A New Procedure for the Oxidation of Saturated Hydrocarbons

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The oxidation of adamantane can be achieved with unusual efficiency using molecular oxygen and a system comprising hydrogen sulphide and iron powder in pyridine containing acetic acid and a little water.

The direct oxidation of paraffin hydrocarbons in natural gas under mild conditions is an intellectually challenging and industrially important objective of current relevance. The selective hydroxylation of an unactivated carbon–hydrogen bond in nature by use of enzymatic systems such as the iron–porphyrin based cytochrome P-450[1] or the non-haem iron protein ω-hydroxylase[2] indicates clearly that such a process exists. Nevertheless, despite intensive study, the use of model systems *in vivo* has to date given very poor yields when based on percentage oxidation of the hydrocarbon. Moreover, in many instances, the important problem of activation of molecular oxygen is bypassed and alternative sources such as iodosobenzene[3] and hydroperoxides[4] are used.

Consideration of the conditions prevailing in a preaerobic atmosphere suggested to us that, in the first instance, an even simpler mechanism should have functioned for oxygen 'detoxification'. We were particularly attracted to the use of elemental iron, reasoning that it would function not only as a source of metallic cations but also as a reducing agent. Initially we elected to study the use of the sulphide anion as a

Table 1. Variation in the acid used.[a]

Acid	Quantity/ mol. equiv.	Products, % yield: Adamantan-1-ol	Adamantan-2-ol	Adamantanone
Sulphuric acid	4.0	0.3	1.7[b]	
Hydrochloric acid	3.6	0.07	0.5	
Formic acid	12.0	0.19	0.26	0.37
Acetic acid	10.0	0.50	0.13	2.50
Ascorbic acid	10.0	0.06	0.28	0.10
Tartaric acid	10.0	0.48	0.40	2.70

[a] These experiments were performed at room temperature for 18 h using iron powder (10 atom equiv.) and sodium sulphide nonahydrate (1 mol. equiv.) in pyridine without additional water under 1 atm of oxygen. [b] Yield of adamantan-2-ol and -2-one combined; peaks not sufficiently resolved in g.l.c. system.

Table 2. Variation in the cation used.[a]

Sulphide	Quantity/ mol. equiv.	Products, % yield: Adamantan-1-ol	Adamantan-2-ol	Adamantanone
Sodium sulphide	1.0	1.6	5.9[b]	
Potassium sulphide[c]	1.0	1.1	0.9	5.2
Lithium sulphide	1.0	1.1	0.6	4.2
Calcium sulphide	1.0	0.75	0.8	4.15
Iron(II) sulphide	1.0	1.50	3.0	

[a] These experiments were performed at room temperature for 18 h using iron powder (10 atom equiv.), acetic acid (10 mol. equiv.), and pyridine containing water (6.6% by volume) under 1 atm of oxygen. [b] See Table 1, footnote b. [c] A solution of commercial potassium sulphide (44% pure, 1 mol. equiv.) was prepared in aqueous pyridine and filtered before use.

Table 3. Variation in the solvent used.[a]

Solvent	Products, % yield: Adamantan-1-ol	Adamantan-2-ol	Adamantanone	C^2/C^3
Acetic acid	1.3	2.7	0.6	2.6
Pyridine	0.5	0.13	2.50	5.26
Acetone	0.3	1.10	—	3.6
Pyridine–Water 3.3%	0.4	0.6	2.3	7.3
Pyridine–Water 6.6%	0.7	4.8[c]		6.9
Acetone–Pyridine 10%	0.5	1.3	1.8	7.0
Acetone–Water 6.6%	3.9	2.8	1.4	1.1
Acetone (90.1)–Pyridine (3.3)–Water 6.6%	2.1	1.6	4.0	2.7

[a] These experiments were performed at room temperature for 18 h using iron powder (10 atom equiv.), sodium sulphide nonahydrate (1 mol. equiv.), and acetic acid (10 mol. equiv.) under 1 atm of oxygen. [b] C^2/C^3 represents the relative ratio of attack at the secondary and tertiary positions, respectively. [c] See Table 1, footnote b.

ligand for iron. Although several systems feature the use of organic thiolates[5] the simple sulphide appears to have been largely neglected.† We now describe our preliminary results in this area. The spherically symmetrical hydrocarbon, adamantane, possessing four tertiary and twelve secondary carbon–hydrogen bonds was selected as a suitable probe.

In a typical experiment, iron powder (Prolabo, 10 atom equiv.) and sodium sulphide (6 mol. equiv.) were added to a pyridine solution of adamantane (1 mol. equiv.) containing acetic acid (10 mol. equiv.) and water (6% by volume). The reaction mixture was stirred under an atmosphere of oxygen for 18 h at room temperature. Extraction of the adamantane fraction and g.l.c. analysis revealed the presence of adamantan-1-ol (1.6%) and adamantan-2-ol + adamantanone (5.9%). The yield of the ketone was routinely confirmed by isolation of its corresponding 2,4-dinitrophenylhydrazone derivative.

This basic system is relatively unaffected by the order of mixing of the components. A series of blank experiments served to establish that each component was essential for a successful reaction. Significant yields can also be obtained with other acids (Table 1) or alkali metal sulphides (Table 2). Although optimal conditions have yet to be established, it is apparent that the choice of solvent (Table 3) is also important in controlling not only the yields, but also the ratio of products obtained. Replacement of sodium sulphide by thiourea (3 mol. equiv.) leads to 5% oxidation of adamantane, although in this instance a higher percentage of adamantan-1-ol (1.5%) is formed. A similar yield and site-selectivity is also observed on using iron(II) sulphide in place of iron powder and sodium sulphide.

We considered that the primary role of acetic acid in the system was to protonate the sulphide anion and thereby to generate hydrogen sulphide. Initially however, oxidation of adamantane in the presence of iron powder with hydrogen sulphide gave relatively modest yields of products (adamantan-1-ol, 0.04%; adamantan-2-ol, 0.05%; adamantanone, 0.21%). However, addition of acetic acid and water restored completely the activity observed previously.

We have also made a systematic study of the effect of hydrogen sulphide and sodium sulphide concentrations on the reaction (Table 4). It is possible to achieve 11% oxidation of adamantane using only 0.02 mol. equiv. of hydrogen sulphide! Clearly, the function of hydrogen sulphide in this reaction is *not* that of a reducing agent. We therefore attempted to oxidise adamantane by using the iron cluster compound[7] $(Bu^n{}_4N)_2[Fe_4S_4(Bu^tS)_4]$. Use of this complex in stoicheiometric

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† The u.v. spectrum of an iron(III) chloride–sodium sulphide–2-mercaptoethanol complex purported to mimic several features of the non-haem oxidases has been described.[6]

Table 4. Variation in sodium sulphide and hydrogen sulphide concentrations.[a]

<table>
<tr><th rowspan="2">Sulphide</th><th rowspan="2">Quantity/ mol. equiv.</th><th colspan="3">Products, % yield</th><th rowspan="2">C^2/C^3[b]</th></tr>
<tr><th>Adamantan-1-ol</th><th>Adamantan-2-ol</th><th>Adamantanone</th></tr>
<tr><td>Sodium sulphide</td><td>1.0</td><td>1.6</td><td colspan="2">5.9[c]</td><td>3.7</td></tr>
<tr><td>,, ,,</td><td>0.4</td><td>0.9</td><td>0.8</td><td>4.1</td><td>3.3</td></tr>
<tr><td>,, ,,</td><td>0.2</td><td>2.1</td><td colspan="2">7.0</td><td>3.3</td></tr>
<tr><td>,, ,,</td><td>0.05</td><td>2.0</td><td colspan="2">6.7</td><td>3.4</td></tr>
<tr><td>Hydrogen sulphide</td><td>1.0</td><td>1.2</td><td colspan="2">5.5</td><td>4.6</td></tr>
<tr><td>,, ,,</td><td>0.5</td><td>1.8</td><td colspan="2">7.9</td><td>4.4</td></tr>
<tr><td>,, ,,</td><td>0.02</td><td>1.95</td><td colspan="2">9.0</td><td>4.6</td></tr>
<tr><td>,, ,,</td><td>0.01</td><td>2.30</td><td colspan="2">8.5</td><td>3.7</td></tr>
<tr><td>,, ,,</td><td>0.00</td><td>0.07</td><td colspan="2">0.11</td><td>—</td></tr>
</table>

[a] These experiments were performed at room temperature for a period of 18—24 h with iron powder (10 atom equiv.) and acetic acid (10 mol. equiv.) in pyridine containing water (6.6%) under 1 atm of oxygen. [b] See Table 3, footnote b. [c] See Table 1, footnote b.

amount led to the isolation of adamantanone in 3.6% yield but with concomitant destruction of the model ferredoxin.

Throughout this investigation, we have consistently monitored the relative ratios of attack at the secondary (C^2) and tertiary (C^3) positions of adamantane. With the exception of iron(II) sulphide and thiourea, the observed ratio indicates that functionalisation of the two positions occurs with almost equal readiness (C^2/C^3 *ca.* 3). This result is in contrast with the oxidation of adamantane by the iron–porphyrin–iodosobenzene system[3] where predominant formation of the tertiary alcohol is observed ($C^2/C^3 = 0.08$). Clearly our oxidation process is not radical in nature.

The yields of alcohol and ketone described in this communication are generally significantly greater than those observed currently in many model systems.[3,5,8] Therefore this procedure could provide the basis for a simple and economically viable method of hydrocarbon oxidation.

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