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The Selective Functionalization of Saturated Hydrocarbons. Part 40. Aspects of Fe^{II} Based Peroxide Fragmentation in Pyridine solution.

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Abstract : The Haber-Weiss mechanism does not apply to the Fe^{II} induced fragmentation of primary and secondary hydroperoxides in pyridine. However, it does apply to tertiary hydroperoxides. Steric bulk is an important factor in Fe^{II} induced dialkyl peroxide decomposition in pyridine. On the contrary in tetrahydrofuran a different relatively unhindered electron transfer process predominates where the Fe^{II} becomes a catalyst. © 1997 Elsevier Science Ltd.

INTRODUCTION

The Centenary of the Fenton Reaction was celebrated in 1994.[1] There have been many applications of this reaction even up to the present time.[2] The Haber-Weiss mechanism was first proposed in 1934.[3] The first step was suggested to be the transfer of one electron from Fe^{II} to H_2O_2 forming (after protonation) Fe^{III}, water and the hydroxyl radical. Over the years, the nature of the $^{\cdot}OH$ radical has been the subject of much discussion. Some authors have presented evidence that indicates that a higher valence state of iron (Fe^{IV}) is involved,[4] but there is an important recent article which shows that there is a dependence on the Fe^{II} concentration with low concentrations affording hydroxyl radicals.[5] Also, potential applications in industrial synthesis have been reported.[6] An article of major importance[7] summarizes the evidence up to 1974. One of the conclusions reached was that outer-sphere electron transfer was probable in Fe^{II} and Fe^{III} reactions.

With the passage of time, it has become generally accepted that the Haber-Weiss mechanism can be applied to hydroperoxides and peroxides.[8] In connection with our work on Gif Chemistry,[9] the reaction of Fe^{II} with hydrogen peroxide (Fe^{II}-Fe^{IV} manifold) and with other peroxides, is of major interest. We decided to study the importance of steric and other effects in the fragmentation of peroxides induced by Fe^{II} in pyridine solution.

RESULTS AND DISCUSSION

We begin by consideration of the fragmentation of typical tertiary, secondary and primary hydroperoxides (Table 1). We have worked with ferrous perchlorate (no anion bonding) and with excess of picolinic acid (PA) for Gif type carboxylate bonding. In the case of cumyl hydroperoxide, the reactions were very fast and the cumyloxy radical was the major product as shown by the formation of acetophenone.[10] A stoichiometric ratio of Fe^{II} to hydroperoxide was used in all experiments. As shown by titration,[11] most of the Fe^{II} was converted to Fe^{III} in this case, as the Haber-Weiss mechanism would require. However, the reaction with cyclopentyl hydroperoxide was very different. The conversion to cyclopentanone was nearly quantitative and most of the Fe^{II} was not oxidized to Fe^{III}.

Table 1. Kinetic Data and Products Distribution for the Fe^{II} Induced Decomposition of Three Representative Hydroperoxides in Pyridine.[a]

Entry	$ROOH/Fe^{II}/PA$ (mmol)	$t_{1/2}$(mn)	Fe^{II} recovered (%)	ONE (or AL)	OL (in mmol)	MB(%)[b]
				3°/R=cumyl[c]		
1a	1/0.8/0	<1	26	0.67	0.33	100
1b	1/0.8/4	<1	34	0.80	0.17	97
				2°/R=cyclopentyl[c,d]		
2a	1/0.8/0	<1	67	1.04	0.13	117
2b	1/0.8/4	<1	77	0.85	0.03	88
				1°/R=n-pentyl[c,d]		
3a	1/0.8/0	<1	71	0.74	0.11	85
3b	1/0.8/4	<1	95	0.74	0.07	81

[a] Reactions were carried out at 25°C under Argon in air-purged flasks using degassed pyridine (33 mL) as solvent. [b] MB: Mass Balance. [c]ONE stands for acetophenone or cyclopentanone; AL for *n*-pentanal. OL stands for the corresponding alcohol. [d]Basic decomposition of primary and secondary hydroperoxides was confirmed by blank experiments performed without Fe^{II} and picolinic acid, but the rate of those reactions remains very slow compared to the above values.

A good test for alkoxy and hydroxy radicals is to run the reaction in the presence of an excess of a secondary alcohol. When the reaction of cumyl hydroperoxide was carried out in the presence of 3-pentanol (Table 2), little acetophenone was formed. Instead more than 90% of cumyl alcohol resulted along with the equivalent formation of 3-pentanone. Clearly the cumyloxy radical had been captured before it could fragment. Similar conclusions were drawn from a reaction in the presence of 2,3-dimethylbutane (alkoxy radical capture by tertiary C-H bond breaking). In contrast when the same reaction was run with cyclopentyl hydroperoxide in the presence of excess of 3-pentanol, there was no change in the amount of cyclopentanone formed and almost no 3-pentanone was produced. The result with 2,3-dimethylbutane was the same.

We conclude that alkoxy (or hydroxy) radicals cannot be formed in the cyclopentanone reaction. The attachment of the terminal oxygen of the hydroperoxide to Fe^{II} (1) would not provide a strong driving force.

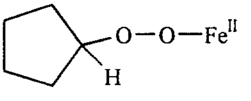

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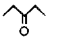
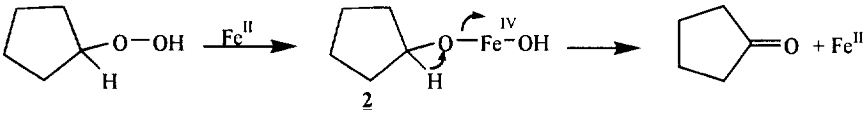
Table 2. Effect of Hydrogen Atom Donor Addition on the Fe^{II} Induced Decomposition of Peroxides (ROOR′) in Pyridine.[a]

Entry	R, R′	3-pentanol[b]				2,3-dimethylbutane[c]		
		ONE[d]	OL	MB(%)[e]		ONE[d]	OL	MB(%)[e]
1	cumyl, H	0.08	0.92	100	0.66	0.09	0.37	98
2	cyclopentyl, H	0.80	0.13	93	0.06	0.35	0.06	90
3	*n*-pentyl, H	No data available				0.40	0.10	106
4	cumyl, methyl	0.08	0.85	93	0.54	0.09	0.39	103

[a] See table 1. The reactions were carried out with stoichiometric ratio of Fe^{II}/peroxide without any ligand. [b] 1.00 mmol ROOR′ in pyridine (5.70 mL) and 3-pentanol (4.30 mL). [c] 0.47 mmol ROOR′ in pyridine (10.00 mL) and 2,3-dimethylbutane (4.00 mL). [d] ONE stands for ketone or aldehyde. OL stands for the corresponding alcohol. [e] MB: Mass Balance.

However, the insertion, direct or indirect, of Fe^{II} between the peroxide oxygens would afford 2 whose fragmentation back to Fe^{II} would give a good driving force for ketonization (Scheme 1). This sequence would also explain why the Fe^{II} was largely unconsumed.



Scheme 1

In order to study the behaviour of primary hydroperoxides, we prepared *n*-pentyl hydroperoxide. This behaved like cyclopentyl hydroperoxide (Table1). In a fast reaction *n*-pentanal was formed and Fe^{II} largely recovered. On application of the 2,3-dimethylbutane test, the yield of aldehyde was 82% which is very similar to the value reported in Table 1 (90%). So the same ionic fragmentation mechanism is operative as with cyclopentyl hydroperoxide. Our results with the primary hydroperoxide are indeed very similar to those reported by Goosen.[12] Our work shows that, contrary to general opinion, the fragmentation of secondary and primary hydroperoxides in pyridine is ionic and not radical in nature.

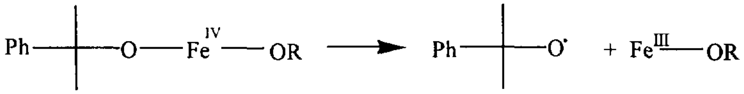
To examine the importance of steric effects in the Fe^{II} based chemistry of peroxides, we prepared methyl, ethyl, *iso*-propyl and *tert*-butyl derivatives of cumyl hydroperoxide. In addition we studied the reactions of di-*tert*-butyl peroxide. Two sets of experiments were carried out using Fe^{II} perchlorate in pyridine (Table 3), without any extra ligand (a series) or combined with a defined excess of picolinic acid (b series). Major steric effects were at once apparent. With or without picolinic acid, *tert*-butyl cumyl peroxide showed no sign of reaction even after 100 days at 25°. The same lack of reactivity was seen with di-*tert*-butyl peroxide. Even cumyl *iso*-propyl peroxide required 15 days to reach its half-life in the presence of picolinic acid. Without this ligand, there was incomplete reaction at 61 days. In contrast, the half-life for the mixed methyl peroxide was 120 minutes without picolinic acid and only 7 minutes with. For the ethyl derivative, the rates were slower at 2.5 days and 23 minutes respectively for the half-lives. It would seem that these results are not in accord with an electron outer-sphere transfer process.

Table 3. Effect of Various Alkyl Groups on the Reaction of the Corresponding Mixed Cumyl Peroxides with Fe^{II} in Pyridine.^{a}

Entry	CumOOR/Fe^{II}/PA (mmol)	Fe^{II} recovered (%)	$t_{1/2}$(ONE)	ONE^b OL (in mmol)	MB(%)^c
		R=Me^{d,e}			
1a	0.80/0.80/0	72	120mn	0.50 0.23	92
1b	0.80/0.80/4	72	7mn	0.58 0.18	95
		R=Et^{d,e}			
2a	0.80/0.80/0	75	2.5 days	0.47 0.29	95
2b	0.80/0.80/4	65	23mn	0.50 0.22	91
		R=iPr			
3a	0.80/0.80/0	---	Partial decomposition after 60 days		
3b	0.80/0.80/4	58	~15 days	0.49 0.23	90
		R=tBu			
4a	0.80/0.80/0	No reactions after 100 days with or without picolinic acid.			
4b	0.80/0.80/4				

^{a} See table 1. ^{b}ONE stands for acetophenone. OL stands for cumyl alcohol. ^{c}MB: Mass Balance. ^{d}No formaldehyde (R=Me) or acetaldehyde (R=Et) were detected after the addition of such an efficient trap as dimedone to the final reaction mixtures. ^{e}Blank experiments (without Fe^{II}) carried out for 24 h (R=Me) and 20 days (R=Et) showed that the extent of basic decomposition of the two peroxides was negligible (See Reference 13).

The use of the cumyl group facilitates analysis. The aromatic substituent directs the fragmentation exclusively to cumyloxy radical formation (Scheme 2). A second fragmentation to acetophenone, (readily determined by u.v. absorption), and methyl radicals takes place. Pyridine is a good trap for carbon radicals. The adduct formed has strong reducing properties (hydrogen atom transfer) and can reduce alkoxy radicals to alcohols and Fe^{III} to Fe^{II}.[14] Additional evidence for the intermediacy of the cumyloxy radical in these reactions was secured using cumyl methyl peroxide (Table 3, Entry 1b). A reaction in the presence of an excess of 3-pentanol trapped almost all the cumyloxy radical as the corresponding alcohol with formation of an equivalent amount of 3 pentanone (Table 2, Entry 4).

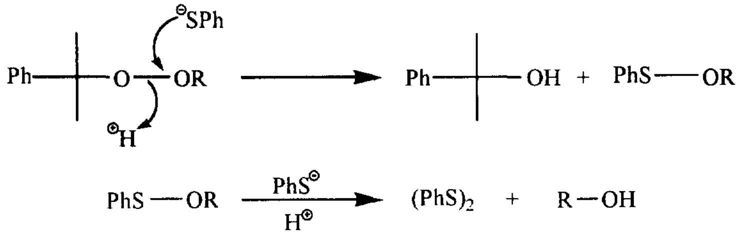


3 4

Scheme 2

The major steric effects observed (Table 3) have no relationship to the strength of the peroxidic bond. For dimethyl, diethyl, di-*n*-propyl and di-*t*-butyl peroxides, bond dissociation energies (in kcal/mol) are reported to be 37.1, 37.9, 37.7 and 36.4 respectively.[15] Similar values (38-40 kcal/mol) are given for the methyl, ethyl, *iso*-propyl and *t*-butyl derivatives of methyl hydroperoxide.[15] The attack of a nucleophilic species on the peroxidic bond might well show the type of steric effects that we have observed.[16,17]

With prior experience of the smooth SN_2 like reactions of thiols with the sulfenic acids formed in penicillin chemistry,[18] we decided to examine the base catalyzed reaction of thiophenol with the series of peroxides (Scheme 3). Prior work by Adam[19] had shown that the reaction of a thiol with a peroxide afforded the appropriate disulfide in quantitative yield.



Scheme 3

Our measured half-life time values for the reaction of the methyl, ethyl, *iso*-propyl and *t*-butyl cumyl peroxides with thiophenolate anions in deuterated methanol are respectively 17, 43, 80 h and ∞ (no reaction). From those kinetic data, it can be easily concluded that the relative rates for methyl and ethyl peroxides are approximately the same as for the Fe^{II} based reactions.

If peroxide fission by an S_N2 type reaction on the O-O bond is correct, then the reaction should be second order (Scheme 3). Variation of the ratio of the two reagents and measurement of half-lives showed that this was correct. However in the S_N2 process, it must be the less sterically hindered oxygen which is attacked. Thus, the cumyloxy anion is formed. In order to explain that only the cumyloxy radical is produced, we can invoke inner sphere electron transfer or, as we prefer, the formulation of an Fe^{IV} species (3) which fragments into this radical and the alcohol bonded to Fe^{III}. As usual, we do not indicate all the ligands on the iron species. However, we know that with Fe^{II} the number of picolinate residues on the iron is two[20] as on Fe^{III}.[21]

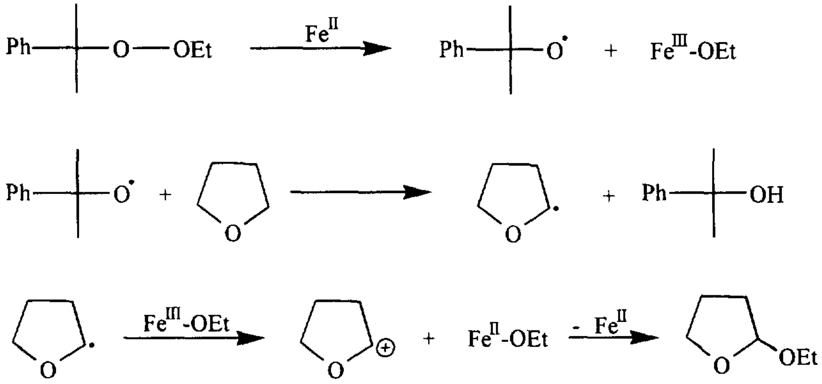
The marked steric effects seen in the series of mixed cumyl peroxides in pyridine solution do not accord well with the extensive results already reported for di-tertiary peroxides in artemisinin and its congeners[22]. In pyridine it is clear that an outer sphere electron transfer of the Haber-Weiss type does not take place. With artemisinin type compounds much of the peroxide fragmentation, especially with Posner's group [22], is carried out in tetrahydrofuran (THF) using $FeBr_2$. Some relevant experiments are summarized in Table 4.

Table 4. Decomposition of Mixed Cumyl Peroxides (CumOOR) Induced by FeX_2 in THF.

Entry	R	X	CumOOR / Fe^{II} (mmol)	Fe^{II} recovered (%)	Time[a]	OL[b] (mmol)	Phenol (mmol)	MB[c] (%)
1[d]	Et	Br	0.94 / 0.88	64	< 25 mn	0.90	0.04	100
2	tBu	Br	0.96 / 0.90	48	20 hr	0.87	0.03	100
3a	Et	ClO_4	0.94 / 0.88	Partial decomposition after 18 hours				
3b[e]	Et	ClO_4	Same + LiBr (2eq)	43	< 100 mn	0.90	tr	96
4	Et	Cl	0.94 / 0.86	74	< 35 mn	0.90	0.02	98
5	Et	Br	0.94 / 0.10	40	3 h	0.91	0.02	99
6	Et	Cl	0.94 / 0.10	20	< 1 h	0.95	-	100

[a] Time needed for the completion of the reaction. [b] OL stands for cumyl alcohol. [c] MB: Mass Balance. [d] Cumyl ethyl peroxide remained stable for 18 hr in the corresponding blank experiment carried out with LiBr and without any Fe^{II} salt. [e] Lithium bromide (1.76 mmol) was added after 18 hr to the previous mixture (entry 3).

Using cumyl ethyl peroxide and equimolar $FeBr_2$, the reaction (Entry 1) was complete in less than 25 mn. Moreover, there was no fragmentation of the cumyloxy radical. It was reduced by hydrogen atom transfer to furnish cumyl alcohol and a tetrahydrofuranyl radical (Scheme 4). Finally the Fe^{III} was reduced by electron transfer to refurnish Fe^{II} and the THF oxonium ion which reacted with the ethoxy group from the $Fe^{II}OEt$ species to give 2-ethoxy-THF. Even the *t*-butyl cumyl peroxide now reacted with $FeBr_2$ in THF (Entry 2) to give in a relatively slow reaction cumyl alcohol and 2-*t*-butoxy-THF. Authentic specimens of the two alkoxy-tetrahydrofuran derivatives were synthesized for comparison. And finally di-*t*-butyl peroxide reacted using a 1 : 1 molar ratio (peroxide : $FeBr_2$) in 5 hours. This could be an electron transfer reaction, now made much easier by the absence of ligation to pyridine. In Entry 3a, $Fe^{II}(ClO_4)_2$, $6H_2O$ was used for comparison purposes. It reacted very slowly, so in Entry 3b an appropriate amount of LiBr (2 eq) was added. At once the reaction started and after less than 100 mn, it was complete. A comparison with $FeCl_2$, $4H_2O$ was made in Entry 4. Now the reaction with cumyl ethyl peroxide was fast again and was finished in less than 35mn. In both Entry 3b and 4, cumyl alcohol was formed very efficiently and major amounts of Fe^{II} remained at the end. Since so much Fe^{II} was recovered, as explained in Scheme 4, we decided to use a catalytic amount of Fe^{II}. In Entries 5 and 6, both reactions with $FeBr_2$ and $FeCl_2$ were fast. In fact the $FeCl_2$ induced decomposition was about three times faster than the reaction with $FeBr_2$. Both reactions gave only cumyl alcohol and a significant amount of Fe^{II} was retained.



Scheme 4

Whilst the formation of 3, and its fragmentation, explain the extreme steric effects seen in pyridine, the far less steric difficulties found in THF leave open the simple possibility of electron transfer in the conventional manner. In the more complex artemisinin molecule studied by Posner *et al.*[22] the simple THF interactions seen here have not been observed. The comparable work done by Jefford [22] was carried out in acetonitrile, a solvent that we have not studied.

CONCLUSION

We started this work to see if the Gif solvent pyridine had some unusual properties with respect to peroxide fragmentation. From the point of view of steric hindrance, this is certainly true. From the point of view of primary and secondary hydroperoxides, the fragmentation observed is completely different from the Haber-Weiss mechanism and corresponds to probable Fe^{IV} chemistry (Scheme 1). In pyridine primary and secondary hydroperoxides do not, on reaction with Fe^{II}, give alkoxy radicals. This is shown by tests with 3-pentanol for hydrogen atom transfer. On the other hand in AcOH-H_2O or CH_3CN-AcOH mixtures, this kind of hydroperoxide with Fe^{II} affords immediately the corresponding alkoxy radicals which behave in a normal radical manner and do not fragment to aldehyde or ketone.[23] Tertiary hydroperoxides always fragment to give radicals irrespective of the solvent.[24]

EXPERIMENTAL SECTION

Instrumentation : Column chromatography was carried out on silica gel (0.040-0.063 mm). TLC analysis was performed on thin layer analytical plates 60 F254 (Merck). UV-Visible spectra were recorded either on a Beckmann DU-7 spectrophotometer (Fe^{II} titration) or a Hewlett-Packard 8450 A Diode Array spectrophotometer (Acetophenone quantification). ^1H NMR (200 MHZ) and ^{13}C NMR (50 MHZ) spectra were obtained using a Varian XL 200E spectrometer. Chemical shifts are reported in parts per million (δ, ppm) relative to tetramethylsilane ($\delta = 0.0$ ppm), whereas the residual solvent peak was used as an internal reference for ^{13}C NMR spectra. GC analyses were performed on a Hewlett-Packard 5890 Series II gas chromatograph equipped with a FID and using a DB-Wax capillary column (30 m x 0.32 mm i.d., film thickness : 0.25 µm, J&W Scientific). MS data were obtained on a Hewlett-Packard 5890 GC-MS station equipped with a Hewlett-Packard 5971 mass selective detector.

Caution : This work involved perchlorate anions and peroxides in dilute solution. However, we did not see any indications of dangerous reactivity.

Materials : Excepting tetrahydrofuran which was distilled from sodium benzophenone ketyl prior to use, all the solvents (of the best grade commercially available) were not further purified ; the only requirement was that they were degassed and stored under Argon before use.
Ferrous perchlorate hexahydrate, chloride tetrahydrate or bromide anhydrous were checked regularly for their purity using the standard method developed by Clark[11] and the initial conditions reported in the different tables are corresponding to the real amount of Fe^{II} (usually between 80 and 90 %).

All the decomposition products mentioned in the tables were unambiguously identified by comparison to commercial authentic samples. They were quantified by GC with naphtalene as the internal standard.

Di-*tert*-butyl peroxide, cumene hydroperoxide (80% in cumene) and *tert*-butyl cumyl peroxide (tech. grade) were the only peroxides commercially available respectively from Aldrich Chemical Co. and Lancaster Synthesis Inc.. The second one had to be extracted with KOH 50% and was recovered pure after acidification of the aqueous phase and re-extraction with diethylether. The last one was isolated from flash chromatography (hexanes).

All the other peroxides or hydroperoxides were synthesized according to the procedures reported below. The hydroperoxides were assayed by iodometric titration.

Preparation of n-Pentyl Hydroperoxide : The compound was obtained by nucleophilic displacement of the corresponding mesylate[25] according to the procedure described by Mosher.[26]

To a stirred solution of hydrogen peroxide (44.4 g of a 30% wt. soln. in H_2O, 390 mmol, 4.9 eq) and n-pentylmethanesulfonate (13.3 g, 80 mmol, 1 eq) in methanol (80 mL) at 0°C was added dropwise a 50% soln. of KOH (10 g, 90 mmol, 1.1 eq). The reaction mixture was stirred overnight 24 hr and then worked up as reported in the literature.[26] The hydroperoxide was only obtained in 35% yield (lit.[26] 43%) due to the competitive formation of n-pentyl peroxide (35 %, same ^{1}H NMR as lit.[27]).

^{1}H NMR (C_6D_6) (δ, ppm) : 0.70-1.60 (m, 9H) ; 4.80 (t, 2H) ; 7.65 (bs, 1H).
^{13}C NMR (C_6D_6) (δ, ppm) : 14.1 ; 22.75 ; 27.6 ; 28.3 ; 76.7.

Preparation of Cyclopentyl Hydroperoxide : The procedure described before afforded the hydroperoxide in 20% yield (based on the corresponding mesylate[25]).

^{1}H NMR (C_6D_6) (δ, ppm) : 1.40-1.90 (m, 8H), 4.60 (m, 1H), 6.60 (bs, 1H). **^{13}C NMR (C_6D_6) (δ, ppm) :** 23.9 ; 30.7 ; 87.6.

Preparation of Cumyl Methyl Peroxide[28] : To a vigorously stirred solution of cumyl hydroperoxide (10.30 g of the 80% soln. in cumene, 54 mmol, 1 eq) and KOH (20 mL of a 25% soln. in H_2O, 1.6 eq) at 0°C was added dropwise dimethyl sulfate (6.80 g, 54.0 mmol, 2 eq). The mixture stirred for 2 days at r.t. was diluted with diethylether and the aqueous phase extracted twice. The combined organic layers were dried and evaporated under reduced pressure below 30°C. The residue was purified by column chromatography (hexanes) and the peroxide was obtained as a colorless oil in 58 % yield.

^{1}H NMR ($CDCl_3$) (δ, ppm) : 1.62 (s, 6H) ; 3.79 (s, 3H) ; 7.2-7.5 (m, 5H) (same as lit.[29] ^{1}H NMR). **^{13}C NMR ($CDCl_3$) (δ, ppm) :** 26.4 ; 62.9 ; 82.9 ; 125.4 ; 127.1 ; 145.4. **IR (neat, cm^{-1}) :** 875 and 1153.

Preparation of Cumyl Ethyl Peroxide : The aforementioned procedure was applied successfully to the ethyl derivative starting from cumyl hydroperoxide and diethyl sulfate. The compound was obtained as a colorless oil in 60% yield.

^{1}H NMR ($CDCl_3$) (δ, ppm) : 1.18 (t, 3H) ; 1.60 (s, 6H) ; 4.00 (q, 2H) ; 7.20-7.60 (m, 5H) (same as lit.[29] ^{1}H NMR). **^{13}C NMR ($CDCl_3$) (δ, ppm) :** 13.2 ; 26.5 ; 70.2 ; 82.6 ; 125.5 ; 127.0 ; 128.0 ; 145.5.
IR (neat, cm^{-1}) : 866 and 1156.

Preparation of Cumyl iso-Propyl Peroxide : This compound was prepared by a procedure that was modified from that published by Baj.[30] To a solution of cumyl hydroperoxide (2.37 g of the 80% soln. in cumene, 13 mmol, 1 eq) in methanol (10 mL) was added dropwise tetrabutylammonium hydroxide (12.87 g of a 1.0 M soln. in MeOH, 13 mmol, 1 eq) at 0°C under argon. The resulting mixture was stirred overnight. Methanol was evaporated, replaced by benzene (20 mL) and 2-bromopropane (7.86 g, 64 mmol, 5 eq) was then added in one portion to the cooled solution. The solvent and excess of the bromide reagent were evaporated under reduced pressure 48 hr later. The residue was purified by column chromatography (hexanes) affording the isolation of a colorless oil in 50% yield.

^{1}H NMR ($CDCl_3$) (δ, ppm) : 1.15 (d, 6H) ; 1.60 (s, 6H) ; 4.15 (h, 1H) ; 7.20-7.50 (m, 5H). **^{13}C NMR ($CDCl_3$) (δ, ppm) :** 20.4 ; 26.6 ; 75.7 ; 82.3 ; 125.53 ; 126.91 ; 127.91 ; 145.6. **IR (neat, cm^{-1}) :** 881 and 1151.

Preparation of 2-Ethoxy-Tetrahydrofuran : To a solution of *p*-toluenesulfonic acid monohydrate (0.20 g, 1 mmol, 1/130 eq) in ethyl alcohol (15.0 mL, 0.26 mol , 2 eq) at 0°C was added 2,3-dihydrofuran (9.27 g, 0.13 mol, 1 eq). Stirring for an additional hour at r.t. completed the reaction. The solution was then diluted with diethylether (100 mL) and washed with saturated $NaHCO_3$.The aqueous phase was extracted twice with diethylether (20 mL) and the resulting organic layers were combined, dried and evaporated. The residue was purified by distillation under atmospheric pressure affording a colorless oil (b.p. 112-114°C / 760 mm ; lit.[31] b.p. 110-112°C / 699 mm) in 40 % yield.

^{1}H NMR ($CDCl_3$) (δ, ppm) : 1.15 (t, 3H) ; 1.70-2.10 (m, 4H) ; 3.40 (m, 1H) ; 3.65 (m, 1H) ; 3.70-3.90 (m, 2H) ; 5.10 (m, 1H).**^{13}C NMR ($CDCl_3$) (δ, ppm) :** 15.1 ; 23.4 ; 32.3 ; 62.5 ; 66.7 ; 103.5 (same as lit.[32] ^{1}H and ^{13}C NMR). **SM m/z :** 116 (M^+, 3.5) ; 115 (23.2) ; 71.05 (100). **IR (neat, cm^{-1}) :** 1057.

Preparation of 2-tert-Butoxy-Tetrahydrofuran : To a solution of *p*-toluenesulfonic acid monohydrate (0.22 g, 1.1 mmol, 1/120 eq) and *tert*-butyl alcohol (13.43 g, 0.13 mol, 1.4 eq) in THF (15 mL) at 0°C was added 2,3-dihydrofuran (9.27 g, 0.13 mol, 1 eq). The resulting solution was stirred overnight at r.t. and worked up as described before. The residue was purified by distillation under reduced pressure affording a colorless oil (b.p. 58-60°C / 30 mm ; lit.[33] b.p. 40-42°C / 13 mm) in 60 % yield.

^{1}H NMR ($CDCl_3$) (δ, ppm) : 1.18 (s, 9H) ; 1.65-2.05 (m, 4H) ; 3.68-3.95 (m, 2H) ; 5.38 (m, 1H). **^{13}C NMR ($CDCl_3$) (δ, ppm) :** 23.8 ; 28.8 ; 33.4 ; 66.3 ; 73.6 ; 98.5. **SM m/z :** 143.9 (M^+, 0.1) ; 129 (9.8) ; 70.95 (100) ; 57 (52.3). **IR (neat, cm^{-1}) :** 1390 and 1362.

General Procedure for the Fe^{II} Induced Decomposition Reactions : All the reactions were carried out at 25°C under Ar in air-purged 125ml-flasks containing the iron(II) salt (0.8 mmol) with or without picolinic acid (4.0 mmol) depending on the run considered ($Fe(ClO_4)_2,6H_2O$ was used in pyridine-based solutions). The

solvent was then added with a seringe and finally the oxidant (1.00 mmol) at t=0. The progress of the reactions was followed by TLC (hexanes / diethylether : 3 /2) until complete disappearance of the peroxides ($Fe(SO_4)_2$, $7H_2O$ / NaSCN in H_2O-acetone being used as a stain).

Work-up Procedure for GC analysis : A 2 mL - aliquot withdrawn from the reaction mixture (1 mL for the runs carried out with 3-pentanol or 2,3-dimethylbutane) was diluted in 10 mL of diethylether and washed with 5 mL of distilled water. Once dried over $MgSO_4$, the sample was analyzed with naphtalene as the internal standard.

Work-up procedure for UV-Vis. Quantification of Acetophenone : The determination of acetophenone was carried out on 1 mL - aliquots from the reaction mixture. The sample diluted, first in 10 mL of hexanes, had to be washed either by 5 mL of distilled water or H_2SO_4 (20 %) depending on the solvent used for the reaction, respectively THF or Pyridine - based mixtures. Measurements were performed in dry hexanes (after dilution to 25 mL). Preliminary blank experiments showed then that the absorbances of the corresponding mixed peroxides and cumyl alcohol did not interfere with acetophenone (λ_1 = 278 nm (ε_1 = 925 $dm^3.mol^{-1}.cm^{-1}$) and λ_2 = 286 nm (ε_2 = 800 $dm^3.mol^{-1}.cm^{-1}$)).

Search for formaldehyde (or acetaldehyde) :

Preparation of the Authentic Samples : Derivatives of the aldehydes with 5,5-dimethyl-1,3-cyclohexanedione (dimedone) were used for an easy quantification.[34] The adducts were prepared in pyridine (33 mL) by adding 4.00 mmol of dimedone to 1.00 mmol of formaldehyde (37% in water) or acetaldehyde and stirring the resulting solution overnight at room temperature. The reaction mixture was then poured into chilled water and then slowly acidified by 60 mL of H_2SO_4 (20%). The aqueous phase was extracted 3 times with diethylether and the combined organic layers treated successively with saturated $NaHCO_3$ and brine. Evaporation of the dried diethylether solutions afforded respectively the isolation of the formaldehyde and acetaldehyde adducts in 91 and 92% yields.

Formaldehyde adduct : m.p.190°C ; lit.[34] m.p. 191-191.5 °C.
Acetaldehyde adduct : m.p. 144°C ; lit.[34] m.p. 141-142 °C

Procedure for the recovery and the quantification of the aldehydes in the reaction mixture

After checking that the presence of $Fe(ClO_4)_2$, $6H_2O$ (1.00 mmol), picolinic acid (4.00 mmol), cumyl alcohol (0.20 mmol) and acetophenone (0.75 mmol) in the previous conditions did not change the yields of the two adducts, dimedone (4.00 mmol) was directly introduced in the reaction mixture 2 hr (R = Me) or 6 hr (R = Et) after the addition of the corresponding peroxide (completion of the reaction). The work-up procedure described before afforded the isolation of a crude mixture whose analysis by ^1H NMR using 1,1,2,2,-tetrachloroethane as an internal standard lead to the conclusion that only 6% of formaldehyde and 9% acetaldehyde are produced under our conditions.

Peroxide Displacement by Thiophenol under Basic Conditions : The reaction was conveniently studied at 25°C by ^1H NMR using anisole as the internal standard. In a typical run, the mixed peroxide (1.00 mmol) and DBU (0.65 mmol) were solubilized in deuterated methanol (800 µl) and introduced into an NMR tube. Addition of thiophenol (1.00 mmol) was done at t=0. Half life values reported here have been evaluated from

the rate of disappearance of the peroxide. The following signals (δ, ppm) : 3.52 (s, OOMe), 3.75 (q, OOEt), 3.95 (h, OO*i*-Pr) and 1.02 (s, OO*t*-Bu) were used for the comparison with anisole.
Blank experiments performed in the absence of thiophenol showed that the basic decomposition of the peroxides CumOOR (R = Me, Et, *i*-Pr) was relatively slow. There was still remaining 63% of cumyl methyl peroxide after 1 month, 80% of the ethyl derivative after 4 days and 74 % of the *iso*-propyl one after 17 days compared to respectively 0, 20, 47 % under the usual reaction conditions.

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