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# The Mechanism of the Cationic Cyclooligomerization of Ethylene Oxide and the Concomitant Degradation of the Crown Ether Products Formed

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Cyclooligomerization of ethylene oxide-$d_4$ with $BF_3$ in $CH_2Cl_2$ in the presence of the higher cyclic oligomers, from 1,4-dioxan-$h_8$ to 18-crown-6-$h_{24}$, each separately, has been studied as a function of time, analyzing the product composition by gas chromatography, and the distribution of isotopically different species within each ring size by GLC-MS using chemical ionization.

It is found that non-deuteriated units from any one of these rings become incorporated in both larger and smaller rings before they end up in dioxan, either alone or together with deuteriated units from ethylene oxide.

The particular patterns observed for the degree of deuteriation permit quite far-reaching conclusions as to the detailed mechanism of these reactions, the most important of which is that the transition state for attack by ether oxygen on an oxonium ion has a strict linear $S_N2$-like geometry.

In the presence of $BF_3$, $PF_5$ or $SbF_5$ in inert solvents, ethylene oxide (oxiran*) gives almost exclusively cyclic oligo- and polymers *1*, together with only small amounts of the cyclic acetals *2*, $n=2$ and 3.[1]

$$[-CH_2CH_2O-]_n$$
*1*

$$[-CH_2CH_2O-]_{n-1}-CH(CH_3)-O-$$
*2*

* For the naming of such heterocyclic oligomers the Hantzsch-Widman system stops at the trimer (1,4,7-trioxonan). The rational names (1,4,7-trioxacyclononane) soon become cumbersome, and the pictorial names (9-crown-3) would be artificial for smaller rings. For the present discussion it seems preferable to speak simply about (cyclic) monomer, dimer, trimer, *etc.*

The steady-state distribution of *1* according to ring size is clearly the result of a balance between the rate of building up the larger rings from oxiran, the rate of breakdown of these products to the thermodynamically stable end product 1,4-dioxan* and the rate of incorporation of the products, including dioxan, in the growing chains and hence into new cyclization products.[1] Since not only dioxan, but also the higher homologues, several of which are known as cation-complexing "crown-ethers", are perfectly stable in the presence of $BF_3$ alone[2] at 160 °C, but unstable even below 0 °C when also oxiran is present, the degradation must be initiated by *O*-alkylation and therefore also dependent on the concentration of oxiran.

We have already reported[3] that when non-deuteriated monomer (oxiran-$h_4$) is oligomerized in the presence of fully deuteriated dimer (1,4-dioxan-$d_8$), both deuteriated units become incorporated in the cyclic pentamer and larger rings, but not in the trimer and tetramer. Similarly, when oligomerization takes place in the presence of partially deuteriated cyclic pentamer (15-crown-5-$d_8h_{12}$) the labelled units are incorporated in both higher and lower homologues. The only two observed acetals, *2*, $n=2$ and 3, are always free of deuterium. These observations could be understood[3] on the basis of a series of assumptions, mainly concerned with the stereochemistry of the transition state in nucleophilic attack on oxonium ion intermediates.

Conversely, the same assumptions permit quite far-reaching and detailed predictions about the deuteriation pattern in each of the products that would arise if any other cyclic oligomer is present

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during $BF_3$ oligomerization of the monomer and becomes degraded or incorporated to give larger rings. The validity of the assumptions can thus be tested experimentally. Instead of preparing each oligomer in partially or fully deuteriated form, a more convenient way of labelling the reactants for these experiments was to prepare deuteriated monomer and carry out the reactions in the presence of easily available non-deuteriated cyclic oligomers.

We have now developed a very efficient route for the preparation of oxiran-$d_4$ from commercially available ethylene glycol-$d_6$ *via* the cyclic carbonate, which is readily decarboxylated by heating to 180 °C with LiCl (see Experimental). Two sets of oligomerization reactions in $CH_2Cl_2$ containing $BF_3$ have been carried out with this labelled monomer; one in the presence of 15 mol %, the other 50 mol %, of any one of the non-deuteriated oligomers (*1*, $n=2-6$), each at a time. The total product composition was followed as a function of time by GLC, and the distribution of species with differing degree of deuteriation within each product determined by GLC/MS. Since these oligoethers fragment very extensively on electron bombardment, chemical ionization (isobutane) was used, giving the M+1 ion as a strong peak suitable for analysis. Isotopic separation was observed on polysiloxane columns, so that the mass spectrum had to be swept continuously to monitor all isotopically different species through each fraction. Surprisingly, the deuteriated compounds are eluted first (see Experimental).

The analytical data obtained are presented in Tables 1 to 5 and will be discussed in relation to the predictions presented graphically in Schemes 1 to 5.

## THE BASIC ASSUMPTIONS

The rationalization of the previous observations necessitated[3] a number of assumptions about relative chemical reactivities and the stereoelectronic requirements controlling initiation, chain growth, chain termination, cyclization and transannular ring opening. These will now be restated in more detail.

*1. Initiation of a catalytic cycle.* Only the $BF_3$ adduct of the strained 3-membered ring of the monomer can initiate oligomerization, that is, open its CO bond when attacked by a neutral monomer molecule (Fig. 1). The $BF_3$ adducts of

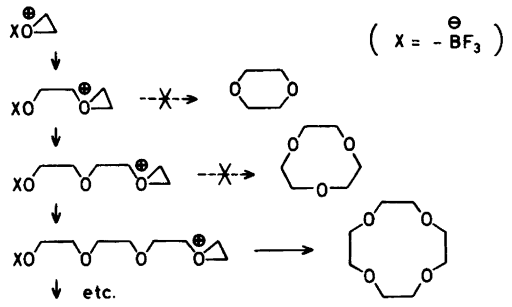



*Fig. 1.* Normal chain growth and termination by direct cyclization.

unstrained cyclic (and acyclic) ethers are known to be stable against CO bond opening.[4] On the other hand, $BF_3$ can be transferred easily from one ether oxygen to another.[4]

*2. Chain growth.* An intermediate oxonium ion involving a strained 3-membered ring is non-discriminating against nucleophilic attack at a ring carbon, and reacts not only with the ether oxygen of normal basicity present in unstrained cyclic oligomers (as well as acyclic ethers) but also with the weakly basic[5] oxygen of the monomer and even with adjacent hydride by a 1,2-shift. The α-carbon of the unstrained side chain of such an oxonium intermediate is much less reactive. In the presence of a high concentration of monomer, the chain will therefore tend to grow in the "normal" way shown in Fig. 1.

*3. Chain termination.* Since the solvent $CH_2Cl_2$ furnishes no permanent end groups, a growing chain can only be terminated by cyclization, whereby the reactive trialkyloxonium intermediate is converted to the unreactive $BF_3$ adduct of some unstrained cyclic product. To start a new catalytic cycle, $BF_3$ must be transferred to a new monomer molecule. Cyclization of the chain is favoured when little monomer is present to continue chain growth. The terminal oxygen carrying the negatively charged $-BF_3$ substituent should be the strongest nucleophile present and should at any time stay very close to the oxonium charge at the other end as its counter-ion. However, as the attack must occur on the already loosened carbon of the strained ring, and the transition state is assumed to have an $S_N2$-like geometry,[6] direct cyclization requires a minimum chain length. This is illustrated in Fig. 2 where the chain linking the attacking and the

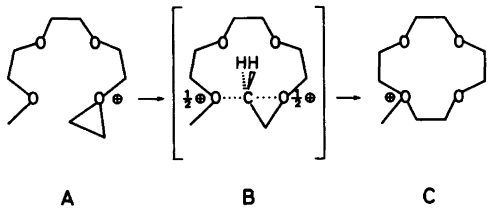



*Fig. 2.* Stereoelectronic minimum requirements in the irreversible direct cyclization.

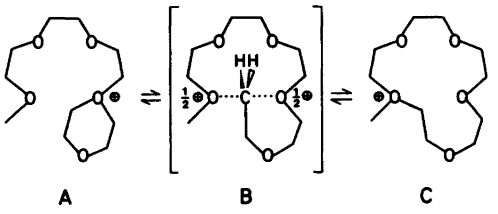



*Fig. 4.* Stereoelectronic minimum requirements in ring expansion (A→C) and in ring contraction by transannular attack (C→A).

leaving oxygen atoms contains three monomer units. The transition state thus contains a ring that can be defined as 11-membered and leads to a product with a 12-membered ring, the cyclic tetramer.

Chains which have not reached this minimum length may instead undergo 1,2-hydride shift. The migrating hydride can then leave carbon collinear with and opposite to the attacking oxygen (Fig. 3). The product will be a cyclic 5- or 8-membered acetal, 2-methyl-1,3-dioxolan or 2-methyl-1,3,6-trioxocan (2,$n$=2 and 3).

*4. Product incorporation.* When the cyclic oligomers start to accumulate as products, or are added deliberately, these stronger[5] nucleophiles will, of course, compete effectively with the monomer and may enter the growing chain. The resulting oxonium intermediate, shown in Fig. 4A and Fig. 5A, for the case of attack by dimer, is unstrained and becomes discriminating as to the next nucleophilic attack, excluding the less basic monomer. Further normal chain growth is thereby prevented, but additional product molecules may, in principle, enter the chain in a reaction similar to the reaction C→A in Fig. 5. Cyclization of the unstrained oxonium intermediate can occur in two different ways, since all three α-$CH_2$ groups are now equally vulnerable. Attack on ring carbon would lead to cyclization with net ring expansion (Fig. 4, A→C). Cyclization within the side chain (Fig. 5, A→C) leads to expulsion of the oligomer that terminated chain growth, so that its function has then only been that of a chain breaker. In the former cyclization the minimum ring size in the transition state is again 11-membered, although the product oligomer has a larger ring (in the example of Fig. 4 it is 15-membered). In the latter cyclization, the transition state geometry puts no restriction on ring size, since the departing oxygen is not part of the ring being formed. The ring size is, therefore, the same as in the product and only influenced by conformational factors familiar from other cyclization reactions. Thus, the 6-membered ring is formed particularly easily and the 9-membered ring with more difficulty, although the overriding effect of the chemical reactivity of the terminal oxygen carrying the negatively charged $-BF_3$ substituent favours cyclization involving the full chain length. Even the cyclic trimer will be formed in preference to dimer if the chain contains just three units.

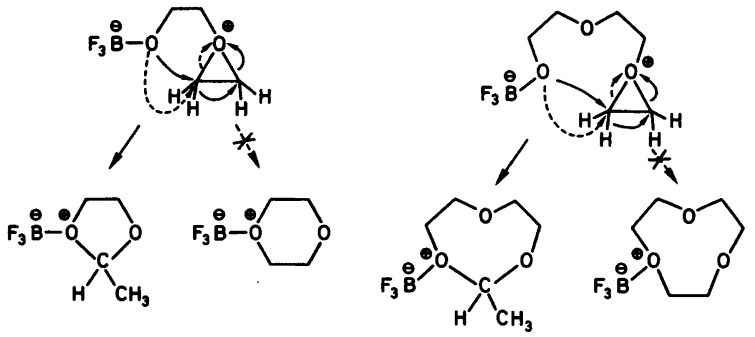


*Fig. 3.* Mechanism for acetal formation by hydride shift in short chains.

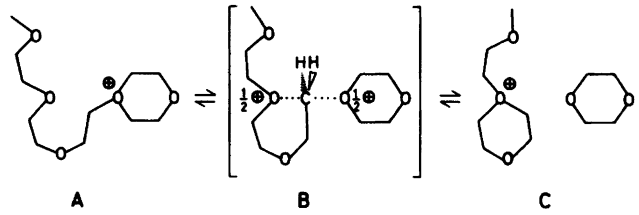



*Fig. 5.* Side-chain cyclization with expulsion of chain terminator (A→C), and incorporation of a second cyclic oligomer molecule (C→A).

*5. Degradation.* Reactions of the type A→C shown in Fig. 5, when repeated, lead to a stepwise degradation of a linear chain to cyclic dimer molecules. If the chain is terminated initially by attack from a larger cyclic oligomer, the same type of oxonium intermediate can be formed by a transannular ring opening (or strictly ring contraction) as shown for the case of the cyclic pentamer in Fig. 4, C→A. This reversed ring expansion reaction is subject to the same restrictions with regard to the minimum length of the chain linking the attacking and departing oxygen, so that the smallest ring for easy transannular opening is just the pentamer shown and the cyclic dimer is the only possible product. Contraction to dimer is clearly favoured also in larger rings, although some competition from other modes of transannular attack may be expected in cyclic oligomers larger than the hexamer.

## COMPARISON OF EXPERIMENTAL RESULTS WITH PREDICTED REACTION PATHS

The results of the cyclooligomerization of oxiran-$d_4$ in the presence of non-deuteriated oligomer will be discussed separately for each ring size, starting with the hexamer, for which all types of reactions envisaged are possible. Detailed predictions of the most likely paths are given as three reaction schemes* for each case, supposing attack by the oligomer either on activated monomer, on the growing dimeric chain, or on the growing trimeric chain (Fig. 1, left). The still longer chains are expected to undergo reactions analogous to those predicted for the trimeric chain. The experimental results are presented as tables showing, as a function of reaction time, the total molar concentration of each product as determined by GLC and referred to the initial concentration of the starting oligomer (=100), and showing also for each product the distribution of species with different degrees of deuteriation as determined by GLC/MS. This deuteriation pattern is presented only for one selected sample from each experiment. It corresponds to an intermediate reaction time, since samples taken very early contain so low concentrations of some products that the isotopic analysis is disturbed by the presence of impurities in the starting material, while on the other hand samples taken very late have a washed-out deuteriation pattern due to secondary degradation of accumulated deuteriated products.

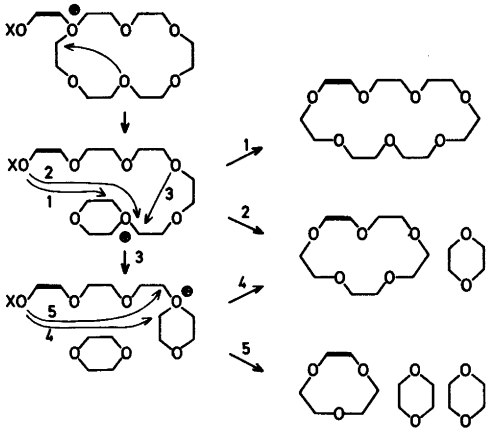
Some common general features are evident. (1) The rate of disappearance of the added oligomer depends on the initial concentration of monomer. (2) Fully deuteriated oligomers (beyond dimer) are only observed when the ratio of monomer to added oligomer is high, presumably because they can only be formed when the chain gets a chance to grow to a sufficient length to be able to cyclize directly* (Fig. 2) or in the side-chain of an oligomer-terminated intermediate (Fig. 5). (3) Cyclic acetals accumulate with reaction time in all experiments and are always 100% deuteriated, even after 7 days. This confirms the idea that acetals are only formed by rearrangement in the growing chain (Fig. 3) and never as products of degradation. Furthermore, since the only observed acetals are

* Heavy lines symbolize $-CD_2-CD_2-$ units, thin lines $-CH_2-CH_2-$ units. $X=-BF_3^-$.

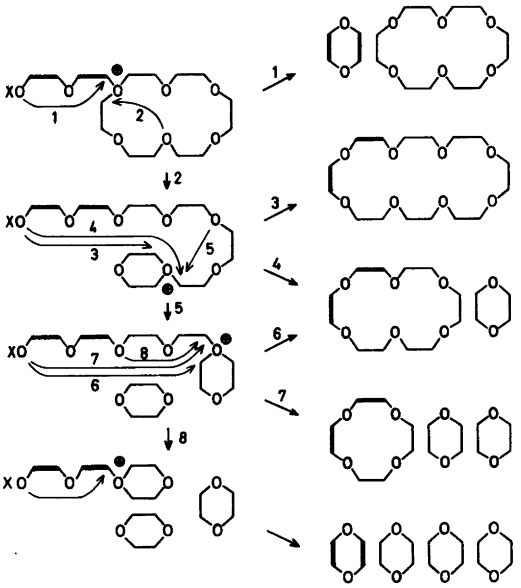
* Oligomerization of oxiran alone in $CH_2Cl_2$ under similar conditions gives exclusively cyclic tetramer in the very early phase of the reaction showing that cyclization does occur as soon as the chain length permits. Dioxan and higher oligomers appear only after a certain concentration of tetramer has accumulated. Nevertheless, cyclization to rings larger than tetramer seems to be more easy, as revealed when competing recyclization paths are available (*cf.* the separate discussions of each degradation experiment).

isomeric with the dimer (2-methyl-1,3-dioxolan) and the trimer (2-methyl-1,3,6-trioxocan), and no trace of the higher ones are seen, this confirms the idea that 1,2-hydride shift is an alternative reaction resorted to only when the growing chain is too short to cyclize in the normal way.

*Oxiran-*$d_4$ *in the presence of 18-crown-6-*$h_{24}$. Schemes 1a, b and c show the most likely reactions

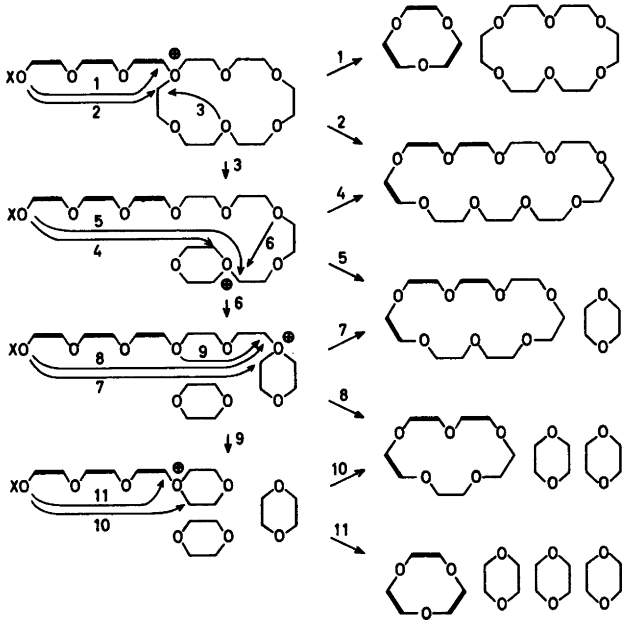


*Scheme 1a.*



*Scheme 1b.*

of the three smallest primary oxonium intermediates. It is immediately seen that dimer molecules produced should contain none or two deuteriated units, in perfect agreement with the isotopic



*Scheme 1c.*

analysis (Tables 1a and 1b) which shows the complete lack of dimer-$d_4$ in the early phases of the reaction. It is also seen that dimer-$h_8$, which must originate from the degradation of the ring, dominates by far. This means that only a short chain is built up from monomer before being terminated by hexamer and broken down according to Scheme 1.

The cyclic oligomers with one deuteriated unit expected from Scheme 1a should be the hepta-, penta- and trimer, in perfect agreement with the isotopic analysis (Tables 1a and 1b). Taking also into account the total amounts formed, as determined by gas chromatography (Tables 1a and 1b) it is clear that the dominating reaction is transannular ring opening and subsequent recyclization of the resulting secondary intermediate along paths 1 and 2 to give net ring expansion and ring contraction. The degradative step to the tertiary intermediate (path 3) seems less important.

The oligomers with two deuteriated units expected from Scheme 1b should be the octa-, hexa- and tetramer, and again this is what is observed in the isotopic analysis (Tables 1a and 1b). Taking into account the total amounts formed, the dominating reaction is once again transannular ring opening (path 2) with subsequent recyclization of the secondary intermediate along paths 3 and 4 to give net ring expansion and the original ring size back.

The oligomers with three deuteriated units expected from Scheme 1c should be the nona-, hepta-, penta- and trimer. The isotopic analysis (Table 1a) confirms the latter three, but the nonamer escaped analytical detection. The dominating reactions are again transannular ring opening (path 3), with subsequent recyclization of the secondary intermediate in the (very long) side chain only (path 5), and further degradation along path 6 to the tertiary

*Table 1a.* Oligomerization of oxiran-$d_4$ (0.88 g, 20 mmol) in the presence of 18-crown-6-$h_{24}$ (0.79 g, 3 mmol).

| Oligomer *1* | Molar concentration of oligomers relative to hexamer (=100) | | | | Distribution of isotopically different species (in %) after 30 min. | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | start | 30 min | 20 h | 7 d | $d_0$ | $d_4$ | $d_8$ | $d_{12}$ | $d_{16}$ | $d_{20}$ | $d_{24}$ |
| $n=1$ | 667 | 374 | 169 | 55 | – | 100 | | | | | |
| 2 | | 12 | 41[a] | 178[a] | 80 | – | 20[c] | | | | |
| 3 | | >0 | 1[b] | 3 | 6[d] | *91* | – | 3 | | | |
| 4 | | >0 | >0 | >0 | 10[d] | 20 | *40* | – | 30 | | |
| 5 | | 1 | 9 | 12 | 4[d] | *94* | 1 | *2* | – | – | |
| 6 | 100 | 91 | 63 | 27 | *98* | – | *2* | – | – | – | – |
| 7 | | 1 | 12 | 19 | – | *95* | – | *5* | – | – | – |
| 8 | | >0 | 3 | 5 | – | – | *95* | – | *5* | – | – |

[a] Acetal concentration = 5. [b] Acetal present after 6 h. [c] Same distribution after 2 min; after 20 h: 15 % $d_0$, 10 % $d_4$, 75 % $d_8$. [d] Partly from impurity in 18-crown-6.

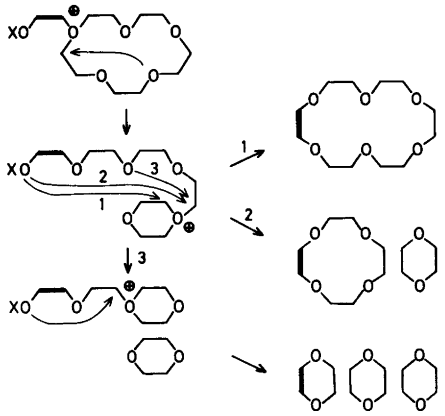
*Table 1b.* Oligomerization of oxiran-$d_4$ (0.88 g, 20 mmol) in the presence of 18-crown-6-$h_{24}$ (2.64 g, 10 mmol).

| Oligomer *1* | Molar concentration of oligomers relative to hexamer (=100) | | | | Distribution of isotopically different species (in %) after 20 h. | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | start | 30 min | 20 h | 7 d | $d_0$ | $d_4$ | $d_8$ | $d_{12}$ | $d_{16}$ | $d_{20}$ | $d_{24}$ |
| $n=1$ | 200 | 152 | 49 | 17 | – | 100 | | | | | |
| 2 | | 4 | 48[a] | 57[a] | 80 | 10 | 10[c] | | | | |
| 3 | | >0 | 1 | 1[b] | – | *100* | – | – | | | |
| 4 | | >0 | >0 | >0 | 10[d] | 35 | *55* | – | – | | |
| 5 | | 1 | 5 | 8 | – | *100* | – | – | – | – | |
| 6 | 100 | 97 | 81 | 64 | ~*100* | – | >0 | – | – | – | – |
| 7 | | 2 | 2 | 6 | – | *95* | – | *5* | – | – | – |
| 8 | | – | >0 | >0 | – | – | *100* | – | – | – | – |

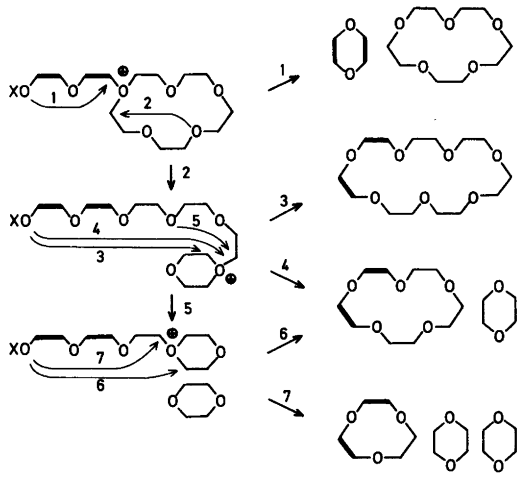
[a] Acetal concentration = 2. [b] Acetal not observed. [c] After 2 min: 70 % $d_0$, 30 % $d_8$; after 4d: 10 % $d_0$, 5 % $d_4$, 85 % $d_8$. [d] Partly from impurity in 18-crown-6.

intermediate, with cyclization now along both paths 7 and 8.

With time, oligomers having incorporated deuteriated units accumulate and will, of course, in their turn act as chain terminators and enter the degradation schemes. Since also these contain a majority of non-deuteriated units, the relatively rapid production of mainly non-deuteriated dimer can be understood.



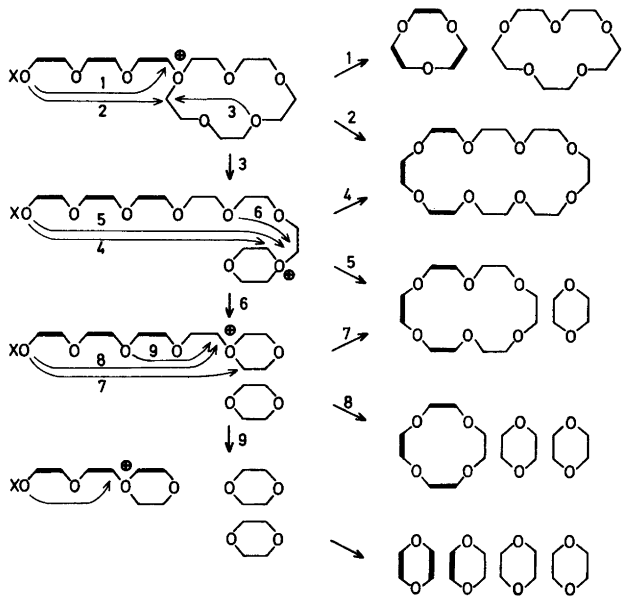
*Scheme 2a.*



*Scheme 2 b.*

A possible reaction not shown in Scheme 1 cannot be revealed by the experimental results, namely the attack on the intermediates by a second molecule of hexamer. The molecular weight of the products formed would be too high to be detected by gas chromatography.

*Oxiran-*$d_4$ *in the presence of 15-crown-5-*$h_{20}$. Schemes 2a, b and c show the most likely reactions



*Scheme 2c.*

of the three smallest primary oxonium intermediates. Dimer molecules of any isotopic composition can now be formed, and this is verified by the isotopic analysis for the very first phases of the reaction (Tables 2a and 2b). The dominance of dimer-$h_8$, as well as of dimer-$d_4$ over dimer-$d_8$, suggests that under these conditions the side chain has not had time to grow to more than a few units before being terminated by the pentamer.

The cyclic oligomers with one deuteriated unit to be expected from Scheme 2a are the hexa- and tetramer, which is in accord with the isotopic analysis (Tables 2a and 2b). Taking into account also the total amount formed (Tables 2a and 2b) it can be concluded that the dominant reaction is transannular ring opening with subsequent re-cyclization of the secondary intermediate. This cyclization occurs preferentially with net ring expansion (path 1), and less within the side chain (path 2), presumably because of the inherent greater difficulty of folding the chain to a 12- than to a 14-membered ring in the transition state. In the experiment using a higher concentration of pentamer (Table 2b), the observation that a small amount of cyclic nonamer is formed, and that it contains mainly one deuteriated unit, can only be rationalized by attack of a second molecule of pentamer on α-carbon of the side chain of the secondary intermediate (Scheme 2a) to expel dimer, and subsequent cyclization to nonamer-$d_4$. The equally probable cyclization to give tetramer-$d_4$ cannot be demonstrated since this is also formed in path 2.

*Table 2a.* Oligomerization of oxiran-$d_4$ (0.88 g, 20 mmol) in the presence of 15-crown-5-$h_{20}$ (0.66 g, 3 mmol).

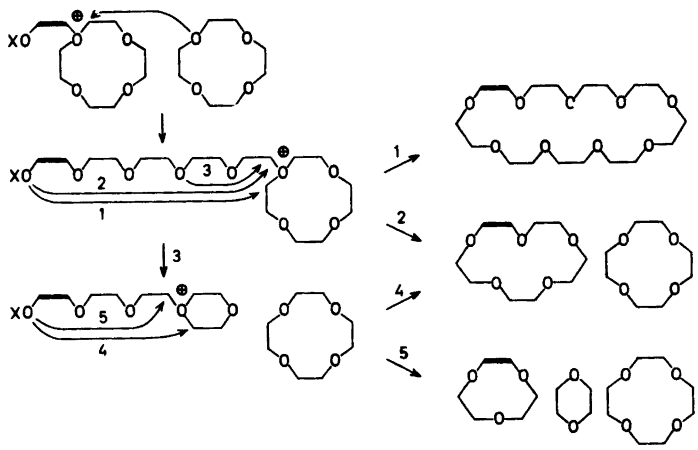
| Oligomer *l* | Molar concentration of oligomers relative to pentamer (=100) start | 30 min | 20 h | 7 d | Distribution of isotopically different species (in %) after 30 min. $d_0$ | $d_4$ | $d_8$ | $d_{12}$ | $d_{16}$ | $d_{20}$ | $d_{24}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $n=1$ | 667 | 366 | 148 | 45 | – | 100 | | | | | |
| 2 | | 18 | 43 | 211[a] | 70 | 25 | 5[c] | | | | |
| 3 | | >0 | >0 | 2[b] | 10 | 15 | 70 | 5 | | | |
| 4 | | 2 | 11 | 15 | – | *95* | – | – | 5 | | |
| 5 | 100 | 84 | 48 | 17 | 95 | – | *5* | – | – | – | |
| 6 | | 9 | 18 | 28 | 5 | *90* | – | *5* | – | – | – |
| 7 | | 1 | 11 | 16 | – | 10 | *80* | – | *10* | – | – |
| 8 | | 1 | 7 | 9 | – | – | 25 | *75* | – | – | – |

[a] Acetal concentration = 4; present after 30 min. [b] Acetal concentration = 2; present after 2 h. [c] Same distribution after 2 min; after 20 h: 65 % $d_0$, 25 % $d_4$, 10 % $d_8$.

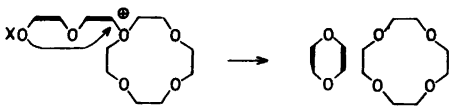
*Table 2b.* Oligomerization of oxiran-$d_4$ (0.88 g, 20 mmol) in the presence of 15-crown-5-$h_{20}$ (2.20 g, 10 mmol).

| Oligomer *l* | Molar concentration oligomers relative to pentamer (=100) start | 30 min | 20 h | 7 d | Distribution of isotopically different species (in %) after 2 h. $d_0$ | $d_4$ | $d_8$ | $d_{12}$ | $d_{16}$ | $d_{20}$ | $d_{24}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $n=1$ | 200 | 143 | 51 | 9 | – | 100 | | | | | |
| 2 | | 10 | 31 | 70[a] | 75 | 20 | 5[c] | | | | |
| 3 | | – | >0 | >0[b] | 20 | 30 | 50 | – | | | |
| 4 | | 1 | 3 | 5 | 15[d] | *85* | – | – | – | | |
| 5 | 100 | 90 | 75 | 58 | ~*100* | – | >0 | – | – | – | |
| 6 | | 5 | 9 | 12 | – | *100* | – | – | – | – | – |
| 7 | | 2 | 3 | 3 | – | 35 | *60* | 5 | – | – | – |
| 8 | | >0 | 1 | 1 | – | 20 | 50 | *30* | – | – | – |
| 9 | | >0 | >0 | >0 | – | 90 | 5 | 5 | – | – | – |
| 10 | | – | >0 | >0 | – | 20 | 80 | – | – | – | – |

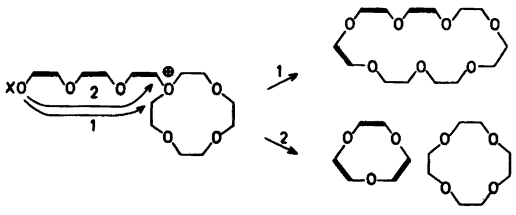
[a] Acetal present after 2h. [b] Acetal present after 2h. [c] Same distribution after 2 min; after 20h: 65 % $d_0$, 30 % $d_4$, 5 % $d_8$. [d] Partly from impurity in 15-crown-5.



*Scheme 3a.*



*Scheme 3b.*



*Scheme 3c.*

In full analogy, the occurrence of substantial quantities of heptamer-$d_4$ (Table 2b) can be explained by attack of pentamer on the tertiary intermediate (Scheme 2a). There is, of course, no reason to believe that the primary intermediate (Scheme 2a) is not similarly attacked, with expulsion of pentamer, but this leads to an identical product and cannot be seen.

The oligomers with two deuteriated units expected from Scheme 2b are the hepta-, penta- and trimer, and this is in agreement with the isotopic analysis in Table 2a. When also the total amounts are taken into account, the dominant reaction is seen to be transannular ring opening (path 2) with subsequent recyclization of the secondary intermediate along paths 3 and 4 to give net ring expansion and the original ring size back. In the experiment using a higher concentration of pentamer (Table 2b) small quantities of decamer-$d_8$ and octamer-$d_8$ are observed, and this can again be explained as the result of attack by a second molecule of pentamer on the α-carbon of the side chain in the secondary and tertiary intermediates (Scheme 2b) and subsequent cyclization.

The oligomers with three deuteriated units expected from Scheme 2c are the octa-, hexa- and tetramer, but only the two largest are found by isotopic analysis (Table 2a). Taking into account the total quantities formed, it is seen that the octamer-$d_{12}$ dominates over hexamer-$d_{12}$. This enforces the conclusion that in addition to the transannular ring opening (path 3) and subsequent recyclization of the secondary intermediate along paths 4 and 5 to give comparable quantities of octa- and hexamer, there may also be direct cyclization of the primary intermediate (path 2). This is, of course, not unexpected since the side chain is now long enough to permit an unstrained transition state.

*Oxiran-*$d_4$ *in the presence of 12-crown-4-*$h_{16}$. In this ring the transition state for transannular ring opening, as already discussed, would be too strained, and the other and presumably slower reactions of the primary intermediates should dominate. This is clearly reflected in the much slower disappearance of the tetramer (Table 3), as compared with the larger rings, and the much earlier detection of the fully deuteriated oligomers (Table 3), including the dimer, which appears exclusively as dimer-$d_8$ in the early phases of the reaction. The most likely reactions

*Table 3.* Oligomerization of oxiran-$d_4$ (0.88 g, 20 mmol) in the presence of 12-crown-4-$h_{16}$ (0.53 g, 3 mmol).

| Oligomer *l* | Molar concentration of oligomers relative to tetramer (=100) start | 20 h | 7 d | Distribution of isotopically different species (in %) after 30 min. $d_0$ | $d_4$ | $d_8$ | $d_{12}$ | $d_{16}$ | $d_{20}$ | $d_{24}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $n=1$ | 667 | 186 | 25 | – | 100 | | | | | |
| 2 | | 24 | 60[a] | 10 | 10 | 80[c] | | | | |
| 3 | | >0 | >0[b] | – | 60 | – | 40 | | | |
| 4 | 100 | 93 | 75 | 95 | – | – | – | 5 | | |
| 5 | | 1 | 3 | 15[d] | 45 | 10 | 5 | – | 25 | |
| 6 | | 1 | 3 | 5[d] | – | 80 | 5 | 5 | – | 5 |
| 7 | | 3 | 6 | – | – | – | 100 | – | – | – |
| 8 | | 2 | 3 | – | – | – | – | 100 | – | – |
| 9 | | >0 | >0 | – | 50 | – | – | – | 50 | – |

[a] Acetal concentration = 6; present after 2 min. [b] Acetal present after 2 min. [c] After 2 min: 100 % $d_8$; after 20 h: 35 % $d_0$, 20 % $d_4$, 45 % $d_8$. [d] Partly from impurity in 12-crown-4.

of the three smallest primary intermediates are shown in Schemes 3a, b and c.

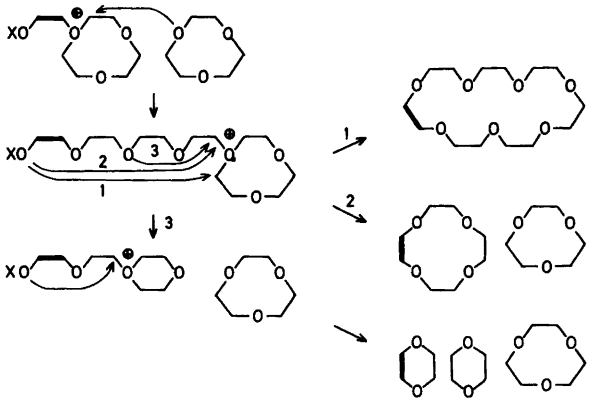
When the side chain contains only one (deuteriated) unit, not only is transannular ring opening prohibited, but also cyclization within the side chain and with ring expansion. Thus, the only alternative left is attack on the primary intermediate by a second molecule of tetramer (Scheme 3a). Such a bimolecular reaction must be relatively slow and lead to ring opening and formation of a secondary intermediate with five units in the side chain, capable of the familiar recyclization reactions. The cyclic oligomers with one deuteriated unit expected from Scheme 3a are the nona-, penta- and trimer, as confirmed by the isotopic analysis (Table 3). Taking also into account the total amounts formed (Table 3), the dominant reaction is side-chain cyclization of the secondary intermediate (path 2). In principle the resulting product, pentamer-$d_4$, might have been explained by postulating transannular ring opening of the primary intermediate and recyclization with ring expansion, but the concurrent formation of nonamer-$d_4$ supports the mechanism shown in Scheme 3a.

When the side chain contains two (deuteriated) units, the primary intermediate can cyclize in a more rapid reaction to give dimer-$d_8$ with expulsion of unchanged tetramer, and this is the only path shown in Scheme 3b. In addition, there is also here a certain probability of attack on the primary intermediate by a second molecule of tetramer, in analogy with Scheme 3a, with subsequent recyclization or degradation of the secondary intermediate. The cyclic oligomers with two deuteriated units to be expected are then the deca-, hexa- and tetramer, but the isotopic analysis reveals only the hexamer-$d_8$. The favoured path is thus seen to correspond exactly to the favoured path 2 of Scheme 3a.

When the side chain contains three (deuteriated) units, the primary intermediate can cyclize both within the side chain and with ring expansion, and these are the only paths shown in Scheme 3c. The expected products are the hepta- and trimer, and this is confirmed by the isotopic analysis (Table 3). Taking into account also the amounts formed, the dominant reaction is clearly ring expansion (path 1). Again, the attack by a second molecule of tetramer, in analogy with Scheme 3a, may produce a secondary intermediate from which the expected cyclic oligomers with three deuteriated units would be undeca-, hepta- and pentamer. By further analogy, it is the heptamer-$d_{12}$ that should be dominant, but as this can here also be formed directly from the primary intermediate by path 1, it can only be stated that the analytical data (Table 3) do not suggest that this bimolecular reaction is of importance.

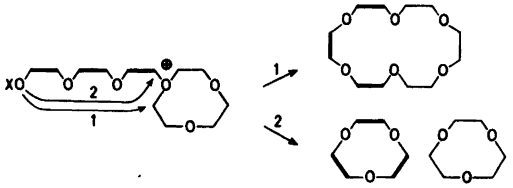
Table 3 also shows the formation of oligomers with four and five deuteriated units and the observed ring sizes can be easily rationalized along the same lines.

*Oxiran-*$d_4$ *in the presence of 9-crown-3-*$h_{12}$. The degradation rate for this 9-membered ring (Table 4) is about the same as for the 12-membered (Table 3). An acceptable geometry for the transannular ring opening is certainly impossible for the trimer, and so the similar rates of disappearance lend support to the conclusion that also in the case of the



*Scheme 4a.*

*Scheme 4b.*



*Scheme 4c.*

tetramer the reason for its slow degradation is the impossibility of transannular ring opening. Furthermore, the appearance of fully deuteriated oligomers and the exclusive formation of dimer-$d_8$ in the early phases of the reaction (Table 4) suggests that the competition from transannular ring opening is suppressed. The predictions in Scheme 4 are, therefore, analogous to those in Scheme 3.

The cyclic oligomers with one deuteriated unit expected from Scheme 4a are the hepta- and tetramer, in agreement with the isotopic analysis (Table 4). Taking also into account the total amount formed (Table 1), the dominating reaction is cyclization of the secondary intermediate with ring expansion (path 1). The reason for the more easy formation of heptamer-$d_4$ than tetramer-$d_4$ is probably the difficulty of chain-folding in the side-chain (12-ring

*Table 4.* Oligomerization of oxiran-$d_4$ (0.88 g, 20 mmol) in the presence of 9-crown-3-$h_{12}$ (0.40 g, 3 mmol).

| Oligomer *1* | Molar concentration of oligomers relative to trimer (=100) start | 20 h | 7 d | Distribution of isotopically different species (in %) after 30 min. $d_0$ | $d_4$ | $d_8$ | $d_{12}$ | $d_{16}$ | $d_{20}$ | $d_{24}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $n=1$ | 667 | 217 | 31 | – | 100 | | | | | |
| 2 | | 8 | 56[a] | 15 | 15 | 70[c] | | | | |
| 3 | 100 | 91 | 69[b] | *100* | – | – | – | | | |
| 4 | | >0 | 1 | – | *10* | 5 | – | 85 | | |
| 5 | | 1 | 1 | – | – | *90* | >0 | >0 | 10 | |
| 6 | | 1 | 5 | – | – | – | *90* | >0 | >0 | 10 |
| 7 | | 2 | 2 | – | *80* | – | – | *20* | – | – |
| 8 | | – | – | – | – | – | – | – | – | – |

[a] Acetal concentration = 2; present after 2 min. [b] Acetal present after 2 h. [c] After 2 min: 100 % $d_8$; after 20 h: 30 % $d_0$, 30 % $d_4$, 40 % $d_8$.

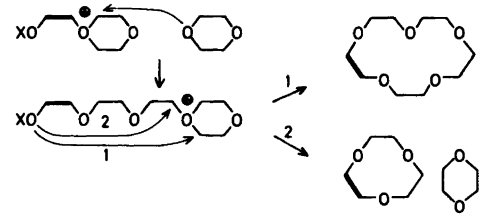
formation) as compared with folding to a 14-membered ring in the transition state for ring expansion (*cf.* discussion of Scheme 2a).

When the side chain contains two (deuteriated) units, this primary intermediate can now cyclize in the side chain to give dimer-$d_8$ and expel the trimer, and this is the only path shown in Scheme 4b. In addition, attack may also occur by a second molecule of trimer, in analogy with Scheme 4a, to yield a secondary intermediate which may then re-cyclize or degrade. The expected cyclic oligomers with two deuteriated units are the octa-, penta- and trimer. The isotopic analysis (Table 4) reveals only pentamer-$d_8$, so that this time recyclization in the side chain to form the smaller ring (pentamer) is favoured over recyclization with ring expansion (octamer). This supports the idea that cyclization of unstrained intermediates to form pentamer and larger rings is, in fact, more easy than to form the tetra- and trimer and that the reason for accumulation of the latter two is their greater resistance to degradation.

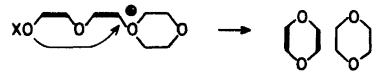
When the side chain contains three (deuteriated) units, the primary intermediate can cyclize both within the side chain and with ring expansion, and these are the only paths shown in Scheme 4c. The expected products are the hexa- and trimer, but the isotopic analysis reveals only hexamer-$d_{12}$ (Table 4), again showing the preference for cyclization to the larger rings. The attack by a second molecule of trimer, in analogy with Scheme 4a, would give a secondary intermediate from which the expected cyclic oligomers are the nona-, hexa- and tetramer. Of these, only hexamer-$d_{12}$ is seen analytically, but as it is also formed directly from the primary intermediate, the data of Table 4 give no indication that this bimolecular reaction is of much importance.

Table 4 also shows that oligomers with four deuteriated units are formed and the observed ring sizes can be similarly rationalized.

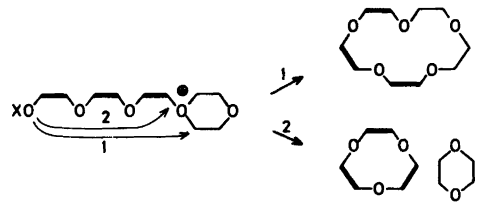
*Oxiran-*$d_4$ *in the presence of 1,4-dioxan-*$h_8$. This experiment differs from the preceding ones in that the added oligomer is identical with the final product and is therefore accumulating instead of



*Scheme 5a.*



*Scheme 5b.*



*Scheme 5c.*

*Table 5.* Oligomerization of oxiran-$d_4$ (0.88 g, 20 mmol) in the presence of 1,4-dioxan-$h_8$ (0.26 g, 3 mmol).

| Oligomer *l* | Molar concentration of oligomers relative to dimer (=100) start | 20 h | 7 d | Distribution of isotopically different species (in %) after 30 min. $d_0$ | $d_4$ | $d_8$ | $d_{12}$ | $d_{16}$ | $d_{20}$ | $d_{24}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $n=1$ | 667 | 198 | 29 | – | 100 | | | | | |
| 2 | 100 | 137 | 173[a] | *90* | – | 10[b] | | | | |
| 3 | | >0 | 1 | – | – | – | 100 | | | |
| 4 | | 2 | 5 | – | – | 5 | – | 95 | | |
| 5 | | 1 | 1 | – | *50*[c] | – | *50*[c] | – | – | |
| 6 | | 1 | 1 | – | – | *45*[d] | – | *55*[d] | – | – |
| 7 | | 2 | 2 | – | – | – | *45* | – | *55* | – |
| 8 | | 2 | 2 | – | – | – | – | *45* | – | *55* |

[a] Acetal present after 2 min. [b] Same distribution after 2 min; after 7 days: 55 % $d_0$, 45 % $d_8$. [c] After 7 days: 20 % $d_4$, 80 % $d_{12}$. [d] After 7 days: 20 % $d_8$, 80 % $d_{16}$.

disappearing during the reaction (Table 5). As expected the newly formed dimer is fully deuteriated and the total absence of dimer-$d_4$, not only in the early phase but even after 7 days, is striking (Table 5).

The cyclic oligomers with one deuteriated unit expected from Scheme 5a are the penta- and trimer. The isotopic analysis (Table 5) reveals only the pentamer-$d_4$, showing that the secondary intermediate cyclizes preferentially with ring expansion (path 1). In the earlier experiment[3] with monomer-$h_4$ and dimer-$d_8$ the corresponding product (pentamer-$d_{16}h_4$) was not observed, presumably because a larger excess of monomer was used which favoured the formation of longer chains before attack by dimer.

When the side chain contains two (deuteriated) units, the primary intermediate can cyclize in the side chain to give dimer-$d_8$ and expel dimer-$h_8$, and this is the only path shown in Scheme 5b. In addition, attack by a second molecule of dimer may also occur, in analogy with Scheme 5a, to yield a secondary intermediate which may then recyclize. The expected higher oligomers with two deuteriated units are the hexa- and tetramer. The isotopic analysis (Table 5) reveals mainly the hexamer-$d_8$, so that, as before, cyclization to the larger ring is favoured over tetramer formation. The earlier experiment[3] with larger excess of monomer did not give the corresponding product (hexamer-$d_{16}h_8$).

When the side chain contains three (deuteriated) units, the primary intermediate can cyclize both within the side chain and with ring expansion and these are the only paths shown in Scheme 5c. The expected products are the penta- and trimer, but the isotopic analysis (Table 5) reveals only the pentamer-$d_{12}$, showing once more that cyclization to the larger ring is preferred (path 1). Ring opening by attack from a second molecule of dimer, in analogy with Scheme 5a, should give a secondary intermediate from which the expected higher oligomers are the hepta- and pentamer. The isotopic analysis (Table 5) shows in fact both heptamer-$d_{12}$ and pentamer-$d_{12}$, but the latter may also originate by the more direct route discussed above.

Table 5 further demonstrates the presence of oligomers containing four (and more) deuteriated units, to be explained in an analogous manner. The ample formation of tetramer-$d_{16}$ must be ascribed to a direct cyclization of the growing chain (Fig. 2) without the intervention of dimer as a chain terminator, since cyclization within the side chain has been shown above to be little favoured.

A further striking feature of this experiment is that longer reaction times do not lead to a washing-out of the sharp deuteriation pattern of Table 5, only a shift from four incorporated, non-deuteriated units to two. This is because the same dimeric units are dominantly involved not only as products of degradation but also in chain termination and incorporation. Only dimer-$h_8$ is incorporated in the early phase, while more and more dimer-$d_8$ accumulates and becomes incorporated as the reaction proceeds.

## THE NATURE OF THE TRANSITION STATE

Molecular models suggest that in the transannular ring opening of cyclic oligomers, assumed to be necessary to initiate degradation, the chain connecting the incoming oxygen and the departing oxygen must contain three or more oxyethylene units. This agrees well with the data of Tables 1–5 insofar that fast degradation is not observed with trimer and tetramer, where the connecting chain would contain only one and two oxyethylene units.

However, the experimental data show an unexpected additional feature, namely that when the connecting chain is longer than necessary, the degradation becomes somewhat slower. The hexamer is thus degraded more slowly than the pentamer, and this is most clearly seen in the product composition after very long reaction times in the experiment with the pentamer (Table 2a). The hexamer has accumulated to reach a concentration that even exceeds the concentration of the pentamer from which it is formed by ring expansion. In contrast, a corresponding strong accumulation of heptamer is not observed in the experiment with hexamer (Table 1a). We think that this difference is due to subtle conformational effects, and propose, on the basis of existing knowledge about conformational details of free and cation-complexed crown ethers,[7] likely conformations for the $S_N2$-like transition state for transannular ring opening of the cyclic tetra-, penta- and hexamer (Figs. 6, 7 and 8). It is seen that for the tetramer (Fig. 6), as already expected, even a considerable deviation from linearity at the carbon undergoing inversion will not permit the di(oxyethylene) chain to reach over without intolerable steric strain, comparable to the strain in 8-membered rings. For the pentamer (Fig. 7), even with a linear OCO-arrangement at the inverting carbon, the

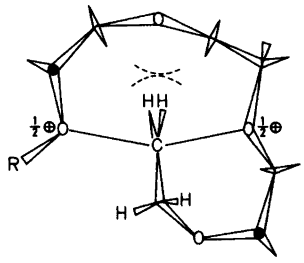


*Fig. 6.* Strained transition state for transannular ring opening of cyclic tetramer (or for ring-expansion cyclization by a dimeric side chain).

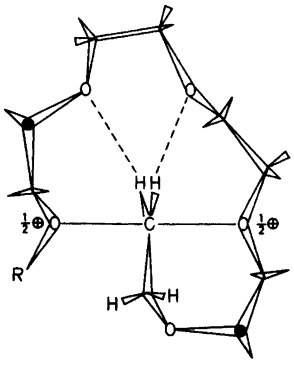


*Fig. 7.* Unstrained and internally solvated transition state for transannular ring opening of cyclic pentamer (or for ring-expansion cyclization by a trimeric side chain).

tri(oxyethylene) chain spans comfortably from nucleophile to leaving group, forming an unstrained 11-membered ring, whereby two ether oxygens come in perfect positions for internal solvation of both hydrogens of the positively charged $CH_2$ group. For the hexamer (Fig. 8), internal solvation becomes less efficient since the chain of the 14-membered ring is too long. The loop shown is the same that occurs twice in the crystal conformation of the hexamer[8] and only one of the three oxygens of the tetra(oxyethylene) chain is, at any time, within reach of the $CH_2$ group.

## CONCLUSION

The experimental results confirm that the thermodynamically stable end product 1,4-dioxan is not formed directly from oxiran, but after termination of a growing chain by an already formed cyclic

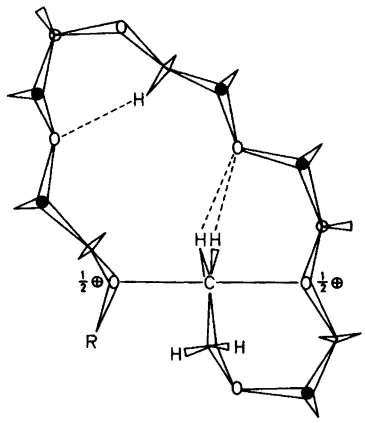


*Fig. 8.* Unstrained transition state for transannular ring opening of cyclic hexamer (or for ring-expansion cyclization by a tetrameric side chain).

oligomer with subsequent degradation of this oligomer and/or the chain. Each catalytic cycle must be initiated by the reactive $BF_3$ adduct of oxiran and is finished when cyclization yields the stable $BF_3$ adduct of any of the cyclic products. A new cycle can only be started by transfer of $BF_3$ to a new molecule of oxiran.

The results also confirm that the smallest ring that can be formed directly from oxiran alone is the tetramer, due to the geometric restrictions in an $S_N2$-like transition state, but that a growing chain terminated by a cyclic oligomer is able to cyclize within the chain to produce also cyclic trimer and dioxan.

They further show that the fast degradation of penta- and hexamer is due to the possibility of rapid transannular ring opening of the oxonium-activated ring. This is impossible in the tri- and tetramer due to the same geometric restrictions of the transition state as are operative in cyclization. The resulting oxonium intermediate also recyclizes to a large extent to yield larger rings, which in their turn become activated and degraded.

The results reveal in addition that for degradation of the tri- and tetramer to occur, the oxonium-activated ring must be opened in a slower reaction by attack of a second molecule of the same ring. Such intermediates may also recyclize to larger rings, whereby effectively one or two product molecules become incorporated. It is particularly noteworthy that 1,4-dioxan molecules are similarly incorporated. Thus, cyclic pentamer is produced

from two molecules of the thermodynamically stable end product dioxan and only one molecule of the energy-supplying monomer.

## EXPERIMENTAL

*Oxiran-*$d_4$. To a vigorously stirred mixture of ethylene glycol-$d_6$, Merck, 99 % $d$ (5.45 g, 0.08 mol) and $CCl_4$ (100 ml) at 50 °C was slowly dropped a solution of phosgene (carbonyl chloride) (7.9 g, 0.08 mol) in $CCl_4$ (25 ml). After refluxing for 1 h, the upper layer was separated from the lower layer consisting mainly of $CCl_4$ with small quantities of the bis(chloroformate) of ethylene glycol-$d_4$. Gas chromatography showed the upper layer to be essentially pure ethylene carbonate-$d_4$, which crystallized on standing. M.p. 38 °C (6.6 g, 89 %).

Ethylene carbonate-$d_4$ (9.2 g, 0.1 mol) was heated to 40 °C and to this melt was added LiCl (10 mg) previously dried at 400 °C for 18 h. On further heating to 180 °C, oxiran-$d_4$ distilled off and was condensed at −40 °C. After 90 min, the reaction was finished, leaving only a small residue (0.3 g). The condensate (4.5 g, 94 %) contained no higher-boiling products (GLC) and was redistilled before use to remove condensed $CO_2$.

*Crown ethers.* These were prepared by Borregaard Industries Limited according to our method[2] and further purified as follows.

9-Crown-3. A crude fraction containing 75 % of 9-crown-3 was chromatographed on basic alumina with $CHCl_3$ – benzene (1:4). The solvents were evaporated carefully from the collected pure fractions.

12-Crown-4, containing 7 % of 15-crown-5, was redistilled in a Fischer Spaltrohr column (HMS 500) at 106 °C/10 mmHg.

15-Crown-5, containing 4 % of 12-crown-4 and 6 % of 18-crown-6, was redistilled in the same column at 152 °C/1.3 mmHg.

18-Crown-6 was sufficiently pure.

All products were dried by azeotropic distillation with benzene and kept in a desiccator.

*Degradation experiments.* These were carried out in an atmosphere of dry nitrogen. To a solution at 0 °C of the required quantity of the oligomer (3 or 10 mmol) in $CH_2Cl_2$ (25 ml) that had previously been saturated with $BF_3$, was added a solution made up at −20 °C of oxiran-$d_4$ (20 mmol, measured with a microsyringe) in $CH_2Cl_2$ (2 ml). The temperature was kept at 0 °C for the first 6 h, and thereafter at 5 °C. Samples were withdrawn after 1, 2, 4, 8 and 30 min, then after 2, 6 and 20 h, and after 3 and 7 days, and the reaction was stopped by neutralization with $NH_3$.

To study the rate of degradation and product distribution, each experiment was carried out with *cis*-decahydronaphthalene as an internal standard. Withdrawn samples were analyzed directly by GLC on a polysiloxane column (SE-30) using a Hewlett-Packard 5700 A instrument equipped with a flame ionization detector. The response factor for each compound was determined on mixtures of known composition. The values for oxiran are less reliable than the others. The data shown in the tables are recalculated relative values after setting the initial quantity of starting oligomer = 100.

To study the distribution of isotopically different species, the experiments had to be carried out without the internal standard. Withdrawn samples were analyzed by combined GLC-MS using a Micromass 12F mass spectrometer coupled to a Varian Associates 2400 gas chromatograph equipped with a polysiloxane column (SE-30). Chemical ionization was used and the gas had to be isobutane since with methane too much fragmentation occurred. Irreproducible results were first obtained due to isotopic separation on the column. The interesting mass-unit interval (<30 units) was therefore swept continuously so that the M+1 peak of all isotopically different species were monitored through each chromatographic fraction. In Fig. 9 is shown as an example the repeated

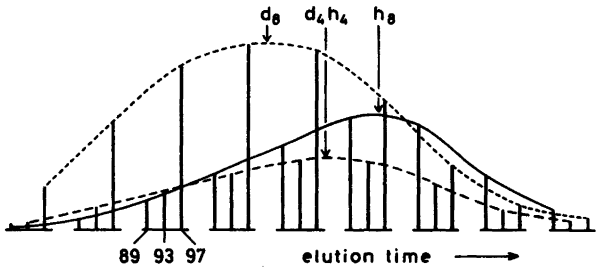



*Fig. 9.* The repeated MS (showing only the M+1 peaks) through a GLC fraction of dioxan consisting of 32 % $h_8$, 18 % $d_4h_4$ and 50 % $d_8$.

spectrum of a dioxan fraction. In view of the many sources of error in the analysis, it was considered sufficiently accurate to use the maximum intensity signal instead of integrating each envelope curve.

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## REFERENCES

1. Dale, J., Borgen, G. and Daasvatn, K. *Acta Chem. Scand. B 28* (1974) 378.
2. Dale, J. and Daasvatn, K. *Chem. Commun.* (1976) 295.
3. Dale, J., Daasvatn, K. and Grønneberg, T. *Makromol. Chem. 178* (1977) 873.
4. *Gmelin Handbuch der Anorganischen Chemie, Erg.werk. Band 53, Teil 19* (1978) 86.
5. Searles, S. and Tamres, M. *J. Am. Chem. Soc. 73* (1951) 3704.
6. Price, C. C. *Acc. Chem. Res. 7* (1974) 294.
7. Dale, J. *Israel J. Chem. 20* (1980) 3.
8. Dunitz, J. D. and Seiler, P. *Acta Crystallogr. B 30* (1974) 2739.

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