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Hydroperoxidation of Tertiary Alkylaromatics Catalyzed By *N*-Hydroxyphthalimide and Aldehydes under Mild Conditions

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The authors dedicate this article to Prof. Francesco Minisci on the occasion of his 80th birthday.

Abstract: A metal-free catalytic system consisting of an aldehyde and *N*-hydroxyphthalimide (NHPI) for the selective oxidation of tertiary alkylaromatics with molecular oxygen has been developed. Cumene was oxidized efficiently to the corresponding hydroperoxide under mild conditions. The molecule-induced homolysis between peracids generated *in situ* and NHPI ensured the formation of the phthalimide *N*-oxyl (PINO) radical even at room temperature. Investigations on aldehyde, solvent and temperature effects allowed us to achieve good conversions with high selectivity in hydroperoxide. The optimized procedure was successfully extended to phenylcyclohexane, a valuable alternative for the production of phenol. The mechanism is discussed in detail.

Keywords: autoxidation; co-oxidation; cumene; hydroperoxides; *N*-hydroxyphthalimide

Introduction

The aerobic oxidation of hydrocarbons is a major issue in the chemical industry.[1] In a generic process, catalysis by transition metal salts is usually required in order to activate the molecular oxygen.[2] However, if the target compound is a hydroperoxide, the presence of metal salts should be avoided, as they easily decompose the desired product according to a fast redox reaction.[3]

The main process oriented to the production of a hydroperoxide consists in the autoxidation of cumene to cumene hydroperoxide (CH), which is then decomposed by means of acidic catalysis to afford phenol and acetone, according to the well-known Hock process (Scheme 1).[4]

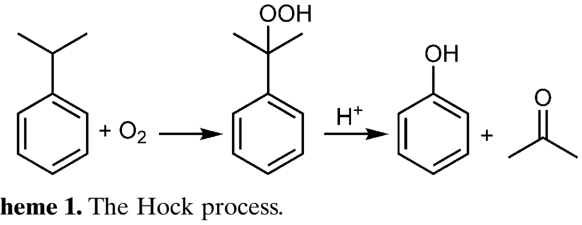
Nowadays, about 95% of phenol produced worldwide is manufactured following this procedure.

The free-radical autoxidation step of the Hock process is carried out under metal-free conditions and at temperatures higher than 110 °C, in order to promote the homolytic thermal decomposition of tiny amounts of CH, which acts in turn as radical chain initiator. However, the selectivity in the hydroperoxide decreases to the extent in which the CH itself acts as initiator, as its decomposition produces acetophenone (AP), which is the main by-product at these relatively high temperatures, and cumyl alcohol (CA).

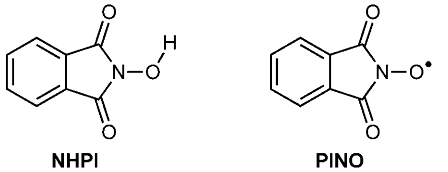
Hence, at temperatures lower than 100 °C, the non-catalyzed oxidation of cumene is too slow; upon increasing the temperature, the conversion increases but the selectivity decreases. For these reasons, many efforts have been devoted over the years for the development of new catalytic systems in order to afford the desired hydroperoxides with higher selectivity at lower temperatures.

In the last decade, a new derivative, *N*-hydroxyphthalimide (NHPI), has been reported as an effective catalyst for C–H activation by hydrogen abstraction (Scheme 2).[5]

Due to its unique behaviour and to its general efficiency, NHPI has attracted increasing interest, both in academia and in industry.[6,7] It acts as a precursor of



Scheme 1. The Hock process.



Scheme 2. Structures of NHPI and PINO.

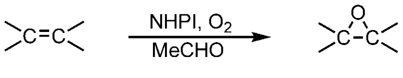
the phthalimide *N*-oxyl (PINO) radical, which is the effective abstracting species in all of the free radical processes mediated by this *N*-hydroxy derivative.[5,8]

A few years ago we reported that an NHPI/Co(II) catalytic system could efficiently promote the selective aerobic oxidation of diisopropyl aromatic compounds to the corresponding tertiary alcohols in high yields.[9] Very recently Orlińska has reported a detailed investigation of the catalytic system consisting of NHPI in combination with various Cu(II), Co(II) and Mn(II) salts for the oxidation of cumene with oxygen.[10] However, as mentioned before, in order to directly obtain the desired hydroperoxides, the presence of transition metal salts is generally detrimental. For this reason, in the last decade several procedures were reported for the aerobic oxidation of hydrocarbons using NHPI as organocatalyst in combination with initiators such as alkaline earth chlorides,[11] oximes,[12] quinones,[13] phenantrolines,[14] xanthones in combination with tetramethylammonium chloride,[15] quaternary ammonium bromides[16] and α,α-azobisisobutyronitrile.[17] Nevertheless, all these processes required relatively high temperatures (80 °C), affording the corresponding carbonylic and carboxylic derivatives as major products and no or limited amounts of hydroperoxides.

In this context, in 2006 we reported a new and effective metal-free aerobic epoxidation of olefins catalyzed by NHPI,[18] using stoichiometric amounts of acetaldehyde (MeCHO) as co-oxidant, both to promote the *in situ* generation of PINO and as source of the epoxidizing agent (Scheme 3).

Aldehyde autoxidation rates are very high even at room temperature and atmospheric pressure and this property has been often used to promote the so-called "co-oxidation" processes, in which a mixture of an aldehyde and another less reactive organic substrate is submitted to molecular oxygen.[19]

In 1997, Einhorn and co-workers conducted a series of aerobic oxidations on a wide range of hydrocarbons,[20] combining stoichiometric amounts of MeCHO with catalytic quantities of NHPI. Among the organic substrates, they considered the oxidation of cumene, obtaining a moderate conversion (37%) only after 72 h, and the formation of acetophenone (AP) as a unique product, while CH was not observed.



Scheme 3. Aerobic epoxidation of olefins catalyzed by the NHPI/MeCHO catalytic system.

On the bases of our previous studies on NHPI reactivity, we were encouraged to investigate this specific reaction and its potentialities in greater depth. Hence, the present work, which follows the granting of two patents,[21] is addressed to the investigation of the key role played by the NHPI/aldehyde catalytic system in the autoxidation of tertiary alkylaromatics, being especially aimed at the investigation of the best reaction conditions to achieve good conversions and high selectivity in hydroperoxides.

Results and Discussion

The results related to the optimization of the catalytic system for the aerobic oxidation of cumene are reported in Table 1.

Initial experiments, conducted in the presence of stoichiometric amounts of MeCHO, afforded conversions analogous to those reported by Einhorn et al.

Table 1. Optimization of the NHPI/MeCHO catalytic system for the aerobic oxidation of cumene.[a]

Run	MeCHO [%]	NHPI [%]	Conv. [%][b]	Selectivity [%][b]		
				CH	CA	AP
1	100	10	35	63	35	2
2	50	10	34	74	25	1
3	25	10	38	80	19	1
4	10	10	36	81	18	1
5	5	10	23	89	11	–
6	–	10	–	–	–	–
7	10	20	69	77	22	1
8	10	1	5	73	21	6
9	10	–	–	–	–	–
10[c]	–	10	62	82	17	1
11[d]	–	10	62	79	19	2
12[e]	10	10	49	78	19	3

[a] 5 mmol of cumene in 10 mL of acetonitrile were stirred for 6 h at 25 °C and atmospheric pressure of O_2 in the presence of NHPI/MeCHO catalytic system, in the percent amount with respect to cumene as reported in the Table.

[b] Conversions and selectivity of the known reaction products were determined by HPLC with 2-phenylethanol added as internal standard and confirmed by ^1H NMR.

[c] 0.25 mmol of *m*-CPBA were added in place of acetaldehyde.

[d] 0.25 mmol of *m*-CPBA were diluted in 2 mL of acetonitrile and added dropwise in 3 h.

[e] 0.025 mmol of *m*-CPBA were added to the reaction mixture.

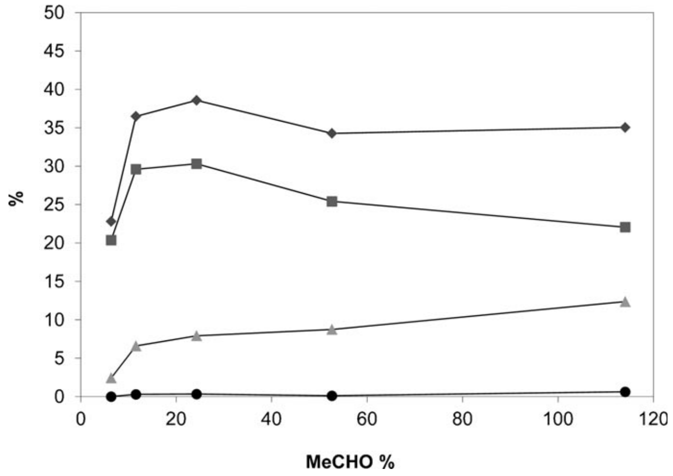


Figure 1. Cumene conversion (◆) and yield in CH (■), CA (▲) and AP (●) *versus* percent amount of acetaldehyde.

(35%), but in a shorter time (5 h) and with opposite selectivity (run 1). Indeed, only traces of acetophenone were detected, the hydroperoxide and the alcohol being the main products, in a ratio of 2:1, respectively.

Moreover, in contrast to the co-oxidative mechanism explanation reported by Einhorn, we believed that, for this specific reaction, aldehyde had the unique role of initiator of the radical chain, causing the formation of PINO. If this had been true, lower quantities of MeCHO could be sufficient to promote the process, making it interesting from an applicative point of view.

To verify this hypothesis and improve the efficiency of the protocol, we progressively reduced the amount of MeCHO in the reaction medium (entries 2–5). In doing so, we were able not only to achieve similar conversions, but also to increase the CH selectivity up to 80%, simply by operating with 10% of acetaldehyde with respect to starting cumene (Figure 1).

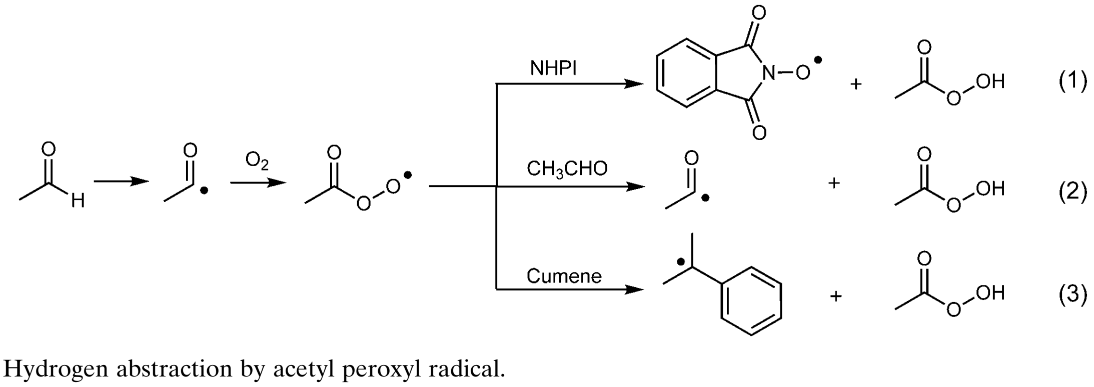
The lower selectivity observed in the presence of stoichiometric amounts of MeCHO could be ascribed to the formation of high concentrations of fast terminating radical species, such as acetyl peroxyl and methyl peroxyl radicals, generated *in situ* according to the mechanisms which will be discussed later on. Moreover, peracetic acid, generated in solution, could be consumed *via* a non-radical process, reacting with another molecule of MeCHO, present at high concentration, and forming acetic acid.

By further decreasing the amount of aldehyde, yields were lowered again (run 5), while in the absence of the initiator no conversion was observed (run 6), thus confirming the key role played by MeCHO in the reaction mechanism.

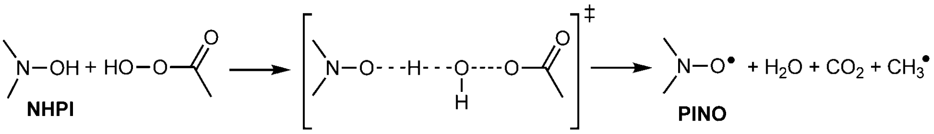
The effect of amount of NHPI was also considered. As expected, an increase in organocatalyst concentration led to higher conversions with still a good selectivity in CH (run 7). On the contrary, by decreasing the amount of NHPI, conversions fell down (run 8), while in the absence of the *N*-hydroxy derivative no trace of products was observed (run 9).

According to our interpretation, in an initiation step the acetaldehyde is oxidized to the corresponding acyl peroxyl radical which, in turn, may abstract a hydrogen atom from cumene, NHPI or another molecule of MeCHO, respectively (Scheme 4). In all the cases the abstraction occurs faster than by an alkyl peroxyl radical for both polar and enthalpic reasons ($BDE_{RCOOO-H} = ca.$ 93 kcal mol^{-1}; $BDE_{ROO-H} =$ *ca.* 88 kcal mol^{-1}).

Peracetic acid, formed *in situ* according to Eqs. (1)–(3) of Scheme 4, may in turn be involved in the generation of PINO from NHPI, through a molecule-induced homolysis mechanism, which leads to the formation of two radicals (Scheme 5). Our group has already reported experimental evidence of the intervention of this process by combining *m*-chloroperbenzoic acid (*m*-CPBA) with NHPI in a neutral deoxygenated solvent.[18,22] The generation *in situ* of the PINO radical was detected by EPR spectroscopy, while experiments conducted in benzene, which acted as a radical trapping source, demonstrated the formation of *m*-chlorobenzenecarboxyl radical and of the corresponding decarboxylated *m*-chlorophenyl radical. Under these mild conditions, the simple thermal homolysis of the peracid could not occur. On the contrary, the



Scheme 4. Hydrogen abstraction by acetyl peroxyl radical.



Scheme 5. Molecule-induced homolysis of NHPI with peracetic acid.

low BDE value of the O–H bond for NHPI (88.1 kcal mol^{-1})[8] suggested that peracids could induce homolysis of the *N*-hydroxy derivative.

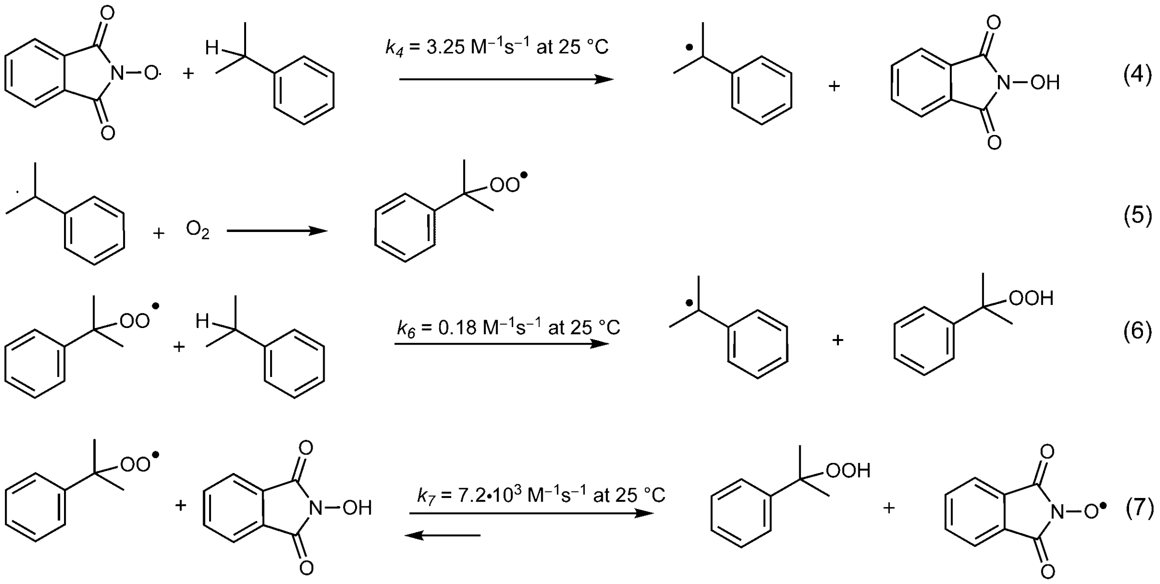
Thus, we wanted to verify the intervention of this mechanism in our process by conducting experiments in the presence of *m*-CPBA in place of acetaldehyde as radical initiator. Indeed, we succeeded in increasing the conversion up to *ca.* 60%, while maintaining the high selectivity in CH (run 10). Further attempts based on the dropwise addition of the peracid over time did not afford significative improvements (run 11), while the combination of MeCHO with lower amounts of *m*-CPBA led to lower conversions in comparison with the NHPI/peracid system (run 12).

Once formed, PINO is able to promote a free-radical chain according to Scheme 6. The nitroxyl radical can abstract a hydrogen from cumene [Eq. (4)], generating the corresponding cumyl radical. The latter undergoes fast addition to oxygen, leading to the formation of the cumyl peroxyl radical [Eq. (5)], which in turn can promote the hydrogen abstraction from NHPI [Eq. (6)] or cumene, present in large excess [Eq. (7)].

The relative rates[8] referred to these hydrogen abstraction reactions depend on the absolute kinetic constants and on the concentration of the different H-donors. By comparing k_4 and k_6 we can conclude that PINO abstracts the hydrogen from cumene 18 times faster than the cumyl peroxyl radical [Scheme 6, Eqs. (4) and (6), respectively], which justifies the faster autoxidation occurring in the presence of the organocatalyst, if compared with the non-catalysed process. Under the same reaction conditions, cumyl peroxyl radical abstracts the hydrogen from NHPI about 4000 times faster than from cumene (value determined by considering both the ratio between k_7 and k_6 and the ratio between the concentrations of NHPI and cumene). The faster reaction between cumyl peroxyl radical and NHPI dramatically decreases the stationary concentration of the peroxyl radicals, increasing the free-radical chain length and allowing the achievement of higher selectivity in CH.

To understand various aldehyde effects, both aliphatic and aromatic aldehydes were used to promote the oxidative process (Table 2).

When operating in the presence of benzaldehyde, lower conversions were observed. The propagation rates for free-radical chain processes of autoxidation involving aldehydes are generally comparable. Nevertheless, the initiation step for aromatic aldehydes is generally slower. The reasons of this difference are mainly due to polar effects, the BDE of the C–H bond being independent of the aldehyde structure.



Scheme 6. Propagation mechanism leading to the formation of CH.

Table 2. Aerobic oxidation of cumene catalyzed by NHPI in the presence of different aldehydes.[a]

Run	RCHO	Conv. [%][b]	Selectivity [%][b] CH	CA	AP
1	MeCHO	36	81	18	1
2	PhCHO	25	93	7	–
3	EtCHO	41	85	14	1
4[c]	$(Et)_2CHCHO$	40	86	14	–
5	$(Et)_2CHCHO$	69	71	27	2
6c	$(Me)_3CCHO$	62	58	37	5
7	$(Me)_3CCHO$	77	52	43	5

[a] The reaction conditions are those reported in Table 1, run 4; see also Table 1, note[a].

[b] See Table 1, note[b].

[c] Reaction time 2 h.

Other primary aldehydes like propionaldehyde (EtCHO, run 3) acted similarly to MeCHO, while in the presence of secondary and tertiary aldehydes the reactions ran faster (Figure 2). In particular, 2-ethylbutyraldehyde $(Et)_2CHCHO$ afforded conversions and selectivity analogous to those observed with MeCHO in just 2 h (run 4), while for longer reaction times conversion increased but selectivity decreased (run 5), probably due to the higher concentration of peroxyl radicals in solution, which favours fast termination. Pivalaldehyde $[(Me)_3CCHO]$ led to conversions even higher with respect to $(Et)_2CHCHO$, but with poor selectivity in CH (entries 6 and 7). The faster kinetics in the presence of secondary and tertiary aldehydes and the poor selectivity with $(Me)_3CCHO$ could be due to the fact that, being more electron-rich than primary ones, they are easily oxidized under our reaction conditions and undergo fast decarbonylation.[23]

However, from an industrial application point of view, MeCHO still remains the aldehyde of choice due to its low commercial value and the limited mass loss. Thus, other parameters were considered, in order to increase the efficiency of the process.

For this reason, different solvents were used as reaction media to study their effects and establish the most convenient one (Table 3). Acetonitrile still resulted as the best choice, combining good conversions and high selectivity in CH. Low yields observed in the presence of *t*-BuOH were probably due to the protic nature of the solvent, which is able to undergo hydrogen bonding with NHPI, inhibiting the hydrogen abstraction propagation step of the process. On the contrary, dimethyl carbonate afforded high conversions but a poor selectivity in CH, while in the presence of acetone both lower conversions and slightly lower selectivity were achieved.

Finally, we wanted to investigate the temperature effect on our process (Table 4). By progressively increasing the temperature from 25 to 45 °C in the presence of acetaldehyde, we were able to reach a conversion limit value of 65%, while, when operating with *m*-CPBA in the same range of temperatures, we did

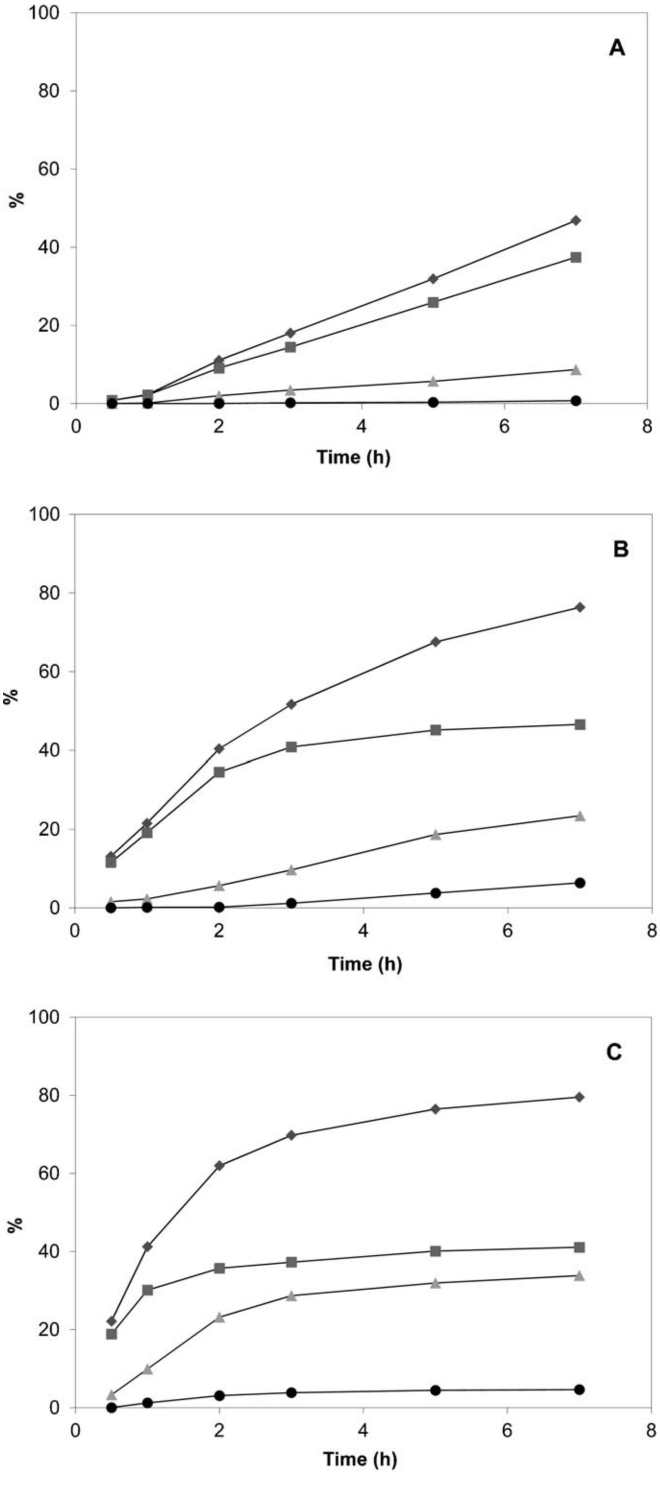


Figure 2. Cumene conversion (◆) and yield in CH (■), CA (▲) and AP (●) *versus* reaction time for the aerobic oxidation catalyzed by NHPI in the presence of acetaldehyde (**A**), 2-ethylbutyraldehyde (**B**) and pivalaldehyde (**C**).

Table 3. Aerobic oxidation of cumene catalyzed by NHPI in the presence of different solvents.

Solvent	Method[a]	Conv. [%][b]	Selectivity [%][b] CH	CA	AP
MeCN	A	36	81	18	1
MeCN	B	62	82	17	1
t-BuOH	A	11	82	16	2
t-BuOH	B	21	78	16	6
$(MeO)_2CO$	A	84	40	56	4
$(MeO)_2CO$	B	67	66	32	2
$(Me)_2CO$	A	27	72	24	4
$(Me)_2CO$	B	45	80	17	3

[a] The reaction conditions are those reported in Table 1, run 4 (Method A) and run 10 (Method B); see also Table 1, note[a].

[b] See Table 1, note[b].

Table 4. Temperature effect on the aerobic oxidation of cumene catalyzed by NHPI.

Run	*T* [°C]	Method[a]	Conv. [%][b]	Selectivity [%][b] CH	CA	AP
1	25	A	36	81	18	1
2	25	B	62	82	17	1
3	35	A	55	72	26	2
4	35	B	67	80	19	1
5	45	A	65	73	25	2
6	45	B	67	77	21	2
7	45	A[c]	86	70	26	4

[a] See Table 3, note[a].

[b] See Table 1, note[b].

[c] 20% of NHPI was employed.

not observe any significant differences in cumene consumption.

In both the cases the processes seem to verge to a limiting value of conversion (faster with *m*-CPBA), as also confirmed by the kinetics reported in Figure 3, which show a gradual slowdown of the reactions. This behaviour could be ascribed to the reversibility of Eq. (7). The increase of CH during the course of the reaction shifts Eq. (7) to the left.[24] This determines a higher concentration of peroxyl radicals, inducing higher termination rates, and at the same time a lower concentration of PINO, with a consequent overall decrease of the reaction rate. A higher termination rate also means a lower selectivity due to the formation of the alcohol CA parallel with CH (Scheme 7). Furthermore, cumyl alkoxyl radical may undergo β-scission affording the AP as an undesired by-product. This process is favoured at higher temperatures (Table 4) and for this reason we limited the temperature range of investigation. Indeed, AP represents the real waste product of the process, as CA can be reconverted to cumene by a two-step process consisting in the dehydration to methylstyrene and subsequent hydrogenation, or transformed into phenol as well by H_2O_2 and acid catalysis.[25] Thus, under our optimized conditions, we were able to perform good conversions of cumene under very mild conditions, with selectivity in $CH+CA>99\%$.

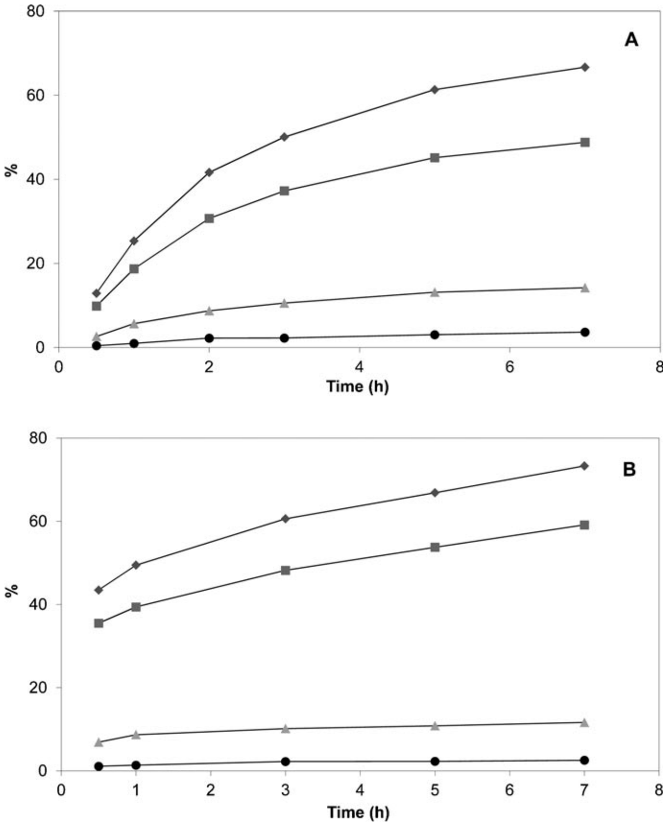
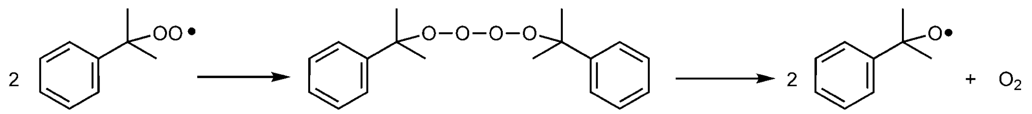


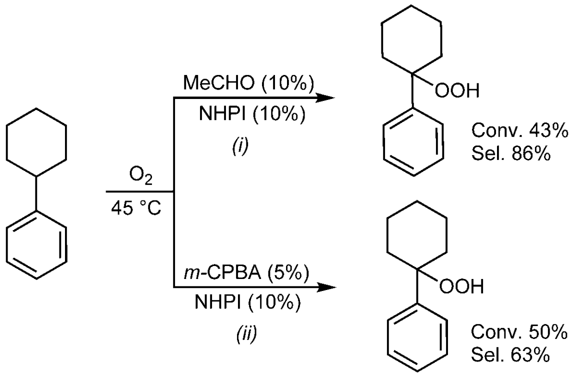
Figure 3. Cumene conversion (◆) and yield in CH (■), CA (▲) and AP (●) versus reaction time for the aerobic oxidation catalyzed by NHPI in the presence of acetaldehyde (**A**) and *m*-CPBA (**B**).

The main drawback concerning the oxidation of cumene for the production of phenol *via* the Hock process is the overproduction of acetone (Scheme 1). The demand for phenol, in fact, is growing more rapidly than that for acetone and consequently the production of acetone exceeds the market requirrement. For this reason, different approaches have been proposed to overcome this limitation. One of the most promising solutions consists in substituting the isopropyl group of cumene with different alkyl groups, in order to produce, in the last step of the process, industrially interesting ketones.

Phenylcyclohexane (PC) was mainly considered for this purpose,[17c] as it affords cyclohexanone as coproduct, an important precursor for the synthesis of different substrates like adipic acid, ε-caprolactone and ε-caprolactam. Moreover, cyclohexanone can be also directly converted to phenol by dehydrogenation.[26] Phenylcyclohexane is produced by acid-cata-



Scheme 7. Termination mechanism.



Scheme 8. Aerobic oxidation of phenylcyclohexane in the presence of NHPI and MeCHO (*i*) or *m*-CPBA (*ii*).

lyzed alkylation of benzene in the presence of cyclohexene or by direct reductive alkylation of benzene, which is partially converted to cyclohexene *in situ*.

By applying the present MeCHO/NHPI catalytic system for the aerobic oxidation of PC, under our optimized mild conditions (Scheme 8), it was possible to achieve good conversions (*ca.* 40%) with a high selectivity in the corresponding hydroperoxide, while, when operating in the presence of *m*-CPBA, conversion increased but selectivity declined.

Conclusions

We have investigated a novel catalytic system consisting of MeCHO and NHPI for the aerobic oxidation of cumene. The molecule-induced homolysis between NHPI and the peracid generated *in situ* leads to the formation of PINO radical under very mild conditions in the absence of transition metals, allowing us to apply this catalytic system for the selective synthesis of cumyl hydroperoxide. A detailed optimization of the reaction conditions allowed us to extend the procedure to phenylcyclohexane, which can be considered as another intriguing precursor of phenol with the concomitant production of cyclohexanone. This new route towards the selective synthesis of tertiary hydroperoxides provides an attractive and cheaper alternative for the production of phenol with respect to the classical autoxidative process which requires high temperatures.

Experimental Section

All starting materials and catalysts were purchased from commercial suppliers and used without further purification.

General Procedure

5 mmol of cumene and the desired amounts of MeCHO and NHPI were added to 10 mL of acetonitrile in a 50-mL double-neck, round-bottom flask. The solution was maintained for 6 h under an atmospheric pressure of O_2 and at the temperature of choice, with magnetic stirring. The oxidation products deriving from cumene (CH, CA and AP) were identified by comparison with authentic samples commercially available. The hydroperoxide of PC was isolated by flash chromatography (40–63 μm silica gel packing; hexane/ethyl acetate, 9/1) and characterized by H NMR by comparison with a sample prepared from the corresponding commercial alcohol using H_2O_2 and H_2SO_4, according to a procedure reported in literarure.[17c,27]

Conversions and yields were determined by HPLC analysis (reverse phase column; MeCN/MeOH/H_2O, 35/5/60), with 2-phenylethanol added as internal standard, and confirmed by ^{1}H NMR.

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References

[1] a) P. R. Schreiner, A. A. Fokin, *Chem. Rec.* **2004**, *3*, 247–257; b) E. N. Jacobson, *Adv. Synth. Catal.* **2004**, *346*, 109; c) M. Beller, *Adv. Synth. Catal.* **2004**, *346*, 107–108; d) U. Schuchardt, D. Cardoso, R. Sercheli, R. Pereira, R. S. da Cruz, M. C. Guerreiro, D. Mandelli, E. V. Spinacé, E. L. Pires, *Appl. Catal. A* **2001**, *211*, 1–17; e) I. Hermans, E. S. Spier, U. Neuenschwander, N. Turrà, A. Baiker, *Top. Catal.* **2009**, *52*, 1162–1174; f) I. Hermans, J. Peeters, P. Jacobs, *Top. Catal.* **2008**, *50*, 124–132.

[2] a) T. Punniyamurthy, S. Velusamy, J. Iqbal, *Chem. Rev.* **2005**, *105*, 2329–2363; b) A. K. Suresh, M. M. Sharma, T. Sridhar, *Ind. Eng. Chem. Res.* **2000**, *39*, 3958–3997; c) C. I. Herrerias, X. Q. Yao, Z. P. Li, *Chem. Rev.* **2007**, *107*, 2546–2562; d) A. A. Fokin, P. R. Schreiner, *Adv. Synth. Catal.* **2003**, *345*, 1035–1052; e) J. M. Thomas, R. Raja, *Chem. Commun.* **2001**, *8*, 675–687; f) F. Minisci, F. Recupero, G. F. Pedulli, *J. Mol. Catal. A: Chem.* **2003**, *204–205*, 63–90.

[3] a) R. A. Sheldon, J. K. Kochi, in: *Metal Catalyzed Oxidations of Organic Compunds*, Academic Press, New York, **1981**, pp 18–25, 38–41; b) E. T. Denisov, I. B. Afanas'ev, in: *Oxidation and Antioxidants in Organic Chemistry and Biology*, Taylor & Francis Group, Boca Raton, **2005**, pp 23–72, 359–382.

[4] a) H. Hock, S. Lang, *Ber. Desch. Chem. Ges.* **1944**, B77, 257–264; b) W. Jordan, H. van Barneveld, O. Gerlich, M. K. Boymann, J. Ullrich, *Ullmann's Encyclopedia of Industrial Organic Chemicals*, Wiley-VCH, Weinheim, **1985**, Vol. A9, pp 299–312.

[5] For recent reviews in the field, see: a) C. Punta, C. Gambarotti, in: *Ideas in Chemistry and Molecular Sciences: Advances in Synthetic Chemistry*, (Ed.: B. Pignataro), Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, **2010**, pp 3–24; b) F. Recupero, C. Punta, *Chem. Rev.* **2007**, *107*, 3800–3842; c) F. Minisci, C. Punta, F. Recupero, *J. Mol. Catal. A: Chem.* **2006**, *251*, 129–149; d) Y. Ishii, S. Sakaguchi, *Catal. Today* **2006**, *117*, 105–113; e) Y. Ishii, S. Sakaguchi, in: *Modern Oxidation Methods*, (Ed.: J.-E. Bäckvall), Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, **2005**, pp 119–164; f) Y. Ishii, S. Sakaguchi, T. Iwahama, *Adv. Synth. Catal.* **2001**, *343*, 393–427; g) R. A. Sheldon, I. W. C. E. Arends, *Adv. Synth. Catal.* **2004**, *346*, 1051–1071; h) C. Galli, P. Gentili, O. Lanzalunga, *Angew. Chem.* **2008**, *120*, 4868; *Angew. Chem. Int. Ed.* **2008**, *47*, 4790 –4796; i) S. Coseri, *Catal. Rev.* **2009**, *51:2*, 218–292; j) S. Coseri, *Mini-Rev. Org. Chem.* **2008**, *5*, 222–227.

[6] For some examples on selective oxidations see: a) F. Minisci, C. Punta, F. Recupero, F. Fontana, G. F. Pedulli, *J. Org. Chem.* **2002**, *67*, 2671–2676; b) F. Minisci, F. Recupero, C. Punta, C. Guidarini, F. Fontana, G. F. Pedulli, *Synlett* **2002**, *7*, 1173–1175; c) F. Minisci, F. Recupero, C. Gambarotti, C. Punta, R. Paganelli, *Tetrahedron Lett.* **2003**, *44*, 6919–6922; d) A. Shibamoto, S. Sakaguchi, Y. Ishii, *Org. Process Res. Dev.* **2000**, *4*, 505–508; e) O. Fukuda, S. Sakaguchi, Y. Ishii, *Tetrahedron Lett.* **2001**, *42*, 3479–3481.

[7] For some examples on selective functionalizations see: a) F. Minisci, F. Recupero, C. Punta, C. Gambarotti, F. Antonietti, F. Fontana, G. F. Pedulli, *Chem. Commun.* **2002**, 2496–2497; b) F. Minisci, F. Recupero, A. Cecchetto, C. Punta, C. Gambarotti, F. Fontana, G. F. Pedulli, *J. Heterocycl. Chem.* **2003**, *40*, 325–328; c) F. Minisci, O. Porta, F. Recupero, C. Gambarotti, R. Paganelli, G. F. Pedulli, F. Fontana, *Tetrahedron Lett.* **2004**, *45*, 1607–1609; d) O. Tayama, T. Iwahama, S. Sakaguchi, Y. Ishii, *Eur. J. Org. Chem.* **2003**, 2286–2289; e) N. Sawatari, S. Sakaguchi, Y. Ishii, *Tetrahedron Lett.* **2003**, *44*, 2053–2056; f) K. Hirano, S. Sakaguchi, Y. Ishii, *Tetrahedron Lett.* **2002**, *43*, 3617–3620; g) S. Tsujimoto, T. Iwahama, S. Sakaguchi, Y. Ishii, *Chem. Commun.* **2001**, 2352–2353.

[8] a) F. Minisci, C. Punta, F. Recupero, F. Fontana, G. F. Pedulli, *Chem. Commun.* **2002**, 688–689; b) R. Amorati, M. Lucarini, V. Mugnaini, G. F. Pedulli, F. Minisci, F. Recupero, F. Fontana, P. Astolfi, L. Greci, *J. Org. Chem.* **2003**, *68*, 1747–1754.

[9] F. Minisci, F. Recupero, A. Cecchetto, C. Gambarotti, C. Punta, R. Paganelli, *Org. Process Res. Dev.* **2004**, *8*, 163–168.

[10] B. Orlińska, *Tetrahedron Lett.* **2010**, *51*, 4100–4102.

[11] X. Yang, L. Zhou, Y. Chen, C. Chen, Y. Su, H. Miao, J. Xu, *Catal. Commun.* **2009**, *11*, 171–174.

[12] G. Zheng, C. Liu, Q. Wang, M. Wang, G. Yang, *Adv. Synth. Catal.* **2009**, *351*, 2638–2642.

[13] a) G. Y. Yang, Y. F. Ma, J. Xu, *J. Am. Chem. Soc.* **2004**, *126*, 10542; b) G. Yang, Q. Zhang, H. Miao, Z. Tong, J. Xu, *Org. Lett.* **2005**, *7*, 263–266; c) Q. H. Zhang, C. Chen, H. Ma, H. Miao, W. Zhang, Z. Q. Sun, J. Xu, *J. Chem. Technol. Biotechnol.* **2008**, *83*, 1364 –1369; d) L. Zhou, Y. Chen, X. Yang, Y. Su, W. Zhang, J. Xu, *Catal. Lett.* **2008**, *125*, 154–159; e) X. Yang, Y. Wang, L. Zhou, C. Chen, W. Zhang, J. Xu, *J. Chem. Technol. Biotechnol.* **2010**, *85*, 564–568.

[14] X. Tong, J. Xu, H. Miao, *Adv. Synth. Catal.* **2005**, *347*, 1953.

[15] Z. Du, Z. Sun, W. Zhang, H. Miao, H. Ma, J. Xu, *Tetrahedron Lett.* **2009**, *50*, 1677–1680.

[16] K. Matsunaka, T. Iwahama, S. Sakaguchi, Y. Ishii, *Tetrahedron Lett.* **1999**, *40*, 2165–2168.

[17] a) Y. Aoki, N. Hirai, S. Sakaguchi, Y. Ishii, *Tetrahedron* **2005**, *61*, 10995–10999; b) Y. Aoki, S. Sakaguchi, Y. Ishii, *Adv. Synth. Catal.* **2004**, *346*, 199–202; c) I. W. C. E. Arends, M. Sasidharan, A. Kühnle, M. Duda, C. Jost, R. A. Sheldon, *Tetrahedron* **2002**, *58*, 9055–9061.

[18] F. Minisci, C. Gambarotti, M. Pierini, O. Porta, C. Punta, F. Recupero, M. Lucarini, V. Mugnaini, *Tetrahedron Lett.* **2006**, *47*, 1421–1424.

[19] a) K. Kaneda, S. Haruna, T. Imanaka, M. Hamamoto, Y. Nishiyama, Y. Ishii, *Tetrahedron Lett.* **1992**, *33*, 6827–6830; b) K. Kaneda, S. Ueno, T. Imanaka, E. Shimotsuma, Y. Nishiyama, Y. Ishii, *J. Org. Chem.* **1994**, *59*, 2915; c) A. Bravo, F. Fontana, F. Minisci, A. Serri, *Chem. Commun.* **1996**, 1843–1844.

[20] C. Einhorn, J. Einhorn, C. Marcadal, J.-L. Pierre, *Chem. Commun.* **1997**, 447–448.

[21] a) F. Minisci, O. Porta, F. Recupero, C. Punta, C. Gambarotti, M. Pierini, *Patent* WO2008037435, **2008**; b) F. Minisci, O. Porta, C. Punta, F. Recupero, C. Gambarotti, R. Spaccini, *Patent* WO2009115275, **2009**.

[22] C. Punta, D. Moscatelli, O. Porta, F. Minisci, C. Gambarotti, M. Lucarini, in: *Mechanisms in Homogeneous and Heterogeneous Epoxidation Catalysis*, (Ed.: S. T. Oyama), Elsevier, Amsterdam, The Netherlands, **2008**, pp 217–229.

[23] a) C. Chatgilialoglu, D. Crich, M. Komatsu, I. Ryu, *Chem. Rev.* 1**999**, 99, 1991–2070; b) T. Punniyamurthy, B. Bhatia, J. Iqbal, *J. Org. Chem.* **1994**, *59*, 850–853.

[24] a) I. Hermans, L. Vereecken, P. A. Jacobs, J. Peeters, *Chem. Commun.* **2004**, 1140–1141; b) I. Hermans, P. A. Jacobs, J. Peeters, *Phys. Chem. Chem. Phys.* **2007**, *9*, 686–690; c) I. Hermans, P. A. Jacobs, J. Peeters, *Phys. Chem. Chem. Phys.* **2008**, *10*, 1125–1132.

[25] D. L. Boger, R. S. Coleman, *J. Org. Chem.* **1986**, *51*, 5436–5439.

[26] W. Jordan, H. Barneveld, O. van Gerlich, M. Kleine-Boymann, J. Ullrich, *Ullmann's Encyclopedia of Industrial Chemistry*, Wiley-VCH, Weinheim, **1991**, Vol. A19, p 307.

[27] A. G. Davies, R. V. Foster, A. M. White, *J. Chem. Soc.* **1953** 1541–1547.