

A mechanistic study of the liquid phase autoxidation of nonan-5-one†

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The liquid phase autoxidation of nonan-5-one has been studied as a model for the degradation of ketones formed from the oxidation of lubricants in automotive combustion engines. The oxidation, at 120 °C, gives a large number of products (32 identified), including derivatives of the substrate with an intact carbon skeleton and low molecular mass compounds, from radical fragmentations, as well as carbon oxides. The products were identified and quantified by GC-MS and GC, with the characterisation of isomers being aided by measuring the deuterium content of products from the autoxidation of 4,4,6,6-[²H₄]-nonan-5-one. Products arising from hydrogen atom abstraction from all the secondary C–H bonds were observed, with the main site of attack being α to the carbonyl group. The ketoalkyl, ketoperoxyl and ketoalkoxyl radicals formed in the reaction undergo radical dimerisation, disproportionation and hydrogen atom abstraction. With the ketoalkoxyl radicals the dominant pathway is β -scission, indeed ~58% of the total product yield arises from this fragmentation of the α -ketoalkoxyl radical. Mechanisms for the formation of the observed products are proposed and used to determine the selectivity of the autoxidation for the different C–H bonds in the substrate.

Introduction

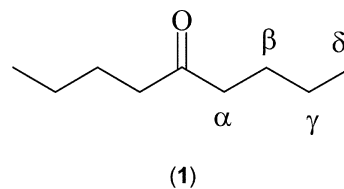
Heightened environmental concerns to improve efficiency and to reduce emissions, coupled with continued advances in modern technology, are forcing increasing demands on automotive engines. As a consequence, lubricants, essential to reduce friction and prevent wear, must have thermo-oxidative stability to withstand ever-harsher operating conditions. Lubricants typically consist of a base oil (usually a mixture of petroleum-based hydrocarbons) together with an additive package containing antioxidants, detergents, dispersants and anti-wear agents.¹ Unfortunately, oxidation of the lubricant under the harsh operating conditions in a combustion engine leads to changes in viscosity and the formation of insoluble deposits that can severely affect the efficiency and performance of the engine.²

A widely used approach to understand the mechanisms of base oil degradation has been to study the oxidation of chemically pure smaller model compounds.² With careful choice of substrate, this simplifies the analytical problems and allows greater control of the experimental conditions. The results can then be extrapolated to larger molecular weight base oils, with the aim of designing lubricants with improved thermo-oxidative stability.

The autoxidation of a wide range of alkanes has been extensively studied^{3,4} and the primary products have been shown to include hydroperoxides, alcohols, aldehydes and

ketones. However, there are few reported studies of the oxidation of these primary products, studies that are needed if we are to understand which are likely candidates to produce compounds which, in turn, polymerise and form insoluble deposits.

In this paper we report our studies on the mechanism of autoxidation of nonan-5-one, **1**, as a model for the ketones formed as primary autoxidation products of alkane-based lubricants. A symmetrical ketone was selected in favour of unsymmetrical analogues to simplify the product analysis. The distribution of products is used to obtain information about the selectivity of the reaction for the three different types of secondary (α , β and γ) and one primary (δ) C–H bond and this in turn provides useful generic data to account for the breakdown of ketones formed in the autoxidation of lubricants.



Results and discussion

Methods

All the reactions were carried out in a stirred, stainless steel micro-reactor that was pressurised with oxygen or nitrogen and heated to the desired temperature. The standard oxidation conditions for the substrates used were: 0.5 cm³ of substrate at 120 °C and 537 kPa oxygen pressure at the operating temperature (400 kPa at ca. 20 °C). The time taken for the micro-reactor to reach the reaction temperature was typically

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10 min.⁵ For the reaction of nonan-5-one with *tert*-butoxyl radicals, a solution of di-*tert*-butyl peroxide in nonan-5-one was heated under nitrogen in the micro-reactor. The change in pressure inside the reactor allowed the extent of reaction to be monitored.

Autoxidation of nonan-5-one

Products. Control experiments carried out under an inert atmosphere demonstrated that nonan-5-one is stable at 120 °C and that the products formed in oxygen arise as a result of autoxidation rather than pyrolysis of the starting material. In total, 32 products have been identified by comparison of mass spectra with library reference data⁶ and, for some compounds, by comparison of GC retention times with those of authentic materials, some of which were specifically prepared. Two isomeric minor products with mass 170 (EI- and CI-MS) were also detected but could not be identified. The nonan-5-one hydroperoxides formed (see below) were not stable to the GC analytical conditions and the individual compounds could not be identified.

The major volatile products from the autoxidation of nonan-5-one under these conditions are carbon monoxide and carbon dioxide (Table 1), with smaller amounts of alkanes (methane, ethane, propane and butane), alkenes (ethene, propene and but-1-ene) and ethanal.

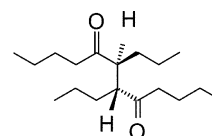
Table 1 Oxygen consumption and product yields in the autoxidation of nonan-5-one at 120 °C, 537 kPa oxygen and deuterium content of products from 4,4,6,6-[²H₄]-nonan-5-one

	Oxygen consumption (%)				Number of deuterium atoms
	12.0	45.5	49.2	83.4	
Gas phase prods/ 10 ⁻³ mol dm ⁻³ ^a					
CO	0.1	17.1	16.9	14.2	
CO ₂	0.1	33.8	27.6	55.0	
Liquid phase prods/ 10 ⁻³ mol dm ⁻³					
Ethanal	3.0	3.0	4.0	5.0	0
Propanal	1.0	4.0	4.0	6.0	0
Butanal	13	17	17	18	1
Butanone	3.0	24	21	24	2
Hexan-2-one	8.0	13	11	18	4
Heptan-3-one	7.0	7.0	6.0	13	4
Propan-1-ol	1.0	5.0	3.0	7.0	0
Butan-1-ol	5.0	8.0	6.0	11	2
Ethanoic acid	40	35	30	56	0
Propanoic acid	20	25	18	36	0
Butanoic acid	14	123	102	184	0
Pentanoic acid	20	120	120	182	2
3-Hydroxynonan-5-one	3.0	7.0	8.0	13	4
4-Hydroxynonan-5-one	6.0	16	14	22	3
Nonane-2,5-dione	11	18	19	40	4
Nonane-4,5-dione	7.0	14	16	20	2
Nonan-3-en-5-one	<1.0	2.0	3.0	6.0	3
4,5-Dihydro-5-methyl-2 (3 <i>H</i>)-furanone (5)	2.0	2.0	2.0	3.0	2
Butyl pentanoate	Nd ^b	Nd ^b	Nd ^b	Nd ^b	4
Dehydro-dimer (2)	<1.0	5.0	5.0	11	6
Dehydro-dimer (3)	<1.0	2.0	2.0	4.0	6

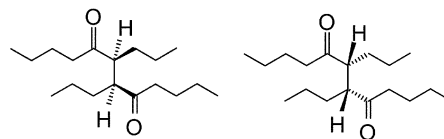
^a For ease of comparison with the liquid phase products, the yields of the gas phase products are expressed as the concentrations they would have if they were dissolved in the liquid. ^b Yield not determined; the GC peak from butyl pentanoate overlapped that of the substrate.

Analysis of the liquid phase products showed that five major functional groups, acids, alcohols, aldehydes, esters and ketones, were formed in the reactions (Table 1). Trace amounts of unidentified high molecular mass products, with molecular ions of *m/z* 368, 434 and 662, were detected by direct CI-MS analysis of the liquid phase of the autoxidation mixtures.

For regioisomers, structural identification was aided by isotopic labelling experiments using GC-MS to examine the deuterium content of the products from 4,4,6,6-[²H₄]-nonan-5-one; this allowed a distinction between those arising from attack on the α-C-H bonds as opposed to other positions. For example, two products from the oxidation of undeuterated nonan-5-one have a molecular ion *m/z* 158 (GC-MS), corresponding to two of the four possible hydroxynonan-5-ones. The fragments present in the EI mass spectra of both were similar, making it difficult to give a definitive identification of the two compounds. Oxidation of 4,4,6,6-[²H₄]-nonan-5-one yielded the same compounds but with molecular ions *m/z* 161 and 162, with mass increases of 3 and 4, respectively. As the deuterium labels were only present in the α-position of the substrate, the product with *m/z* 161 must be the α-hydroxyketone, 4-hydroxynonan-5-one, and the other compound, with *m/z* 162, must have arisen from hydroxylation of the β, γ or δ position (identified as 3-hydroxynonan-5-one, see below). This approach was also used to identify nonan-4,5-dione and nonan-2,5-dione and the α,α-dehydro-dimers, 2 and 3.



(2)



(3)

In addition to aiding product identification, comparison of the product distributions from the deuterated and undeuterated substrates provides information about the pathways to the oxidation products (see below).

Dependence of the reaction product profile on the extent of reaction. The yields of products were measured as a function of oxygen consumed; this showed that there was a fair linear relationship between yields of stable products and oxygen consumed (Table 1 and see for example Fig. 1 and ESI Fig. S1–S5†). Thus the product distribution effectively remained unchanged during the course of the reaction. The hydroperoxides were relatively unstable under the reaction conditions and their yields increased to a maximum at 40–50% oxygen consumption and then decreased (Table 2).

Autoxidation of 4,4,6,6-[²H₄]-nonan-5-one

4,4,6,6-[²H₄]-Nonan-5-one was autoxidised under the same experimental conditions as nonan-5-one and GC-MS analysis

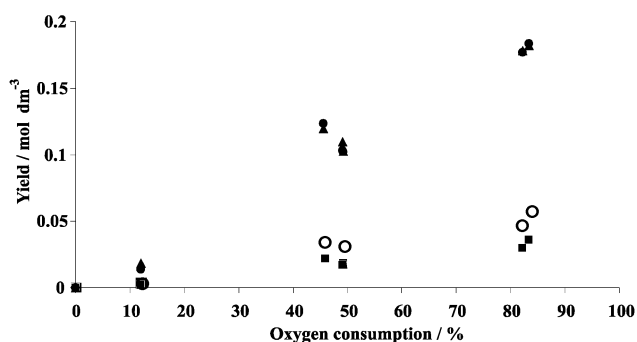


Fig. 1 Autoxidation of nonan-5-one, 0.5 cm³, 120 °C, 537 kPa oxygen; yields of carboxylic acids as a function of oxygen consumption. Legend: ○ ethanoic acid, ■ propanoic acid, ● butanoic acid, ▲ pentanoic acid.

revealed that butanoic acid and all compounds containing two or three carbon atoms were undeuterated whereas the other four-carbon products and all the larger compounds contained deuterium labels ranging from one for butanal to six for the two dehydro-dimers (Table 1). The yields of the products with an intact nine-carbon skeleton from the deuterated and undeuterated ketone, at 96% oxygen consumption, are compared in Table 3.

Autoxidation of nonanal

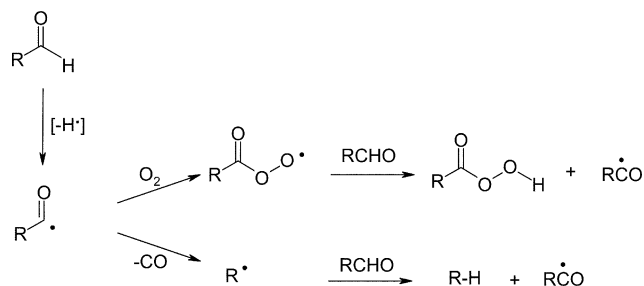
A 10% (v/v) solution of nonanal in nonan-5-one was oxidised, under the same conditions as nonan-5-one, to provide information on the fate of aldehydes in the autoxidation. In addition to the products observed from the ketone, this gave nonanoic acid and some octane but no aldol condensation products were detected. We conclude that the main reactions of aldehydes, formed during the autoxidation of nonan-5-one, involve initial removal of a hydrogen atom to give acyl radicals. These can react with oxygen to form acylperoxyl radicals and subsequently peroxyacids or decarbonylate to alkyl radicals which by hydrogen-atom abstraction give alkanes (Scheme 1).⁷ The peroxyacids react further with aldehydes to give acids (see below). The absence of aldehyde aldol condensation products in these oxidations suggests that this reaction is unimportant in the autoxidation of ketones, where the concentration of aldehydic products remains low.

Autoxidation of nonanoic acid

The rate of nonanoic acid autoxidation is very slow compared to that of nonan-5-one under the same conditions and it

Table 2 Total peroxide yields, as a function of oxygen consumption, in the autoxidation of nonan-5-one; 120 °C, 537 kPa oxygen

Oxygen consumption (%)	Peroxide yield/10 ⁻³ mol dm ⁻³
9.8	5
32.8	12
38.3	12
57.6	2
93.2	1
93.4	<1

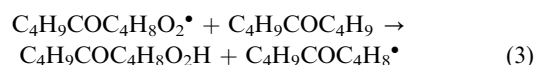
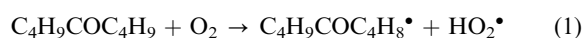


Scheme 1 Generation of alkyl and acylperoxyl radicals in the autoxidation of aldehydes.

generated very low yields of smaller carboxylic (ethanoic, propanoic, butanoic, pentanoic and hexanoic) acids. We conclude that the further oxidation of carboxylic acids formed in ketone autoxidation is of minor significance.

Mechanism of nonan-5-one autoxidation

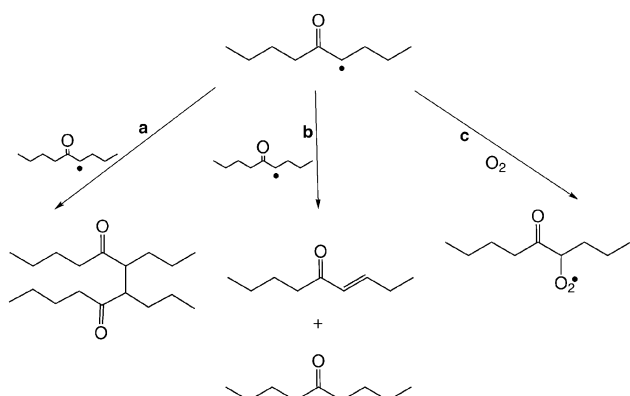
The generation of ketoalkyl and ketoperoxyl radicals. The primary steps in the autoxidation of ketones are effectively the same as for an alkane and involve a free radical chain reaction [Reactions (1)–(3)].



Hydrogen atom abstraction is expected to occur from all the C–H bonds, although the main site of attack is next to the carbonyl group to give the resonance-stabilised α -ketoalkyl radical (4).^{8,9} The self-reaction of ketoalkyl radicals and their trapping by oxygen to give ketoperoxyl radicals (illustrated for the α -ketoalkyl radical in Scheme 2) occur at close to diffusion rate. However, even at the start of the reaction, where the

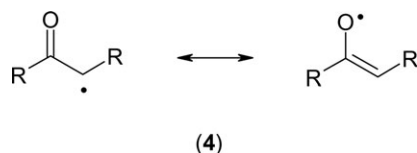
Table 3 Yields of products, with an intact carbon skeleton, and product ratios ($X_{\text{H}}/X_{\text{D}}$) from the autoxidation nonan-5-one and 4,4,6,6-[²H₄]-nonan-5-one at 96% oxygen consumption; 120 °C, 537 kPa oxygen

Autoxidation product	Yields from nonan-5-one/10 ⁻³ mol dm ⁻³	Yields from 4,4,6,6-[² H ₄]-nonan-5-one/10 ⁻³ mol dm ⁻³	Product ratio ($X_{\text{H}}/X_{\text{D}}$)
3-Hydroxynonan-5-one	5.3	4.8	1.1
4-Hydroxynonan-5-one	12	5.3	2.3
Nonane-2,5-dione	39	77	0.5
Nonane-4,5-dione	19	4.9	3.9
Nonan-3-en-5-one	7.0	3.4	2.0
Dehydro-dimers (2 and 3)	6.9 and 2.3	2.6 and 0.81	2.8 and 2.6



Scheme 2 Reactions of the α -nonan-5-one radical during the autoxidation of nonan-5-one.

oxygen concentration is at its highest ($3.4 \times 10^{-3} \text{ mol dm}^{-3}$), not all the ketoalkyl radicals are trapped by oxygen (Scheme 2, path c). In a typical reaction, the products from radical–radical dimerisation and disproportionation (Scheme 2, paths a and b), ketoalkyl radical dimers and nonan-3-ene-5-one, account for $\sim 3.0\%$ each of the ketone consumed.



Only one nonenone isomer was detected in the nonan-5-one autoxidation mixture. Using the α -deuterated ketone as substrate, this contained three deuterium atoms indicating the formation of the α,β -unsaturated compound, non-3-en-5-one, presumably as the (*E*)-diastereoisomer. This product is expected from disproportionation of the major ketoalkyl radical, α to the carbonyl group, although it can also be formed from the β -radical where disproportionation would be expected to give the conjugated α,β -enone in preference to the β,γ -isomer.

The formation of the ketoalkyl radical dimers. The two ketoalkyl radical dimers in the autoxidation of nonan-5-one have identical EI mass spectra (Fig. S6 and S7[†]), suggesting that they are a pair of diastereoisomers. The equivalent products from the autoxidation of 4,4,6,6-[$^2\text{H}_4$]-nonan-5-one each contain six deuterium atoms identifying the compounds as arising from the self-reaction of two α -ketoalkyl radicals, the *meso*-compound **2** and the racemate **3**. In a previous study on the autoxidation of neopentyl butanoate,¹⁰ we also identified dehydro-dimer products (GC-MS, ^1H NMR spectroscopy and X-ray crystallography), the major pair also arising from self-reaction of the radical α to the carbonyl group.

To confirm the structures of the ketone dehydro-dimers, an authentic sample of the mixture of α,α -diastereoisomers was obtained from the thermolysis of di-*tert*-butyl peroxide (DTBP) in nonan-5-one at 160°C , under nitrogen. This approach of using radical initiators to synthesise dimers has been used extensively by Coffman *et al.*¹¹ to make diesters, dicarboxylic acids, dihalides and diamines and by ourselves to make dimers from a series of neopentyl esters.¹⁰

Four pairs of product peaks were observed by GC-MS analysis of the DTBP reaction (labelled as compounds **A1**, **A2**, **B1**, **B2**, **C1**, **C2**, **D1** and **D2** in Fig. 2), each of which has a molecular ion of m/z 282, characteristic of the ketone dehydro-dimers. In addition, the EI-MS fragmentation patterns of **B1** and **B2** are identical, as are those of **C1** and **C2**, and **D1** and **D2** but not those of **A1** and **A2**. The fragmentation patterns of each pair are, however, different from those of the other pairs, *i.e.* the spectra of **C1** and **B1** are not identical (Figs. S8–S15[†]). The GC retention times and MS-EI fragmentation patterns of the major products, **B1** and **B2**, are identical to those of **2** and **3**, formed in the autoxidation reaction.

A small sample of a mixture of **2** and **3**, free from the other isomers, from the DTBP reaction in nonan-5-one, was isolated by chromatography and analysed by ^1H NMR spectroscopy. This revealed two multiplets (δ 2.87 and 2.76 ppm) each characteristic of a single proton α to the carbonyl group of the α,α -dehydro-dimer diastereoisomers [*meso*- and (\pm) *threo*-6,7-dipropyldodecane-5,8-dione, **2** and **3**]. Attempts to separate and isolate the single diastereoisomers were unsuccessful and, due to their low yields, all attempts to purify the minor products **A1**, **A2**, **C1**, **C2**, **D1** and **D2** were also unsuccessful.

The deuterium content of the dehydro-dimers from the DTBP reaction in the deuterated nonan-5-one showed that **C1**, **C2**, **D1** and **D2**, each of which contained seven deuterium atoms, arise from crossed α,β and α,γ radical couplings. That no dimer with eight deuterium atoms was detected rules out any β,β , β,γ or γ,γ radical couplings. Surprisingly, however, two pairs (**A1** and **A2**, and **B1** and **B2**) were labelled with six deuterium atoms expected for α,α -isomers. Thus **A1** and **A2**, like **B1** and **B2**, must arise from the combination of two α -ketoalkyl radicals. We suggest they are the *E* and *Z* isomers formed by carbon to oxygen dimerisation (Scheme 3). It is noteworthy that in the EPR spectra of α -ketoalkyl radicals typically 10–15% of the spin density lies on the oxygen.¹² Thus all the radical dimer products detected involve at least one α -radical, presumably because the *tert*-butoxyl radical preferentially abstracts the α -hydrogen atom resulting in a high concentration of the α -radical relative to the β - and γ -analogues. The absence of the α,δ -coupling product, which would have

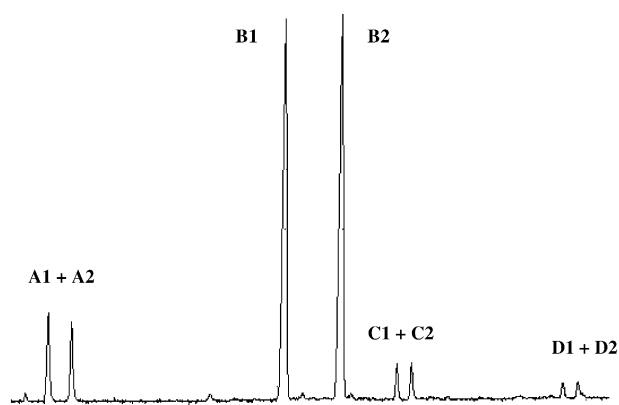
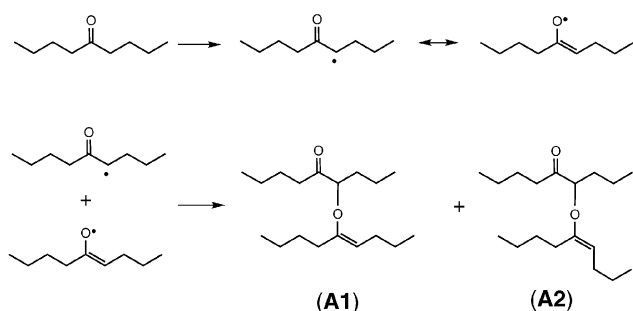


Fig. 2 GC trace of the eight ketone dehydro-dimers, **A1**, **A2**, **B1**, **B2**, **C1**, **C2**, **D1** and **D2** formed during the thermolysis of DTBP in nonan-5-one, at 160°C under nitrogen.



Scheme 3 Possible mechanism for the formation of carbon to oxygen dimers (A1 and A2) of α -ketoalkyl radicals.

given a single peak in the GC analysis, can be accounted for by the low reactivity of the primary C–H bonds.

It is interesting to note that the thermolysis of DTBP in nonan-5-one gives four pairs of radical dimers, whereas only one pair was observed in the autoxidation of the ketone. We attribute this to peroxy radicals being the main hydrogen atom abstracting species in the autoxidation. Peroxy radicals, being more selective than *tert*-butoxyl, should show a very marked preference for the α -position of the ketone. Thus the only significant dimers would be A1, A2, B1 and B2. Further oxidation of A1 and A2 either *via* hydrogen atom abstraction or by addition to the vinyl ether accounts for their absence in the product mixture.¹³

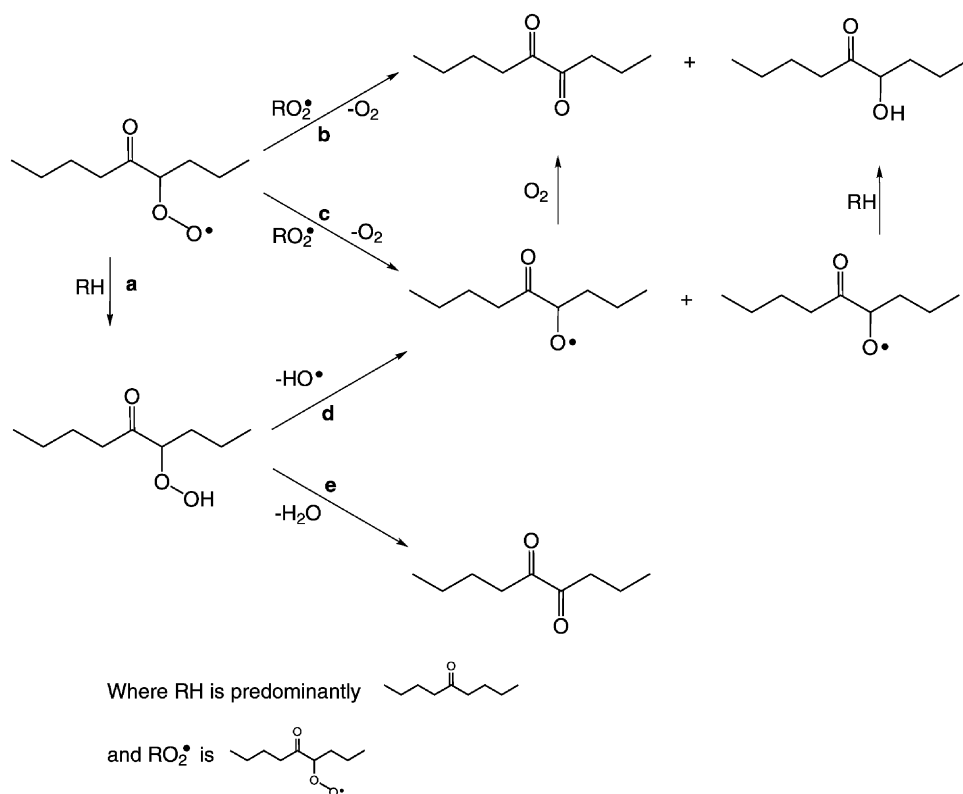
Reactions of peroxy radicals and hydroperoxides of nonan-5-one. In the temperature regime used in these investigations, ketoperoxy radicals would mainly undergo hydrogen atom

abstraction from the substrate to form a ketone hydroperoxide and self-reactions to give diketone and ketoalcohol or ketoalkoxyl radicals (paths a, b and c in Scheme 4, illustrated for nonan-5-one 4-hydroperoxyl radical).^{4b,14} Subsequent reactions of the hydroperoxides would lead, by homolysis, to ketoalkoxyl radicals (path d) or, by loss of water, to diketones (path e).

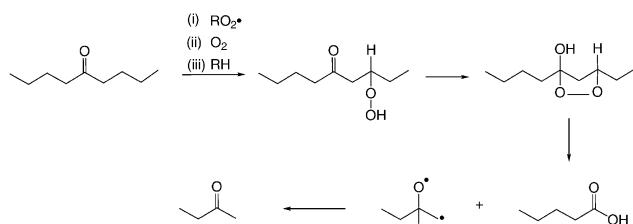
The nonan-5-one autoxidation mixture contains both the 2,5- and the 4,5-dione, from the γ - and α -hydroperoxides, respectively, but nonane-3,5-dione from the β -isomer was not detected. Earlier work by Riff *et al.*,¹⁵ on the autoxidation of undecan-6-one, also failed to detect the corresponding 1,3-dione, undecane-4,6-dione, and the authors suggested that this may arise from the rapid oxidation of the methylene group α to both carbonyl groups and subsequent oxidative decomposition. Another possible explanation for the absence of the 3,5-dione, based on a mechanism proposed by Aldrich *et al.*¹⁶ for the formation of methyl ketones in the autoxidation of polyol esters, is that the β -hydroperoxide is involved in an intramolecular reaction in preference to dehydration (Scheme 5). Fragmentation of the resulting cyclic peroxide would lead to butanone, which was observed in the oxidation mixtures.

Reactions of ketoalkoxyl radicals. The two main pathways to the α -, β - and γ -ketoalkoxyl radicals are paths c and d in Scheme 4. No evidence for δ -radical, from attack on the primary C–H bonds was observed.

The expected reactions of these radicals are hydrogen atom abstraction and fragmentation. The former leads to the observed α - and β -hydroxyketones. The absence of the γ -isomer, 2-hydroxynonan-5-one, is attributed to the favourable



Scheme 4 Reactions of nonan-5-on-4-ylperoxy radicals in the autoxidation of nonan-5-one.



Scheme 5 A route to butanone during the autoxidation of nonan-5-one based on a mechanism proposed by Aldrich *et al.* for polyol ester autoxidation.²²

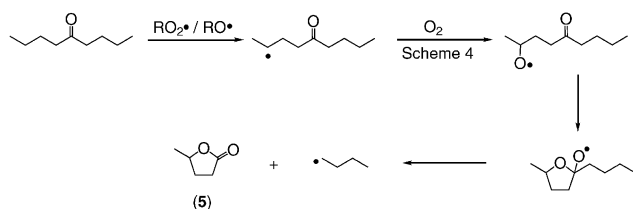
competitive intramolecular cyclisation of the ketoalkoxyl radical followed by fragmentation to give the lactone of 3-hydroxypentanoic acid, 4,5-dihydro-5-methyl-2(3*H*)-furanone (**5**), detected in the product mixtures (Scheme 6).

All three ketoalkoxyl radicals undergo fragmentation of the carbon skeleton. Cleavage of the α -radical is the main pathway of ketone autoxidation and in this instance it gives the pentanoyl radical and butanal. The predominant reaction of the former is with oxygen to give peroxy-pentanoic acid: a minor pathway involves decarbonylation (*cf.* the autoxidation of nonanal, above). Some of the butanal escapes into the gas phase in the reactor; however, the main fate of the aldehydes is oxidation by oxygen transfer with peroxyacids¹⁷ which in this instance gives butanoic and pentanoic acids (Scheme 7).

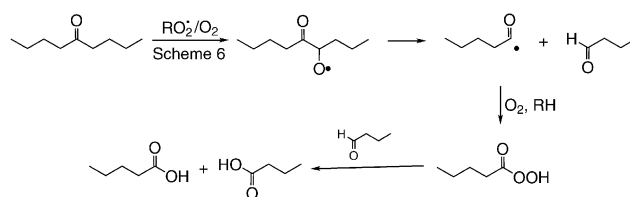
The peroxyacids can also bring about a Baeyer–Villiger reaction with nonan-5-one to form butyl pentanoate. This is likely to be the major route to this ester rather than the alternative reaction between the products butanol and pentanoic acid since no butyl butanoate from butanol and butanoic acid was detected.

Butanoic and pentanoic acids account for 66% of the products formed on a mole for mole basis. Interestingly the observed 1:1 ratio of butanoic to pentanoic acids is that predicted from the mechanism in Scheme 7 (the small amounts of aldehyde and pentanoyl radical that escape this reaction have a negligible effect on this ratio). Riff *et al.*,¹⁸ in their studies on the oxidation of the four symmetrical ketones, heptan-4-one, nonan-5-one, undecan-6-one and tridecan-7-one, found a greater proportion of the longer chain carboxylic acid (ratio 1.35–1.49). The difference in acid ratios from the two investigations, may arise from the improved GC analysis used in the present study (capillary *versus* packed columns). In support of this conclusion, Riff *et al.*¹⁵ reported only ten products from the autoxidation of undecan-6-one compared with more than thirty in this study.

Fragmentation of the β - and γ -ketoalkoxyl radicals leads to aldehydes, propanal and ethanal, and 2-oxohexan-1-yl and



Scheme 6 Formation of 4,5-dihydro-5-methyl-2(3*H*)-furanone (**5**) during the autoxidation of nonan-5-one.

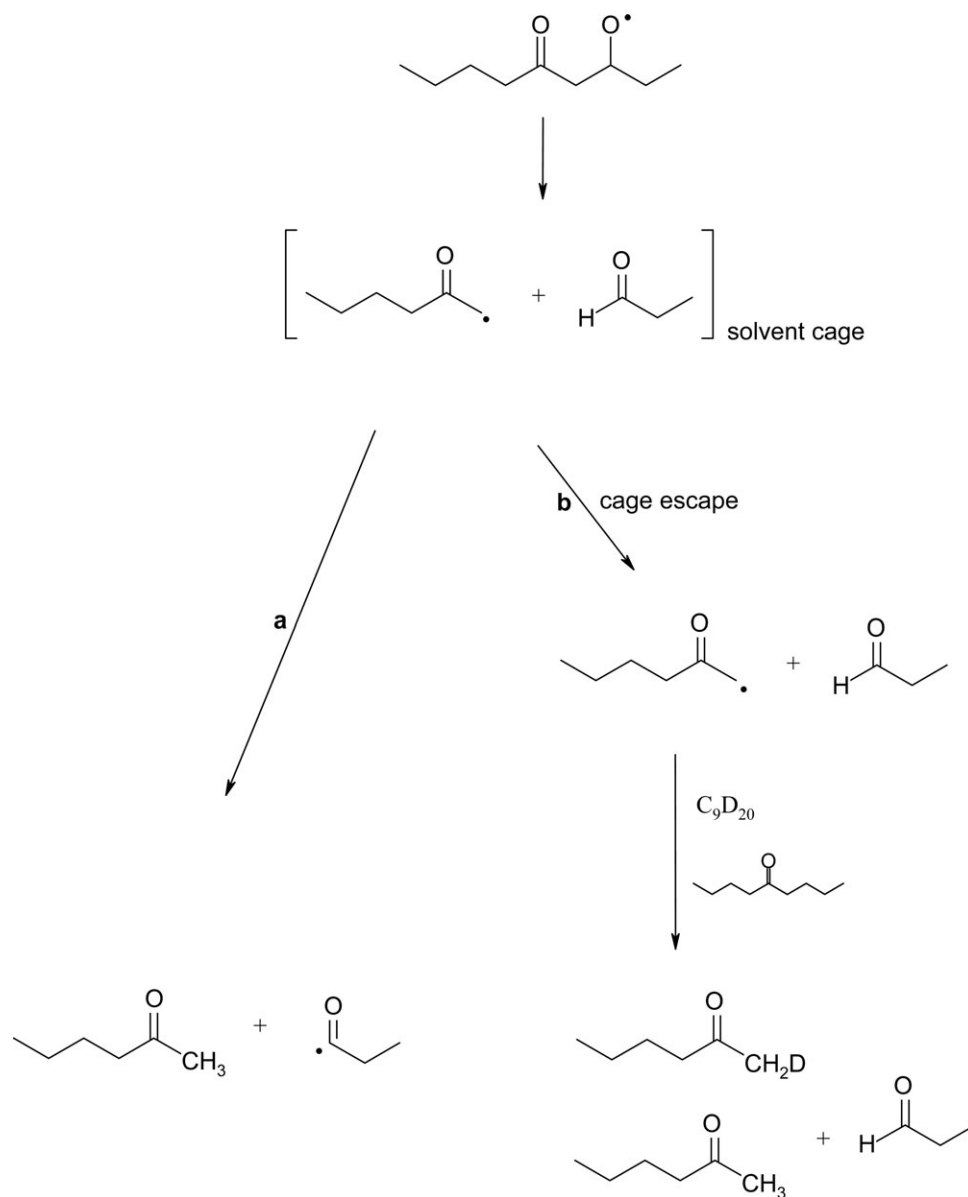


Scheme 7 Formation of pentanoic and butanoic acids during the autoxidation of nonan-5-one.

3-oxoheptan-1-yl radicals, respectively. The ketoalkyl radicals react with oxygen or alternatively abstract hydrogen atoms, the latter route leading to hexan-2-one and heptan-3-one detected. It was presupposed that reaction with oxygen should dominate due to its much larger rate constant and it was therefore surprising to detect noticeable amounts of products formed by hydrogen atom abstraction by ketoalkyl radicals in the reaction. Since the ketoalkyl radicals from fragmentations are formed in the close vicinity of aldehydes it was argued that hexan-2-one and heptan-3-one could form *via* hydrogen atom transfer within a solvent cage. This mechanism was investigated by carrying out the reaction in perdeuteriononane as solvent. If hydrogen atom transfer takes place within a cage environment, there will be no deuterium incorporation into hexan-2-one (Scheme 8, pathway a), whereas diffusion from the cage followed by hydrogen/deuterium abstraction from nonan-5-one or the solvent would lead to both ketone and deuteroketone (Scheme 8, pathway b). Analysis of the product hexan-2-one showed it to contain significant deuterium label. Since the relative yields of labelled and unlabelled hexan-2-one, in the cage-free reaction, will depend on the relative concentrations of nonan-5-one and perdeuteriononane, the reaction was investigated using two different ketone concentrations. A 3.2-fold increase in the undeuterated ketone concentration (from 0.6 to 1.9 mol dm⁻³) led to an almost equal increase (3.6-fold) in the hexan-2-one/1-[²H₁]-hexan-2-one ratio (from 1.4 to 5.0). We conclude that the major proportion of hydrogen abstraction takes place outside the cage environment.

Formation of carbon oxides, hydrocarbons, alcohols and acids. Carbon monoxide and dioxide arise from the decarbonylation and decarboxylation of acyl or carboxyl radicals, respectively. The former are produced by hydrogen abstraction from aldehyde products, and the latter by the homolysis of peroxyacids. The alkyl radicals from these reactions and butyl, arising from the minor fragmentation pathway of cyclised γ -ketoalkoxyl radicals (Scheme 6), can undergo hydrogen atom abstraction, dimerisation and disproportionation to give alkanes and alkenes. In competition with these reaction, trapping by oxygen gives alkylperoxyl radicals which react further to give alcohols and acids.

The formation of small hydrocarbon fragments from the autoxidation of alkanes is not extensively reported in the literature since most liquid phase oxidation studies do not investigate gas phase products. Furthermore, since they are normally carried out in an open reactor with a continuous flow of oxygen, the volatile products are lost. Hydrocarbons were, however, observed in our earlier studies on ester autoxidation in a closed reactor.¹⁹



Scheme 8 Alternative cage and non-cage pathways for the formation of hexan-2-one during the autoxidation of nonan-5-one in perdeuterononane.

The effect of deuteration on the autoxidation profile

The ratio of the product yields from the autoxidation of nonan-5-one and its α -deutero analogue (X_H/X_D), at equivalent stages in the reaction (96% oxygen consumption) is shown in Table 3. Although these values are not equivalent to the more conventional kinetic isotope effects (k_H/k_D), they are related to them and provide useful mechanistic information on the autoxidation. To avoid problems arising from products that can be formed by multiple pathways (typically fragmentation products) only the compounds with an intact nonan-5-one carbon skeleton are considered here.

Because there is competition between the α , β and γ -C-H bonds of nonan-5-one for the attacking radicals, deuteration of the α -hydrogen atoms favours attack on the β - and γ -positions (reverse isotope effect, X_H/X_D , < 1) at the expense of the α -C-H bonds (normal isotope effect, X_H/X_D , > 1). Thus formation of

nonane-2,5-dione shows a reverse isotope effect (X_H/X_D , 0.5) whereas normal isotope effects of between 2.0 and 2.8 were obtained for 4-hydroxynonan-5-one, nonan-3-en-5-one and dehydro-dimer formation. The magnitude of the isotope effect also depends on the number of deuterium atoms removed to form the product, accounting for the larger isotope effect for nonane-4,5-dione which requires two C-D bonds to be broken (X_H/X_D , 3.9, effectively 2.0 for each C-H bond). The explanation for the anomalous small positive isotope effect for 3-hydroxynonan-5-one (X_H/X_D , 1.1) remains unclear.

To our knowledge, kinetic isotope effects for hydrogen-atom abstraction from the α -C-H bonds of ketones by alkoxy or peroxy radicals (k_H/k_D) have not been reported. However, bearing in mind the higher temperature²⁰ of the present study, the X_H/X_D values obtained here are consistent with those for other substrates, measured at 30–40 °C, which typically lie in the range 2.4 to 11.5.^{14a,21}

Overall selectivity of the autoxidation of nonan-5-one

Following the abstraction of a hydrogen atom from the substrate, the resultant carbon centred radical is consumed in four competitive reactions (radical coupling and disproportionation, hydrogen atom abstraction and oxygen addition). Comparison of the relative yields of the products from each of these reactions shows that 62% of the products arise from α -attack, with 21 and 17% from reactions at the β - and γ - positions, respectively. No products from reaction of the primary C–H bonds were detected.

The regioselectivity of hydrogen-atom abstraction from a substituted alkane is determined by a number of factors including the philicity of the attacking radical, the electronic effect of the substituent, the exothermicity of the process and the stability of the product radical.²² Although peroxy and alkoxy radicals are both electrophilic,^{20,23} the reactions of the latter are significantly more exothermic. The result is that hydrogen abstraction by alkoxy radicals has an early transition state where polar effects are important,^{22,24,25} whereas that of peroxy radicals is late. Consequently the regioselectivity for peroxy radicals is determined more by the stability of the radicals formed than by polar effects,²⁶ favouring attack at the α -position to give the resonance stabilised radical (4).

The observed regioselectivity of the nonan-5-one autoxidation (a preference for the α -position with an approximately equal reactivity of the β - and γ -positions) suggests that the dominant hydrogen atom abstraction reactions are those of the peroxy radicals. Further support for this comes from the absence of detectable products from attack on the primary hydrogens (δ -position). Based on the selectivity of hydrogen-atom abstraction by the *tert*-butoxy radical (primary : secondary selectivity $\sim 1 : 10$ at 40 °C^{23a,27}), alkoxy radicals would be expected to give detectable amounts of products from the primary C–Hs of nonan-5-one. However, peroxy radicals being more selective²⁸ would give significantly less attack on the primary hydrogens and these products are likely to have been below the detection limit.

Conclusions

(1) The liquid and gas phase products from the autoxidation of nonan-5-one, in a sealed micro-reactor, provide a significant insight into the reaction mechanisms of ketone autoxidation.

(2) The products include compounds with an intact carbon skeleton and those arising from fragmentations, with the latter being dominant.

(3) Oxidation occurs at all the secondary C–H bonds with a preference for the α -position. It is worth noting, however, that for a much longer chain ketone statistical factors would outweigh this regioselectivity so that non- α attack would predominate.

(4) It is interesting to note that even in an oxygenated environment some of the alkyl radicals, formed in fragmentation, decarbonylation and decarboxylation reactions, escape being trapped by oxygen and are detected as hydrocarbons.

(5) The oxidation mechanisms proposed show strong parallels with those of alkane autoxidations and involve ketone, ketoalkylperoxy and ketoalkoxy radical intermediates.

(6) That ketones are autoxidised predominantly to carboxylic acids has important implications for the oxidative degradation of alkane-based lubricants in combustion engines, where the formation of acids can have a strong corrosive effect.

Experimental

Methods

Apparatus. All the autoxidations were carried out in a stainless steel autoclave (internal volume 4.85 cm³), described previously.^{10,19,29} At the end of the reaction the autoclave was cooled, connected to a vacuum line and a gas sample was transferred *via* a sample loop for GC analysis. The autoclave was opened and liquid samples were removed for analysis by GC.

Instrumentation. GC analyses were performed on two temperature programmed Pye Unicam gas chromatographs, a model PU4500 fitted with thermal conductivity and flame ionisation detection systems and a GCD with flame ionisation detection. Data acquisition and manipulation were carried out using a PC running the JCL6000 software 2.0 for Windows and with a Trio Trivector integrator. The liquid phase oxidation products were separated on a Carbowax 20 M capillary column (30 m, 0.25 mm id, 0.25 μ m film thickness) (Alltech); the gas phase organic compounds on a GS-Q capillary column (30 m, 0.32 mm id) (J and W Scientific) and oxygen and the carbon oxides on Carbosieve SII (Supelco) with a Tenax TA (Supelco) pre-column (3 m, 3 mm id). Quantification was achieved using authentic materials and chlorobenzene as the internal standard. Where authentic compounds were not available, response factors were obtained using the effective carbon number concept.³⁰

¹H and ¹³C NMR spectra were obtained on JEOL EX270 (270 MHz) and Bruker AMX 500 spectrometers (500 MHz) with tetramethylsilane as an internal standard.

GC-EI and GC-CI mass spectra were obtained with a VG AutoSpec, S Series A027 mass spectrometer coupled to a Hewlett Packard 5890 Series II gas chromatograph. Data collection and processing were carried out with a VAX3100 workstation.

Peroxide analyses. The levels of hydroperoxides in autoxidation mixtures were determined by reducing them to alcohols, with triphenylphosphine,^{19,31} and measuring their yields by comparing GC chromatograms before and after this treatment. Total hydroperoxide and peroxyacid yields were determined colorimetrically, as iodine from the oxidation of iodide ions under acidic conditions, by the method of Banerjee and Budke.³²

Determination of the oxygen concentration in nonan-5-one. Nonan-5-one (0.29 mmol) was thoroughly degassed with stirring under vacuum in the micro-reactor and then, with the stirrer turned off, oxygen was introduced to a pressure of 100 kPa into the headspace above the liquid. The stirrer was turned on and the resulting pressure drop, due to the dissolution of oxygen in the nonan-5-one, was measured.

Materials

All compounds were obtained from commercial suppliers and used without further purification unless stated otherwise. Perdeuteriononane (98 atom%) was from Aldrich. Nonan-5-one was purified by passing it through a dry alumina column (activated, neutral, Brockmann I, standard grade, *ca.* 150 mesh) prior to use. Tetrahydrofuran was dried with sodium wire and distilled immediately prior to use.³³

4,4,6,6-[²H₄]-Nonan-5-one was synthesised from nonan-5-one and deuterium oxide (Goss Scientific Instruments Ltd.; 99.7 atom% D) by the method of Hammond *et al.*³⁴ Nonan-5-one (10 cm³), purified by column chromatography, was added to a stirred solution of deuterium oxide (44 cm³), 2,2-dimethoxypropane (126 cm³), and anhydrous sodium carbonate (2.23 g). After heating for 16 h at reflux, the nonan-5-one was recovered by extraction into ethoxyethane and solvent removal and the deuteration experiment was repeated. Extraction with ethoxyethane, drying (MgSO₄) and distillation gave 4,4,6,6-[²H₄]-nonan-5-one, ~98 atom% by ¹H NMR analysis; tetradeuteroketone (88%) and trideuteroketone (12%) by EI-MS.

Authentic samples of hydroxynonan-5-ones and nonanediones for GC and GC-MS identification of products were prepared by standard literature procedures. 2-Hydroxynonan-5-one was prepared by the reaction of *n*-butyl lithium with 4,5-dihydro-5-methyl-2(3*H*)-furanone in anhydrous tetrahydrofuran;³⁵ MS(EI) *m/z* 158(1), 145(5), 129(4), 103(14), 85(83), 59(56), 58(96), 57(65), 43(100). 3-Hydroxynonan-5-one was obtained from a crossed aldol reaction by the addition of propanal to hexan-2-one in the presence of lithium di-isopropylamide;³⁶ MS(EI) *m/z* 158 (1, M), 116 (25), 101 (46), 85 (55), 83 (57), 72 (35), 59 (47), 58 (83), 57 (90), 55 (100), 43 (64). 4-Hydroxynonan-5-one was synthesised by basic hydrolysis (KOH) of 4-bromononan-5-one,³⁷ prepared by bromination of nonan-5-one with trimethylsilyl bromide–dimethyl sulfoxide;³⁸ MS(CI) *m/z* 176 (100, MNH₄⁺), 159 (48, MH⁺), 141 (21), 85(10). Nonane-4,5-dione and nonane-2,5-dione were prepared by oxidation of the corresponding hydroxynonan-5-one with acid dichromate;³⁹ 4,5-dione MS(EI) *m/z* 156 (10), 127 (1), 114 (1), 85 (100), 71 (94), 57 (100), 43 (80), 41 (45), and 2,5-dione MS(EI) *m/z* 156 (1), 114 (22), 99 (32), 85 (22), 71 (37), 57 (49), 43 (100), 41 (35).

The α,α-dehydrodimers of nonan-5-one were obtained by reacting the ketone (5.8 mmol) with di-*tert*-butyl peroxide (0.44 mmol) in the autoclave at 160 °C under a nitrogen atmosphere for 16 h. The unreacted starting material was removed by vacuum distillation and the α,α-dehydrodimers (~10%) were separated from the residue by column chromatography on silica gel with dichloromethane; δ_H (CDCl₃) 0.91 (12H, m), 1.21 (8H, m), 1.43 (8H, m), 2.35 (8H, m), 2.73 (1H, m), 2.84 (1H, m); MS(EI), *m/z* 282 (1), 253 (1), 240 (2), 225 (21), 197 (9), 155 (37), 141 (17), 113 (17), 100 (8), 85 (100), 57 (77), 41 (36).

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