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APPLIED ELECTROCHEMISTRY AND CORROSION PROTECTION OF METALS

Reduction of Nitrophenols in an Electrocatalytic System

N. M. Ivanova, E. A. Soboleva, E. V. Kulakova, V. P. Malyshev, and I. V. Kirilyus

Kazakh Republic Institute of Organic Synthesis and Coal Chemistry, Joint-Stock Company, Karaganda, Kazakh Republic

Abishev Chemicometallurgical Institute, Daughter State Enterprise, Karaganda, Kazakh Republic

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Abstract—Results of research into hydrogenation of *o*- and *p*-nitrophenols in an electrocatalytic system on a cathode activated with *d*- and *s*-metal catalysts are presented. The optimal conditions for *o*-aminophenol formation on Raney nickel were identified by the probability-determined method for the experimental design.

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Nitrophenols belong to aromatic nitro compounds that are the subject of much investigation in connection with their conversion to anilines. This process ranks among the most important reactions in organic chemistry and yields amines that find extensive industrial, agricultural, and pharmaceutical applications. Probably, this is specifically responsible for large developmental efforts dedicated to reduction of nitroaromatic compounds, in particular, nitrophenols. They range from the earliest developments in which reduction was effected with pig-iron chips [1] to the modern ones applying nanostructured activated iron, silver, and palladium powders [2–4].

As known, electrochemical reduction of nitroaromatic compounds is complicated by various side chemical transformations which are strongly dependent on pH of the medium [5]. For example, reduction of *o*-nitrophenol (*o*-NP) on porous copper hydrophobized electrodes in 15% aqueous NaOH at 50–70°C yields *o*-azoxyphenol, *o*-azophenol, and *o*-aminophenol (*o*-AP), and in an acid electrolyte (10% H_2SO_4) *o*-NP is reduced to *o*-AP in a virtually quantitative yield [6]. Reduction of *p*-NP in an electrolytic cell on an amalgamated copper cathode yields a mixture of *p*-AP and aniline (in approximately 22:1 molar ratio) [7]. Electrochemical reduction of *o*-, *m*-, and *p*-nitrophenols on glassy carbon and copper cathodes against 1 M NaOH background yields aminophenols in high yields [8].

An example of chemical methods for reduction of nitrophenols is that utilizing $FeS–NH_4Cl–CH_3OH–H_2O$ system in which *o*-NP is reduced within 8 h with 56% yield of the product, and *p*-NP, within 5 h with 74% yield [9]. In a similar system with iron sulfide replaced by aluminum metal and under ultrasonic irradiation the reduction of *o*-NP proceeds, by contrast, more vigorously (within 2.5 h, with *o*-AP in 90% yield), than in the case of *p*-NP (within 3 h, 86% yield) [10]. Also, *o*-NP is reduced under the action of Na_2S or NaSH with 90% yield of the amine product [11]. In the $FeCl_3·6H_2O$/indium powder system in a methanol solution under ultrasonic irradiation the reduction of *p*-NP within 2 h gives *p*-AP in 86% yield [12].

Also, the catalytic reduction of nitroaromatic compounds can be accompanied by interaction and isomerization of intermediates. At the same time, numerous methods of their successful catalytic reduction to corresponding amines in high yields are also known. For example, *o*-, *m*-, and *p*-nitrophenols react with formic acid (or ammonium formiate) in the presence of Raney nickel in methanol at T~20°C and form the corresponding aminophenols in 85–90% yield within 10–20 min [13]. With 5% Pt/C and the same reactants, the reduction of *p*-NP takes 45 and 60 min, respectively, for 91% yield of the product, and that of *o*-NP, 60 and 100 min, respectively, for 89% yield [14, 15]. The maximal yields for *p*-AP are observed in hydrogenation of *p*-NP with molecular hydrogen in the

presence of platinum or palladium complexes with hydroxyquinones [16].

Studies of the reactivity of the nitro group in reduction of nitroaromatic compounds in relation to the nature of substituents in the benzene ring showed [17–19] that the electron-acceptor substituents most often accelerate these processes, and electron-donating, decelerate, by contrast. At the same time, the influence of the nature and position of the substituent in the ring can be determined by many factors. In catalytic systems, these factors include, above all, the nature of the catalyst and the solvent, governing both the adsorption of the substance being hydrogenated on the catalyst and the rate-limiting stage in the multistage process examined.

Electrocatalytic methods of reduction of nitro compounds are suitable as a special group, since electrocatalysis proved to be fairly efficient with respect to the examined representatives of this class of substances (nitrobenzene [20], ethyl 4-nitrobenzoate [21]): On Raney nickel in a weakly alkaline medium hydrogenation goes to completion with formation of aromatic amines.

The above-presented brief review of nitrophenol reduction methods demonstrates the following. First, there exists a broad spectrum of such methods; second, much promise is offered by selective preparation of aminoaromatic compounds from nitrophenols; and third, this research is topical, since aromatic amines are in high demand by manufacturers of various chemicals.

The major stages of reduction of nitrophenols (ommiting the possible side transformations) can be represented by the scheme:

$$HO{-}C_6H_5{-}NO_2 \xrightarrow[-H_2O]{2H} HO{-}C_6H_5{-}NO \xrightarrow{2H} HO{-}C_6H_5{-}NHOH \xrightarrow[-H_2O]{2H} HO{-}C_6H_5{-}NH_2.$$

Here, we examined reduction of *o*-NP and *p*-NP in an electrocatalytic system, in which the cathode was activated with catalysts based on *d* and *s* metals, skeletal Ni, Zn, Cu, Co, Fe, and electrocatalytic copper powder (0.1 μm particles [22]).

Table 1. Results of electrocatalytic reduction of *o*-NP and *p*-NP on various catalysts

Catalyst	W, (H_2 ml) min^{-1}	η, %	CE, %	t, min
o-Nitrophenol				
$Cu_{el.powd}$	6.9	99.3	71.5	60
Co_{sk}	6.5	97.0	52.8	80
Zn_{sk}	6.3	92.3	53.1	80
Cu_{sk}	6.2	93.5	51.5	80
Ni_{sk}	6.0	93.9	47.8	80
Fe_{sk}	5.9	91.8	42.9	100
Without catalyst	4.3	58.6	23.8	180
p-Nitrophenol				
$Cu_{el.powd}$	6.9	99.8	72.9	60
Co_{sk}	6.5	97.0	52.8	80
Zn_{sk}	6.3	93.4	53.4	80
Cu_{sk}	6.2	93.5	53.4	80
Ni_{sk}	5.8	89.7	43.2	90
Fe_{sk}	6.1	94.7	47.5	90
Without catalyst	3.8	65.9	22.6	190

EXPERIMENTAL

Electrocatalytic hydrogenation of *o*-NP and *p*-NP was carried out in an electrolytic cell divided into anode and cathode parts (60 ml in volume each) with an MA-40 membrane diaphragm. As anode we used a platinum grid, and as cathode, a copper plate (substrate) with the visible surface area of 5×10^{-4} m^2, tightly fit to the electrolyzer bottom. The cathode was activated with ferromagnetic skeletal catalysts Co, Ni, and Fe, held onto the substrate surface with a magnet placed outside the electrolyzer, as well as with skeletal Cu, Zn, and electrochemical copper (for details, see [23, 24]).

The experiments were run at the current strength of 1 A and temperature of 30°C maintained with a thermostat. As anolyte we used 50 ml of 20% NaOH, and as catholyte, 60 ml of 2% NaOH. The amount of *o*-NP or *p*-NP was 0.62 g (concentration 0.074 M), calculated for 300 ml of hydrogen uptake. As the substrate hydrogenation rate we took the volume of the hydrogen taken up per unit time by the reaction mass. At the current strength of 1 A the maximal hydrogenation rate did not exceed 6.96 (H_2 ml) min^{-1}.

Table 1 lists the basic characteristics of electrocatalytic reduction of *o*-NP and *p*-NP on various catalysts, calculated from the following experimental

data: W, the average rate of the process, determined for the period corresponding to 50% hydrogen taken up; η, hydrogen consumption coefficient; CE, current efficiency for the substance; and t, process time. Figure 1 shows how the rate of *o*-NP hydrogenation on various catalysts varies with the amount of the hydrogen uptake.

As seen from Table 1, the rate of *o*-NP reduction decreases in a series $Cu_{el.powd}$ > Co_{sk} > Zn_{sk} > Cu_{sk} > Ni_{sk} > Fe_{sk}. For *p*-NP this rate varies as $Cu_{el.powd.}$ > Co_{sk} > Zn_{sk} > Cu_{sk} > Fe_{sk} > Ni_{sk}. The maximal hydro-genation rate *W* (as well as η and CE), observed for electrolytic Cu powder, can be associated with its larger reaction surface area compared to those of skeletal catalysts.

It should be noted that, with 100% hydrogen taken up, these isomers of NP are also hydrogenated without catalysts, i.e., electrochemically, though at appreciably lower average rates *W*, and this takes more time (Fig. 1, Table 1).

Study of the electrocatalytic reduction of *o*-NP on Raney nickel in relation to other factors was carried out by the probability-determined method for the experimental design [25], based on four-factor five-level matrix (25 runs). The values of the active factors were varied as follows: current strength 0.5–2.5 A; catalyst amount 0.1–0.5 g; initial concentration of the substance 0.025–0.124 M, calculated for 100–500 ml of hydrogen uptake; and temperature of the reaction medium 293–313 K. The results obtained were analyzed in terms of the conversion of the substance α, which was determined as the ratio of the volume of the hydrogen taken up by the moment t to total amount of the hydrogen required for exhaustive hydrogenation of the initial substance. Each run involved repeatedly recording the results until the process was complete, which allowed, after matrix experiments, integrating the time of experiment as the fifth factor. To this end,

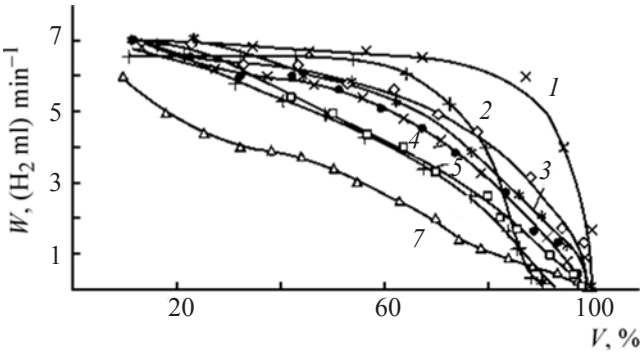

Fig. 1. Rates *W* of (*1–6*) electrocatalytic and (*7*) electrochemical hydrogenation of *o*-NP vs. the volume of hydrogen taken up *V*. Catalyst: (*1*) $Cu_{el.powd}$; (*2*) Co_{sk}; (*3*) Zn_{sk}; (*4*) Cu_{sk}; (*5*) Ni_{sk}; and (*6*) Fe_{sk}

the corresponding initial data and results were introduced into the experimental design matrix at the code levels of vacant factor.

The experimental results were processed via appropriate sampling at levels and selecting partial dependences. Figure 2 shows the point diagrams and the approximation curves for the conversion of *o*-NP, and Table 2 presents the resulting *Y* functions, as well as the correlation coefficients *R* and their significances t_R calculated by the known correlation analysis equations [25].

The resulting partial dependences suggest that the conversion of *o*-NP substantially increases with increasing current density and hydrogenation time, weakly depends on the catalyst amount, and appreciably decreases with increasing initial concentration of *o*-NP being hydrogenated. The last-named trend is apparently associated with a decrease in the ratio of the amount of the hydrogen evolved at identical current strengths to the initial concentration of *o*-NP. Table 2 suggests that these functions are significant. Insignificant temperature dependence of the conversion is, probably, associated with a too

Table 2. Partial dependences of the conversion of *o*-NP on various factors and their significances

Factor	Function	*R*	t_R	Significance
Current strength, A (X_1)	$Y_1 = 0.237X_1+0.117$	0.982	48.33 > 2	Significant
Catalyst amount, kg (X_2)	$Y_2 = 256X_2+0.397$	0.971	29.40 > 2	"
o-NP concentration, M (X_3)	$Y_3 = -2.734X_3+0.677$	0.989	81.61 > 2	"
Temperature, K (X_4)	$Y_4 = 0.002X_4-0.248$	0.321	0.62 < 2	Insignificant
Process time, s (X_5)	$Y_5 = 0.0013X_5^{0.835}$	0.985	58.88 > 2	Significant

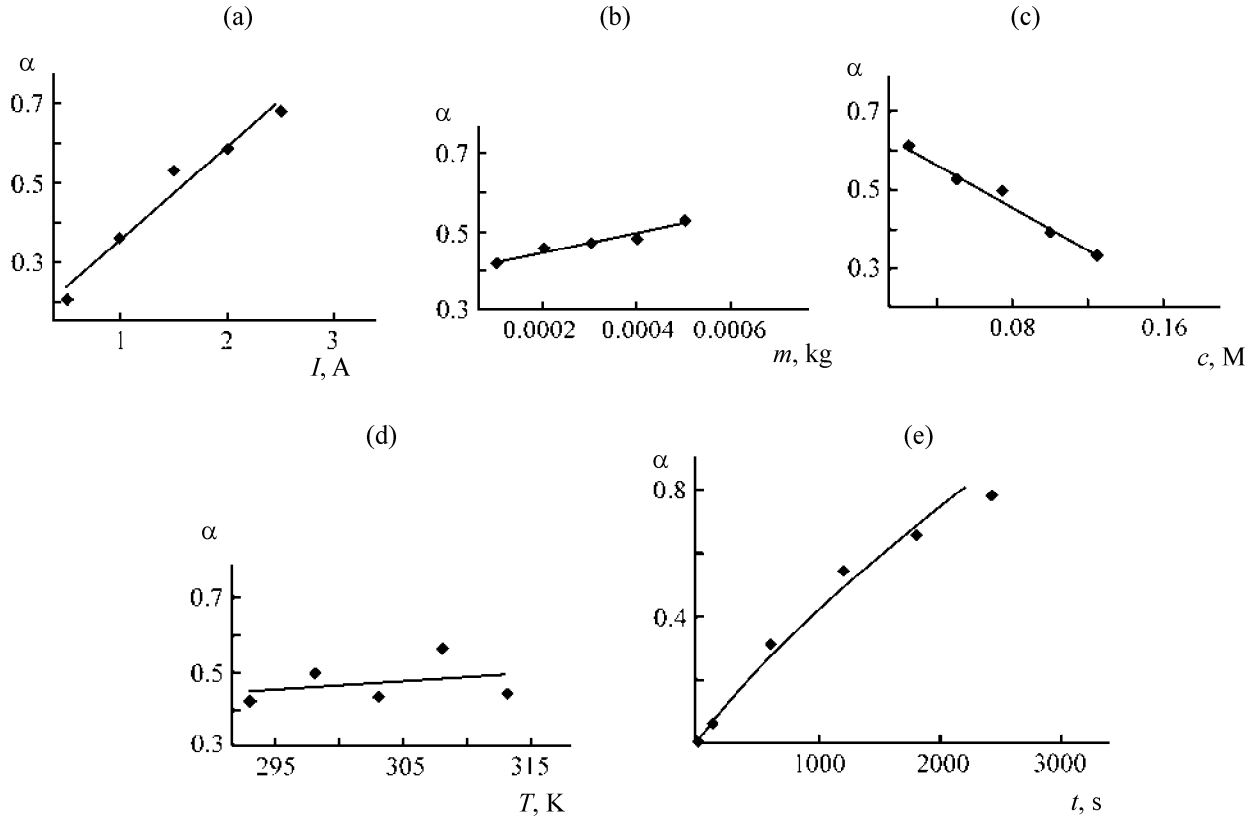

Fig. 2. Point diagrams and approximation curves for the partial dependences of the conversion of *o*-NP on (a) current strength *I*; (b) catalyst mass *m*; (c) *o*-NP concentration *c*; (d) temperature *T*; and (e) process time *t*.

narrow temperature range (293–313 K) chosen for the experiments. This is an ascending dependence, which is not inconsistent with the physical implication of this factor. This made it suitable for subsequent analysis as part of the generalized equation, considering its significance, slightly lower than that for 95% reliability level [25].

These partial dependences for α were substituted into Protod'yakonov's equation describing the multifactor dependences [26], which yielded the following generalized equation for theoretically calculating the extent of hydrogenation of *o*-NP:

$$\alpha = (0.237X_1 + 0.117)(256X_2 + 0.397) \times (-2.734X_3 + 0.677)(0.002X_4 - 0.248) \times \frac{(0.0013X_5^{0.835})}{0.473^4}. \quad (1)$$

The correlation coefficient R for the α values calculated by this equation and from the experimental data, as well as the significance of this factor t_R, were estimated at 0.951 and 33.85 > 2, respectively. Next, generalized Eq. (1) is to be moved under the exponent sign to set the upper limit of the conversion at unity [27]:

$$Y_\alpha = \exp\{-0.2[(0.237X_1 + 0.117)(256X_2 + 0.397) \times (-2.734X_3 + 0.677)(0.002X_4 - 0.248) \times \frac{(0.0013X_5^{0.835})}{0.473^4}]^{-1.12}\}. \quad (2)$$

Considering its adequacy, the resulting equation can be used for deriving, via the known analytical transformations [27], a multifactor dependence of the rate of the process, provided constant extent of reaction and, consequently, concentrations of the reactants. This allows transforming this equation to that in the Arrhenius coordinates $\ln(d\alpha/dt)$–$1/T$

$$K = (0.237X_1 + 0.117)(256X_2 + 0.397) \times \frac{(-2.734X_3 + 0.677)(0.002X_4 - 0.248)_0.0013}{0.473^4}, \quad (3)$$

The rate of the process is a partial derivative with respect to time, and all other variables in Eq. (2) are time-independent. Taking

$$\alpha = \exp\left[-0.2(KX_5^{0.835})^{-1.12} \right]$$

$$= \exp\left[a(KX_5^b)^c \right], \quad (4)$$

we will obtain for Eq. (2) the following expression, where $a = -0.2$, $b = 0.835$, $c = -1.12$.

Hence, the rate of the process can be represented as

$$\frac{d\alpha}{dt} = \alpha a K^c b c X_5^{bc-1} . \quad (5)$$

For maintaining constant the extent of reaction α, which is necessary for strictly transforming the equation of the rate to that of a straight line in the Arrhenius coordinates, the extent of reaction in multifactor Eq. (4) should be replaced by the time. The resulting expression should be substituted, instead of time, into Eq. (5), so that the dependence on the extent of reaction will be introduced into the equation of the rate. This yields the following equation

$$\frac{d\alpha}{dt} = \alpha a K^{\frac{1}{b}} \left(\frac{\ln \alpha}{a} \right)^{1-\frac{1}{bc}} . \quad (6)$$

Or, taking into account the *a, b* and *c* values,

$$\frac{d\alpha}{dt} = 0.187 \alpha K^{1.198} \left(\frac{\ln \alpha}{-0.2} \right)^{2.06} . \quad (7)$$

Equation (7) can be used for calculating the sets of the rates at varied temperature and fixed values of all other variables, including α. This allows calculating the activation energy for the initial, intermediate, and final stages of the process, via setting the conversion at 0.1, 0.5, and 0.9. The remaining factors can be fixed for all the three calculation versions at their average levels: $X_1 = 1.5$ A, $X_2 = 0.3$ g, $X_3 = 0.074$ M, $X_4 = T$, K. Table 3 lists the calculated data.

Using the straight line equations for the semilogarithmic dependence ln $(d\alpha/dt)$–$1/T$ (Fig. 3) ($y_1 = -558.51x - 4.350$, $R_1 = 0.9999$, $t_R = 17319.64 > 2$; $y_2 = -558.51x - 5.219$, $R_2 = 0.9999$, $t_R = 17319.64 > 2$, and $y_3 = -558.51x - 8.521$, $R_3 = 0.9999$, $t_R = 17319.64 > 2$), the activation energies were estimated at 4.64 kJ mol^{-1} for all the set extents of the reaction. This suggests that the mechanism and the limiting stage of hydrogenation of *o*-NP are uniform throughout the process.

Based on generalized Eq. (2) we compiled a nomogram of variation of the *o*-NP conversion for real ranges of variation of the examined factors (amount of catalyst spent 0.5 g) and identified their optimal zones

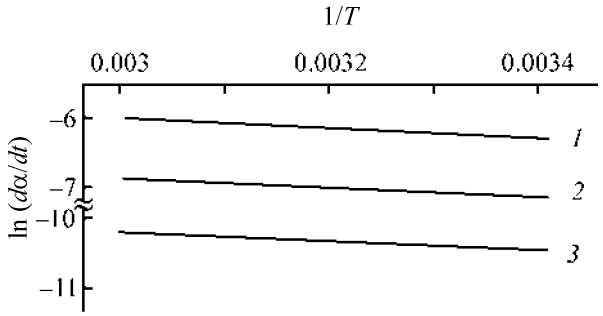

Fig. 3. Temperature dependence of the rate of electrocatalytic reduction of *o*-NP in the Arrhenius coordinates. Conversion α: (*1*) 0.1; (*2*) 0.5; and (*3*) 0.9.

in electrocatalytic reduction of *o*-NP (Table 4). For example, this nomogram suggests the optimal value for conversion α = 0.94, corresponding to the following values of the examined factors: current strength 2 A; initial concentration of the substance 0.074 M (calculated for 300 ml of hydrogen uptake); temperature 303 K; and time of the process 100 min. We carried out electrocatalytic hydrogenation of *o*-NP and *p*-NP under the optimal conditions. For comparison, based on the experimental data obtained, we estimated the average hydrogenation rates W for α = 0.5 at 9.6 and 9.4 (H_2 ml) min^{-1}, respectively. The difference in the hydrogenation rates for these isomers proved to be insignificant, and to a first approximation (since this is a multiphase process) can be associated with the difference in the effective charges on the NO_2 group in the molecules of the NP isomers examined. This follows from the performed quantum-chemical calculations (B3LYP/6-31G** method with account of polarization *p*-and d-functions [26, 28, 29]). For more energetically stable conformation *o*-NP, in which the hydroxide hydrogen reacts with the oxygen atom of the NO_2 group, the effective charge on the NO_2 group was estimated at –0.453, and in the para isomer, at –0.427 (in electron units).

Table 3. Rates of *o*-NP hydrogenation

T, K	$d\alpha/dt$ at indicated α		
	0.1	0.5	0.9
293	1.9×10^{-3}	8.1×10^{-4}	3.0×10^{-5}
303	2.0×10^{-3}	8.6×10^{-4}	3.2×10^{-5}
313	2.2×10^{-3}	9.1×10^{-4}	3.3×10^{-5}
323	2.3×10^{-3}	9.6×10^{-4}	3.5×10^{-5}
333	2.4×10^{-3}	10.1×10^{-4}	3.7×10^{-5}

Table 4. Nomogram of conversion of *o*-NP in electrocatalytic hydrogenation in a laboratory cell. Catalyst amount 0.5 g. (*I*) is current strength, A; (*c*) is *o*-NP concentration, M; (*T*) is temperature, K; and (*t*) is time, s

I	*c*	0.025	0.025	0.025	0.025	0.050	0.050	0.050	0.050	0.050	0.074	0.074
	T/*t*	3000	3600	4200	4800	3000	3600	4200	4800	5400	3600	4200
0.5	293	0.75	0.78	0.81	0.83	0.72	0.76	0.78	0.81	0.83	0.72	0.75
0.5	298	0.75	0.79	0.81	0.83	0.72	0.76	0.79	0.81	0.83	0.73	0.76
0.5	303	0.76	0.79	0.82	0.84	0.73	0.77	0.79	0.82	0.83	0.74	0.77
0.5	308	0.77	0.80	0.82	0.84	0.74	0.77	0.80	0.82	0.84	0.74	0.77
0.5	313	0.77	0.80	0.83	0.85	0.74	0.78	0.80	0.83	0.84	0.75	0.78
1	293	0.83	0.86	0.87	0.89	0.81	0.84	0.86	0.87	0.89	0.81	0.84
1	298	0.84	0.86	0.88	0.89	0.81	0.84	0.86	0.88	0.89	0.82	0.84
1	303	0.84	0.86	0.88	0.89	0.82	0.85	0.86	0.88	0.89	0.82	0.85
1	308	0.84	0.87	0.88	0.90	0.82	0.85	0.87	0.88	0.89	0.83	0.85
1	313	0.85	0.87	0.89	0.90	0.80	0.85	0.87	0.89	0.90	0.83	0.85
1.5	293	0.88	0.89	0.91	0.92	0.86	0.88	0.89	0.91	0.92	0.86	0.88
1.5	298	0.88	0.90	0.91	0.92	0.86	0.88	0.90	0.91	0.92	0.87	0.88
I	*c*	0.074	0.074	0.074	0.099	0.099	0.099	0.099	0.099	0.124	0.124	0.124
	T/*t*	4800	5400	6000	4800	5400	6000	6600	7200	6000	6600	7200
0.5	293	0.78	0.80	0.82	0.74	0.77	0.79	0.80	0.82	0.74	0.76	0.78
0.5	298	0.79	0.81	0.82	0.75	0.77	0.79	0.81	0.82	0.75	0.77	0.79
0.5	303	0.79	0.81	0.83	0.76	0.78	0.80	0.81	0.83	0.76	0.78	0.79
0.5	308	0.80	0.82	0.83	0.76	0.78	0.80	0.82	0.83	0.76	0.78	0.80
0.5	313	0.80	0.82	0.84	0.77	0.79	0.81	0.82	0.83	0.77	0.79	0.80
1	293	0.85	0.87	0.88	0.83	0.85	0.86	0.87	0.88	0.83	0.84	0.85
1	298	0.86	0.87	0.88	0.83	0.85	0.86	0.87	0.88	0.83	0.85	0.86
1	303	0.86	0.88	0.89	0.84	0.85	0.87	0.88	0.89	0.84	0.85	0.86
1	308	0.87	0.88	0.89	0.84	0.86	0.87	0.88	0.89	0.84	0.86	0.87
1	313	0.87	0.88	0.89	0.85	0.86	0.87	0.88	0.89	0.85	0.86	0.87
1.5	293	0.89	0.90	0.91	0.87	0.89	0.90	0.90	0.91	0.87	0.88	0.89
1.5	298	0.90	0.91	0.91	0.88	0.89	0.90	0.91	0.91	0.88	0.89	0.90
I	*c*	0.025	0.025	0.025	0.025	0.050	0.050	0.050	0.050	0.050	0.074	0.074
	T/*t*	3000	3600	4200	4800	3000	3600	4200	4800	5400	3600	4200
1.5	303	0.88	0.90	0.91	0.92	0.87	0.89	0.90	0.91	0.92	0.87	0.89
1.5	308	0.88	0.90	0.91	0.92	0.87	0.89	0.90	0.91	0.92	0.87	0.89
1.5	313	0.89	0.90	0.92	0.93	0.87	0.89	0.91	0.92	0.92	0.88	0.89
2	293	0.90	0.92	0.93	0.94	0.89	0.90	0.92	0.93	0.93	0.89	0.90
2	298	0.90	0.92	0.93	0.94	0.89	0.91	0.92	0.93	0.94	0.89	0.91
2	303	0.91	0.92	0.93	0.94	0.89	0.91	0.92	0.93	0.94	0.90	0.91

Table 4. (Contd.)

I	*c*	0.025	0.025	0.025	0.025	0.050	0.050	0.050	0.050	0.050	0.074	0.074
	T/*t*	3000	3600	4200	4800	3000	3600	4200	4800	5400	3600	4200
2	308	0.91	0.92	0.93	0.94	0.90	0.91	0.92	0.93	0.94	0.90	0.91
2	313	0.91	0.92	0.93	0.94	0.90	0.91	0.93	0.93	0.94	0.90	0.91
2.5	293	0.92	0.93	0.94	0.95	0.91	0.92	0.93	0.94	0.95	0.91	0.92
2.5	298	0.92	0.93	0.94	0.95	0.91	0.92	0.93	0.94	0.95	0.91	0.92
2.5	303	0.92	0.94	0.94	0.95	0.91	0.93	0.94	0.94	0.95	0.91	0.93
2.5	308	0.93	0.94	0.95	0.95	0.92	0.93	0.94	0.94	0.95	0.92	0.93
2.5	313	0.93	0.94	0.95	0.95	0.92	0.93	0.94	0.95	0.95	0.92	0.93
I	*c*	0.074	0.074	0.074	0.099	0.099	0.099	0.099	0.099	0.124	0.124	0.124
	T/*t*	4800	5400	6000	4800	5400	6000	6600	7200	6000	6600	7200
1.5	303	0.90	0.91	0.92	0.88	0.89	0.90	0.91	0.92	0.88	0.89	0.90
1.5	308	0.90	0.91	0.92	0.88	0.89	0.90	0.91	0.92	0.88	0.89	0.90
1.5	313	0.90	0.91	0.92	0.89	0.90	0.91	0.91	0.92	0.89	0.90	0.90
2	293	0.92	0.92	0.93	0.90	0.91	0.92	0.93	0.93	0.90	0.91	0.92
2	298	0.92	0.93	0.93	0.90	0.91	0.92	0.93	0.93	0.90	0.91	0.92
2	303	0.92	0.93	0.93	0.91	0.92	0.00	0.93	0.93	0.91	0.91	0.92
2	308	0.92	0.93	0.94	0.91	0.92	0.92	0.93	0.94	0.91	0.92	0.92
2	313	0.92	0.93	0.94	0.91	0.92	0.93	0.93	0.94	0.91	0.92	0.92
2.5	293	0.93	0.94	0.94	0.92	0.93	0.93	0.94	0.94	0.92	0.92	0.93
2.5	298	0.93	0.94	0.94	0.92	0.93	0.93	0.94	0.94	0.92	0.93	0.93
2.5	303	0.93	0.94	0.95	0.92	0.93	0.94	0.94	0.95	0.92	0.93	0.93
2.5	308	0.94	0.94	0.95	0.92	0.93	0.94	0.94	0.95	0.92	0.93	0.94
2.5	313	0.94	0.94	0.95	0.93	0.93	0.94	0.94	0.95	0.93	0.93	0.94

CONCLUSIONS

(1) Electrocatalytic reduction of *o*- and *p*-nitrophenols on a cathode activated with some d- and s-metal catalysts gives aminophenols in high yields.

(2) Using the probability-determined method for the experimental design, a generalized multifactor equation was derived that adequately describes the electrocatalytic hydrogenation of *o*-nitrophenol on Raney nickel under the simultaneous action of several factors: current strength; initial concentration of the substance being hydrogenated; amount of the catalyst; temperature of the reaction medium; and process time.

(3) Based on the equation derived (or mathematical model), the activation energies were calculated, and a four-factor nomogram for the conversion of *o*-nitrophenol was compiled. It was used for identifying the optimal conditions zones for the process examined.

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