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KINETICS OF *N*-OXYL RADICALS' DECAY

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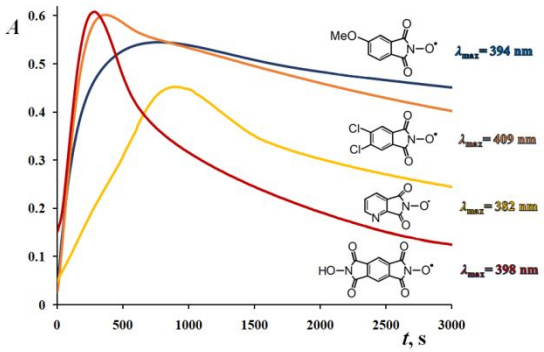
ABSTRACT

N-oxyl radicals of various structure were generated by oxidation of corresponding N-hydroxyimides with iodobenzene diacetate, [bis(trifluoroacetoxy)]iodobenzene and ammonium cerium (IV) nitrate in acetonitrile. The decay rate of imide-N-oxyl radicals follows first-order kinetics and depends on the structure of N-oxyl radicals, reaction conditions, the nature of the solvent and oxidant. The values of the self-decay constants change within $1.4 \cdot 10^{-4}$ s^{-1} for 3,4,5,6-tetraphenylphthalimide-N-oxyl radical to $1.4 \cdot 10^{-2}$ s^{-1} for 1-benzotriazole-N-oxyl radical. It was shown that the rate constants of the phthalimide-N-oxyl radicals' self-decay with different electron withdrawing or donor substituents in the benzene ring are higher than that of unsubstituted phthalimide-N-oxyl radical in most cases. The solvent effect on the process of phthalimide-N-oxyl radical self-decomposition was investigated. It was shown the dependence of the rate constants on the Gutmann donor numbers.



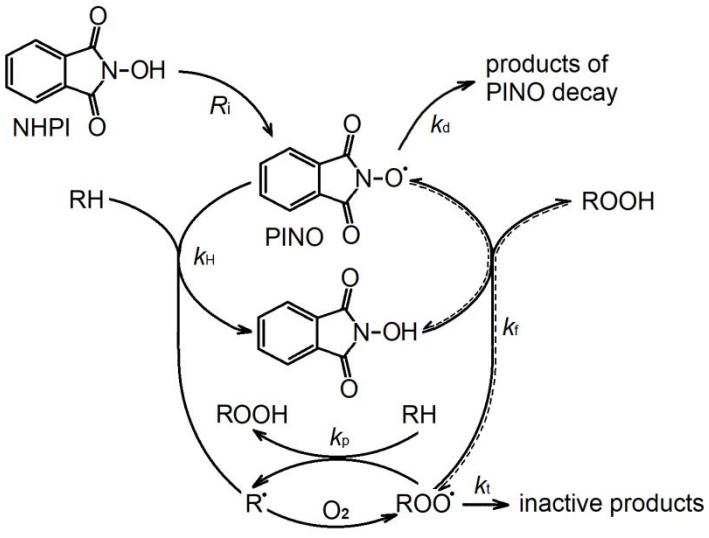
INTRODUCTION

Oxidation of organic compounds with molecular oxygen is an important environmentally friendly method to produce various oxygen-containing products.[1, 2] The selectivity of these

processes is difficult to achieve without the use of catalysts.[3] It is known that *N*-hydroxyphthalimide (NHPI) exhibits high catalytic activity and selectivity in the oxidation of organic compounds with molecular oxygen under mild conditions.[4] One of the main drawbacks, which limits its use, is the spontaneous decay of phthalimide-*N*-oxyl radical (PINO), formed *in situ* from NHPI. The PINO radicals are the key intermediates in oxidation processes. To maintain their high concentration in the reaction mixture, the oxidation of organic compounds is carried out at high concentrations (10-20 mole %) of NHPI.[5] This fact poses problems when developing commercially acceptable technologies with participation of NHPI.

The catalytic cycle promoted by the NHPI / PINO system is presented in Scheme 1. PINO is formed in initiation stage (R_i) by oxidation of NHPI with transition metal salts and complexes, enzymes, quinones, aldehydes, and traditional radical initiators as azo-compounds or peroxides.[6] PINO abstracts the H-atom from the C-H bond of organic molecule (k_H) with formation of alkyl radical and regeneration of NHPI. Formed C-centered radical readily reacts with molecular oxygen to give peroxyl radical, which abstracts the H-atom from RH (k_p) (classical propagation reaction) or NHPI (k_f) to form the hydroperoxide as primary product. PINO radicals do not terminate chains by reaction with ROO$^\bullet$ or by dimerization,[7] therefore chain termination in catalytic process occurs through the reaction of peroxyl radicals with each other (k_t). k_d in Scheme 1 is the self-decay rate constant of *N*-oxyl radicals.

Scheme 1. Mechanism of catalytic oxidation of organic compounds RH with molecular oxygen in the presence of NHPI.



As shown in Scheme 1 the *N*-oxyl radicals work as mediators that efficiently transfer H-atoms from the substrates to the ROO$^\bullet$ radicals. Obviously, the efficiency of such chain radical process depends on the stability of the NHPI catalyst and its PINO radical, since recyclability of NHPI will significantly affect the selectivity of the process.

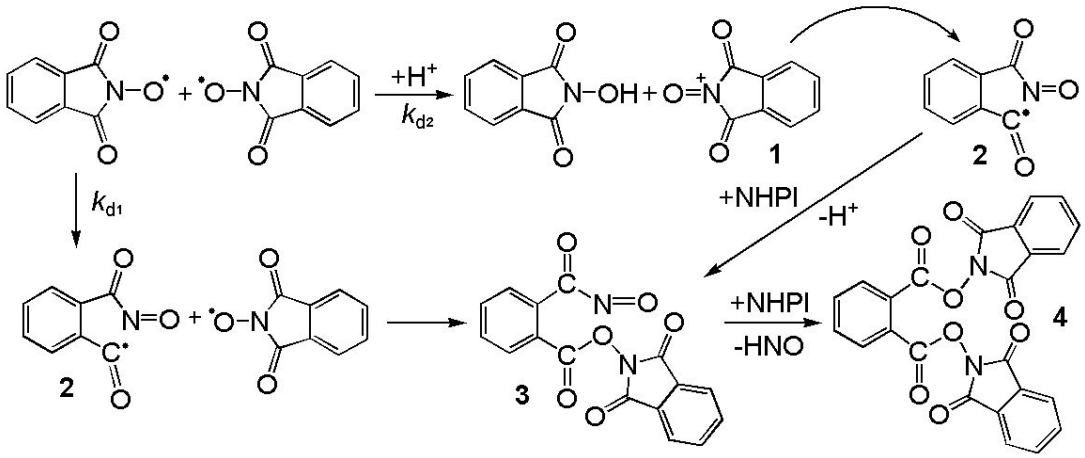
Kinetic studies of PINO decay have been carried out by various research groups.[8] But the current views on the mechanism and kinetics of this process are contradictory. Depending on the solvent and the radical generation method, different constants of the PINO self-decay are given.

Masui et al.[8d] have reported the results of investigation of PINO stability when radical was generated *via* electrochemical oxidation of NHPI in acetonitrile in the presence of pyridine and $NaClO_4$. The self-decomposition of PINO obeyed second-order kinetics with a k_d = 24.1 $M^{-1}s^{-1}$ at 25 °C. It was shown that the reaction rate depends little on temperature, concentration of dissolved oxygen, water, or added base. Trimer 4 (71 %) was identified as the main product of the PINO self-decay (Scheme 2). Masui[8d] has concluded that the PINO decay proceeds through the radical disproportionation, including the formation of NHPI molecule and *N*-oxonium cation 1, which transforms to acyl radical 2. Then NHPI as nucleophile attacks radical 2 to give dimer 3. Trimer 4 is a reaction product of NHPI with dimer 3, as shown in Scheme 2. In addition to the trimer phthalic acid (2.5 %), phthalic anhydride (8 %), phthalimide (trace), and NHPI (3.5 %) were found among the products.

Espenson et al.[8a] have generated PINO by oxidation of NHPI with $Pb(OAc)_4$ and obtained the same value for the second-order constant of PINO decay in both acetic acid and acetonitrile (0.6 $M^{1}s^{-1}$), which is significantly less than that reported by Masui et al.[8d] As per opinion of Espenson, the PINO decay acceleration in acetonitrile in the experiments by Masui[8d] could be attributed to the addition of pyridine. The constants presented by Espenson[8a] were confirmed by Baciocchi,[9] which obtained values of k_d 0.4, 4 and 0.9 $M^{-1}s^{-1}$ in acetonitrile, CCl_4 and 1,1,1,3,3,3-hexafluoro-2-propanol, respectively. However, Pedulli et al. reported the first-order of the PINO self-decomposition rate constant k_d = 0.1 s^{-1} [8c] using EPR method. In this case radical was produced photochemically from NHPI in the presence of dicumyl peroxide (20 % by weigth) in benzene solutions containing 10 % acetonitrile. Recupero and Punta[4b] believe that a reason for different observations by Masui[8d], Espenson[8a], Baciocchi[9] and Pedulli[8c] is the different experimental conditions. At low concentrations of PINO, such as in the Pedulli's case[8c], radical undergoes a first-order decay. In contrast, when radical was generated at high concentrations like in the works of Masui[8d], Espenson[8a] and Baciocchi[9], PINO decay occurs by second-order kinetics.

Scheme 2 illustrates the possible ways of PINO transformations with the cleavage at one of the C-N bonds with formation of acyl radical 2. Thus, in both processes, proposed by Pedulli[8c] (first-order kinetics, k_{d1}) and Masui[8d] (second-order kinetics, k_{d2}) identical products can be formed:

Scheme 2. The PINO self-decay reaction following a first- and second-order kinetics with the formation of dimer 3 and trimer 4.

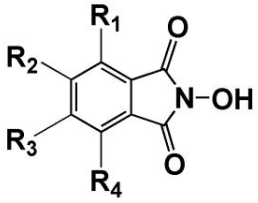


Considering such a mechanism of radical decay, it is necessary to take into account that under the aerobic oxidation, the resulting acyl radical 2 may turn into highly reactive peroxyacyl radicals, which can participate in the chain propagation stage.

Unlike initiator radicals involved only in the initial stages of radical-chain process, PINO take part in propagation stage (see Sheme 1) and its structure have a significant impact on the oxidation process. For example, the introduction of various electron-withdrawing or donor substituents into the benzene ring affects the persistence[8b] and reactivity of PINO radicals.[10] Nevertheless, as far as we know, systematic study of the influence of the PINO radicals' structure on their persistence[8b] has not been carried out. The investigation of decay of *N*-oxyl radicals is important for the design of new structures, expand the structural diversity of *N*-oxyl radical catalysts for their potential use in selective functionalization of aliphatic C-H bonds. In this study, we present new kinetic data of self-decomposition reactions of various *N*-oxyl radicals.

RESULTS AND DISCUSSION

The structures of *N*-hydroxy compounds under study are presented in the Scheme 3:



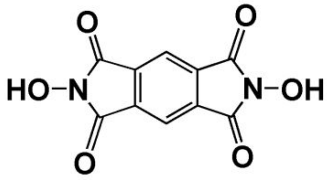
NHPI (R_1=R_2=R_3=R_4= H)

Ph_4-PINO (R_1=R_2=R_3=R_4= Ph)

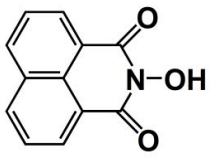
3-CH_3-NHPI (R_1=CH_3, R_2=R_3=R_4= H)

4-CH_3-NHPI (R_2=CH_3, R_1=R_3=R_4= H)

3-F-NHPI (R_1=F, R_2= R_3=R_4= H)



N, N-dihydroxypyromellitimide (NDHPI)



N-hydroxynaphthalimide (NHNI)

4-F-NHPI (R_2=F, R_1= R_3=R_4= H)

3-I-NHPI (R_1=I, R_2= R_3=R_4= H)

4-I-NHPI (R_2=I, R_1= R_3=R_4= H)

3-Br-NHPI (R_1=Br, R_2=R_3=R_4= H)

4-Br-NHPI (R_2=Br, R_1=R_3=R_4= H)

3-Cl-NHPI (R_1=Cl, R_2=R_3=R_4= H)

4-Cl-NHPI (R_2=Cl, R_1=R_3=R_4= H)

4-CH_3O-NHPI (R_2=CH_3O, R_1= R_3=R_4= H)

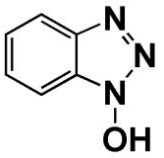
4,5-diCl-NHPI (R_1= R_4= H, R_2=R_3=Cl)

4-HOOC-NHPI (R_2=COOH, R_1= R_3=R_4= H)

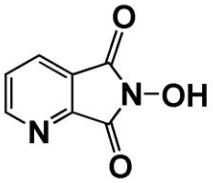
Cl_4-NHPI (R_1= R_2=R_3=R_4= Cl)

F_4-NHPI (R_1= R_2=R_3=R_4= F)

Br_4-NHPI (R_1= R_2=R_3=R_4= Br)



1-hydroxybenzotriazole (1-HBT)

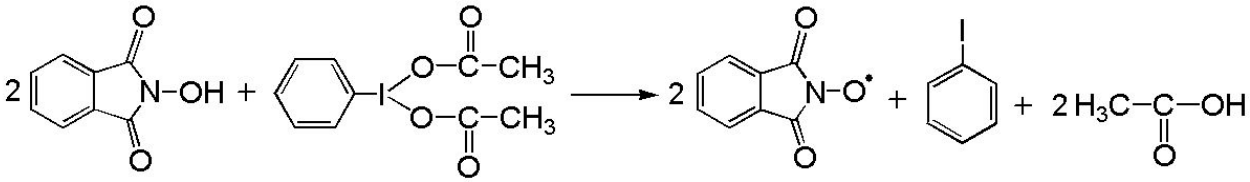


N-hydroxyquinolinimide (NHQI)

Scheme 3. The structures of *N*-hydroxy compounds.

The kinetic studies of *N*-oxyl radical reactions require a reliable, efficient and simple methods for producing radicals. *N*-oxyl radicals can be generated from their parents *N*-hydroxy compounds in oxidation processes by different ways[6] including photoactivation,[11] electrochemical,[10a, 12] and chemical methods with inorganic,[13] organic and enzymatic oxidants.[14] In recent years special attention was paid to nonmetallic methods for generating *N*-oxyl radicals.[4b, 4c, 15]

In this study we have used effective method for the generation of *N*-oxyl radicals from the corresponding *N*-hydroxy compounds (Scheme 4) with the metal-free oxidant (diacetoxyiodo)benzene $PhI(OAc)_2$ (PIDA), which is stable and readily soluble in organic solvents. The method allows us to produce high concentrations of PINO at room temperature. PIDA has the mild and highly selective oxidizing properties and was used for the C–O and C–C bond formation in the presence of NHPI,[16, 17] and also for the NHPI-mediated oxidation of sulfonamides to *N*-sulfonylimines.[18] Previously we have successfully used this method for recording the EPR spectra of the imide-*N*-oxyl radicals[19] and also for determining of the rate constants of the H-abstraction from the C-H bonds[20, 21] of organic compounds by PINO.



Scheme 4. Generation of PINO from NHPI using PIDA.

When PIDA is added to the *N*-hydroxy compounds solutions, the absorption bands appear in the region of 350 – 600 nm with λ_{max}, depending on the structure of *N*-hydroxy compounds. This result indicates the formation of *N*-oxyl radicals (Figure 1 and Figure S1-S2 in the SI). We used a stoichiometric excess of *N*-hydroxy compounds to minimize the effect of the oxidant on the radical decay. The *N*-oxyl radical bands do not overlap with the absorption region of oxidant (Figure S3 in the SI), as well as of iodobenzene and acetic acid, formed from oxidant (see Scheme 4). *N*-hydroxy compounds absorb in the UV region, and the bands of radicals are usually in the visible region. This allows us to correctly carry out kinetic measurements using UV/Vis spectroscopy.

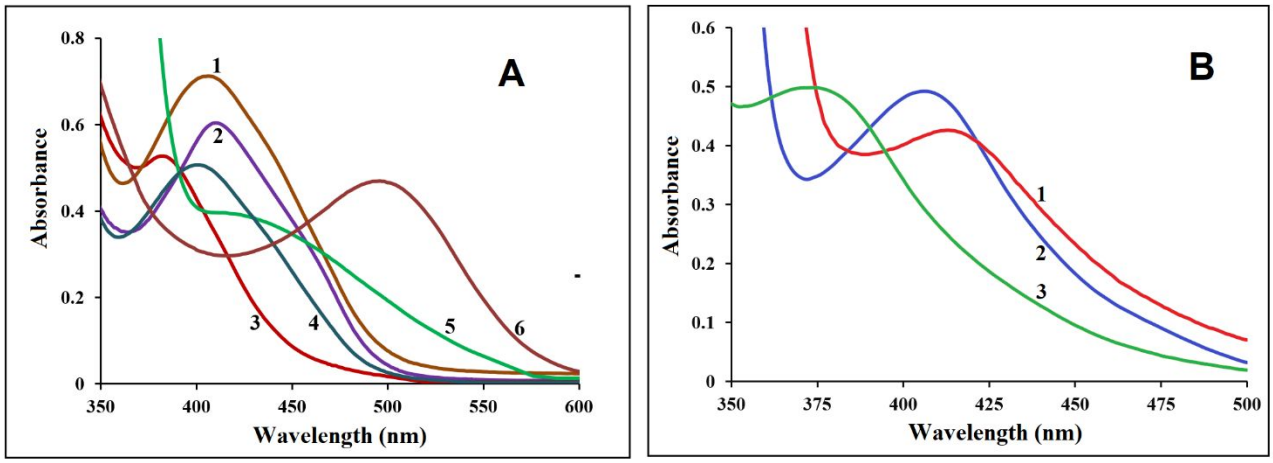


Figure 1. UV/Vis spectra of *N*-oxyl radicals generated by oxidation of *N*-hydroxy compounds (3.0 mM) with PIDA (0.3 mM) in CH_3CN, t = 30 ℃. **A)** 4-Br-PINO (1), 4,5-diCl-PINO (2), 4-Cl-PINO (3), PINO (4), Ph_4-PINO (5), 4-CH_3O-PINO (6). **B)** Br_4-PINO (1), Cl_4-PINO (2), F_4-PINO (3).

During the oxidation of *N*-hydroxy compounds with PIDA, the formation of *N*-oxyl radicals can be observed by increasing the absorption at λ_{max} of the corresponding radicals. Over time, the absorbance of the solutions decreases, which indicates decay of the radicals (Figure 2). The point corresponding to the maximum on the absorption−time curve is taken as start of the radical decay process. *N*-oxyl radicals decompose slowly, they are reasonably persistent to record accurate UV/Vis spectra.

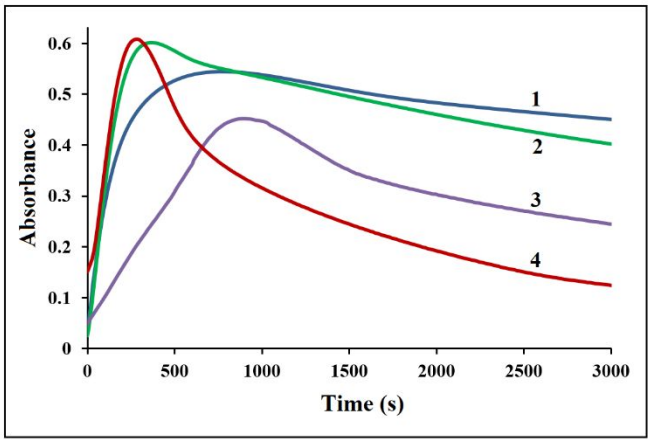


Figure 2. Absorption−time curves for the generation and decay of *N*-oxyl radicals in CH_3CN at corresponding λ_{max}. [*N*-hydroxy compound]$_o$ = 3.0 mM; [PIDA]$_o$ = 0.3 mM; 4-CH_3O-PINO (1) at 494 nm, 4,5-diCl-PINO (2) at 409 nm, quinolineimide-*N*-oxyl radical (QINO) (3) at 382 nm, pyromellitimide-*N*-oxyl radical (NDNO) (4) at 398 nm, 30 °C.

The decay reaction of *N*-oxyl radicals follows first order kinetics. The initial sections of kinetic curves of radical decay (Figure 2) are nicely described by equation 1. A plots of $\ln(A_t\text{-}A_\square)/(A_0\text{-}A_\infty)$ *versus* time give a straight line.

$$ln\frac{(A_t - A_\infty)}{(A_0 - A_\infty)} = -k_d t, \qquad (1)$$

where k_d is the first-order rate constant for spontaneous decay, A_0, A_∞ and A_t are the absorbances at $t = 0$, ∞, and t, respectively.

The first-order rate constants for the self-decay of *N*-oxyl radicals (k_d) were obtained from the slopes of the linear plots (Figure 3 and Figure S4 – S20 in the SI), using equation 1.

As per Figures 2, 3 and Figures 4-20 in SI, after the period of the radical accumulation and reaching the maximum absorbance, the kinetic curves of the radical decay consist of two parts. The first part could be attributed to the fast decay, which follows well the first-order kinetics. The second part describes the slow reaction (with about the same rate for the many radicals studied) (Figure 2). This type of kinetic traces, in our opinion, is explained by the complex mechanism of the decay. Obviously, based on principle of valency conservation, a monomolecular elementary act of PINO transformation into a stable molecular product is impossible. This process can only be a staged one. In particular, Pedulli[8c] and Masui[8d] proposed two alternative routes, as shown in Scheme 2. This is a bimolecular reaction between two PINO radicals; and a monomolecular process with a cleavage of C-N bond of PINO and subsequent bimolecular interaction of the resulting acyl radical and PINO. Since the final molecular product is the same for both routes, it is impossible to carry out their kinetic differentiation by product and we cannot expect that the

kinetics of the process of PINO spontaneous decay will be simple and to strictly follow the kinetics of the first or second order for a long period of time. The kinetics of the overall process will be described by a first-order equation if the first stage of the PINO transformation to an acyl radical is limiting.

We have used initial segments of the kinetic curves for the determination of the reaction rate constants, which under standard conditions are best described by a first-order equation. And it is these constants that we have chosen as a parameter to compare the radical stability.

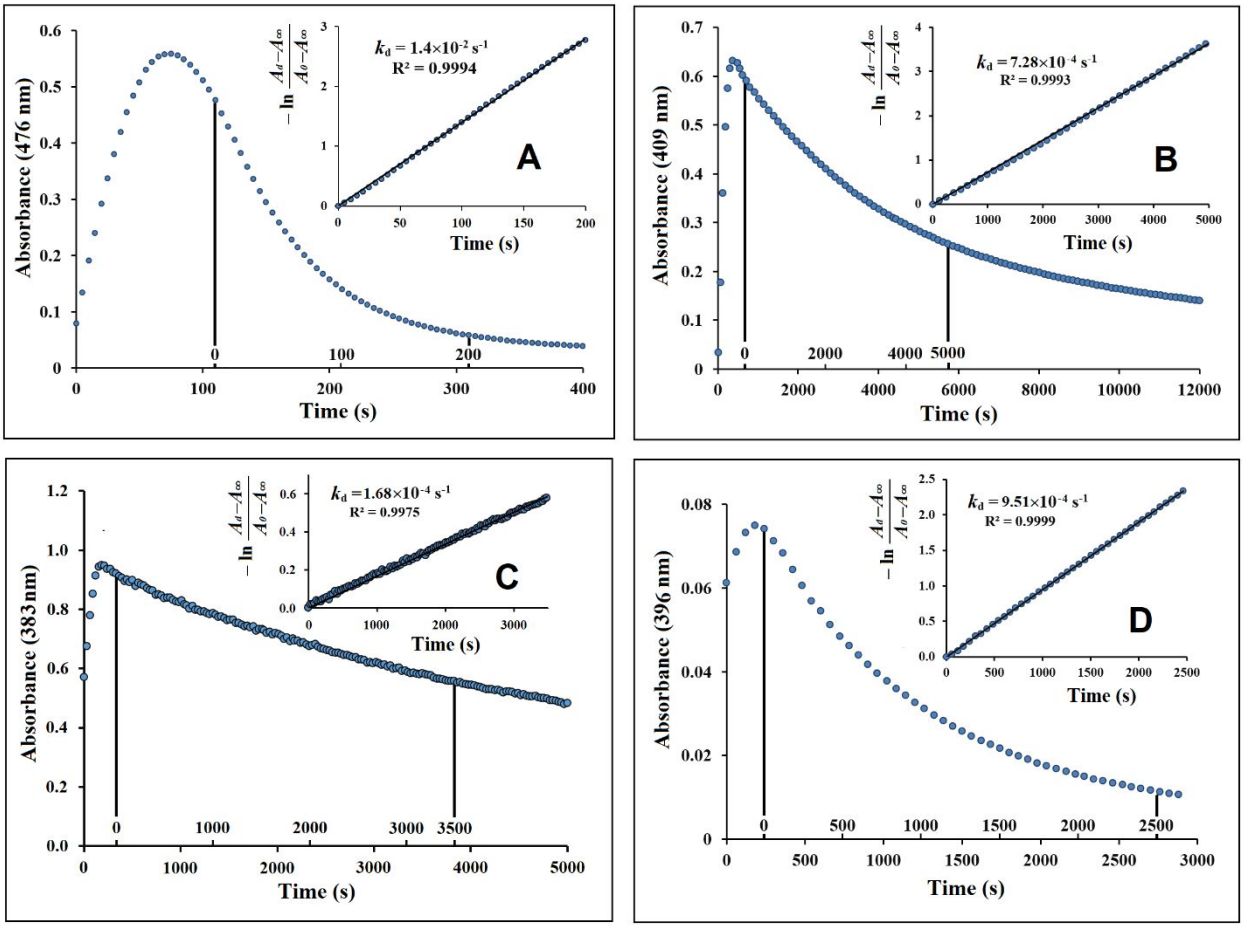


Figure3. Absorption−time curves for the generation and decay of *N*-oxyl radicals. Inset: first-order plots for the self-decomposition of *N*-oxyl radicals. [*N*-hydroxy compound]$_o$ = 3.0 mM; [PIDA]$_o$= 0.3 mM, 30 ℃. **A)** benzotriazole-*N*-oxyl radical (BTNO) at 476 nm; **B)** 4,5-diCl-PINO at 409 nm; **C)** 3-I-PINO at 383 nm; **D)** 4-CH_3-PINO at 396 nm.

[Bis(trifluoroacetoxy)]iodobenzene (PIFA) is also effective oxidant for generation of *N*-oxyl radicals at room temperature. Hypervalent iodine compounds as PIDA and PIFA are efficient alternatives to toxic heavy metal-based oxidants in many organic transformations.[22]

As can be seen in Figure 4 rates of radical accumulation and decomposition when using hypervalent iodine compounds and ammonium cerium (IV) nitrate (CAN) as oxidants are

different. This indicates an effect of the oxidant nature on the process; therefore, the measured rate constants do not relate to elementary reaction. Under oxidation by CAN, radical accumulation occurs immediately. On the contrary, during the oxidation of *N*-hydroxy compounds with PIDA or PIFA, the radical buildup can be observed.

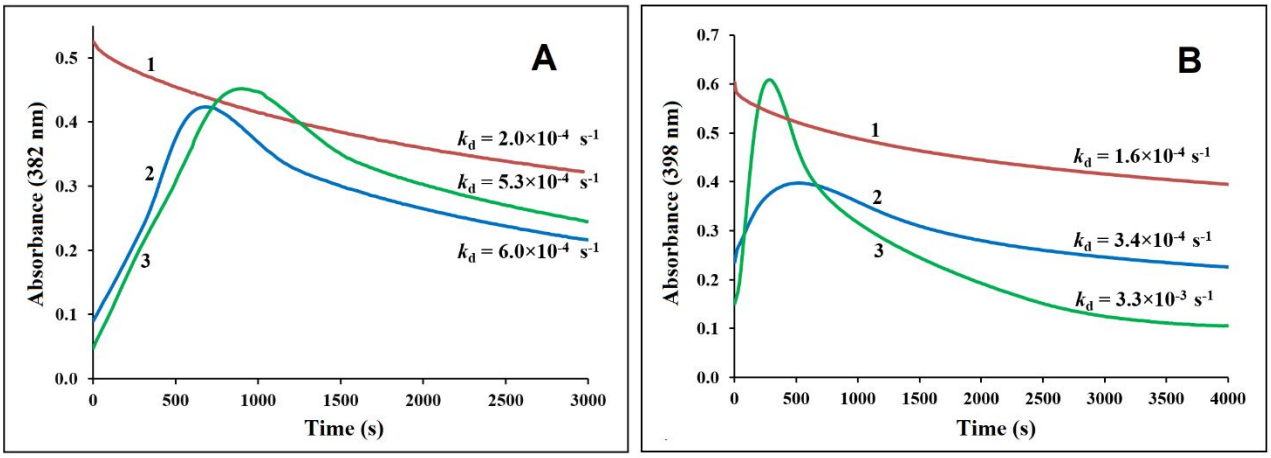
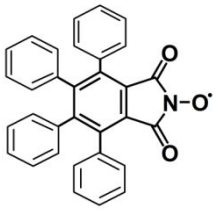
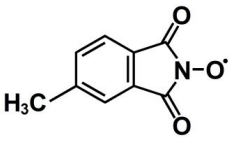
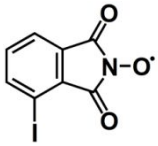
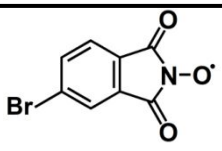
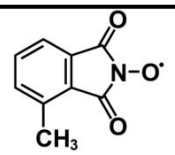
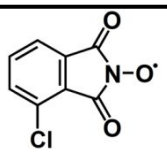
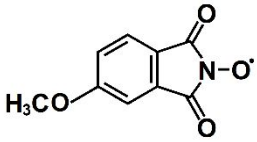
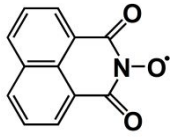
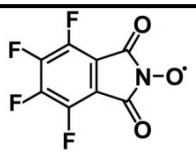
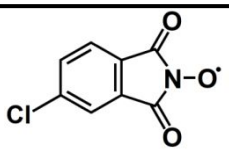
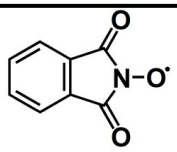
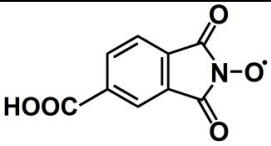
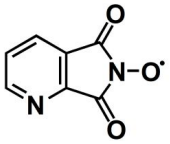
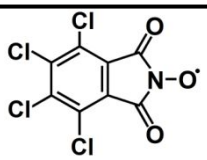
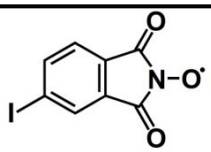
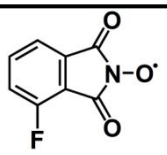
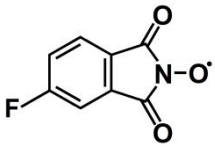
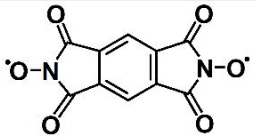
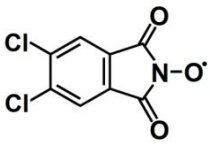
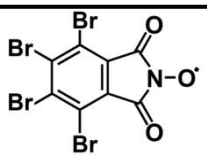


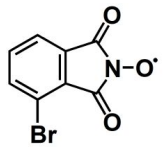
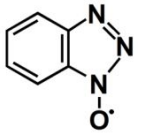
Figure4. Absorption–time curves for the generation and decay of *N*-oxyl radicals using different oxidants. Conditions: [*N*-hydroxy compound]$_o$ = 3.0 mM; [oxidant]$_o$= 0.3 mM (1–CAN; 2–PIFA; 3–PIDA), 30 ℃. A) QINO at 382 nm; B) NDNO at 398 nm.

The rate constants of *N*-oxyl radical self-decomposition were calculated using equation 1. In Table 1 wavelengths of maximum absorbance of radicals as well as the first-order rate constants for radical decay k_d are presented. All reactions were run at 30 °C under same conditions ([NHI]$_o$ = 3.0 mM; [PIDA]$_o$= 0.3 mM), as described in "Experimental Section". All rate constants were determined from several experimental runs with typical error ±10 %.

Table 1. The wavelengths of maximum absorbance of the *N*-oxyl radicals and the decay rate constants (k_d)

N-oxyl radical	λ_{max} (nm)	$k_d\times10^4$ (s^{-1})	*N*-oxyl radical	λ_{max} (nm)	$k_d\times10^4$ (s^{-1})
 Ph$_4$-PINO	435	1.4	 4-CH$_3$-PINO	396	9.5
	383	1.7	 4-Br-PINO	394	10

3-I-PINO					
 3-CH_3-PINO	386	2.4	 3-Cl-PINO	378	10
 4-CH_3O-PINO	494	2.7	 NINO	378	11
 F_4-PINO	374	4.1	 4-Cl-PINO	399	12
 **PINO**	**382**	**5.0**	 4-HOOC-PINO	379	17
 QINO	382	5.3	 Cl_4-PINO	406	26
 4-I-PINO	422	5.9	 3-F-PINO	370	28
 4-F-PINO	387	7.3	 NDNO	398	33
 4,5-diCl-PINO	409	7.3	 Br_4-PINO	415	86

 3-Br-PINO	371	7.6	 BTNO	476	140

It can be observed from Table 1 that the values of constants of *N*-oxyl radicals' decay vary within two orders of magnitude from $1.4 \cdot 10^{-4}$ s^{-1} for Ph_4-PINO to $1.4 \cdot 10^{-2}$ s^{-1} for BTNO (Table 1). Only five of them, within experimental error, decompose slower than PINO. A shift of the absorption maxima in the long-wave region for 4-substituted NHPI compared with 3-substituted NHPI is observed.

For most of the radicals presented in Table 1, the decay constants were measured for the first time, however catalytic activity of their *N*-hydroxy compounds precursors in aerobic oxidation of organic compounds was studied earlier. In some cases, the catalytic behavior of *N*-hydroxy compounds was interpreted in terms of stability of the corresponding *N*-oxyl radicals. Espenson et al.[23] investigated NHPI and its derivatives, such as 3-F-NHPI, 4-CH_3-NHPI, NDHPI and NHPI, in the presence of cocatalyst $Co(OAc)_2$ for the autoxidation of p-xylene and other methyl arenes. The activity of the substituted NHPIs shows an increase in the following order: 4-CH_3-NHPI < 3-F-NHPI < NHPI. Cai et al. reported[8b] that the self-decomposition of PINO radicals obeys second-order kinetics in benzene and the radical decay rate follows the order 4-CH_3-PINO < 3-F-PINO < PINO, consistent with the reactivity of the NHPIs in the catalytic cycle.[23]

Xu et al.[24] also considered the reactivity of tetra-halogen substituted NHPIs from the point of view of radical stability. The authors showed that F_4-NHPI in combination with 4-diamino-2,3-dichloroanthraquinone in the oxidation of ethylbenzene exhibited an abnormally lower catalytic activity compared with Cl_4-NHPI and Br_4-NHPI. The reason may be that four strongest electron-withdrawing fluoro-groups in F_4-NHPI decrease the stability of the corresponding PINO radical, which leads to a lower efficiency in catalysis. We have generated corresponding *N*-oxyl radicals from halogen substituted NHPIs using PIFA and measured the decay rate constants (Table 1), which increase in the order F_4-PINO < Cl_4-PINO < Br_4-PINO. The obtained results show that the instability of the F_4-PINO radical is not the main reason of its lower efficiency in the oxidation of ethylbenzene.

Many aspects of the catalytic behavior of NHPI were studied in detail, and it was shown that the catalyst activity depends on many parameters.[10b, 25] However, the discussion about the influence of various factors on the oxidation of organic compounds in the presence of NHPI is still open in the literature.

The investigations of NHPI derivatives for the functionalization of organic molecules have been presented in many reports. For example, 3-CH_3O-NHPI,[26, 27] 4-CH_3O-NHPI,[10a, 26, 27, 28] 4-CH_3-NHPI,[26, 27, 28] 3-F-NHPI,[26, 27, 28] 4-Cl-NHPI,[10a] 4,5-diCl-NHPI, F_4-NHPI[10a] successfully tested in the processes of oxidation of alcohols under aerobic[26], laccase-catalyzed[27, 28] and electrochemical oxidation conditions[10a, 12b]. Cl_4-NHPI demonstrated a high potential as catalyst for electrochemical C–H oxidation of allylic compounds,[12b] primary and secondary alcohols.[10a, 29] The observed electrochemical reactivity of NHPI catalysts is determined by their redox potential and does not correlate with their reactivity under conditions of aerobic catalytic or laccase oxidation. The decomposition of the electro-generated PINO radical is the limiting factor in development of electrochemical oxidation processes[12c].

Study of various *N*-hydroxy compounds facilitates the development of new methods and strategies for the functionalization of organic molecules, opens up new possibilities for new and well-known structures of NHPI-type catalysts. For example, recently the groups of Brown[30] and Liu[31] demonstrated that Cl_4-NHPI and 4-CH_3O-NHPI can be used as components of catalytic systems for enantioselective synthesis.

The effect of the *N*-hydroxy compounds structure in the oxidation of *n*-butylbenzene was studied by Boaz et al.[32] The authors used a catalyst system consisting of ammonium iodate with an NHPI-type catalyst and showed that yield of the main product 1-phenylbutyl acetate slightly decreased in the presence of 4-CH_3-NHPI (76 %), F_4-NHPI (76 %), Br_4-NHPI (73 %), NDHPI (81 %), NHNI (67 %) compared with unsubstituted NHPI (86 %).

Lanzalunga et al.[33] reported the oxidation of cyclohexane, toluene, ethylbenzene and triphenylmethane by the nonheme iron (IV)−oxo complex $[(N_4Py)FeIV{=}O]^{2+}$ using NHPI, 4-FNHPI, 3-CH_3-NHPI and 3-CH_3O-NHPI as mediators. It was found a slight decrease in the mediation efficiency for 4-CH_3−NHPI and 4-CH_3O−NHPI compared with NHPI and 4-F-NHPI. The effect of substitution in the aromatic ring of NHPI on the oxidation of ethylbenzene using 3-CH_3-NHPI, 4-CH_3-NHPI, 3-F-NHPI, 3-CH_3O-NHPI and 4-CH_3O-NHPI in combination with cobalt (II) acetate was studied by Nolte et al.[34] It was shown that NHPIs with electron-withdrawing substituents accelerate the oxidation of ethylbenzene. Xu[35] and Lanzalunga[13b, 26] observed similar effects in the oxidation of other substrates. For example, Xu et al.[35] reported that the catalytic activity of system NHQI / metal salts in acetonitrile in the aerobic oxidation of toluene is significantly higher than that of NHPI through an electron-withdrawing effect of *N*-heteroaromatic ring containing *N*-hydroxy compound. The combination of $CuCl_2$ with NHQI showed the best activity in toluene oxidation. Substrate was transformed with 70.9 % conversion and 93.5 % selectivity to benzoic acid at 90 ℃ within 2 h. Later Lanzalunga,[13b] demonstrated an increase in

the reactivity of QINO compared with PINO in the reaction of the H-abstraction due to the presence of the *N*-heteroaromatic ring in QINO.

On the other hand, Marcadal-Abbadi reported[36] that NHPIs with electron-donating substituents such as 4-CH_3O-NHPI and Ph_4-NHPI show high activity in the oxidation of ethylbenzene in the presence of CuCl. Catalysts with electron-withdrawing substituents 4-Cl-NHPI, 4,5-diCl-NHPI, Cl_4-NHPI, F_4-PINO and NHQI are less effective. For example, a very low efficiency of the NHQI / CuCl system was observed for the oxidation of ethylbenzene in acetonitrile at 25 ℃.[36] The conversion of the substrate was only 10 % with 5 % acetophenone yield. Earlier we have shown that NHPI is much more effective than 4-HOOC-NHPI with an electron-withdrawing substituent in the cumene oxidation when using cocatalysts CuCl, CuBr[10g] and $Co(OAc)_2$.[10i, 37] Li et al. successfully used 4-HOOC-NHPI in combination with NHQI for the aerobic oxidation of ethylbenzene,[38] but it was shown that 4-HOOC-NHPI alone is an ineffective catalyst in the allylic oxidation of cholesteryl acetate.[39] Thus, the high reactivity of *N*-oxyl radicals with electron-withdrawing substituents in H-abstraction does not always correlate with overall catalytic activity. A strong O-H bond of *N*-hydroxy compounds with electron-withdrawing substituents facilitates the H-abstraction from substrates by corresponding *N*-oxyl radicals, but simultaneously decreases quasi stationary concentration of *N*-oxyl radicals formed in *situ* as a result of the reaction ($ROO^{\bullet}$ + NHPI → ROOH + PINO, k_f) [10i, 34] (see Scheme 1).

The data in Table 1 demonstrate, that the NDNO, BTNO, NINO radicals decompose with high rates, but in many cases the high catalytic efficiency of corresponding *N*-hydroxy compounds was observed. NHNI demonstrated high catalytic performance in aerobic oxidation of ethylbenzene[40] and *p*-xylene compared with NHPI.[41] On the other hand, NHNI exhibited a very low catalytic effect in the process of cumene oxidation in the presence of Cu (I) salts.[10i]

NDHPI has two NOH groups in the molecule and provides efficient catalysis in various oxidation processes,[36, 42] although a low conversion of substrates was obtained in the presence of NDHPI for both the aerobic oxidation of cumene[10i, 43] and electrochemical C–H oxidation of allylic compounds.[12b] Besides, NDHPI along with 4-HOOC-NHPI is effective in the processes of stereospecific radical polymerization of methyl methacrylate.[44]

BTNO radical is not stable and quickly decomposes with a half-lifetime of 49 s and a first-order rate constant $k_d = 6.3\times10^{-3}$ s^{-1} at 25 ℃.[45] We have generated BTNO using PIDA and PIFA and observed the decay of radical with rate constants 14.0×10^{-3} s^{-1} and 6.7×10^{-3} s^{-1}, respectively. Despite the low stability of the BTNO radical, its 1-HBT precursor is well-known as mediator of laccase oxidation of benzyl alcohols,[46] the laccase oxidative degradation of dyes[47] and as catalyst for the electrochemical oxidation of allylic C–H bonds.[12b]

The smallest rate constant of self-decay is observed for Ph_4-PINO radical (Table 1). It is known that Ph_4-NHPI is more soluble than NHPI in most of the classical solvents and it is one of the most successful organic catalysts of aerobic oxidation. Einhorn et al.[48] found that Ph_4-NHPI with CuCl in the oxidation of benzylic compounds shows good catalytic activity, even better than NHPI / CuCl. We have also showed, that system Ph_4-NHPI / CuCl is effective in the oxidation of cumene[10g] and system Ph_4-NHPI / $Cu(NO_3)_2$ successfully used for the mild oxidation of 5-hydroxymethylfurfural to 2,5-diformylfuran with molecular oxygen.[49] However, the oxidation rate of cumene in acetic acid in the presence of the Ph_4-PINO/$Co(OAc)_2$[37] system is lower compared with the oxidation catalyzed by NHPI. This is explained by steric hindrances during the interaction of cobalt ions and a bulk Ph_4-PINO molecule in the internal coordination sphere of the metal. Stahl et al.[50] also reported a lower activity of Ph_4-NHPI compared with NHPI during electrochemical iodination of methylarenes.

Comparative kinetic study of degradation of PINO and Ph_4-PINO indicated the steric factor importance. The introduction of four bulky phenyl substituents in the Ph_4-PINO radical limits the opening of the five-membered ring by breaking the C-N bond and increases the radical stability. Such results are consistent with the data discussed by Vanel[51] and Jacq.[52] Various polyaromatic catalysts analogous to NHPI were synthesized with the aim of tuning the catalyst performances in aerobic oxidation. It was shown that half-life of catalysts with polyaromatic structures is longer than that of PINO. Einhorn et al.[48] investigated the processes of generation and self-decomposition of the corresponding radicals in acetonitrile at 35 ℃. High kinetic stability of the corresponding radicals allows using such catalysts with low loading in aerobic oxidation of various substrates.

The presented analysis shows, despite that the decay of radicals is an important reaction responsible for deactivation of the catalyst, that there is no simple correlation between the rate of decomposition of radicals and the catalytic activity of *N*-hydroxy compounds. A complex catalytic oxidation process involves several stages with different radicals. The rates of reactions depend on the process conditions, the presence of cocatalysts, the structure of the *N*-hydroxy compounds, substrates and reaction intermediates. In addition, radicals with increased stability are often inactive in the key stage of oxidation process such H-atom transfer reaction. Thus, effective catalysis involving *N*-hydroxy compounds suggests a favorable balance between reactivity and stability of the resulting radicals.

Another factor that can significantly affect the decay rate of PINO is medium effect. The solvent is an important component and active participant of the reaction system; it can significantly affect the transformations of PINO and its reactivity. Numerous researchers discussed the solvent effect on the NHPI-catalyzed process of aerobic oxidation of organic compounds.[8c, 25c, 37, 53] It was shown, that the conversion of the substrate and the yield of the products can be controlled by

solvent properties. For example, catalytic activity of NHPI changes in polar protic solvents due to the formation of hydrogen bonds between solvent molecules and NHPI.[54] This effect is not observed in non-polar solvents, but their use is limited due to the poor solubility of NHPI. Unfortunately, data on the solvent effects on the radical decay rate are limited to reports from Espenson[8a] and Baciocchi.[9] Rafiee and co-workers examined the effect of solution pH on PINO decomposition rates and showed[55] that the rate increases with the basicity of the medium (0.18, 0.37, 1.4, and 6.2 s^{-1} at pH 2.5, 4.7, 7.2 and 8.3 respectively). The instability of electrogenerated PINO at increasing pH could be explained in terms of occurrence of some side reactions in aqueous solution.

To investigate the kinetic solvent effect, the rate constants of the PINO decay were determined in series of solvents. In Table 2 the values of the obtained constants are given, PINO was generated by oxidation of NHPI with PIDA.

Table 2. **Rate constants k_d for the PINO decay and solvent properties. $[NHPI]_o$ = 3.0 mM; $[PIDA]_o$= 0.3 mM; monitored wavelength, 382 nm; temperature, 30 ℃.**

Solvent	$k_d \times 10^3 (s^{-1})$	ε^a	DN[b] (kcal/mol)	AN[c] (kcal/mol)	$\alpha_2^{H\,d}$
Acetonitrile	0.5	37.5	14.1	18.9	0.09
Ethyl acetate	0.7	6	17.1	9.3	
Acetic acid	0.8	6.2	20.0	52.9	0.55
Benzonitrile	20.0	25.2	11.9	15.5	
Nitromethane	38.0	38.6	2.7	20.5	0.12
Chlorobenzene (PhCl) / Acetonitrile (2:1)	11.0	2.6 (for PhCl)	3.3(for PhCl)	–	–

[a]the dielectric constant. [b]Gutmann donor number; ref 56. [c]Gutmann acceptor number; ref 56. [d]Abraham's value; ref 57.

The lowest decay rate of PINO is observed in acetonitrile, which is in good agreement with the results of effective oxidation of various organic compounds in the presence of NHPI in acetonitrile.[8c, 10g, 10i, 25c, 49, 58] As can be seen from the data in Table 2, the rate of PINO decay varies little in solvents, which differ greatly in their ability as hydrogen bond donors, as confirmed by Abraham's α_2^H values.[57] These results are in agreement with the observations by Espenson[8a] and Baciocchi.[9]

The data in Table 2 allow us to trace the dependence of the rate constants on the Gutmann donor numbers, which characterize the nucleophilic properties of solvents.[59] The rate constants of

radical decay are low in the solvents with a high donor numbers such as acetonitrile, ethyl acetate and acetic acid, but in benzonitrile and nitromethane, which have a low donor numbers, the decay rate constants are sharply increasing. We can assume the formation of molecular complexes (solvates) between PINO radical and solvent molecule. Their formation will be facilitated by the large dipole moment of PINO and its elecrtrophilic character.[9, 20, 25c, 60] The higher the value of the solvent donor number, the larger the degree of the PINO solvation, that prevents its spontaneous decay.

CONCLUSIONS

Aerobic oxidation of organic compounds in the presence of NHPI-type catalysts is a complex multi-stage process. *N*-hydroxy compounds simultaneously participate in several reactions and their catalytic activity in such processes is determined by a complex of factors. One of the main reasons for limiting the use of *N*-hydroxy compounds as catalysts for industrial oxidation processes is non-persistence of derived radicals. We have found that the kinetics of *N*-oxyl radicals' decay strongly depends on the solvent, oxidant, reaction conditions, and the structure of radicals. Our experimental observations showed that different substituents of NHPI can impact the kinetic stability of corresponding radicals. However, substituted PINO radicals both with electron-donating and with electron-withdrawing substituents, within experimental error, have lower kinetic stability than unsubstituted PINO, except for 3-CH_3-, 3-I-, 4-CH_3O-, F_4- and Ph_4-PINO. The introduction of bulky phenyl substituents into the aromatic ring of the NHPI molecule contributes to the stability of the corresponding radical. It can be assumed that steric hindrances will affect the rate of radical decomposition. In this case, one might expect the slow decay of radicals formed from NDHPI and NHNI, but, on contrary, we have observed high rates of self-decomposition. Perhaps such complex structures decompose by another mechanism.

The presented study does not yet give an unambiguous answer to the question of how the radical structure affects their stability, but we hope that it adds valuable information for understanding the mechanisms of catalysis in the presence of *N*-hydroxy compounds. To establish a quantitative relationship between the structure and stability of radicals, additional studies are needed, which are carried out by our research group and will be published later.

EXPERIMENTAL SECTION

Materials. (Diacetoxyiodo)benzene, [bis(trifluoroacetoxy)]iodobenzene, *N*-hydroxyphthalimide, 1-hydroxybenzotriazole hydrate, ammonium cerium (IV) nitrate $(NH_4)_2Ce(NO_3)_6$ were commercial reagents and used without purification. CH_3CN used "HPLC gradient grade" without additional purification.

Instrumentation. Spectrophotometric measurements were performed on UV/Vis spectrophotometer Analytic Jena SPECORD 50 using a quartz cuvette (10 mm path length) equipped with a thermostated cell holder. IR spectra were recorded on Perkin-Elmer Spectrum BX using a KBr pellets. NMR spectra were recorded on a Bruker BioSpin 400 using DMSO-d_6 as solvent with tetramethylsilane as an internal reference. Elemental analysis was performed using Vario EL III. MS analysis was performed on an LCMS instrument (Agilent 1100) with chemical ionization.

Spectrophotometric Kinetic Studies. *N*-oxyl radicals were generated in a 3-mL spectrophotometric quartz cuvette by quickly mixing *N*-hydroxy compounds (3.0 mM) with PIDA, PIFA or CAN (0.3 mM) in deoxygenated acetonitrile at 30 ℃. All kinetic experiments were carried out by using freshly prepared samples.

Synthesis of *N*-hydroxyimides. *N*-hydroxyimides were synthesized by the reaction of corresponding phthalic anhydride with hydroxylamine hydrochloride according to the modified literature procedures and characterized by elemental analysis, ^{1}H NMR, ^{13}C NMR, IR-spectroscopy and HPLC/MS analysis (Figures 21-24 in SI).

The general approach to the synthesis of substituted NHPI can be shown by 3-methyl-*N*-hydroxyphthalimide synthesis[34]. 2.01 g. (30 mmol) of hydroxylamine hydrochloride were dissolved in 50 ml pyridine in ambient conditions under constant stirring. Stirring continued for another 20 min until complete dissolution of solid. Then, 4,48 g (27,6 mmol) finely ground 3-methylphthalic anhydride were added. The resulted solution was refluxed for 8 hours. After cooling to the room temperature, 100 ml of distilled water were added to formed yellow solution. pH was adjusted to the 2-3 by slowly adding 3 M. HCl solution. The target compound was formed as white powder, which was washed with cold water, filtered and dried in vacuum over P_2O_5 (45 °C / 10 torr).

3-Methyl-N-hydroxyphthalimide (3-CH_3-NHPI):[19, 34] yield: 2.54 g, 52%, m.p. 223 ℃. ^{1}H NMR (400 MHz, DMSO-d_6) δ 10.72 (s, 1H), 7.73–7.58 (m, 3H), 2.60 (s, 3H). ^{13}C{1H} NMR (75 MHz, DMSO-d_6) δ 164.8, 163.9, 137.0, 136.6, 133.9, 129.1, 125.3,120.5. IR (KBr), cm^{-1}: 3221, 2935, 2829, 1774, 1674, 1604. Anal. Calcd for $C_9H_7O_3N$: C 61.01; H 3.95; N 7.91. Found: C, 61.86; H, 3.71; N, 7.75.

4-Methyl-N-hydroxyphthalimide (4-CH_3-NHPI):[19, 34] yield: 1.56 g, 43%, m.p. 202 ℃. ^{1}H NMR (400 MHz, DMSO-d_6) δ 10.72 (s, 1H), 7.70 (d, J = 7.6 Hz, 1H), 7.65 (s, 1H), 7.62 (d, J = 7.6 Hz, 1H), 2.46 (s, 3H). ^{13}C{1H} NMR (101 MHz, DMSO-d_6) δ 164.7, 164.6, 145.9, 135.3, 129.5, 126.5, 123.9, 123.4, 21.9. IR (KBr), cm^{-1}: 3120, 2925, 2840, 1750, 1690,1604. Anal. Calcd for $C_9H_7O_3N$: C, 61.01; H, 3.95; N, 7.91. Found: C, 60.89; H, 4.11; N, 8.21.

N-hydroxynaphthalimide (NHNI):[61, 62] yield: 1.17 g, 68%, m.p. 299°C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 10.76 (s, 1H), 8.52 (d, J = 7.2 Hz, 2H), 8.48 (d, J = 8.2 Hz, 2H), 7.89 (t, J = 7.7, 7.7 Hz, 2H). ^{13}C{1H} NMR (101 MHz, DMSO-d_6) δ 160.9, 134.6, 131.4, 130.9, 127.4, 126.3, 122.4. IR (KBr), cm^{-1}: 3107, 2925, 1716, 1584, 1496. Anal. Calcd for $C_{12}H_7O_3N$: C, 67.61; H, 3.31; N, 6.57. Found: C, 67.81; H, 3.28; N, 6.90.

4-Methoxy-N-hydroxyphthalimide (4-CH_3O-NHPI):[19, 34] yield: 2.76 g, 65%, m.p 222 ℃. ^{1}H NMR (300 MHz, DMSO-d_6) δ 10.70 (s, 1H), 7.76 (d, J = 8.3 Hz, 1H), 7.36 (d, J = 2.3 Hz, 1H), 7.29 (dd, J = 8.3, 2.3 Hz, 1H), 3.91 (s, 3H). ^{13}C{1H} NMR (75 MHz, DMSO-d_6) δ 164.4, 164.0, 163.8, 131.4, 125.1, 120.3, 119.5, 108.7, 56.3. IR (KBr), cm^{-1}: 3138, 2942, 2829, 1778, 1688, 1608. Anal. Calcd for $C_9H_7O_4N$: C, 55.96; H, 3.65; N, 7.25. Found: C, 56.02; H, 3.72; N, 7.29.

4-Carboxy-N-hydroxyphthalimide (4-HOOC-NHPI):[19, 63] yield: 5.21 g, 70%, m.p 239 – 242 ℃ ^{1}H NMR (400 MHz, DMSO-d_6) δ 13.09 (br s, 1H), 11.01 (br s, 1H), 8.35 (d, J = 7.7 Hz, 1H), 8.18 (s, 1H), 7.95 (d, J = 7.7 Hz, 1H). ^{13}C{1H} NMR (101 MHz, DMSO-d_6) δ 165.8, 163.4, 136.2, 135.3, 132.2, 129.3, 123.3, 122.9. IR (KBr), cm^{-1}: 3451, 2758, 1767, 1672. Anal. Calcd for $C_9H_5O_5N$: C, 52.19; H, 2.43; N, 6.76. Found: C, 52.11; H, 2.49; N, 6.69.

3,4,5,6-Tetraphenyl-N-hydroxyphthalimide (Ph_4-NHPI):[64] yield: 2.81g, 70%, m.p 295 – 296 ℃. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25–7.15 (m, 6H), 7.14–7.09 (m, 4H), 6.95–6.88 (m, 6H), 6.77–6.72 (m, 4H). ^{13}C{1H} NMR (101 MHz, $CDCl_3$) δ 163.1, 148.1, 139.7, 137.8, 135.1, 130.7, 129.9, 127.5, 127.4, 127.1, 126.4, 125.1. IR (KBr), cm^{-1}: 3255, 3061, 1777, 1731, 1444, 1092. Anal. Calcd for $C_{32}H_{21}O_3N$: C, 82.23; H, 4.5; N, 2.99. Found: C, 82.34; H, 4.34; N, 3.21.

4,5-Dichloro-N-hydroxyphthalimide (4,5-diCl-NHPI):[19, 48] yield: 2 g, 72%, m.p. 202−205 ℃. ^{1}H NMR (400 MHz, DMSO-d_6) δ 11.05 (br s, 1H), 8.12 (s, 2H). ^{13}C{1H} NMR (101 MHz, DMSO-d_6) δ 162.4, 137.2, 128.8, 125.2. IR (KBr), cm^{-1}: 3362, 2907, 1774, 1716. Anal. Calcd for $C_8H_3Cl_2NO_3$: C, 41.41; H, 1.30; N, 6.04. Found: C, 41.50; H, 1.39; N, 5.99.

N,N-dihydroxypyromellitimide (NDHPI):[23] yield: 2.39 g, 50 %, m. p. 330 ℃ (dec). ^{1}H NMR (400 MHz, DMSO-d_6) δ 11.18 (s, 2H), 8.13 (s, 2H). ^{13}C{1H} NMR (101 MHz, DMSO-d_6) δ 162.6, 134.3, 117.0. Anal. Calcd for $C_{10}H_4O_6N_2$: C, 42.27; H, 2.84; N, 9.86. Found: C 42.5; H 2.70; N 9.91.

3,4,5,6-Tetrachloro-N-hydroxyphthalimide (Cl_4-NHPI):[24] yield: 2.11 g, 68 %, m. p. 253°C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 11.25 (s, 1H). ^{13}C{1H} NMR (101 MHz, DMSO- d_6) δ 172.3, 167.2, 140.1, 128.0, 125.8. IR (KBr), cm^{-1}: 3578, 3495, 3254, 2921, 1774, 1724, 1363, 1159, 1040. Anal. Calcd for C8HCl4NO3: C, 31.93; H, 0.33; N, 4.65. Found: C, 32.03; H, 0.41; N, 4.78.

3,4,5,6-Tetrafluoro-N-hydroxyphthalimide (F_4-NHPI):[24] yield: 2.41 g, 41 %, m. p. 165°C. ^{1}H NMR (400 MHz, DMSO-d6) δ 11.31 (s, 1H). ^{13}C{1H} NMR (101 MHz, DMSO-d_6) δ 172.7,

167.7, 142.1, 126.4, 121.8. IR (KBr), cm^{-1}: 3389, 3188, 1798, 1734, 1512, 1412, 1330, 1165, 1074. Anal. Calcd for $C_8HF_4NO_3$: C, 40.87; H, 0.43; N, 5.96. Found: C 41.05; H 0.52; N 5.81.

3,4,5,6-Tetrabromo-N-hydroxyphthalimide (Br_4-NHPI):[24] yield: 2.86 g, 55 %, ^1H NMR (400 MHz, DMSO-d_6) δ 11.25 (s, 1H). $^{13}C\{1H\}$ NMR (101 MHz, DMSO-d_6) δ 168.4, 163.2, 138.1, 128.0, 124.3. IR (KBr), cm^{-1}: 3242, 3074, 1778, 1728, 1543, 1333, 1150, 1024. Anal. Calcd for $C_8HBr_4NO_3$: C, 20.07; H, 0.21; N, 2.93. Found: C 20.15; H 0.32; N 2.81.

4-Iodo-N-hydroxyphthalimide (4-I-NHPI):[65] yield: 2.35 g, 73 %, m.p. 205 ℃ (dec). ^1H NMR (400 MHz, DMSO-d_6) δ 10.89 (s, 1H), 8.19 (d, J = 7.4 Hz, 1H), 8.13 (s, 1H), 7.59 (d, J = 6.3 Hz, 1H). $^{13}C\{1H\}$ NMR (101 MHz, DMSO-d_6) 162.9, 143.0, 131.2, 130.2, 127.9, 124.5, 102.1. IR (KBr), cm^{-1}: 3136, 2943, 2843, 1766, 1702. Anal. Calcd for $C_8H_4IO_3N$: C, 33.32; H, 1.28; N, 4.92. Found: C, 33.25; H, 1.39; N, 4.85.

3-Iodo-N-hydroxyphthalimide (3-I-NHPI):[65] yield: 2.84 g,68 %, m.p. 272–273 °C. ^1H NMR (400 MHz, DMSO-d_6) δ 10.90 (br s, 1H), 8.18 (d, J = 8.0 Hz, 1H), 7.82 (d, J = 7.2 Hz, 1H), 7.51 (t, J = 7.7, 7.7 Hz, 1H). $^{13}C\{1H\}$ NMR (101 MHz, DMSO-d_6) δ 163.8, 162.9, 145.5, 135.9, 131.5, 130.1, 123.3, 90.3. IR (KBr), cm^{-1}: 3114, 2945, 2841, 1776, 1707. Anal. Calcd for $C_8H_4IO_3N$: C, 33.25; H, 1.39; N, 4.85. Found: C, 33.12; H, 1.45; N, 4.96.

3-Chloro-N-hydroxyphthalimide (3-Cl-NHPI):[66, 67, 68] yield: 3.24 g, 52 %, m.p. 234−237 ℃ (dec.). ^1H NMR (300 MHz, DMSO-d_6) δ 10.91 (br s, 1H), 7.88−7.73 (m, 3H). $^{13}C\{1H\}$ NMR (75 MHz, DMSO-d_6) δ 162.7, 161.9, 135.9, 135.6, 131.1,129.2, 124.7, 121.8. IR (KBr), cm^{-1}: 3362, 2907, 1774, 1716. Anal. Calcd for $C_8H_4O_3NCl$: C, 48.63; H, 2.04; N, 7.09. Found: C, 48.77; H, 2.00; N, 7.13.

4-Chloro-N-hydroxyphthalimide (4-Cl-NHPI):[19] yield: 2.27 g, 73 %, m.p. 209 ℃. ^1H NMR (400 MHz, DMSO-d_6) δ 10.94 (s, 1H), 7.98–7.81 (m, 3H). $^{13}C\{1H\}$ NMR (75 MHz, DMSO-d_6) δ 163.3, 162.9, 139.2, 134.2, 130.8, 127.4, 124.7, 123.1. IR (KBr), cm^{-1}: 3110, 2914, 1774, 1694. Anal. Calcd for $C_8H_4O_3NCl$: C, 48.63; H, 2.04; N, 7.09. Found: C, 48.71; H, 1.98; N, 7.11.

4-Fluoro-N-hydroxyphthalimide (4-F-NHPI): yield: 2.54 g, 52 %, m.p. 183-185 ℃. ^1H NMR (400 MHz, DMSO-d_6) δ δ 10.93 (s, 1H), 7.91 (dd, J = 8.1, 4.6 Hz, 1H), 7.79–7.73 (m, 1H), 7.70–7.61 (m, 1H). $^{13}C\{1H\}$ NMR (101 MHz, DMSO-d_6) δ 167.0, 164.5, 163.3, 162.9, 131.9, 131.8, 125.9, 125.8, 121.2, 121.0, 117.4, 117.2, 111.4, 111.1. IR (KBr), cm^{-1}: 3115, 2920, 1781, 1689. Anal. Calcd for $C_8H_4O_3NF$: C, 53.05; H, 2.33; N, 7.73. Found: C, 53.19; H, 2.32; N, 7.85.

3-Fluoro-N-hydroxyphthalimide (3-F-NHPI):[34, 69] yield: 2 g, 79 %, m.p. 216 ℃. ^1H NMR (400 MHz, DMSO-d_6) δ 10.94 (s, 1H), 7.92–7.84 (m, 1H), 7.71–7.61 (m, 2H). $^{13}C\{1H\}$ NMR (101 MHz, DMSO-d_6) δ 161.7, 158.2, 155.6, 138.1, 138.0, 131.5, 123.4, 123.2, 120.1.IR (KBr), cm^{-1}: 3523, 3435, 3063, 2910, 2707, 1744, 1709, 1600. Anal. Calcd for $C_8H_4O_3NF$: C, 53.05; H, 2.33; N, 7.73. Found: C, 52.99; H, 2.42; N, 7.69.

3-Bromo-N-hydroxyphthalimide (3-Br-NHPI):[68] yield: 1.82 g, 84 %, m.p. 251–253 °C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 10.91 (br s, 1H), 7.98 (d, J = 8.1 Hz, 1H), 7.82 (d, J = 7.2 Hz, 1H), 7.71 (t, J = 7.7, 7.7 Hz, 1H). ^{13}C{1H} NMR (101 MHz, DMSO-d_6) δ 162.6, 162.4, 138.7, 135.8, 131.4, 126.5, 122.3, 117.1. IR (KBr), cm^{-1}: 3354, 3118, 2909, 2836, 1780, 1719, 1694. Anal. Calcd for $C_8H_4BrNO_3$: C, 39.70; H, 1.67; N, 5.79. Found: C, 39.81; H, 1.73; N, 5.82.

4-Bromo-N-hydroxyphthalimide (4-Br-NHPI): yield: 2.95 g, 75 %, m.p. 215 °C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 10.95 (s, 1H), 8.05–7.99 (m, 2H), 7.75 (d, J = 8.4 Hz, 1H). ^{13}C{1H} NMR (101 MHz, DMSO-d_6) δ 164.1, 163.5, 137.7, 131.3, 128.5, 128.3, 126.4, 125.4. IR (KBr), cm^{-1}: 3360, 2903, 1777, 1674. Anal. Calcd for $C_8H_4BrNO_3$: C, 39.70; H, 1.67; N, 5.79. Found: C, 39.91; H, 1.82; N, 5.69.

N-hydroxyquinolinimide (NHQI):[35, 70] yield: 3.13 g, 40 %, m.p. 163-165 °C. ^{1}H NMR (400 MHz, DMSO-d_6) δ 10.76 (s, 1H), 8.89-8.84 (m, 1H), 8.24-8.19 (m, 1H), 7.34-7.27 (m, 1H). ^{13}C{1H} NMR (101 MHz, DMSO-d_6) δ 163.3, 162.1, 151.1, 139.9, 126.7, 124.9, 123.9. IR (KBr), cm^{-1}: 3513, 3086, 2548, 1749, 1724, 1607, 1385, 1155, 1101. Anal. Calcd for $C_7H_4N_2O_3$: C, 51.23; H, 2.46; N, 17.07. Found: C, 51.38; H, 2.31; N, 17.21.

ASSOCIATED CONTENT

Supporting Information

UV/Vis spectra of *N*-oxyl radicals in CH_3CN, absorption-time curves for the generation and decay of *N*-oxyl radicals, the first-order plots for the self-decomposition of *N*-oxyl radicals, HPLC/MS analyses of *N*-hydroxyimides (PDF).

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Notes

The authors declare no competing financial interest.

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