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Photo-oxygenation of Indene and 1,2-Dihydronaphthalene: Formation of 1,2-Dioxetanes and 1,2,4-Trioxanes

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Abstract. The methylene blue (MB)-sensitized photo-oxygenation of indene (**1**) in CH_3OH gave *trans*-2-hydroperoxy-1-methoxyindane (**9**), homophthalaldehyde (**4**), and its cyclic acetal **8**. The same reaction conducted in acetaldehyde gave only **4**. Repetition of the photo-oxygenation of **1** in slightly acidic aq. acetone (1:9) gave essentially *trans*-2-hydroperoxy-1-hydroxyindane (**14**) together with some *cis*-5,6-dihydro-3,3-dimethyl-1,2,4-trioxinol[1,2-*e*]indene. The MB-sensitized photo-oxygenation of 1,2-dihydronaphthalene (**16**) in CH_3OH gave 1,4-dihydro-1-hydroperoxynaphthalene (**17**) and *trans*-1,2,3,4-tetrahydro-2-hydroperoxy-1-methoxynaphthalene (**19**). In acetaldehyde, **16** furnished only **17**. In aq. acetone (1:9) **16** gave **17** and *trans*-2-hydroperoxy-1-hydroxy-1,2,3,4-tetrahydronaphthalene (**23**). Product compositions were rationalized in terms of the 2-peroxides of the 1-cation of **1** and **16**, namely **11** and **20**. Treatment of **23** with aldehydes and ketones on catalysis with *Amberlyst-15* or trimethylsilyl trifluoromethanesulfonate afforded the *trans*-fused 1,2,4-trioxanes **25**. The 1,2-dioxetanes of **1** and **16** condensed with acetaldehyde on catalysis with CF_3COOH to give the *cis*-fused 1,2,4-trioxanes **12** and **22**.

by Hock cleavage (**2** → **3**; Scheme 1). In other words, the initial event was assumed to be an ene-type reaction of singlet oxygen (**1** → **2**). Later, **2** was shown not to be an intermediate as a separately prepared sample did not rearrange to **3** [3]. Subsequently, it became apparent that the product composition varies enormously with the solvent, sensitizer, and the conditions used [4]. Consequently, it is no surprise that interpretations on the mechanism of reaction have differed widely. A typical instance is provided by the photo-oxygenation of **1** in CH_3OH where rose bengal (RB) in high concentration was used as sensitizer (Scheme 2) [5]. Only traces of **4** were observed, but substantial quantities of its cyclic acetal (**8**, 25%), *cis*-indane-1,2-diol (**7**, 21%) and the *trans*- and *cis*-2-hydroperoxy-3-methoxyindanes (**9**, 34% and **10**, 17%) were obtained instead. All products were ascribed to a common intermediate, the 1,2-dioxetane **5**. Scission accounted for **4** and **8**, while electron-transfer from RB to **5** was supposed to produce **7**. The pair of indane hydroperoxides **9** and **10** was thought to spring from **5** by protonation to the hydroperoxy cation **6** which was finally quenched indiscriminately by CH_3OH .

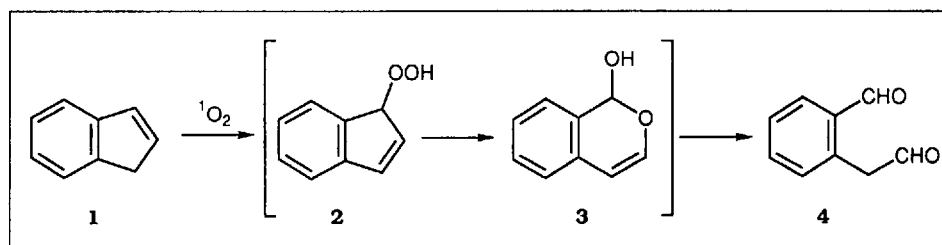
Recent evidence has shown that RB is to be shunned as a sensitizer, especially

Introduction

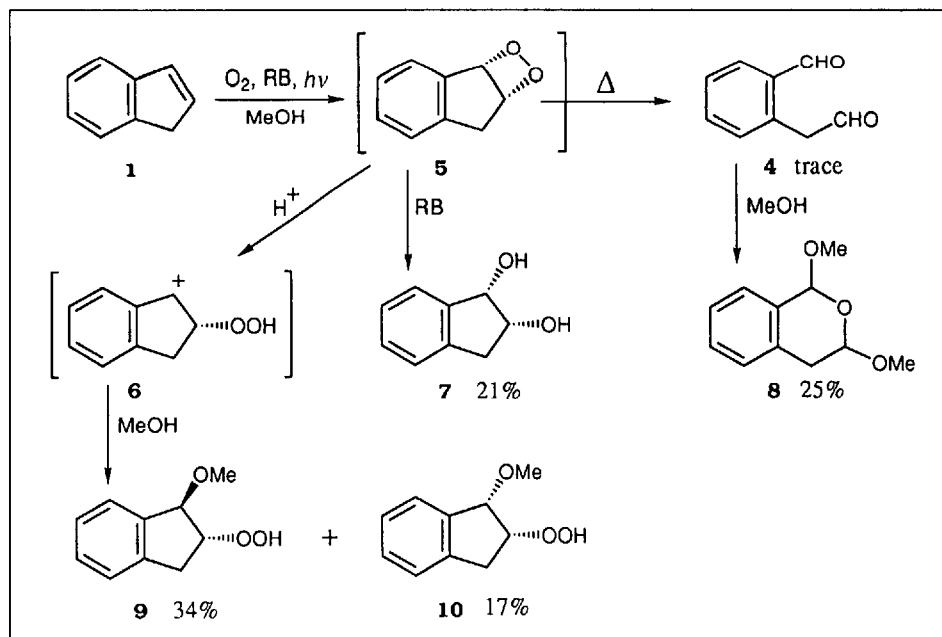
The dye-sensitized photo-oxygenation of olefins constitutes an important chapter in organic chemistry [1]. Depending on the olefin, reaction can occur to give hydroperoxides, 1,2-dioxetanes, and endoperoxides. These oxygenated products are of obvious synthetic value, but the manner of their formation is also important and has commanded considerable attention over the years. As a molecule for testing mechanism, indene (**1**) has been much studied, since its structure allows it to undergo all three of the above-mentioned reaction courses.

The first photo-oxygenation of **1** was carried out in 1968, and innocuously enough was the start of a long polemic on the nature of the primary intermediates [2]. In CH_2Cl_2 , a single product, homophthalaldehyde **4**, was obtained which was thought to arise from the hydroperoxide **2**

Scheme 1

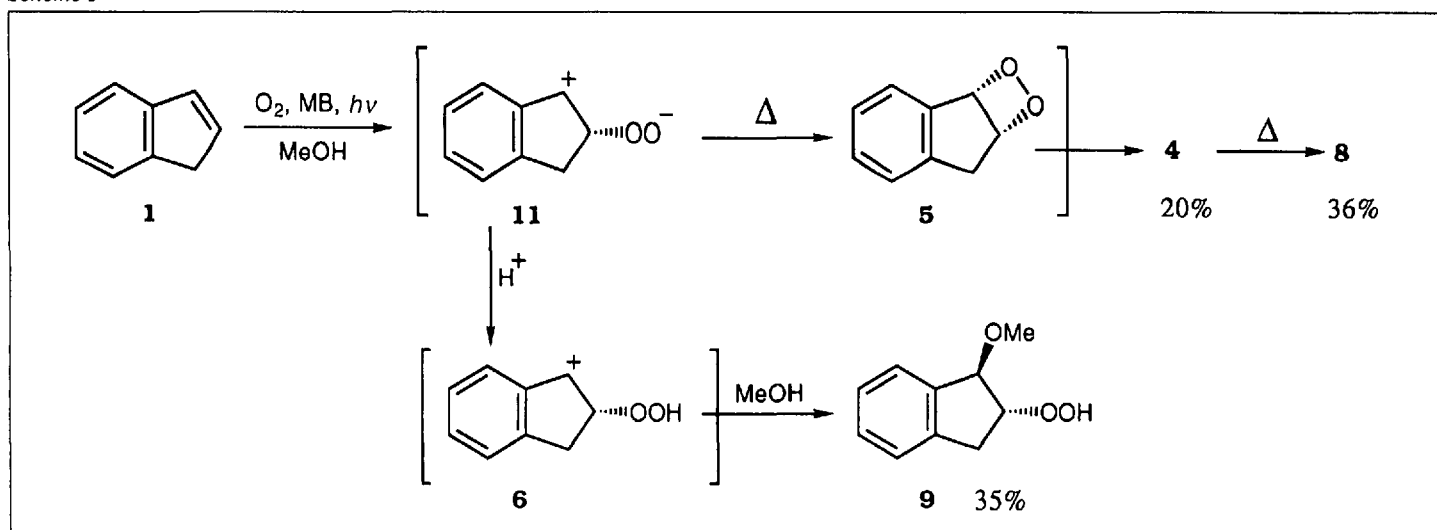


Scheme 2



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Scheme 3



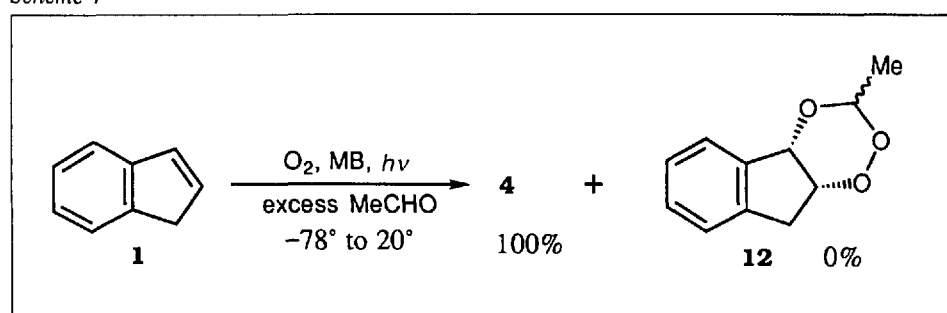
for mechanistic studies. RB possesses the additional property of being able to reduce singlet oxygen to superoxide radical anion [6]. Decomposition of the latter to H_2O_2 then results in the epoxidation of susceptible olefins such as adamantylidene-adamantane. Some of the aforementioned products could have arisen from the action of superoxide radical anion or H_2O_2 on **1**.

Other evidence obtained from the photo-oxygenation of 1,3-dimethylindole [7] and 2-methoxynorbornene [8] suggests that singlet oxygen reacts with electron-rich double bonds to form zwitterionic peroxides as the first event. Indene (**1**) should behave similarly. By a suitable choice of solvent, namely CH_3OH or acetaldehyde, the identity of the relevant ionic peroxides could be revealed.

Results and Discussion

We now report on such trapping experiments which have been carried out on **1** and for good measure on 1,2-dihydro-

Scheme 4

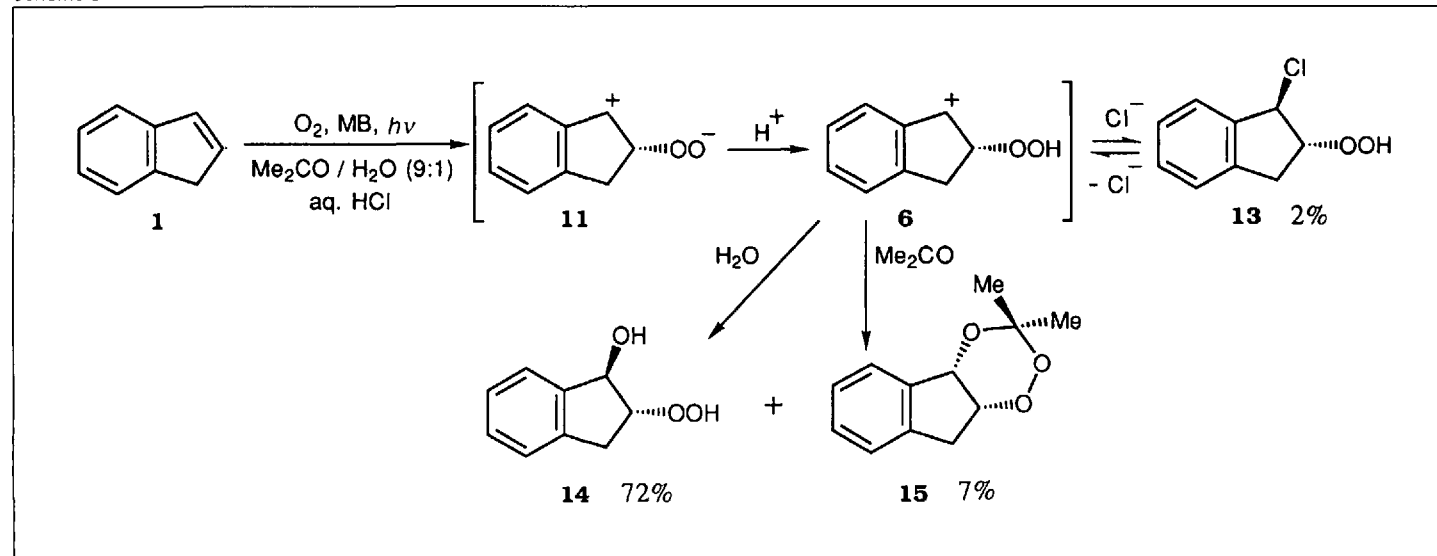


naphthalene (**16**) and two derivatives **26** and **27** which resemble **1**. The photo-oxygenation of **1** was sensitized by methylene blue (MB) in CH_3OH and performed for 10 h at 10° . Three products were isolated, *trans*-2-hydroperoxy-1-methoxyindane (**9**, 35%), homophthalaldehyde (**4**, 20%), and the cyclic acetal (**8**, 36%) (Scheme 3). This result indicates that a molecule of singlet oxygen has added to **1** to form the zwitterionic species **11** which enjoys stabilization as a benzylic cation. Closure to dioxetane **5** soon follows. Cleavage to-

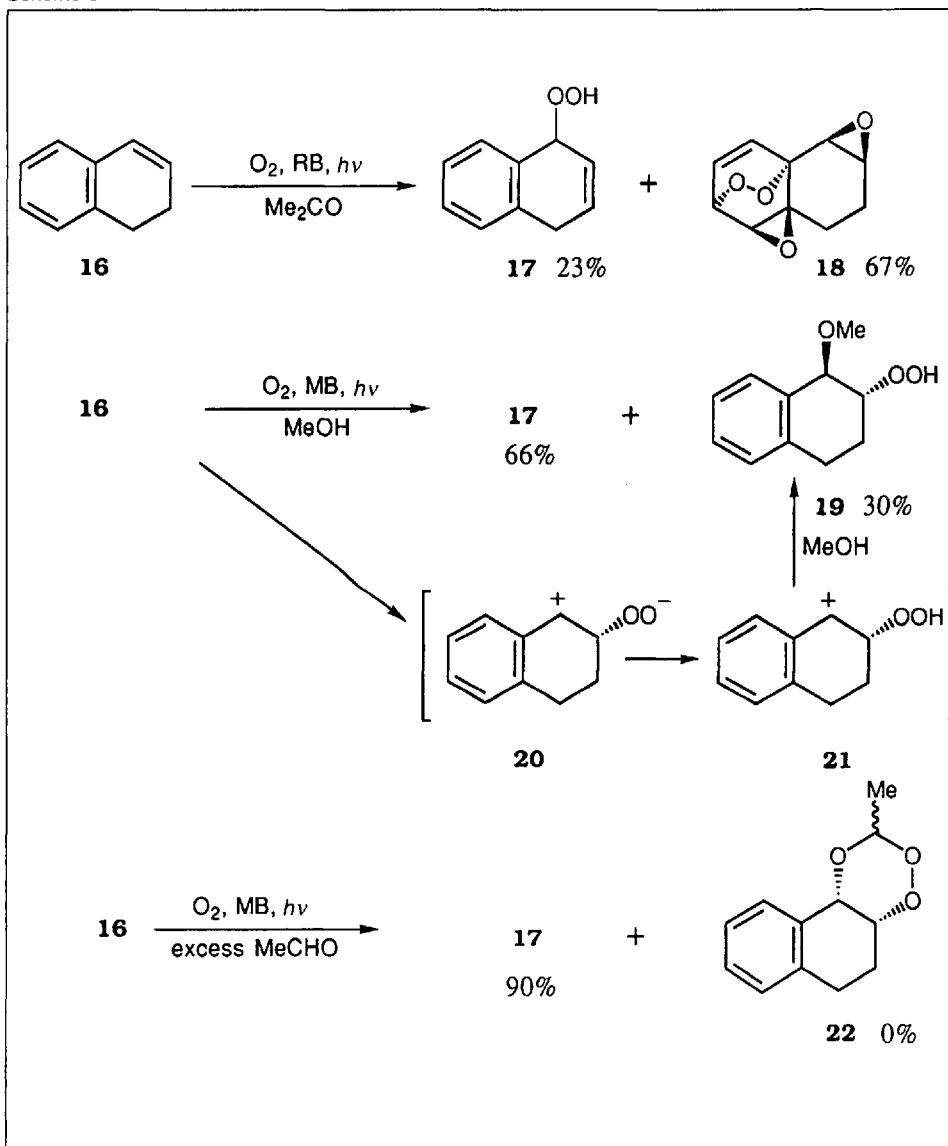
gether with methanolysis accounts for **4** and **8**. Significantly, **11** lives long enough to undergo external capture by a molecule of CH_3OH . The peroxide group first acquires a proton to give the cation **6** which is then attacked on its least hindered side by CH_3OH so producing **9**. The resulting *trans*-product does not equilibrate with the *cis*-isomer **10** owing to the poor nucleofugacity of the CH_3O group.

Repetition of the photo-oxygenation in a ten-fold excess of acetaldehyde several times at temperatures between -78° and

Scheme 5



Scheme 6



general, such hydroperoxy cations readily condense with carbonyl partners to afford *cis*-fused 1,2,4-trioxanes [10].

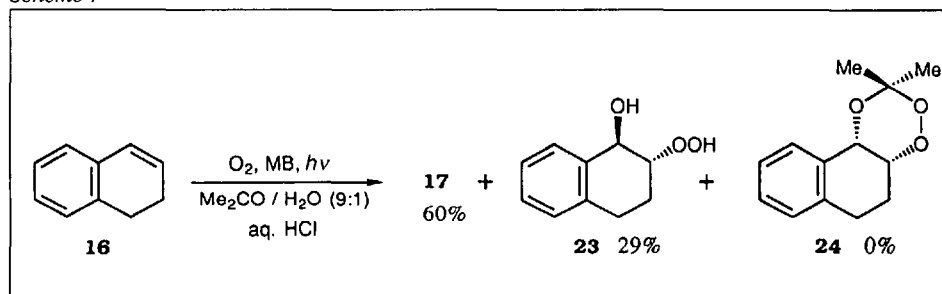
1,2-Dihydronaphthalene (16) has a structure which is similar to that of indene (1), but its photo-oxygenation has been studied less [11]. The products obtained in the RB-sensitized experiment [12] in acetone at -78° were just the 1-hydroperoxy derivative 17 (23%) and the adduct of a double addition of oxygen (18, 67%) (Scheme 6). Re-examination of this reaction at 10° in CH_3OH by using MB as sensitizer gave a result reminiscent of that found with indene (1). The hydroperoxide 17 (66%) was obtained as before, but accompanied by *trans*-1,2,3,4-tetrahydro-2-hydroperoxy-1-methoxynaphthalene (19, 30%) (Scheme 6). Again, the provenance of 19 can be attributed to the primary peroxidic zwitterion 20 which has successfully captured a proton and CH_3OH to give successively 21 and 19. As before, 20 could not be intercepted to give trioxane 22, even when the photo-oxygenation of 16 was conducted in an overwhelming excess of acetaldehyde (Scheme 6). Evidently, 20 and 11 are equally inert towards aldehydes. An essential difference between 1 and 16 is that the ene-type reaction operates for the latter as a competing mode.

In an aq. medium, acetone/ H_2O 9:1 with or without a drop of HCl, 16 reacted with singlet oxygen to give the usual ene product 17 (60%) and the *trans*-hydroperoxy alcohol 23 (29%) (Scheme 7). No trace of 1,2,4-trioxane 24 was detected.

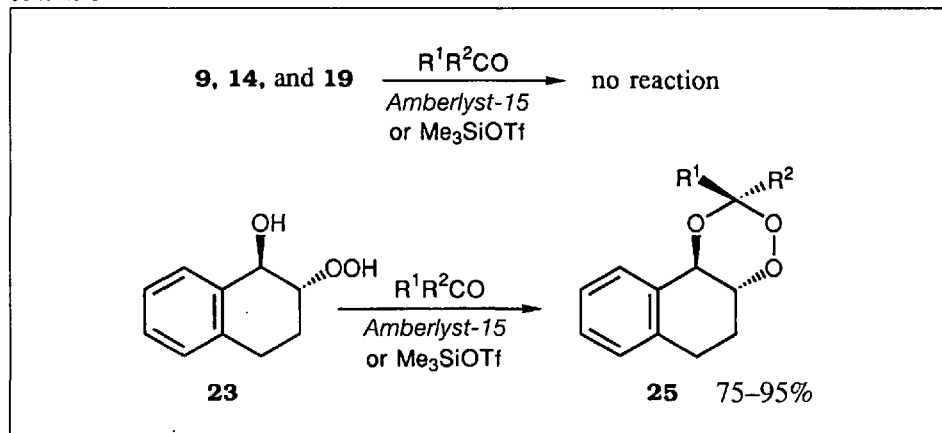
20° gave none of the expected 1,2,4-trioxane 12, but only 4 (Scheme 4). Clearly, the intermediate 11 is either not reactive enough or too short-lived to be intercepted by a molecule of acetaldehyde. However, when the above experiment was carried out in aq. acetone (1:9) containing traces of HCl, *trans*-2-hydroperoxy-1-hydroxyindane (14) became the main product (72%) (Scheme 5). A tiny amount of the chloro analogue 13 (2%) and the *cis*-fused 3,3-dimethyl-1,2,4-trioxane 15 (7%) were also obtained. The configurations of 14 and 15 were ascertained by their reduction with $NaBH_4$ and $LiAlH_4$, resp., to the known *trans*- and *cis*-1,2-indane diols [9].

The origin of 15 was not the *trans*-hydroperoxy alcohol 14, since it did not react with acetone on catalysis with Amberlyst-15 or $CuSO_4$. The *trans*-methoxy hydroperoxide 9 was equally inert. Obviously, the dipolar species 11 is inert towards acetone as it did not even react with the more electrophilic acetaldehyde molecule. A reasonable candidate is the hydroperoxybenzyl cation 6 which is in equilibrium with the chloro derivative 13. In

Scheme 7



Scheme 8



Varying the amount of HCl had no effect on the product composition.

The failure to isolate trioxane prompted further tests on **19** and **23**. Like **9**, **19** proved unreactive to acetaldehyde on catalysis with *Amberlyst-15* or trimethylsilyl trifluoromethanesulfonate (TMSOTf) (Scheme 8). On the other hand, unlike *trans*-2-hydroperoxy-1-hydroxyindane (**14**), **23** underwent efficient condensation with both aldehydes and ketones (R^1R^2CO) on catalysis with *Amberlyst-15* to give the corresponding *trans*-fused 1,2,4-trioxanes (**25**) in high yield. Several of these compounds were stable, crystalline solids which permitted their structures to be determined by X-ray analysis [13]. The trioxane obtained from acetone (**25a**, $R^1=R^2=Me$) revealed that the fusion of the new oxygenated ring is *trans*, and that the ring itself adopts a chair conformation

(Fig.). This result is of synthetic utility as most bicyclic 1,2,4-trioxanes prepared so far are *cis*-fused.

Lastly, the effect of substituents on the course of the photo-oxygenation of **16** was assayed. The 6-nitro derivative **26** proved to be totally unreactive which undoubtedly is due to the lowering of the energy of the HOMO of the styrene-like part of the molecule (Scheme 9). Conversely, the 6-methoxy derivative **27** in acetone/ H_2O (9:1) as solvent underwent complete reaction within 1 h to deliver the dialdehyde **29** (81%) and its cyclization product **30** (10%). No sign of the 2-hydroperoxy-1-hydroxy derivative analogous to **23** was seen. Obviously, a capturable, discrete zwitterionic peroxide is not formed; therefore, formation of the dioxetane **28** from **27** is likely to be concerted.

A final set of experiments was per-

formed with authentic samples of the 1,2-dioxetanes of indene (**5**) [15] and 1,2-dihydronaphthalene (**31**) [16] to rule out the possibility that they were intermediates rather than the zwitterionic species (Scheme 10). Both were inert to neutral CH_3OH , however, on catalysis with CF_3COOH both underwent ready condensation with acetaldehyde in CH_2Cl_2 to afford the *cis*-fused 1,2,4-trioxanes (**12** and **22**) in yields of 95 and 75%, resp.

Conclusion

The present results attest to the formation of zwitterionic peroxides **11** and **20**, when singlet oxygen collides with indene (**1**) and 1,2-dihydronaphthalene (**16**). The positive charge in **11** and **20** is stabilized as a benzylic cation, whereas the negative charge exists simply as the free peroxide ion. The latter is easily protonated, but is unable to add to the aldehyde function. In CH_3OH , some of **11** escapes capture and closes to dioxetane **5**. In contrast, **20** is completely captured by CH_3OH . Furthermore, **16** undergoes hydroperoxidation as a second course of reaction.

Both olefins **1** and **16** are different from 2-methoxynorbornene and 2-(methoxymethylidene)adamantane, the zwitterionic peroxides of which are readily captured by acetaldehyde [8]. However, the behavior of **1** and **16** parallels that of 2-(phenoxymethylidene)adamantane which always gives 1,2-dioxetane product even in the presence of acetaldehyde [17].

A final difference between **1** and **16** is revealed by their ability to form 1,2,4-trioxanes. The synthesis of both *cis*- and *trans*-fused bicyclic trioxanes (e.g. **22** and

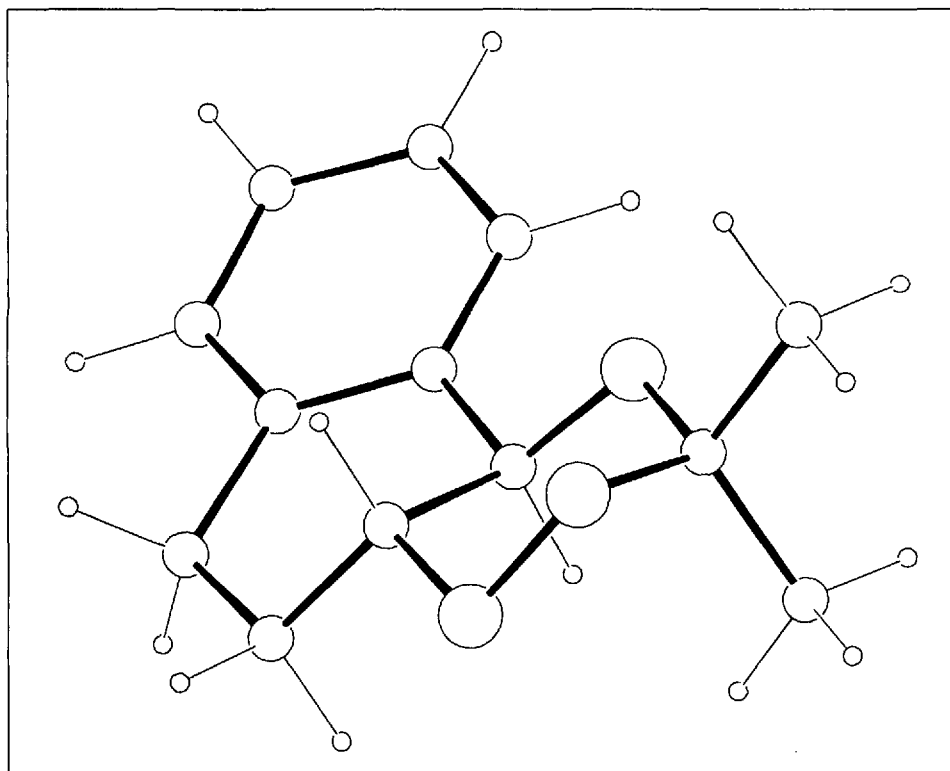
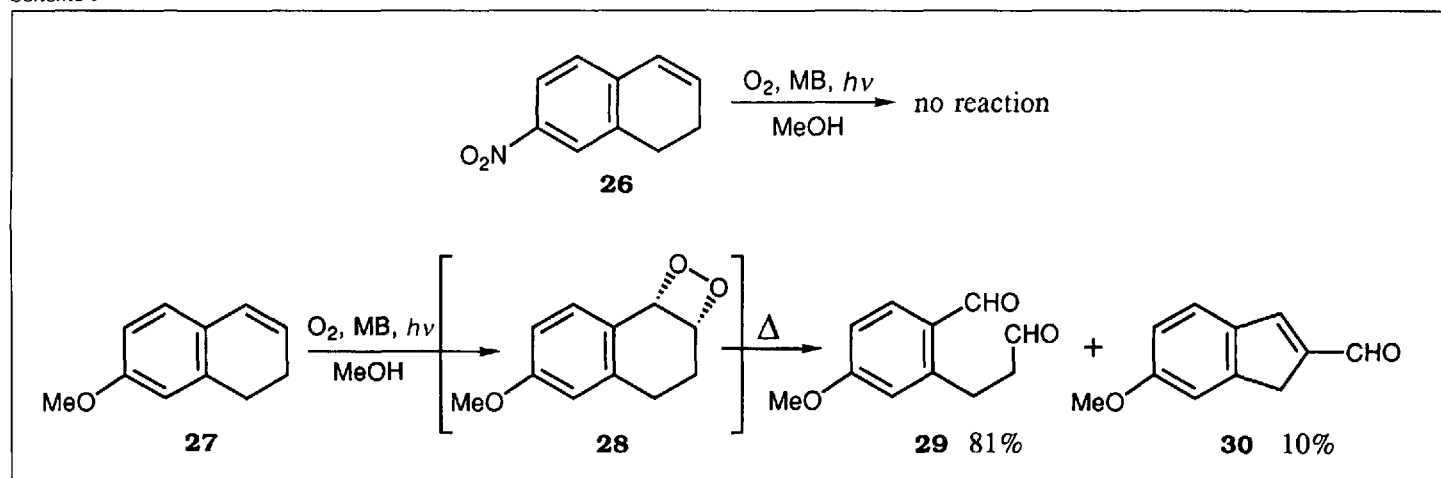
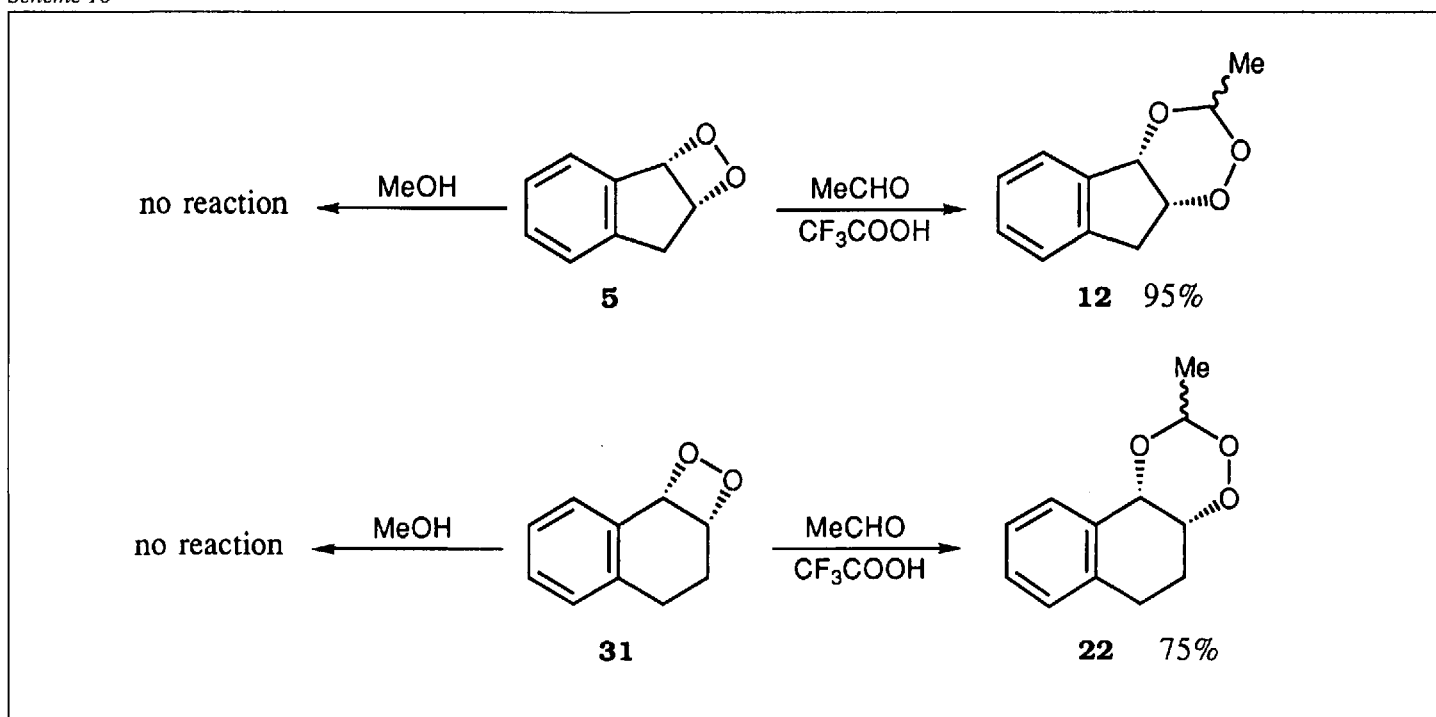


Figure. Perspective drawing of the X-ray structure of trioxane **25a**

Scheme 9



Scheme 10



25) is possible for **16** through the intermediacy of the 2-hydroperoxy cation **21** derived from **31** and the *trans*-2-hydroperoxy alcohol **23**, resp. Indene (**1**) only affords the *cis*-fused trioxanes (**12** and **15**), through the 2-hydroperoxy cation **6**. Inexplicably, *trans*-fused trioxanes are inaccessible.

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