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**THE OXIDATION OF ALLYLIC METHYLENE GROUPS
UNDER Fe^{III}-TBHP AND Fe^{III}-TBHP-PA CONDITIONS**

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Abstract: Oxidation of allylic methylene groups under Fe^{III}-TBHP (Fe^{III}-t-butyl hydroperoxide) and Fe^{III}-TBHP-PA (Fe^{III}-t-butyl hydroperoxide-picolinic acid) conditions gave α - and γ -ketonization products.

Gif systems were developed as models of enzymatic oxidation of saturated hydrocarbons.¹ All of them involve a pyridine/acetic acid solution of the hydrocarbon being oxidized, an Fe-catalyst and an oxidant. Non-activated methylene groups were ketonized with near quantitative yield at conversions from 15% to 30% and with unusual chemical selectivity for the C-H bond (*sec.* C-H > *tert.* C-H > *prim.* C-H). Both H₂O₂ and t-butylhydroperoxide (TBHP) were used as the oxidizing reagent. Usually the reaction of TBHP is more efficient. Benzylic methylene groups are more reactive than saturated methylene groups under Fe^{III}-TBHP and Fe^{III}-TBHP-PA conditions.¹ Terminal methylene carbon-carbon bonds as in 1,1-diphenylethylene and methylenecyclohexane were oxidized to give the corresponding ketones and formaldehyde by a possible adduct intermediate of an ^VFe=O species to the carbon-carbon double bonds.^{2,3} We herein wish to report the oxidation of allylic methylene groups under Fe^{III}-TBHP and Fe^{III}-TBHP-PA conditions by employing β -(-)-pinene and R-(+)- and S-(-)-limonenes as the model compounds. In these compounds, competition amongst different types of carbon-carbon double bonds and allylic C-H bonds could be studied. To avoid the further oxidation of the reaction products, an excess of substrate was used.

β -(-)-Pinene was oxidized under Fe^{III}-TBHP and Fe^{III}-TBHP-PA conditions to give pinocarvone 2, myrtenal 3 and nopinone 4. In the presence of picolinic acid, the reaction was faster (Table 1, Entry 4). The reaction was oxygen dependent. When the reaction was run under argon, the yield was greatly reduced (Entry 1). No reaction took place at the tertiary C-H bonds.

A possible reaction mechanism is proposed in Scheme 1. Formally the ^VFe=O reacts with the double bond of 1 to form intermediate A, which is a π -allyl complex. Dioxygen might then insert into the ^VFe-C bond at the α - or γ -carbon to form B or C, which would decompose to give pinocarvone 2 or myrtenal 3 respectively. Nopinone 4

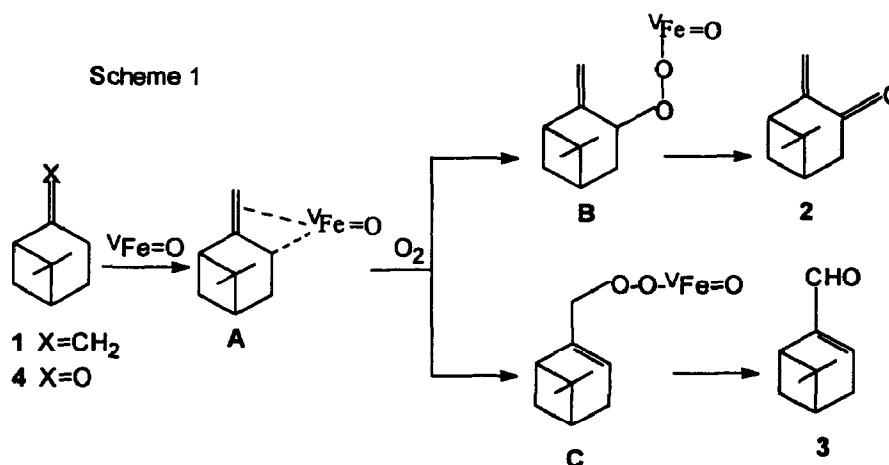
Table 1 The Oxidation of β -(-)-Pinene 1 under Fe^{III} -TBHP and Fe^{III} -TBHP-PA Conditions.

Entry	Cond.	Time (h)	1 (%)	2 (%)	3 (%)	4 (%)	MB ^{a)} (%)
1	Ar	18	98.2	1.4	1.0	0	100.6
2	Air	18	90.3	7.6	4.7	0	102.6
3	Air	48	75.3	11.7	6.1	1.0	94.1
4b)	Air	18	80.3	13.3	5.8	0.4	99.8

Conditions: 1 30 mmol; $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ 1 mmol; Pyridine 30 mL; AcOH 3 mL; TBHP 5 mmol.

a) MB=mass balance; b) 3 mmol of PA was added.

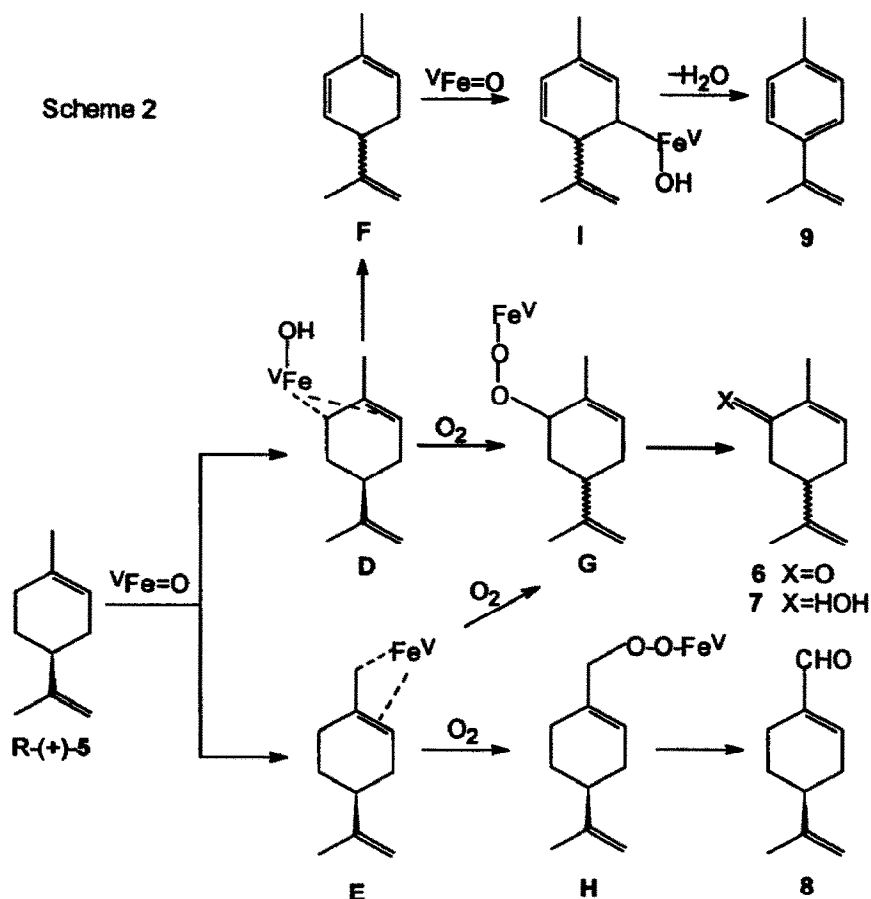
might have been formed from the oxidative cleavage of the double bond, as was discussed in the case of 1,1-diphenylethylene.³



The reactions of R-(+)- and S-(-)-limonenes 5 under Fe^{III} -TBHP and Fe^{III} -TBHP-PA conditions gave a mixture of carvone 6, carveol 7, perillaldehyde 8 and 4-(2-propenyl)toluene 9. Carvone 6 is the major product. The reaction in the presence of picolinic acid was faster (Table 2, comparing Entry 2 and 5). The reaction was oxygen dependent. When the reaction was run under argon, the yields were reduced largely (Entry 1). When the reaction was run in 100 psi oxygen, the reaction yield was increased (Entry 4). The reactions of R-(+)- and S-(-)-limonenes gave almost the same results under Fe^{III} -TBHP-PA reactions (Entry 2, 3). Carvone 6 was racemic from either R-(+)- or S-(-)-limonenes 5. This may result from the reaction at both α - and γ -carbons. The terminal double bond was stable during the reaction.

A possible reaction mechanism, within the usual Gif hypothesis (Fe^{V} -Carbon bond), is proposed in Scheme 2. The postulated $\text{VFe}=\text{O}$ species reacts with the allylic C-H bond to form intermediate D. This reacts with dioxygen at both the α - and γ -carbon to give racemic intermediate G, whose decomposition gave racemic carvone 6 and carveol 7.

D may undergo elimination to give cyclohexadiene F, which was more reactive toward the $VFe=O$ species. This intermediate I was formed and aromatized to give the product 9. This type of reaction has been discussed before.¹ The VFe oxenoid, to a less extent, reacts with the primary C-H bond to form intermediate E. This gives G or H. The decomposition of H gives perillaldehyde 8. We appreciate that what is written in Scheme 2 could also be formulated as simply radical chemistry, but after the initial insertion chemistry.



In the oxidation of β -(-)-pinene and the limonenes, the insertion of oxygen takes place at both the α - and γ -carbons. When these two carbons were equivalent as in the limonenes, the reactivities of the α - and γ -carbons were the same and thus racemic carvone 6 was formed; When they are not equivalent as in β -(-)-pinene 1, the secondary carbon was more reactive than the primary carbon. Under the same reaction conditions, the activation of the allylic C-H bonds was faster than the oxidative fission of the terminal carbon-carbon double bond. It was also consistent with the usual Gif chemoselectivity that no reaction took place at the tertiary carbon in β -(-)-pinene.

Table 2 The Oxidation of Limonites **5** under Fe^{III}-TBHP and Fe^{III}-TBHP-PA Conditions.

Entry	Cond.	5 (%)	6 (%)	7 (%)	8 (%)	9 (%)	MB (%)
1a),d)	Ar	96.7	1.4	0.3	0.3	0.02	98.9
2a),d)	Air	90.0	8.9	1.1	1.2	1.4	102.6
3b),d)	Air	88.2	9.4	1.2	1.1	1.6	101.5
4a), d)	O ₂ ^{e)}	85.6	13.5	1.0	0.3	0.3	100.7
5a)	Air	85.2	7.4	0.8	0.9	1.2	95.5
6a), c)	Air	78.0	14.1	1.3	0.9	1.3	95.6

Conditions: **5** 30 mmol; FeCl₃·6H₂O 1 mmol; Pyridine 30 mL; AcOH 3 mL; TBHP 5 mmol.
Reaction time 18 h. a) R-(+)-**5**; b) S-(-)-**5**; c) 100 psi; d) PA 3 mmol; e) Reaction time 48 h.

Oxygen gas was necessary for the formation of carbonyl compounds as it is in the cleavage of methylene double bonds³ and in the oxidation of saturated hydrocarbons⁴ with t-butyl hydroperoxide. Thus all the oxidation reactions that produce alcohol or ketone that we have studied so far do so *via* atmospheric oxygen⁵, except when a mixed t-butyl peroxide is involved as intermediate¹.

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