Stereochemical and Mechanistic Aspects of Sulphoxide, Epoxide, Arene Oxide, and Phenol Formation by Photochemical Oxygen Atom Transfer from Aza-aromatic *N*-Oxides

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Stereoselectivity and relative yields are determined for the sulphoxide formation resulting from the u.v. irradiation of a range of aza-aromatic *N*-oxides in the presence of cyclic thioethers. A comparison is made with the results of oxidation by oxaziridines and by mono-oxygenase enzymes present in the fungus *Aspergillus niger*. The photochemical oxidation results are consistent with a transition state involving an oxaziridine intermediate where partial bonding of the oxygen atom to the ring nitrogen atom is maintained during the oxygen transfer process.

Photolysis of aza-aromatic *N*-oxides in the presence of *cis*- and *trans*-olefins yields epoxides. *cis*-4-Methylpent-2-ene yielded both *cis* and *trans*-epoxides in almost equal proportions indicating that the oxygen atom addition to a carbon–carbon bond in this system is non-concerted.

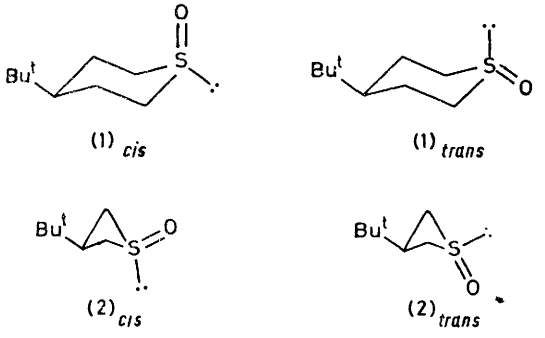
The photochemically induced oxygenation of perdeuteriated aromatic substrates provides no evidence for direct insertion of an oxygen atom into an aromatic carbon–hydrogen bond. Addition of an oxygen atom to form an epoxide (arene oxide) intermediate in this system is evidenced by the NIH shift in a wide range of aromatic substrates, and by the detection of arene oxide intermediates (and their isomeric phenols) from naphthalene and phenanthrene.

BIOLOGICAL oxygen-atom transfer reactions catalysed by mono-oxygenase enzymes may involve bond formation between oxygen and either carbon, nitrogen, phosphorus, or sulphur atoms. A preliminary report [1] of a portion of the present work examined a range of chemical oxidizing agents which gave similar products to those obtained by molecular oxygen–mono-oxygenase oxidation. The most satisfactory mechanistic model system examined was the photolysis of aza-aromatic *N*-oxides. Thus, a range of oxidations, including sulphoxidation, epoxidation, aliphatic, and aromatic hydroxylation, was observed, and a systematic evaluation was made of these model systems in terms of 'the NIH shift' [2] during aromatic hydroxylation. Further studies have since appeared in which other chemical oxidants have been considered as possible models using the NIH shift [3] as a criterion. Our initial report [1] of arene oxide formation by direct oxidation of an aromatic ring has been followed recently by examples using alternative oxidants.[4] The continuing interest in this area (exemplified by results [5,6] which demonstrate that the ratio of oxygen transfer reaction relative to photochemical *N*-oxide rearrangements may be markedly enhanced) has prompted the present report.

RESULTS AND DISCUSSION

3-t-Butylthiacyclobutane and 4-t-butylthiacyclohexane were selected as oxygen atom acceptors in the *N*-oxide photolytic oxidations since the product sulphoxides (1) and (2) were stable under the reaction conditions and could be analysed by g.l.c.–m.s. Furthermore, since both the *cis*- and *trans*-sulphoxide isomers could be formed, the stereoselectivity of *N*-oxide photooxidation could readily be compared to that found with other chemical- and enzyme-catalysed oxidations. Preliminary experiments were designed to determine the optimal yields under a range of experimental conditions.

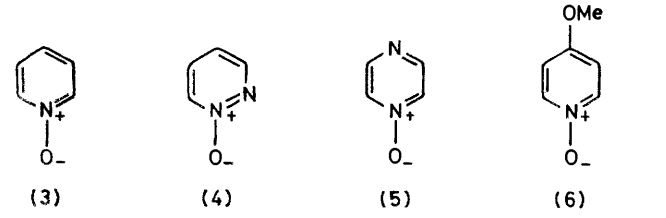
No significant increase in sulphoxide yield above the values given in Tables 1 and 2 could be achieved with changes in duration of irradiation, concentration of *N*-oxide, solvent, temperature, or addition of photosensitizers. The major limitation of this oxidation system was the poor yield resulting from (i) alternative photochemical transformations occurring and (ii) the formation of dark, insoluble products which diminished the



amount of u.v. light entering the cell. Thus, under the standard conditions adopted, the optimal yield was 8—9% for both sulphoxides (1) and (2). Whereas the yields obtained were generally similar (Table 1), the polycyclic *N*-oxides (8) and (9) and the monocyclic *N*-oxide (5) were marginally better oxygen donors. While the yields of sulphoxides produced were low (<10%), the oxidations were quite reproducible as determined by g.l.c.–m.s. analysis. Since the present studies were primarily concerned with an investigation of the mechanism, stereochemistry, and range of products from the photolytic *N*-oxide oxidations, with the 'oxenoid' [7]

nature of the reactions, and with comparative results from mono-oxygenase enzyme systems, a low yield was of lesser importance.

The average *cis–trans* ratio of sulphoxides (1) and (2) was similar in each case for the range of *N*-oxides used [*ca.* 34% for $(1)_{cis}$ and ~56% for $(2)_{cis}$, Table 1]. The



(3) (4) (5) (6) (7) (8) (9)

peroxide oxidants, *meta*-chloroperoxybenzoic acid (MCPBA) and hydrogen peroxide, gave similar proportions of $(1)_{cis}$ (*ca.* 37%) but a slightly lower proportion of $(2)_{cis}$ (*ca.* 44%) (Table 1). The deviation in the *cis–trans* ratios of (1) and (2) for the peroxide oxidations from the ratios at equilibrium has been interpreted in terms of steric approach control.[8] If steric factors also predominate in the formation of (1) and (2)

TABLE 1

Distribution of $(1)_{cis}$–$(1)_{trans}$ [or 2_{cis}–2_{trans}] after *N*-oxide photolysis [a] or oxidation in the presence of 4-t-butylthiacylohexane (or 3-t-butylthiacyclobutane)

	% Products (total % yield) [b]			
Oxygen donor	$(1)_{cis}$	$(1)_{trans}$	$(2)_{cis}$	$(2)_{trans}$
(3)	34	66 (3.0)	48	52 (0.9)
(4)	36	64 (1.5)	53	47 (3.4)
(5)	39	61 (3.8)	54	46 (1.6)
(6)	32	68 (0.9)	57	43 (2.4)
(7)	28	72 (1.3)	63	37 (1.6)
(8)	35	65 (8.0)		
(9)	34	66 (6.5)	58	42 (8.9)
(10a)	38	62 (7.3)	56	44 (4.6)
Aspergillus niger	8	92	56	44
MCPBA	36	64	45	55 [c]
H_2O_2	37	63	43	57 [c]
Equilibrium ratio	80	20	82	18 [c]

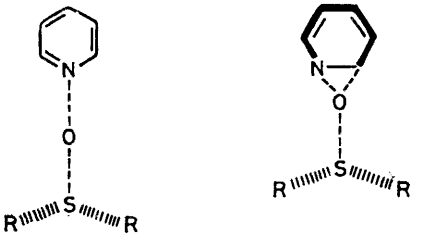
[a] Equimolar quantities of thioether and *N*-oxide, in dichloromethane, irradiated with u.v. light (2 537 Å) for 3 min under N_2. [b] Separated, identified, and estimated by g.l.c.–m.s. using a 2-m FFAP column at 150 °C [retention times for $(1)_{cis}$ and $(1)_{trans}$ were 17 and 25 min, respectively] or at 200 °C [retention times for $(2)_{cis}$ and $(2)_{trans}$ were 23 and 28 min, respectively]. [c] See ref. 8.

from *N*-oxide photolysis then the relatively small range found in the proportion of $(1)_{cis}$ [or $(2)_{cis}$] indicates that the oxygen-atom transfer agents (3)—(9) have similar steric requirements.

McKenna and his co-workers [9] have reported the electrophilic addition of a photochemically generated carbene and nitrene to 4-t-butylthiacyclohexane. The carbene addition to form a sulphonium ylide was found to occur exclusively from the equatorial direction to yield the *trans*-product while the imino-sulphurane formed from the nitrene showed no stereochemical preference. As in the previous work on peroxide oxidations of 4-t-butylthiacyclohexane,[8] non-bonding interactions (larger for carbene relative to nitrene attack) were considered to be the dominant factor. The preference shown for the formation of $(1)_{trans}$ (61—72%) during the photochemical *N*-oxide oxidations of 4-t-butylthiacyclohexane (in comparison with carbene and nitrene attack) suggests that the oxenoid species may be intermediate in steric requirements. The present observations support the proposal [10] that atomic oxygen (oxene) is not involved in the oxidations mediated by *N*-oxide photolysis. Oxene addition to 4-t-butylthiacyclohexane should have produced a smaller proportion of $(1)_{trans}$ than 61—72% from steric considerations (*i.e.* carbene > nitrene > oxene).

The formation of sulphoxides (1) and (2) from the t-butyl-substituted thiacycloalkanes in growing cultures of the fungus *Aspergillus niger* (Table 1) demonstrates that the cyclic thioethers used in the present study are substrates for mono-oxygenase enzymes.

The isolation of both *cis*- and *trans*-isomers of (1) and (2) from these microbial incubations was in concurrence



(A) (B)

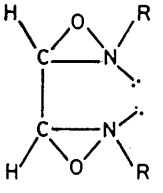
with earlier work from these laboratories with *A. niger*, where a range of stereoselectivity among the optically active sulphoxide products was obtained.[11] No particular significance should be attached to the magnitude of the *cis–trans* ratios for (1) and (2) isolated after the fungal oxidations since stereoselective metabolism of the initially formed sulphoxides probably occurs.

The present results of thioether oxidation indicate that steric requirements of the photochemically generated oxenoid species from aza-aromatic *N*-oxides are probably (i) similar, regardless of the *N*-oxide used, (ii) larger than an oxygen atom, and (iii) smaller than a carbene. Among the possible transition states which should be considered for these oxenoid reactions are (A) and (B).

Transition states (A) and (B) both imply partial sulphur–oxygen bond formation and partial nitrogen–oxygen bond cleavage. The steric effects in (A) would be larger than those where oxene (but smaller than those where carbene) attack on sulphur was occurring. In the photolytic oxidations a transition state of type (A) would be expected to involve larger steric interactions for the tricyclic *N*-oxides (8) and (9) than for the monocyclic

N-oxides (3)—(6). This is not, however, reflected by any significant change of stereoselectivity or yield in the formation of (1) or (2) (Table 1).

Transition state (B) would result initially from photorearrangement of an *N*-oxide to an oxaziridine. Initial formation of an oxaziridine during the u.v. irradiation of *N*-oxides has been postulated in virtually all reports [12] although the generality of this photoisomerization has recently been questioned.[10] Oxaziridines are known to be mild oxidizing agents,[13,14] and it has previously been proposed that the unstable oxaziridines formed from photoisomerization of aza-aromatic *N*-oxides would act as powerful oxygen atom donors since deoxygenation would be facilitated by rearomatization of the heterocycle.[15,16] Oxaziridines have been shown to be capable of transferring their ring oxygen atom to tertiary phosphines and of oxidizing HI.[13,14] The stable oxaziridine (10a), however, was found to yield the sulphoxides (1) and (2) from the corresponding thioethers upon being stirred together in dichloromethane solvent at ambient temperature. No attempts were made to optimize the yields of (1) and (2) which were relatively low (5—7%) with (10a) as oxidant. The oxidation of thioethers by oxaziridines proved to be a general reaction and thus (10b) was found to transfer an oxygen atom to benzyl



(10a) R = Bu^t
(10b) R = C_6H_{11}

p-tolyl sulphide under similar conditions. In the course of the present study Davis *et al.*[17] also showed that oxaziridines (containing an *N*-arenesulphonyl substituent) were able to oxidize thioethers to sulphoxides at ambient temperature but at a faster rate and in higher yield. These studies strengthen the view that an oxaziridine moiety such as that shown in the transition state (B) can behave as a strong oxidant capable of organosulphur oxidations and probably also a further range of oxygen-atom transfer reactions.

The stereoselectivity of the oxidation of 4-t-butylthiacyclohexane and 4-t-butylthiacyclobutane by oxaziridine (10a) is noteworthy (Table 1). The proportions of $(1)_{trans}$ and $(2)_{trans}$ obtained (62% and 44%, respectively) are almost identical to the average values found using the photolysis of the *N*-oxides (3)—(9) (66% and 44%). Furthermore, oxidation with 2-phenylsulphonyl-3-phenyloxaziridine [17] occurred to give a 64% yield of $(1)_{trans}$. The stereoselectivity of the photolytic *N*-oxide oxidations is consistent with a transition state of type (B) involving an oxaziridine. The latter datum does not, however, permit the total exclusion of alternative transition states [*e.g.* (A)].

Epoxidation reactions which occur *in vivo* under the influence of mono-oxygenase enzymes should also be found in mono-oxygenase model systems. Cyclohexene oxide and styrene oxide were obtained in low yield from photolysis of pyridine *N*-oxide in the presence of cyclohexene and styrene, respectively (Table 2). These results are in concurrence with those obtained in other laboratories with pyridazine *N*-oxide.[18] The stereoselectivity of the epoxidation reaction was investigated using pyridine *N*-oxide as oxygen donor in the

TABLE 2

Product distribution after pyridine *N*-oxide photolysis in the presence of a range of substrates

Substrate	Identified products	Product ratio [a]
Cyclohexene	Cyclohexanone [b]	1
	Cyclohexen-3-ol [b]	1
	Cyclohexene oxide [b]	4
Styrene	Acetophenone [c]	1
	Styrene oxide [c]	10
cis-4-Methylpent-2-ene	*cis*-4-Methylpent-2-ene oxide [d,e]	1
	trans-4-Methylpent-2-ene oxide [d,e]	1
trans-4-Methylpent-2-ene	*trans*-4-Methylpent-2-ene oxide [d,e]	

[a] Yields, in the range 1—4% after irradiating in dichloromethane solvent at ambient temperature, were determined by g.l.c.–m.s. analysis on the specified columns. [b] 10% DC–710 silicone oil column at 135 °C. [c] 3% Trixylyl phosphate column at 120 °C. [d] 17% Polyethylene glycol column at 50 °C. [e] Photolyses were carried out at −70 °C.

presence of *cis*- or *trans*-4-methylpent-2-ene. Photolysis of the *cis*-olefin in dichloromethane at −70 °C yielded a mixture (1 : 1) of the *cis*- and *trans*-epoxides. A similar result has been obtained using *cis*-but-2-ene [19] (pyridine *N*-oxide–dichloromethane). Epoxidation of the *trans*-olefin gave a number of products including the *trans*-epoxide, but excluding the *cis*-epoxide. A detailed interpretation of the latter results is difficult in view of the low yields, the limited number of photolytic epoxidation reactions carried out, and the formation of additional products. However, it is clear that since *cis–trans* isomerization of neither olefins nor epoxides occurred under these photochemical conditions the epoxidation does not proceed by a concerted *cis*-addition mechanism.

The formation of cyclohexen-3-ol (Table 2) during irradiation of pyridine *N*-oxide in the presence of cyclohexene provides an example of aliphatic hydroxylation. Aliphatic hydroxylations by photolysis of pyridazine *N*-oxide have been reported previously.[20]

In the present studies particular emphasis has been placed on the mechanism of aromatic hydroxylation using *N*-oxide photolytic oxidants. With 4-^{2}H and 2-^{2}H-labelled anisole and a range of *N*-oxides low yields of *ortho*- and *para*-deuteriated hydroxyanisoles were obtained. Separation and analysis for deuterium content of the phenolic products were generally carried out directly using g.l.c.–m.s. In all cases the phenols contained a significant proportion of the original deuterium, indicating that arene oxide intermediates were formed initially, which then rearranged to phenols (NIH

shift[2]). On average the deuterium retention was greater for *para*- than for *ortho*-hydroxylation (Table 3). When a range of deuteriated aromatic substrates was hydroxylated by the *N*-oxide photolytic method (Table 4) a significant proportion of deuterium migration and retention was observed in all cases. The magnitude of

TABLE 3

% Deuterium in 2- and 4-hydroxyanisole, obtained by *N*-oxide photochemical oxidation of [2-^{2}H]- and [4-^{2}H]-anisole

Amine *N*-oxide	% D [a]
(3)	45 [b]
	36 [c]
(4)	34 [b]
	17 [c]
(5)	52 [b]
	29 [c]

[a] Analysed by g.l.c.–m.s. using a 3% ECNSS–M column at 160 °C or a 3% XE–60 column at 160 °C. [b] Reactant was [4-^{2}H]anisole and % D refers to 4 hydroxyanisole product. [c] Reactant was [2-^{2}H]anisole and % D refers to 2-hydroxyanisole product.

deuterium retention was found to vary markedly with the solvent used and the presence of additives (*e.g.* acetamide). Thus, mechanistic conclusions based upon these retention values should be treated with caution.

The possibility of several mechanisms being involved

TABLE 4

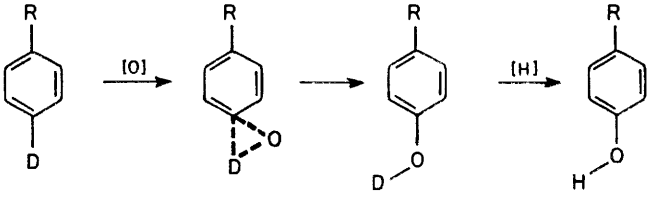
% Deuterium in phenolic products obtained by pyridine *N*-oxide photochemical oxidation and liver microsomal oxidation

		% Deuterium	
Substrate	Phenolic product	*N*-Oxide oxidation	Liver microsomes oxidation
[4-^{2}H]Anisole	4-Hydroxyanisole	45 [a,b]	60 [b,c]
		74 [b,d]	
[4-^{2}H]Toluene	4-Hydroxytoluene	59 [e,f]	
Chloro[4-^{2}H]-benzene	4-Hydroxychloro-benzene	62 [a,g]	54 [g]
		51 [d,g]	
Bromo[4-^{2}H]-benzene	4-Hydroxybromo-benzene	49 [a,g]	40 [g]
		22 [d,g]	
[4-^{2}H]Acetanilide	4-Hydroxy-acetanilide	28 [a,h]	30 [i]
		73 [d,h]	
[1-^{2}H]Naphthalene	1-Naphthol	68 [a,i,j]	64 [i]
[2-^{2}H]Naphthalene	1-Naphthol	64 [a,i,j]	64 [i]

[a] Pyridine *N*-oxide photolysis in CH_2Cl_2 under N_2 at room temperature. [b] G.l.c. analysis as shown in footnote *b* in Table 3. [c] See ref. 2. [d] Pyridine *N*-oxide photolysis in aqueous acetone (pH 8–phosphate buffer) under N_2 at room temperature. [e] Pyridine *N*-oxide photolysis in neat substrate under N_2 at room temperature. [f] Analysed by g.l.c.–m.s. using a 3% tricresyl phosphate column at 135 °C. [g] Analysed by g.l.c.–m.s. after methylation in alkaline dimethyl sulphate using a 20% Carbowax column at 115—130 °C. [h] Separated by paper chromatography using Whatman No. 1 paper and eluting with benzene–acetic acid–water (2 : 2 : 1) prior to direct m.s. analysis. [i] Analysed by g.l.c.–m.s. on the trimethylsilyl ethers using 3% SE–30 columns at 135 °C. [j] See D. R. Boyd, J. W. Daly, and D. M. Jerina, *Biochemistry*, 1972, **11**, 1961.

in the above hydroxylations could explain the range of deuterium retentions observed. An oxygen atom, in principle, might insert directly into a carbon–hydrogen bond by analogy with carbene and nitrene reactions. This process would involve total loss of the label by exchange of the hydroxy-deuteron. This possibility was tested using a mixture of benzene–perdeuteriobenzene (1 : 1) and the *N*-oxides (3)—(5). After irradiation and work-up the phenol–perdeuteriophenol product mixture was found to be in the ratio 1 : 1. A similar experiments, using pyrazine *N*-oxide (5) oxidant and naphthalene–perdeuteronaphthalene (1 : 1), showed that the major phenolic product (1-naphthol) was a mixture of the normal and perdeuteriated material (1 : 1). While a large primary kinetic isotope effect might normally be anticipated if a direct insertion mechanism were operating, the latter mechanism cannot be totally excluded. The *N*-oxide photolytic oxidation of cyclohexene, allied to similar results from other laboratories [18] indicates that addition products predominate over insertion products. The results obtained using mixtures of normal and perdeuteriated aromatic substrates would support this conclusion.

The major hydroxylation products were the *ortho*- and *para*-isomers, with generally little trace of the *meta*-product. The ' NIH shift ' demonstrated in the results from Tables 3 and 4 can best be rationalized in terms of arene oxide intermediates. Thus the *para*-hydroxylation product will be derived from a 3,4-oxide while the *ortho*-hydroxylation product may ensue from either a 1,2- or a 2,3-oxide. In general, the percentage of



deuterium retained in the phenolic products was comparable to that observed when liver microsomes was the oxidant (Table 4), suggesting that arene oxide intermediates are involved in both oxidations.

Attempts to detect the presence of benzene oxide during hydroxylation of benzene by the *N*-oxide system were thwarted by the instability of benzene oxide under the photolysis conditions. Since arene oxides derived from polycyclic aromatic hydrocarbons (PAHs), are frequently more stable than the monocyclic analogues, naphthalene was examined. The stability of naphthalene 1,2-oxide under the *N*-oxide photolysis conditions was found to be improved if an excess of *N*-oxide was present.

An authentic mixture of naphthalene 1,2-oxide, 1-naphthol, and naphthalene was partially separated and the individual components were detected after elution on triethylamine-washed silica gel t.l.c. plates. Elution with a mixture of benzene–chloroform–ethyl acetate–triethylamine showed the elution sequence to be naphthalene (R_F 0.60), naphthalene 1,2-oxide (R_F 0.57), and 1-naphthol (R_F 0.24). The t.l.c. plates were analysed by u.v. and when sprayed with Gibbs reagent showed the naphthalene 1,2-oxide as a crescent-shaped grey area on the lower edge of the naphthalene spot and the 1-naphthol as a violet spot. Extraction with 1N-sodium

hydroxide removed 1-naphthol leaving the naphthalene and naphthalene 1,2-oxide unaffected.

The crude product mixture after *N*-oxide photolysis, in the presence of naphthalene, was analysed by the above t.l.c. method and naphthalene 1,2-oxide was unequivocally identified from the following evidence. (i) The R_F value and appearance of the spot under u.v. light (and after spraying with Gibbs reagent) was identical to that of naphthalene 1,2-oxide.

(ii) The presence of 1-naphthol in the crude product mixture before washing with NaOH, and after acidification of both the NaOH extract and the residual dichloromethane layer, is consistent with the formation and acid-catalysed rearrangement of naphthalene 1,2-oxide.

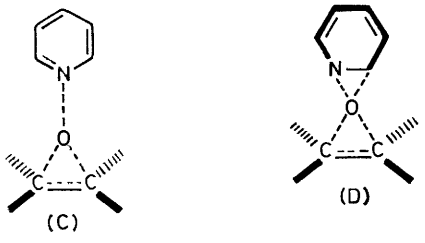
(iii) A large proportion of the deuterium originally present in [1-^{2}H]naphthalene (>98%D) or [2-^{2}H]-naphthalene (>98%D) was retained in the 1-naphthol product (68 and 64%D). These high deuterium retention values were observed when the naphthalene oxide portion obtained after *N*-oxide photolysis (*i.e.* in dichloromethane solution after NaOH treatment) was isolated and rearranged to 1-naphthol. The 1-naphthol obtained directly from the crude product mixture had a variable but lower deuterium content.

This variability contrasted with the good reproducibility observed for the deuteriated monocyclic aromatic rings and suggests that a minor loss of label from deuteriated 1-naphthol was occurring.

(iv) Naphthalene 1,2-oxide was isolated by preparative t.l.c. separation of the product mixture and elution of the band at R_F (0.60) or by counter-current distribution, the separation being effected by partition between n-hexane and methanol–water–ethyl acetate (20 : 4 : 1). While the separation of naphthalene 1,2-oxide from naphthalene was incomplete by either method, the characteristic peaks and coupling constants for protons H-1, H-2, and H-4 in the n.m.r. spectrum of the arene oxide (Figure) were clearly evident. Confirmatory n.m.r. spectra of naphthalene 1,2-oxide were obtained using both separation methods and the *N*-oxides (3) and (5) as oxygen atom donors. T.l.c. evidence also confirmed that *N*-oxide (4) produced naphthalene 1,2-oxide and it is probable that this arene oxide synthesis is general for all aromatic *N*-oxides.

The yield of naphthalene 1,2-oxide produced in these photolytic *N*-oxide oxidations was very low (<3%), despite attempts at optimization. While the yields of arene oxides recently derived from direct oxenoid type oxidation of other PAH's are much higher, to date only the more stable K region arene oxides have been isolated. Attempts[3,4,21,22] to isolate non-K region arene oxides such as naphthalene 1,2-oxide, and phenanthrene 1,2- and 3,4-oxides by direct oxidation of naphthalene and phenanthrene do not appear to have been successful.

The present isolation of naphthalene 1,2-oxide as a reaction product from the u.v. irradiation of naphthalene in the presence of a range of aromatic *N*-oxides prompted an investigation of further PAHs. Phenanthrene, acenaphthene, anthracene, pyrene, chrysene and perylene were subjected to u.v. irradiation in the presence of pyrazine *N*-oxide (5) and the product mixture was analysed by t.l.c. in an identical manner to that used for naphthalene. While t.l.c. evidence of phenol formation was found in all cases except perylene (NaOH treatment, Gibbs spray, R_F values) only phenanthrene and acenaphthene showed spots corresponding to arene oxides. Since three arene oxides could result from epoxidation of phenanthrene the possibility of stereoselectivity was investigated. Authentic samples of 1-, 2-, 3-, 4-, and 9-phenanthrol were found to give different colours on treatment with Gibbs reagent or *p*-nitrobenzenediazonium fluoroborate. T.l.c. analysis showed a slight separation of spots corresponding to 3-ol (R_F 0.46), 2-ol (R_F 0.30), 1-ol (R_F 0.36), 9-ol (R_F 0.37), and 4-ol (R_F 0.41). On the basis of t.l.c. colour and R_F comparison with authentic phenanthrols, the crude photolysis product mixture contained 4-, 9-, and 1-phenanthrols with only traces of the 2- and 3-isomers. H.p.l.c. analysis of this crude mixture confirmed the presence of these three major phenanthrols. After washing the crude product mixture with NaOH to remove phenolic products, the remaining dichloromethane layer (containing mainly phenanthrene and phenanthrene oxides) was acidified to yield 1-, 4-, and 9-phenanthrols in approximately the ratio (2 : 1 : 0.1). Attempts to obtain unequivocal n.m.r. evidence for the presence of the arene oxides of phenanthrene were unsuccessful because of the low concentration of the arene oxides present. If these unstable arene oxide intermediates are *totally* converted into stable phenanthrols then the ratio of phenols (1 > 4 > 9) will reflect the ratio of phenanthrene oxides formed (1,2- > 3,4- > 9,10-). Some selective arene oxide decomposition may, however, occur during the photolysis reaction. Further evidence for the formation of these arene oxides is found in the



observation that authentic samples of the phenanthrene oxides isomerize predominantly to 1-, 4-, and 9-phenanthrols under neutral or slightly basic conditions.[23,24]

The inability to detect arene oxide intermediates, except in the hydroxylation of naphthalene, phenanthrene, and possibly acenaphthene, is probably a consequence of the instability of arene oxides and the increasing chances of alternative photochemical reactions occurring in more highly conjugated PAHs.

No evidence from the present results is available to permit a distinction to be made between possible transition states [including (C) and (D)] for the epoxide

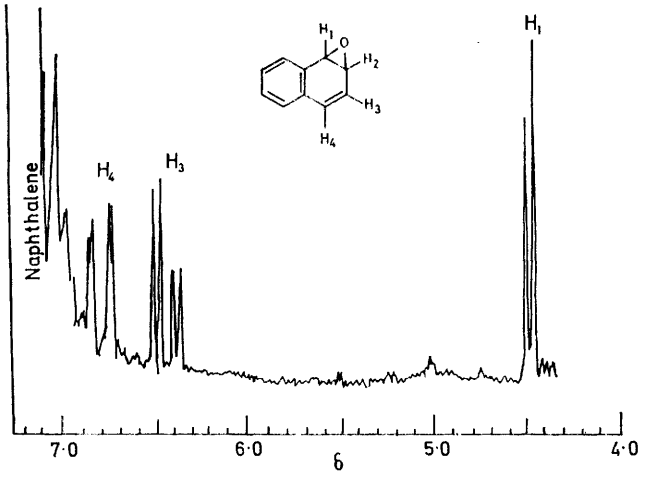
(arene oxide) reaction. To date no precedent exists for the epoxidation of olefins by oxaziridines. The initial photochemical transfer step of an oxygen atom from either the *N*-oxide or oxaziridine isomer to an olefin or aromatic ring probably occurs by a stepwise or non-synchronous mechanism.

EXPERIMENTAL

Materials.—The *N*-oxides used in the present study were either obtained commercially [(3) and (6)] or synthesized by literature methods. The physical and spectral properties of the synthesized *N*-oxides were in agreement with literature values; (4),[25] (5),[25] (7),[26] (8),[27] (9).[28] The bis oxaziridines (10a) and (10b) were available from previously reported studies.[29] 4-t-Butylthiacyclohexane, 4-t-butylthiacyclobutane, and the corresponding *cis*- and *trans*-sulphoxides, (1) and (2), were prepared according to the literature methods.[8] Reactants and products in Table 2 were available commercially.

The deuterium-labelled materials [4-^{2}H]anisole, [4-^{2}H]-toluene, [4-^{2}H]chlorobenzene, [4-^{2}H]bromobenzene, [4-^{2}H]-acetanilide, [1-^{2}H]naphthalene, and [2-^{2}H]naphthalene were available from previously reported studies.[30] Per-deuteriated benzene and naphthalene were commercially obtained. Authentic samples of phenanthrols [(1),[31] (2),[32] (3),[32] (4),[31] and (9) [33]] were prepared according to the literature methods.

Methods.—Analytical and preparative t.l.c. plates coated with silica gel were obtained from Merck (Kieselgel $PF_{254,366}$). Preliminary t.l.c. analysis of hydroxyanisoles and phenanthrols was carried out with chloroform–benzene–ethyl acetate–triethylamine (20 : 10 : 20 : 1) and chloroform–triethylamine (20 : 1), respectively, as eluants. Benzene–chloroform–ethyl acetate–triethylamine (1 : 1 : 1 : 0.2) mixtures were used in t.l.c. detection and purification of



90 MHz N.m.r. spectrum of naphthalene 1,2-oxide in the presence of naphthalene

naphthalene and phenanthrene oxides. Naphthalene 1,2-oxide was prepared according to the literature method [34] and had identical n.m.r. characteristics to that shown (Figure). Phenolic products were detected by u.v. light (Hanovia Chromatolite) and spraying with *N*-2,6-trichlorobenzoquinone imine (1% in ethanol, Gibbs reagent) followed by exposure to ammonia vapour, or *p*-nitro-benzenediazonium tetrafluoroborate (1% in acetone) and then KOH (10% in methanol).

Mass spectra (m.s.) were obtained at 70 eV using either an AEI MS902 instrument, an LKB 9000, or a Pye-Unicam 104-AEI MS gas liquid chromatograph–mass spectrometer (g.l.c.–m.s.). Column packings and temperatures for g.l.c. separations are given as Table footnotes. The deuterium contents of phenolic products were determined directly by m.s. or after g.l.c. separation. High-pressure liquid chromatographic (h.p.l.c.) analysis of the phenanthrols was carried out using a Spectra-Physics 3500 Model and a 25 cm × 3 mm ODS column coupled to a Cecil CE212 variable-wavelength detector; the separation was comparable to that reported [35] when eluted with methanol–water (35 : 65) at 0.04 × 25 ml/min.

U.v. irradiation (2 537 Å) was provided by either a Nuclear Supplies, Inc., spiral low-pressure mercury lamp, model W-K^2 (72 W) or a combination of a similar spiral lamp (PCQ-XI, Ultra-Violet Products Inc.) with two U-shaped arc tubes of a Hanovia Reading Photochemical Reactor (45 W each).

General Procedures used for N-Oxide Photolysis Reactions.—(a) *Cyclic thioethers.* The *N*-oxide (0.005 mol) and cyclic thioether (0.005 mol) in dichloromethane was placed in a quartz tube (1 cm. diam.) and irradiated (2 537 Å) under nitrogen for 3 min. This experiment was generally carried out using three tubes simultaneously. The reaction product mixture was then concentrated and taken up in di-isopropyl ether (0.4 ml) prior to g.l.c.–m.s. analysis. Yields were determined by g.l.c. peak areas using standard samples of known concentration.

(b) *Monocyclic aromatic molecules.* Using an identical vessel and low-pressure lamp, the *N*-oxide (0.001 mol) and aromatic substrate (0.001 mol) in dichloromethane (1 ml) were irradiated for 30 min. The phenolic products were removed by treatment with sodium hydroxide solution (2 ml; 1N), then, upon acidification, were extracted (dichloromethane) prior to g.l.c.–m.s. analysis.

(c) *Naphthalene.* The procedure used in (b) was repeated using increased concentrations (0.005—0.01 mol) of the *N*-oxides (3) or (5). The combined products from multiple experiments (× 15) were washed with sodium hydroxide (2 × 10 ml; 1N) and the aqueous layer was removed. The organic layer was concentrated at 0 °C and diluted with hexane (7 ml). Naphthalene 1,2-oxide was partially separated from naphthalene and other products by countercurrent distribution using hexane as the upper layer and methanol–water–ethyl acetate (20 : 4 : 1) as the lower layer, or by preparative t.l.c. using triethylamine washed silica gel.

Thioether Oxidation by Oxaziridines (10a) *and* (10b).—The thioether (0.005 mol) was stirred with the bis oxaziridine (0.005 mol) in dichloromethane (10 ml) for 24 h under nitrogen at room temperature. G.l.c.–m.s. analysis of the sulphoxide products (1) and (2) showed that the yields were 7 and 5%, respectively. The yield of benzyl *p*-tolyl sulphoxide, isolated after oxidation with (10a) under similar conditions and chromatography on deactivated alumina, was lower (1—2%). Only traces of sulphones were present after the oxaziridine oxidations.

Thioether Oxidation by Aspergillus niger.—The cyclic thioethers were added to growing cultures of *Aspergillus niger* in the manner previously described for a range of thioethers [11] and the sulphoxides (1) and (2) were detected by the usual method.

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