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Full Paper

Mono, Di and Trifunctional Cyclic Organic Peroxides: The Effect of Substituents and Ring Size on their Thermolysis in 1,4-dioxan

Rosa Nesprias,[A,B,C] *Gladys Eyler,*[B] *and Adriana Cañizo*[B]

[A]Department of Science Basic, Agronomy Faculty, National University of Center of The Buenos Aires Province (UNCPBA), Italy Republic 780, (PC: 7300), Azul, Buenos Aires, Argentina.
[B]Department of Chemistry Engineering, Engineering Faculty, National University of the Center of the Buenos Aires Province (UNCPBA), del Valle Avenue 5737, (B7400JWI) Olavarría, Buenos Aires, Argentina.
[C]Corresponding author. Email: knespria@faa.unicen.edu.ar

The thermal decomposition reaction of cyclic organic peroxides was studied in 1,4-dioxan at initial concentrations between ~10^{-4} and 10^{-2} mol L^{-1} and at a temperature interval between 100 and 170°C, according to the thermal stability of each compound. The kinetic behaviour observed in all systems studied follows a pseudo first order kinetic law up to at least ~86 % of peroxide conversion. An important substituent effect is operative on the rate constant values and consequently on the activation parameters of the thermal decomposition reaction. The application of different treatments (compensation affect or a statistical treatment) on the kinetic data shows the existence of two sets of cyclic peroxides with comparable kinetic behaviour. Different peroxide–solvent interaction mechanisms can be considered within each series.

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Introduction

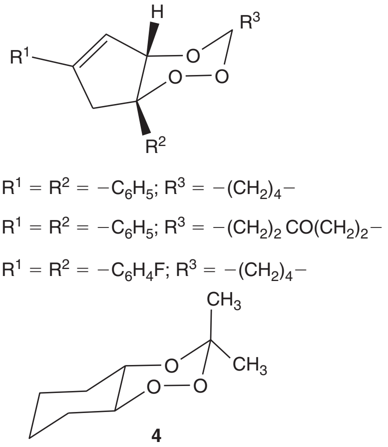
In recent years, cyclic organic peroxides with one or more peroxidic bonds (O–O) in the molecule, have gained great importance worldwide due to the different uses and applications found for this family of compounds. Among the most important are substituted 1,2,4-trioxacyclohexanes with interesting pharmacological properties. On the other hand, substituted 1,2,4,5-tetraoxacyclohexanes and 1,2,4,5,7,8-hexaoxacyclononanes are used in industry as polyfunctional initiators of polymerization.[1]

Currently 300–500 million people worldwide have malaria. Each year, 1–2 million people, mostly young children in Africa, Asia, and South America, die as a result of this infectious disease.[2] There are several drugs that, in the past, were effective against malaria, spread by the parasite *Plasmodium falciparum*. Due to the increasing resistance of this kind of malaria to traditional drugs such as chloroquine, considerable effort has been made in the past years to discover more powerful chemotherapeutics against the disease.[3,4] Artemisinin, a natural product of the vegetal extract of the Artemisia annual used in an old Chinese fever-reducing medicine is the prototype of a new class of anti-malarial drugs.

The artemisinin-like high activity might be attributed to a *cis*-fused bicyclic ring of 1,2,4-trioxacyclohexane and reinforced by an aryl substituent attached to the heterocycle.[3,4] The existence of a peroxidic bond in the 1,2,4-trioxane ring is essential for the anti-malarial activity of this class of drugs. These molecules act on heme released by the parasite. The transference of one electron from iron(II) to peroxide leads to the formation of carbon-centred free radicals of trioxane. Finally, the damage of key proteins necessary for the parasite's survival occurs. The structural arrangement of the heterocyclic ring in the region of the peroxide group is essential information to investigate its activation mechanism. A strong indication about the importance of the steric hindrance in the reaction with iron(II) has been reported.[5]

On the other hand, cyclic organic peroxides are usually used as free radical initiators in free radical polymerization of most commercial, industrially produced vinyl polymers such as polystyrene, poly(methyl methacrylate), polyethylene, and poly(vinyl chloride). Cyclic organic di- and triperoxides decompose thermally by homolytic cleavage of the O–O bond to give an intermediate biradical, which in turn initiates the polymerization of vinyl monomers. The biradical species is incorporated into the polymer structure yielding polymeric species containing peroxide groups that decompose later during the polymerization process. Since the nature of the biradical formed is dependent on the peroxide structure and has a strong influence on the final polymer properties, it is important to clarify the initiation mechanism of organic peroxides, in particular di- and triperoxides, which can be considered as multifunctional initiators as a consequence of the presence of two or three active sites in the peroxide molecule.[6]

In this work, a kinetic study of the thermal decomposition of different mono-, di-, and trifunctional cyclic organic peroxides **1**–**3**, **5**–**7**, and **9** (Figs 1–3) in 1,4-dioxan at different temperatures is reported. Kinetic and activation parameters can be compared with those previously found for **4**,[7] **8**,[8] and **10**[9] (Figs 1–3) in the same solvent.



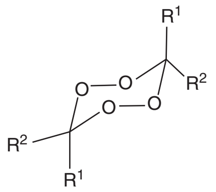
1 $R^1 = R^2 = -C_6H_5$; $R^3 = -(CH_2)_4-$

2 $R^1 = R^2 = -C_6H_5$; $R^3 = -(CH_2)_2CO(CH_2)_2-$

3 $R^1 = R^2 = -C_6H_4F$; $R^3 = -(CH_2)_4-$

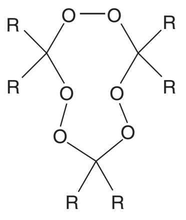
4

Fig. 1. Chemical structures of the 1,2,4-trioxacyclohexanes: *cis*-6-phenyl-5,6-(2-phenylpropylidene)-3,3-tetramethylene-1,2,4-trioxacyclohexane (**1**), *cis*-6-phenyl-5,6-(2-phenylpropylidene)-3,3-(pentan-3-ona)-1,2,4-trioxacyclohexane(**2**), *cis*-6-p-fluorphenyl-5,6-(2-p-fluorphenylpropylidene)-3,3-tetramethylene-1,2,4-trioxacyclohexane (**3**), and *trans*-3,3-dimethyl-5,6-tetramethylene-1,2,4-trioxacyclohexane (**4**).



5 $R^1 = R^2 = -(CH_2)_2CH_3$
6 $R^1 = -CH_3$; $R^2 = -C(CH_3)_3$
7 $R^1 = R^2 = -CH_3$
8 $R^1 = -C_6H_5$; $R^2 = -CH_3$

Fig. 2. Chemical structures of the 1,2,4,5-tetraoxacyclohexanes: 3,3,6,6-tetra-*n*-propyl-1,2,4,5-tetraoxacyclohexane (**5**), 3,6-ditertbutyl-3,6-dimethyl-1,2,4,5-tetraoxacyclohexane (**6**), 3,3,6,6-tetramethyl-1,2,4,5-tetraoxacyclohexane (7), and *trans*-3,6-dimethyl-3,6-diphenyl-1,2,4,5-tetraoxacyclohexane (**8**).



9 $R = -CH_3$
10 $R = -CH_2CH_3$

Fig. 3. Chemical structures of the 1,2,4,5,7,8-hexaoxacyclononanes: 3,3,6,6,9,9-hexamethyl-1,2,4,5,7,8-hexaoxacyclononane (**9**) and 3,3,6,6,9,9-hexaethyl-1,2,4,5,7,8-hexaoxacyclononane (**10**).

Results and Discussion

The thermal decomposition reaction of organic cyclic peroxides was studied in 1,4-dioxan at initial concentrations between ~10^{-4} and 10^{-2} mol L^{-1} and at a temperature interval between 100 and 170°C, according to the thermal stability of each compound (Table 1). The kinetic behaviour observed in all systems studied follows a pseudo first order kinetic law up to at least ~86 % of peroxide conversion. The initial peroxide concentration is relatively low to avoid effects of induced second order decomposition reactions that would accelerate the thermal decomposition of the peroxides at higher conversions.

Table 1. Pseudo-first-order rate constant values (k_{exp}) for the thermal decomposition reaction of cyclic organic peroxides in 1,4-dioxan

Peroxide	T [°C]	k_{exp} ($\times 10^{-6}$) [s^{-1}]	r^A
1	110	39.1	0.999
	120	117	
	130	327	
	140	788	
2	120	61.7	0.982
	130	213	
	140	672	
	150	1105	
3	110	69.9	0.993
	120	143	
	130	342	
	140	991	
4^B	135	19.8	0.988
	143	41.1	
	143	31.9	
	150	70.7	
	150	72.0	
	165	158	
5	140	16.6	0.997
	150	73.0	
	160	216	
	170	792	
6	120	18.5	0.989
	130	70.4	
	140	132	
	150	349	
7	140	4.84	0.999
	150	14.8	
	160	23.2	
	170	68.2	
8^C	140	9.00	0.990
	150	18.5	
	160	38.5	
	170	117	
9	140	1.18	0.999
	150	6.43	
	160	14.1	
	170	70.1	
10^D	140	45.0	0.998
	145	105	
	150	233	
	165	1680	
	172	2150	

^{A}Correlation coefficient according to the Arrhenius equation.
^{B}Ref. [7].
^{C}Ref. [8].
^{D}Ref. [9].

The temperature effect on the experimental rate coefficient (k_{exp}) in the investigated solvent for each of the investigated compounds can be represented by the Arrhenius equation (see Table 2 for data). The linearity of the Arrhenius equations over a relatively large temperature interval (30°C) suggests that calculated activation parameters for all the organic cyclic peroxide thermal decomposition reactions in 1,4-dioxan belong to a simple process. The rate constant values (Table 1) could be associated

Table 2. Data for the Arrhenius equations for the experimental rate coefficients (k_{exp}) of compounds 1–3, 5–7, and 9 in 1,4-dioxan

The Arrhenius equation is given by $\ln k_{exp}$ (s^{-1}) = $\ln A - E_a/RT$, where E_a is the activation energy, where conversion factor is 1 cal = 4.19 joul, A is a pre-exponential factor, R is the gas constant, and T is the temperature (K). The errors correspond to the standard deviations derived from a treatment of the kinetic data by the method of minimum squares.[10]

Compound	lnA	E_a [cal mol^{-1}]
1	31.4 ± 0.7	31610 ± 292
2	31.9 ± 3.9	32391 ± 1264
3	28.5 ± 1.7	29158 ± 690
5	47.0 ± 1.7	47621 ± 711
6	29.3 ± 3.0	31298 ± 1241
7	26.2 ± 3.1	31535 ± 1320
9	46.0 ± 4.8	48981 ± 2052

with the initial O–O bond rupture to form an intermediate biradical species. Thus, the first step in the thermolysis mechanism of these peroxides in solution is initiated by a process of the type represented in Scheme 1 for generic molecules of a substituted mono-, di-, and trifunctional cyclic organic peroxide.

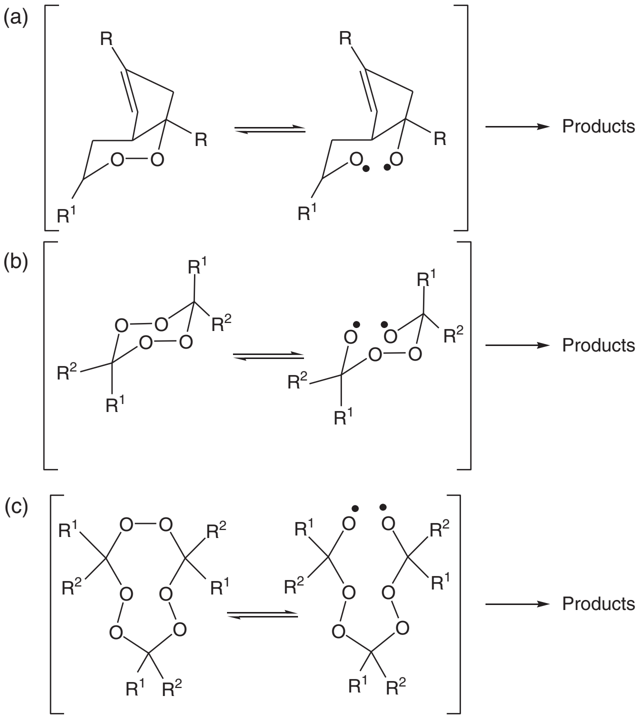
In previous studies,[11] it has been demonstrated that the initial biradical species undergo a further thermal decomposition either by C–C, C–O, or O–O bond rupture, to form free radicals that react with the solvent or combine together to generate a different final product.

Schuster and Bryant[12] in 1978 demonstrated that upon thermolysis the trioxane **4** undergoes unimolecular cleavage to form acetone and adipaldehyde and reported that the biradical formed from homolysis of the O–O bond (Scheme 1a) must rearrange rapidly by an α-cleavage reaction.

Cyclopentanone was the main reaction product of the decomposition of **1** and **3** (Scheme 2) as identified by HPLC and originated from C–O rupture of the initial biradical. Moreover, the observation of benzene as a minor product from the decomposition of **1** and **2** evidences the C–C bond rupture to form a phenyl radical which later extracts hydrogen from the solvent (Scheme 3 where R = Ph).

The biradical species obtained from the decomposition of compound **5** (Scheme 1b) can undergo either C–O bond cleavage, to give 4-heptanone and O_2 (Scheme 4, paths a and b, where $R^1 = R^2 = CH_3CH_2CH_2$), or O–O and C–C bond cleavages occur to give *n*-propyl and butanoate radicals (Scheme 4, paths c and d). Butanoate radicals can abstract a hydrogen atom from the solvent to give butanoic acid and a new radical species ($S^\bullet$) derived from the solvent (Scheme 3, where $R = R^2COO$) or take part in some radical–radical reaction to form *n*-propylbutanoate (Scheme 4, path e). A radical–radical coupling reaction between two *n*-propyl radicals may explain the *n*-hexane detected as a product (Scheme 4, path f). The presence of 4-heptanone as a peroxide decomposition product was verified through the interpretation of the mass spectrum and also by comparison of retention times with an authentic sample of this compound. The presence of hexane, *n*-propyl butanoate, and propane was qualitatively identified by interpretation of their mass spectrum.[13]

3,3-Dimethyl-2-butanone (Scheme 4, paths a and b, where $R^1 = (CH_3)_3C$, and $R^2 = CH_3$) and 2-methylpropane (Scheme 3, where $R = (CH_3)_3C$), were detected by gas chromatography–mass spectrometry (GC-MS). The radical species (2-methylpropyl radical) formed by C–C bond rupture



Scheme 1.

(Scheme 4, path a) abstracts a hydrogen atom from the solvent to form 2-methylpropane (Scheme 3, where $R = (CH_3)_3C$) and 2-tertbutyl-1,4-dioxane (Scheme 5, where $R^1 = (CH_3)_3C$).

The decomposition of **7** gives acetone (Scheme 4, paths a and b, where $R^1 = R^2 = CH_3$), methane (Scheme 3), and ethane (Scheme 4, path f) as the main organic products identified, in all cases $R = CH_3$.

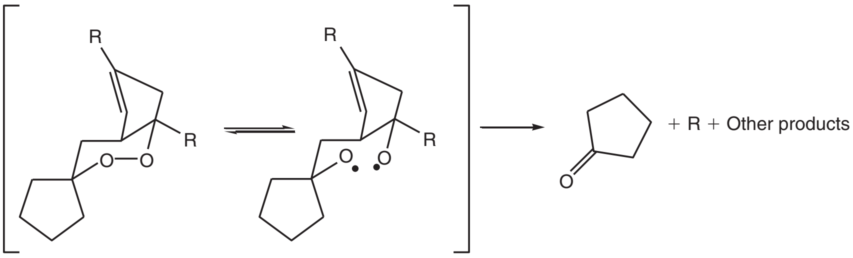
During the thermal decomposition of **9** (Scheme 1c), methane (Scheme 3, where $R = CH_3$), ethane (Scheme 4, path f), acetone (Scheme 6, upper), and a solvent derived product (2,2-bi-1,4-dioxan) (Scheme 6, lower) were formed.

According to the kinetic data reported in Table 1 monofunctional cyclic organic peroxides (Fig. 1) are more reactive than the di- and trifunctional compounds investigated in this work (Figs 2 and 3).

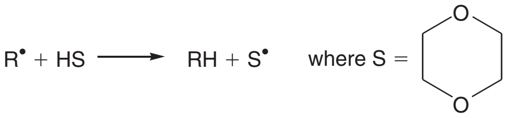
Compounds **1**–**3** have similar structures around the 1,2,4-trioxacyclohexane ring in a *chair* conformation, have large volumes (Table 3), possess aromatic rings or an unsaturated ring bonded directly to the peroxidic cycle, and a cyclic substituent of five or six members, and as a consequence they show analogous kinetic behaviour (Table 1). The high reactivity of these trioxanes is probably associated with the large size of the substituents.

Thus, once the ring is opened through the initial O–O bond (Scheme 1a) the intermediate species formed would adopt highly stable conformations within a new reorganized solvent cage that complicates the recyclization process. Consequently, the reaction progresses with the decomposition of the initial biradical to form the detected reaction products with high values of k_{exp} (Table 1).

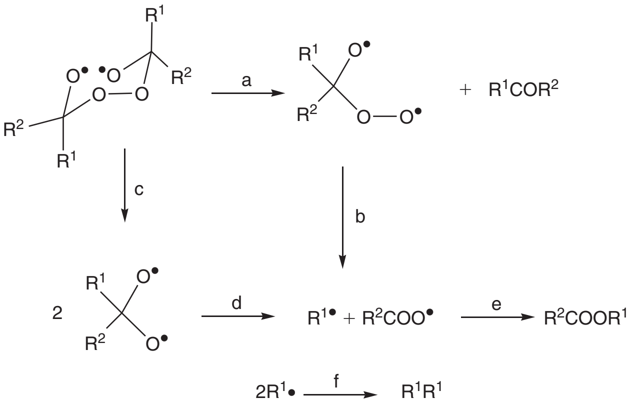
Studies carried out by Jubert[14] et al. on trioxane **1** have revealed that there are 18 different conformers geometrically optimal within the energy range of 14 kcal mol^{-1} corresponding to a mixture of chair and boat conformations of the molecule



Scheme 2.



Scheme 3.



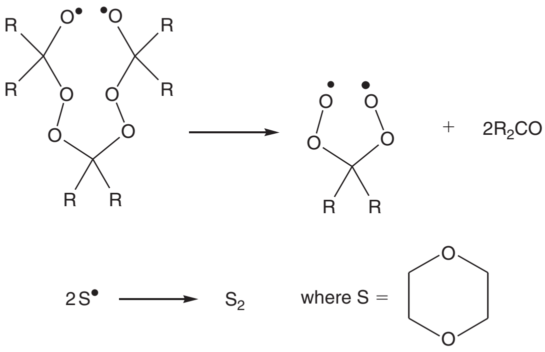
Scheme 4.

Scheme 5.

studied. The existence of different conformations for 1,2,4-trioxacyclohexane plus the large size of substituents in **1**–**3** (Fig. 1) gives good reasons to interpret the differences observed in their reactivities in solution assuming that they have differences in their solvation mechanisms.

The van der Waals volumes of trioxanes **1**–**3** approximately duplicate the size of **4**[7] (Fig. 1, Table 3) which behaves as the most stable member of this family (Table 1). Compound **4** has methyl groups attached directly to the cycle and decomposes 24 times more slowly than **3**, 19 times more slowly than **1**, and 16 times more slowly than **2**. It can be postulated that the compound **4**–solvent interaction mechanism within the solvent cage would be different from that proposed for trioxanes **1**–**3**.

The rate constant values are influenced by changing substituent as can be clearly observed when the reactivity of diperoxide **7** (methyl substituted) is compared with **5**, **6**, and **8** in 1,4-dioxan (Table 1) and in other organic solvents like toluene, acetone, and propan-1-ol (Table 4). The presence of methyl groups as



Scheme 6.

Table 3. Calculated van der Waals volumes for the different cyclic organic peroxides according to the expression deduced by Zhao et al.[25]

Peroxide	van der Waals volume [Å^3 molecule^{-1}]
1	313.5
2	336.9
3	318.4
4	165.9
5	273.6
6	238.9
7	135.2
8	245.8
9	203.9
10	308.4

Table 4. First order rate constant values (k_{exp}) for the thermal decomposition reaction of cyclic peroxides in different solvents

Peroxide	k_{exp} ($\times 10^{-6}$) [s^{-1}]		
	Toluene (145°C)	Acetone (150°C)	Propan-1-ol (150°C)
1^A	1170	–	–
4^A	4	–	–
5^{A,B}	59	183	591
6^{A,B}	560	1178	1283
7^{A,B}	2.8	6.67	26.7
8^A	2.2	–	–
9^{A,B}	4.9	9.1	25
10^{A,B}	66	255	268

[A] Ref. [16].
[B] Ref. [17].

substituents of the tetraoxacyclohexane ring in **7** clearly stabilizes the molecule, probably because it is confined in a compact solvent cage where the recyclization reaction is highly probable. Similar kinetic results have been obtained in previous works while studying the thermal decomposition in benzene,[15] toluene,[16] acetone, and propan-1-ol,[17] which demonstrates that **7** decomposes at the lowest rates in comparison with those cyclic peroxides with voluminous substituents (e.g., *n*-propyl, *tert*-butyl, and phenyl) (Table 4).

A comparison between the molecular structures of **9**[18,19] and **10**[20] shows that substitution of a methyl group by an ethyl groups does not introduce additional strain in the cyclononane ring system. The hexaoxacyclononane core in **10** is stabilized in a twisted-boat–chair conformation with a local symmetry of approximately D_3,[20] very close to that previously described for **9**.[19] Triperoxide **9**, in its solid state, has been used as a primary explosive in terrorist acts[21] such as the 2005 London bombing,[22] nevertheless, in its crystalline form **10** is not as sensitive to impact or temperature changes as **9**. On the other hand, when methyl groups are replaced by ethyl groups as substituents on the hexaoxacyclononane ring (**10** in Fig. 3) the reactivity in solution is substantially increased (Table 1 and 4). In this work, it was found that **10** is 38 times more reactive than **9** in 1,4-dioxan at 140°C, even so the differences in reactivity are greater at higher temperatures.

It has been demonstrated that **9** is highly stable in different organic solvents (Table 4).[23,24] On the other hand, when comparing acetone cyclic peroxides **7** and **9** with cycles of different size it is possible to observe that in 1,4-dioxan at 170°C their reactivities are practically the same, as it was observed in propan-1-ol at 150°C (Table 4).

The dependence of the rate constant values at 140°C on the calculated van der Waals volumes for the cyclic organic peroxides (Table 3) were in accord with the expression deduced by Zhao et al.,[25] and is represented in Fig. 4. Compounds **4**, **7**, and **9** have the smallest volumes in each family, include methyl substituents, and show the lowest reactivity in solution. It is likely that the solvent molecules are able to interact more strongly with a small peroxide molecule generating a close packed system. Thus, peroxides **4**, **7**, and **9** in solution would be confined to a small 'solvent cage' with strong interaction energy, delaying the subsequent decomposition of the critical state of the reaction (formation of a biradical species) to yield the corresponding reaction products (Scheme 1).

Diperoxide **6** has shown a very high reactivity not only in 1,4-dioxan (Table 1) but in aprotic non-polar (toluene),[16] aprotic mildly polar (acetone), and protic solvents (propan-1-ol) (Table 4),[17] probably because of the presence of the bulky *tert*-butyl groups which causes a particular substituent effect on the rate constant values assigned to the O–O bond linkage. The thermal stability of **6** in solution appears close to that observed for voluminous trioxanes **1**–**3** rather than diperoxides **7** and **8** with similar van der Waals volumes (Fig. 4). It can be assumed that the intermediate biradical species resulting from diperoxide **6** (Scheme 1b), would tend to quickly move away from the 'solvent cage', rather than reform the cyclic peroxide. Therefore, the reaction progresses in the direction of the products and k_{exp} reaches very high values compared with those determined for the others diperoxides investigated (Table 1 and 4).

Activation Parameters

The peroxidic compounds studied in the present work show structural differences that typically affect the reactivity of these molecules in solution, and also generate a significant variation on the activation parameters ($\Delta\Delta H^{\ddagger} = 24.1\ \text{kcal mol}^{-1}$ and $\Delta\Delta S^{\ddagger} = 51.8\ \text{cal mol}^{-1}\ \text{K}^{-1}$ or $\Delta\Delta \text{H}^{\ddagger} = 100.9\ \text{kJ mol}^{-1}$ and $\Delta\Delta \text{S}^{\ddagger} = 216.5\ \text{J mol}^{-1}\text{K}^{-1}$, where conversion factor is $1\text{cal} = 4.19\ \text{J}$) assigned to the unimolecular thermal decomposition reaction. Those variations are large compared with the maximum probable errors of those parameters ($2.1\ \text{kcal mol}^{-1}$ and $4.8\ \text{cal mol}^{-1}\ \text{K}^{-1}$, respectively) (Table 5).

By evaluating the activation parameters (Table 5), it can be observed that a change in the activation enthalpy ($\Delta H^{\ddagger}$) is accompanied by a change in the same sense in the corresponding activation entropy ($\Delta S^{\ddagger}$). This phenomenon is known as the *compensation effect* and can be represented by a linear relationship between the activation parameters (Eqn 1) where the slope β, known as the isokinetic temperature, has an important physical meaning; it represents a temperature at which all reactions of the series should proceed at the same rate.[26]

$$\Delta H^{\ddagger} = \Delta H_0^{\ddagger} + \beta \Delta S^{\ddagger} \tag{1}$$

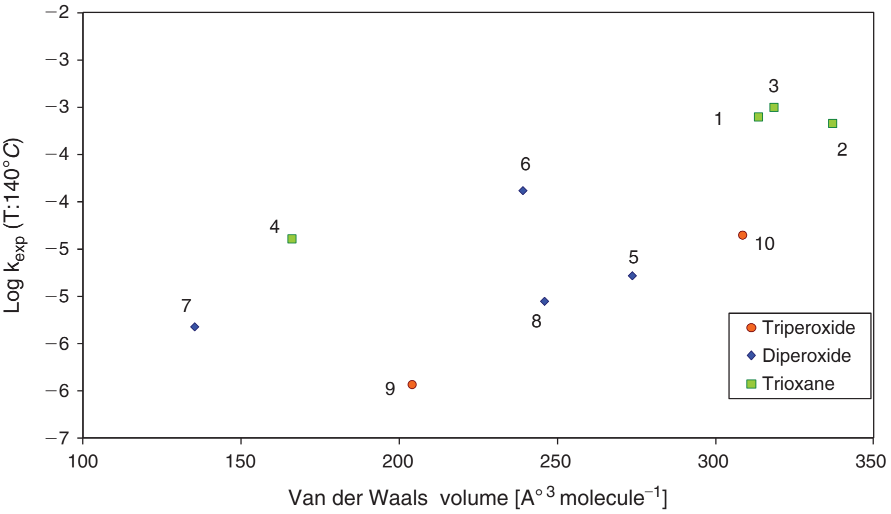


Fig. 4. Dependence of log k_{exp} for the unimolecular thermolysis reaction of different cyclic organic peroxides in 1,4-dioxan at 140°C with the van der Waals volume of each molecule.

Table 5. Activation parameters for the unimolecular thermal decomposition reaction of different cyclic organic peroxides in 1,4-dioxan
ΔT, change in temperature; $\Delta H^{\ddagger}$, activation enthalpy; $\Delta S^{\ddagger}$, activation entropy; $\Delta G^{\ddagger}$, free energy of activation

Peroxide	ΔT [°C]	$\Delta H^{\ddagger}$ [kcal mol^{-1}]	$\Delta S^{\ddagger}$ [cal mol^{-1} K^{-1}]	$\Delta G^{\ddagger A}$ [kcal mol^{-1}]
1	30	30.9 ± 0.3	1.3 ± 0.7	30.3 ± 0.3
2	30	31.6 ± 1.6	2.3 ± 3.9	30.7 ± 1.6
3	30	28.4 ± 0.7	-4.3 ± 1.7	30.2 ± 0.7
4^{B}	30	24.0 ± 1.1	-19.8 ± 2.6	32.6 ± 1.1
5	30	46.7 ± 0.7	32.0 ± 4.8	33.0 ± 0.7
6	30	30.4 ± 1.2	-3.2 ± 3.0	31.7 ± 1.2
6	30	30.7 ± 1.5	-9.2 ± 3.5	34.6 ± 1.5
8^{C}	30	30.6 ± 1.3	-8.5 ± 3.1	34.1 ± 1.3
9	30	48.1 ± 2.1	30.2 ± 4.8	35.2 ± 2.1
10^{D}	32	45.5 ± 1.7	31.4 ± 3.9	32.2 ± 1.7

^{A}Calculated at 140°C.
^{B}Ref. [7].
^{C}Ref. [8].
^{D}Ref. [9].

Two series of reactions can be observed when the relationship according to Eqn 1 is studied (Fig. 5). One of the lines, line a, includes peroxides with methyl substituents (**4** and **7**–**9**, series a), and the other, line b, includes peroxides with bulky substituents and consequently greater volumes (**1**–**3**, **5**, and **10**, series b). Both lines have excellent correlations coefficients (line a, $r = 0.999$ and line b, $r = 0.999$). As it was previously discussed, compound **6**, with methyl and *tert*-butyl substituents, shows an unexpectedly high reactivity in solution, nevertheless, the activation parameters are similar to those obtained for other peroxides, so it is not surprising that the corresponding point appears in the middle of both correlation series (Fig. 5).

The linearity of both lines and the fact that they are nearly parallel make it possible to consider them as two reaction series[26] with a common reaction stepwise mechanism initiated by the homolytic cleavage of one O–O bond. This initial step is influenced by the dimensions of the substituents, the number of O–O bonds in the cycle, the size of the cycle, and the different conformations that these compounds may adopt, so, different specific interactions mechanism can be considered. The activation parameter values obtained and the nature of the detected products support the above proposed mechanism where specific interactions between each peroxide molecule or biradical and 1,4-dioxan solvent molecules could be postulated. Changes observed in activation parameters in lines a and b generate a practically distinguishable variation of the free energy of activation (series a: $\Delta\Delta G^{\ddagger} = 2.6$ kcal mol^{-1} and series b: $\Delta\Delta G^{\ddagger} = 2.8$ kcal mol^{-1}). These later values are close to the order of the calculated experimental error for these parameters.

Both series represented in Fig. 5 show a slight difference (4.3 %) in the isokinetic temperature values: series a, $\beta'^{a} = 470$ K (~197°C for methyl substituted peroxides) and series b: $\beta'^{b} = 491$ K (~210°C for the group of peroxidic compounds with bulky substituents). These values fall outside of the experimental temperature interval selected to carry out the kinetic study (110–172°C).

The isokinetic relationship is valid for a series of reactions, when the general plot of the Arrhenius equation ($\ln k_{exp}$ versus $1/T$, Fig. 6) is represented by linear correlations according to the data in Table 2 and all lines intersect at a point, or a region, that corresponds to a reduced interval of temperatures. As it was proposed by Exner,[27] this point of intersection in the Arrhenius plane, known as the inverse of the isokinetic temperature, has greater reliability and validity because $\ln k_{exp}$ and T are statistically independent.

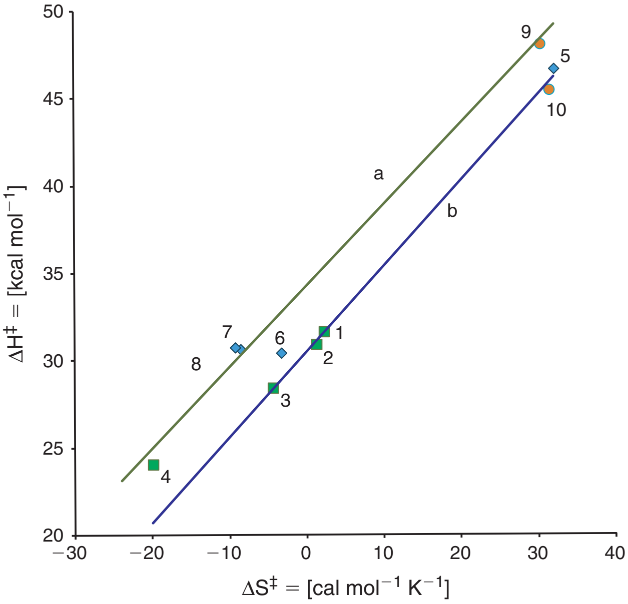


Fig. 5. Representation of 'isokinetic relationship' according to the Leffler treatment (Eqn 1) for the unimolecular thermolysis reaction of different organic peroxides in 1,4-dioxan.

The use of a simplified statistical technique based on the least-squares method allows us to obtain the function S_u, the residual sum of squares.[28,29] In this procedure $1/\beta$ corresponds with the minimum of function, a value coincident with the point (or region) of intersection of the lines in the Arrhenius plane.

In Fig. 6 it is possible to differentiate two groups of compounds called series a (containing peroxides with methyl substituents directly attached to the cycle like **4** and **7**–**9**), and series b (including compounds with bulky substituents or fused rings like **1**–**3**, **5**, and **10**). Once again, diperoxide **6** was not included in the treatment because its Arrhenius line moves away from both series.

According to the mathematical treatment[27–29] applied for the kinetic data of the thermolyses of **4** and **7**–**9** in 1,4-dioxan, the isokinetic temperature value (β'^{a}) was 461 K (188°C). The maximum value of the S_u function falls in the range of experimental temperature (Fig. 6) as was desirable. The β^{a} value calculated by Eqn 1 (Fig. 5) and β'^{a} value obtained by the statistic treatment represented in Fig. 6 are practically coincident; only a difference of 1.9 % was detected.

The same treatment applied to compounds included in series b gives a value of isokinetic temperature (β'^{b}) of 508 K (235°C) obtained at the minimum value of S_u. The discrepancy between both values of isokinetic temperature (β^{b} and β'^{b}) is negligible (3.3 %) compared with the errors in the experimental determinations of this work.

Conclusions

The analysis of the reaction products and the kinetic parameters of the thermal decomposition reaction of some substituted cyclic organic peroxides belonging to different families (trioxanes, diperoxides, and triperoxides) in 1,4-dioxan support a general homolytic stepwise mechanism. The different organic products

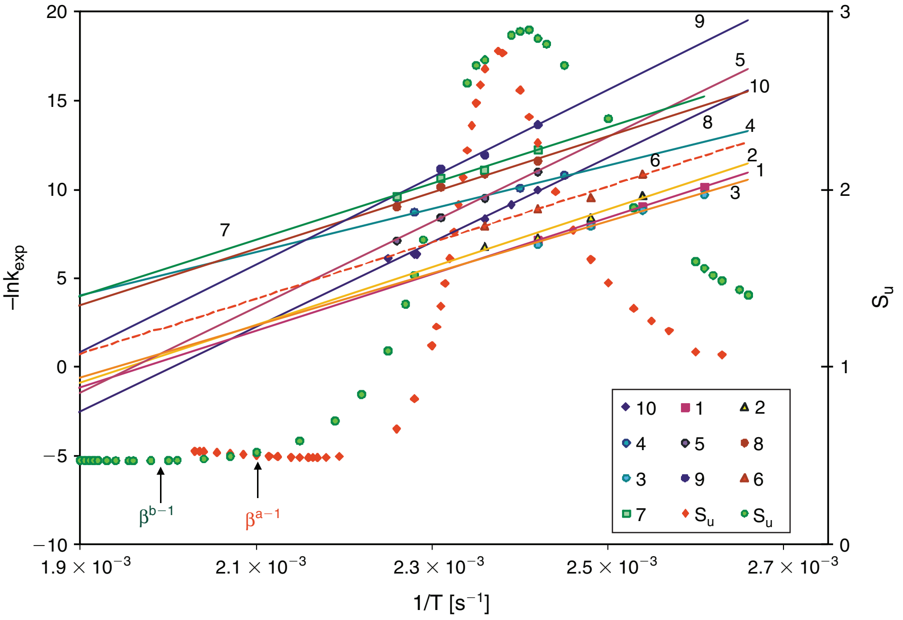


Fig. 6. Arrhenius equation plot for the thermal decomposition reaction of different cyclic organic peroxide in 1,4-dioxan in the 110–170°C temperature ambit. Dependence of the residual sum of squares, S_u, on the isokinetic temperature.

detected demonstrate the existence of O–O, C–O, and C–O bond ruptures and solvent derived products obtained by radical attack.

An important substituent effect is operative on the rate constant values and consequently on the activation parameters of the thermal decomposition reaction. The application of different treatments (compensation effect or a statistical treatment) on the kinetic data shows the existence of two sets of cyclic peroxides with comparable kinetic behaviour: Series a contains cyclic peroxides with methyl substituents (**4** and **7**–**9**), and series b contains peroxides with voluminous substituents or condensed rings (**1**–**3**, **5**, and **10**). Different peroxide–solvent interaction mechanisms can be considered within each series. Peroxide **6** with two *tert*-butyl groups attached to the cycle exhibits anomalous behaviour. Thus, the rate of reaction is influenced mainly by the substituents attached to the ring, and in some cases by the size of the cycle.

Experimental

Materials

The cyclic monofunctional peroxides[30] (**1**–**3**, Fig. 1) and the di- and trifunctional cyclic organic peroxides[13,31–33] (**5**–**7** and **9**, Figs 2 and 3) employed in this work were prepared by methods described in the literature indicated.

Warning: The preparation and handling of cyclic organic peroxides are dangerous operations that require standard safety precautions for handling primary explosives. These compounds are sensitive to impact, friction, electric discharge, and flame.

Solvents

The 1,4-dioxan employed for the kinetic reactions was purified with the appropriate technique[34,35] and its purity was checked by GC and high-resolution liquid chromatography (HPLC) analysis. The solvents employed as the mobile phase were of HPLC quality.

Kinetic Methods

Pyrex glass tubes (7 cm long × 4–6 mm outer diameter) half filled with the appropriate cyclic peroxide solution were thoroughly degassed under vacuum at −196°C and then sealed with a flame torch using a mixture of natural gas and oxygen. To perform the runs, the ampoules were submerged in a thermostatic silicone oil bath stabilized at a chosen temperature (±0.1°C) and extracted after predetermined times, the peroxide decomposition reaction was stopped by cooling them in an ice-water bath (0°C).

The quantitative determination of the remaining peroxide 1–3 in the reaction solution in 1,4-dioxane and the reaction products were determined by analysis with a reverse phase column (ODS Hypersil, 5 μm, 100 mm long × 4.6 mm) installed in a HPLC Hewlett–Packard instrument series 1050C with UV detection ($\lambda = 254$ nm). The mobile phase employed with **1** was a mixture of methanol/acetonitrile/water (40/30/30), with a flow of 0.5 mL min^{-1}. The mobile phase used for the corresponding analysis of **2** and **3** was a mixture of methanol/acetonitrile/water (40/40/20), with a flow of 0.8 mL min^{-1}. Under these experimental conditions, the retention times were 5.6 min for **1**, 8.1 min for **2**, and 6.3 min for **3**.

The concentration of **5**–**7** and **9** remaining in the solution was determined by gas chromatography (GC, internal standard method, naphthalene, 0.5 % P/V) in a DB-5 capillary column (5 % biphenyl–95 % dimethyl polysiloxane, 30 m × 0.32 mm internal diameter, 0.25 mm film thickness) installed in a Konik-2000C gas chromatograph, with nitrogen as the carrier gas and flame ionization detection (250°C). The injection port was fixed at 150°C in split mode. The experiments were carried out under programmed conditions: for **5** (80°C, 4 min, 25°C min^{-1}, 160°C, 15 min), for **6** (60°C, 6 min, 15°C min^{-1}, 160°C, 15 min), for **7** (60°C, 5 min, 10°C min^{-1}, 250°C, 15 min), and for **9** (60°C, 5 min, 20°C min^{-1}, 160°C, 15 min). Under these instrumental conditions the retention times of **5**–**7**, and **9** were ~10, 12.7, 5.9, and 8.6 min, respectively.

Product Analysis

The reaction products were identified by GC-MS analysis in a Rtx-5MS capillary column (5 % biphenyl–95 % dimethyl polysiloxane, 30 m, 0.25 mm internal diameter, 0.25 μm film thickness), installed in a Thermo Quest Race 2000 CG model gas chromatograph with helium as carrier gas (0.5 mL min^{-1}) and the injection port at 150°C in split mode (split ratio: 1 : 33). The detection was carried out with a Finnigan Polaris Ion Trap MS detector with the transfer line at 275°C and the ion source at 200°C. The analyses were carried out under programmed conditions (50°C, 3 min, 20°C min^{-1}, 200°C, 10 min). The identification of the reaction products was verified through the interpretation of mass spectra and by comparison of retention times with authentic samples of each compound analysed by GC.

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