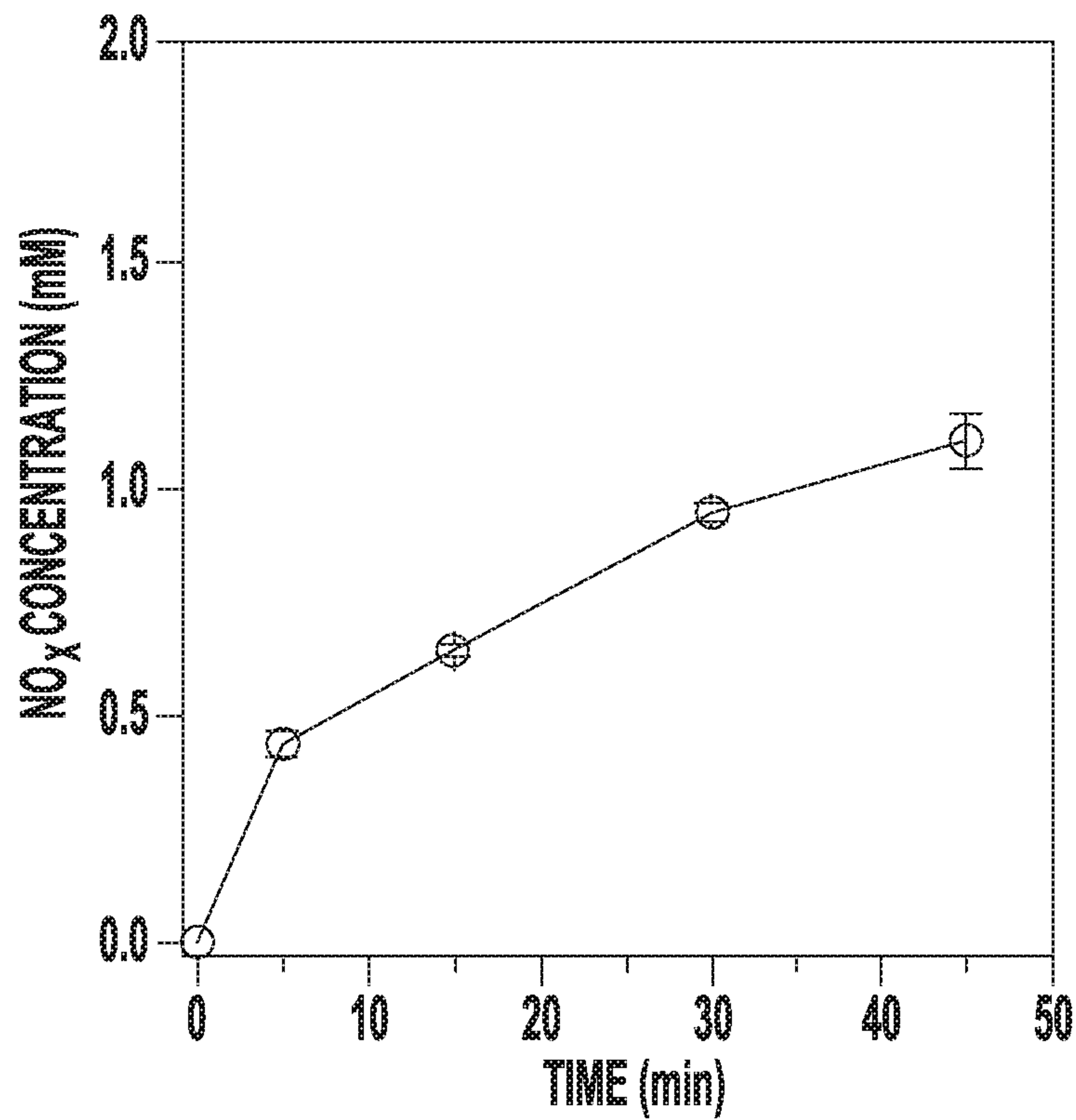


FIG. 15

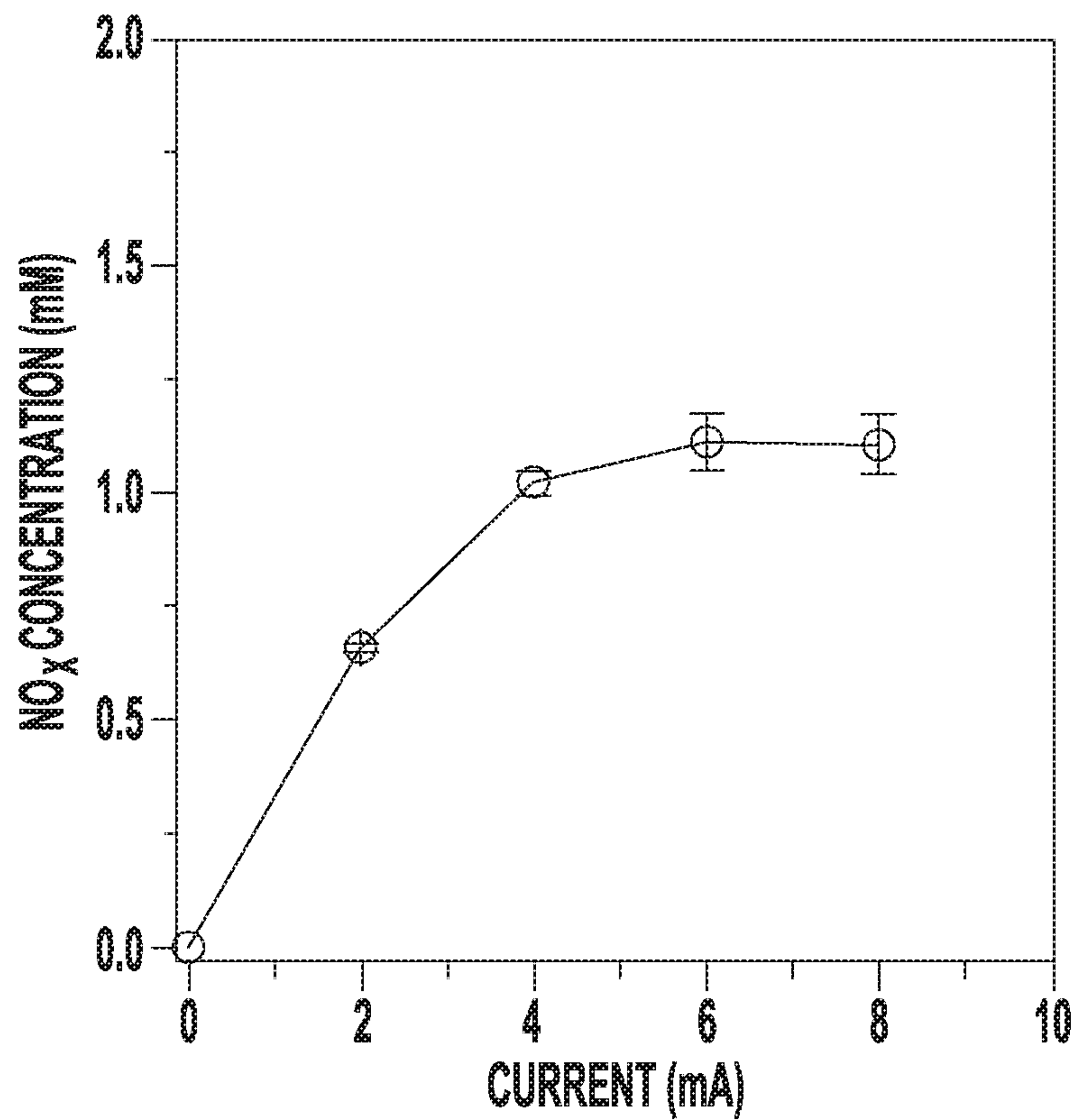


FIG. 16

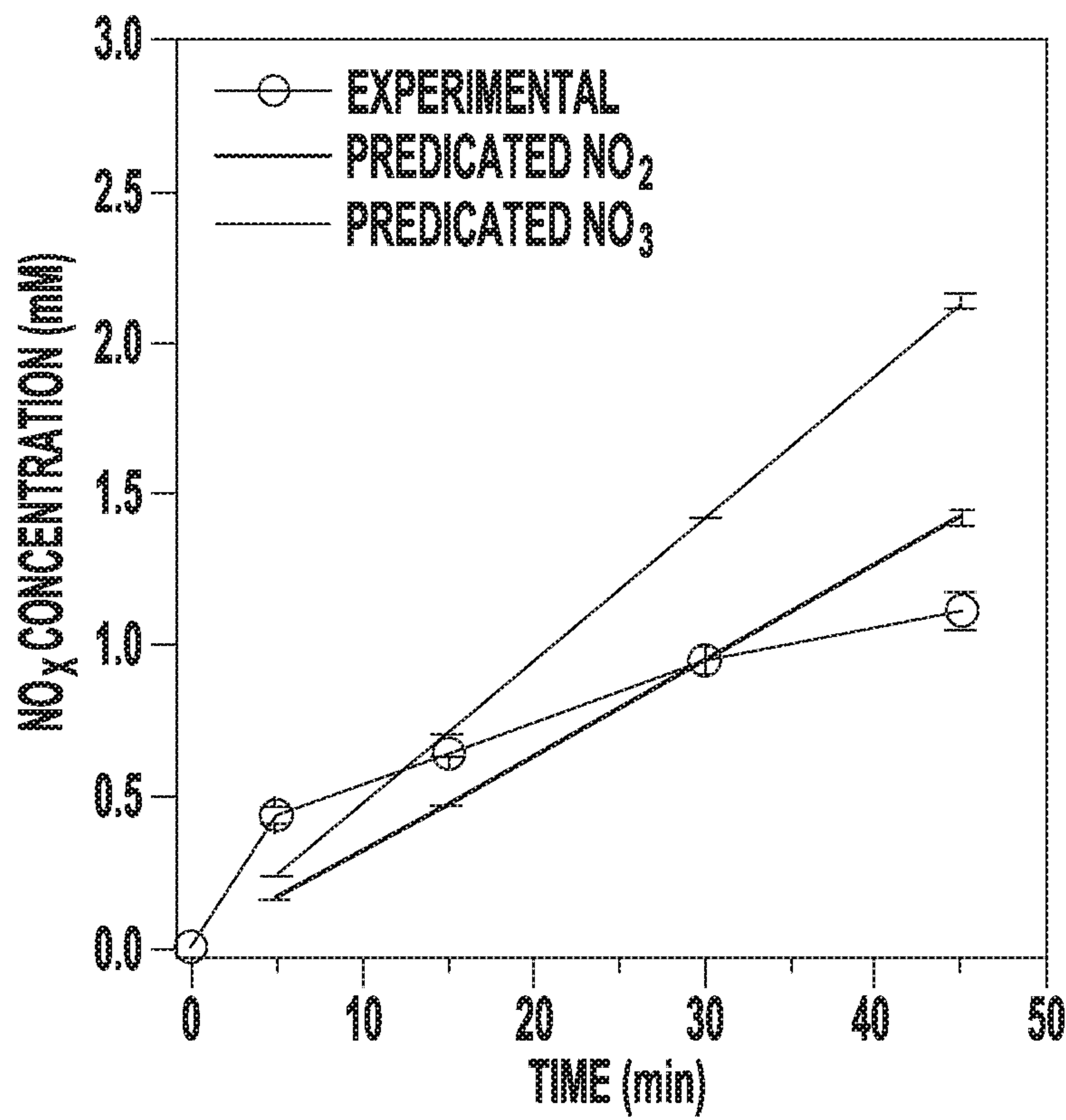


FIG. 17

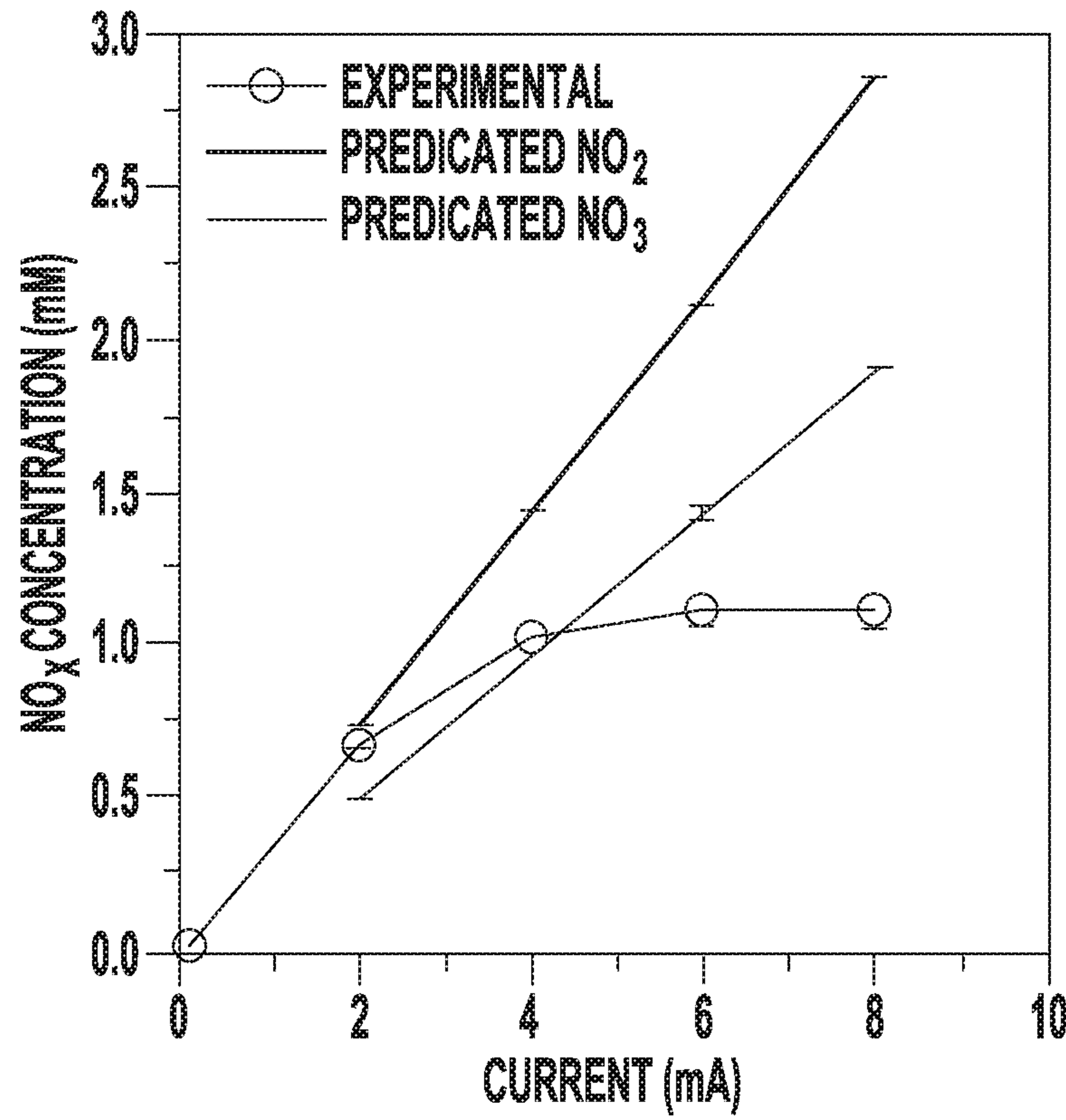


FIG. 18

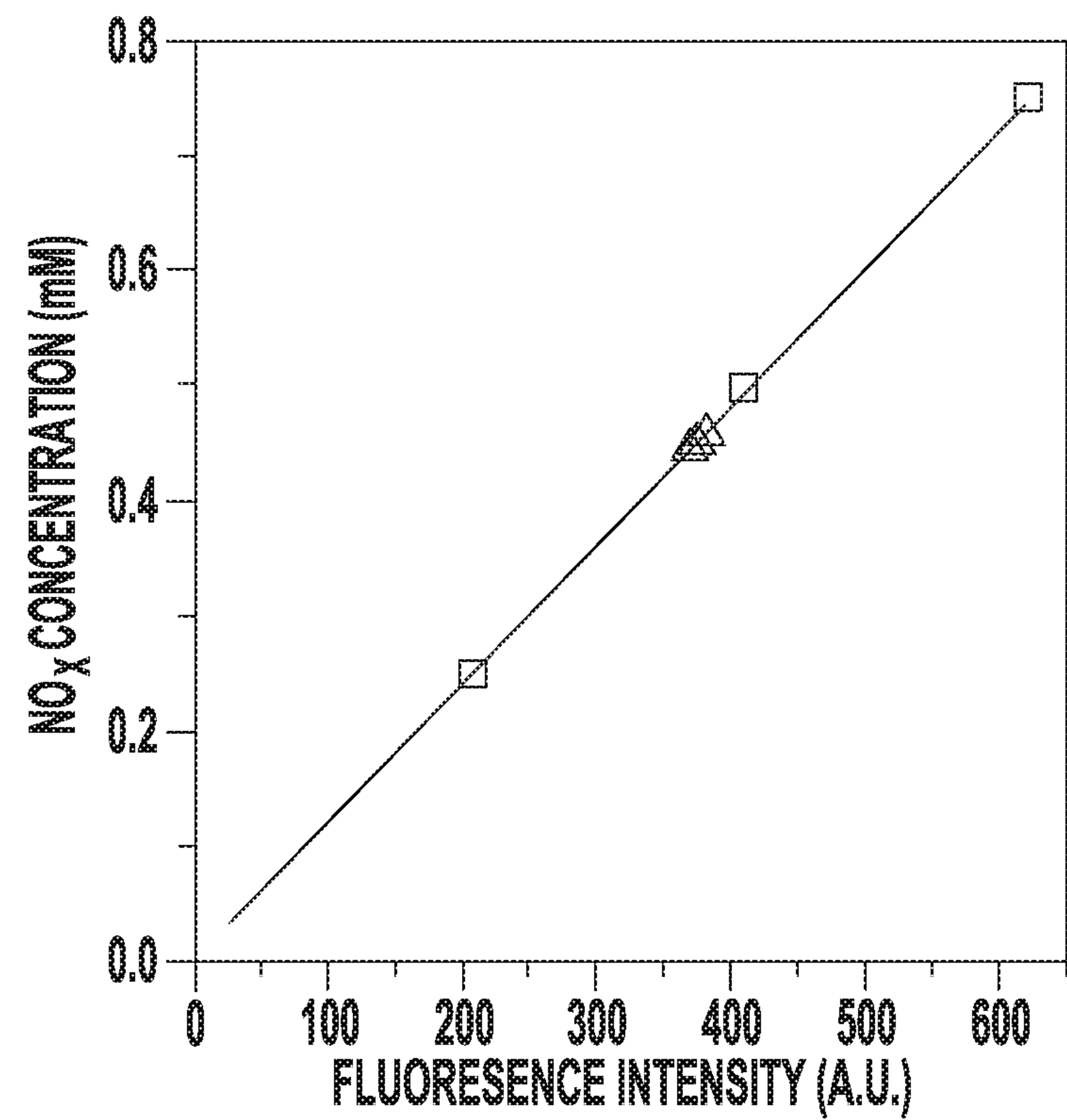


FIG. 19

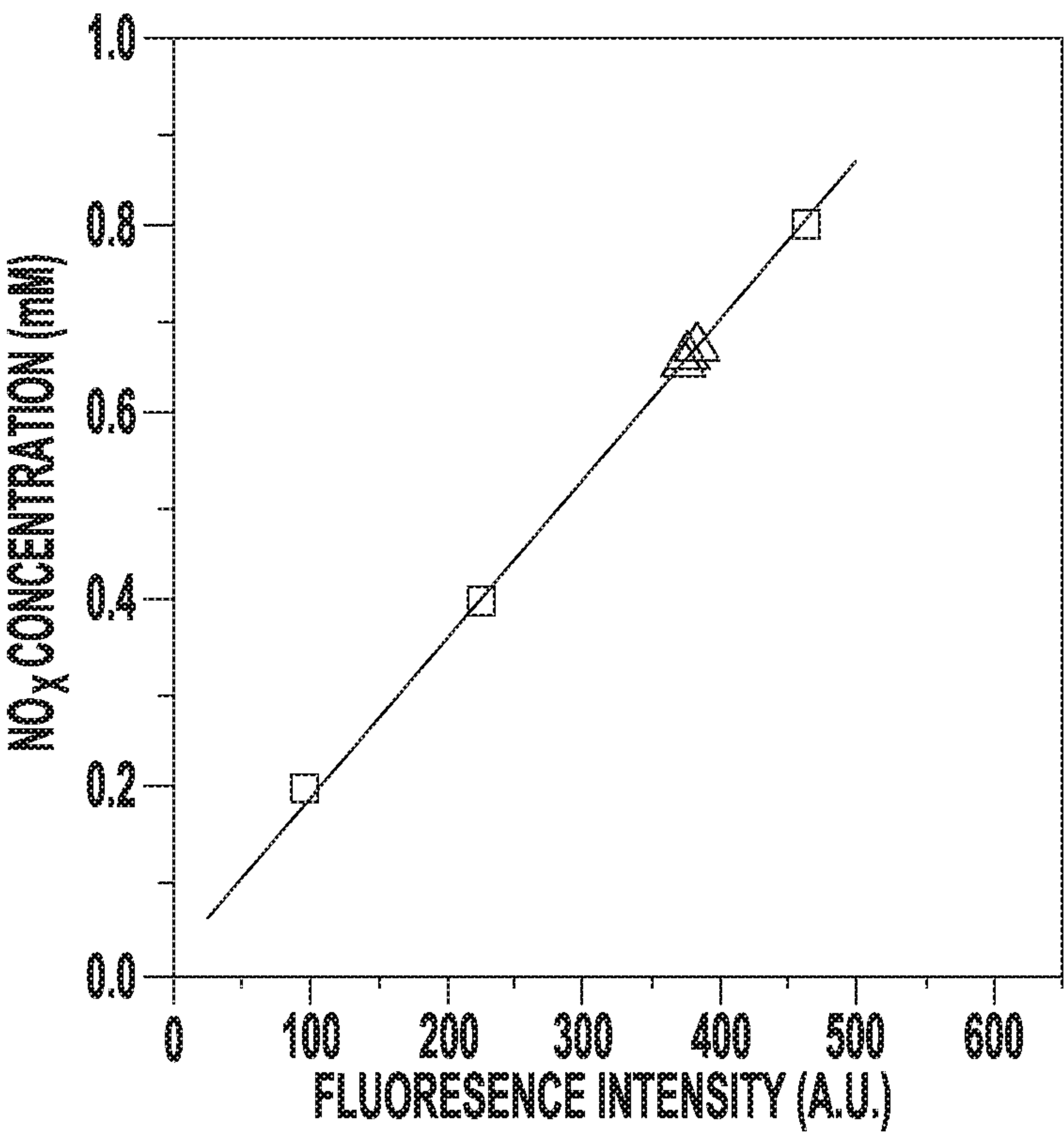


FIG. 20

AMMONIA SYNTHESIS USING PLASMA-PRODUCED ELECTRONS

RELATED APPLICATION DATA

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 62/647,021, filed Mar. 23, 2018, which is incorporated by reference herein.

GOVERNMENT FUNDING

[0002] The present invention was made with government support under grant W911NF-17-0119 awarded by the Department of Defense/Army Research Office. The government has certain rights in this invention.

BACKGROUND OF THE INVENTION

[0003] The fixation of nitrogen (N_2) has an enormous energy, environmental, and societal impact, the most important of which is the synthesis of ammonia (NH_3) for fertilizers that helps support nearly half of the world's population. Industrially, NH_3 is currently produced via the Haber-Bosch (H-B) process by reacting N_2 with hydrogen (H_2) over an iron-based catalyst at high pressure, about 150-300 standard atmosphere (atm) and high temperature, about 400-500 degree Celsius ($^{\circ}C$). See Appl. M., Ammonia, 1. Introduction. In Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH Verlag GmbH & Co. KGaA: 2012. This heterogeneous reaction scheme consumes more energy and contributes more greenhouse gas emissions than any other process associated with the top large-volume chemicals manufactured worldwide. A critical reason is that the source of H_2 for H-B process is fossil fuels, and either coal or natural gas must also be catalytically converted in multiple steps before NH_3 synthesis takes place. Because of the low single-pass conversion efficiency (15%) and high temperatures and high pressures, plants that implement H-B process are large and centralized to be economical, making them difficult to integrate with renewable sources of H_2 such as electrolysis.

[0004] Strategies for large-scale NH_3 synthesis at ambient conditions that use renewable sources of H_2 or water are being explored including photochemical processes (See Medford, A. J. et al., *Acs Catalysis* 2017, 7, (4), 2624-2643) and electrochemical processes (See Giddey, S. et al., *Int. J. Hydrog. Energy* 2013, 38, (34), 14576-14594). The major bottleneck with these approaches has been poor selectivity (<1%) for the desired NH_3 product, especially at mild temperatures (<80 $^{\circ}C$), which, in turn, means higher energy consumption, as well as higher capital cost and equipment footprint. See van der Ham et al., *Chem. Soc. Rev.* 2014, 43, 5183-5191 and Kuglar, K. et al., *Phys. Chem. Chem. Phys.* 2014, 16, 6129-6138. Photocatalytic reduction suffers from weak adsorption of N_2 on the surface of and oxidation of the reaction products by the holes in semiconductor catalysts. See Mozzanega, H. et al., *J. Phys. Chem.* 1979, 83, 2251-2255. Electrocatalytic reduction has been characterized by large overpotentials that are required for the relatively stable N_2 to associatively or dissociatively adsorb on a metal catalyst and energetically satisfy multiple intermediates involved in the complex reaction mechanism. See Skulason, E. et al., *Phys. Chem. Chem. Phys.* 2012, 14, 1235-1245, and Montoya, J. H. et al., *ChemSusChem* 2015, 8, 2180-2186. Moreover, the electrocatalysts with the lowest over-

potentials are metals that favor the adsorption of hydrogen species (H_2 , H^+ , etc.) over N_2 , making it difficult to suppress the hydrogen evolution reaction (HER), which ultimately compromises NH_3 formation. See Singh, A. R. et al., *ACS Catalysis* 2017, 7, 706-709.

[0005] Plasma-based processes are capable of activating N_2 without a catalyst by generating highly energetic electrons. In fact, nitrogen fixation occurs naturally in the atmosphere from lightening and before H-B process was developed. The very first method for nitrogen fixation was an electric arc in air known as the Birkeland-Eyde process. See Eyde, H. S., *J. Royal Soc. Arts* 1909, 57, 568-576. More recently, plasmas have been combined with solid catalysts to enhance the heterogeneous reaction of N_2 and H_2 and enable NH_3 synthesis at atmospheric pressure and room temperature. See Kim, H-H. et al., *Plasma Proc. Poly.* 2017, 14, 1-9. The synthesis of NH_3 has also been reported from other sources of hydrogen such as ethanol and water. Water in particular is attractive to avoid the dependence on fossil fuels. See Kubota, Y. et al., *J. Plasma. Fusikon Res.* 2010, 5, 042, and Haruyama, T. et al., *Green Chem.* 2016, 18, 4536-4541.

SUMMARY OF THE INVENTION

[0006] The present invention is directed to a method and a system to synthesize ammonia. Strategies for scalable ammonia synthesis at ambient conditions that use renewable sources of energy and feedstocks are being explored to replace the Haber-Bosch process. Here the inventors present a catalyst-free, electrolytic hybrid plasma system which is capable of high faradaic efficiency (up to 100%) and production rate (up to 0.44 mg ammonia/hour) at atmospheric temperature and pressure using nitrogen gas in the plasma, and water as a proton source. Adding scavenging nitrates to the system demonstrates that the ammonia production process occurs through a mechanism involving hydrogen radical ($H\cdot$) and solvated electrons and additional experiments. Compared to alternative electricity-driven demonstrations which use water as the proton source at atmospheric temperatures and pressures, the hybrid plasma process emerges as an efficient technique with high production rates and is therefore promising for renewable ammonia generation where there is an abundance of renewable energy.

[0007] In some embodiments, the invention includes a catalyst-free, electrolytic approach to form NH_3 at ambient (e.g., 25 $^{\circ}C$.) temperature and pressure from N_2 and water by injecting electrons from a plasma into liquid water. Solvated electrons, one of the most powerful reducing agents known, are created in a plasma by electrical breakdown of a gas in contact with a liquid surface such as water. See Rumbach, P. et al., *Nat. Comm.* 2015, 7248. The feasibility of solvated electrons reducing N_2 to NH_3 has been previously demonstrated using boron-doped diamond films, but required ultraviolet (UV) radiation to generate the solvated electrons and the selectivity for NH_3 was not determined. See Zhu, D. et al., *Nat. Mater.* 2013, 8, 836-841. By using only electricity to form the solvated electrons, the inventors are able to calculate the current (faradaic) efficiency for NH_3 synthesis and show that up to 100% selectivity is possible. The role of solvated electrons and hydrogen radicals ($H\cdot$) in the reaction mechanism is clarified by scavenger experiments which show that NH_3 synthesis is reduced by removing them. The reducing potential of solvated electrons, lack

of a solid catalyst surface, and the localized flow of N_2 are all suggested as possible reasons for the remarkably high selectivity of this hybrid electrolytic approach.

[0008] In one embodiment, a method of ammonia synthesis includes contacting a nitrogen gas-containing plasma with an aqueous solution, thereby forming ammonia from the nitrogen gas and water.

[0009] In another embodiment, an electrochemical cell for ammonia synthesis includes a container including an acidic liquid electrolyte. The electrochemical cell also includes a source of nitrogen gas, a metal electrode at least partially immersed in the electrolyte, a metal tube electrode spaced apart from a surface of the electrolyte by a predetermined spacing, and a plasma spanning the predetermined space from the metal tube electrode to contact the surface of the electrolyte.

BRIEF DESCRIPTION OF THE FIGURES

[0010] The present invention may be more readily understood by reference to the following figures wherein:

[0011] FIG. 1 provides a schematic illustration of a hybrid plasma electrolytic system configured for catalyst-free, electrolytic NH_3 production from N_2 and water using plasma-produced solvated electrons.

[0012] FIG. 2 provides a graph illustrating total NH_3 produced after 45 minutes at 6 milliamperes (mA) for various gas configurations (no plasma, Ar plasma, Ar plasma and N_2 , and N_2 plasma).

[0013] FIG. 3 provides a schematic illustration of key reaction pathways involving solvated electrons (e^-_{aq}) and hydrogen radicals ($H\cdot$) that lead to NH_3 formation.

[0014] FIG. 4 provides a graph illustrating NH_3 yield and efficiency in a plasma electrolytic system, where total NH_3 produced and corresponding faradaic efficiency are shown as a function of process time at 6 mA.

[0015] FIG. 5 provides a graph illustrating representative current waveforms measured in plasma electrolytic system during NH_3 synthesis, where the total charge is 5448 mAs.

[0016] FIG. 6 provides a graph illustrating representative current waveforms measured in plasma electrolytic system during NH_3 synthesis, where the total charge is 10858 mAs.

[0017] FIG. 7 provides a graph illustrating representative current waveforms measured in plasma electrolytic system during NH_3 synthesis, where the total charge is 16717 mAs.

[0018] FIG. 8 provides a graph illustrating representative current waveforms measured in plasma electrolytic system during NH_3 synthesis, where the total charge is 21647 mAs.

[0019] FIG. 9 provides a graph illustrating NH_3 yield and efficiency in plasma electrolytic system, where the total NH_3 produced and corresponding faradaic efficiency are shown as a function of current after 45 minutes.

[0020] FIG. 10 provides a schematic illustration of a hybrid plasma electrolytic system in a split H-cell geometry.

[0021] FIG. 11 provides a graph illustrating stability and trapping of NH_3 in a plasma electrolytic system, where the total NH_3 produced in a split-compartment cell and in single-compartment cell at representative times and current are compared.

[0022] FIG. 12 provides a graph illustrating stability and trapping of NH_3 in a plasma electrolytic system, where total NH_3 captured in a main reaction cell and a secondary trap vessel (e.g., a strongly acidic H_2SO_4 bath; pH=2) as a function of pH in the main reaction cell are compared.

[0023] FIG. 13 provides a schematic illustration of the influence of NO_x on NH_3 formation in a plasma electrolytic system; in the illustration the potential scavenging reaction pathways of NO_3^- are represented in green and NO_2^- in purple.

[0024] FIG. 14 provides a graph illustrating a comparison between total NH_3 produced after 45 minutes at 6 mA for low (10 mM) and high (1 M) concentrations of NO_3^- and NO_2^- , and total NH_3 produced for the same conditions in the absence of any scavenger.

[0025] FIG. 15 provides a graph illustrating NO_x concentration measured as a function of processing time at 6 mA.

[0026] FIG. 16 provides a graph illustrating NO_x concentration measured as a function of current after 45 minutes.

[0027] FIG. 17 provides a graph illustrating a comparison of experimentally produced NO_x (empty circle data points with black solid line for guide) with predicted NO_2 and NO_3 based on O_2 gas evolved at anode in a plasma electrolytic system as a function of process time.

[0028] FIG. 18 provides a graph illustrating a comparison of experimentally produced NO_x (empty circle data points with black solid line) with predicted NO_2 and NO_3 based on O_2 gas evolved at anode in a plasma electrolytic system as a function of current.

[0029] FIG. 19 provides a graph illustrating representative fluorescence assay calibration used to determine NH_3 produced, where the empty black square data points correspond to control solutions and filled blue triangle data points correspond to solutions synthesized in a plasma electrolytic system.

[0030] FIG. 20 provides a graph illustrating representative fluorescence assay calibration used to determine NO_x produced, where the empty black square data points correspond to control solutions and the filled blue triangle data points correspond to solutions synthesized in a plasma electrolytic system.

DETAILED DESCRIPTION OF THE INVENTION

Definitions

[0031] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this application pertains. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the exemplary embodiments, suitable methods and materials are described below. In case of conflict, the present specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

[0032] The terminology as set forth herein is for description of the embodiments only and should not be construed as limiting the application as a whole. Unless otherwise specified, “a,” “an,” “the,” and “at least one” are used interchangeably. Furthermore, as used in the description of the application and the appended claims, the singular forms “a,” “an,” and “the” are inclusive of their plural forms, unless contraindicated by the context surrounding such.

[0033] The recitations of numerical ranges by endpoints include all numbers subsumed within that range (e.g., 1 to 5 includes 1, 1.5, 2, 2.75, 3, 3.80, 4, 5, etc.).

[0034] The term “about” as used herein when referring to a measurable value such as an amount, a temporal duration, and the like, is meant to encompass variations of $\pm 20\%$ or

110%, more preferably $\pm 5\%$, even more preferably $\pm 1\%$, and still more preferably $\pm 0.1\%$ from the specified value, as such variations are appropriate to perform the disclosed methods.

[0035] As used herein, “plasma” is a state of matter in which an ionized gaseous substance becomes highly electrically conductive to the point that long-range electric and magnetic fields dominate the behavior of the matter. Plasma is an electrically neutral medium of unbound positive and negative particles.

[0036] As used herein, the term “nitrogen gas in the plasma,” “nitrogen gas-containing plasma,” or “nitrogen plasma” encompasses plasma created using nitrogen gas. “Nitrogen gas in the plasma” or “nitrogen plasma” contains ionized nitrogen.

[0037] Faradaic efficiency is calculated by the equation below.

$$\text{Faradaic efficiency}(\%) = \frac{\text{Experimentally measured NH}_3 \text{ concentration}}{\text{Faradaic NH}_3 \text{ concentration}} \times 100,$$

where Faradaic NH_3 concentration = $\frac{Q}{FzV}$, where Q is the total charge, F is Faraday’s constant, z is the number of electrons and equal to 3 for the NH_3 reaction, and V is the volume of the solution and equal to 20 milliliter (mL).

An Electrochemical Cell and A Method for Synthesizing Ammonia

[0038] The present invention is directed to methods for ammonia synthesis at ambient conditions that use renewable sources of energy and feedstocks. These methods can be used, for example, to replace the Haber-Bosch process. In one aspect, the invention provides a catalyst-free, electrolytic hybrid plasma system which is capable of achieving a high faradaic efficiency and an ammonia production rate at atmospheric temperature and pressure using nitrogen gas in the plasma, and water as a proton source. In particular, the faradaic efficiency may be between about 70% and about 100%, between about 80% and about 100%, between about 90% and about 100%, and about 100%. The ammonia production rate may be between about 0.2 milligram per hour (mg/hour) and 0.44 mg/hour, between about 0.3 mg/hour and 0.44 mg/hour, between about 0.4 mg/hour and 0.44 mg/hour, and about 0.44 mg/hour.

[0039] In one aspect, the present invention provides a method of ammonia (NH_3) synthesis. The method may include contacting a nitrogen gas (N_2) containing plasma with an aqueous solution, thereby forming ammonia from the nitrogen gas and water. An aqueous solution is a solution in which the solvent is water. Preferably, the aqueous solution includes electrolytes that help to conduct current within the aqueous solution. While not intending to be bound by theory, the inventors believe that the presence of solvated electrons and $\text{H}\cdot$ in plasma electrolytic synthesis of NH_3 play an important role in providing the improved characteristics of the ammonia synthesis method described herein.

[0040] In some embodiments, the nitrogen gas-containing plasma (e.g., nitrogen plasma) is a microplasma, which is a plasma of small dimensions. A microplasma can have a diameter ranging from about 10 to 100 micrometers, or from 100 to 1000 micrometers. The nitrogen gas-containing

plasma may be present in an electrochemical cell including a plasma-generating cathode and a metal anode. Details of the electrochemical cell are discussed herein (see for example FIG. 1 and Example 1). The nitrogen gas is delivered to the aqueous solution from the plasma-generating cathode while an electrical current is applied to generate the nitrogen gas-containing plasma.

[0041] The electrical current used to generate the plasma may range from about 1 milliamper (mA) to about 20 mA, about 1 mA to about 15 mA, or about 1 mA to about 8 mA. The nitrogen gas may be delivered at a flow rate of about 100 milliliter per minute (mL/min) to about 150 mL/min, about 110 mL/min to about 140 mL/min, about 120 mL/min to about 130 mL/min, or about 125 mL/min.

[0042] The method may be carried out at a suitable temperature and pressure such that the water in the aqueous solution is in liquid form. Accordingly, in some embodiments, the temperature is greater than 0 degree Celsius ($^{\circ}\text{C}$) and lower than 100°C ., between about 5 degree Celsius ($^{\circ}\text{C}$) and 45°C ., between about 10°C . and 40°C ., between about 15°C . and 35°C ., between about 20°C . and 30°C ., between about 22°C . and 28°C ., between about 24°C . and 26°C ., and about 25°C . In some embodiments, the method may be carried out at room temperature (e.g. 25°C .) and atmospheric pressure. The method can also be carried out at a variety of moderate pressures. The pressure may be between about 1.5 atmospheric pressure (atm) and 0.5 atm, between about 1.3 atm and 0.7 atm, between about 1.2 atm and 0.8 atm, between about 1.1 atm and 0.9 atm, and about 1 atm.

[0043] In another aspect, the present invention provides an electrochemical cell for ammonia synthesis. An electrochemical cell is a device capable of using electrical energy to cause a chemical reaction such as the formation of ammonia. The electrochemical cell may include a container including an acidic liquid electrolyte, a source of nitrogen gas, a metal electrode at least partially immersed in the electrolyte, and a metal tube electrode spaced apart from a surface of the electrolyte by a predetermined spacing. When in operation, the electrochemical cell includes a plasma spanning the predetermined space from the metal tube electrode to contact the surface of the electrolyte. The plasma is generated when power is applied to the metal tube electrode. Power can be provided by an electrical power supply device that supplies electric power. The predetermined spacing may be between about 1 millimeter (mm) and about 1 centimeter (cm), between about 1 mm and about 0.5 cm, between about 0.5 mm and 0.5 cm, between about 1 mm and about 0.1 cm, and less than about 1 mm. The electrochemical cell is configured to synthesize ammonia from the nitrogen gas and water (e.g., water in the acidic liquid electrolyte) under moderate (e.g., atmospheric) pressure.

[0044] The container is configured to contain the acidic liquid electrolyte. An advantage of the present invention is that the method of ammonia synthesis can be carried out on a relatively small scale. The volume of the container or the electrochemical cell may be any suitable values. For example, the container or the electrochemical cell may have a volume of about 1 liter or less, about 500 milliliters (mL) or less, about 300 mL or less, about 200 mL or less, about 100 mL or less, about 50 mL or less, about 30 mL or less, about 20 mL or less, about 10 mL or less, or 5 mL or less. The acidic liquid electrolyte may be an aqueous solution has a pH of 5 or less, 4 or less, 3.5, or 2. The acidic liquid may

include a solution containing sulfuric acid (H_2SO_4) in deionized water having a pH of 5, 4, 3.5, or 2. In further embodiments, acids other than sulfuric acid, such as hydrochloric acid or nitric acid, can also be used in the electrolyte solution.

[0045] The source of nitrogen gas is configured to supply nitrogen gas to the metal tube electrode (e.g., the plasma generating cathode). The source of nitrogen gas may include a hollow conductive body including a first opening and a second opening comprising a nitrogen gas outlet and the second opening being separated from the surface of the acidic liquid electrolyte by the predetermined spacing. Preferably, the nitrogen gas supplied is relatively pure, but in some embodiments the nitrogen gas can include additional non-reactive gases such as argon. The source of nitrogen may be configured to deliver the nitrogen gas at a flow rate of about 100 milliliter per minute (mL/min) to about 150 mL/min, about 110 mL/min to about 140 mL/min, about 120 mL/min to about 130 mL/min, or about 125 mL/min.

[0046] The metal electrode (e.g., anode) may be any suitable anode material and in any suitable shape or dimension. For example, the metal electrode may be made of platinum (Pt), gold, silver, or copper. The metal tube electrode may be made of any suitable cathode material and in any suitable shape or dimension capable of deliver the nitrogen gas toward the acidic liquid electrolyte gas. For example, the metal tube electrode may be made of stainless steel.

[0047] FIG. 1 shows a schematic depiction of the chemical electrochemical cell for ammonia synthesis set forth above. In the illustrated embodiment, an electrochemical cell **10** may include a container **12** including an acidic liquid electrolyte or an aqueous solution **14**. The electrochemical cell **10** may include a source **16** of nitrogen gas, a metal electrode **18** (e.g., anode) at least partially immersed in the electrolyte **14**, and a metal tube electrode **20** (e.g., cathode) spaced apart from a surface **22** of the electrolyte **14** by a predetermined spacing **24**. The nitrogen gas may be delivered to the electrolyte or aqueous solution **14** from the metal tube electrode **20**, which is a plasma-generating cathode. The metal tube electrode **20** may be connected to a power supply and the metal electrode **18** may be wired to a resistor to ground the metal electrode **18**. When a negative high vol-

tage is applied via the power supply, a plasma **26** is created spanning the predetermined space **24** from the metal tube electrode **20** to contact the surface **22** of the electrolyte **14**. In some embodiments, the electrochemical cell **10** may include a first purging tube **28** and a second purging tube **30** to ensure that the electrochemical cell **10** is isolated from ambient gasses. The first purging tube **28** may be used for bubbling nitrogen through the electrolyte **14** and the second purging tube **30** may be used as an exhaust.

[0048] Below synthesis of NH_3 from N_2 and water using plasma-produced solvated electrons is discussed with reference to the electrochemical cell **10**.

[0049] The setup bears similarity to electrochemical approaches except that the metal cathode was replaced by a plasma formed in a gas gap between a stainless steel nozzle and the solution surface. Details of reactions at the plasma-liquid interface have been reported elsewhere. See Richmonds, C. et al., Appl. Phys. Lett. 2008, 93, 131501, Richmonds, C. et al., J. Am. Chem. Soc. 2011, 133, 17582-17585, and Ghosh, S. et al., J. Electrochem. Soc. 2017, 164, D818-D824.

[0050] Here, in order to study NH_3 formation, both argon (Ar) and N_2 were investigated as the plasma gas and the purge gas, the latter of which was bubbled through the electrolyte solution. All experiments were performed with a platinum (Pt) electrode immersed in the solution which operated as the anode. The electrolyte may include a solution containing sulfuric acid (H_2SO_4) in deionized water (18.2 M Ω) to both supply and conduct protons (H^+) for N_2 reduction and trap the as-synthesized NH_3 , as will be discussed.

[0051] The inventors initially performed a series of control experiments to verify NH_3 formation under the same amount of time and current of 45 minutes and 6 milliamperes (mA), respectively. FIG. 2 shows the average mass of NH_3 produced for the following configurations: 1) N_2 gas flowing into the cathode where the plasma is normally generated, and bubbled through the solution, but electrical power applied (i.e. plasma generated), 2) Ar gas in the plasma and bubbled, 3) Ar gas in the plasma and N_2 gas bubbled, and 4) N_2 gas in the plasma and bubbled. The complete set of data for all trials which produced ammonia is shown in Table 1.

TABLE 1

Summary of NH ₃ produced and Faradaic efficiencies by plasma electrolytic synthesis for Ar gas in the plasma and N ₂ gas bubbled in solution and N ₂ gas in the plasma and N ₂ gas bubbled in solution. The current was 6 mA, the processing time was 45 minutes, and the reaction volume was 20 milliliter (mL) in both cases					
Ar plasma + N ₂ bubbling					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.022	0.007	16254	2.81	0.8
Trial 2	0.172	0.059	16227	2.80	6.1
Trial 3	0.067	0.023	16198	2.80	2.4
Trial 4	0.003	0.001	16394	2.83	0.1
Trial 5	0.144	0.049	16252	2.81	5.1
Trial 6	0.029	0.010	16228	2.80	1.0
Average	0.025±0.018			2.58±1.85	
N ₂ plasma + N ₂ bubbling					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.919	0.313	16240	2.86	32.1
Trial 2	0.889	0.303	16314	2.87	30.9
Trial 3	0.902	0.307	16387	2.89	31.2
Trial 4	0.929	0.317	16288	2.87	32.4
Trial 5	0.919	0.313	16322	2.88	31.9
Trial 6	0.926	0.315	16263	2.87	32.3
Trial 7	0.896	0.305	16253	2.81	31.9
Trial 8	0.902	0.307	16227	2.80	32.2
Trial 9	0.908	0.309	16199	2.80	32.5
Trial 10	0.990	0.337	16394	2.83	35.0
Average	0.313±0.006			32.2±0.6	

[0052] Without a plasma, or with only Ar in the system, no detectable amount of NH₃ was found. In comparison, substantially zero NH₃ was produced when N₂ was either bubbled or in the plasma, confirming that it was not coming from other sources including background contamination. The NH₃ yield was significantly larger with N₂ in the plasma compared to Ar in the plasma. See Table 2 below.

TABLE 2

Summary of one-sample and two-sample t-tests carried out on data sets in Table 2					
One-Sample t, Test of $\mu = 0.00$ vs $\mu = t$ 0.00					
	Algebraic Mean	Standard Deviation	95% Lower Bound	Probability	
N ₂ plasma Ar	0.313	0.010	0.306	0.000	0.050
plasma + N ₂	0.025	0.024			
Two-Sample t, Test of $\mu_1 - \mu_2 = 0$					
	Difference	95% Lower Bound	95% Upper Bound	Probability	
N ₂ plasma vs. Ar	0.288	0.263	0.313	0.000	
plasma + N ₂					

[0053] A potential mechanism for NH₃ synthesis is illustrated in FIG. 3, highlighting the key reactions that could be initiated by solvated electrons. As noted, solvated electrons in liquid water are highly reactive with a reduction potential of -2.86 V and could be involved in a multitude of reactions. See Buxton, G. V. et al., J. Phys. Chem. Ref. Data 1988, 17, 513-886. Previous work on solvated electron-mediated formation of NH₃ has shown that a likely

pathway is through the formation of hydrogen radicals (H \cdot), for example $H^+ + e^-(aq) \rightarrow H\cdot$, followed by reaction of H \cdot with N₂ to form N₂H. See Christianson, J. R. et al., J. Phys. Chem. B 2014, 118, 195-203. This is generally consistent with the identification of N₂H as the critical intermediate in reduction of N₂ by proton and electron transfer. See Bazhenova, T. A. et al., Coord. Chem. Rev. 1995, 144, 69-145. The intermediate, N₂H, then continues to react with H \cdot to ultimately produce NH₃. Analogous to electrochemical synthesis of NH₃, the HER is a major competing reaction, reducing selectivity, and occurs via either the second order recombination of solvated electrons, $2e^-(aq) + 2H_2O \rightarrow H_2(g) + 2OH^-$, or hydrogen radicals, $2H\cdot \rightarrow H_2(g)$. Without these side reactions occurring, NH₃ production only requires three electrons. The inventors note that while other reaction pathways to produce H₂ involving solvated electrons and/or hydrogen radicals exist, these two are the most kinetically important.

[0054] NH₃ yield and efficiency in the plasma electrolytic system were examined by measuring the amount of NH₃ synthesized for different periods of time and at different steady-state operating currents. FIG. 4 shows the average mass of NH₃ obtained as a function of time at a current of 6 mA. The complete set of data for all trials is shown in Table 3. A linear increase in NH₃ produced with time would indicate a constant production rate, but the inventors find that the rate changes, decreasing after 10 minutes. The efficiency was estimated by comparing the measured NH₃ mass at each time point to the amount of NH₃ calculated from Faraday's law assuming a three electron reaction.

TABLE 3

Summary of NH ₃ produced and Faradaic efficiencies by plasma electrolytic synthesis after different processing times. The current was 6 mA and the reaction volume was 20 mL in all cases					
t=5 min					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.206	0.070	1838	0.317	64.9
Trial 2	0.073	0.025	1862	0.322	22.8
Trial 3	0.339	0.116	1832	0.317	107.1
Trial 4	0.150	0.051	1866	0.322	46.5
Average			0.065±0.033		60.3±30.9
t=15 min					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.335	0.114	5508	0.951	35.2
Trial 2	0.285	0.097	5532	0.956	29.8
Trial 3	0.324	0.110	5493	0.949	34.2
Trial 4	0.346	0.118	5519	0.935	37.1
Trial 5	0.461	0.157	5511	0.933	49.4
Trial 6	0.359	0.122	5541	0.938	38.2
Average			0.120±0.015		37.3±4.9
Trial 1	0.574	0.196	11026	1.905	30.2
Trial 2	0.602	0.205	11038	1.907	31.6
Trial 3	0.529	0.180	11014	1.902	27.8
Trial 4	0.572	0.195	11030	1.905	30.0
Average			0.194±0.009		29.9±1.3
Trial 1	0.919	0.313	16567	2.86	32.1
Trial 2	0.889	0.303	16643	2.87	30.9
Trial 3	0.902	0.307	16717	2.89	31.2
Trial 4	0.929	0.317	16615	2.87	32.4
Trial 5	0.919	0.313	16651	2.88	31.9
Trial 6	0.926	0.315	16590	2.87	32.3
Trial 7	0.896	0.305	16253	2.81	31.9
Trial 8	0.902	0.307	16227	2.80	32.2
Trial 9	0.908	0.309	16199	2.80	32.5
Trial 10	0.990	0.337	16394	2.83	35.0
Average			0.313±0.006		32.2±0.6

[0055] The inventors note that while the set point for the current through the hybrid electrolytic system was kept constant, there were small fluctuations over the duration of the experiments arising from plasma instabilities, particularly when the plasma was ignited. See FIGS. 5-8. Although over the experimental period, these fluctuations did not contribute significant deviations from the average current because they occurred on very short time scales on the order of seconds, to ensure that the faradaic amount of NH₃ calculated was precise, the temporal current was monitored, I(t), and integrated to obtain the total charge, $Q = \int I(t)dt$. As a function of time, the average faradaic efficiency is found to decrease from ~60% at 5 minutes to a statistically indistinguishable value of ~30% at 30 and 45 minutes as shown in Table 4, consistent with the observed changes in the NH₃ production rate.

TABLE 4

Summary of one-sample and two-sample t-tests carried out on data sets in Table 3				
One-Sample t on NH ₃ production Test of $\mu = 0.00$ vs $\mu = t$ 0.00				
	Algebraic Mean	St. Deviation	95% Lower Bound	Probability
5 min	0.065	0.038	0.005	0.021
15 min	0.120	0.020	0.099	0.000
30 min	0.194	0.010	0.178	0.000
45 min	0.312	0.016	0.305	0.000

TABLE 4-continued

Summary of one-sample and two-sample t-tests carried out on data sets in Table 3				
One-Sample t on NH ₃ production Test of $\mu = 0.00$ vs $\mu = t$ 0.00				
	Algebraic Mean	St. Deviation	95% Lower Bound	Probability
Two-Sample t on NH ₃ production Test of $\mu_1 - \mu_2 = 0$				
	Difference	95% Lower Bound	95% Upper Bound	Probability
5 vs. 15 min	0.054	0.003	0.112	0.059
15 vs. 30 min	0.074	0.051	0.097	0.000
30 vs. 45 min	0.118	0.102	0.133	0.000
One-Sample t on FE Test of $\mu = 0.00$ vs $\mu > 0.00$				
	Algebraic Mean	St. Deviation	95% Lower Bound	Probability
5 min	60.3	35.6	18.4	0.021
15 min	37.3	6.59	31.9	0.000
30 min	29.9	1.56	28.1	0.000
45 min	32.1	1.70	31.5	0.000
5 vs. 15 min	23.0	-80.4	34.3	0.291
15 vs. 30 min	7.42	0.23	14.6	0.045
30 vs. 45 min	2.24	0.175	4.66	0.062

TABLE 4-continued

One-Sample t on FE Test of $\mu = 0.00$ vs $\mu > 0.00$				
Algebraic Mean	St. Deviation	95% Lower Bound	Probability	
45 min				

[0056] FIG. 9 shows the average mass of NH₃ produced after 45 minutes as a function of current in the plasma electrolytic system. The complete set of data for all trials is shown in Table 5.

[0057] The processing time was 45 minutes and the reaction volume was 20 mL in all cases.

TABLE 5

Summary of NH ₃ produced and Faradaic efficiencies by plasma electrolytic synthesis at different currents					
I=1 mA					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.456	0.155	2709	0.468	97.4
Trial 2	0.470	0.160	2705	0.467	100.7
Trial 3	0.465	0.158	2700	0.466	99.8
Trial 4	0.463	0.158	2732	0.472	98.1
Average			0.158±0.002		99.0±1.3
I=2 mA					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.849	0.289	5438	0.939	90.4
Trial 2	0.939	0.320	5483	0.947	99.1
Trial 3	0.944	0.322	5448	0.941	100.3
Trial 4	1.017	0.346	5798	1.002	101.5
Trial 5	1.050	0.358	5690	0.983	106.8
Trial 6	1.043	0.355	5643	0.975	107.0
Average			0.332±0.020		100.9±4.6
I=3 mA					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.586	0.199	8132	1.405	41.7
Trial 2	0.514	0.175	8189	1.415	36.3
Trial 3	0.431	0.147	8072	1.394	30.9
Average			0.174±0.025		36.3±5.1
Trial 1	0.674	0.230	11121	1.921	35.1
Trial 2	0.714	0.243	11156	1.927	37.1
Trial 3	0.664	0.226	11015	1.903	34.9
Trial 4	0.724	0.247	11049	1.909	37.9
Trial 5	0.664	0.226	11076	1.913	34.7
Trial 6	0.719	0.245	11076	1.902	37.8
Average			0.236±0.007		36.3±1.1
Trial 1	0.919	0.313	16567	2.86	32.1
Trial 2	0.889	0.303	16642	2.87	30.9
Trial 3	0.902	0.307	16717	2.89	31.2
Trial 4	0.929	0.317	16615	2.87	32.4
Trial 5	0.919	0.313	16650	2.88	31.9
Trial 6	0.926	0.315	16591	2.87	32.3
Trial 7	0.896	0.305	16253	2.81	31.9
Trial 8	0.902	0.307	16227	2.80	32.2
Trial 9	0.908	0.309	16199	2.80	32.5
Trial 10	0.990	0.337	16394	2.83	35.0
Average			0.313±0.006		32.2±0.6
Trial 1	0.962	0.328	22063	3.81	25.2
Trial 2	0.900	0.307	22152	3.83	23.5
Trial 3	0.953	0.325	22111	3.82	25.0
Trial 4	0.877	0.299	22028	3.81	23.0
Trial 5	0.961	0.327	22037	3.81	25.2
Trial 6	0.882	0.300	22047	3.81	23.2
Average			0.314±0.010		24.2±0.8

[0058] The current that drives the plasma electrolytic system is measured at the power supply and is the same as the plasma current which, like the Pt anode, is electrically connected in series. Increasing the plasma current leads to an increase in the number of gas-phase electrons injected from

the plasma into solution that then solvate, and based on the mechanism shown in FIG. 3, should, thus, increase NH_3 production. Here, however, the inventors find that the NH_3 yield exhibits a rather complicated dependence on current, significantly increasing from 1 mA to 2 mA, then decreasing significantly from 2 mA to 3 mA, then increasing again from 3 mA to 4 mA and 5 mA to 6 mA before staying constant at 6 mA and 8 mA (See Table 6). These results suggest that as the current is increased to greater than 2 mA, the injected electrons are involved in competing reactions that do not form NH_3 . This apparent decrease in selectivity towards NH_3 is corroborated by the faradaic efficiency which decreases significantly from 2 mA to 3 mA, and then decreases more slowly, but statistically significantly from 4 mA to 8 mA (See Table 6). The most likely reaction pathway that competes with NH_3 formation is the HER which occurs either by recombination of solvated electrons or H^\cdot (See FIG. 3). In general, the HER is kinetically favored at higher concentrations of solvated electrons or H^\cdot because of the second order dependence. Assuming that the solution volume over which the solvated electrons or H^\cdot are generated is constant, increasing the current would increase their concentrations and support the observed trends in faradaic efficiency.

TABLE 6

Summary of one-sample and two-sample t-tests carried out on data sets in Table 5.

One -Sample t on NH_3 production				
Test of $\mu = 0.00$ vs $\mu > 0.00$				
	Algebraic Mean	St. Deviation	95% Lower Bound	Probability
1 mA	0.158	0.002	0.155	0.000
2 mA	0.332	0.027	0.310	0.000
3 mA	0.174	0.026	0.130	0.004
4 mA	0.236	0.010	0.228	0.000
6 mA	0.313	0.010	0.307	0.000
8 mA	0.314	0.014	0.303	0.000

Two-Sample t on NH_3 production Test of $\mu_1 - \mu_2 = 0$				
	Difference	95% Lower Bound	95% Upper Bound	Probability
1 vs. 2 mA	0.174	0.146	0.202	0.000
2 vs. 3 mA	0.158	0.106	0.210	0.001
3 vs. 4 mA	0.062	-0.005	0.130	0.058
4 vs. 6 mA	0.077	0.065	0.088	0.000
6 vs. 8 mA	0.002	-0.013	0.016	0.819

One-Sample t on NH_3 production FE Test of $\mu = 100$ vs $\mu < 100$				
	Algebraic Mean	St. Deviation	95% Upper Bound	Probability
1 mA	99.0	1.51	100.7	0.000
2 mA	1.01	6.12	105.9	0.000
3 mA	36.3	5.39	45.4	0.000
4 mA	36.2	1.52	37.5	0.000
6 mA	32.2	1.08	32.9	0.000
8 mA	24.2	1.06	25.1	0.000
1 mA	99.0	1.51	97.2	0.000
2 mA	1.01	6.12	95.8	0.000
3 mA	36.3	5.39	27.2	0.004
4 mA	36.2	1.52	35.0	0.000
6 mA	32.2	1.08	31.6	0.000
8 mA	24.2	1.06	23.3	0.000
1 vs. 2 mA	1.88	-8.59	4.84	0.505
2 vs. 3 mA	64.6	53.5	75.6	0.000
3 vs. 4 mA	0.00	-13.6	13.7	0.986
4 vs. 6 mA	4.00	2.38	5.63	0.000
6 vs. 8 mA	8.05	6.82	9.28	0.000

[0059] While abundant NH_3 was produced in a single-compartment cell setup, the inventors addressed the potential decomposition of NH_3 by comparing with a split H-cell geometry where the plasma cathode was formed in one compartment, the Pt anode was contained in the other, and the solutions in the two compartments were separated by a glass frit that allowed ionic contact, but prevented mixing (See FIG. 10). If NH_3 is decomposed by oxidation at the anode in the single cell, the measured amount of NH_3 would be lower than what is actually produced at the cathode and the split cell would show a higher yield.

[0060] FIG. 11 shows the average masses of NH_3 produced in a single and split cell at several representative currents and times. The complete set of data for all trials is shown in Table 7. The NH_3 yields were found to be statistically identical, indicating that NH_3 is not decomposed at the anode (See Table 8). This is consistent with a previously reported proposed mechanism for NH_3 decomposition that occurs through reaction with OH^- and only becomes significant in basic solutions. See Kim, K-W. et al., *Electrochimica Acta* 2005, 50, 4356-4364.

[0061] The reaction volume was 20 mL in all cases.

TABLE 7

Summary of NH ₃ produced and Faradaic efficiencies by plasma electrolytic synthesis in a split cell					
6 mA, 45 min					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.874	0.298	16265	2.81	31.1
Trial 2	0.935	0.318	16171	2.79	33.5
Trial 3	0.930	0.317	16180	2.79	33.3
Average		0.311±0.011			32.6±1.2
4 mA, 45 min					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.691	0.235	10791	1.86	37.1
Trial 2	0.651	0.222	10834	1.87	34.8
Trial 3	0.686	0.234	10885	1.88	36.5
Average		0.230±0.007			36.1±1.1
6 mA, 15 min					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.391	0.133	5417	0.936	41.8
Trial 2	0.287	0.098	5402	0.933	30.8
Trial 3	0.447	0.152	5489	0.948	47.2
Trial 4	0.382	0.130	5391	0.931	41.0
Trial 5	0.322	0.110	5393	0.932	34.5
Trial 6	0.362	0.123	5402	0.933	38.8
Average		0.124±0.014			39.0±4.3

TABLE 8

Summary of two-sample t-tests carried out on data sets in Table 7 (and Table 5 and Table 3)				
Two-Sample t on NH ₃ production Test of $\mu_1 - \mu_2 = 0$				
	Difference	95% Lower Bound	95% Upper Bound	Probability
6-45 single vs. split	0.002	-0.030	0.033	0.837
4-45 single vs. split	0.004	-0.012	0.020	0.535
split 6-15 single vs. split	0.005	-0.021	0.030	0.692

[0062] Another possible loss mechanism for NH₃ is simply vaporization because of its relatively low solubility. The

inventors studied the effectiveness of NH₃ trapping by varying the pH of our solution in the single cell and connecting the gas effluent from the cell to a second vessel containing a strongly acidic H₂SO₄ bath (pH=2) to ensure complete capture. FIG. 12 shows the average mass of NH₃ measured in the main reaction cell and the second trap vessel at different pH. The complete set of data for all trials is shown in Table 9.

[0063] The pH was controlled by the concentration of sulfuric acid. “MC” refers to the main reaction cell and “Trap” refers to a second trapping vessel where the gas exhaust from the main reaction cell was bubbled through a solution of sulfuric acid at pH=2. The reaction volume was 20 mL in all cases.

TABLE 9

Summary of NH ₃ produced and Faradaic efficiencies by plasma electrolytic synthesis at different pH					
pH=2					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	1.116	0.380	16252	2.81	39.8
Trial 2	1.146	0.390	16227	2.80	40.9
Trial 3	1.104	0.376	16199	2.78	39.5
Trial 4	1.154	0.393	16395	2.83	40.8
Average		0.385±0.007			40.2±0.6
pH=5.5					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.884	0.301	16252	2.81	31.5
Trial 2	0.821	0.280	16227	2.80	29.3
Trial 3	0.834	0.284	16198	2.80	29.8
Trial 4	0.796	0.271	16395	2.83	28.1
Average		0.284±0.011			29.7±1.2

pH=7					
Trial 1 (MC)	0.134	0.045	16290	2.81	4.7
Trial 1 (Trap)	0.041	0.014	16290	2.81	1.5
Trial 2 (MC)	0.066	0.022	16231	2.80	2.3
Trial 2 (Trap)	0.105	0.036	16231	2.80	3.7

[0064] The results confirm that for pH <7, no detectable amount of NH₃ is lost from the reaction cell. The lack of any NH₃ collected in the trap at acidic conditions also shows that the NH₃ measured in our electrolytic process is not formed in the gas phase, for example by reaction in the plasma between N₂ and H₂ produced from the HER, but is formed in solution. Interestingly, the inventors also observe that the NH₃ yield and faradaic efficiency significantly increase with decreasing pH (See Table 10).

[0065] “MC” refers to the main reaction cell and “Trap” refers to a second trapping vessel where the gas exhaust from the main reaction cell was bubbled through a solution of sulfuric acid at pH=2.

TABLE 10

Summary of one-sample and two-sample t-tests carried out on data sets in Table 9

One-Sample t on NH ₃ production Test of $\mu = 0$ vs $\mu > 0.00$				
	Algebraic Mean	St. Deviation	95% Lower Bound	Probability
pH 2.0 (MC)	0.385	0.008	0.375	0.000
pH 3.5 (MC)	0.313	0.010	0.307	0.000
pH 5.5 (MC)	0.284	0.013	0.269	0.000
pH 7 (MC)	0.034	0.016	-0.039	0.104
pH 7 (Trap)	0.025	0.015	-0.043	0.131
Two-Sample t on NH ₃ production Test of $\mu_1 - \mu_2 = 0$				
	Difference	95% Lower Bound	95% Upper Bound	Probability
2.0 (MC) vs. 3.5 (MC)	0.072	0.060	0.085	0.000
3.5 (MC) vs 5.5 (MC)	0.029	0.048	0.009	0.015
5.5 (MC) vs 7.0 (MC)	0.250	0.083	0.417	0.033
7.0 (MC) vs 7.0 (Trap)	0.009	-0.210	0.192	0.668
pH 2.0 (MC)	40.22	0.708	39.39	0.000
pH 3.5 (MC)	32.24	1.080	31.62	0.000
pH 5.5 (MC)	29.67	1.404	28.02	0.000
pH 7 (MC)	3.55	1.700	-4.030	0.104
pH 7 (Trap)	2.60	1.610	-4.560	0.131
2.0 (MC) vs 3.5 (MC)	7.978	6.844	9.113	0.000
3.5 (MC) vs 5.5 (MC)	2.569	0.402	4.736	0.030
5.5 (MC) vs 7.0 (MC)	26.13	8.470	43.79	0.034
7.0 (MC) vs 7.0 (Trap)	0.950	-20.04	21.93	0.669

[0066] This is consistent with the potentially important roles of H[•] and the competing HER pathways (see FIG. 3). Decreasing pH leads to an increase in the proton (H⁺) concentration and enhances the rate of H⁺ reacting with solvated electrons via mass action to produce H[•] relative to the second order recombination of solvated electrons (see FIG. 3), ultimately increasing the NH₃ production rate and selectivity. The inventors do not find a decrease in the NH₃ yield and faradaic efficiency even at the lowest pH tested of pH = 2, which indicates that the second order recombination of H[•] does not become important; this suggests that N₂ may be sufficiently abundant in our process and reacts quickly with any available H[•] to form NH₃. The inventors note that the dependence of NH₃ formation on H⁺ is independent of its trapping since all the NH₃ formed is effectively captured in the reaction cell below pH=7.

[0067] The crucial role of solvated electrons and H[•] in plasma electrolytic synthesis of NH₃ was verified by scavenger experiments. The high reactivity of these species allows a controlled impurity or scavenger to be added to the solution which rapidly reacts with and essentially quenches them, impeding their subsequent reaction. This approach is well known in radiation chemistry to elucidate reaction pathways involving solvated electron formation and their reaction byproducts. See Wolff, R. K. et al., J. Chem. Phys. 1970, 53, 4211. Relevant to the present invention, scavengers have also been shown to reduce the concentration of solvated electrons generated by a plasma. The inventors initially studied NO₃⁻ which has a high reactivity for solvated electrons with a measured rate constant for plasma-injected solvated electrons, $k=7.0 \pm 2.6 \times 10^9 \text{ M}^{-1}\text{s}^{-1}$ (Rumbach, P. et al., Nat. Comm. 2015, 7248) and would be expected to rapidly lower the solvated electron concentration, as depicted in FIG. 13.

[0068] FIG. 14 shows that the NH₃ yield is reduced by the addition of NO₃⁻, reflecting the effect of scavenging solvated electrons, but the NO₃⁻ concentration needs to be sufficiently high (10 mM vs. 1 M) to observe ~50% reduction. The complete set of data for all trials is shown in Table 11. The inventors believe this is because 1) NO₃⁻ competes with H⁺, which based on radiation chemistry has a similar rate constant for reaction with solvated electrons ($k=2.3 \times 10^{10} \text{ M}^{-1}\text{s}^{-1}$) (Buxton, G. V. et al., J. Phys. Chem. Ref. Data 1988, 17, 513-886) and 2) transport limitations which will lower the concentration of NO₃⁻ at the plasma-liquid interface where the solvated electrons are generated as compared to the bulk.

[0069] The concentration of NO₃ and NO₂ was controlled by NaNO₃ and NaNO₂. The reaction volume was 20 mL in all cases.

TABLE 11

Summary of NH ₃ produced and Faradaic efficiencies by plasma electrolytic synthesis in the presence of NO ₃ and NO ₂ scavengers					
10 mM NO ₃					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.779	0.265	5409	0.934	83.3
Trial 2	0.797	0.272	5437	0.939	84.9
Trial 3	0.727	0.248	5402	0.933	77.9
Average			0.261±0.011		82.0±3.5
100 mM NO ₃					
	NH ₃ produced (mM)	NH ₃ produced (mg)	Total charge (mAs)	Faradaic NH ₃ conc. (mM)	Faradaic efficiency (%)
Trial 1	0.553	0.188	5379	0.929	59.5
Trial 2	0.568	0.194	5409	0.934	60.8
Trial 3	0.584	0.199	5402	0.933	62.6
Average			0.194±0.005		61.0±1.5
Trial 1	0.330	0.112	5419	0.936	35.3
Trial 2	0.314	0.107	5428	0.938	33.4
Trial 3	0.322	0.110	5411	0.935	34.5
Average			0.110±0.003		34.4±0.8
Trial 1	0.211	0.072	5390	0.931	22.6
Trial 2	0.188	0.064	5392	0.932	20.1
Trial 3	0.136	0.046	5421	0.936	14.5
Average			0.061±0.012		19.1±3.9
Trial 1	0.376	0.133	5303	0.916	41.0
Trial 2	0.406	0.138	5338	0.922	44.1
Trial 3	0.389	0.133	5216	0.901	43.2
Average			0.133±0.005		42.7±1.5
Trial 1	0.026	0.009	5314	0.918	2.9
Trial 2	0.037	0.013	5319	0.918	4.1
Trial 3	0.032	0.011	5030	0.869	3.7
Average	0.032	0.011			3.6±5.7

[0070] The inventors addressed the former issue by also studying NO₂⁻ which has been found to have a similar reactivity as NO₃⁻ for plasma-injected solvated electrons, $k=5.2 \pm 2.6 \times 10^9 \text{ M}^{-1}\text{s}^{-1}$, but reacts close to 500 times faster with H[•] (Madden, K. P. et al., J. Phys. Chem. Ref. Data 2011, 40,, 023103). At the same concentrations as NO₃⁻, NO₂⁻ showed much stronger reduction of NH₃ production, with almost complete suppression at 1 M (see FIG. 14 and Table 12). These results substantiate that the formation of NH₃ occurs through solvated electron chemistry and that one of the key intermediates is H[•]. Previous work on reduction of N₂ to NH₃ by solvated electrons suggested either a mechanism based on N₂⁻ or H[•] (see Zhu, D. et al., Nat. Mater. 2013, 8, 836-841 and Christianson, J. R. et al., J. Phys. Chem. B 2014, 118, 195-203) and while the solvated electrons were generated here by a different approach, our scavenger experiments support NH₃ formation through H[•].

TABLE 12

Summary of one-sample and two-sample t-tests carried out on data sets in Table 11				
One-Sample t on NH ₃ production Test of $\mu = 0$ vs $\mu > 0.00$				
	Algebraic Mean	St. Deviation	95% Lower Bound	Probability
No Scavenger	0.313	0.010	0.307	0.000
10-mM N-	0.261	0.012	0.240	0.000

TABLE 12-continued

Summary of one-sample and two-sample t-tests carried out on data sets in Table 11				
One-Sample t on NH ₃ production Test of $\mu = 0$ vs $\mu > 0.00$				
	Algebraic Mean	St. Deviation	95% Lower Bound	Probability
O ₃ 10-mM N-O ₂	0.133	0.005	0.124	0.000
1 M N-O ₃	0.110	0.003	0.105	0.000
1 M N-O ₂	0.011	0.002	0.008	0.005
No-ne vs. 10-mM N-O ₃	0.051	0.018	0.085	0.023
10-mM N-O ₃ vs. 10-mM N-O ₂	0.128	0.095	0.162	0.004
No-ne vs. 1 M N-	0.203	0.195	0.211	0.000

TABLE 12-continued

Summary of one-sample and two-sample t-tests carried out on data sets in Table 11				
One-Sample t on NH ₃ production Test of $\mu = 0$ vs $\mu > 0.00$				
Algebraic Mean	St. Deviation	95% Lower Bound	Probability	
O ₃ 10-mM N-O ₃ vs. 1 M N-O ₃	0.152	0.120	0.184	0.002
1 M N-O ₃ vs. 1 M N-O ₂	0.099	0.093	0.105	0.000

[0071] Although the single-compartment cell was closed and purged with Ar or N₂ to remove background ambient air, the oxidation process at the Pt anode in our system evolves O₂ gas which could serve as an unintended impurity during the experiments in several ways. The presence of O₂ in the plasma could lead to reaction with gas-phase electrons and reduce their flux to the solution surface, thus, decreasing the concentration of solvated electrons produced. See Rumbach, P. et al., J. Phys. D 2015, 48, 424001. In addition, O₂ could react with N₂ in the plasma to produce NO_x in the gas phase, as historically demonstrated by the Birkeland-Eyde process, and its subsequent dissolution forms NO₂⁻ and NO₃⁻ in solution which would affect solvated electron chemistry via the aforementioned scavenging reactions (see FIG. 13). The relative similarity of NH₃ yields in the split and single cells show that the former is not a significant issue.

[0072] To address the latter, the inventors measured the NO_x generated in solution for our plasma electrolytic system. FIG. 15 and FIG. 16 show the NO_x concentration as a function of process time at 6 mA and as a function of current after 45 minutes, respectively. The complete set of data for all trials is shown in Table 13.

[0073] The current was 6 mA in the time trials, the processing time was 45 minutes in the current trials, and the reaction volume was 20 mL in all cases.

TABLE 13

Summary of NO _x produced by plasma electrolytic synthesis after different processing time and at different currents				
NO _x produced (mM)				
	t = 5 min	t = 15 min	t = 30 min	t = 45 min
Trial 1	0.412	0.654	0.951	1.18
Trial 2	0.438	0.659	0.929	1.09
Trial 3	0.468	0.629	0.971	1.06
Average	0.439	0.647	0.951	1.11
NO _x produced (mM)				
	I=2 mA	I = 4 mA	I = 6 mA	I=8 mA
Trial 1	0.653	1.04	1.18	1.13
Trial 2	0.671	0.990	1.09	1.03
Trial 3	0.658	1.03	1.06	1.16
Average	0.661	1.02	1.11	1.11

[0074] The NO_x concentrations were not found to be large enough to substantially scavenge and quench the solvated electrons (see FIG. 14). The inventors verified that the NO_x formation was from O₂ gas evolution at the Pt anode by also carrying out these measurements in the split cell which showed no detectable amount of NO_x. This was further corroborated by comparing the measured NO_x with an expected amount from the faradaic yield of O₂ and assuming that all of it reacts with N₂ (in the plasma) to form either NO₂ or NO₃ (see FIG. 17 and FIG. 18).

[0075] Given that O₂ gas evolution and subsequent NO_x formation does not likely have a large impact on NH₃ production in our specific reactor, and that our results collectively point to solvated electron concentration, H⁺ concentration, and H[•] concentration as all being important, the inventors speculate that there is a combination of factors that lead to the decreased NH₃ yield and faradaic efficiency as the current is increased above 2 mA, as shown in FIG. 4 and FIG. 5. The increased production of solvated electrons and their reaction may deplete the H⁺ at the plasma-liquid interface such that there is insufficient H⁺ for NH₃ formation. While H⁺ may be present in the bulk from the initial acid and water oxidation at the anode, transport limitations could prevent the H⁺ from reaching the interface. As discussed, low concentrations of H⁺, and high concentrations of H[•] would result in higher rates of HER. Thus, at higher currents and solvated electron concentrations, the HER becomes significant and reduces the selectivity towards NH₃ formation. The change in rate with time shown in FIG. 4 supports a potential interplay between kinetics and transport that needs further investigation. This interplay has been observed before in a similar reactor in our laboratory, where the goal was to make silver nanoparticles. There, a minimal concentration of 150 mM silver ions was needed to overcome transport limitations in the cell.

[0076] While the exploration of the kinetic and transport parameters is subject to future studies, the inventors have shown that the plasma hybrid system is capable of highly efficient NH₃ production. compare our results with recent electrochemical demonstrations at room temperature and pressure which use water as the proton source for ammonia generation in Table 14.

TABLE 14

Comparison of electrically-driven N ₂ reduction to ammonia demonstrations at atmospheric temperatures and pressures			
Reference	Production Rate (mg/hr)	Demonstration Size (geometric area, catalyst loading)	Faradaic Efficiency (%)
Shi 2017	0.021	1 cm ² area, 1 mg /cm ²	8%
Kong 2017	0.0038	6.25 cm ² , 1 mg/cm ²	10%
Zhou 2017	0.000063	0.25 cm ² , 146 ug/cm ²	60%
Bao 2017	0.00016	1 cm ² , 0.33 mg/cm ² catalyst	4%
Our Study	0.44	n/a, catalyst free	100%

[0077] The inventors note that only studies which utilize a non-nitrogen control gas are included, for a fair comparison. The inventors also only include the highest faradaic efficiency recorded in each study. The comparison reveals that the process described in this study has the highest faradaic efficiency while maintaining high production rate, which is over an order of magnitude higher compared to other electrochemical methods at similar reaction geometric areas.

Additionally, recent relevant work by Kong et al. demonstrated NH_3 production in a membrane-based device at 1.7 cell voltage allowing an estimate of power consumption. It was estimated that a power consumption of 8000 kwh/kg NH_3 at the highest 10% faradaic efficiency is achieved in the first hour of operation. While the present invention has a high power consumption (estimated to be 2700 kwh/kg NH_3 produced at 2 mA for 45 minutes) compared to H-B, which requires about 9-13 kWh/kg of NH_3 produced, the inventors note that the present invention doesn't require catalyst, high pressures, or temperatures and can operate at a small scale. This makes the present invention a promising technology for distributed production with high renewable energy resources.

[0078] The inventors demonstrate high faradaic efficiencies (up to 100%) are possible at ambient temperature and pressure for NH_3 production in liquid water using a catalyst-free, electrolytic hybrid plasma system which contained N_2 in the plasma gas. Scavenger experiments show that NO_x compounds reduce the NH_3 production, and show that this process occurs through a mechanism involving $\text{H}\cdot$ and solvated electrons. Experiments conducted at different pH, show that H^+ concentration is also significantly important to the overall production and efficiency. A comparison of this technology with other ammonia generation alternatives suggests that this is a promising approach for distributed, renewable NH_3 production.

Example 1: Ammonia Synthesis Using Plasma Electrochemical Cell

Plasma Electrochemical Cell Setup

[0079] The custom designed electrochemical cell contains a stainless steel capillary tube (Restek inc, 1/16" O.D., 0.02" I. D. and 10 cm long) that is connected to a negative high voltage power supply (Gamma High Voltage, RR15-10R) through a variable ballast resistor (0.25-1 M Ω) in series as the cathode. A Pt foil (Alfa Aesar, 99.9% purity, 0.001" thick) was wired through a 500 Ω resistor to ground to form the anode. The electrodes, along with two purging tubes were fed into the reactor cell through a custom polytetrafluoroethylene (PTFE) lid that ensured that the reactor cell is isolated from ambient gasses. One of the purging tubes was used for bubbling nitrogen through the solution and the other served as exhaust. The capillary tube was set at a high voltage and then lowered into the cell through the lid until the microplasma ignited close to the solution surface. All experiments were performed at a constant current mode of the power supply and in 20 mL of electrolyte solution.

[0080] Some control experiments were performed using a H-shaped electrochemical cell. A representative drawing of the cell is shown in FIG. 10. In this cell, the cathode and the anode chambers were separated with a glass frit. Each of these two compartments are sealed with PTFE lids. The lids are designed such that they allow the insertion of a pair of purging tubes and an electrode in the respective half-cells. In general, the split-cell experiments were operated using similar plasma initiation protocols as that of the previously described single cell. However, the presence of the frit usually increases the resistance of the circuit and thus needs a relatively higher operating voltage for the same current. Each half-cell contained 20 mL electrolyte solution.

Calculation of Charge Transferred and Power Yield

[0081] The current passing through the microplasma and the electrolyte was determined by measuring and dividing the voltage drop across the 500 Ω resistor, every 30 ms. This data was recorded continuously for the duration of each experiment using a custom LabView interface between the computer and the voltmeter. The obtained current vs. time plot was then integrated to calculate the total amount of charge transferred during each individual experiment.

Sample Preparation and Treatment

[0082] Unless stated otherwise, pH 3.5 sulfuric acid solution was prepared from 18.2 M Ω water and sulfuric acid (Sigma Aldrich, 99.999% purity) and 20 mL used for each sample solution. The sample solution is then bubbled with nitrogen (Airgas, 99.99+%) for 30 minutes ensuring the removal of any dissolved gasses and to fill the container headspace with N_2 . The purging tube was then raised out of the sample solution and the Pt metal anode lowered into the solution. 60 sscm of N_2 was then flowed through the capillary tube cathode and a DC microplasma formed at the surface of the sample solution. Standard conditions of operation were 45 minutes of plasma treatment at 6 mA unless otherwise noted. Experiments were also performed with varying concentrations of NaNO_3 and NaNO_2 (Acros Organics, purity 99+%) as radical scavengers.

[0083] In order to ensure that during the plasma-electrochemical process all ammonia was produced in the electrolyte, a secondary trap-cell was incorporated. The reaction effluents were passed through a trap-cell containing H_2SO_4 solution of pH = 2. The trap-cell contents were later analyzed for ammonia.

Ammonia Identification

[0084] Immediately following plasma treatment experiments, 2 mL electrolyte was stored in a N_2 purged, sealed vial and refrigerated until ammonia analysis. The ammonia assay (BioAssay Systems, QuantiFluo DNH3-200) utilized an o-phthalaldehyde method and quantified with fluorescence at wavelengths of 360/450 nm. The fluorescent intensity of the assay has a lower detection limit at 12 μM and increases proportionally with ammonia concentration in the sample solution. The fluorescence of the assay is calibrated using four known solutions of basic water containing ammonium hydroxide at 0.001, 0.01, 0.1 and 1 M for every batch of measurements. A sample dataset of assay calibration and NH_3 concentration calculations can be found in FIG. 19 and FIG. 20.

Statistical Analysis

[0085] All data are represented as the mean of a data set \pm the standard error which was calculated from the variance in the raw data within two standard deviations of the mean (approximately 95% confidence interval). Statistical differences between data sets were determined using a two-sample t-test (Minitab). To determine if a data set was nonzero, a one sample t-test was employed. All t-tests were performed using Minitab Software Version X. The results of all of the t-tests and the sample size for each data set is tabulated. For all statistical tests, a threshold value of $\alpha = 0.05$ was chosen, and a p-value at or below 0.05 indicated significance.

[0086] The complete disclosure of all patents, patent applications, and publications, and electronically available material cited herein are incorporated by reference. The foregoing detailed description and examples have been given for clarity of understanding only. No unnecessary limitations are to be understood therefrom. The invention is not limited to the exact details shown and described, for variations obvious to one skilled in the art will be included within the invention defined by the claims.

What is claimed is:

1-12. (canceled)

13. An electrochemical cell for ammonia synthesis, comprising: a container comprising an acidic liquid electrolyte; a source of nitrogen gas; a metal electrode at least partially immersed in the electrolyte; a metal tube electrode spaced apart from a surface of the electrolyte by a predetermined spacing; and wherein the electrochemical cell is configured to provide a plasma spanning the predetermined space from the metal tube electrode to contact the surface of the electrolyte when power is applied to the metal tube electrode.

14. The electrochemical cell of claim **13**, wherein the source comprises a hollow conductive body including a first opening and a second opening comprising a nitrogen gas outlet and the second opening being separated from the surface of the acidic liquid electrolyte by the predetermined spacing.

15. The electrochemical cell of claim **13**, wherein the metal electrode comprises a platinum electrode.

16. The electrochemical cell of claim **13**, wherein the acidic liquid electrolyte has a pH of 5 or less.

17. The electrochemical cell of claim **13**, wherein the source of nitrogen gas is configured to deliver the nitrogen gas at a flow rate of about 125 milliliter (mL) per minute.

18. The electrochemical cell of claim **13**, wherein the metal tube electrode comprises a stainless electrode.

19. The electrochemical cell of claim **13**, wherein the electrochemical cell has a volume of about 1 liters or less.

20. The electrochemical cell of claim **13**, wherein the electrochemical cell has a volume of about 100 milliliter (mL) or less.

* * * * *