Oxygen Electrode Bifunctional Electrocatalyst NiCo$_2$O$_4$ Spinel

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SUMMARY

A significant increase in energy density may be possible if a two-unit alkaline regenerative H₂-O₂ fuel cell is replaced with a single-unit system that uses passive means for H₂O transfer and thermal control. For this single-unit system, new electrocatalysts for the O₂ electrode will be required which are not only bifunctionally active but also chemically and electrochemically stable between the voltage range of about 0.7 and 1.5 V. NiCo₂O₄ spinel is reported to have certain characteristics that make it useful for a study of electrode fabrication techniques. High surface area NiCo₂O₄ powder was fabricated into unsupported, bifunctional, PTFE-bonded, porous gas fuel cell electrodes by commercial sources using varying PTFE contents and sintering temperatures. The object of the present study was to measure the bifunctional activities of these electrodes and to observe what performance differences might result from different commercial electrode fabricators.

O₂ evolution and O₂ reduction data were obtained at 80 °C (31 percent KOH). An irreversible reaction (i.e. aging) occurred during O₂ evolution at potentials greater than about 1.5 V. Anodic Tafel slopes of 0.06 and 0.12 V/decade were obtained for the aged electrodes. Within the range of 15 to 25 percent, the PTFE content was not a critical parameter for optimizing the electrode for O₂ evolution activity. Sintering temperatures between 300 and 340 °C may be adequate but heating at 275 °C may not be sufficient to properly sinter the PTFE-NiCo₂O₄ mixture.

Electrode disintegration was observed during O₂ reduction. Transport of O₂ to the NiCo₂O₄ surface became prohibitive at greater than about -0.02 A/cm². Cathodic Tafel slopes of -0.06 and -0.12 V/decade were assumed for the O₂ reduction process. A PTFE content of 25 percent (or greater) appears to be preferable for sintering the PTFE-NiCo₂O₄ mixture.

INTRODUCTION

An effective and efficient electrical power system is a major requirement for most NASA missions. One system of interest is an energy storage device in conjunction with a photovoltaic array. Desired characteristics for the storage device are light weight, low volume, high efficiency, long life and reliability. The two-unit alkaline regenerative H₂-O₂ fuel cell is one of the candidates for use in the low earth orbit (LEO) manned space station. For example, a H₂-O₂ fuel cell may be used to generate power during the dark portion of the orbit and an electrolyzer may be used to regenerate H₂ and O₂ during the light portion (ref. 1). While the energy density for a H₂-O₂ system is large, the efficiency is considerably less than 100 percent due to the irreversibility of the O₂ electrode. Improved electrocatalysts are needed to minimize the
kinetic polarization losses resulting from this irreversibility for both fuel
cell and electrolyzer conditions.

Recent GEO mission analysis indicated that a significant increase in the
energy density is possible if the two-unit system is replaced with a single-
unit system that uses passive means for water transfer and thermal control
(ref.2). For this single-unit system, it is essential to develop new electro-
catalysts for the \( \text{O}_2 \) electrode which are not only bifunctionally active and
efficient but also chemically and electrochemically stable over the voltage
range of about 0.7 to 1.5 V (i.e. the probable range for a practical single-
unit regenerative \( \text{H}_2-\text{O}_2 \) fuel cell).

Perovskite and spinel oxides have been investigated for monofunctional
electrocatalytic activity for either \( \text{O}_2 \) evolution or reduction. Studies of
bifunctional electrocatalytic activity, however, are rare. The NiCo\(_2\)O\(_4\) spinel
is one of the more active electrocatalysts for \( \text{O}_2 \) evolution as illustrated in
figure 1 (ref. 3). NiCo\(_2\)O\(_4\) powder which can be made in high surface form is
chemically stable in KOH and is a moderate electrical conductor. Electrolysis
porous gas electrodes, fabricated from a mixture of NiCo\(_2\)O\(_4\) powder and polyte-
trafluoroethylene (PTFE) (i.e. PTFE-bonded), were reported to give over
1.3 A/cm\(^2\) at 1.63 V in 5N KOH at 70 \( ^\circ \)C (ref. 4). Furthermore, this type of
electrode was reported to be stable during \( \text{O}_2 \) evolution at 1 A/cm\(^2\) with less
than a 0.05 V increase in polarization after 3000 hr (ref. 5).

Very limited work has been done on electrocatalytic activity of spinel
oxide catalysts for \( \text{O}_2 \) reduction. A polarization curve was reported for an
"optimized" PTFE-bonded NiCo\(_2\)O\(_4\) electrode which suggests that greater than
0.2 A/cm\(^2\) can be obtained at 0.8 V. While very slow decomposition of the
NiCo\(_2\)O\(_4\) can be inferred from the reported corrosion currents, long time dura-
bility for the electrode was not established (ref. 6).

NiCo\(_2\)O\(_4\) is reported to have certain characteristics other than bifunc-
tional activity that make it useful as the electrocatalyst for a study of opti-
mization of electrode fabrication techniques: ease of preparation as a high
surface area powder; suitable preparation of a single phase by low temperature
treatment of the precursors; and sufficient durability for proper electrode
evaluation. Therefore, NiCo\(_2\)O\(_4\) spinel was chosen as the electrocatalyst for a
study of unsupported electrocatalysts fabricated into bifunctional, PTFE-
bonded, porous gas fuel cell electrodes. The object of the present study was
to measure its bifunctional activity and to observe what performance differ-
ces might result from different commercial electrode fabricators, using the
same catalyst powder, held to similar specifications.

EXPERIMENTAL

Fabrication of Electrodes

High surface area NiCo\(_2\)O\(_4\) powder was prepared by ELTECH Corp. using the
coprecipitation method (ref. 7). Hydroxides were coprecipitated from dilute
solutions of Co and Ni (2:1 ratio) chlorides by KOH. The gelatinous mixture
was filtered and washed. The resulting residue was heated at 400 \( ^\circ \)C for 5 hr
in air to produce NiCo$_2$O$_4$ powder. This powder, which contains a wide range of particle or agglomerate sizes, was primarily NiCo$_2$O$_4$ spinel with some NiO present as an impurity (ref. 8). A surface measurement (BET) of this powder, using a Beta Scientific Automatic Surface Analyzer Model 4200, gave an area of 43 m$^2$/g.

PTFE-bonded, porous gas electrodes were fabricated by three commercial sources using the NiCo$_2$O$_4$ powder prepared by ELTECH Corp. While fabrication techniques are considered by the fabricators to be proprietary, some details are reportable. A catalyst-PTFE mixture was pressed onto a 100 mesh Au plated Ni screen and the resulting "green" electrode was heat treated. Electrode parameters are given in Table I. All electrodes contain essentially the same weight loadings of NiCo$_2$O$_4$. PTFE contents of either 15 or 25 percent of the NiCo$_2$O$_4$ were used. Electrodes 1 and 5 have a Gortex PTFE backing at the gas side. This type of backing serves as a barrier to liquid electrolyte but not to gaseous O$_2$.

**Electrochemical Apparatus and Measurements**

A floating half-cell was used for all electrochemical measurements (ref. 9). A schematic of the cell is shown in figure 2. A working electrode (1.266 cm$^2$ of geometric area) was introduced into the cell with the catalyst side of the electrode touching the surface of the 31 percent KOH. Pt foil served as the counter electrode and a Hg/HgO electrode served as the reference electrode. The temperature coefficient for the Hg/HgO reference, shown in figure 3, was about $-4.5 \times 10^{-4}$ V/°C. Therefore, Hg/HgO reference potentials obtained at 25 and 80 °C correspond to reversible H$_2$ electrode potentials (RHE) of 0.926 and 0.902 V, respectively. Gaseous O$_2$ was passed through a presaturator, maintained at the same temperature as the cell, and then into the cell. This presaturation minimizes H$_2$O loss and thus changes in KOH concentration during the test runs.

For most of the measurements, a potentiostat (EG&G Princeton Applied Research Model 173), with a plug-in unit (EG&G Model 276) was interfaced with a computer system (Apple IIe). A computer program (EG&G Electrochemistry Program Volume I) was used to drive and control the potentiostat. IR polarization values were determined by means of an IR instrument (Electrosynthesis Corp. Model 800) in conjunction with a 7 V Zener diode. Schematics are shown in figures 4(a) and 4(b). The IR instrument interrupts the run periodically for an interval of a few microseconds. The Zener diode limits the voltage rise of the potentiostat to 7 V during the interruption.

PTFE-bonded, porous gas electrodes often require preconditioning, prior to steady-state measurements, to minimize polarizations. Therefore each NiCo$_2$O$_4$ electrode was preconditioned at 80 °C by slowly increasing the anodic currents (at less than 2 V) until 1 A could be obtained. Usually, this time interval required less than 20 to 30 min. The anodic current was then decreased to about 0.1 A and held for about 1 hr. While holding at 0.1 A the height of the working electrode was adjusted relative to the KOH surface to minimize electrode and IR polarizations.

$^1$Gortex is a trade name of W.L. Gore & Co.

$^2$All potential values in this report will refer to RHE unless otherwise stated.
Steady-state, potential-current values were determined galvanostatically starting at the larger currents (e.g. 1 A). Each potential measurement was recorded with time for an interval of 3 to 6 min. As illustrated for electrode 5 in figures 5 (a) and (b), steady-state conditions were usually obtained after 10 to 30 sec, particularly for the larger currents. Even at the smaller currents (e.g. 0.001 A), less than 3 min was required to obtain steady-state conditions.

IR corrected potentials were obtained from plots of IR polarizations versus currents as illustrated in figure 6 for a typical run.

RESULTS

O₂ Evolution

O₂ evolution at nonaged PTFE-bonded NiCo₂O₄ electrodes. - At larger anodic currents, O₂ gas produced in the electrode pores may force some of the KOH electrolyte out of these pores (ref. 4). In addition, detachment of O₂ bubbles from the electrode surface becomes increasingly more difficult at these larger currents. As a consequence, the steady-state potentials (and IR polarizations) at larger currents become more erratic and difficult to measure. This is illustrated in figure 7 for a typical run at 0.6 A where the potential became erratic after only a few seconds. Therefore, data obtained at anodic currents above about 0.2 A were not recorded.

Electrode 5 (table I) was anodically preconditioned at 0.1 A but was not held at potentials more anodic than 1.5 V for an extended period of time (i.e. aged) prior to its being examined for O₂ evolution. Then, O₂ evolution data were obtained galvanostatically for this nonaged electrode. An IR corrected Tafel plot, obtained at 80 °C, is shown in figure 8. The Tafel slope for this nonaged electrode at the smaller current region (i.e. less than 0.060 A/cm²) was about 0.045 V/decade. This value of 0.045 is in excellent agreement with the value of 0.047 reported for a PTFE-bonded NiCo₂O₄ electrode at 25 °C (ref. 10). Sufficient data were not obtained for the larger current region to determine its slope.

O₂ evolution at aged PTFE-bonded NiCo₂O₄. - Nonaged NiCo₂O₄ undergoes slow irreversible changes at more anodic potentials with accompanying changes in its electrocatalytic activity for O₂ evolution. The aging process was reported to be complete after about 2 hr if the electrode is maintained at potentials more anodic than 1.5V (ref. 11). It can be seen in figure 9 that the performance of the aged electrode is poorer than that of the nonaged electrode. However, the characteristics of the aged electrode will determine long-term performance of the catalyst in a practical energy storage system. Therefore, all NiCo₂O₄ electrodes were aged anodically at 1 A for about 6 to 7 hr.

After aging, steady-state, current-potential data were obtained galvanostatically for the 6 electrodes starting at the larger currents. The IR corrected Tafel data for each aged electrode could be fitted to 2 straight line regions: a slope of 0.12 V/decade was obtained for the larger currents and a slope of 0.060 V/decade was obtained for the smaller currents. A typical IR corrected Tafel plot (electrode 5) is shown in figure 9. For comparison, the corresponding Tafel data for nonaged electrode 5 are also shown in figure 9 as a dashed line.
The geometric exchange current density can be determined by extrapolation of the Tafel data to the thermodynamic potential of H2O at 80 °C (i.e. 1.18 V). This extrapolated value can be calculated from the data using the following expression:

\[ 1.18 = A + (S)(\log i_0) \]

where \( A \) is the potential at 1 A/cm² in volts, \( S \) is the slope in V/decade, and \( i_0 \) is the geometric exchange current density in A/cm². Estimating the "true" exchange current density for a porous gas electrode involves relating the total available surface area of the catalyst in the electrode to the electrode geometric surface area. The total surface area of the NiCo2O4 powder in the electrode can be estimated from the powder surface area (43 m²/g), as determined by BET, and the quantity of powder used in the electrode. The "true" surface of the electrode can then be calculated by assuming 100 percent availability of the NiCo2O4 powder surface area. This assumption of 100 percent availability is supported by a BET measurement of electrode 1 after it had been used for electrochemical studies. For example, electrode 1 initially contained 0.027 g/cm² of NiCo2O4 powder corresponding to a value of about 1.2x10⁴ cm² of "true" available surface area if 100 percent availability is assumed. A BET measurement of this electrode after aging gave a value of about 1.4x10⁴ cm².

The Tafel results for each electrode are listed in Table II. For the 0.12 V/decade slope region, electrodes 1, 2, 3, and 4 gave essentially the same value for the potential at 0.1 A/cm² and, consequently, essentially the same geometric exchange current density for this region. Averaging the values for these 4 electrodes gave values of 1.466 V for the potential at 0.1 A/cm², 4.2x10⁻⁴ A/cm² for the geometric exchange current density and 3.9x10⁻⁸ A/cm² for the "true" exchange current density. If a maximum error of about 0.01 V is estimated for the potentials at 0.1 A/cm², the potentials for similar electrodes should range between 1.436 and 1.456 V. The corresponding calculated geometric exchange current densities for these potentials of 1.436 and 1.456 V are 3.4x10⁻⁴ and 5.5x10⁻⁴ A/cm², respectively. Electrodes 1, 2, 3, and 4 lay within this range. There were differences, however, in the fabrication processes for these 4 electrodes both in PTFE content and heat treatment. Consider electrodes 2 and 4; both had been fabricated by Electrochem Inc. with a 300 °C heat treatment, but with PTFE contents of 25 and 15 percent, respectively. Since both gave essentially the same Tafel data for the higher current region, PTFE contents within the range of 15 to 25 percent may not be a critical parameter for optimizing PTFE-bonded NiCo2O4 electrodes for O₂ evolution. Unlike that for electrodes 1, 2, 3, and 4, the geometric exchange current density for electrode 6 was almost a factor of 2 smaller than the estimated lower limit of 3.4x10⁻⁴ A/cm². Electrodes 4 and 6 were fabricated by Electrochem Inc. with the same PTFE content (15 percent) but were heat treated at 300 and 275 °C, respectively. A minimum heat treatment of 300 °C, therefore, is considered to be an important parameter for optimizing an electrode for O₂ evolution performance. Heating at 275 °C may not be sufficient to properly sinter the PTFE-NiCo2O4 mixture.

For the smaller current region (0.060 V/decade), electrodes 1, 2, 3, and 4 gave similar values for the potentials at 0.01 A/cm² and for the corresponding geometric exchange current densities. Averaging the results for these 4 electrodes gave values of 1.382 V for the potential at 0.01 A/cm², 4.8x10⁻⁶ A/cm² for the geometric exchange current density and 4.3x10⁻¹⁰ A/cm² for the "true"
geometric exchange current density. If a maximum error of about 0.01 V is estimated for these potentials at 0.01 A/cm², the range for the geometric exchange current densities is between 2.9x10⁻⁶ and 6.3x10⁻⁶ A/cm². While the values for electrodes 1, 2, 3, and 4 lie close to this range, the value for the geometric exchange current density for electrode 6 is almost an order of magnitude smaller than the average of these 4 electrodes.

The O₂ evolution data for aged electrode 1 (obtained in the present study) is compared in figure 10 as a dashed line with data reported in the literature for aged, PTFE-bonded NiCo₂O₄ electrodes. Values for one electrode at 25 °C were taken from figure 1 of Botejue Nadesan (ref. 7). For this electrode, the "true" catalyst surface area, assuming 100 percent utilization of the NiCo₂O₄ powder surface area, was similar to that calculated for electrode 1 but its catalytic activity is less than that of electrode 1. The values for a second electrode at 84 °C were taken from figure 1 of Davidson (ref. 12). Its total catalyst surface area was estimated to be about one-half that of electrode 1. While complete details of the fabrication techniques (e.g. PTFE contents) for the Davidson electrode were not reported, its Tafel data for both current regions were similar to that obtained for electrode 1 of the present study particularly when the data are normalized to similar total catalyst surface areas.

Mechanisms for O₂ evolution at NiCo₂O₄ - Mechanisms have been proposed for the O₂ evolution process at oxide surfaces, but a definitive mechanism is still in question. For example, one proposed mechanism suggests that a higher valence oxide intermediate is formed at the NiCo₂O₄ spinal surface. This intermediate is subsequently decomposed to produce O₂ (ref. 13). More recently, molecular orbital calculations have been used to study O₂ evolution at the surface of a SrFeO₃ perovskite. For this oxide, the Fe species is forced into the +4 valence state if the O sites are filled. It was proposed that the reaction was initiated by an attack of OH⁻ at the Fe⁺⁴ species on a face site (ref. 14). The first two steps for both of these mechanisms are similar in that an oxide intermediate is formed at the surface. The two mechanisms differ, however, in the subsequent formation of O₂ from the oxide intermediate. Mehandru's mechanism (ref. 14) involves the formation and then decomposition of a peroxide species while Rasiyah's mechanism (ref. 13) involves the decomposition of the oxide intermediate by means of a second metal species.

A series of reactions, which involves only a minor modification of Mehandru's mechanism, is presented here to account for the O₂ evolution processes occurring with slopes of 0.12 and 0.06 V/decade at aged NiCo₂O₄ surfaces. In this series, M represents a higher valence cation species (e.g. Co⁺³) rather than Fe⁺⁴ as proposed by Mehandru for SrFeO₃.

\[
\begin{align*}
M & + OH^- \rightarrow M-OH \\
M-OH & + OH^- \rightarrow (M-O)-1 \\
(M-O)-1 & + OH^- \rightarrow M-O \\
M-O & + OH^- \rightarrow M-O-O + e \\
M-O-O & + OH^- \rightarrow M-O-HOH + e \\
M-O-O + HOH & \rightarrow M + O_2 \\
\end{align*}
\]

Rasiyah reported a slope of about 0.04 V/decade for the smaller current region. A reaction similar to reaction (C) (given above) was proposed for the rate controlling step for this region (ref. 13). In the present study, a slope of about 0.045 V/decade was obtained for a nonaged NiCo₂O₄ electrode for
the smaller current region; but, after aging, the slope became 0.06. A more plausible explanation for the change from 0.045 to 0.06, therefore, involves aging of the NiCo₂O₄ by conversion of the metal species at the surface to higher valence states. This aging process will be discussed later in more detail.

After aging, all 6 aged NiCo₂O₄ electrodes gave slopes of 0.12 and 0.060 V/decade. These values of 0.12 and 0.06 are in agreement with the hypothesis that reaction (A) is the rate-determining step for the larger current region and that reaction (B) is the rate-determining step for the smaller current region. For example, if a Langmuir condition (i.e. small absorption) is assumed, an anodic Tafel slope can be calculated from the number of electrons transferred using the following expression:

\[
S_a = \frac{[RT]}{[F]b(\ell - k + n/v) - \ell}
\]  

where \(S_a\) is the anodic slope in V/decade, \(b\) is the beta symmetry factor (0.5), \(\ell\) is the number of electrons which must be removed prior to the rate-determining step to permit the rate-determining step to occur once, \(k\) is the number of electrons which must be removed to permit the products of one occurrence of the rate-determining step to be transferred to the final state, \(n\) is the total number of electrons transferred in the over-all reaction, \(v\) is the stoichiometric number which is equal to the number of times that the rate-determining step occurs when the over-all reaction occurs once, and \(R, T, \) and \(F\) have the usual significance (i.e. \(RT/F = 0.059\) for 25 °C) (ref. 15). For the larger current region, a value of about 0.12 V/decade is calculated for the slope if reaction (A) is assumed to be the rate-determining step. For this calculation, the following values are used for reaction (A): \(n = 4, \ell = 0, k = 3,\) and \(v = 1\). For the smaller current region, a slope of about 0.06 is calculated for the slope if reaction (B) is assumed to be the rate-determining step. For this calculation of the smaller current slope, the following values are used for reaction (B): \(n = 4, \ell = -1, k = 3\) and \(v = 1\).

An alternative type of mechanism has been proposed in an attempt to account for the observed change in slope from 0.12 to 0.06 for processes occurring at Pt catalysts. As the current decreases from the larger currents, the coverage changes from a Langmuir adsorption (i.e. small coverage) to Temkin adsorption (larger coverage). It has been proposed that for some electrochemical processes the coverage proceeds linearly with potential, thereby modifying the relation between the slope and the number of electrons transferred (refs. 16 and 17). As a consequence, the slope may change from 0.12 to 0.06 V/decade for the same 1 electron transfer step. If this type of mechanism is the controlling one for \(O_2\) evolution at the NiCo₂O₄ surface, reaction (A) could predominate for both current regions with Temkin adsorption controlling for the smaller current region and Langmuir adsorption controlling for the larger current region. However, a recent study suggests that a change from Langmuir to Temkin adsorption does not contribute significantly to an observed change in slope. For example, this study indicated that the difference between steady-state, current-potential curves during the change from Langmuir to Temkin adsorption is relatively small owing to the dual effects of Temkin adsorption on the coverage and on the apparent rate constants (ref. 18). Therefore, the authors of the present study believe that this alternate type of mechanism does not contribute significantly to the observed change in slope for \(O_2\) evolution at aged NiCo₂O₄ surfaces.
Anodic aging of the NiCo$_2$O$_4$ surface. - As discussed previously, the slope for the O$_2$ evolution process for the smaller current region changed from about 0.045 to 0.06 V/decade during anodic aging at 1 A for more than about 6 hr. During this aging process certain irreversible changes occurred at the NiCo$_2$O$_4$ surface.

This change in the surface composition during aging is supported by analyses reported for aged and nonaged NiCo$_2$O$_4$ electrodes. For example, analyses for Ni, Co, O and C, as determined by x-ray photoelectron spectroscopy (XPS), were reported by Haenen for surfaces of "freshly" prepared (i.e. nonaged) and for aged NiCo$_2$O$_4$ electrodes using NiCo$_2$O$_4$ powder prepared by decomposing Co and Ni (2:1) mixed nitrates at 300 and 400 °C (ref. 19). Carbon, present as a contaminant from the experimental system, was also included in the analyses. The reported analytical results were recalculated in the present paper for Ni, Co and O by excluding C. The stoichiometries of the NiCo$_2$O$_4$ surfaces for aged and nonaged electrodes were then calculated. For this calculation, an ideal NiCo$_2$O$_4$ spinel structure of (Co + Ni)$_6$O$_4$ is assumed. For the nonaged electrodes (300 and 400 °C), the stoichiometries indicated that O deficiencies were present for both electrode surfaces. The surface compositions for these 2 nonaged electrodes were then calculated by assuming the following: the total Co and Ni content was equal to 3; Co is oxidized more readily than Ni; and charge balance is maintained. Therefore, the surface compositions for the 2 nonaged NiCo$_2$O$_4$ electrodes can be expressed as follows:

1. (Ni$^{+2}$)$_{0.83}$(Co$^{+2}$)$_{1.80}$(Co$^{+3}$)$_{0.37}$(O$^{-2}$)$_{3.16}$ (NiCo$_2$O$_4$ prepared at 300 °C)
2. (Ni$^{+2}$)$_{1.48}$(Co$^{+2}$)$_{0.90}$(Co$^{+3}$)$_{0.62}$(O$^{-2}$)$_{3.33}$ (NiCo$_2$O$_4$ prepared at 400 °C)

Both of these nonaged electrodes have similar surface compositions: a large O deficiency is present; most (or all) of the Ni is present in the +2 valence state; and Co is present in both the +2 and +3 state.

For the aged electrode, analyses were reported only for the electrode which was fabricated using NiCo$_2$O$_4$ that was prepared at 300 °C (ref. 19). The surface stoichiometry was recalculated in the present study by excluding C. This calculation indicated that the O content had increased sufficiently during aging so that a stoichiometry of 4 can be assumed for the O content at the surface with a corresponding deficiency of cation species (Co + Ni). Therefore, the surface composition for this aged NiCo$_2$O$_4$ can be expressed as follows:

(Ni$^{+2}$)$_{0.50}$(Ni$^{+3}$)$_{0.18}$(Co$^{+3}$)$_{2.16}$(O$^{-2}$)$_{4.00}$ (NiCo$_2$O$_4$ prepared at 300 °C)

By comparing the compositions calculated for the surfaces of the above aged and nonaged electrodes, it is concluded that the aging process for the NiCo$_2$O$_4$ electrodes used in the present study is accompanied by the following:

1. O is added to the surface thereby minimizing the large O deficiency that was present initially in the nonaged NiCo$_2$O$_4$.
2. The Co deficiency, present initially in the nonaged electrode (where some of the Co sites are filled with Ni$^{+2}$), is minimized.
3. Some of the Ni$^{+2}$, which was the principal Ni species at the nonaged NiCo$_2$O$_4$ surface, is oxidized to Ni$^{+3}$.  

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Most (or all) of the Co species, present in the nonaged electrode as Co$^{+2}$, is oxidized to Co$^{+3}$.

**O$_2$ Reduction**

**Stability of PTFE-bonded NiCo$_2$O$_4$ electrodes.** - If NiCo$_2$O$_4$ is to be considered as a bifunctional catalyst in a single-unit energy storage system, the NiCo$_2$O$_4$ should have good stability between the voltage range of 0.7 and 1.5 V as well as good activity. The long time durability of NiCo$_2$O$_4$ has not been sufficiently established to date. For example, moderate stability, as indicated by corrosion current measurements, has been reported for NiCo$_2$O$_4$ at voltages more anodic than about 0.6 V (ref. 6). Another study, however, suggested that NiCo$_2$O$_4$ decomposes irreversibly below about 0.7 to 0.9 V (ref. 11). A third study also indicated that decomposition occurred for a NiCo$_2$O$_4$ coating formed on a oxidized Ni:2Co alloy, as indicated by a decrease in O$_2$ reduction current with time at potentials below about 0.6 V (ref. 20).

In the present study, all 6 aged NiCo$_2$O$_4$ electrodes showed electrode disintegration even at moderate cathodic currents. For example, solids were observed in the electrolyte at potentials below about 0.7 V. While some of the NiCo$_2$O$_4$ spinel in the electrode may be decomposing at these voltages, it appeared that most of the electrode disintegration was due to shedding of NiCo$_2$O$_4$ from the current collector.

O$_2$ reduction at PTFE-bonded NiCo$_2$O$_4$ electrodes. - While decomposition of NiCo$_2$O$_4$ occurs at lower potentials, its rates probably are sufficiently slow in the voltage range of interest to allow steady-state, current-potential data to be obtained. Atomic absorption spectrophotometer analysis supports this assumption. For example, analyses of the KOH solutions, after the electrodes had been used for the O$_2$ reduction studies, showed that the solutions contained less than 5 µg/cm$^3$ (the limit of detection) of both Ni and Co.

The 6 electrodes which were used previously for the O$_2$ evolution studies were cathodically preconditioned by holding at about -0.05 A for about 5 min. Current-potential data were then obtained galvanostatically starting at about -0.05 A and then reducing the current a few millivolts for each subsequent steady-state measurement. The Tafel results for O$_2$ reduction at the 6 electrodes are shown in figure 11. Poor O$_2$ mass transfer and poor electrode optimization for all 6 electrodes were evident as indicated by the short current range for which O$_2$ reduction data could be fitted to straight line regions. For example, the highest activity was obtained for electrode 5. The deviation from straight line regions for electrode 5 is shown more clearly in figure 12. Tafel data were obtained for electrode 5 only up to about -0.02 A/cm$^2$ after which the potential decreased rapidly with only small increases in current.

While O$_2$ reduction data for most of the NiCo$_2$O$_4$ electrodes were not obtained at currents less than about -0.0005 A/cm$^2$, two Tafel regions were assumed to be present for all 6 electrodes. For electrode 5, as illustrated
in figure 13, a slope of \(-0.06 \text{ V/decade}\) was obtained for the current range of \(-0.001 \text{ to } -0.010 \text{ A/cm}^2\). For the current range of \(-0.010 \text{ to } -0.020 \text{ A/cm}^2\), the data for electrode 5 could be fitted to a straight line with a slope of \(-0.12 \text{ V/decade}\). Determining this Tafel slope was difficult since increased \(\text{O}_2\) concentration polarization was occurring. For electrode 6 as illustrated in figure 14, a slope of about \(-0.12 \text{ V/decade}\) was obtained for the current range of \(-0.0008 \text{ to } -0.004 \text{ A/cm}^2\). Presumably, a slope of \(-0.06\) would also have been observed if smaller currents had been used. Therefore, slopes of \(-0.06\) and \(-0.12 \text{ V/decade}\) were assumed for all 6 electrodes as given in Table III.

As seen in table III, more scatter in the data was observed for the reduction of \(\text{O}_2\) in the region of \(-0.12 \text{ volt/decade}\) than for the corresponding \(\text{O}_2\) evolution process. For example, the calculated geometric exchange current densities for the \(\text{O}_2\) reduction process ranged between \(9 \times 10^{-7} \text{ and } 2.8 \times 10^{-5} \text{ A/cm}^2\) for the 6 electrodes for this region. This scatter may be related to the quantity of PTFE used and its effect on the electrode structure. The effect of PTFE content would be expected to be more significant for the \(\text{O}_2\) reduction process since \(\text{O}_2\) is transported to the reaction sites by moving through the PTFE fibers.

The geometric exchange densities for the \(-0.12\) region for electrodes 1, 2, and 5 are larger than those for electrodes 3, 4, and 6. Electrodes, 1, 2, and 5 had PTFE contents of 25 percent while electrodes 3, 4, and 6 all contained 15 percent PTFE. This effect of increased activity with increased PTFE content is also illustrated by comparing electrodes 2 and 4, both of which were obtained from the same commercial source. Both electrodes were sintered at the same temperature, 300 °C, but had PTFE contents of 25 and 15 percent respectively. The geometric exchange current density for electrode 2 was almost twice that of electrode 4. It was concluded, therefore, that a PTFE content of 25 percent (or greater) may be preferred for optimizing PTFE-bonded NiCo2O4 porous gas electrodes for \(\text{O}_2\) reduction catalytic activity.

The data obtained in the present study for electrode 5 is compared in figure 15 with data reported for \(\text{O}_2\) reduction at NiCo2O4. For one study, one datum point was reported for \(\text{O}_2\) reduction at 0.9 V at 80 °C. For this electrode, NiCo2O4 powder of 80 m²/g was used, but the sintering conditions were not given (ref. 21). The current at 0.9 V is in reasonable agreement with that obtained in the present study for electrode 5. Electrode 5 was also compared with data reported for an "optimized" electrode (ref. 22). While only a few data points were reported for this electrode, slopes of about \(-0.06\) and \(-0.12 \text{ V/decade}\) can be assumed for these data along with an initiation of \(\text{O}_2\) concentration polarization at larger currents, in reasonable agreement with the present study. The currents obtained for this optimized electrode were about 5 times larger than those found in the present study for electrode 5. The "optimization" technique, however, was not reported.

Mechanisms for \(\text{O}_2\) reduction at NiCo2O4. - A slope of about \(-0.06 \text{ V/decade}\) was reported for a NiCo2O4 electrode at 80 °C (ref. 23) which is in good agreement with that found in the present study for the smaller current region. Conflicting results, however, were reported for the \(\text{O}_2\) reduction process by Trasatti (ref. 3 p. 243). For example, Trasatti reported that one study obtained 2 regions with slopes of \(-0.06\) and \(-0.12 \text{ V/decade}\) and corresponding exchange current densities of \(3.2 \times 10^{-13}\) and \(6.3 \times 10^{-10} \text{ A/cm}^2\).
respectively. These values are in fair agreement with the values obtained in the present study. Two other studies reported by Trasatti gave conflicting results. One study suggested slopes of -0.06 and -0.20 V/decade while the second study suggested 3 slopes of -0.06, -0.12 and -0.20 V/decade.

While O₂ reduction proceeds by means of a peroxide mechanism for several oxides (e.g. NiO), this is not the case for O₂ reduction at NiCo₂O₄ spinel surfaces. Instead, it has been reported that the process proceeds primarily by means of a 4 electron process to form OH⁻ for the potential range between 0.7 and 0.8 V as indicated by the rotating ring-disk study (ref. 20). At these potentials, the formation of peroxide was found to produce less than 10 percent of the total current. But at 0.3 V, where the rate of decomposition of NiCo₂O₄ spinel to produce NiO is much faster, the rate of peroxide formation is essentially equal to the direct 4 electron process.

A mechanism for the initial steps in O₂ reduction at a NiCo₂O₄ surface has been reported which is similar to the reverse process for O₂ evolution (ref. 24). A series of reactions which involves only a minor modification of Tarasevich's mechanism (ref. 24) is proposed to account for the two slope regions observed in the present study. In this series, M probably represents a lower valence metal species (e.g. Co⁺²). Breaking the peroxide bond is difficult. As a consequence, several steps are involved for the continuing reduction of peroxide to form OH⁻. Steps for the continued reduction of the peroxide are combined and are shown below as reaction (K).

\[
\begin{align*}
M & + O₂ \rightarrow M-O₂ \quad \text{(G)} \\
M-O₂ & + e \rightarrow (M-O₂)^- \quad \text{(H)} \\
(M-O₂)^- & + HOH \rightarrow M-O₂H + OH^- \quad \text{(I)} \\
M-O₂H & + e \rightarrow (M-O₂H)^- \quad \text{(J)} \\
(M-O₂H)^- & + 2e + HOH \rightarrow M + 3OH^- \quad \text{(K)}
\end{align*}
\]

The values of -0.12 and -0.06 V/decade obtained in the present study for the slopes are in agreement with the hypothesis that reaction (H) is the rate-determining step for the larger current region and that reaction (I) is the rate-determining step for the small current region. For these calculations, the expression is as follows:

\[
S_c = \frac{(-RT)}{F[k + (1 - b)(2 - k + n/v)]}
\]

where \( S_c \) is the cathodic slope, \( k \) is the number of electrons which must be added prior to the rate-determining step to permit the rate-determining step to occur once, \( \ell \) is the number of electrons that must be added to permit the products formed by one occurrence of the rate-determining step to be transferred to the final state, \( b \) is the beta symmetry factor (0.5), \( n \) is the total number of electrons transferred in the over-all reaction and \( v \) is the stoichiometric number (ref. 15). For the larger current region, a value of about -0.12 V/decade is calculated for the slope if reaction (H) is assumed to be the rate-determining step. For this calculation, the following values are used for reaction (H): \( n = 4, k = 0, \ell = -3, \) and \( v = 1 \). For the smaller current region, a value if -0.06 is calculated for the slope using the following values for reaction (I): \( n = 4, k = 1, \ell = -3, \) and \( v = 1 \).

As discussed previously, the authors of the present study believe that an alternate mechanism involving Langmuir and Temkin adsorption is not a major
contributor to changing the slope from -0.12 to -0.06 V/decade for the smaller current region.

**SUMMARY**

NiCo2O4 spinel was chosen as the catalyst for a study of its bifunctional electrocatalytic activity for the O2 electrode and of techniques of fabricating it into PTFE-bonded, porous gas electrodes. For this study, 6 electrodes were fabricated by 3 commercial sources by means of proprietary techniques using varying PTFE contents and sintering temperatures.

The following may be stated regarding the O2 evolution studies:

1. An irreversible reaction occurs at the NiCo2O4 surface if the electrode is held at more anodic potentials (i.e. aged at greater than about 1.5 V) for a few hours. This change is due to the oxidation of Ni and Co surface sites to form stable, higher oxidation states.

2. Good catalytic activity for O2 evolution is obtained for aged electrodes at current densities up to about 0.2 A/cm². Removal of O2 bubbles at current densities above 0.2 A/cm², however, becomes increasingly more difficult.

3. Tafel data, obtained for all 6 aged electrodes, are similar in that 2 slopes are obtained for each electrode. A slope of 0.12 V/decade is obtained for the larger current region while a slope of 0.06 is obtained for the smaller current region.

4. Four of the electrodes gave essentially the same calculated values for the geometric exchange current densities, particularly for the 0.12 slope region. The PTFE content for these 4 electrodes was either 15 or 25 percent of the NiCo2O4, while the sintering conditions ranged between 300 and 340 °C. One electrode which was sintered at only 275 °C gave a smaller value for the exchange current density (i.e. by a factor of 3).

Therefore, within the range of 15 to 25 percent, the PTFE content is not a critical parameter for optimizing aged PTFE-bonded NiCo2O4 electrodes for improved activity for O2 evolution. Furthermore, sintering temperatures between 300 and 340 °C may be adequate, but that heating at 275 °C may not be sufficient to properly sinter the PTFE-NiCo2O4 mixture.

The following may be stated regarding the O2 reduction studies:

1. Electrode disintegration was observed during cathodic runs. It is still not clear whether this disintegration was due primarily to a physical shedding of the NiCo2O4 from the current collector screen or to electrochemical decomposition of the spinel to form oxides of Ni and Co.

2. Transport polarization of O2 to the NiCo2O4 surface became prohibitive for all of the electrodes at current densities greater than about -0.02 A/cm².

3. Two Tafel regions can be assumed for all 6 Tafel curves. A slope of -0.12 V/decade was assumed for the moderate current density region and a slope of -0.06 was assumed for the smaller current density region.
4. The catalytic activity for O₂ reduction at these electrodes was much smaller than that which was obtained for the corresponding O₂ evolution processes as indicated by the respective exchange current densities. Furthermore, the activity for O₂ reduction in the present study was about a factor of 5 smaller than that which was estimated from data reported by others for an "optimized" NiCo₂O₄ electrode.

Therefore, a PTFE content of 25 percent (or greater) appears to be preferable for sintering PTFE-bonded NiCo₂O₄ porous gas electrodes for improved O₂ reduction activity.

REFERENCES


TABLE I. - PTFE-BONDED, NiCo$_2$O$_4$ POROUS GAS ELECTRODES

<table>
<thead>
<tr>
<th>Electrode number</th>
<th>Fabrication source</th>
<th>NiCo$_2$O$_4$ content, Mg/cm$^2$</th>
<th>PTFE content, percent of NiCo$_2$O$_4$</th>
<th>Heating temperature, °C</th>
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</tr>
<tr>
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</tr>
<tr>
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<td>Electromedia Corp.</td>
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<td>25</td>
<td>340</td>
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<td>6</td>
<td>Electrochem Inc.</td>
<td>25</td>
<td>15</td>
<td>275</td>
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TABLE II. - POTENTIALS AND EXCHANGE CURRENT DENSITIES FOR O$_2$ EVOLUTION USING AGED, PTFE-BONDED NiCo$_2$O$_4$ POROUS GAS ELECTRODES

(a) Region of 0.12 V/decade slope (larger currents)

<table>
<thead>
<tr>
<th>Electrode number</th>
<th>Potential at 0.1 A/cm$^2$, V</th>
<th>Exchange current density</th>
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<tr>
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<td>2.2</td>
</tr>
<tr>
<td>6</td>
<td>1.516</td>
<td>1.6</td>
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(b) Region of 0.06 V/decade slope (smaller currents)

<table>
<thead>
<tr>
<th>Electrode number</th>
<th>Potential at 0.01 A/cm$^2$, V</th>
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<td>1.436</td>
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TABLE III. - POTENTIALS AND EXCHANGE CURRENT DENSITIES FOR O₂ REDUCTION
USING PTFE-BONDED, NiCo₂O₄ POROUS GAS ELECTRODES

(a) Region of -0.12 V/decade slope (moderate currents)

<table>
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<tr>
<th>Electrode number</th>
<th>Potential at 0.01 A/cm², V</th>
<th>Exchange current</th>
<th>Current density range, A/cm²</th>
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<td>a.753</td>
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<td>a,b,692</td>
<td>9×10⁻⁷</td>
<td>8×10⁻¹¹</td>
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(b) Region of -0.06 V/decade slope (smaller currents)

<table>
<thead>
<tr>
<th>Electrode number</th>
<th>Potential at 0.001 A/cm², V</th>
<th>Exchange current</th>
<th>Current density range, A/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Geometric, A/cm²</td>
<td>&quot;True&quot;, A/cm²</td>
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<tr>
<td>5</td>
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<td>2.5×10⁻⁹</td>
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<td>4</td>
<td>b.798</td>
<td>4×10⁻¹⁰</td>
<td>4×10⁻¹⁴</td>
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</table>

*a Extrapolated.
*b Estimated.

FIGURE 1. - OVERPOTENTIAL-CURRENT DENSITY CURVES FOR O₂ EVOLUTION ON VARIOUS OXIDES FROM ALKALINE SOLUTIONS.
**Figure 2.** Schematic of floating half-cell.

**Figure 3.** Hg/HgO reference electrode potential compared with dynamic H₂ electrode potential (1 atm O₂, 31% KOH).

**Figure 4.** (a) Schematic for connection of cell and equipment to Electro-Synthesis Corporation Model 800 IR instrument. (b) Schematic of typical IR waveform for working electrode.
FIGURE 5. - POTENTIAL VERSUS TIME FOR O₂ EVOLUTION RUNS FOR NiCo₂O₄ ELECTRODE 5 (1 ATM O₂, 80 °C, 31% KOH).

FIGURE 6. - IR POLARIZATION VERSUS CURRENT FOR STEADY-STATE GALVANOSTATIC O₂ EVOLUTION RUN FOR AGED NiCo₂O₄ ELECTRODE 2 (1 ATM O₂, 80 °C, 31% KOH).

FIGURE 7. - POTENTIAL VERSUS TIME FOR GALVANOSTATIC O₂ EVOLUTION RUN AT 0.6 A FOR TYPICAL NiCo₂O₄ ELECTRODE (1 ATM O₂, 80 °C, 31% KOH).

FIGURE 8. - TAFEL PLOT FOR STEADY-STATE GALVANOSTATIC O₂ EVOLUTION RUN FOR AGED NiCo₂O₄ ELECTRODE 5 (1 ATM O₂, 80 °C, 31% KOH).
1.5G

AGED ELECTRODE

NONAGED ELECTRODE

1.52

SLOPE = 0.12 V/DECADE

SLOPE = 0.060 V/DECADE

FIGURE 9. - TAFEL PLOT FOR STEADY-STATE GALVANOSTATIC O₂ EVOLUTION RUN FOR NiCo₂O₄ ELECTRODE 5 (1 ATM O₂, 80 °C, 31% KOH).

FIGURE 10. - COMPARISON OF TAFEL O₂ EVOLUTION DATA FOR ELECTRODE 1 WITH THAT OF DAVIDSON AND BOTEJUE NADASAN.

FIGURE 11. - TAFEL PLOT FOR STEADY-STATE GALVANOSTATIC O₂ REDUCTION OF NiCo₂O₄ ELECTRODES (1 ATM O₂, 80 °C, 31% KOH).
FIGURE 12. - TAFEL PLOT FOR STEADY-STATE GALVANOSTATIC O\textsubscript{2} REDUCTION AT AGED NiCo\textsubscript{2}O\textsubscript{4} ELECTRODE 5 (1 ATM O\textsubscript{2}, 80 °C, 31% KOH).

SLOPE = -0.12 V/DECADE

FIGURE 13. - TAFEL PLOT FOR STEADY-STATE GALVANOSTATIC O\textsubscript{2} REDUCTION AT AGED NiCo\textsubscript{2}O\textsubscript{4} ELECTRODE 5 (1 ATM O\textsubscript{2}, 80 °C, 31% KOH).

SLOPE = -0.12 V/DECADE

FIGURE 14. - TAFEL PLOT FOR STEADY-STATE GALVANOSTATIC O\textsubscript{2} REDUCTION AT AGED NiCo\textsubscript{2}O\textsubscript{4} ELECTRODE 6 (1 ATM O\textsubscript{2}, 80 °C, 31% KOH).

SLOPE = -0.12 V/DECADE

FIGURE 15. - COMPARISON OF TAFEL O\textsubscript{2} REDUCTION DATA FOR ELECTRODE 5 WITH THAT OF REPORTED DATA.
A significant increase in energy density may be possible if a two-unit alkaline regenerative H₂—O₂ fuel cell is replaced with a single-unit system that uses passive means for H₂O transfer and thermal control. For this single-unit system, new electrocatalysts for the O₂ electrode will be required which are not only bifunctionally active but also chemically and electrochemically stable between the voltage range of about 0.7 and 1.5 V. NiCo₂O₄ spinel is reported to have certain characteristics that make it useful for a study of electrode fabrication techniques. High surface area NiCo₂O₄ powder was fabricated into unsupported, bifunctional, PTFE-bonded, porous gas fuel cell electrodes by commercial sources using varying PTFE contents and sintering temperatures. The object of the present study was to measure the bifunctional activities of these electrodes and to observe what performance differences might result from different commercial electrode fabricators. O₂ evolution and O₂ reduction data were obtained at 80 °C (31 percent KOH). An irreversible reaction (i.e. aging) occurred during O₂ evolution at potentials greater than about 1.5 V. Anodic Tafel slopes of 0.06 and 0.12 V/decade were obtained for the aged electrodes. Within the range of 15 to 25 percent, the PTFE content was not a critical parameter for optimizing the electrode for O₂ evolution activity. Sintering temperatures between 300 and 340 °C may be adequate but heating at 275 °C may not be sufficient to properly sinter the PTFE-NiCo₂O₄ mixture. Electrode disintegration was observed during O₂ reduction. Transport of O₂ to the NiCo₂O₄ surface became prohibitive at greater than about -0.02 A/cm². Cathodic Tafel slopes of -0.06 and -0.12 V/decade were assumed for the O₂ reduction process. A PTFE content of 25 percent (or greater) appears to be preferable for sintering the PTFE-NiCo₂O₄ mixture.