Expanded product, plus kinetic and mechanistic, studies of polyoxoanion-based cyclohexene oxidation catalysis: the detection of ~70 products at higher conversion leading to a simple, product-based test for the presence of olefin autoxidation

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Abstract

First, catalyst variation and solvent optimization studies are reported for polyoxoanion-supported transition-metal pre-catalysts, novel complexes such as $[(1,5\text{-COD})Ir^I \cdot P_2W_{15}Nb_3O_{62}]^{8-}$, $[(C_6H_6)Ru^{II} \cdot P_2W_{15}Nb_3O_{62}]^{7-}$ and $[(OC)_3Re^I \cdot P_2 W_{15}Nb_3O_{62}]^{8-}$, catalyzing cyclohexene oxidation at low ($\leq 25\%$) conversion with O_2 to, predominatly, four main autoxidation products: 2-cyclohexen-1-yl hydroperoxide, 2-cyclohexen-1-one, 2-cyclohexen-1-ol, and cyclohexene oxide, all at a mass balance of ≥ 80–92% under the low conversion conditions. Next, radical-chain initiator, inhibitor, and other kinetic (rate law) evidence for the reaction behaving, at lower conversions, as classical Haber–Weiss autoxidation was obtained. Those studies lead, in turn, to the study of cyclohexene autoxidation at higher conversions, notably the identification of ca. 70 gas chromatography (GC)-detectable products. This was followed by identification of 27 of those ca. 70 products, the first reported detailed identification of more than 8–10 products of cyclohexene autoxidation. These results led, in turn, to the five main findings of this study: (i) product and kinetic—overall compelling—evidence that the main reaction is free-radical-chain autoxidation; (ii) the first detection of ca. 70 cyclohexene autoxidation products, followed by the identification of 27 of those products—this is not trivial given that complete product studies are the required first step of rigorous mechanistic work; (iii) plausible arrow-pushing mechanisms to many of the observed products using known radical chemistry—previously unavailable schemes; (iv) the observation of chlorinated hydrocarbons among the products, results which require the precedented participation in the oxidation catalysis by CH_2Cl_2 solvent-derived, $^\bullet CHCl_2$ radicals, and perhaps most significantly (v) the development of a relatively simple and quick, yet definitive, GC and GC–MS fingerprint method for detecting autoxidation catalysis using the prototype olefin, cyclohexene. Such product studies should prove to be a useful tool in the continuing problem of detecting, or ruling out, classical autoxidation in attempts to develop new oxidation chemistry using O_2 as a highly desirable terminal oxidant.
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Keywords: Detection of autoxidation; Oxidation catalysis; Cyclohexene autoxidation catalysis; Catalysis with molecular oxygen; Polyoxoanions in catalysis; Homogeneous catalysis; Kinetic and mechanistic studies; Free-radical-chain mechanisms

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1. Introduction

Autoxidation is the series of elementary, radical-chain reactions which occurs when organic compounds react with molecular oxygen in the liquid phase and at temperatures generally <150–200 °C to yield alkylhydroperoxides, alcohols, aldehydes, ketones, acids and other products [1,2]. Autoxidation has been around as long as organic compounds have been exposed to O_2; autoxidation is a central pathway for the oxidative degradation of fats, plastics, gasoline, lubricating oils, rubber and other common organic compounds; hence, it is of fundamental significance. It is, as a referee noted, "almost unavoidable." Autoxidation is also of practical importance for the synthesis of selected industrial organic chemicals from petroleum [3], Table 1, and in promoting desirable reactions such as the drying of paints.

Autoxidation's inherent significance means this topic has been widely investigated since the 1930s, resulting in numerous reviews, including more recent reviews [4]. Additional publications covering hydrocarbon autoxidation have appeared within the last 20 years as well[1] [5].

Knowledge about and, ultimately, the ability to detect and control[2] autoxidation is, therefore, of central importance in both the stability of organic compounds under atmospheric oxygen as well as in the quest to develop modern, more selective, non-autoxidation routes for the selective *oxygenation* of organic molecules. Unfortunately, autoxidation often seems to go undetected by at least less experienced researchers in oxidation chemistry—despite the well-precedented prevalence of autoxidation [4,5]. There are, however, well-recognized tests for autoxidation of olefins, notably: (i) the presence of alkylhydroperoxide products

and the allylic alcohol to allylic ketone to epoxide product ratios; (ii) various kinetic tests (variable induction periods, inhibition or initiation by free-radical-chain inhibitors or initiators; or inhibition by $CBrCl_3$ with the formation of halogenated products, for example) [4,5]. But even with these classic tests autoxidation continues to go undetected, with claims for new types of oxidation chemistry continuing to appear, so that a body of literature correcting these claims and trying to develop additional, even easier to use, diagnostics or probe molecules for the participation of free-radicals in oxidation chemistry is available [6]. In this regard, additional simple, readily applicable tests for the presence of autoxidation are always important.[3] The present work will show that a GC trace plus GC–MS of the products at higher conversion for the prototype olefin cyclohexene is just such a diagnostic, arguably as simple, yet as definitive, a single diagnostic for autoxidation as is presently available.

Detecting autoxidation, as well as figuring out how to control it if not avoid it, is important since new oxidation catalysts are still of considerable interest [1,2,7]. This is particularly true if the new catalysts are all inorganic and thus oxidation resistant (for lead references to polyoxometalate in oxidation catalysis

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[1] Note that the autoxidation literature cited [4,5], while seemingly extensive, is actually *only a selection* of a more voluminous literature. A summary (Table S1) of 30 additional references since 1996 on cyclohexene autoxidation *alone* is available from the authors by request and as supplementary materials. Hence, the references cited have been restricted to the papers that we found most useful is attempting to answer definitively the question "is the oxidation catalysis we are seeing autoxidation or not?"

[2] One important, commercialized autoxidation reactions is duPont's $Co^{II/III}$ plus O_2 autoxidation of cyclohexane to adipic acid [4v]. Of interest here is the fact that this reaction produces >100 products (by GC) under non-optimized conditions, yet is still commercially viable.
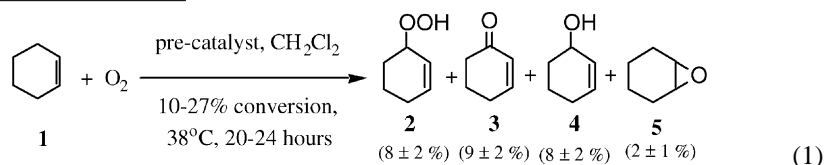
[3] Interestingly, two referees—both obviously quite knowledgeable in autoxidation and its detection—commented that "The problem is to prove that a given oxidation reaction of interest *does not* proceed through autoxidation" and "The issue is to prove that you do not have any autoxidation (not to prove its presence) or to demonstrate a system in which you completely avoid it." Although, obviously well-intended, we find these comments conceptually confused. One never proves anything in science; instead and as Platt has reminded us [J.R. Platt, Science 146 (1964) 347] science is about *disproof of alternative hypotheses*, thereby offering support for the original hypothesis. Hence, the best one can hope to do is develop systems that do apparently only dioxygenase or monooxygenase oxygenation chemistry, but then also subject them to the methods and probes others have developed [6] and to experiments employing easily autoxidized olefins, such as the cyclohexene used herein, to test for their ability to do autoxidation under the specific conditions employed. Only if those tests disprove the alternative hypothesis (i.e., that "autoxidation ability is present and can be kinetically dominant under the chosen reaction condition") will one be in a position to claim that autoxidation is not occurring. Note that this disproof is, ultimately, kinetic in nature. However, the present work emphasizes that all studies must be conducted under conditions where one first establishes the *complete* stoichiometry and mass balance of the reaction(s) being studied—such stoichiometry and mass balance being the first requirement of rigorous mechanistic work.

Table 1
Major industrial autoxidations of hydrocarbons [3]

Hydrocarbons	Oxidation products	Applications
Cyclohexane	Cyclohexanol, cyclohexanone	Converted to adipic acid and caprolactam (polyamide precursors)
Cyclododecane	$C_{12}H_{23}OH$ and $C_{12}H_{22}O$	Oxidized to dodecanedioic acid and lauryl lactam (polyamide precursors)
Butane	Acetic acid	Solvent, vinyl acetate polymers
Toluene	Benzoic acid	Caprolactam (polyamide precursors), phenol, food preservative
Toluene	Benzaldehyde	Agrichemicals, flavorings, and fragrances
m-Xylene	Isophtalic acid	Polymers and plasticizers
p-Xylene	Terephtalic acid, terephtalate esters	Polyester fibers, films, plastics, and plasticizers

see [8a]; for lead references and reviews in polyper-oxotungstatophosphates see [9a]). Detecting autoxidation is also important if the new catalysts utilize the preferred oxidant O_2, namely autoxidation, with a leading class of oxidation-resistant precatalysts, namely polyoxoanions.

$$\text{1} + O_2 \xrightarrow[\substack{10\text{-}27\% \text{ conversion,} \\ 38\,^{\circ}C, \; 20\text{-}24 \text{ hours}}]{\text{pre-catalyst, } CH_2Cl_2} \quad \underset{(8\pm2\,\%)}{\text{2}} + \underset{(9\pm2\,\%)}{\text{3}} + \underset{(8\pm2\,\%)}{\text{4}} + \underset{(2\pm1\,\%)}{\text{5}} \qquad (1)$$

preferred oxidant dioxygen [8,9] in dioxygenase type catalysis that, by definition, does not involve autoxidation (for lead references using polyoxometalates and dioxygen see [10a]).

Our own interests in oxidation chemistry have focused in the area of polyoxometalate-based all-inorganic oxidation catalysts [13], with an ultimate goal on the development of dioxygenase catalysis [14]. In 1993–1994 we reported the first examples of polyoxoanion-supported catalyst precursors (in other work we have shown that $(n\text{-}Bu_4N)_5Na_3[(1,5\text{-}COD)Ir\cdot P_2W_{15}Nb_3O_{62}]$ is a precatalyst for hydrogenation, leading to novel polyoxoanion-stabilized nanoclusters [15c,d]), a patent [15a] and then a *Journal of Catalysis* paper [15b] reporting that polyoxoanion-supported metal complexes, such as $[(1,5\text{-}COD)Ir\cdot P_2W_{15}Nb_3O_{62}]^{8-}$, are effective precatalysts for O_2-based oxidation chemistry (Eq. (1)) at lower conversions ($\leq 25\%$). Based on initial product studies (e.g., the finding that 2-cyclohexen-1-one and 2-cyclohexene-1-ol are among the primary products due, in part, to the expected decomposition of Russell, cyclohexenyl–OO–OO–cyclohexenyl, intermediates [16]), we noted in our original paper the likely presence of autoxidation catalysis [15b]. The work that follows is, therefore, of further fundamental interest in that it examines the most common type of oxidation chemistry of

Following a careful analysis of the autoxidation literature, we realized that six important goals remained following our earlier work [15] and in autoxidation catalysis in general: (a) to provide unequivocal evidence for, or against, free-radical-chain autoxidation chemistry for our (and by implication, other analogous) polyoxoanion-based oxygenations using dioxygen; (b) to undertake a modern, detailed evaluation of the products resulting from autoxidation reactions at *higher* conversion and by capillary GC, GC–MS and other methods (such as reductions with $NaBH_4$, $LiAlH_4$, or derivatizations with volatilizing $–SiMe_3$ groups, followed by GC and GC–MS)—as this had never been done and since it became apparent, as our studies proceeded, that this might prove to be highly diagnostic of olefin autoxidation; (c) to examine products in different solvents (e.g. especially in the often-used chlorinated hydrocarbon solvents) to see if those product studies indicate the expected participation of solvent-derived radicals; and (d) to achieve, overall, a modern study illustrating a viable approach to detecting autoxidation unequivocally, ideally a fairly complete study that might help others in their own, similar attempts to detect and quantitate autoxidation. Our long term goal is to detect, understand and then control autoxidation en route to developing highly selective and active *dioxygenase* catalysts

for commodity scale reactions such as 2 propylene + $O_2 \rightarrow$ 2 propylene oxide (a lead reference to recent propylene epoxidation studies with a $Au/TiO_2/O_2/H_2$ catalyst system is [17b]) or 2 benzene + $O_2 \rightarrow$ 2 phenol, such targets being Holy Grail [5] of oxygenation chemistry using dioxygen [14,17].

Two other unanswered questions, and thus outstanding research goals following our initial publication [15b], were: (e) to see whether or not additional evidence could be obtained in support of our initial finding [18] that the true catalyst is actually a *polyoxoanion-supported catalyst*, a point of conceptual significance since polyoxoanion-supported catalysts such as $[(1,5\text{-}COD)Ir \cdot P_2W_{15}Nb_3O_{62}]^{8-}$ are one of only eight new classes of polyoxoanion-based catalysts that have been developed in the last ca. 20 years (see Fig. 1 in [19]), and (f) to see whether or not the products seen from polyoxoanion-based catal-

ysis could be manipulated towards the more valuable epoxide product, cyclohexene oxide.

Herein we report our efforts addressing the first four of the six goals listed above. In particular we report: (i) compelling product, initiator and inhibitor, and other kinetic evidence that the oxidation of cyclohexene in Eq. (1) is an autoxidation process; (ii) modern product identification studies which reveal for the first time that ~70 products are formed from cyclohexene at higher (≥25%) conversions, plus the identification of 27 of those products; (iii) plausible arrow-pushing mechanisms to many of the observed products using known radical chemistry; (iv) unequivocal evidence from the product studies that solvent-derived, chlorinated hydrocarbon radicals mediate at least some of the autoxidations as one expects; and perhaps most significantly (v) the finding that a GC trace plus GC–MS of cyclohexene oxidation at higher conversion is a relatively simple and quick, yet definitive, fingerprint test for the detection of at least cyclohexene autoxidation catalysis. In an accompanying paper we (vi) provide additional evidence that the true catalyst is indeed polyoxoanion supported [18].

Elsewhere we (vii) have reported that one can convert the totally unselective, high-conversion cyclohexene autoxidation reaction and its 70 products into a highly selective, 88–94% cyclohexene oxide and thus *single-product forming reaction* (at $97 \pm 3\%$ conversion) simply by adding excess aldehyde (isobutyraldehyde) to convert the autoxidation into a $RC(O)OO^\bullet$ mediated, co-oxidative epoxidation process [20]. That work also reports the importance of the key control experiments of leaving out the catalyst and comparing the "catalyzed" results to those obtained with simple radical-chain initiators such as ROOH or AIBN [20]. Those findings led, in turn, to our development of a non-metal catalyzed, but radical-chain initiated, optimized $RCHO/olefin/O_2$ co-oxidative epoxidation process, including the important finding that the optimized reaction is more selective than even one of the best metal catalyzed processes developed to date [20]—that is, metal catalysis is actually *harmful* from the standpoint of enhancing the reaction's selectivity.

Finally, the understanding of autoxidation and co-oxidations using polyoxoanion precatalysts that we have attained has also been important in allowing us to develop record catalytic activity catechol dioxygenase
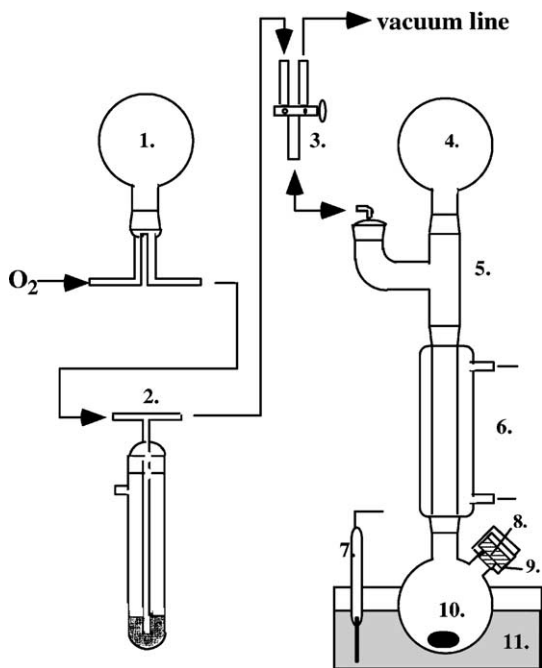

Fig. 1. Oxidation apparatus: 1, 1 L round-bottomed flask (oxygen reservoir 1); 2, bubbler with silicon oil; 3, stopcock (double oblique bore); 4, round-bottomed flask (oxygen reservoir 2); 5, Claisen adapter; 6, condenser; 7, temperature control unit; 8, double septum; 9, glass cup; 10, 25 ml round-bottomed flask with stir bar; 11, constant temperature bath (paraffin oil).

catalysis of >100,000 total turnovers. That work is also available elsewhere for the interested reader [12].

2. Results and discussion

2.1. Catalyst survey studies

The oxidation of cyclohexene by molecular oxygen (1 atm) was carried out using the straightforward apparatus shown in Fig. 1, a constant temperature bath ($38 \pm 0.1 \,^\circ$C), and in the presence of $[n\text{-Bu}_4\text{N}]_5$-$\text{Na}_3[(1,5\text{-COD})\text{Ir}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$ or the other polyoxoanion-supported organometallic complexes as precatalysts, Table 2.

Reaction times of 24 h were used in these catalyst and solvent survey studies. The disappearance of cyclohexene and the appearance of the main oxidation products (cyclohexen-1-yl hydroperoxide, 2-cyclohexen-1-one, 2-cyclohexen-1-ol, cyclohexene oxide; mass balance of $\geq$80–92%) were readily followed in these 24 h, $\leq$58% conversion (Table 3) experiments using authentic-product-calibrated GC. The smooth loss of cyclohexene, and the formation of mainly the four products noted above, continues at somewhat longer reaction times, Fig. 2.

The yields of products in decreasing order shown in Fig. 2 of 2-cyclohexen-1-one, **3**, then 2-cyclohexen-1-ol, **4**, then cyclohexene oxide, **5**, is highly suggestive of, but by itself not definitive evidence

(a)

(b)

Fig. 2. (a) Time course of cyclohexene autoxidation in dichloromethane at $38\,^\circ$C and 1 atm oxygen in the presence of the catalyst precursor $[n\text{-Bu}_4\text{N}]_5$ $\text{Na}_3[(1,5\text{-COD})\text{Ir}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$ and with 0.14 mmol of 2-cyclohexen-1-yl hydroperoxide (CyHP) added initialy. Main non-peroxidic products: cyclohexene, **1**; 2-cyclohexen-1-one, **3**; 2-cyclohexen-1-ol, **4**; and cyclohexene oxide, **5**; the initialy formed amounts of **3**–**5** due to the added CyHP have been subtracted from the data shown. The formation of the hydroperoxide CyHP, **2**, is not shown in this figure. (b) First-order plot of cyclohexene disappearance over a time range of 50 h.

Table 2

The autoxidation of cyclohexene in dichloromethane at $38\,^\circ$C and 1 atm O_2 using different polyoxoanion-supported organometallic precatalysts[a]

No.	Precatalyst	Conversion (%)[b]	Yield (%)[c]			TOF (h^{-1})[d]
			3	**4**	**5**	
I	$\text{TBA}_8[(\text{CO})_3\text{Re}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$	58	30	20	7	27
II	$\text{TBA}_{4.5}\text{Na}_{2.5}[(\text{benzene})\text{Ru}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$	56	28	20	8	26
III	$\text{TBA}_5\text{Na}_3[(\text{COD})\text{Ir}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$	24	12	10	2	11
IV	$\text{TBA}_5\text{Na}_3[(\text{COD})\text{Rh}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$	12	9	3	–	6
V	$\text{TBA}_5\text{Na}_3[(\text{Cp}^*)\text{Rh}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$	10	8	1	–	5
VI	$\text{TBA}_9\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}$ (control reaction)	<3	–	–	–	–

[a] Reaction conditions: 6 ml CH_2Cl_2; 1.0 ml (9.87 mmol, 1.4 M) cyclohexene; catalyst ($\sim$1.26 mM; mol ratio catalyst/substrate $\sim$1:1200); 1 atm dioxygen; $38 \pm 0.1\,^\circ$C; $t = 24$ h; estimated error bars $\pm$10%.

[b] Conversion (%) is defined as [cyclohexene (mmol)]$_{t=t}$/[cyclohexene (mmol)]$_{t=0}$ $\times$ 100%.

[c] Yield (%) is defined as [product (mmol)]/[cyclohexene (mmol)] $\times$ 100%; products, 2-cyclohexen-1-one, **3**; 2-cyclohexen-1-ol, **4**; and cyclohexene oxide, **5**.

[d] The turnover frequency is defined as: $\sum$[products **3**–**5**]/{[catalyst](per 24 h)}.

Table 3

The solvent dependence of cyclohexene oxygenation using molecular oxygen and the precatalyst $(n\text{-}Bu_4N)_5Na_3[(1,5\text{-}COD)Ir\cdot P_2W_{15}Nb_3O_{62}]$

Solvents	Initial rate constants ($\times 10^3 \text{ h}^{-1}$)[a]	Conversion (%)[b]	Yield (%)[c]		
			(O)	(OH)	(O epoxide)
CH_2Cl_2	11	24	10	12	2
$1,1,2,2\text{-}C_2H_2Cl_4$	7	14	11	1	2
$1\text{-}C_2H_4Cl_2$	3	7	4	2	1
CH_3CN[b]	4	8	6	1	1
CH_3COCH_3[b]	1	2	1	1	
CH_3SOCH_3	–	–	–	–	
CH_3OH	1	3	2	1	
C_2H_5OH	2	4	2	1	
DMF[b]	2	4	1	2	1

[a] The rate constants were obtained from first-order ln plots of cyclohexene concentrations vs. time; reaction conditions: 6 ml CH_2Cl_2; 1.0 ml (9.87 mmol, 1.4 M) cyclohexene; catalyst (~1.26 mM; mol ratio catalyst/substrate ~1:1200); 1 atm dioxygen; $38 \pm 0.1\,^{\circ}C$; $t = 24$ h; estimated error bars $\pm 10\%$.

[b] Conversion (%) is defined as [cyclohexene (mmol)]$_{t=t}$/[cyclohexene (mmol)]$_{t=0}$ × 100%.

[c] Yield (%) is defined as [product (mmol)]/[cyclohexene (mmol)] × 100%; products, 2-cyclohexen-1-one, **3**; 2-cyclohexen-1-ol, **4**; and cyclohexene oxide, **5**.

for, autoxidation. A limiting 1:1 ratio of 2-cyclohexen-1-one to 2-cyclohexen-1-ol above 100 Torr [1b], and as appears to be the case in Eq. (1) above, is sometimes cited in the literature as strong evidence for autoxidation in which chain termination is dominated by the classic Russell tetraoxide intermediate pathway [16], Eq. (2). In this pathway two cyclohexenyl peroxy radicals combine, followed by decomposition of the resultant tetraoxide intermediate, to yield a 1:1 ratio of 2-cyclohexen-1-one to 2-cyclohexen-1-ol.


(2)
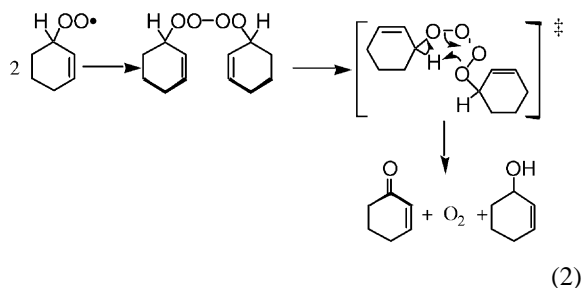
However, the ratio of these two products is clearly a function of time, the 2-cyclohexen-1-ol participating in co-oxidation of more cyclohexene as time goes on (and itself forming more of the ketone, 2-cyclohexen-1-one). In addition, the addition of steps (a)–(c) and (f) in the upcoming Haber–Weiss autoxidation Scheme 1 predicts something closer to a 1:2 ratio of 2-cyclohexen-1-one:2-cyclohexen-1-ol at shorter reaction times, vide infra. Other routes to the ketone are also possible; see Eq. (A.27) of the Appendix of supporting information. Hence, the ratio of these products is, by itself, *not* an easily used, definitive test for autoxidation.

The data in Table 2 reveal that the best polyoxoanions from the standpoint of highest conversion (or turnover frequency (TOF)) are the Re^I and Ru^{II} containing polyoxoanion precatalysts, $[(OC)_3Re\cdot P_2W_{15}Nb_3O_{62}]^{8-}$ and $[(C_6H_6)Ru\cdot P_2W_{15}Nb_3O_{62}]^{7-}$. The product conversions versus time, and first-order ln plots of the loss of cyclohexene for both precatalysts, are shown in Figs. 3 and 4. Note also in both these figures that the yields of the 2-cyclohexen-1-one, 2-cyclohexen-1-ol and cyclohexene oxide decrease in just this order, again suggestive (but not by itself definitive) evidence for autoxidation.

The data in Table 2 reveal that the Re and Ru complexes are more than two-fold better in both their TOF and their percentage epoxide formed than is the Ir precatalyst, but that the Ir precatalyst is, in turn, about two-fold better than Rh in these same categories. A control shows that, as expected, the $P_2W_{15}Nb_3O_{62}^{9-}$ polyoxoanion alone is inactive, Table 2, entry VI. Hence, and also since the Ir precatalyst is the one emphasized in our earlier [15a,b] and subsequent studies

INITIATION

PROPAGATION

TERMINATION
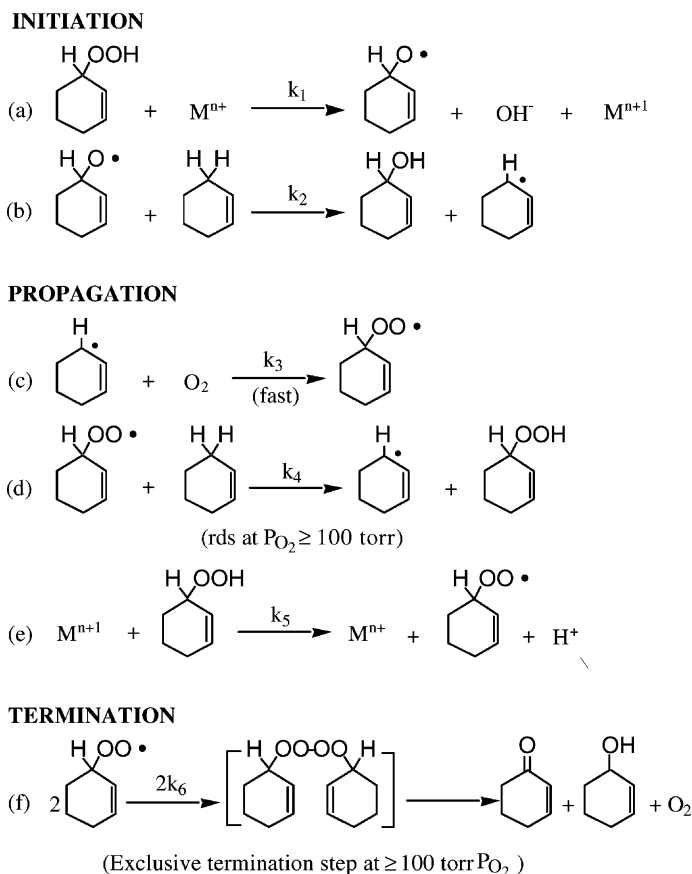
Scheme 1. The classic Haber–Weiss [5a,21a] radical-chain sequence applied to cyclohexene autoxidation at low conversion.

[16,18], the Ir system, $[(1,5\text{-COD})\text{Ir}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3 \text{O}_{62}]^{8-}$, and the Ru system, $[(\text{C}_6\text{H}_6)\text{Ru}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3 \text{O}_{62}]^{7-}$, were picked as representative, polyoxoanion-supported transition-metal precatalyst systems for further studies.

2.2. Solvent survey studies

Solvent survey studies were carried out using $[(1,5\text{-}$ COD$)\text{Ir}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]^{8-}$ and $38\,^{\circ}\text{C}$ for the nine solvents summarized in Table 3: dichloromethane, 1,2-dichloroethane, 1,1,2,2-tetrachloroethane, aceto-nitrile, acetone, DMSO, methanol, ethanol, and DMF. The results reveal that the best solvents for the au-toxidation catalysis, in terms of initial rate (and per-cent conversion after 24 h), are, not unexpectedly, the chlorinated solvents CH_2Cl_2 (24% conversion),

$1,1,2,2\text{-C}_2\text{H}_2\text{Cl}_4$ (14%), and $1,2\text{-C}_2\text{H}_4\text{Cl}_2$ (7%). The lowest conversions among the nine solvents inves-tigated are found for the more polar solvents (or oxidizable solvent in DMSOs case): 4% conversion in DMF, and no conversion of cyclohexene in DMSO. Of interest is that the product ratios between the three products 2-cyclohexen-1-one, 2-cyclohexen-1-ol, and cyclohexene oxide *do change significantly as a func-tion of solvent*; note that the ca. 1:1 ratio for 2-cyclo-hexen-1-one:2-cyclohexen-1-ol is formed in CH_2Cl_2, but a 11:1 ratio is formed in $1,1,2,2\text{-C}_2\text{H}_2\text{Cl}_4$, and a 1:2 ratio is formed in DMF. This is further, clear evidence that the ratio of 2-cyclohexen-1-one to 2-cyclohexen-1-ol cannot, by itself, be used as unequi-vocal evidence for autoxidation. The highest yields for the epoxide, cyclohexene oxide, are observed for 1,1,2,2-tetrachloroethane and dichloromethane,
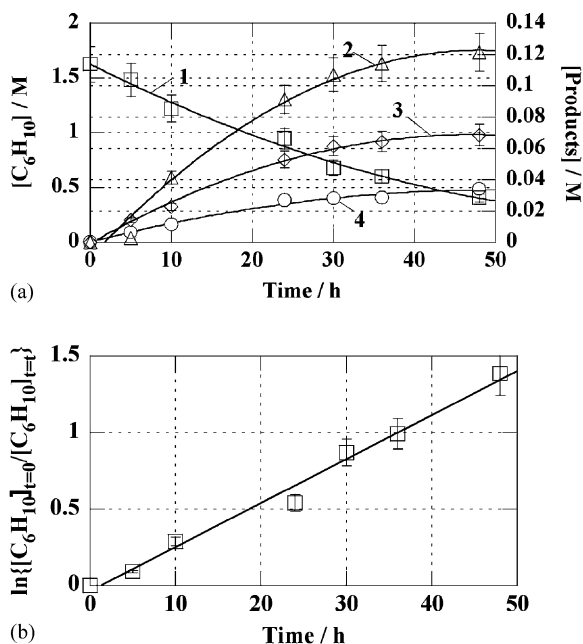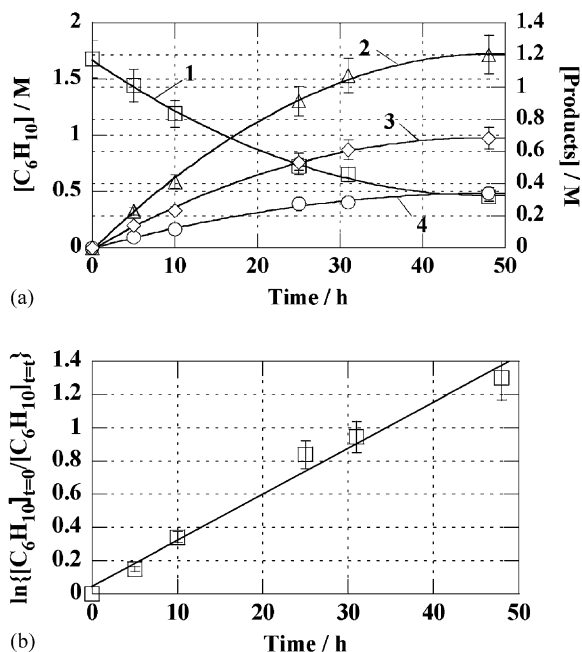
Fig. 3. (a) Time course of cyclohexene autoxidation in dichloromethane at 38 °C and 1 atm oxygen in the presence of the catalyst precursor $[n\text{-}Bu_4N]_8[(CO)_3Re \cdot P_2W_{15}Nb_3O_{62}]$ and with 0.14 mmol of CyHP added initially. Main non-peroxidic products: cyclohexene, **1**; 2-cyclohexen-1-one, **3**; 2-cyclohexen-1-ol, **4**; and cyclohexene oxide, **5**; the initially formed amounts of **3–5** due to the added CyHP have been subtracted from the data shown. The formation of the hydroperoxide CyHP, **2**, is not shown in this figure. (b) First-order plot of cyclohexene disappearance over a time range of 50 h.

Fig. 4. (a) Time course of cyclohexene autoxidation in dichloromethane at 38 °C and 1 atm oxygen in the presence of the catalyst precursor $[n\text{-}Bu_4N]_{4.5}Na_{2.5}[(C_6H_6)Ru \cdot P_2W_{15}Nb_3O_{62}]$ and with 0.14 mmol of CyHP added initialy. Main non-peroxidic products: cyclohexene, **1**; 2-cyclohexen-1-one, **3**; 2-cyclohexen-1-ol, **4**; and cyclohexene oxide, **5**; the initialy formed amounts of **3–5** due to the added CyHP have been subtracted from the plotted data shown. The formation of the hydroperoxide (2-cyclohexen-1-yl hydroperoxide, **2**, is not shown in this figure. (b) First-order plot of cyclohexene disappearance over a time range of 50 h.

respectively, but still low (2%). Based primarily on their higher conversions (and common use in oxidation chemistry), the chlorinated hydrocarbon solvents were chosen for further studies.

2.3. Kinetic studies at lower conversion: initiator, inhibitor and other kinetic evidence that cyclohexene autoxidation is occurring

2.3.1. Predicted kinetics and experimental design

Before proceeding to higher conversion product studies, it was deemed crucial to obtain good kinetic evidence that autoxidation was present, especially since initial GC studies at higher conversions indicted that a wealth of products were formed (and, therefore, that the time-consuming identification of those products would be worthwhile *only* if independent

evidence for autoxidation had first been obtained). The kinetics of radical-chain reactions teaches the well-known point [21] that the initiation and termination steps have a strong influence on the observed kinetics (see also the classic studies provided in references [1,2,4]). Hence, only with as much control over those steps as possible—that is, with deliberate initiation—is it generally possible to do meaningful, reproducible kinetic studies of autoxidation or other radical-chain reactions. Indeed, in his classic 1973 paper in Kochi's free-radical text [21a], Howard noted that ". . . self-initiated autoxidations are generally unsuitable for precise studies of reaction kinetics" [22].

It is also important to make clear here our *approach* to the kinetic studies. First, and despite our extensive use of kinetics as a main tool of mechanism over the

years and in ∼33% (44 total) of our publications to date, we have no illusion that we might contribute anything new or novel herein to the underlying kinetics of autoxidation. *That is not our goal*. Indeed, any familiarity at all with the autoxidation literature [4,5] reveals that detailed kinetic studies already exist and that autoxidation kinetics is a relatively complicated topic. Instead, our goal with the kinetic studies which follow is: (i) to use as a starting point the simplest ("Occam's Razor") autoxidation mechanism in the literature, namely the classic Haber–Weiss mechanism (vide infra); (ii) to illustrate how one needs to derive the expected kinetics up-front before one can even plan any studies that will be reproducible and meaningful, such kinetic considerations and derivations showing what the literature also teaches [1,22], *that uninitiated* autoxidation reactions must be avoided; and overall; (iii) to be sure that the kinetic studies provide strong support for, or against, autoxidation. In addition, (iv) it is also our hope that our approach to the kinetics of autoxidation might be one that is straightforward, yet useful, enough that others might follow it when trying to determine if they have autoxidation present in their own oxidation reactions and even if kinetic studies are not a common part of their research. In short, the kinetic studies which follow are *by design* a *minimalistic approach*. Of course the other underlying concept here is that "catalysis is a wholly kinetic phenomenon" [23], so that no study lacking kinetics

can claim to have compelling evidence for, or against, autoxidation.

The classic Haber–Weiss mechanism *at low conversion*, with its chain initiation, propagation, and termination steps [5a], is shown in Scheme 1, along with information about which step is rate determining at >100 Torr of O_2 (p. 278 in [1b]). We emphasize that this scheme is a minimalistic scheme[4] describing the initial products only, a scheme which does not account for any of the subsequent reactions or co-oxidations.

A derivation of the expected kinetics for the Scheme 1 reaction under low conversion conditions, and assuming steady state conditions for all the key intermediates and the M^{n+}/M^{n+1} catalyst, is straightforward and leads to the predicted rate law shown in Eq. (3) (a summary of the kinetic derivations is provided in the Section A.1).

$$-\frac{d[C_6H_{10}]}{dt} = k_4\left(\frac{k_1}{2k_6}\right)^{1/2}[C_6H_{10}]\,[M^{n+}]^{1/2}[C_6H_9OOH]^{1/2} \tag{3}$$

Fig. 5. The influence of different amounts of added radical initiator, CyHP, in the cyclohexene autoxidation at 38 °C and 1 atm O_2 in dichloromethane as solvent (6 ml) with, and without, added metal catalyst, [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$], 50 mg; 8.82×10^{-3} mmol; 1.26 mM]. Legend: 1, no CyHP, no catalyst; 2, no CyHP, catalyst added; 3, 0.18 mmol CyHP (25.7 mM), catalyst added; 4, 0.44 mmol CyHP (62.9 mM), catalyst added.

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[4] There are a number of points that anyone doing kinetics of autoxidation needs to be aware of; reading Sheldon and Kochi's classic treatment is recommended [1b]. First, while only the $ROOH + M^{n+} \rightarrow M^{n+1} + HO^- + RO^\bullet$ shown in Scheme 1 dominates in *non-polar* solvents (such as the CH$_2$Cl$_2$ used herein) [1b], significant solvent effects exist so that, in water, dual initiation pathways exist consisting of the above M^{n+} reaction plus a M^{n+1} one: $ROOH + M^{n+1} \rightarrow M^{n+} + ROO^\bullet + H^+$. This leads to a net initiation reaction of $2\,ROOH \rightarrow RO^\bullet + HO^- + ROO^\bullet + H^+$ and a limiting rate α [olefin]^2; (see Eqs. 95–100 and 110 elsewhere [1b] pp. 292–295).

Secondly, in principle one should do initial rates [31], thereby obtaining rate laws from data extrapolated back to time = 0; this also avoids complications from co-oxidations (e.g., involving further oxidation of the allylic alcohol product) which apparently do not follow any simple rate law. Such initial rate measurements are, however, not always possible; note that even with ROOH initiation, we see induction periods in the present kinetic data (see Fig. 5) which make the initial rate method problematic. Such induction periods are not unexpected in cases where a precatalyst is being used and the true catalyst is not known or isolable.

Thirdly, catalyst deactivation is common and can further complicate kinetic studies of autoxidation—although in the present case the polyoxoanion is *perhaps ideal as a precatalyst due to its high oxidative stability*. Overall, a careful reading of the key literature [1] is needed before meaningful autoxidation kinetic studies can be designed.
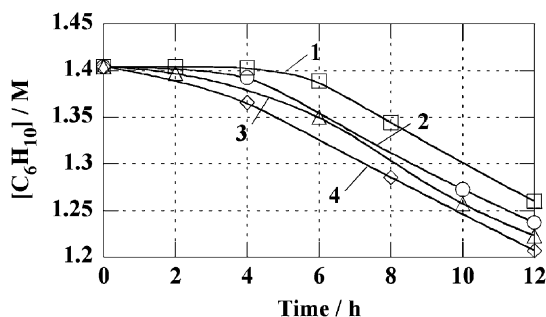
The expected dependence of the rate of the reaction *upon added initiator* is an important result of the predicted rate law, so this was investigated experimentally first via qualitative studies without, then with, added ROOH initiator (ROOH = 2-cyclohexen-1-yl hydroperoxide). In experiments carried out in the *absence* of both the ROOH initiator or metal catalyst (and with cyclohexene that was deliberately *not* prepurified to otherwise remove ROOH impurities and which was deliberately not stored under N_2 prior to its use), we found the anticipated, *non-reproducible and up to* 4 h *induction periods*. The expected, variable induction periods can be explained by the uncontrolled, trace amounts of peroxidic impurities, most likely 2-cyclohexen-1-yl hydroperoxide, in the unpurified cyclohexene.

If, however, the cyclohexene was freshly prepurified, but *no* metal catalysts or initiators were deliberately added, then *longer, up to* 8 h induction periods were observed for cyclohexene oxidation and under the specific conditions detailed in the Section 3.3. With prepurified cyclohexene and added $[n\text{-Bu}_4\text{N}]_5$ $\text{Na}_3[(1,5\text{-COD})\text{Ir}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$ precatalyst, but without deliberately initiator, induction periods of up to 2 h were still found. Hence, and as expected based on the kinetic considerations and derivations, the deliberate addition of a radical-chain initiator is needed for reproducible kinetics—as well as for reproducible synthetic runs—of the present, as it turns out, autoxidation[5] reaction.

2.3.2. Added initiator studies

Given the results in Section 2.3.1 above, all subsequent kinetic studies were carried out with freshly prepurified cyclohexene (which was then stored under N_2), in the presence of added 2-cyclohexen-1-yl

hydroperoxide as deliberately added initiator, and in the presence of the precatalyst,[6] $[n\text{-Bu}_4\text{N}]_5\text{Na}_3[(1,5\text{-}$ $\text{COD})\text{Ir}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$. (The 2-cyclohexen-1-yl hydroperoxide was picked as an initiator since it is the most probable, common initiator present in unpurified, unstabilized cyclohexene, i.e., we wanted to reproduce the "natural" cyclohexene autoxidation system as close as possible.) The results of the aerobic cyclohexene oxidations as a function of different amounts of added ROOH initiator are summarized in Fig. 5; they provide clear evidence for the rate-enhancing effect of the ROOH initiator and, therefore, for the presence of a radical-chain oxidation mechanism.

2.3.3. Added inhibitor studies

As either the literature [4,5] or a look back at the Haber–Weiss mechanism in Scheme 1 makes clear, the addition of appropriate radical traps to autoxidation reactions can inhibit,[7] or even stop completely, autoxidation by scavenging, for example, initiator radicals, alkylperoxy radicals or by reacting with, and thereby destroying, alkyl hydroperoxides themselves [24]. Under the experimental conditions detailed in the Section 3, the addition of 20 mg (0.11 mmol) of *N-tert*-butyl-α-phenylnitrone free-radical trap [25] to a cyclohexene oxidation reaction with $[n\text{-Bu}_4\text{N}]_5\text{Na}_3\text{-}$ $[(1,5\text{-COD})\text{Ir}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$ precatalyst, but deliberately *without* added ROOH initiator, lead to a longer, ~8 h induction period (versus ca. 2 h under otherwise identical conditions) and only a 7% conversion of cyclohexene after 24 h (12% after 48 h). The addition of the same amount of the nitrone free-radical trap to a reaction mixture also containing 16 mg (0.14 mmol)

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[5] It is of course true that once we add initiator, we are biasing the reaction kinetically towards autoxidation. After this point (i.e., for studies with added initiator), the only remaining issues then become: (a) if the catalyst can do facile autoxidation for the substrate at hand, (b) how efficient an autoxidation catalyst is it, and (c) what are its rate law and rate constants. However, once armed with the rate law and rate constants for the catalyst, one would then be in a position to start to *control* the autoxidation, at least in principle and *assuming* one could determine the true initiation steps and the concentrations of the species involved—these being the hard, often still indeterminate, parts of autoxidation kinetic and mechanistic studies [4,5].

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[6] As detailed in Howard's chapter (see p. 11 in [22]), in the absence of catalysts to control the ROOH decomposition, AIBN or other initiators are recommended over ROOH initiators, due to the uncontrolled nature, in the absence of catalyst, of the (catalyst)-induced ROOH decomposition. Hence, in our metal-free co-oxidative epoxidations of RCHO/olefin/O_2 published elsewhere [20b], we use AIBN as the radical-chain initiator.

[7] Common autoxidation inhibitors are substituted phenols (e.g., 2,6-di-*tert*-butyl-4-methylphenol, "Ionol®") or nitrones (e.g., *N-tert*-butyl-α-phenylnitrone) which interrupt the autoxidation chain by forming stablilized phenoxyl radicals or nitroxides, respectively (see also [1a,1b]). The reactions of metals such as Cu(I) or Co(II), above a critical concentration [1b; p. 335], can also lead to the inhibition of autoxidation by reaction with alkoxy (RO•) and alkylperoxo (ROO•) radicals, for example by: $\text{RO}_2\bullet + \text{M}^{n+} \rightarrow$ $\text{RO}_2\text{M}^{n+1}$.

of 2-cyclohexen-1-yl hydroperoxide initiator gave a slightly shorter, but still substantial, induction period of approximately 6 h with 18% conversion after 24 h (and 32% conversion after 48 h).

The addition of Cu(I) as a free-radical inhibitor at relatively high concentrations [1b; see p. 335] (30 mM) lead to no or low (≤5%) conversion of cyclohexene after 24 h, the expected result due to a precedented [1b] Cu(I) radical scavenging effect of relatively high Cu(I) concentrations. Overall, the results of these qual- ititative inhibitor studies are, again, consistent with, and strongly supportive of, a radical-chain autoxida- tion pathway for the aerobic oxidation of cyclohexene.

2.3.4. Additional kinetic studies

These studies were performed with: (i) added 2-cyclohexen-1-yl hydroperoxide; (ii) under >100 Torr of O_2 pressure so that chain termination via 2 $ROO^\bullet \rightarrow$ ROO–OOR (and its follow-up reactions), Scheme 1, are the predicted dominant termination steps based on the literature [1,21a]. The time-depen- dent disappearance of cyclohexene GC data ($\pm 10\%$) were used to obtain the experimental rate law over a total reaction time of 48 h. First-order ln plots (i.e. Figs. 2b, 3b and 4b) are consistent with a first-order dependence on cyclohexene concentration under the relatively modest range of cyclohexene concentrations examined. During the cyclohexene autoxidation in the presence of the polyoxoanion-supported Ir com- plex, the formation of a precipitate after ≥15–20 h reaction is observed. Hence, a control experiment was carried out over a reaction time of 100 h to see if the formation of a precipitate altered the kinetics; the resultant first-order plot is still linear (see Fig. 10, Section A.2 of the Appendix A), indicating that the formation of this precipitate does not influence ob- servably the shape, nor the rate constants, of the first-order kinetic plots. The expected one-half order dependence of the catalyst concentration was also confirmed in independent experiments by plotting k_{obs} versus the amount of initially added precatalyst [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$], Fig. 6.

The predicted quantitative dependence of the rate law on [ROOH]$^{1/2}$ proved harder to verify, since at the lower temperatures and lower (catalyst) and (initiator) concentrations employed, induction periods were still observed (see Fig. 5 for example). However, treatment of the data for curves 2, 3 and 4 in Fig. 5 does re-
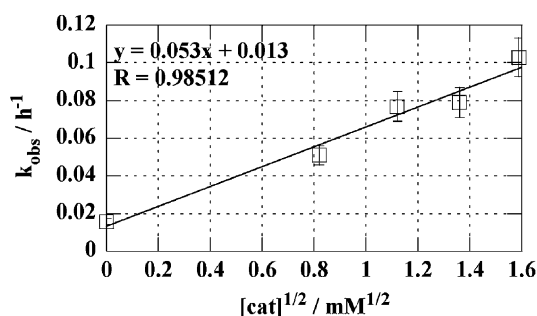

Fig. 6. The dependence of the rate law upon different catalyst concentrations in the cyclohexene autoxidation in the presence of [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$] at 38 °C, 1 atm O_2 and with a constant amount of initialy added cyclohexene hydroper- oxide initiator (20.0 mM). The linear k_{obs} vs. [cat]$^{1/2}$ (catalyst concentration in mM) plot confirms the one-half-order dependence upon the catalyst predicted (see Eq. (3)) for the Haber–Weiss au- toxidation mechanism.

veal a reasonable k_{obs} versus [ROOH]$^{1/2}$ plot (Fig. 11, Appendix A).

To summarize the kinetic studies under low conver- sion (≤25%) reaction conditions, the kinetics provide excellent kinetic evidence that the observed reac- tion is the expected cyclohexene free-radical-chain autoxidation reaction, Scheme 1, again at least un- der low conversion conditions. Scheme 2 provides a summary, now in catalytic cycle form, of the ob- served autoxidation, as well as the connection points of other, product-generating cycles (e.g., β-scission, alcohol and ketone product generating cycles) that will become important in a moment.

2.4. Product studies at higher conversions

A bit of back-of-the-envelope, arrow-pushing pre- diction of some of the additional products one should expect from a radical-chain pathway for cyclohexene autoxidation, and based on a knowledge of fundamen- tal radical reactions and autoxidation reactions (e.g., Schemes 6–8 of the Appendix A), quickly leads to *the realization that, at higher conversion, autoxidation of cyclohexene should generate a wealth of products*. A few of the predicted, acyclic products are shown in Scheme 3.

It also occurred to us that a simple GC trace at higher conversion might even prove to be a quick—yet powerful and perhaps even definitive—fingerprint for
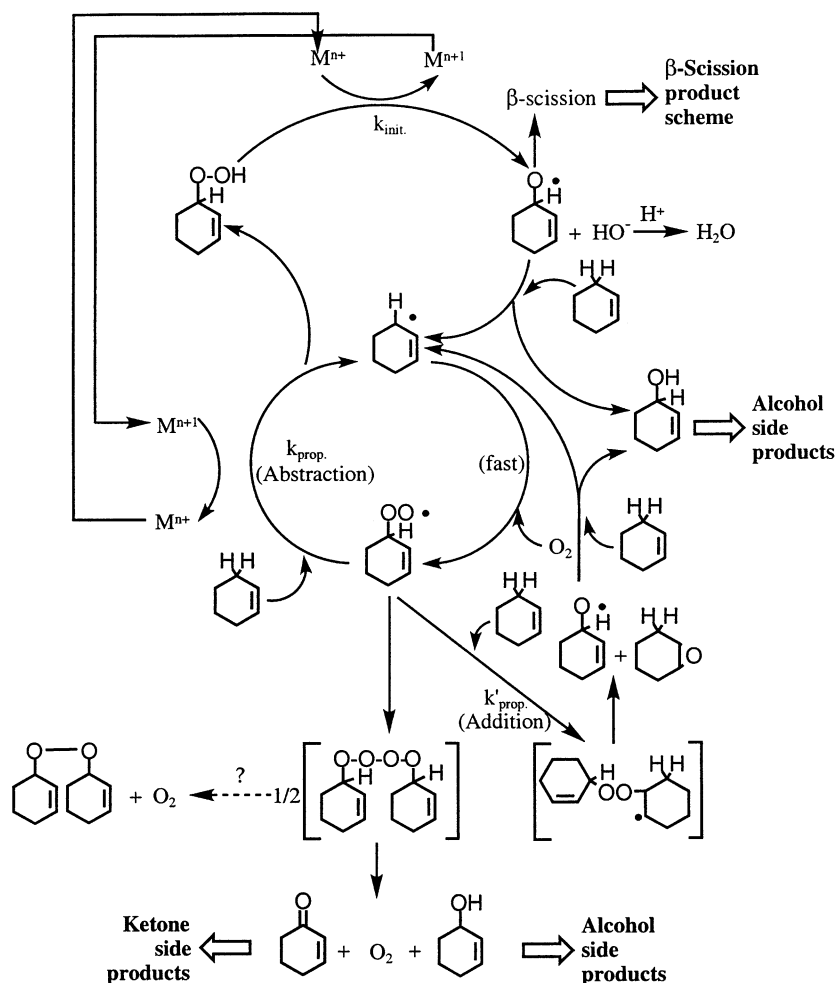
Scheme 2. The main catalytic cycle for the *hydroperoxide initiated*, metal catalyzed cyclohexene autoxidation. Some expected β-scission, alcohol- and ketone-producing cycles are shown in Appendix A, Schemes 6–8.

autoxidation (i.e., after as many as possible of the products at higher conversion had been identified, assuming the products could be accounted for by a radical-chain autoxidation mechanism). We were somewhat surprised when a search of at least the open literature of olefin autoxidations *failed to reveal any such diagnostic GC trace*, *nor any more complete product studies*, *of prototype olefin autoxidation*, for example, cyclohexene autoxidation (nor has such a GC trace, nor more complete product studies at higher conversion, ever been mention in *any* of the numerous reviews of autoxidation that are available [1,2,4]). Typically no more than 8–12 prod-

ucts at most [5h,q] are identified and quantitated, and then typically only at lower conversions[8]—again a surprising result since full product studies and high

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[8] We do, however, strongly suspect that such GC traces of a multitude of autoxidation products have been observed—*perhaps often*—in industrial or other laboratories, but then simply discarded due to the complexity of the GC trace or since those studies may have mostly been performed prior to the routine availability of modern, powerful capillary GC/GC–MS. In any event, the prior oxidation catalysis literature lacks such more complete product studies and, therefore, also lacks a "olefin autoxidation GC fingerprint" that is diagnostic of autoxidation taken to higher conversions.
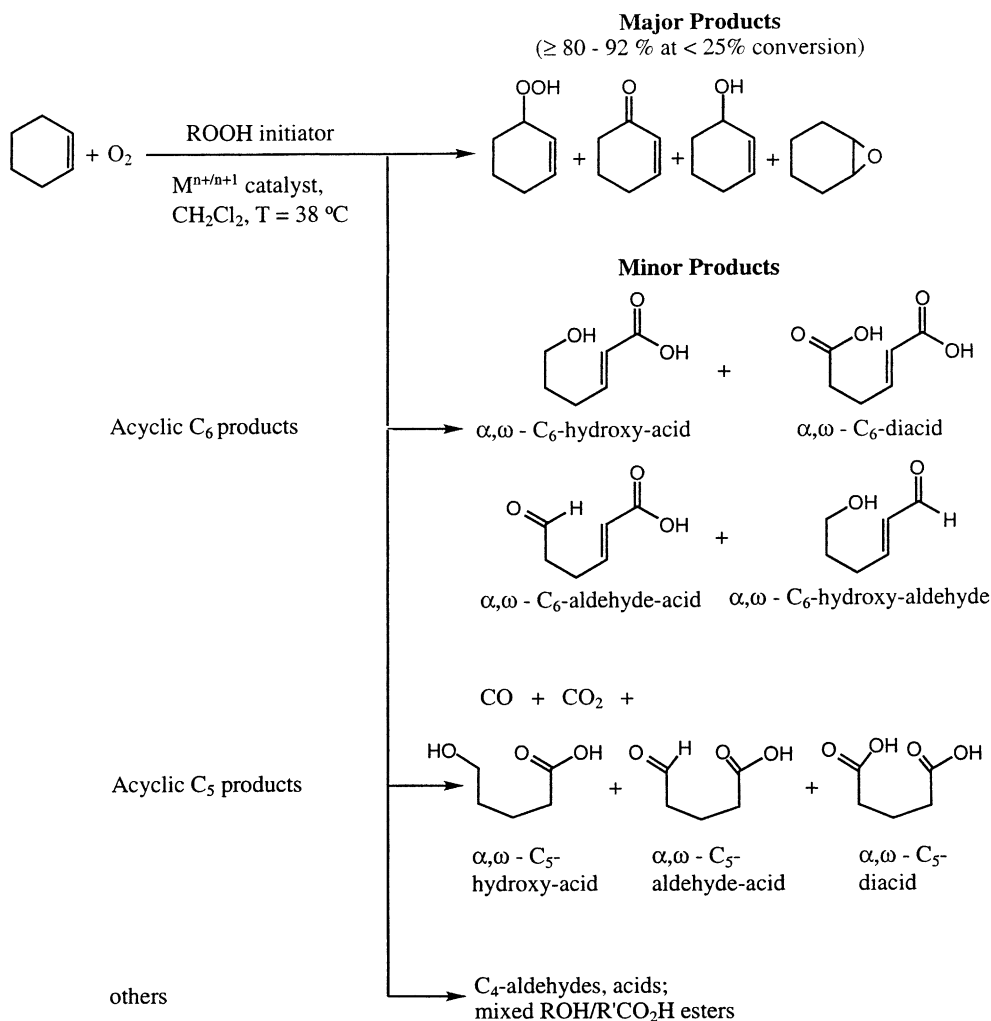
Scheme 3. The observed major, plus a few of the predicted minor, products from the metal catalyzed autoxidation of cyclohexene.

mass balance are well-known prerequisites to reliable mechanistic work. Hence, a careful look at the products of cyclohexene autoxidation at higher conversion became a focal point of the present studies. A GC trace of ROOH initiated and catalyzed aerobic cyclohexene oxidation at higher (>25%) conversions quickly revealed up to 70 discernible products after only ∼48 h reaction time, Fig. 7, vide infra.

Taking into account the large number of products revealed at higher conversion, Fig. 7, it appeared that an autoxidation fingerprint GC was at hand, assuming that characterization of as many of the products as possible would reveal that only a free-radical, autoxi-

dation pathway could account for both the number, and the identities, of the observed products.

2.4.1. General scheme for product identification and quantitation

The qualitative and quantitative analysis of 27 products, from the total mixture of ∼70 GC-detected products (plus the expected, involatile, polymeric products [1,2,4,5d,e,n,o,q]), was accomplished via a variety of analytic techniques: GC and GC–MS in comparison to authentic compounds, chromatographic product separations, ^{1}H nuclear magnetic resonance (NMR), and ^{13}C NMR spectroscopy (for peroxidic products),
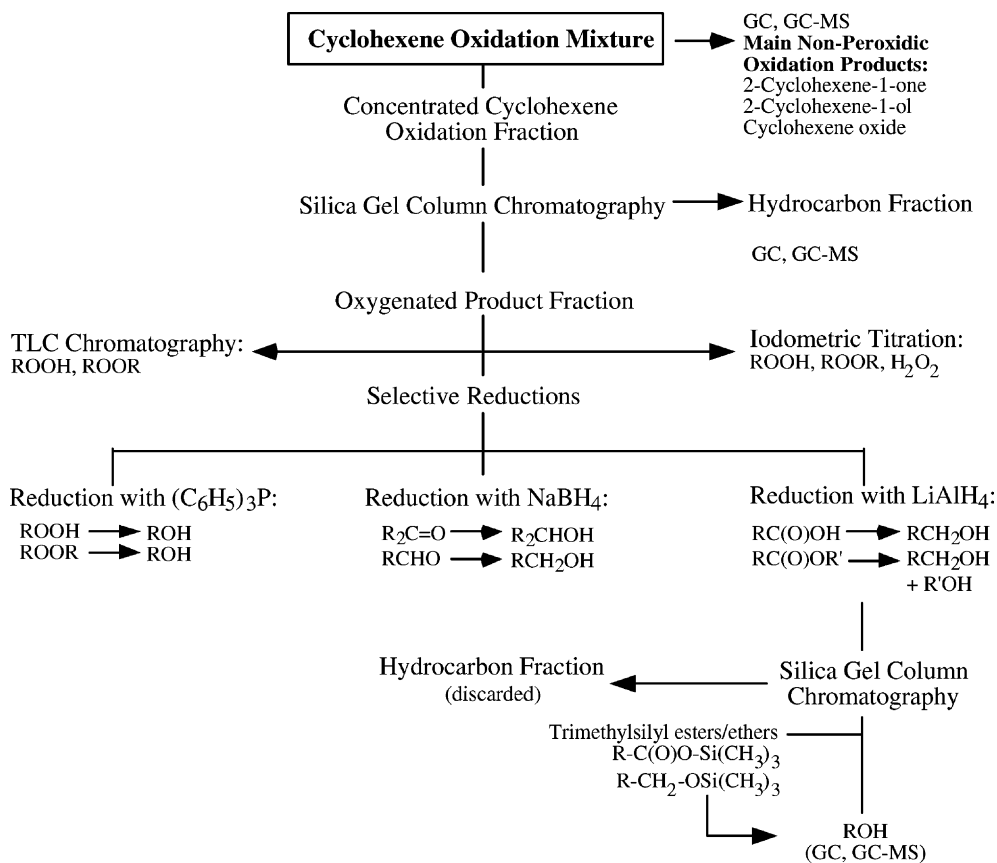
Scheme 4. The product separations and analytical methods used for identification of 27 of the GC-observed ∼70 products of cyclohexene autoxidation at higher conversions.

determination of physical constants (bp, mp, n_D) when compounds could be isolated (and a comparison of that data to literature data for authentic compounds), iodometric analysis of organic peroxides and hydroperoxides [5q], selective reductions by PPh₃, NaBH₄ and LiAlH₄ [5q], the characterization of minor products in concentrated product fractions, and product derivatization followed by characterization studies (e.g., as their volatile –SiMe₃ ethers or esters [5q], followed by GC–MS). A summary of the applied product separations and other manipulations is provided in Scheme 4.

2.4.2. Time course of total peroxide/hydroperoxide formation

The yield of total peroxides and hydroperoxides was determined by iodometric titration as described

in Section 3.7.2. The formation of 2-cyclohexen-1-yl hydroperoxide as a major product during the metal catalyzed cyclohexene autoxidation is expected [1,2], specifically at lower temperatures (i.e., at our reaction temperature of 38 °C) and low concentrations of the metal catalyst, although the ROOH products are often under (to not) reported in literature, as Van Sickle has noted [5d]. In two independent experiments, with and without the added pre-catalyst [n-Bu₄N]₅-Na₃[(1,5-COD)Ir·P₂W₁₅Nb₃O₆₂], the total peroxide content was analyzed continuously over 24 h using *initiated* cyclohexene autoxidations under standard conditions. At low conversions (≤10%), the peroxide content was found to be almost exclusively the predicted (Scheme 1) 2-cyclohexen-1-yl-hydroperoxide. A time course of the total peroxide formation, versus
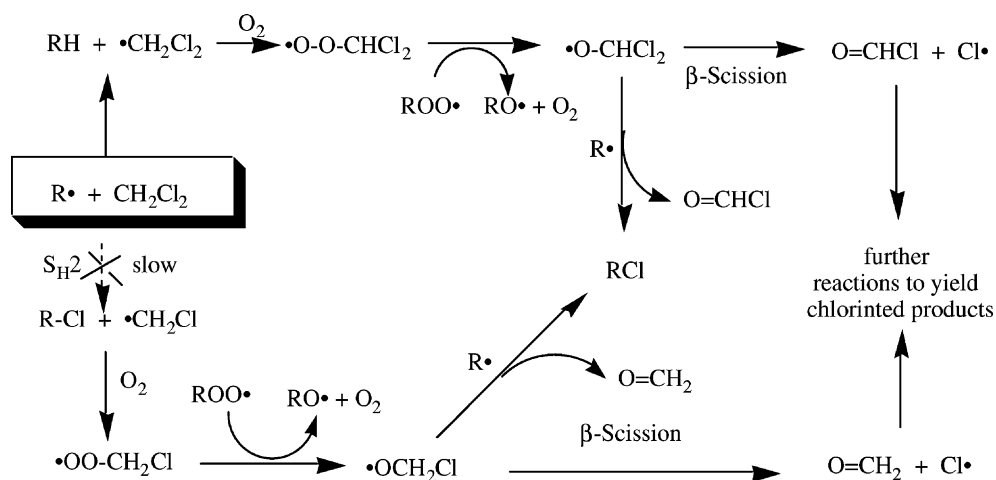
Scheme 5. Plausible (topmost) initial reactions of chlorinated solvents such as CH_2Cl_2 in the formation of chlorinated products beginning with a $H^\bullet$ abstraction from CH_2Cl_2 by a generic $R^\bullet$. The conceivable S_H2 reaction is known to be slow in general (see p. 124–125 in [21a]), and probably somewhat endothermic in the case of CH_2Cl_2; hence, presumably it is unimportant (i.e., and has been included above only for comparison to the topmost, $H^\bullet$ abstraction reaction).

that of the other main hydrogen abstraction products, is shown in Fig. 8, vide infra.

2.4.3. Organic peroxide detection and quantitation

Concentrated oxygenated product fractions after 48 h, obtained from metal catalyzed but necessarily *uninitiated* cyclohexene autoxidation, were separated using thin layer chromatography (TLC). The organic peroxides were collected off the TLC plates, and two hydroperoxides, 2-cyclohexen-1-yl hydroperoxide and 1,1-(2-cyclohexen-1-yl cyclohexyl) hydroperoxide, were unequivocally identified by a comparison to authentic materials [26]. At least three other peroxides or hydroperoxides were also detectable on the TLC plates (one of which was tentatively identified as dicyclohexyl peroxide), but these additional peroxides could not be cleanly separated for their further, unequivocal identification.

In a separate experiment, H_2O_2 was identified following H_2O extraction of the concentrated, cyclohexene oxidation fractions (i.e., containing all the oxidation products plus the unoxidized portion of the original 1 ml of cyclohexene; see the Section 3.7.2.3) by iodometric titration of the combined aqueous extracts. This experiment yielded 2.8% hydrogen per-

oxide (based on the 9.87 mmol cyclohexene used in this experiment).

2.4.4. Main, non-peroxidic product identification and quantitation

A typical chromatogram of a cyclohexene oxidation reaction mixture obtained after 48 h reaction time in dichloromethane using 1 atm oxygen is shown in Fig. 7, in that particular case for the more active, polyoxoanion-supported Ru^{II} precatalyst, $[(C_6H_6)Ru \cdot P_2W_{15}Nb_3O_{62}]^{7-}$ so that higher conversions could be more readily obtained (the GC trace for the Ir^I precatalyst is similar). GC and GC–MS analysis of the original reaction mixture was used to identify and quantitate the three major oxidation products 2-cyclohexen-1-one, 2-cyclohexen-1-ol and cyclohexene oxide, each in comparison to authentic materials. Quantitation of the remaining, unreacted cyclohexene was used to determine the conversion. A concentrated cyclohexene oxidation fraction was prepared by removal the dichloromethane solvent at $0\,^\circ C$; a silica gel column was then used to obtain two fractions: a faster eluting hydrocarbon fraction, and a slower eluting oxygenated fraction (the latter also included the unreacted, somewhat polar cyclohexene). The hydrocarbon fraction was analyzed by GC and
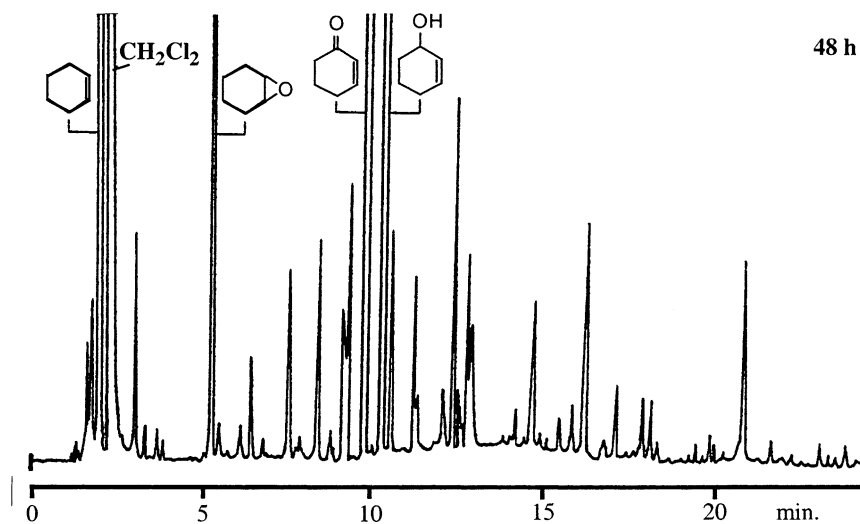
Fig. 7. GC trace of a cyclohexene oxidation mixture obtained after 48 h of reaction time. Conditions: 6 ml CH_2Cl_2; 1.0 ml (9.87 mmol, 1.4 M) cyclohexene; catalyst, $[n\text{-}Bu_4N]_{4.5}Na_{2.5}$ $[(C_6H_6)Ru\cdot P_2W_{15}Nb_3O_{62}]$, ($8.8 \times 10^{-3}$ mmol, 1.26 mM); 1 atm dioxygen; $38 \pm 0.1\,^\circ$C, no added ROOH initiator.

GC–MS. Benzene, cyclohexane, 1,3-cyclohexadiene, 1,4-cyclohexadiene, 1,1-bicyclohexyl and some unreacted cyclohexene ($\leq 5\%$) were found, each again in comparison to authentic, commercial materials. (Cyclohexane and benzene were also identified in a concentrated, original (i.e., non-column chromatographed) cyclohexene oxidation reaction mixture.) A few other products are seen in this column chromatographed hydrocarbon fraction, but they remain unidentified—our goal was not to try to identify all of the ca. 70 products, but, rather, to identify 20–25 more products than previously established in order to obtain a good feel for the products that form and their underlying chemistry.

2.4.5. Product selective reductions and derivatizations

The oxygenated product fractions (obtained by column chromatography, Scheme 3) were further analyzed by selective reduction, in independent experiments, with (in order of the experiments) triphenylphosphine, sodium borohydride, and then lithium aluminum hydride, to obtain selective reduction to the corresponding alcohols of the various aldehydes, ketones, acids or esters (see Scheme 3 and also Section 3.7.4 for details). The reduced fractions were separated by chromatography on a silica gel column; the

resultant fractions of the oxygenated, ROH products were analyzed either directly by GC (i.e. following NaBH$_4$ reduction, Fig. 9), or by GC, as well as by GC–MS, but after formation of the corresponding trimethyl silyl-esters or -ethers (the hydrocarbon fraction obtained from this separation procedure was discarded as shown in Scheme 3).

Using the separation scheme and analytical methods outlined in Scheme 3, a total of 27 of the ca. 70 GC-identifiable products[9] have been

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[9] An important point to mention here is that the identified products reflect heavily the products for which we could obtain commercially available, authentic samples. Other products, for example more of those predicted in Scheme 4, could almost surely be identified if there was a compelling reason to do so, and if one then went to the trouble to synthesize authentic samples where such samples are not available commercially.

In addition, three caveats are that: (i) it is possible that a few of the products in Table 4 are derived from GC injector port thermolysis (see, however, the controls in Experimental Section 3.3), or even; (ii) that a few products in Table 4 have been misassigned—although we have been careful to report only the products where or evidence is good and where authentic products were available as standards. In addition, (iii) at higher conversions, polymeric residues (products) are known to be under reported typically in olefin autoxidation chemistry [5d,e,n,o] (as are ROOH products [5e], although we have worked hard to detect and report herein the peroxidic products). However, the major conclusions of our work should not be influenced by any of these three caveats.
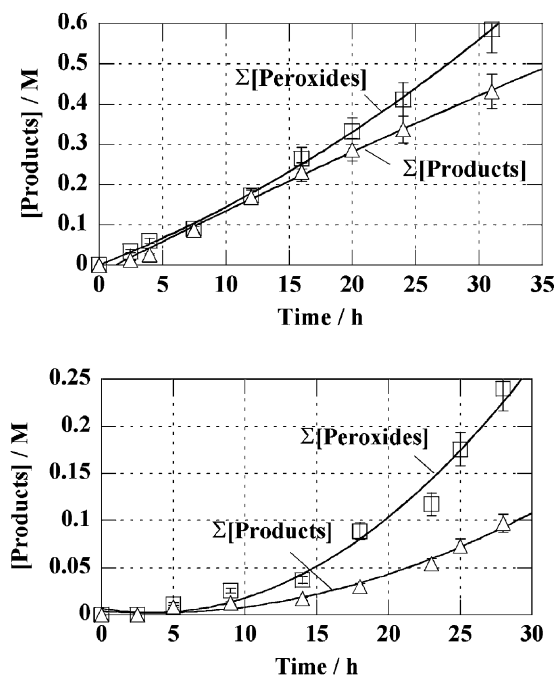
Fig. 8. Time course of total peroxide formation (total ROOH, ROOR and H_2O_2, less the amount of added ROOH initiator) compared to the formation of hydrogen abstraction products (i.e., 2-cyclohexene-1-one, 3, and 2-cyclohexene-1-ol, 4) during the *initiated* cyclohexene autoxidation in dichloromethane at $38\,°C$ and 1 atm oxygen in the presence (top) of the catalyst precursor $[n\text{-}Bu_4N]_5Na_3[(1,5\text{-}COD)Ir\cdot P_2W_{15}Nb_3O_{62}]$, and (bottom) without added precatalyst.

identified, Table 4. The products identified include: alkyl peroxides and hydroperoxides; disproportionation products (such as cyclohexane and benzene; cyclohexan-1-ol and cyclohexan-1-one; cyclohexane-1,2-diol and cyclohexane-1,4-diol; or 1,3-cyclohexadiene); open chain products as anticipated (such as hexanal, hexa-2,4-diene-1-al, 3-hexanoic acid, and adipic acid); cyclic ethers (tetrahydrofuran (THF), tetrahydropyran, and dihydropyrans); and the obvious radical coupling products bicyclohexyl and 3,3′-bicyclohexenyl. The mass balance under high-conversion falls off as expected (is ≤ 75 under the conditions used for the studies in Table 4), most likely due the formation of non-volatile, polymeric products cited in the literature [5d,e,n,o].

Three products have also been identified which contain Cl (see entries 21–23, Table 4) and, therefore, which must be derived from reactions involving the chlorinated solvent since it is the only source of Cl in the reaction. Although, there certainly is precedent for radical attack on chlorinated solvents [27], it is the exception rather then the rule to have such product-based, *prima facie* evidence the participation of chlorinated solvent-derived $R(H)(Cl)C^\bullet$ radicals in an autoxidation reaction. While the detailed schemes by which the chlorinated products in Table 4 arise remain to be elucidated, Scheme 5 shows the most plausible pathway by which chlorinated products (and $Cl^\bullet$ radicals) may be able to form under autoxidation conditions. Given the common use of chlorinated solvents for oxidation chemistry with dioxygen, it is probable that chlorinated solvent-radical participation has been missed in many reactions involving transition metals, olefins or alkanes, and dioxygen as the terminal oxidant—a recent study claiming novel dioxygenase catalysis may be a case in point [11].

A significant point is that there is no way other than radical-chain, autoxidation chemistry to account for these products—that is, the observed products provide incontrovertible evidence for the presence of autoxidation.[10] Moreover, the resultant GC trace of the cycloxehexene autoxidation products at higher conversion, Fig. 7, provides a previously unavailable and relatively simple—yet powerful and definitive—

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[10] While we have written back-of-the-envelope, generally radical mechanisms for many of the products in Table 4, we have made no attempt to provide, as part of this work, full schemes that would rationalize each of the observed products—as those schemes would be speculative in their details and without further studies, and since such schemes do little more than summarize the radical, single-headed-arrow-pushing mechanisms that anyone knowledgeable in radical chemistry can write. However, Schemes 6–8 are provided to summarize some typical radical, autoxidation reactions that one expects and which begin to account for at least some of the major classes of reaction products.

Although, not shown in a separate scheme, we have also written (by beginning retrosynthetically) radical routes to the tetrahydropyran and tetrahydrofuran products that we detect by GC–MS. In tetrahydrofuran formation, for example, plausible routes can be written which lead to possible intermediates such as $^\bullet OCH_2CH_2CH=CH_2$, which could then cyclize and abstract $H^\bullet$ from an appropriate donor to yield tetrahydrofuran.

Table 4
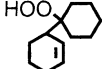Identified major and minor products in cyclohexene autoxidation
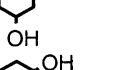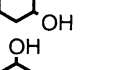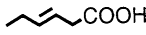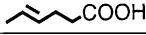
No	Structure	Compound	Yield	Method of identification[a]
1		Cyclohexene hydroperoxide	Major	c, g, h
2		1,1-(2-Cyclohexen-1-yl cyclohexyl) hydroperoxide	Minor	c, d, h
3		2-Cyclohexen-1-one	Major	a, b, e, f, i, j, k
4		2-Cyclohexen-1-ol	Major	a, b, e, f, k
5		Cyclohexene oxide	Major	a, b, e, f
6		Cyclohexane	Minor	a, b
7		Cyclohexanone	Minor	a, b, i, j
8		Cyclohexanol	Minor	a, b, j, k
9		Benzene	Minor	a, b
10		1-Hexanol	Trace	a, b
11		Hexanal	Minor	a, b
12		1,4-Cyclohexane diol[b]	Trace	a, b, j, k
13		1,2-Cyclohexane diol[b]	Trace	a, b
14		1,3-Cyclohexane diol[b]	Trace	a, b, j, k
15		1,3-Cyclohexadiene	Trace	a, b
16		1,4-Cyclohexadiene	Trace	a, b
17		Adipic acid	Trace	a, b, j, k
18		2-Hydroxy cyclohexanone	Trace	a, b
19		Bicyclohexyl	Trace	a, b
20		3,3′-Bicyclohexenyl	Trace	a, b
21		*cis/trans*-2-Chloro-cyclohexanol	Trace	a, b
22		3-Chlorocyclohexene	Trace	a, b

Table 4 (*Continued*)

No	Structure	Compound	Yield	Method of identification[a]
23		2-Chloro-cyclohexanone[c]	Trace	a, b
24		Tetrahydropyran[d,e]	Trace	a, b
25		Tetrahydrofuran[e,f]	Trace	a, b
26	∼∼COOH	3-Hexenoic acid[b,e]	Trace	a, b
27	∼∼COOH	4-Hexenoic acid[b,e]	Trace	a, b

[a] Method of identification: a, GC vs. authentic compound; b, GC–MS vs. authentic compound; c, TLC vs. authentic compound; d, mp; e, bp; f, n_D; g, ^{13}C and ^{13}C NMR; h, corresponding ROH product seen following reaction with PPh$_3$; i, corresponding ROH product seen following reduction with NaBH$_4$; j, corresponding ROH product seen following reduction with LiAlH$_4$; k, SiMe$_3$ derivative of corresponding ROH seen.

[b] Compared to GC–MS of commercial, *cis/trans* compound (Aldrich).

[c] A GC peak which coinjected with *trans*-1,2-dichlorocyclohexane (Aldrich) was also seen, but could not be unequivocally identified.

[d] GC peaks which coinjected with dihydropyrans (3,4-dihydro-2H-pyran, 5,6-dihydro-2H-pyran-2-one) were also observed, but those products could not be unequivocally identified.

[e] Identification is tentative due to overlapping GC and GC–MS peaks which obscured unequivocal identification, even in comparison to authentic materials.

[f] GC peaks which coinjected with a mixture of dihydrofurans (e.g. 2,3-dihydrofuran, and 2,5-dihydrofuran) were also observed, but those products could not be unequivocally identified.

test for the presence of autoxidation using cyclohexene as the test substrate.[11]

2.5. Summary and conclusions

The product studies, as well as the initiator, inhibitor and other kinetic studies, provide incontrovertible evidence for radical-chain, autoxidation chemistry as the predominant route for the production of the ca. 70 GC-detectable, and 27 identified, products formed from polyoxoanion-supported transition-metal catalyzed cyclohexene oxidation with dioxygen. Those results, in turn, lead to the GC trace in Fig. 7 plus GC–MS to confirm some of the products as a relatively simple and quick, yet definitive, method to find out if a new catalysts has facile autoxidation

chemistry. Plausible arrow-pushing mechanisms to representative classes of the new products in terms of established radical chemistry were also provided, previously unavailable results since the products themselves were previously unavailable. The product studies also revealed the presence of chlorinated products and, therefore, the *expected* involvement of chlorinated solvent-derived radicals, specifically •CHCl$_2$. The participation by too often believed "inert" chlorinated solvents in radical-mediated oxidation chemistry is a point that merits closer experimental scrutiny in any current study in such solvents and which also uses dioxygen.

Finally, in an accompanying paper we summarize the evidence that the true redox catalyst in this reaction is indeed polyoxoanion supported, the first such bona fide example [18]. Also available elsewhere are our studies of polyoxoanion-based, stoichiometric [12a] and record catalytic lifetime [12b] dioxygenases.[12]

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[11] To summarize, the main other evidence for autoxidation (under low conversion conditions) is kinetic evidence: (i) the rate law under lower conversion conditions, consistent with a Haber–Weiss mechanism; (ii) the ability to initiate or inhibit the reaction with, respectively, radical-chain initiators and inhibitors; and (iii) the finding that the uninitiated reaction exhibits variable induction periods. It is perhaps obvious that the products, plus the fact that it is impossible to account for them except via a radical-mediated autoxidation pathways, provides the strongest single piece of evidence that the reaction is autoxidation.

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[12] A very intriguing point results from the studies of chlorinated solvents in that catechol dioxygenase study [12b]: there is very likely a radical-mediated, autoxidation of the catechol to the quinone plus H$_2$O$_2$, and we have recently shown that it is H$_2$O$_2$ that turns on the autocatalytic generation of the catechol dioxygenase catalyst. Restated, in the system described elsewhere an autoxidation reaction occurs initially, but then leads to
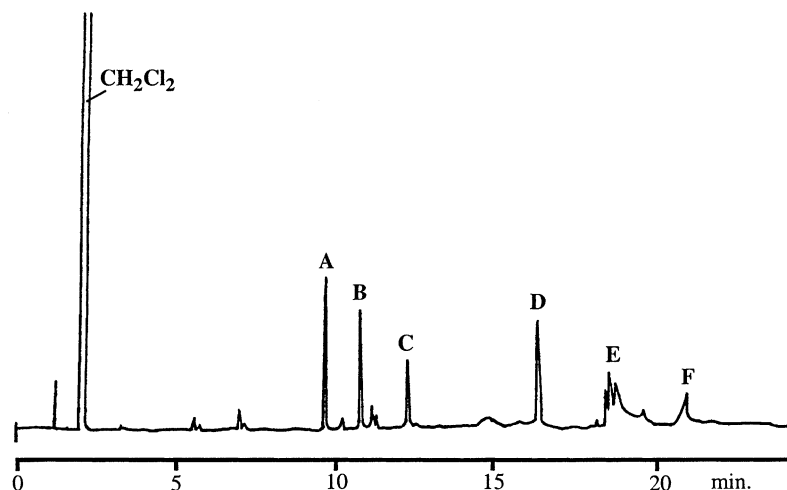
Fig. 9. GC trace of the hydroxy compounds obtained after separation and reduction using LiAlH$_4$ of a concentrated cyclohexene oxidation mixture. The identified compounds are: A, cyclohexanol; B, 2-cyclohexen-1-ol; C, 2,4-hexadien-1-ol; D, 1,6-hexanediol; E, 1,3-cyclohexanediol (*cis* and *trans*); F, 1,4-cyclohexanediol (*cis* and *trans*).

3. Experimental

3.1. Materials

The air-sensitive polyoxoanion-supported organometallic complexes [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$], [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Rh·P$_2$W$_{15}$Nb$_3$O$_{62}$], [n-Bu$_4$N]$_{4.5}$Na$_{2.5}$[(C$_6$H$_6$)Ru·P$_2$W$_{15}$Nb$_3$O$_{62}$], [n-Bu$_4$N]$_5$Na$_3$[{C$_5$(CH$_3$)$_5$}Rh·P$_2$W$_{15}$Nb$_3$O$_{62}$], and [n-Bu$_4$N]$_8$[(CO)$_3$Re·P$_2$W$_{15}$Nb$_3$O$_{62}$] were prepared and characterized according to our detailed procedures [28]; they were handled and stored in a vacuum atmospheres (VAC) drybox. The O$_2$ level was maintained at <1 ppm as continuously monitored by a VAC oxygen analyzer.

All commercially obtained compounds from the indicated vendors were reagent grade and used as received unless specified otherwise. Dichloromethane, 1,2-dichloroethane, and 1,1,2,2-tetrachloroethane were distilled under N$_2$ from CaH$_2$. Acetone, DMSO, DMF, acetonitrile, THF, methanol, ethanol, and triethylamine (all from Aldrich) were dried over activated (10 mmHg, 170 °C, for at least 12 h) molecular sieves 5A (Linde). Cyclohexene (Aldrich) was distilled from Na under N$_2$ and then passed through a neutral aluminum oxide column (under N$_2$) to remove traces of hydroperoxide. The 2-cyclohexen-1-yl hydroperoxide was prepared as described elsewhere [29], characterized by ^{1}H and ^{13}C NMR spectroscopy and its physical constants in comparison to literature data (2-cyclohexen-1-yl hydroperoxide: ^{1}H NMR, δ: 1.83, 5.88, 4.5, 9.13 [29b,c]; ^{13}C NMR, δ: 18.5, 25.5, 26.5, 78.8, 124.3, 134.2 [26d]; bp/mmHg, 51/0.3, n_D = 1.0588 [29a]); the resultant hydroperoxide content was determined by iodometric analysis following literature protocols (for further information see [30][13]). Triphenylphosphine, sodium borohydride, lithium aluminum hydride and trimethylchlorosilane were obtained from Aldrich and used as received.

3.2. Instrumentation/analytical procedures

Air-sensitive samples were prepared in a VAC Atmospheres inert atmosphere glove box (<1 ppm O$_2$). The NMR spectra of routine samples were obtained as CDCl$_3$ or CD$_3$CN solutions in Spectra Tech or Wilmad NMR tubes. Air-sensitive samples were prepared in the drybox, and the solution was placed in

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the generation of a catechol dioxygenase catalyst and reaction [12b].

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[13] For determination of peroxide mixtures see [24] and [86] therein.

an NMR tube (5 mm o.d.) equipped with a Young airtight valve (Wilmad), at room temperature unless otherwise stated. The chemical shifts are reported with downfield resonances as positive. ^{1}H NMR (300.15 MHz) and ^{13}C NMR (75.0 MHz) spectra were recorded in 5 mm o.d. tubes on a Bruker AC-300 NMR spectrometer, at 21 °C unless otherwise noted, and were referenced to the residual impurity in the deuterated solvent (^{1}H NMR) or to the deuterated solvent itself (^{13}C NMR). Spectral parameters for ^{1}H NMR: ^{1}H tip angle = 30° (pulse width 3.0 ms); acquisition time, 1.36 s; repetition rate, 2.35 s; sweep width, ±6024 Hz. Spectral parameters for ^{13}C NMR: ^{13}C tip angle 40° (pulse width, 3.0 μs); acquisition time, 819.2 ms; repetition rate, 1.31 s; sweep width ±20,000 Hz.

GC was performed by using a HP 5890 Series II gas chromatograph equipped with a FID detector, a Supelcowax® 10 capillary column (30 m, 0.32 mm i.d.) and a DB-1 capillary column (30 m, 0.25 mm i.d.). GC–MS analysis was done on a Hewlett-Packard 5890/MSD 5970 instrument in the EI mode with the same DB-1 capillary column. The following conditions were used for all GC runs unless otherwise noted: oven temperature, initial value, 50 °C; heating rate, 10 °C/min; final temperature, 160 °C; final time, 5 min; injector temperature, 250 °C; detector temperature, 250 °C; flow, approximately 1–2 ml/min.; sample volume, 1 μl. The amounts cyclohexene starting material and of the main, non-peroxidic products cyclohexene oxide, 2-cyclohexen-1-ol and 2-cyclohexen-1-one were quantitated via calibration curves obtained using authentic compounds.

3.3. Cyclohexene oxidation procedure

The oxidation of cyclohexene was carried out under one atmosphere oxygen in a thermostatted, constant temperature bath (Fischer Scientific) at 38 ± 0.1 °C. The following standard procedure was used for all oxidation runs using the oxidation apparatus shown in Fig. 1.

In the drybox, 50 mg catalyst (8.82×10^{-3} mmol in case of [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$]) was placed in a 25 ml side-arm round-bottomed flask, equipped with a septum and a magnetic stir bar (10 mm) and was dissolved using 6 ml of

dichloromethane. Freshly distilled, then neutral Al$_2$O$_3$ chromatographed cyclohexene (1 ml, 9.87 mmol) was added to the solution,[14] and the flask was sealed and then brought immediately out of the drybox. Next, the flask was then attached to the oxidation apparatus, Fig. 1, cooled to 77 K with liquid nitrogen and the whole system was evacuated before being refilled with 1 atm O$_2$. The system was then evacuated again, refilled with 1 atm O$_2$, and the liquid N$_2$ was then replaced with a constant temperature bath, warmed up to 38 ± 0.1 °C and vigorously stirred with the stir bar. The reaction's progress was then followed periodically by sampling via a gas-tight syringe and analyzing the reaction mixture by authentic-sample-calibrated GC. Time $t = 0$ was defined after the oxygen had been added and the solution warmed up to 38 ± 0.1 °C a small error of 2–3 min is negligible to an average of 24 h (in some cases up to 48 h) reaction time.

In a series of control experiments to rule out significant GC injector port phenomena, samples of cyclohexene oxidation mixtures (obtained from a catalytic run the above, standard conditions), with and without reductive quenching (triphenylphosphine, P(C$_6$H$_5$)$_3$, tetrabutylammonium iodide, n-Bu$_4$NI, or sodium borohydride, NaBH$_4$), were analyzed by calibrated GC. Three separate samples were prepared by adding, separately, 20 mg (0.08 mmol) triphenylphosphine, 20 mg (0.05 mmol) tetrabutylammonium iodide, and 10 mg (0.26 mmol) sodium borohydride to three separate, 1 ml portions of the reaction mixture in sealable glass vials with a 0.5 cm stir bar. After stirring the mixtures for 15 min at room temperature each sample was chromatographed; no differences in comparison to the original mixture could be found for the samples quenched with triphenylphoshine and tetrabutylammonium iodide. However, the sample treated with sodium borohydride did show a slightly increased amount (8%) of cyclohexen-1-ol, presumably due to a partial reduction of the corresponding ketone. In summary, the decomposition of *low concentrations* of 2-cyclohexen-1-yl hydroperoxide does not significantly influence the quantitation

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[14] In all kinetic experiments unless otherwise noted, a small amount of 2-cyclohexen-1-yl hydroperoxide (0.14 mmol) was also added to avoid irreproducible induction periods during the first 4–6 h of reaction.

of 2-cyclohexen-1-one or 2-cyclohexen-1-ol. Not un-expectedly, GC of a *more concentrated solution* of 50 mg (0.44 mmol) cyclohexene hydroperoxide in 6 ml dichloromethane (no cyclohexene, and no catalyst added) did reveal the presence of cyclohenen-1-one and cyclohexen-1-ol as a result of thermal decomposition of the hydroperoxide on the GC injector port.

3.4. Catalyst survey studies

The influence of different polyoxoanion-supported organometallic complexes on the catalytic autoxidation of cyclohexene in dichloromethane was studied at 38 °C and 1 atm O_2 over a reaction time of 20–25 h. The catalyst concentration was adjusted to 1.26 mM for each compound. In the drybox, ca. 50 mg catalyst (8.82×10^{-3} mmol in case of [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$]) was dissolved in a 25 ml round-bottomed flask using 6 ml of dichloromethane. Then, freshly distilled cyclohexene (1 ml, 9.87 mmol) was added to the solution, the flask was sealed, brought immediately out of the drybox and attached to the oxidation apparatus. The reaction was started as described above (Section 3.3), and the reaction's progress was followed periodically by sampling via a gas-tight syringe and analyzing the mixture by authentic-sample-calibrated GC. The results of the catalyst survey experiments are summarized in Table 2.

3.5. Solvent survey studies

The solvent dependence of the cyclohexene autoxidation in the presence of [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$] was studied at 38 °C and 1 atm O_2 using dichloromethane, 1,2-dichloroethane, 1,1,2,2-tetrachloroethane, acetonitrile, acetone, DMSO, methanol, ethanol, and DMF as solvents. In the drybox, 50 mg (8.82×10^{-3} mmol) [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$] was dissolved in 6 ml of the solvent using a 25 ml round-bottomed flask. Then, 1 ml (9.87 mmol) of freshly distilled cyclohexene was added to the round-bottomed flask. The reaction flask was then transferred outside of the drybox, connected to the oxidation apparatus, and the reaction was started as described in Section 3.3. After 24 h of reaction time the mixtures were analyzed by authentic-

sample-calibrated GC. The results of the solvent survey studies are summarized in Table 3.

3.6. Kinetic studies

Kinetic studies of catalytic cyclohexene autoxidation were performed at low conversions, with controlled addition of initiator (2-cyclohexen-1-yl hydroperoxide, CyHP), in the presence of [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$] and at 38 °C and 1 atm O_2 in dichloromethane solvent; the disappearance of cyclohexene was followed by authentic-sample-calibrated GC during a total reaction time of 48 h. The oxidation reactions were carried out using the procedure and experimental set-up described in Section 3.3. Kinetic derivations were performed based on the classical Haber–Weiss autoxidation mechanism for olefin oxidation, Scheme 1. A summary of the kinetic equations, assumptions and overall expected rate law for the cyclohexene autoxidation under these conditions (low conversion and initiation with 2-cyclohexen-1-yl hydroperoxide) is given in Appendix A.

3.6.1. Added initiator studies

The influence of different amounts of added radical initiators (2-cyclohexen-1-yl hydroperoxide, CyHP) in the cyclohexene autoxidation was studied at 38 °C and 1 atm O_2 in dichloromethane as solvent (6 ml), both with and without added metal catalyst [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$], 50 mg; 8.82×10^{-3} mmol], all using the procedure described in Section 3.3. With *no initiator* and *no precatalyst* an induction period of 4–5 h was observed; without added initiator but precatalyst, the observed induction period was reduced to 1–2 h, while with both added initiator and added precatalyst little to no induction period was found. The results are summarized in Fig. 5.

3.6.2. Added inhibitor studies

N-tert-butyl-α-phenylnitrone radical trap was used to inhibit the cyclohexene oxidation and, thereby, to obtain additional evidence for the expected free-radical-chain mechanism. The experiments were carried in dichloromethane (6 ml) as solvent at 38 °C and 1 atm oxygen as detailed in Section 3.3; 50 mg 8.82×10^{-3} mmol, [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$

O_{62}] and 1 ml (9.87 mmol) cyclohexene were used in all experiments. After initial addition of 20 mg (0.11 mmol) of *N-tert*-butyl-α-phenylnitrone (no ROOH was added) the reaction mixture was analyzed periodically by GC during 48 h of reaction time. After 24 h, 7% conversion was observed following an induction period of approximately 8 h; after 48 h, a conversion of 12% was found. With an initial addition of 20 mg (0.11 mmol) inhibitor and 16 mg (0.14 mmol) 2-cyclohexen-1-yl hydroperoxide initiator, an approximately 6 h induction period was found; after 24 h, ca. 18%, and after 48 h 32%, conversion was observed.

In two additional, separate experiments, 37 mg (0.20 mmol, 28.5 mM) of cobalt(II) acetate tetrahydrate and 21 mg (0.21 mmol, 30.3 mM) copper(I) chloride were added to separate reaction mixtures containing cyclohexene (1 ml, 9.87 mmol) and 16 mg (0.14 mmol) of 2-cyclohexen-1-yl hydroperoxide in 6 ml of dichloromethane. Low conversions of cyclohexene of less than 5% after 24 h reaction time (see the footnote 14) were found in both experiments, an expected result based on precedented Cu(I) or Co(II) inhibition above critical Cu(I) or Co(II) concentrations [1b; see p. 335].

3.6.3. The dependence of the rate law upon the concentration of catalyst

The influence of different catalyst concentrations in the cyclohexene autoxidation in the presence of [*n*-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$] was studied at 38 °C and 1 atm O$_2$ using dichloromethane as the solvent in order to verify the predicted [catalyst]$^{1/2}$ dependence of the rate law, Eq. (3). In four independent experiments (plus a no-catalyst control experiment), reaction mixtures containing various amounts of [*n*-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$] (no catalyst; 26.8 mg, 0.005 mmol, 0.68 mM; 49.8 mg, 0.009 mmol, 1.25 mM; 73.3 mg, 0.013 mmol, 1.84 mM; and 101.0 mg, 0.018 mmol, 2.54 mM precatalyst) were prepared by dissolving the precatalyst in 6 ml solvent in five separate, 25 ml round-bottomed flasks. Then, 1 ml (9.87 mmol) cyclohexene and 16 mg (0.14 mmol) 2-cyclohexen-1-yl hydroperoxide were added to the reaction mixtures. The reaction flasks were sealed, transferred outside of the drybox, connected to the oxidation apparatus (in independent, sequential experiments), and each reaction was started as described in Section 3.3. Each

reaction mixture was then analyzed after 24 h by authentic-sample-calibrated GC. Data for k_{obs} versus [catalyst]$^{1/2}$, Fig. 6, were obtained from first-order ln plots of the cyclohexene concentration versus time data at different catalyst concentrations.

A plot of k_{obs} versus [ROOH]$^{1/2}$ (using the data from curves 2, 3 and 4 back in Fig. 5) is given in Fig. 11 of Appendix A. Attempts to use initial rate data [31] during the first 4 h of reaction were less successful because of the relatively large scatter observed in the *initial* rate data, even with the deliberate initiation with 2-cyclohexen-1-yl hydroperoxide [31].

3.7. Product identification and analysis

Product analysis and determination of the reaction stoichiometry at low (≤25%) conversion were performed by analyzing 1–2 μl aliquots of the reaction mixtures by GC and GC–MS. At higher conversions (≥25%), a variety of separation procedures and analytical methods were used to separate and identify major, minor and trace products of the catalytic cyclohexene oxidation, as summarized in Scheme 4. The individual experimental procedures are described in detail in the following sections. A summary of the major and minor products of the polyoxometalate-catalyzed cyclohexene autoxidation in dichloromethane is provided in Table 4.

3.7.1. Main product identification and quantitation

The main reaction products obtained from catalytic cyclohexene autoxidations after 48 h were analyzed by GC on a Supelcowax$^®$ 10 capillary column (30 m, 0.32 mm i.d.). During the oxidation reaction (reaction time up to 48 h) the mixture was sampled periodically using a gas-tight syringe; 1–2 μl of the reaction mixture was injected for the GC analysis (a typical GC trace after 48 h is provided in Fig. 7 for the precatalyst [*n*-Bu$_4$N]$_{4.5}$Na$_{2.5}$[(C$_6$H$_6$)Ru·P$_2$W$_{15}$Nb$_3$O$_{62}$]). Using the unpolar Supelcowax$^®$ 10 capillary column a good baseline separation of cyclohexene, solvent (dichloromethane) and the three main oxidation products (2-cyclohexen-1-one, 2-cyclohexen-1-ol, cyclohexene oxide) was obtained. The main products were identified by GC–MS using the same capillary column and using 1–2 μl volumes of the original reaction mixtures described above; the identified products were also verified by comparison with authentic compounds

on both the GC and GC–MS systems. The amounts of cyclohexene, 2-cyclohexen-1-one, 2-cyclohexen-1-ol and cyclohexene oxide were calculated using calibration curves obtained by analyzing five calibration mixtures under identical GC conditions.

3.7.2. Organic peroxide detection and quantitation

The determination of the total yield of peroxo and hydroperoxo compounds was accomplished via an iodometric titration; the exact procedure which follows is based on literature suggestions [30] and is for mixtures of peroxy compounds, as were shown to be present in the current case.

3.7.2.1. Iodometric titration. First, 40 ml (522.5 mmol) of isopropyl alcohol were placed in a 250 ml Erlenmeyer flask, equipped with a 2 cm stir bar, a gas inlet tube and reflux condenser. Then, 2 ml (34.9 mmol) of glacial acetic acid and a sample from a original, ROOH-initiated oxidation reaction which was carried out using 12 ml of dichloromethane (1–3 ml sample; see Section 3.3) were added to the flask. The mixture was degassed by bubbling argon through the reaction solution for approximately 15 min, after which the mixture was heated to reflux. Next, 10 ml of a saturated solution of sodium iodide in isopropyl alcohol was added through the top of the condenser and the solution was refluxed under argon for an additional 30 min. The mixture was then removed from the heating plate and immediately titrated with aqueous 0.01 M sodium thiosulfate [32].[15] The data were corrected using the result of the titration of a blind sample (a 2 ml aliquot from a solution of 1 ml cyclohexene in 12 ml dichloromethane), while applying exactly the procedure described above.

In two separate experiments, with and without the precatalyst $[n\text{-Bu}_4\text{N}]_5\text{Na}_3[(1,5\text{-COD})\text{Ir}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}]$, the total peroxide content was analyzed continuously over 24 h of reaction time, and during *initiated* cyclohexene autoxidations under standard reaction conditions (i.e., Section 3.3). For the peroxide versus time plots, the amount of *initially* added ROOH

was subtracted off the experimental data. A zero-time peroxide determination yielded a peroxide content of 0.11 mmol, a value in good agreement with the amount of ROOH initiator added (0.14 mmol), thereby indicating that there is no apparent interference of the olefin [30], cyclohexene, in the experimental procedure. The results are summarized in Fig. 8.

3.7.2.2. TLC and identification of organic peroxides. Organic peroxides were also identified using TLC and following literature protocols [30]. Reaction mixtures from $[n\text{-Bu}_4\text{N}]_{4.5}\text{Na}_{2.5}[(\text{C}_6\text{H}_6)\text{Ru}\cdot\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62}])$ catalyzed cyclohexene oxidations (carried out in the *absence* of added 2-cyclohexen-1-yl hydroperoxide initiator) were obtained after 48 h of reaction, were concentrated by removing the dichloromethane solvent at 0 °C on a vacuum line, and were then chromatographed on silica gel/glass plates (UNIPLATE[TM] Silica Gel GF, preparative layer, 20 cm × 20 cm, 2000 microns, 2 mm thick) using a 1:1 mixture of benzene/acetone as mobile phase. The plates were developed using standard spray-reagents[16] to visualize the separated products. The separated fractions were carefully scraped from the TLC plates, extracted with CDCl₃ and transferred into 15 mm × 45 mm disposable glass vials. After removal of the solvent, the residues were characterized by ¹H and ¹³C NMR spectroscopy. Two organic hydroperoxides were identified by comparison to their literature data [26b,26c]: 2-cyclohexen-1-yl hydroperoxide (major product; ^{1}H NMR, CDCl₃, δ: 1.81, 4.40, 5.91, 9.12; ^{13}C NMR, CDCl₃, δ: 17.9, 25.4, 26.1, 79.0, 124.6, 134.0) and 1,1-(2-cyclohexen-1-yl cyclohexyl) hydroperoxide (minor product; mp = 38–40 °C [29e,29f]). At least three other peroxides or hydroperoxides were observed on the TLC plates (one of which was tentatively identified as dicyclohexyl peroxide), but they were not unequivocally identified since they could not be cleanly separated in order to allow their further, unequivocal characterization.

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[15] Anhydrous sodium thiosulfate was prepared by refluxing 21 g (84.6 mmol) sodium thiosulfate pentahydrate with 100 ml (2.47 mol) methanol for 30 min. The material so obtained was collected by filtration, washed twice with 20 ml methanol and anhydrous diethyl ether and then dried under vacuum overnight and at room temperature [32].

[16] The following reagents were used to visualize separated products: (i) acetic acid (10%) with KI at room temperature (0.5 M on KI), for easy reductible ROOR compounds; (ii) hydrochloric acid (conc., 37%); plates were placed at 100 °C for 30 min, for dialkylhydroperoxide and related compounds; (iii) acidic ethanolic solution of 2,4-dinitrophenylhydrazine (0.4 g 2,4-dinitrophenylhydrazine, 1 ml conc. sulfuric acid, and 120 ml ethanol) for carbonyl compounds.

3.7.2.3. Determination of H_2O_2.

Cyclohexene oxidation mixtures, obtained from $[n\text{-}Bu_4N]_{4.5}Na_{2.5}$ $[(C_6H_6)Ru\cdot P_2W_{15}Nb_3O_{62}]$ catalyzed, *uninitiated* cyclohexene autoxidation reactions after a total reaction time of 48 h, were transferred from the reaction flask into 25 mm × 55 mm disposable glass vials and concentrated by removing the dichloromethane solvent at 0 °C on a vacuum line. The residues were then extracted four times with 20 ml H_2O at 0 °C. The extracts were combined and then analyzed using the iodometric titration procedure described in Section 3.7.2.1. In three independent experiments, an average hydrogen peroxide content of 2.6–3.2% was determined (based on the initial amount of cyclohexene of 9.87 mmol).

3.7.3. Concentration and separation of cyclohexene oxidation fractions

Cyclohexene oxidation reaction mixtures were separated into a hydrocarbon fraction and a fraction containing the more polar, oxygenated products by preparative chromatography on a silica gel column. The column (2.5 cm × 30.5 cm) was slurry packed with *n*-hexane, a gravity flow of 2–3 ml/min was used for elution. Approximately 500 mg of a brown, oily concentrated cyclohexene oxidation reaction mixture was obtained from a $[n\text{-}Bu_4N]_{4.5}Na_{2.5}$ $[(C_6H_6)Ru\cdot P_2W_{15}Nb_3O_{62}]$) catalyzed, but *uninitiated* cyclohexene autoxidation reaction and after a total reaction time of 48 h, by removal of the solvent under vacuum at 0 °C. The 500 mg of brown, oily product mixture was then placed on the top of the silica gel column, and the column was eluted first with 150 ml *n*-hexane to separate the hydrocarbons from the oxygenated products. Then, the oxygenated products were obtained by elution of the column with 150 ml of methanol. The two separate (i.e., hexane, and methanol) fractions were then evaporated using a rotary evaporator (25 °C bath temperature); the resultant oily, light yellow residues were redissolved in 1 ml of dichloromethane (for the hexane, hydrocarbon fraction) or 1 ml of methanol (for the methanol, oxygenated product fraction) and analyzed by GC and GC–MS. The hydrocarbon fraction was found to be free of oxygenated products but to contain some unreacted cyclohexene (<5% total); however, most of the unreacted, somewhat polar cyclohexene was found in the (more polar) oxygenated product fraction.

3.7.4. Product selective reductions and derivatizations

Triphenylphosphine, sodium borohydride and lithium aluminum hydride were used to reduce selectively [4v,5h,q] the autoxidation product mixture. The reductions were carried out in independent experiments using concentrated autoxidation mixtures obtained from *uninitiated* oxidation reactions in CH_2Cl_2, using 1 ml (9.87 mmol) of cyclohexene, 50 mg (9.23×10^{-3} mmol $[n\text{-}Bu_4N]_{4.5}Na_{2.5}[(C_6H_6)Ru\cdot P_2W_{15}Nb_3O_{62}]$) and 48 h of reaction time. The dichloromethane solvent was removed at 0 °C in vacuum and replaced by methanol in case of sodium borohydride and anhydrous diethylether for the reduction with lithium aluminum hydride.

3.7.4.1. PPh₃ reduction.

The reduction with triphenylphosphine was accomplished by adding 100 mg (0.38 mmol) of PPh_3 reductant to the oxygenated product fraction (obtained by column chromatogaphy; Section 3.7.3) in 2 ml of dry THF. The mixture was stirred overnight at room temperature and then a 1–2 µl aliquot was analyzed by GC and GC–MS. The products confirmed by this method are so indicated in Table 4.

3.7.4.2. NaBH₄ reduction.

The reduction of the oxygenated product fraction with sodium borohydride was carried out by adding 250 mg (6.61 mmol) of $NaBH_4$ slowly into a solution of oxygenated products (obtained by column chromatogaphy, Section 3.7.3) in 5 ml of anhydrous methanol maintained at 0 °C. The mixture was then allowed to warm up to room temperature and stirred overnight. After concentration (evaporation of the solvent at room temperature using a vacuum line) to approximately 2–3 ml, 1–2 µl aliquots of the mixture were analyzed by GC and GC–MS. The products confirmed by this method are so indicated in Table 4.

3.7.4.3. LiAlH₄ reductions.

Reduction with lithium aluminum hydride was accomplished by adding 250 mg (6.59 mmol) $LiAlH_4$ to a fraction of oxygenated products (obtained by column chromatogaphy, Section 3.7.3) in 5 ml anhydrous diethylether at 0 °C. The mixture was allowed to warm to room temperature and was then stirred overnight at room temperature. The next morning the excess of reducing

agent was destroyed by slowly adding 200 mg (0.62 mmol) sodium sulfate decahydrate as a controlled source of H_2O; the ether solution was filtered off and the solid residue was washed twice with 5 ml of anhydrous diethylether. The diethylether was then removed from the combined filtrates at room temperature using a vacuum line; the residue was redissolved in 2 ml dichloromethane, and 1–2 μl aliquots were used for GC–MS analysis. Fig. 9 shows the resultant GC trace, the products confirmed by this method are so indicated in Table 4. The products confirmed by this method are so indicated in Table 4.

3.7.4.4. Trimethylsilyl derivatizations. Trimethylsilylated fractions [5q,33] of cyclohexene autoxidation products were prepared from a lithium aluminum hydride reduced original reaction mixtures, obtained as described above. About 200–220 mg of the light-yellow residue of a LiAlH$_4$ reduced (oxygenated) product fraction was placed on top of a silica gel column (1.2 cm × 25 cm) and then eluted with 40 ml of anhydrous methanol at a flow rate of ca. 2 ml/min. The solvent was then removed by rotary evaporation at room temperature, and the residue (80–100 mg) was redissolved in 3 ml of anhydrous THF and transferred into a 15 mm × 45 mm disposable glass vial containing a 10 mm Teflon-coated magnetic stir bar. Next, 100 μl (0.72 mmol) of $N(C_2H_5)_3$ and 84 μl (0.50 mmol) of $(CH_3)_3SiCl$ was added using a gas-tight syringe. The vial was then septum-capped and stirred for 4 h at room temperature. The mixture was the gravity filtered using a Pasteur pipette containing a ca. 5 mm column of dry silica gel and 1–2 μl aliquots were analyzed by GC and GC–MS.

4. Supplementary information available from the authors

Table S1 summarizing 30 additional references since 1996 focusing on cyclohexene autoxidation is available from the author on request (8 pages).
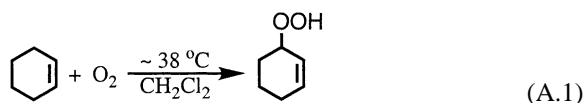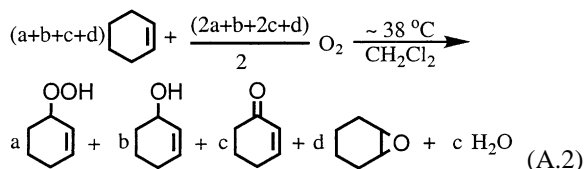
Acknowledgements

Appendix A. Appendix of supporting materials

A.1. Kinetic derivations

Limiting stoichiometry at larger chain lengths, low catalyst concentrations and lower temperatures (so that the ROOH product is stable):

$$(A.1)$$

More complete stoichiometry at low conversions:

$$(A.2)$$

By Eq. (A.1):

$$\frac{-d\left[\bigcirc\right]}{dt} = \frac{-d[O_2]}{dt} = \frac{+d\left[\bigcirc\text{OOH}\right]}{dt} \tag{A.3}$$

At chain lengths ≥10, and at $P_{(O_2)} = 100$ Torr [1b; see p. 278]:

$$\frac{-d\left[\bigcirc\right]}{dt} = k_4\left[\bigcirc\text{OO}\bullet\right]\left[\bigcirc\right] \tag{A.4}$$

By the rate of initiation equal to rate of termination,[17] and for $k_2 \gg k_1$[18] Eq. (A.5) results:

$$k_1\left[M^{n+}\right]\left[\bigcirc\text{OOH}\right] = 2k_6\left[\bigcirc\text{OO}\bullet\right]^2 \tag{A.5}$$
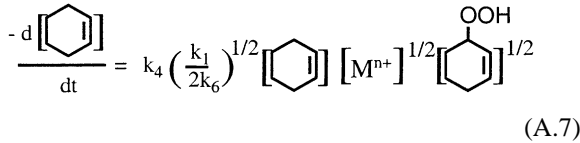
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[17] [4p] (Chapter 3).

[18] (a) Under the conditions $k_2 \gg k_1$, the sum of the first two initiation steps behaves as one, pseudo-elementary step, the kinetics of which are given by the first step. (b) For the use of, plus references to, the pseudo-elementary step concept, see [35].
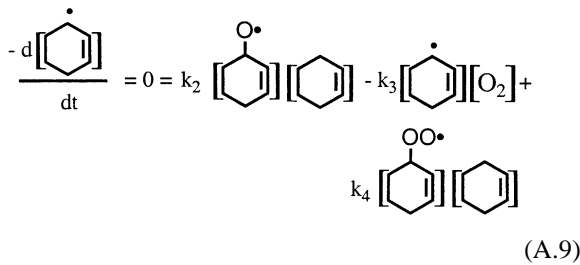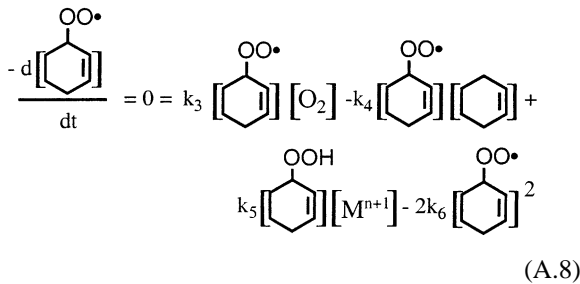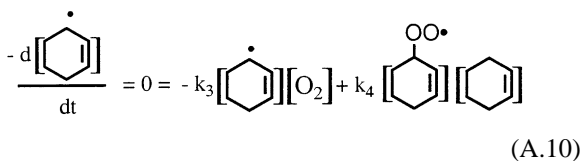
which, rearranging, yields Eq. (A.6):

$$[\text{cyclohexenyl-OO}\bullet] = \left(\frac{k_1}{2k_6}\right)^{1/2}[\text{M}^{n+}]^{1/2}[\text{cyclohexenyl-OOH}]^{1/2} \quad (A.6)$$
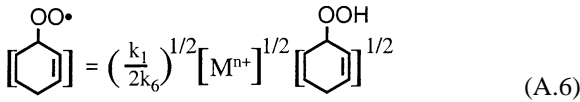
Substituting Eq. (A.6) into (A.4) yields the desired rate law, Eq. (A.7):

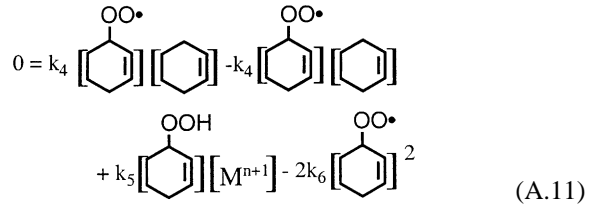$$\frac{-d[\text{cyclohexene}]}{dt} = k_4\left(\frac{k_1}{2k_6}\right)^{1/2}[\text{cyclohexene}]\,[\text{M}^{n+}]^{1/2}[\text{cyclohexenyl-OOH}]^{1/2} \quad (A.7)$$

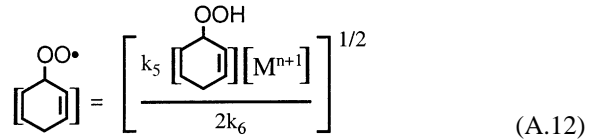An alternative treatment using the full steady state can be done, as a check. By the steady state assumption:

$$\frac{-d[\text{cyclohexenyl-OO}\bullet]}{dt} = 0 = k_3[\text{cyclohexenyl}\bullet][\text{O}_2] - k_4[\text{cyclohexenyl-OO}\bullet][\text{cyclohexene}] + k_5[\text{cyclohexenyl-OOH}][\text{M}^{n+1}] - 2k_6[\text{cyclohexenyl-OO}\bullet]^2 \quad (A.8)$$

$$\frac{-d[\text{cyclohexenyl}\bullet]}{dt} = 0 = k_2[\text{cyclohexenyl-O}\bullet][\text{cyclohexene}] - k_3[\text{cyclohexenyl}\bullet][\text{O}_2] + k_4[\text{cyclohexenyl-OO}\bullet][\text{cyclohexene}] \quad (A.9)$$

or, at high chain lengths, where $k_4[\text{cyclohexenyl-OO}\bullet] > k_2[\text{cyclohexenyl-O}\bullet]$:

$$\frac{-d[\text{cyclohexenyl}\bullet]}{dt} = 0 = -k_3[\text{cyclohexenyl}\bullet][\text{O}_2] + k_4[\text{cyclohexenyl-OO}\bullet][\text{cyclohexene}] \quad (A.10)$$

Substituting Eq. (A.10) into (A.5) yields (A.11):

$$0 = k_4[\text{cyclohexenyl-OO}\bullet][\text{cyclohexene}] - k_4[\text{cyclohexenyl-OO}\bullet][\text{cyclohexene}] + k_5[\text{cyclohexenyl-OOH}][\text{M}^{n+1}] - 2k_6[\text{cyclohexenyl-OO}\bullet]^2 \quad (A.11)$$

which simplifies to Eq. (A.12):

$$[\text{cyclohexenyl-OO}\bullet] = \left[\frac{k_5[\text{cyclohexenyl-OOH}][\text{M}^{n+1}]}{2k_6}\right]^{1/2} \quad (A.12)$$

But, by the steady state:

$$\frac{d[\text{M}^{n+1}]}{dt} = 0 = k_1[\text{M}^{n+}][\text{cyclohexenyl-OOH}] - k_5[\text{M}^{n+1}][\text{cyclohexenyl-OOH}] \quad (A.13)$$
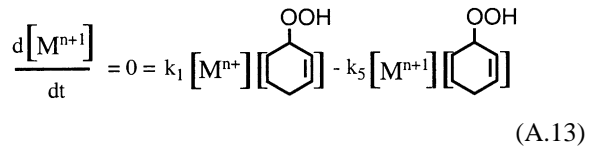
So that Eq. (A.14) results:

$$k_1[\text{M}^{n+}] = k_5[\text{M}^{n+1}] \quad (A.14)$$

Substituting (A.14) into (A.12) yields (A.15), which is identical with the previous Eq. (A.6):

$$[\text{cyclohexenyl-OO}\bullet] = \left(\frac{k_1}{2k_6}\right)^{1/2}[\text{M}^{n+}]^{1/2}[\text{cyclohexenyl-OOH}]^{1/2} \quad (A.15, \text{ also A6})$$
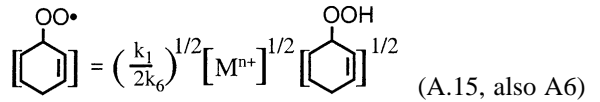
A.2. Control experiment confirming the first-order dependence on the cyclohexene concentration over 100 h of reaction time

In order to confirm the first-order dependence of the cyclohexene concentration over longer (up to 100 h) reaction times, a control experiment was carried out see if the formation of the precipitate discussed in Section 2.3.4 of the main text altered the kinetics.

In this control experiment, the oxidation of cyclohexene was carried out under standard reaction conditions (one atmosphere oxygen; constant temperature bath, $38 \pm 0.1\,^\circ\text{C}$). In the drybox, 50 mg catalyst (8.82×10^{-3} mmol in case of [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$])) was placed in a 25 ml
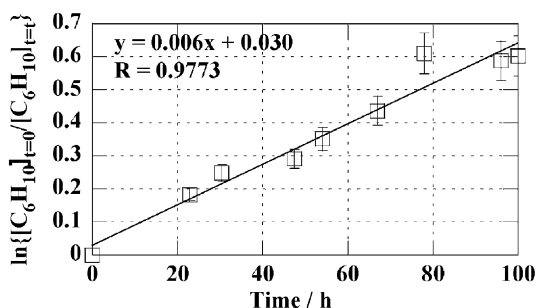
Fig. 10. First-order ln plot of cyclohexene disappearance in the cyclohexene autoxidation in dichloromethane at 38 °C and 1 atm oxygen in the presence of the catalyst precursor [n-Bu$_4$N]$_5$ Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$], over a time range of 100 h. The results indicate that the formation of a precipitate (i.e., Section 2.3.4) does not observably influence the shape, nor the rate constant, of the first-order kinetic plot.

Fig. 11. Three-point kinetic plot of k_{obs} vs. [initiator]$^{1/2}$ from the data from curves 2, 3 and 4 back in Fig. 5. The values for k_{obs} were obtained from first-order ln plots of cyclohexene concentration vs. time for different amounts of ROOH initiator (0, 0.18, and 0.44 mmol of 2-cyclohexen-1-yl hydroperoxide). Reaction conditions: 6 ml CH$_2$Cl$_2$; 1.0 ml (9.87 mmol, 1.4 M) cyclohexene; catalyst, 50 mg (8.82×10^{-3} mmol) [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD) Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$]; 1 atm dioxygen; 38 ± 0.1 °C; t = 12 h. The presence of induction periods still these experiments (see Fig. 5) means that the slope of this plot is not expected to be quantitatively reliable, and hence it was not used for any further analysis.

side-arm round-bottomed flask, equipped with a septum and a magnetic stir bar (10 mm) and was dissolved using 6 ml of dichloromethane. Then, freshly distilled cyclohexene (1 ml, 9.87 mmol) was added to the solution, a small amount of 2-cyclohexen-1-yl hydroperoxide (0.14 mmol) was also added (to avoid irreproducible induction periods during the first 4–6 h of reaction), the flask was sealed and then brought immediately out of the drybox, and the reaction was started as detailed in Section 3.3. The reaction's progress was then followed periodically by sampling via a gas-tight syringe and analyzing the reaction mixture by authentic-sample-calibrated GC. Time t = 0 was defined after the oxygen had been added and the solution warmed up to 38 ± 0.1 °C (a small error of 2–3 min is negligible to the 100 h of reaction time. The results of this control experiment are summarized in Fig. 10; note that the resultant first-order plot is still linear.

A.3. Plot of k_{obs} versus [ROOH]$^{1/2}$

This experiment was carried out as detailed in Section 3.6. The results, albeit only a three-point plot, are consistent with a [ROOH]$^{1/2}$ dependence to the rate law (Fig. 11).

A.4. Additional radical reactions of interest

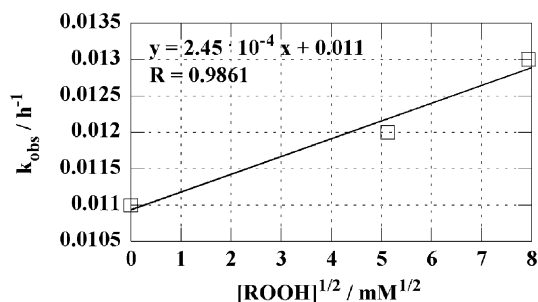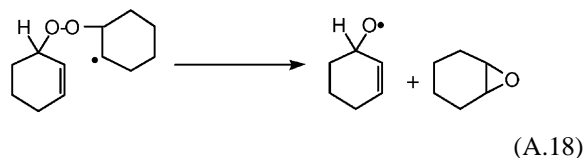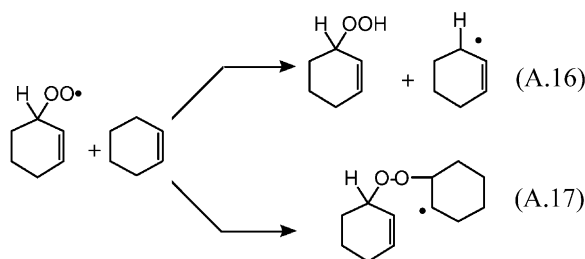Two basic reactions of the cyclohexenyl hydroperoxyl radicals are H$^\bullet$ abstraction from another molecule

of cyclohexene, Eq. (A.1), and addition, then fragmentation, to the epoxide product, Eqs. (A.16) and (A.17):
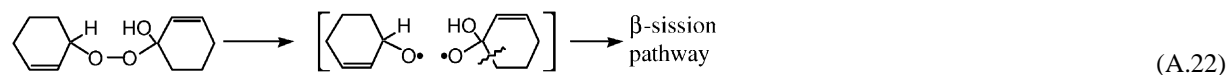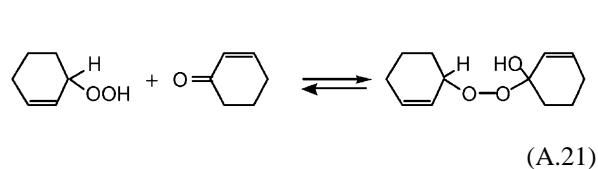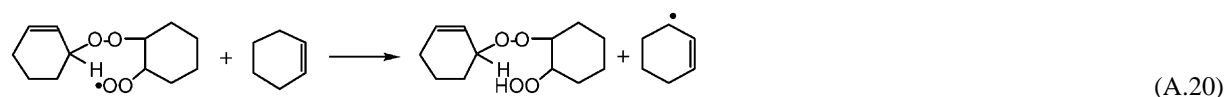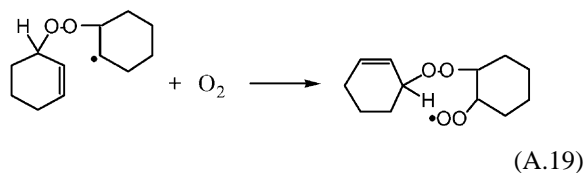

(A.16)

(A.17)

(A.18)

The total yield of epoxide is small for cyclohexenyl peroxyl radical since abstraction predominates over addition: van Sickle et al. report 88% abstraction versus 4.4% addition for the autoxidation of cyclohexene at 20 °C, a ratio of 20:1 [5d], while Sheldon and Kochi reports 95 and 5% at 70 °C, a ratio of 19:1 [2]. The result under our conditions is 95.4% and 4.6%,

for a ratio of 20:1, results which, in comparison to the literature values, confirm the involvement of cyclohexene hydroperoxyl radicals in the (autoxidation) reaction.

Also diagnostic of cyclohexene autoxidation is the low yield of cyclohexene oxide (generally 2–3% under our range of conditions) in comparison to the total yield of hydroperoxides: our value is 0.039 (at 38 °C), while Brill and Barone reports a value of 0.011 [5c] for cyclohexene autoxidation at 60 °C, and van Sickle et al. [5d] reports a value of 0.0097.
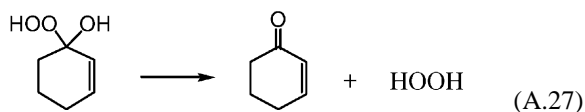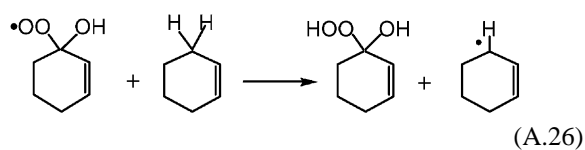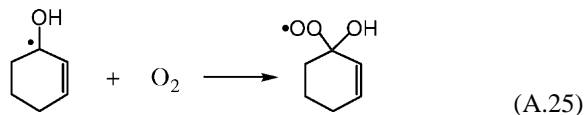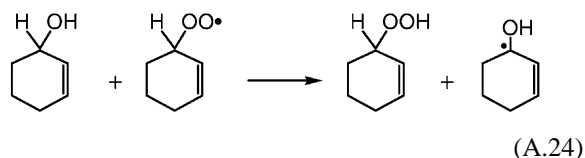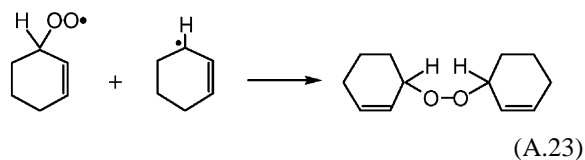
As discussed by van Sickle, higher peroxide radicals (e.g., cyclohexenyl peroxycyclohexyl radical) and hydroperoxides (cyclohexenyl peroxycyclohexyl hydroperoxide) can form from the reactions shown in Eqs. (A.19) and (A.20) which follow. One low-energy pathway for hydroperoxide decomposition is based on the interaction of cyclohexene hydroperoxide and cyclohexen-1-one (a major initial product). The perhemiketal (Eqs. (A.21) and (A.22)) is known to homolyze more easily than cyclohexene hydroperoxide [4v]; rapid subsequent β-cleavage ring opening of the 1-hydroxycyclohexenyloxy radical leads to non-cyclic products. A similar pathway has been discussed in the autoxidation of cyclohexane [4v].
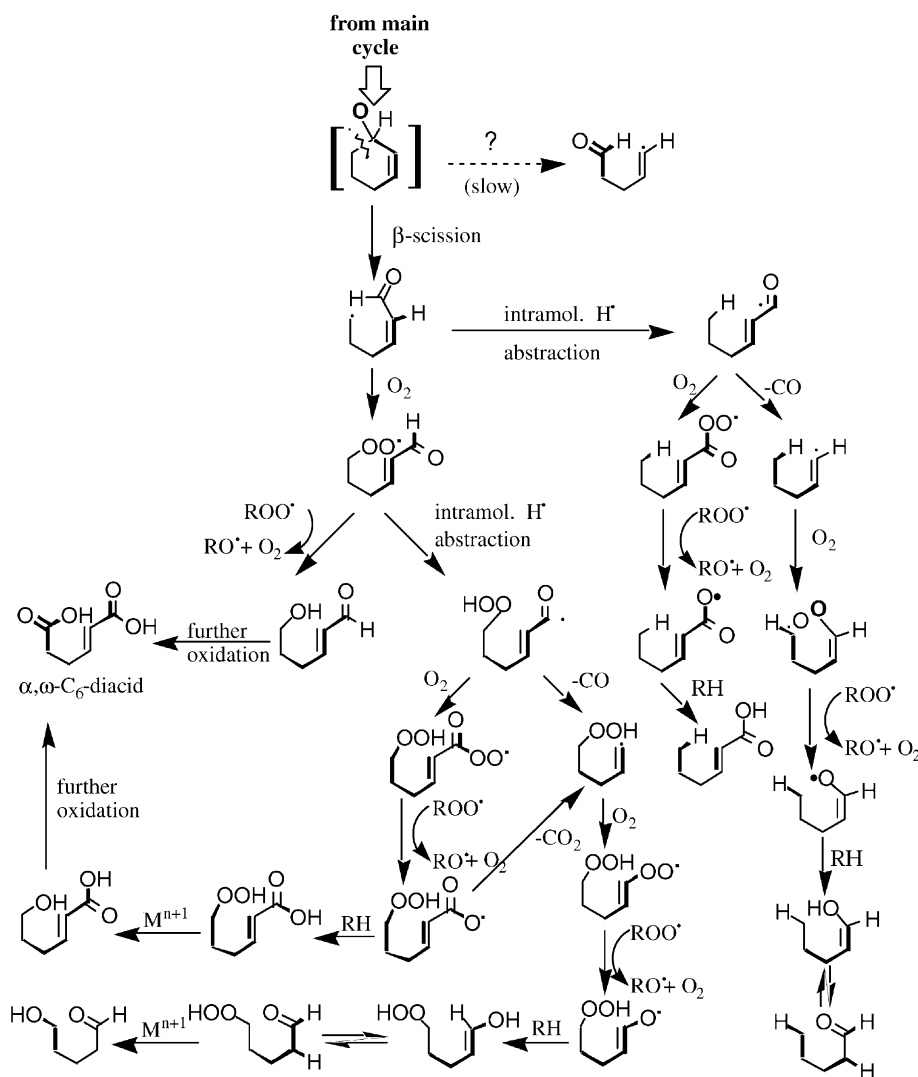
lead to an extensive product spectrum of α,ω-hydroxo acids, acid aldehydes and diacids. A summary of β-scission reactions is given in Scheme 6; possible pathways leading to ketone- and alcohol-based side products (due to the further oxidation of 2-cyclohexene-1-one and 2-cyclohexen-1-ol) are given in Schemes 7 and 8.

The formation of dicyclohexenyl peroxide in the product mixture suggests capture of alkenyl radicals by the predominant cyclohexenyl peroxyradical; hydrogen peroxide is formed in the oxidation of 2-cyclohexen-1-ol to 2-cyclohexen-1-one (Eqs. (A.23)–(A.27)).


(A.23)

(A.24)

(A.25)

(A.19)

(A.20)

(A.26)

(A.21)

β-sission pathway

(A.22)

(A.27)

Particularly under higher conversion conditions, the occurrence of β-scission ring-opening reactions can

Scheme 6. Some plausible β-scission plus other reactions leading to various non-cyclic products.

The presence of H_2O_2 (confirmed in the products; see the main text) indicates further oxidation of 2-cyclohexen-1-ol to 2-cyclohexen-1-one; hydrogen peroxide was also found in the autoxidation of cyclohexane [4v].

A.5. The influence of added transition-metal epoxidation promotors in the polyoxometalate-catalyzed autoxidation of cyclohexene

Because the products and mechanistic evidence implicated a free-radical-chain mechanism with 2-cyclohexen-1-yl hydroperoxide as an intermediate, it was of interest to follow the suggestion in the literature [34] and see if added epoxidation catalysts that work with ROOH (e.g. Mo^{6+}, V^{5+}, Ti^{4+}) were able to influence the product selectivity. The impact of such additives on the selectivity of oxidation products for the catalytic oxidation of cyclohexene in dichloromethane at $38\,°C$ and one atmosphere oxygen was studied using different polyoxometalate-to-additive ratios, and using both the $[n\text{-}Bu_4N]_5Na_3[(1,5\text{-}COD)Ir\cdot P_2W_{15}Nb_3O_{62}]$ and the
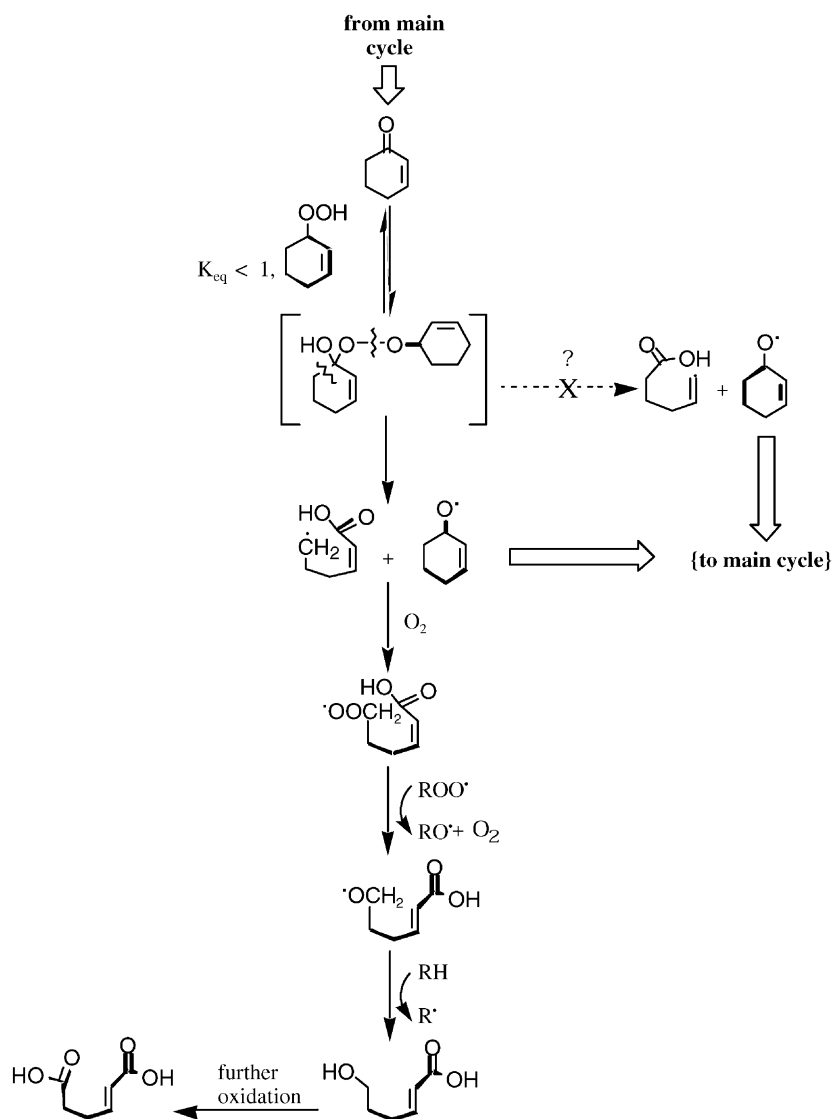
Scheme 7. Plausible ketone side reactions, based on the reaction of two main products, 2-cyclohexane-1-one and 2-cyclohexane-1-yl hydroperoxide.

unsupported, parent polyoxometalate $(n\text{-}Bu_4N)_5P_2$ $W_{15}Nb_3O_{62}$.

The *uninitiated*, catalytic autoxidation of cyclo-hexene was studied in dichloromethane at 38 °C over reaction times of 22–24 h using the experi-mental procedure and standard reaction conditions provided in the Section 3.3. Molecular ratios of 1:1 of $(n\text{-}Bu_4N)_5Na_3[(1,5\text{-}COD)Ir\cdot P_2W_{15}Nb_3O_{62}]$

to promotor $(W(CO)_6$, $Mo(CO)_6$, $MoO(acac)_2$, $Mo(CO)_3(CH_3CN)_3$, $TiO(C_2O_4)_2$, and $VO(acac)_2)$ were employed. A summary of the results is provided in Table A.1. No significant change of the product distribution was found.

In a second set of experiments, different molar ratios of $(n\text{-}Bu_4N)_5Na_3[(1,5\text{-}COD)Ir\cdot P_2W_{15}Nb_3O_{62}]$ to $Mo(CO)_6$ (1:1–1:7) were investigated using the
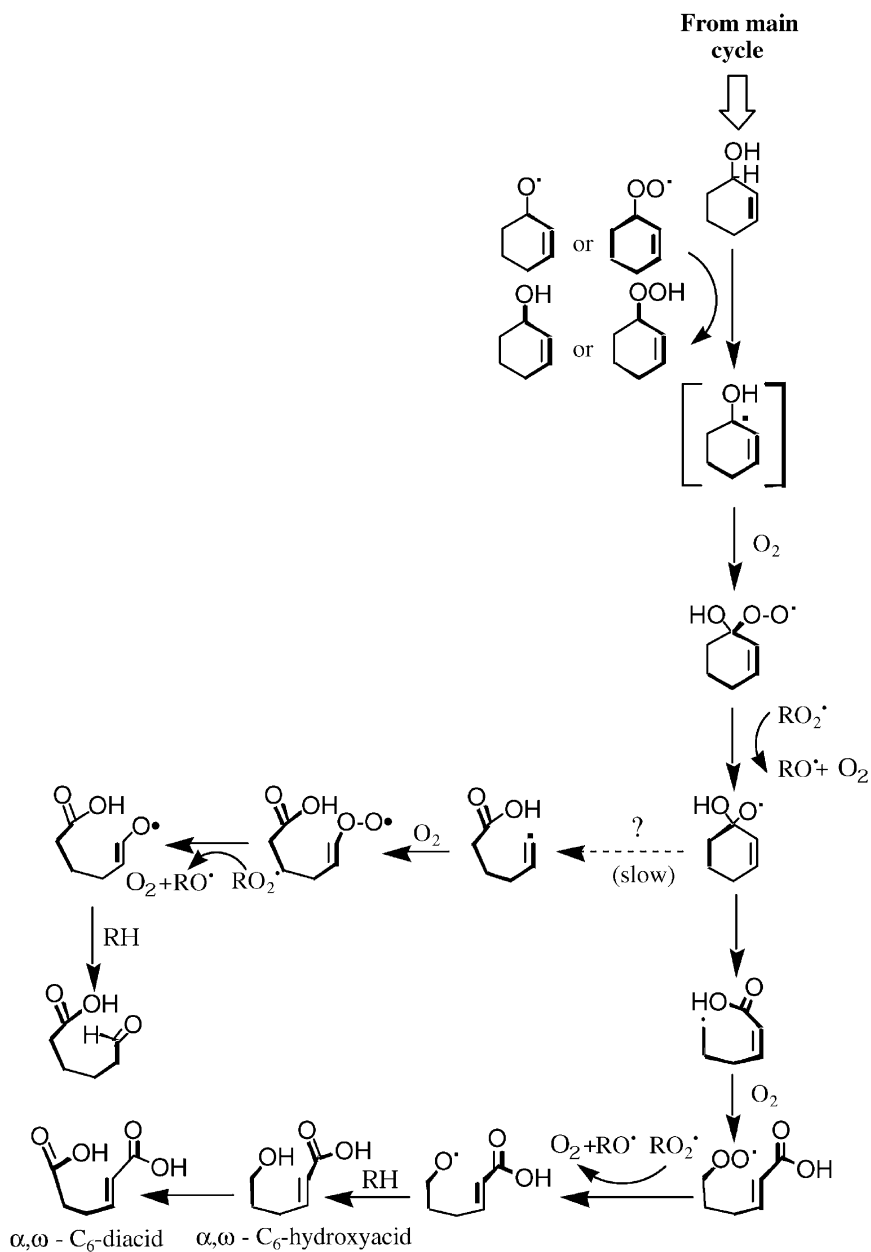
Scheme 8. Plausible side reactions from the further oxidation of 2-cyclohenene-1-ol.

Table A.1

The influence of added transition-metal epoxidation promotors on cyclohexene autoxidation in dichloromethane at 1 atm oxygen, 38 °C, and in the presence of [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$] (Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$ in the Table below) as precatalyst[a]

Catalyst	Time (h)	Conversion (%)[b]	Yield (%)[c]		
			3	**4**	**5** (epoxide)
Ir·P$_2$W$_{15}$/Nb$_3$O$_{62}$	24	24	12	10	2
Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$/VO(acac)$_2$	24	5	1	1	2
Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$/TiO(ox)$_2$	24	6	3	2	1
Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$/W(CO)$_6$	24	13	6	6	1
Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$/MoO$_2$(acac)$_2$	22	13	7	5	1
Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$/Mo(CO)$_6$	22	11	5	3	3
Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$/Mo(CO)$_3$(CH$_3$CN)$_3$	24	5	2	2	1

[a] Reaction conditions: 6 ml CH$_2$Cl$_2$; 1.0 ml (9.87 mmol, 1.4 M) cyclohexene; [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$], (∼1.26 mM; mol ratio catalyst/substrate ∼1:1200, mol ratio polyoxometalate/promotor 1:1); 1 atm dioxygen; 38 ± 0.1 °C; estimated error bars ±10%.

[b] Conversion (%) is defined as [cyclohexene (mmol)]$_{t=t}$/[cyclohexene (mmol)]$_{t=0}$ × 100%.

[c] Yield (%) is defined as [product (mmol)]/[cyclohexene (mmol)] × 100%; products, 2-cyclohexen-1-one, **3**; 2-cyclohexen-1-ol, **4**; cyclohexene oxide, **5**.

Table A.2

The influence of different [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$] (Ir·HPA in the table below) to Mo(CO)$_6$ ratios in the cyclohexene autoxidation in dichloromethane at 1 atm oxygen, and 38 °C[a]

Catalyst	Time (h)	Conversion (%)[b]	Yield (%)[c]		
			3	**4**	**5** (epoxide)
Ir·HPA	24	24	12	10	2
Ir·HPA/Mo(CO)$_6$ (1:1)	22	10	4	4	2
	26	13	5	4	3
Ir·HPA/Mo(CO)$_6$ (1:3.5)	23	14	5	6	3
	46	44	13	12	**8**
Ir·HPA/Mo(CO)$_6$ (1:7)	24	18	6	6	4
	44	46	17	16	**9**
Mo(CO)$_6$	22	5	–	3	2

[a] Reaction conditions: 6 ml CH$_2$Cl$_2$; 1.0 ml (9.87 mmol, 1.4 M) cyclohexene; [n-Bu$_4$N]$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$], (∼1.26 mM; mol ratio catalyst/substrate ∼1:1200); 1 atm dioxygen; 38 ± 0.1 °C; estimated error bars ±10%.

[b] Conversion (%) is defined as [cyclohexene (mmol)]$_{t=t}$/[cyclohexene (mmol)]$_{t=0}$ × 100%.

[c] Yield (%) is defined as [product (mmol)]/[cyclohexene (mmol)] × 100%; products, 2-cyclohexen-1-one, **3**; 2-cyclohexen-1-ol, **4**; cyclohexene oxide, **5**.

same experimental procedure as above. The results are summarized in Table A.2. Using mixtures of (n-Bu$_4$N)$_5$Na$_3$[(1,5-COD)Ir·P$_2$W$_{15}$Nb$_3$O$_{62}$] and molybdenum hexacarbonyl as the precatalyst, an increase in the amount of epoxide at higher Mo(CO)$_6$ ratios was found, Table A.2.

References

[1] (a) R.A. Sheldon, J.K. Kochi, Metal catalyzed oxidations of organic compounds in liquid phase, Oxidation Combustion Rev. 5 (1973) 135;

(b) R.A. Sheldon, J.K. Kochi, Metal catalyzed oxidations of organic compounds in liquid phase: a mechanistic approach, Adv. Catal. 25 (1976) 272–413.

[2] R.A. Sheldon, J.K. Kochi, Metal catalyzed Oxidations of Organic Compounds, Academic Press, New York, 1981.

[3] (a) V.D. Luedecke Adipic Acid, in: J.J. McKetta, W.A. Cunningham (Eds.), Encyclopedia of Chemical Processing and Design, vol. 2, Marcel Dekker, New York, 1977, pp. 128–146;

(b) G.W. Parshall, S.D. Ittel (Eds.), Homogeneous Catalysis, Central Research and Development E.I. du Pont de Nemours and Company/Wiley, Wilmington/New York, 1992, pp. 283–264;

(c) B.C. Gates (Ed.), Catalytic Chemistry, Wiley, New York, 1992, p. 63.

[4] (a) E.H. Farmer, A. Sundralingam, J. Chem. Soc. 121 (1942);
(b) J.L. Bolland, Q. Rev., Chem. Soc. 3 (1949) 1;
(c) D. Swern, J.E. Coleman, J. Am. Oil Chem. Soc. 32 (1955) 700;
(d) J.L. Skellon, Chem. Ind. (London) (1951) 629; (1953) 1047;
(e) L. Bateman, L.Q. Rev., Chem. Soc. 8 (1954) 147;
(f) G.A. Russell, J. Chem. Educ. 36 (1959) 111;
(g) E.T. Denisov, N.M. Emanuel, Russ. Chem. Rev. 29 (1960) 6;
(h) W.O. Lundberg, Autoxidation and Antioxidants, vols. 1 and 2, Wiley, New York, 1962;
(i) N.M. Emanuel, Oxidation of Hydrocarbons in the Liquid Phase, Pergamon, Oxford, 1965, p. 45;
(j) G. Scott, Atmospheric Oxidation and Antioxidants, Elsevier, Amsterdam, 1965;
(k) I.V. Berezin, E.T. Denisov, N.M. Emanuel, The Oxidation of Cyclohexane, Pergamon, Oxford, 1965;
(l) N.M. Emanuel, E.T. Denisov, Z.K. Maizus, Liquid Phase Oxidation of Hydrocarbons, Plenum Press, New York, 1967;
(m) F.R. Mayo, Oxidation of Organic Compounds, Advance Chemical Series 75, 76, 77, American Chemical Society, Washington, DC, 1968;
(n) F.R. Mayo, Accts. Chem. Res. 1 (1968) 193;
(o) L. Reichand, S.S. Stivala, Autoxidation of Hydrocarbons and Polyolefins, Marcel Dekker, New York, 1969;
(p) E.S. Huyser, Free Radical-Chain Reactions, Wiley/Interscience, New York, 1970, p. 39;
(q) J. Betts, Q. Rev., Chem. Soc. 25 (1971) 265;
(r) W.G. Lloyd, Methods Free-Radical Chem. 4 (1973) 1;
(s) J.A. Howard, Free Radicals, vol. 2, Wiley, New York, 1973, p. 3;
(t) E.T. Denisov, N.I. Mitskevich, V.E. Agabekov, Liquid Phase Oxidation of Oxygen-Containing Compounds, Consultants Bureau, Plenum Press, New York, 1977;
(u) R.A. Sheldon, J.K. Kochi, Metal Catalyzed Oxidations of Organic Compounds, Academic Press, New York, 1981;
(v) C.L. Hill (Ed.), Activation and Functionalization of Alkanes, Wiley/Interscience, New York, 1989, pp. 243–279;
(w) C.A. Tolmann, J.D. Druliner, M.J. Nappa, N. Herron, Alkane Oxidation Studies in du Pont's Central Research Department, Wiley/Interscience, New York, 1989, pp. 303–360;
(x) W. Partenheimer, Catal. Today 23 (1995) 69.

[5] (a) F. Haber, J. Weiss, Naturwissenschaften 20 (1931) 948;
(b) V.P. Kurkov, J.Z. Pasky, J.B. Lavingo, J. Am. Chem. Soc. 90 (1968) 4743;
(c) W.F. Brill, B.J. Barone, J. Org. Chem. 29 (1964) 140;
(d) D.E. van Sickle, F.R. Mayo, R.M. Arluck, J. Am. Chem. Soc. 87 (1965) 4824. Note the mechanism in this paper for the formation of higher MW peroxidic products on p. 4827;
(e) D.E. van Sickle, F.R. Mayo, E.S. Gould, R.M. Arluck, J. Am. Chem. Soc. 89 (1967) 977;
(f) M. Koelewijn, Recl. Trav. Chim. Pays-Bas 91 (1972) 759;
(g) F.R. Mayo, J. Am. Chem. Soc. 80 (1958) 2497;
(h) D.E. van Sickle, F.R. Mayo, R.M. Arluck, J. Am. Chem. Soc. 87 (1965) 4832;

(i) E.S. Gould, M. Rado, J. Catal. 13 (1969) 238;
(j) K. Kaneda, T. Itoh, Y. Fujiwara, S. Teranishi, Bull. Chem. Soc. Jpn. 46 (1973) 3810;
(k) R. Criegee, in: K. Wiberg (Ed.), Oxidations in Organic Chemistry, Academic Press, New York, 1965, p. 302;
(l) R. Criegee, H. Pilz, H. Flygare, Chem. Ber. 72 (1939) 1799;
(m) W.J. Brill, J. Am. Chem. Soc. 85 (1963) 141;
(n) A. Fusi, R. Ugo, F. Fox, A. Pasini, C. Cenini, J. Organomet. Chem. 26 (1971) 417. See p. 418 for a reference to non-volatile polymer products from cyclohexene autoxidation;
(o) J.E. Lyons, Tet. Lett. 32 (1974) 2737 (and references [1–7] therein to cyclohexene oxidation products including dimers and polymers);
(p) T. Mlodnicka, J. Mol. Catal. 36 (1986) 205;
(q) R.K. Jensen, S. Korcek, L.R. Mahoney, M. Zinbo J. Am. Chem. Soc. 101 (1979) 7574.

[6] (a) C. Walling, Acc. Chem. Res. 31 (1998) 155;
(b) P.A. MacFaul, D.D.M. Wayner, K.U. Ingold, Acc. Chem. Res. 31 (1998) 159;
(c) M.W. Grinstaff, M.G. Hill, J.A. Labinger, H.B. Gray, Science 264 (1994) 1311;
(d) P.A. MacFaul, K.U. Ingold, D.D.M. Wayner, L. Que Jr., J. Am. Chem. Soc. 119 (1997) 10594;
(e) D.W. Snelgrove, P.A. MacFaul, K.U. Ingold, D.D.M. Wayner, Tet. Lett. 37 (1996) 823;
(f) P.A. MacFaul, I.W.C.E. Arends, K.U. Ingold, D.D.M. Wayner, J.C.S. Perkin Trans. 2 (1997) 135;
(g) F. Minisci, F. Fontana, S. Araneo, F. Recupero, S. Banfi, S. Quici, J. Am. Chem. Soc. 117 (1995) 226;
(h) F. Minisci, F. Fontana, S. Araneo, F. Recupero, L. Zhao, SYNLET, 1996, p. 119;
(i) M. Newcomb, P.A. Simakov, S.-U. Park, Tet. Let. 37 (1996) 819;
(j) K.U. Ingold, P. MacFaul, in: B. Meunier (Ed.), Biomimetic Oxidations Catalyzed by Transition Metal Complexes, Imperial College Press, 2000, Chapter 2, pp. 45–89.

[7] C.L. Hill, C.M. Prosser-McCharta, Homogeneous catalysis by transition metal oxygen anion clusters, Coord. Chem. Rev. 143 (1995) 407.

[8] (a) I.V. Kozhevnikov, Russ. Chem. Rev. 56 (1987) 811;
(b) Y. Ishii, M. Ogawa, in: S. Oae (Ed.), Reviews on Heteroatom Chemistry, MYU Tokyo, 1990, p. 121;
(c) M. Misono, N. Nojiri, Appl. Catal. 64 (1990) 1;
(d) C.L. Hill, in: G. Strukul (Eds.), Metal Catalysis in Hydrogen Peroxide Oxidations, Kluwer Academic Publishers, Dordrecht, 1992, Chapter 8, pp. 253–280;
(e) Y. Ono, in: J.M. Thomas, K.I. Zamaraev (Eds.), Perspective in Catalysis, Blackwell, Oxford, UK, 1992, pp. 431–464;
(f) V. Kozhevnikov, Usp. Khim. 62 (1993) 510;
(g) M. Misono, Stud. Surf. Sci. Catal. 75 (1993) 1;
(h) T. Okuhara, M. Misono, Yuki Gosei Kagaku Kyokaishi 51 (1993) 128;
(i) C.L. Hill, G.-S. Kim, C.M. Prosser-McCartha, D. Judd, Mol. Eng. 3 (1993) 263;
(j) M.H. Dickmann, M.T. Pope, Chem. Rev. 94 (1994) 569;

(k) R.J.J. Jansen, H.M. Vanveldhuizen, M.A. Schwegler, H. Vanbekkum, Recueil des travaux chimiques des pays bas, J. Royal Netherlands Chem. Soc. 113 (1994) 115;
(l) N. Mizuno, M. Misono, J. Mol. Cat. 86 (1994) 319.

[9] (a) C. Venturello, R. D'Aloiso, J.C. Bart, M. Ricci, J. Mol. Catal. 32 (1985) 107;
(b) C. Venturello, M. Gambaro, Synthesis 4 (1989) 295;
(c) Y. Sakata, Y. Ishii, J. Org. Chem. 56 (1991) 6233;
(d) S. Sakaue, Y. Sakata, Y. Nishiyama, Y. Ishii, Chem. Lett. (1992) 289;
(e) L. Salles, C. Aubry, F. Robert, G. Chottard, R. Thouvenot, H. Ledon, J.-M. Brégault New, J. Chem. 17 (1993) 367;
(f) A.C. Dengel, W.P. Griffith, B.C. Parkin, J. Chem. Soc. Dalton Trans. (1993) 2683;
(g) L. Salles, C. Aubry, R. Thouvenot, F. Robert, C. Dorémieux-Morin, G. Chottard, H. Ledon, Y. Jeannin, J.-M. Brégeault, Inorg. Chem. 33 (1994) 871;
(h) F.P. Ballistreri, G.A. Tomaselli, R.M. Toscano, V. Conte, F. Difuria, J. Mol. Catal. 89 (1994) 295.

[10] (a) J.E. Lyons, P.E. Ellis Jr., H.K. Myers Jr., G. Suld, W.A. Langdale, US Patent 4,803,187 (1989);
(b) N.I. Kuznetsova, E.N. Yurchenko, React. Kinet. Catal. Lett. 39 (1989) 399;
(c) D.E. Katsoulis, M.T. Pope, J. Chem. Soc., Dalton Trans. (1989) 1483;
(d) L.I. Kuznetsova, M.A. Fedotov, E.N. Yurchenko, React. Kinet. Catal. Lett. 41 (1990) 333;
(e) P.E. Ellis Jr., J.E. Lyons, U.S. Patent 4,898,989 (1990);
(f) M.A. Fedotov, O.M. Il'inich, L.I. Kuznetsova, G.L. Semin, Y.S. Vetchinova, K.I. Zamaraev, Catal. Lett. 6 (1990) 417;
(g) J.E. Lyons, P.E. Ellis Jr., V.A. Durante, in: R.A. Grasselli, A.W. Sleight (Eds.), Studies in Surface Science and Catalysis, Elsevier, Amsterdam, 1991, pp. 99–116;
(h) R. Neumann, M. Levin, in: L.I. Simandi (Ed.), Dioxygen Activation and Homogeneous Catalytic Oxidation, Elsevier, Amsterdam 1991, pp. 121–127;
(i) E.N. Yurchenko, T.D. Gutsul, L.I. Kuznetsova, Koord. Khim. 18 (1992) 939;
(j) N. Mizuno, M. Tateishi, T. Hirose, M. Iwamoto, Chem. Lett. (1993) 1985;
(k) N. Mizuno, T. Hirose, M. Tateishi, M. Iwamoto, Chem. Lett. (1993) 1839;
(l) N. Mizuno, T. Hirose, M. Tateishi, M. Iwamoto, J. Mol. Catal. 88 (1994) L125.

[11] (a) R. Neumann, M. Dahan, Nature 388 (1997) 363;
(b) R. Neumann, M. Dahan, J. Am. Chem. Soc. 120 (1998) 11969.

[12] (a) H. Weiner, Y. Hayashi, R.G. Finke, Inorg. Chim. Acta 291 (1999) 426;
(b) H. Weiner, R.G. Finke, J. Am. Chem. Soc. 121 (1999) 9831.

[13] (a) D.K. Lyon, W.K. Miller, T. Novet, P.J. Domaille, E. Evitt, D.C. Johnson, R.G. Finke, J. Am. Chem. Soc. 113 (1991) 7209;
(b) D. Mansuy, J.-F. Bartoli, D.K. Lyon, R.G. Finke, J. Am. Chem. Soc. 113 (1991) 7222;
(c) W.M. Droege, R.G. Finke, J. Mol. Catal. 69 (1991) 323;

(d) Polyoxometalates: from platonic solids to anti-retroviral activity, in: A. Müller, M.T. Pope (Eds.), Proceedings of the Meeting at the Center for Interdisciplinary Research in Bielefeld, Germany, 15–17 July, Kluwer Scientific Publishers, Dordrecht, The Netherlands, 1992;
(e) R.G. Finke, Polyoxometalate Chemistry, in: A. Müller, M.T. Pope (Eds.), Proceedings of the Meeting at the Center for Interdisciplinary Research in Bielefeld, Germany; Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 363–390.

[14] C.L. Hill, I.A. Weinstock, On the trail of dioxygen activation, Nature 388 (1997) 332.

[15] (a) N. Mizuno, D.K. Lyon, R.G. Finke, US Patent 5,250,739 (1993);
(b) N. Mizuno, D.K. Lyon, R.G. Finke, J. Catal. 128 (1991) 84;
(c) Y. Lin, R.G. Finke, J. Am. Chem. Soc. 116 (1994) 8335;
(d) Y. Lin, R.G. Finke, Inorg. Chem. 33 (1994) 4891.

[16] (a) G.A. Russell, J. Am. Chem. Soc. 79 (1957) 3871;
(b) K.U. Ingold, Accounts Chem. Res. 2 (1969) 1;
(c) K.U. Ingold, Pure Appl. Chem. 15 (1967) 49;
(d) J.A. Howard, K.U. Ingold, Can. J. Chem. 46 (1968) 2655, 2661; see also [3];
(e) J.E. Bennett, D.M. Brown, B. Mile, Trans. Faraday Soc. 66 (1970) 386, 397;
(f) J.E. Bennett, D.M. Brown, B. Mile, Chem. Commun. (1969) 504;
(g) K. Adamic, J.A. Howard, K.U. Ingold, Chem. Commun. (1969) 505.

[17] (a) J.F. Roth, CHEMTECH June (1991) 357;
(b) T. Hayashi, K. Tanaka, M. Haruta, J. Catal. 178 (1998) 566.

[18] H. Weiner, A. Trovarelli, R.G. Finke, Polyoxoanion-Supported Catalysis: Evidence for a $P_2W_{15}Nb_3O_{62}{}^{9-}$-Supported Iridium Cyclohexene Oxidation Catalyst Starting from $(n\text{-}Bu_4N)_5$ $Na_3[(1,5\text{-}COD)Ir\cdot P_2W_{15}Nb_3O_{62}]$, J. Mol. Catal. 191 (2003) 253–279.

[19] H. Weiner, Y. Hayashi, R.G. Finke, Inorg. Chem. 38 (1999) 2579 (see Fig. 1).

[20] (a) N. Mizuno, H. Weiner, R.G. Finke, J. Mol. Catal. 114 (1996) 15;
(b) H. Weiner, R.G. Finke, Co-oxidative Epoxidations of Olefins with Molecular Oxygen and Aldehyde Reductants. Part II. Development and Kinetic and Mechanistic Studies of a Radical-Initiated, High Yield and High Selectivity but Uncatalyzed Process, in preparation.

[21] (a) J.K. Kochi (Ed.), Free Radicals, vol. II, Wiley, New York, 1973, Chapters II–IV, pp. 5–37;
(c) E.S. Huyser, Free Radical Chain Reactions, Wiley/Interscience, New York, 1970, p. 39;
(c) J.A. Howard, in: K. Kochi (Eds.), Free Radicals, vol. 2, Wiley, New York, 1973, p. 3.

[22] J.A. Howard, in: K. Kochi (Ed.), Free Radicals, vol. 2, Wiley, New York, 1973, p. 11.

[23] (a) J. Halpern, T. Okamoto, A. Zakhariev, J. Mol. Cat. 2 (1976) 65;
(b) J. Halpern, Inorg. Chim. Acta 50 (1981) 11.

[24] (a) G.M. Bulgakova, A.N. Shupik, I.P. Skibida, K.I. Zamaraev, Z.K. Maizus, Docl. Akad. Nauk SSSR 199 (1971) 376;
(b) A.V. Tobolsky, India Rubber World 118 (1948) 363.

[25] (a) E.G. Janzen, Accounts Chem. Res. 4 (1971) 31;
(b) E.G. Janzen, L.D. Haire, Adv. Free Radical Chem. 1 (1990) 253.

[26] (a) R. Criegee, H. Pilz, H. Flygare, Ber. 72 (1939) 1799;
(b) A.A. Fruner, J. Org. Chem. 42 (1977) 3194;
(c) A.J. Bloodworth, H.J. Eggelte, J. Chem. Soc., Perkin Trans. 1 (1981) 1375;
(d) G.O. Schlenck, K.H. Schulte-Elte, Ann. 618 (1958) 185.

[27] (a) L. Bertrand, J.A. Franklin, P. Goldfinger, G. Huybrechts, J. Phys. Chem. 72 (1968) 3926;
(b) L. Bertrand, L. Exsteen-Meyers, J.A. Franklin, G. Huybrechts, J. Olbregts, Int. J. Chem. Kinetics 3 (1971) 89;
(c) V.W. Day, T.A. Eberspacher, W. Klemperer, B. Zhong, J. Am. Chem. Soc. 116 (1994) 3119.

[28] (a) M. Pohl, D.K. Lyon, K. Mizuno, K. Nomiya, R.G. Finke, Inorg. Chem. 34 (1995) 1423;
(b) M. Pohl, Y. Lin, T.J.R. Weakley, K. Nomiya, M. Kaneko, H. Weiner, R.G. Finke, Inorg. Chem. 34 (1995) 767;
(c) T. Nagata, M. Pohl, H. Weiner, R.G. Finke, Inorg. Chem. 36 (1997) 1366;
(d) H. Weiner, J.D. Aiken III, R.G. Finke, Inorg. Chem. 35 (1996) 7905.

[29] (a) R. Criegee, H. Pilz, H. Flygare, Ber. 72 (1939) 1799;
(b) L. Bateman, H. Hughes, J. Chem. Soc. (1952) 4594;
(c) For an alternative route to cyclohexene hydroperoxide see: A.A. Frimer, J. Org. Chem. 19 (1977) 3194;
(d) O.L. Magelli, C.S. Shepard, in: D. Swern (Ed.), Organic Peroxides, vol. I, Wiley/Interscience, New York, 1970, pp. 1–19;
(e) R. Hiatt, in: Organic Peroxides, Wiley/Interscience, New York, 1970, pp. 1–39 and 114–115;

(f) A.G. Davies, Organic Peroxides, Butterworths, London, 1961, pp. 1–41;
(g) A.G. Tobelsky, R.B. Mesrobian, Organic Peroxides, Interscience, New York, 1954, pp. 1–11.

[30] (a) L.W. Fine, M. Grayson, V.H. Suggs, J. Organomet. Chem. 22 (1970) 219;
(b) R.M. Johnson, I.W. Siddigi, The Determination of Organic Peroxides, Pergamon Press, New York, 1970, pp. 15–28.

[31] (a) A.C. Melnyk, N.K. Kildahl, A.R. Rendina, D.H. Busch, J. Am. Chem. Soc. 101 (1979) 3232;
(b) For initial rate method see: R.G. Wilkins (Ed.), Kinetics and Mechanism of Reactions of Transition Metal Complexes, 2nd ed., VCH, New York, 1991, pp. 3–4.

[32] D.C. Harris Quantitative Chemical Analysis, 3rd ed., Freeman, New York, 1991, pp. 410–419.

[33] A.E. Pierce, Silylation of organic compounds, in: Identification of Organic Compounds with the Aid of Gas Chromatography, Pierce Chemical Company/McGraw-Hill, Rockford, IL/New York, 1968/1973, p. 163.

[34] (a) M.N. Sheng, J.G. Zajacek, Hydroperoxide oxidations catalyzed by metals, in: F.R. Mayo (Ed.), Oxidation of Organic Compounds, Advances in Chemistry Series 76, vol. 2, ACS, Washington, DC, 1968, pp. 418–431;
(b) J. Kollar, US Patent 3,351,635 (1967);
(c) H.P. Wulff, US Patent 3,923,843 (1975);
(d) R.A. Sheldon, Aspects Homog. Catal. 4 (1981) 3;
(e) B.H. Isaacs, US Patent 4,590,172 (1986);
(f) M.K. Trost, R.G. Bergmann, Organometallics 10 (1991) 1172;
(g) K.A. Jorgensen, Chem. Rev. 89 (1989) 431;
(h) A.O. Chong, B. Sharpless, J. Org. Chem. 42 (1977) 1587;
(i) T. Iwahama, G. Hatta, S. Sakaguchi, Y. Ishii, Chem. Comm. (2000) 163.

[35] M.A. Wateky, R.G. Finke, J. Am. Chem. Soc. 119 (1997) 10382.