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Catalysis Today 27 (1996) 187–193

CATALYSIS TODAY

Molecular oxygen as environmental acceptable, selective and the most strong oxidant in liquid-phase oxidation

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Abstract

Innovative catalytic processes based on oxidation of anionic forms of organic substrates (mainly oxi- and oxo-derivatives) by dioxygen open up new perspectives in environmentally acceptable production of a wide range of products. A new catalytic system, in many cases, permits to refuse the use of ecologically dangerous oxidising agents such as nitric acid, hypochlorite, permanganate without loss in the selectivity and the rate of processes. Distinctive feature of the proposed catalytic system consists, apparently, in simultaneous transfer of two electrons from the anionic form of the substrate coordinated on a Me^{n+} centre to molecular oxygen. This permits the latter to react as a most strong and selective oxidant in contrast with wide distributed auto-oxidation processes which proceed via a thermodynamically unfavourable one-electron pathway of dioxygen reduction. The proposed oxidation mechanisms are tested using several oxidation processes interesting from a practical point of view.

Keywords: Molecular oxygen; Liquid-phase oxidation

1. Introduction

Oxidation of organic substances is one of the most significant methods for producing diverse chemicals from oil derivatives and vegetable raw materials. Most of the oxidation processes using O_2 as an oxidant, performed at the industrial scale, are based on the radical chain auto-oxidation reaction and give as a rule a very complex mixture of products. The key step of such a reaction is the formation of unstable peroxides in the reaction of dioxygen with free radicals. The more or less high selectivity can be achieved in these cases only at very low conversion degrees due to the high reactivity of free radicals involved in the process [1].

On the other hand, it is known that in most cases the one-electron reduction of oxygen is a thermodynamically unfavourable process while the two- or four-electron reduction of oxygen to hydrogen peroxide or water are, on the contrary, very favourable.

The possibility of the realisation of multi-electronic mechanisms provides obviously the high effective enzyme catalysis in many bio-oxidation processes.

The assistance of metal complexes in the process of electron transfer (oxygen activation) permits to realise the direct interaction of triplet dioxygen with singlet organic substances. The activation of not only dioxygen but also the oxidation substrate in the coordination sphere of the catalyst has to be of great importance in providing the high efficiency of oxidation processes.

New perspectives, in solving the problem, might be given by the creation of a new non-

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SSDI 0920-5861(95)00186-7

radical oxidation reaction, which is interesting from an industrial point of view. They were opened firstly with the oxidation of non-substituted primary alcohols by the use of some copper based catalytic systems in alkali solutions (pH > 10) when the anionic forms of substrates are involved in the reaction [2–4]. In neutral media when the degrees of substrates ionisation are negligible low, even in the presence of a catalyst the oxidation rate is some orders of magnitude lower than that in the presence of the base.

In this article we demonstrate that the use of catalytic systems, including copper complexes, base and solvent, permits the very effective oxidation, also in the case of many different substituted primary alcohols as well as secondary alcohols and polyols. The oxidative activity of O_2 in such system in overwhelming majority approximates the enzymatic one and is equal or even higher than that of the known strong oxygen atom donors, like HNO_3, $Cr_2O_7^-$, MnO_4^- or OCl^-.

The choice of ligand, base and solvent, which have to be used, depends on the nature of the substrate used and the selected oxidation route.

The catalytic system [$Cu^{n+}L_2$/base/solvent/O_2] in many aspects (the temperature interval of its activity, the high selectivity of oxidation and the probable mechanism of the oxygen activation) can be regarded as to mimic the enzymatic systems. It is known that copper, side by side with iron, is one of the most abundant elements for proteins involved in dioxygen metabolism. In many biological systems the formation of anionic forms of substrates plays the crucial role in the oxidation mechanism.

Oxidation potential of the Cu(I)/Cu(II) couple is one of the very important factors governing the interaction of copper complexes and dioxygen and depends strongly on ligand environment, steric and electronic effects of substituents, solvent, etc., providing the large possibility for designing and developing a new catalytic oxidation system with copper as a main catalytic component.

The variation of reaction conditions in oxidation of different substrates with O_2 permits to realise the versatile utilities of copper, known for biological systems using the relatively simple chemical catalytic system [$Cu^{n+}L_2$/base/solvent]. The use of the catalytic system under investigation permits, in some cases, to realise the unusual oxidation pathways, like, for example, the new reaction of the one-step oxidative deformilation of polyfluorinated primary alcohols described below.

2. Experimental

The oxidation of ketones and alcohols was performed at 30–70°C at different O_2 pressures in alkali solutions. In all cases, in the absence of both base and catalyst, the oxidation rates of all substrates under investigation are negligibly low as compared with those that can be obtained in the presence of this two components of the catalytic system.

The copper–*o*-phenanthroline complexes were obtained in situ by dissolving $CuCl_2$ and *o*-phenanthroline (o-phen) in an appropriate inert solvent at different ratios of [Cu(II)]/[o-phen].

The reaction was followed by measuring the oxygen absorption, base and substrate consumption (using GLC and HPLC techniques) and oxidation products accumulation (GLC and HPLC) in the course of the reaction.

The concentration of $Cu(I)(o\text{-phen})_2$ complexes was measured by means of UV–vis. spectroscopy at $\lambda_{max} = 430$ nm.

3. Results and discussion

As can be seen from Table 1 the rate of oxidation of ketones and alcohols in the presence of base and copper catalyst depends strongly on its structure and the solvent used. As a rule the oxidation of monatomic alcohols is depressed in the presence of water and other protic solvents and can be accelerated by several orders on magnitude by using some aprotic solvents. The rate of ketones oxidation in water-containing solutions is

Table 1
The rates of some organic substances oxidation in the presence of the catalytic system [Cu^{n+}/o-phenanthroline/base/solvent]

Oxidation substrate	T, °C	Solvent	Base	$W_{O_2}10^5$, M/s
Cyclopentadiene	50	water/n-propanol	NaOH	300
Cyclohexanone	50	water/n-propanol	$Ca(OH)_2$	200
α-Tetralone	50	water/n-propanol	$Ca(OH)_2$	30
Heptanone-3	50	water/n-propanol	$Ca(OH)_2$	10
Acetophenone	50	water/n-propanol	$Ca(OH)_2$	0.2
α-Tetralol	50	water/n-propanol	$Ca(OH)_2$	0.7
$C_nH_{2n-1}OH$	30–70	water/n-propanol	$Ca(OH)_2$	<0.05
Methanol	30	acetonitrile	NaOH	50
Benzylic alcohol	40	DMFA	NaOH	100
i-Propanol	25	–	KOH	200
Mannitol[a]	50	water	$Ca(OH)_2$	10
Inositol[a]	50	water	$Ca(OH)_2$	<0.1
Sucrose[a]	75	water	NaOH	5

[a] Without o-phenanthroline.
[o-phen] = 2 [Cu^{n+}] = 0.01 M, [Substrate] = 1 M.

much higher than that of alcohols, so that the latter can be used as an inert solvent in the oxidation of ketones. The polyols can be oxidised, with essentially high rate, in water solutions. In many cases the oxidation in basic solutions can be catalysed by copper salts: the substrate plays in these cases the role of active ligand.

The very high flexibility of the catalytic system in question permits relatively easy to go from Cu(I)- to Cu(II)-catalysis governing different pathways of non-radical oxidation and oxygenation of ketones, monatomic primary and secondary alcohols and polyols.

3.1. Cu(I)-catalysis

Using copper-o-phen complexes as a catalyst in alkali solutions it is relatively easy to change the ratio [Cu(I)/Cu(II)] in solution from a negligible small concentration of Cu(I) to a practically complete conversion of Cu(II) to Cu(I) by varying both base and o-phen concentrations in solution and going in such a manner from Cu(II)- to Cu(I)-catalysis and vice versa.

In the conditions when Cu(I)-complexes are stable and act as a catalyst the non-substituted primary alcohols in non-aqueous basic solutions can be oxidised to aldehydes at 20–50°C [4] and the secondary to ketones. The selectivity (S_{RCHO}) of aliphatic non-substituted primary alcohols oxidation to aldehyde achieves more than 95% at a low conversion degree and drops to 75–80% (the concentration of aldehyde in solution not more than 0.1–0.2 M) at conversion $C > 50\%$ due to a low stability of aliphatic aldehydes in the presence of alkali. The selectivity of benzyl alcohol oxidation to benzaldehyde at a high conversion is significantly higher. The concentration of aldehyde can reach 1 M due to its relatively high stability in the reaction conditions [4].

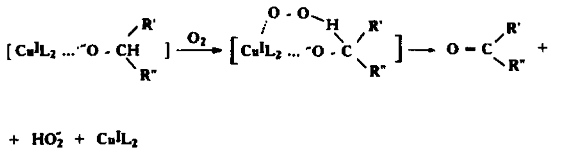
The oxidation of i-propanol at 20°C and a base-to-catalyst ratio of 1 or 2

$$(CH_3)_2CH_2OH + 1/2O_2 \rightarrow (CH_3)_2C{=}O + H_2O_2$$

proceeds with extremely high rate close to that of an enzymatic reaction with a turnover number of about 10^4 and a turnover rate of ca. $1 \div 2\ sec^{-1}$. The unique oxidation product is acetone; the selectivity of its formation is close to 100%. The molar ratio of oxygen consumed to acetone formed is close to 0.5 in accordance with the above stoichiometric equation. The base is practically not consumed in the course of the reaction ($\Delta[NaOH]/\Delta[CH_3C(O)CH_3] < 0.01$) and acts as a co-catalyst.

The coordinatively saturated complexes $[Cu(o\text{-}phen)_2]^+$ are demonstrated to be responsible for the catalytic activity of the catalyst.

The kinetic isotope effect, evaluated from the ratio of the rates of i-propanol and 1,2,3,-D_7-i-propanol oxidation, is close to 2 throughout the reaction course indicating that hydride transfer is the rate-limiting step in the overall reaction mechanism.



Scheme 1.

By its kinetic behaviour the catalytic system [Cu(I)/o-phen/NaOH/solvent] is quite similar to galactose-oxidase [5], whose active centre is known to contain a Cu^+ ion responsible for the oxidation of primary hydroxyl to carbonyl groups.

In contrast with the mechanism proposed for galactose-oxidase mediated oxidation of hydroxy-groups, where the assistance of Cu(III) ions is proposed, we believe that both primary and secondary alcohols oxidation takes place following a two-electron one-stage mechanism.

The formation of the intermediate adduct $Cu(I)(o\text{-phen})_2 \cdots R_2CHO^-$ sharply increases the donor ability of the Cu(I)-complexes and facilitates the reaction of the alcoholate-ion with O_2. The reaction involves the simultaneous transfer of two electrons and proton from an alcoholate-ion to molecular oxygen (Scheme 1).

3.2. *Cu(II)-catalysis*

At the relatively high content of alkali in the solution ($[NaOH]_0/[Cu]_0 \geq 10$) practically all copper exists in the solution in the form of Cu(II). This leads to the realisation in the system of a new oxidation pathway cardinal different from that realised under Cu(I)-catalysis.

The oxidation of primary alcohols and ketones, as a rule in the majority of cases, leads, in this conditions, to the formation of corresponding acids. In the primary alcohols oxidation the carbon skeleton of molecule is conserved and only a $-CH_2OH$ group participates in the process; the oxidation of ketones provides the acid formation with the rupture of α-C–C bonds and formation of dicarbonic acids when using cyclic ketones (cyclohexanone or cyclododecanone, camphor) as substrates or low molecular weight acids as in the case of aliphatic ketones oxidation.

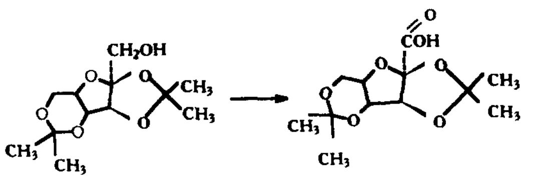
It is necessary to mention here that the aldehydes and α-diketones were found not to be the intermediates in the oxidation of primary alcohols [4] and ketones [6] to acids.

As it was mentioned above the pathway, the rate and the selectivity of the oxidation of alcohols and ketones depend strongly on the substrate structure and are controlled not only by the valence state of catalyst but also by the nature of solvent and base, the reaction temperature, oxygen pressure and so on. Thus in some special conditions (for example, in the presence of some amines as a base) the use of a [Cu^{n+}/base/solvent] catalytic system can provide the oxidation of ketones to α-diketones with a selectivity of up to 40%.

The effective catalysis by the Cu(II) in some cases does not require the use of some special ligands. Thus, the oxidation of the reduced sugars and polyols by molecular oxygen goes with essentially high rates in the presence of copper salts CuX_2 (see Table 1) and does not depend on the X^- used. The adding of any chelating or monodentate ligands depresses drastically the oxidation rate. The analogous effect can be observed in the oxidation of substituted alcohols and other substrates which can serve as chelating agents creating the catalytic system [Cu(II)L/base/solvent] (where L = substrate).

The very important characteristic peculiarity of the catalytic system in question (both Cu(II)- and Cu(I)-catalysis) is the essentially narrow temperature interval of its activity. High selectivity of oxidation can be achieved at temperatures near ambient, in any cases below 60–70°C, when the rates of radical chain oxidation of alcohols and ketones usually is negligibly low. At $T > 80$°C, when the radical chain reaction pathway becomes to be important, the selectivity of oxidation in all cases falls down drastically and as a rule does not exceed 15–20%; also the oxidation rate diminishes strongly.

The variation of reaction conditions permits to oxidise practically any alcohols and ketones by gaseous oxygen (including the oxidation by air) with extremely high rates (the reaction half time



Scheme 2.

Table 2
The dependence of reaction parameters and the yield of base product of DAS to DGA oxidation on the oxidant used

Oxidant	T, °C	reaction time, h	DGA yield, %
NaOCl	60–80	6.0	85
$KMnO_4$	30	4.0	90
$\{O_2/Cu^{2+}-cat\}^a$	20–30	0.5–1.0	>90

[a] Solvent-tert.-butanol; $[DAS]_0=20\%$ (by weight).

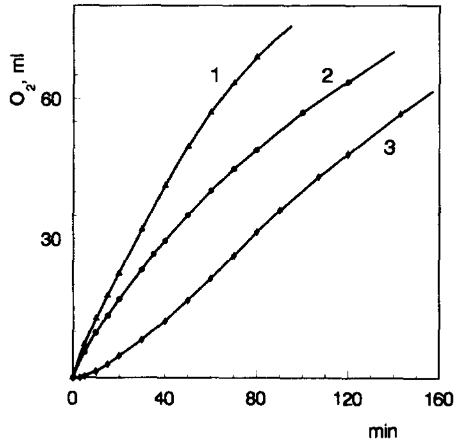


Fig. 1. The kinetic curves of the oxygen consumption in the course of DAS oxidation in the presence of $CuCl_2$ (1), $CuCl_2$/o-phen = 0.5 (2), CuS (3). $[DAS]=25\%$ w/w, $[Cu(II)]=0.005$ M, 0.5 M NaOH, solvent tert.butanol, 50°C.

$\tau_{1/2}$ can vary from some min up to 2–3 h at temperatures of 0–60°C) and the yield of the base product is not lower than 80% at the process selectivity $S \geq 90\%$. It is important to mention here, that in the optimal conditions the rates and the selectivities of oxidation are near to those characteristic for such strong oxidant as potassium permanganate, potassium dichromate, sodium hypochlorite or nitric acid, widely used up to date in practice and environmentally not acceptable.

Such a high efficiency of oxidation of many organic substrates with molecular oxygen permits to design the catalytic systems able to substitute the $KMnO_4$, $K_2Cr_2O_7$ and other strong oxidants on O_2 in practically important processes.

Below we dwell briefly on some of such reactions.

3.3. The oxidation of diacetone-2-keto-L-sorbose

The oxidation of diacetone-2-keto-L-sorbose (DAS) to diacetone-2-keto-L-gulonic acid (DGA) (the semiproduct in the ascorbic acid production) (Scheme 2) is realised in practice using NaOCl and rarely $KMnO_4$ as oxidants. The existing methods permitting to oxidise DAS to DGA using molecular oxygen are based on the support of Pt- or Pd-catalyst and are not very convenient due to the low stability of the catalyst.

The oxidation of DAS in the presence of Cu-catalyst in alkali media in water free solutions permits to achieve a yield of DGA up to 98% at 30–40°C.

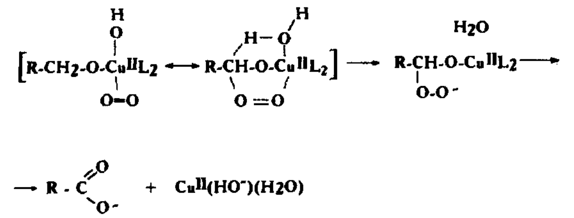
As can be seen from Table 2 the efficiency of DAS oxidation under Cu(II)-catalysis exceeds that achieved in the cases when NaOCl or $KMnO_4$ are employed as the oxidants.

The DAS oxidation is an example of the high activity of copper salts as a component of catalytic system. As can be seen from Fig. 1 the oxidation of DAS take place at 50°C in the presence of, not only, $CuCl_2$ that is well soluble in the reaction mixture, but also CuS that can be solubilised only in the course of the reaction. o-Phen introduced in the reaction depressed the reaction rate.

The strong dependence of the reaction rate and selectivity on oxygen partial pressure is the characteristic of the process. Nevertheless the oxidation rate at atmospheric pressure of O_2 is essentially high and only traces of DGA can be detected in solution. The selectivity of reaction increases with p_{O_2}:

p_{O_2}, atm	1	5	10	15	25
DGA yield, %	traces	45.5	86	89.2	95

It is well known that the rate of the radical chain oxidation does not depend on the oxygen pressure. At $p_{O_2} > 50$–200 mm Hg the interaction of free radicals $R^{\cdot}$ with O_2 goes very quickly and does



Scheme 3.

not limit the overall reaction rate. Thus, one can conclude that the reaction mechanism is changed with the increase of the oxygen partial pressure: obviously at the high oxygen pressure the non-radical mechanism of direct oxidation of DAS with O_2 becomes predominant.

3.4. *The oxidation of ω-hydroperfluoroalcohols, $H(CF_2CF_2)_nCH_2OH$ (n = 1–6) to ω-hydroperfluorocarbonic acids, $H(CF_2CF_2)_nCOOH$*

It is known that the ω-hydroperfluorinated alcohols are non-reactive towards oxygen and its oxidation requires the employ of such strong oxidants as $K_2Cr_2O_7$ or HNO_3.

The use of the catalytic system [Cu(II)/o-phen/NaOH/sec. alcohols or aprotic solvent] permits the oxidation of $H(CF_2CF_2)_nCH_2OH$ (HR_FCH_2OH) to corresponding acids at 30–60°C by molecular oxygen [7]:

$$HR_FCH_2OH + O_2 \rightarrow HR_FCOOH + H_2O$$

The reaction selectivity achieves 80% up to 98% conversion of alcohol. Like in the case of DAS oxidation the reaction rate and selectivity depends strongly on the oxygen partial pressure. The kinetics regularities, extremely high rates and selectivities of DAS, $H(CF_2CF_2)_nCH_2OH$ and some other alcohols oxidation which are very close to those characteristic for the enzymatic one permits to conclude [4,8] that the oxidation goes through the ternary complex $[Cu(II)\cdots RO^-\cdots O_2]$ formation and its consequent one stage conversion with acids formation according to a two-electron mechanism (Scheme 3).

3.5. *The oxidation of ω-hydroperfluoroalcohols, $H(CF_2CF_2)_nCH_2OH$, to α,ω-dihydroperflouroalkanes, $H(CF_2CF_2)_nH$*

The investigation of the kinetic behaviour of HR_FCH_2OH oxidation in the presence of the catalytic system $\{Cu^{n+}/L/\text{base}/\text{solvent}]$ permits to establish that at the absence of the ligand at atmospheric O_2 pressure the alcohols undergo a one step oxidative deformilation with the formation of formic acid and α,ω-dihydroperflouroalkanes as the end products [7].

$$HR_FCH_2OH + 1/2O_2 \rightarrow HR_FH + HCOOH$$

The reaction rate depends strongly on the substrate concentration in solution and, as it can be seen from Fig. 2, the reaction goes only in non-aqueous solutions being maximal at the concentration of substrate about 40% w/w. In optimal conditions the reaction turnover is about 1–2 sec^{-1}, that is very close to the turnover in enzymatic oxidation and exceeds on this parameter all known chemical catalytic reactions using O_2 as an oxidant.

The strong dependence of the reaction rate on the solvent, very low oxidation temperature (the reaction is still very fast at −10°C) and the extremely high selectivity of the process (the yield of alkane is near 100%) permits to exclude

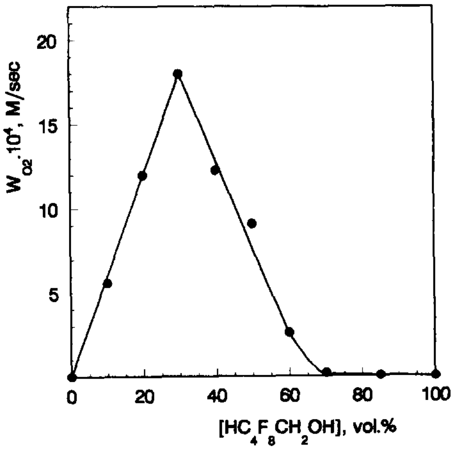
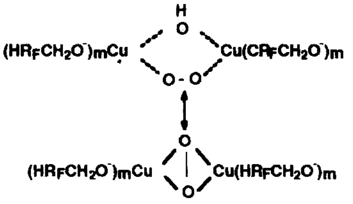


Fig. 2. The dependence of the rate of $H(CF_2)_4CH_2OH$ oxidation to $H(CF_2)_4H$ on its concentration in DMFA. $[CuCl_2] = 0.001$ M, 0.1 M NaOH, $p_{O_2} = 1$ atm, 50°C.



Scheme 4.

the possibility of the realisation of a radical chain mechanism.

We believe that in the o-phen free alkali solution, when the tendency to dimerisation of copper salts is higher than in the presence of o-phen, binuclear OH^--bridged copper complexes $\{[(HR_FCH_2O^-)_mCu]_2OH^-\}$ are formed. The last can react with molecular oxygen forming the active μ-1,2-peroxo- or μ-η^2:η^2-peroxo-binuclear complexes (see Scheme 4).The decomposition of one of this two possible intermediate moieties according to a two-electron mechanism leads to alkane and formic acid formation. Such mechanism in the main features is very close to that proposed for tyrosinase catalysis [9] known to be very effective in phenol oxidation with molecular oxygen.

4. Conclusion

The catalytic system $[Cu^{n+}/base/solvent]$ gives the surprisingly large possibilities to design the catalysts for the very effective oxidation of many different organic substances by molecular oxygen. Only traces of side-products are formed in most part of such processes. This catalytic system opens the way for very selective oxidation by O_2 of many oxi- and oxo-compounds like polyatomic alcohols, non-reducing saccharides, cellosolves, camphor, etc.

In all cases described above the possibility of fast transitions $Cu^+ \leftrightarrow Cu^{2+}$ are of great importance. Nevertheless in contrast with commonly used copper-based catalysts, where the 'Ping-Pong' mechanism is realised, the bulk reaction under study does not lead to the change of the valence state of copper in system. The reaction in all cases proceeds via the ternary complex $[Cu^{n+}\cdots(\text{Substrate anion})\cdots O_2]$ formation. The realisation of the two-electron one-step reduction of O_2 in the coordination sphere of copper ion becomes possible due to the easy change of atom multiplicity in the course of the reforming of chemical bonds in the transition state.

Acknowledgements

This work was supported by the Russian Pure Sciences Foundation under grant 94-03-08733-a and the International Science Foundation under grant MN4 300.

References

[1] N.M. Emanuel, Uspekhi khimii, 47 (1978) 1329.

[2] W. Breckman and J. Gaasbeek, Rec. trav. chim. Pays-Bas, 85 (1966) 242; 257.

[3] I.P. Skibida, A.M. Sakharov and O.N. Emanuel, Itogi nauki i tehniki, ser. Kinetika i kataliz, VINITI, Moskva, v.15, 1986, p. 110.

[4] A.M. Sakharov and I.P. Skibida, J. Molec. Catal., 48 (1988) 157.

[5] G.A. Hamilton, P.K. Adolf, J. de Jersey, G.S. DuBois, G.R. Dyrkaez and R.D. Libby, J. Am. Chem. Soc., 100 (1978) 1899.

[6] A.M. Sakharov and I.P. Skibida, Izvestija Akademii nauk SSSR, 1980, 523 (in Russian). [Bull. Acad. Sci. USSR, Div. Chem. Sci, 29 (1980) 344 (Engl. Trans.)].

[7] I.P. Skibida, A.M. Sakharov et al., PCT/RU91/00266, (WO 9 312 059) 24.06.93.

[8] I.P. Skibida and A.M. Sakharov, Russ. Chem. J., 39 (1995) 14. [Mendeleev Chem. J., 39 (1995) N 1, in press (Engl. Trans.)].

[9] N. Kitajama and Y. Moro-oka, Chem. Rev., 94(3) (1994) 737.