# Flash vacuum pyrolysis of 1,2,5-oxadiazole 2-oxides and 1,2,3-triazole 1-oxides

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**Abstract**

The flash vacuum pyrolysis (FVP, 450-600 ºC/$10^{-3}$ mmHg) of 3,4-diaryl- and 3,4-dialkyl-1,2,5-oxadiazole 2-oxides (furoxans) has been investigated. In all cases the 1,2,5-oxadiazole ring cleaved cleanly at O(1)-N(2) and C(3)-C(4) to afford two nitrile oxide fragments, which were trapped in high yield (75-97%) as their isoxazoline cycloadducts by reaction with alk-1-enes. At higher temperatures (700-800 ºC) isocyanates were formed as by-products. The dimerisation of acetonitrile oxide to dimethylfuroxan was followed by $^{1}$H NMR spectroscopy, and the rate constant for the $2^{nd}$ order reaction determined. The furoxans were converted into isocyanates in good yield (61-95%) by FVP, followed by sulfur dioxide-mediated isomerisation of the resulting nitrile oxides. 2,4,5-Trisubstituted-1,2,3-triazole 1-oxides showed greater thermal stability, but at 700-800 ºC decomposition of the 4,5-dimethyl compound **25b** lead to 1,2-di(5-methyl-2-phenyl-1,2,3-triazol-2-yl)ethane as the major product; attempts to trap acetonitrile oxide were unsuccessful.

**Keywords:** 1,2,5-Oxadiazole 2-oxides, flash vacuum pyrolysis, nitrile oxides, 1,3-dipolar cycloaddition, isocyanates, 1,2,3-triazole 1-oxides

## Introduction

1,2,5-Oxadiazole 2-oxides (furoxans) **1** have often been regarded as unwanted by-products formed during the 1,3-dipolar cycloaddition reactions of nitrile oxides **2**.[1] Thus, when isolated nitrile oxides are used, or even when they are generated *in situ*, then the nitrile oxide dimer **1** may be formed in addition to the target cycloadduct, particularly with less reactive dipolarophiles (Scheme 1). However, it has also been shown that the reverse reaction, involving cleavage of the furoxan ring at O(1)–N(2) and C(3)–C(4), can provide a useful source of nitrile oxides,[2] especially when it is inconvenient to generate the nitrile oxides by traditional methods, such as dehydrohalogenation of hydroximoyl halides **3** or dehydration of nitromethyl

compounds. For example, dodecane(dinitrile oxide) **4** and cyclopentane-1,3-bis(carbonitrile oxide) **5** can be generated from the readily accessible cyclododecanofuroxan **6** and the norbornanofuroxan **7**, respectively.[2c,2g,2i,2l]
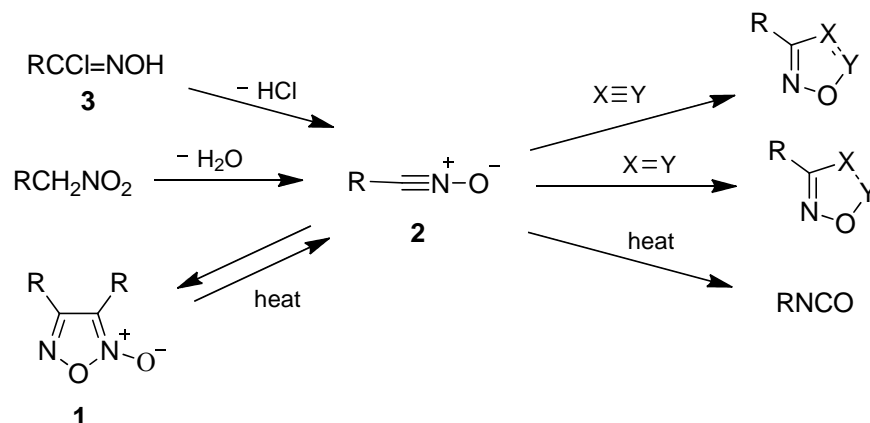


**Scheme 1.** [R = **a** Ph; **b** Me; **c** Et; **d** EtO$_2$C; **e** 4-MeOC$_6$H$_4$; **f** 4-ClC$_6$H$_4$; **g** 4-MeC$_6$H$_4$; **h** Bu].
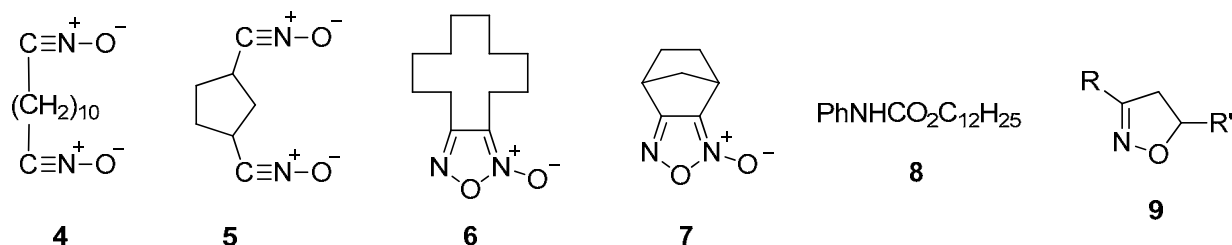


The earliest reports concerning the thermolytic cleavage of a furoxan date from 1886 when it was noted that phenyl isocyanate was among the decomposition products when diphenylfuroxan **1a** was heated above 200 ºC.[3] Further evidence for the formation of the isocyanate was obtained when the furoxan was heated in refluxing dodecanol (257 ºC) and the carbamate **8** isolated in good yield.[2c] A reaction pathway involving initial cleavage of the furoxan to benzonitrile oxide, followed by the known nitrile oxide to isocyanate rearrangement, was supported by the trapping of the nitrile oxide **2a** as its isoxazoline cycloadduct **9** (R = Ph, R′ = C$_{12}$H$_{25}$) during the corresponding reaction in tetradec-1-ene at 245 ºC.[2c] Furoxans bearing bulky substituents (*eg* **1**, R = Bu$^t$, adamant-1-yl) fragment at more moderate temperatures (80-150 ºC),[2b,2f] and ring-strained analogues such as acenaphthofuroxan and the norbornanofuroxan **7** are also cleaved in the temperature range 50-120 ºC to yield products derived from the bis(carbonitrile oxides), *eg* **5**.[2a,2i,2l] Thermolysis of various furoxans has also allowed unstable nitrile oxides to be studied spectroscopically in the gas phase.[4]

As indicated above, the formation of isoxazoline **9** (R = Ph, R′ = C$_{12}$H$_{25}$) from furoxan **1a** and tetradecene was assumed[2c] to proceed *via* initial cleavage to benzonitrile oxide (Scheme 2, Path A). However, the nitrile oxide was not detectable under the reaction conditions and the

possibility of the dipolarophile reacting directly with the C=N$^+$–O$^-$ moiety of the furoxan to give the nitrone-type adduct **10**, followed by fragmentation to **9**, could not be excluded (Scheme 2, Path B). Such nitrone-like behaviour for some furoxans has since been well established by the work of Shimizu *et al*[2h,5] and of Butler *et al*.[6] For example, bis(ethoxycarbonyl)furoxan **1d** reacts with various alkenes to afford the bicyclic products **11** that incorporate two dipolarophile units. The proposed mechanism in this case involves initial formation of the nitrone adduct **10**, followed by extrusion of ethyl cyanoformate, and cycloaddition of the resulting nitronate **12** to the second alkene (Scheme 2, Path C).[5] Butler *et al* showed that such reactions are not dependent on the presence of electron-withdrawing substituents in the furoxan; even the diphenyl and dimethyl furoxans, **1a** and **1b**, undergo nitrone-like cycloadditions to *N*-arylmaleimides and maleic anhydride.[6]
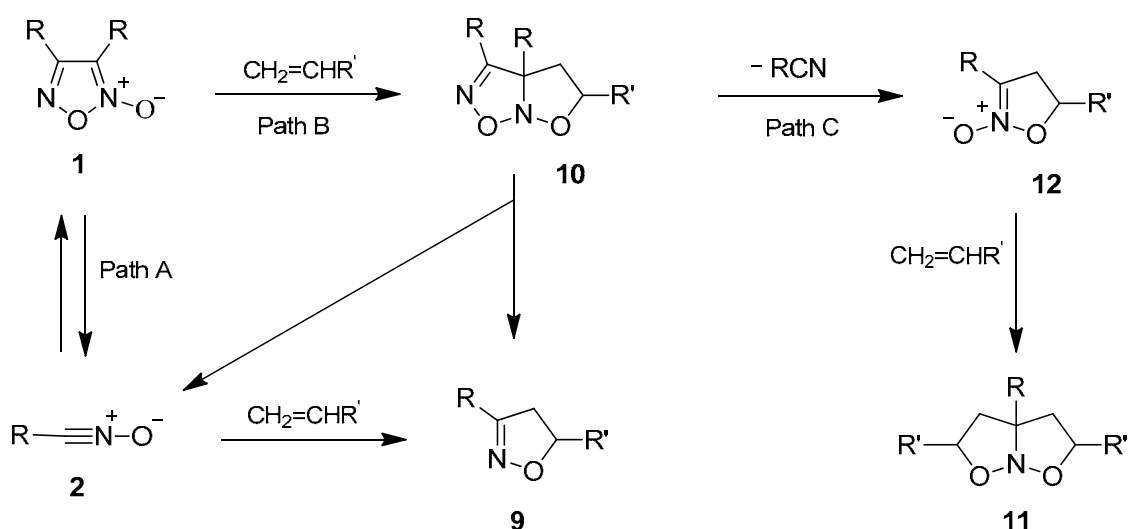


**Scheme 2.** [**a** R = Ph; **d** EtO$_2$C].

We have recently described the use of flash vacuum pyrolysis (FVP) technique[7,8] to study the corresponding furazans (1,2,5-oxadiazoles) and found that under these conditions they cleaved cleanly at O(1)–N(2) and C(3)–C(4) to afford the nitrile oxide and nitrile fragments.[9] In an attempt to isolate nitrile oxides from furoxans, and thus provide evidence for Path A as the route to the isoxazolines **9**, we have made use of the same approach.[10] We also report on the thermal stability of the related 4,5-disubstituted 1,2,3-triazole 1-oxides under FVP conditions.

## Results and Discussion

The furoxans under investigation were all prepared by literature routes[1,11] involving, either oxidation of the corresponding glyoxime using aq. sodium hypochlorite after the method of Boyer,[12] or dimerisation of the nitrile oxide. These nitrile oxides were generated *in situ* by

dehydration of the appropriate nitromethyl compound using phenyl isocyanate,[13] or by base-induced dehydrochlorination of the hydroximoyl chloride (Scheme 1); the latter were conveniently prepared from the aldehyde without unwanted chlorination of the aromatic ring using nitrosyl chloride as reported by Kinney *et al*.[14]

Pilot FVP experiments were carried out with diphenylfuroxan **1a** over a range of temperatures and it was established that at 450 ºC/$10^{-3}$ mmHg all the starting material had been consumed. The presence of benzonitrile oxide **2a** in the pyrolysate was indicated by its characteristic IR peak at 2281 cm$^{-1}$ and by comparison with an authentic sample prepared by base treatment of benzohydroximoyl chloride **3a**.[1] Further confirmation of the identity of the product was obtained by reacting it with diethyl fumarate and isolating in high yield (85%) the known cycloadduct, diethyl *trans*-3-phenyl-2-isoxazoline-4,5-dicarboxylate **13**[15] (Table 1, entry 1).

While conventional methods, such as dehydrochlorination of hydroximoyl halides and dehydrogenation of aldoximes, are satisfactory for the isolation of arene nitrile oxides having long lifetimes, they are less effective for their shorter-lived aliphatic counterparts that undergo rapid dimerisation to the corresponding furoxan.[1] Thus acetonitrile oxide **2b** has been reported to exist for less than one minute at 18 ºC when isolated,[1a] although it has been found to be more stable at -60 ºC and in solution.[16] In contrast, FVP has the potential to provide a straightforward method for the isolation from readily accessible precursors of short-lived nitrile oxides such as **2b**, thus permitting more detailed examination of their spectroscopic properties. To test the approach, dimethylfuroxan **1b** (0.5 g, 4.4 mmol) was pyrolysed at 650 ºC and the pyrolysate condensed onto CDCl$_3$ (~2 ml) at -196 ºC; a second layer of CDCl$_3$ was then distilled into the cold trap to form a 'sandwich'. Having generated **2b** it was conveniently stored at -78 ºC (CO$_2$/acetone slush bath) for several days after which there was no discernable change in its NMR spectra, thus showing that under these conditions recombination back to the furoxan is slow. Using this approach, solutions were prepared of **2b** in CDCl$_3$, and also of the analogous propionitrile oxide **2c**, generated by FVP of diethyl furoxan **1c**.

The $^{13}$C NMR spectrum (CDCl$_3$, -51 ºC) of acetonitrile oxide **2b** consisted of two peaks at 35.6 and 0.8 ppm, which were assigned to the fulmido (C≡N$^+$−O$^-$) and methyl carbons respectively. The signal at 35.6 ppm was a poorly resolved triplet due to coupling to the adjacent $^{14}$N nucleus ($^1J$ 48±2 Hz). Similarly, the $^{13}$C NMR spectrum of propionitrile oxide **2c** had a broad partially resolved triplet at 39.1 ppm with a $^{13}$C-$^{14}$N coupling of 42±2 Hz. Poor resolution for fulmido carbon signals has been reported previously[17] and can be attributed to $^{14}$N nuclear quadrupole relaxation, which is known to cause line broadening. The fulmido $\delta_C$ values for **2b** and **2c** are comparable with those reported in the literature for trimethylaceto- ($\delta_C$ 42.2),[17b] triphenylaceto- ($\delta_C$ 38.4)[17b] nitrile oxides, and for 2,4,6-trimethylbenzo- ($\delta_C$ 35.2),[17a,17b] 2,4,6-trinitrobenzo- ($\delta_C$ 28.9),[17c] and 4-acetoxy-3-methoxybenzo- ($\delta_C$ 34.4 ppm),[17d] nitrile oxides. $^1$H NMR signals were observed for **2b** at 2.26 ppm (CH$_3$),[18] and for **2c** at 2.61 (CH$_2$) and 1.30 ppm (CH$_3$). On allowing the solution of nitrile oxide **2b** to warm to and remain at room temperature for three days, the peaks attributable to the nitrile oxide disappeared and were replaced by those

characteristic of the furoxan dimer **1b** [$\delta_C$ 154.4 (C-4), 112.7 (C-3), 10.5, 6.9 ppm (CH$_3$); $\delta_H$ 2.40, 2.21 ppm (CH$_3$)]. Similarly, those for propionitrile oxide (**2c**) were replaced by those attributable to the corresponding furoxan **1c**. The dimerisation of the nitrile oxides could also be monitored the disappearance of the C≡N peak at 2280 cm$^{-1}$ in the IR spectrum and the appearance of the characteristic furoxan peak at 1615 cm$^{-1}$. In addition to allowing the spectroscopic examination of these short-lived aliphatic nitrile oxides, the FVP technique also enables the kinetics of the dimerisation process to be studied in more detail. While the kinetics of nitrile oxide cycloaddition reactions have been investigated in some detail,[1] there appear to have been few such studies of their dimerisation;[17d,18] those that have been reported concentrated on aryl nitrile oxides, and it has recently been suggested that the dimerisation rate for acetonitrile oxide **2b** is immeasurably fast.[19] The rates of disappearance of **2b** and the formation of dimer **1b** were found to have the expected second order kinetics. The inclusion of 1,4-dioxan as an internal standard allowed the rate constants to be determined; at 23 °C the second order rate constant for the formation of furoxan **1b** in CDCl$_3$ was 6.1±0.2 x 10$^{-4}$ mol$^{-1}$dm$^3$s$^{-1}$. This value compares with those reported for the dimerisations at 25 °C of 4-chlorobenzonitrile oxide in CHCl$_3$ (1.77 x 10$^{-4}$ mol$^{-1}$dm$^3$s$^{-1}$),[18] and 4-acetoxy-3-methoxybenzonitrile oxide in C$_6$D$_6$ (1.21 x 10$^{-4}$ mol$^{-1}$dm$^3$s$^{-1}$)[17d] That the rate constant for the dimerisation of **2b** is greater than those for the 4-chloro- and and 4-acetoxy-3-methoxy-benzonitrile oxides is to be expected; rather, in the light of earlier reports[1c] of the very short lifetime for **2b**, it is perhaps surprising that they are so similar.

In addition to the advantages outlined above with respect to the isolation and spectroscopic examination of short-lived aliphatic nitrile oxides, application of FVP could also enhance the synthetic utility of furoxans as nitrile oxide sources. For example, the synthetic route from these furoxans to isoxazolines has been limited by the necessity for the alkene to boil at >200 °C[2c] if the reaction is to be carried out at atmospheric pressure. Furthermore, the formation of tarry by-products was a feature of the original furoxan-based route, which may be attributed to the limited thermal stability of both the dipolarophiles and the resulting cycloadducts.[2c] To test the synthetic utility of this approach a selection of 3,4-disubstitued furoxans were subjected to FVP and the products reacted with alk-1-enes. In a typical experiment diphenylfuroxan **1a** (0.5 mg, 2.1 mmol) was sublimed (120 °C/10$^{-3}$ mmHg), the vapour pyrolysed at 550 °C/10$^{-3}$ mmHg, and the pyrolysate condensed into a cold trap at -196 °C containing hex-1-ene (2.0 g, 23.8 mmol) in dry Et$_2$O. The product mixture was worked up by removal of the solvent and excess hexene to yield 5-butyl-3-phenyl-2-isoxazoline **9a** (97%) (Table 1, entry 2). Similar results were obtained for the pyrolyses of the di-(4-methoxyphenyl)-, di-(4-chlorophenyl)-, and di-(4-methylphenyl)-furoxans **1e-g** (Table 1, entries 3-5), and for the dialkylfurazans **1b,c** (Table 1, entries 6,7). The isoxazoline cycloadducts **9a-g** were identified from their NMR spectra and by comparison with authentic samples prepared by reaction of the alkene with the appropriate hydroximoyl chloride **3**. Their ^{1}H NMR spectra all show the expected ABX pattern for the heterocyclic ring protons (H-4a, H-4b, H-5), and for the 3-methyl compound **9b** there was also an additional longer range coupling (1.0 Hz) between H-4a/H-4b and the methyl protons.[20]

**Table 1.** 2-Isoxazolines from FVP[a] of furoxans
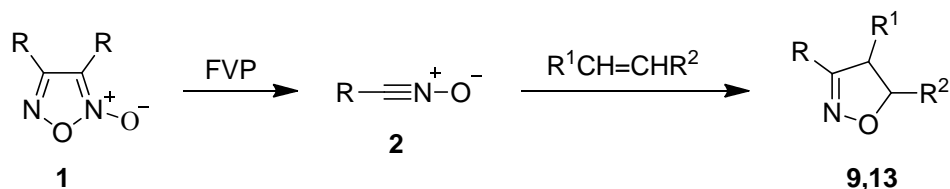


| Entry | Furoxan | R | $R^1$ | $R^2$ | Oven Temp./°C | Product (Yields / %) |
|---|---|---|---|---|---|---|
| 1 | **1a** | Ph | $EtO_2C$ | $EtO_2C$ | 450 | **13** (85) |
| 2 | **1a** | Ph | H | $CH_3(CH_2)_3$ | 550 | **9a** (97) |
| 3 | **1e** | $4\text{-MeOC}_6H_4$ | H | $CH_3(CH_2)_3$ | 500 | **9e** (75) |
| 4 | **1f** | $4\text{-ClC}_6H_4$ | H | $CH_3(CH_2)_3$ | 600 | **9f** (90) |
| 5 | **1g** | $4\text{-MeC}_6H_4$ | H | $CH_3(CH_2)_{11}$ | 500 | **9g** (86) |
| 6 | **1b** | Me | H | $CH_3(CH_2)_3$ | 600 | **9b** (75) |
| 7 | **1c** | Et | H | $CH_3(CH_2)_3$ | 650 | **9c** (95) |

[a]at $10^{-3}$ mmHg

At elevated temperatures nitrile oxides are known to rearrange to isocyanates,[1] and it was therefore anticipated that, under FVP conditions, isocyanates might be formed as by-products accompanying the isolated nitriles oxides and their cycloadducts. To investigate this possibility diphenylfuroxan **1a** was pyrolysed over a range of temperatures, the FVP pyrolysates condensed onto hex-1-ene, and the product mixtures analysed by GC. At 550 ºC the main product was 5-butyl-3-phenyl-2-isoxazoline **9a** (98%) together with traces of phenyl isocyanate (<2%). Raising the oven temperature to 700 ºC had little effect on the yield of these products (isoxazoline **9a** 95%, PhNCO 4%). At 800 ºC, however, the combined yield of the two products fell from 99-100% to 64%; phenyl isocyanate was the main product (37%) and the yield of isoxazoline **9a** reduced to 27%.

In view of the near quantitative combined yield of phenyl isocyanate and isoxazoline **9a** from the pyrolysis at 550 ºC, the observed ratio (PhNCO: **9a** = 1:50) can be taken as a measure of the relative amounts of phenyl isocyanate and benzonitrile oxide in the pyrolysate. Even at 700 ºC only 4% PhNCO is generated. Pyrolysis at 800 ºC did provide more PhNCO, but the yield was still low (37%). On this evidence FVP does not provide a satisfactory method for converting these furoxans directly into isocyanates. We therefore considered ways by which the efficiency of the nitrile oxide to isocyanate rearrangement could be improved. We have previously established that ring-strained bicyclic furoxans can be converted into diisocyanates in good yield in the presence of sulfur dioxide. For example, the diisocyanate **14** was prepared from the

norbornane furoxan **7** by heating in toluene saturated with $SO_2$.[2i] The furoxans in the present investigation were therefore subjected to FVP at 500-600 °C and the products collected in a cold trap (196 °C) containing an excess of sulfur dioxide. Dry toluene was added and the resulting solution heated at reflux for 1 hour. After removal of the excess sulfur dioxide with a stream of dry nitrogen, the presence of isocyanate was established by IR spectroscopy ($v_{max}$ ~2260 cm^{-1}), by GC and by reaction with ethanol or aniline to yield the corresponding urethane or urea derivatives respectively. The isocyanates generated by this method are listed in Table 2.

**Table 2.** Isocyanates from FVP[a] of furoxans

| Entry | Furoxan | R | Oven Temp./°C | RNCO / %[b] | RNHCO$_2$Et / % | RNHCONHPh / % |
|-------|---------|---|---------------|-------------|-----------------|---------------|
| 1 | **1a** | Ph | 500 | 93 | 75 | - |
| 2 | **1g** | 4-MeC$_6$H$_4$ | 500 | 76 | - | 71 |
| 3 | **1e** | 4-MeOC$_6$H$_4$ | 500 | c | - | 95 |
| 4 | **1b** | Me | 550 | c | - | 74 |
| 5 | **1h** | Bu | 600 | c | - | 61 |

[a]at 10^{-3} mmHg; [b]yields determined by GC; [c]not determined

The formation of the isocyanates can be explained in terms of initial cleavage of the furoxan under FVP conditions to its two nitrile oxide components, followed by sulfur dioxide-mediated nitrile oxide to isocyanate rearrangement *via* the 1,3,2,4-dioxathiazole *S*-oxide **15** (Scheme 3). Such a conversion of a nitrile oxide to an isocyanate, which involves 1,3-dipolar cycloaddition of the nitrile oxide to sulfur dioxide yielding **15** followed by its thermal cycloreversion, was first reported by Burk and Carlos,[21] who used this method to prepare in high yield phenylene-1,4-diisocyanate from terephthalodi(nitrile oxide), and later examined in more detail by Trickes and Meier.[22] In the present work the intermediacy of the dioxathiazole *S*-oxide **15b** derived from dimethylfuroxan/$SO_2$ was indicated by a characteristic IR peak at 1240 cm^{-1},[21] and demonstrated by treatment of the product mixture with water and isolation of the corresponding hydroxamic acid ($CH_3CONHOH$). For dioxathiazole *S*-oxide **15e**, formed by pyrolysis of di(4-methoxyphenyl)furoxan **1e** onto sulfur dioxide, the conversion to 4-methoxyphenyl isocyanate was monitored by the changes in the IR spectrum; on heating in toluene at reflux the peak for **15e** at 1240 cm^{-1} decreased in intensity and was replaced by a new peak for the isocyanate at 2265 cm^{-1}. The sulfur dioxide thus plays a key role by effecting the nitrile oxide to isocyanate conversion at temperatures lower than those normally required, and also by minimising competing dimerisation back to the furoxan. This approach can provide a useful alternative to conventional methods for the generation of the low-boiling and toxic methyl isocyanate, as the dimethylfuroxan precursor is readily available in high yield from nitromethane and also from but-2-ene and dinitrogen trioxide.[23]
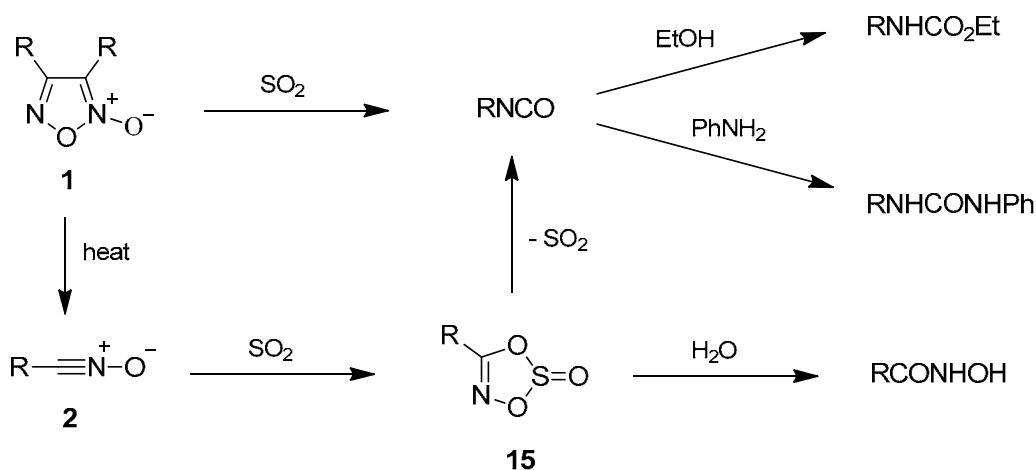
**Scheme 3.** [R = **a** Ph; **b** Me; **e** 4-MeOC$_6$H$_4$].
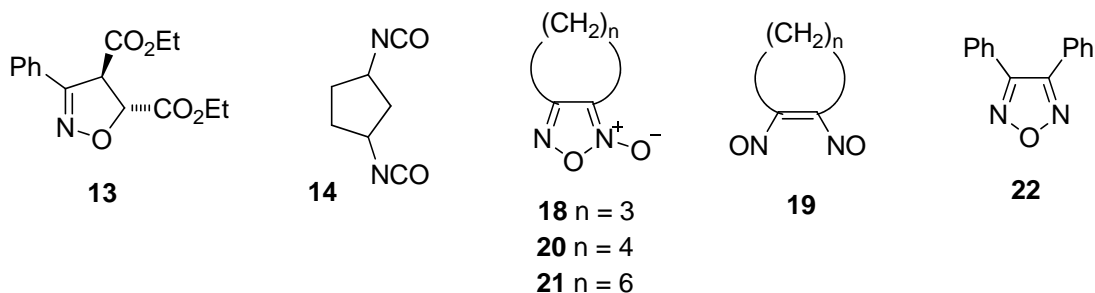


The pathway by which the isocyanate is formed from the dioxathiazole *S*-oxide **15** has not been firmly established. Burk and Carlos showed that cycloaddition of nitrile oxides to SO$_2$ can take place at -10 ºC to afford **15**, from which the isocyanate can be generated at 125 ºC.[21] On the other hand, Franz and Pearl found that heating **15a** at 110 ºC in the presence of dimethyl acetylenedicarboxylate (DMAD) yielded not only phenyl isocyanate, but also dimethyl isoxazole-4,5-dicarboxylate **16a**, the cycloadduct of DMAD and benzonitrile oxide,[24] suggesting that the isocyanate may be formed by cycloreversion of **15a** to the nitrile oxide and its subsequent rearrangement (Scheme 4, path A). In the present work, however, heating **15a** in toluene at reflux (~115 ºC) in the absence of DMAD yielded phenyl isocyanate in near quantitative yield. Moreover, at these temperatures the rearrangement to isocyanate is much slower than dimerisation to furoxan.[25] We therefore favour a mechanism involving an equilibrium between SO$_2$/RCNO and dioxathiazole *S*-oxide **15** and its subsequent fragmentation at O(1)–S(2) and O(3)–N(4) with concomitant C→N migration of the R-group (Scheme 4, path B). Isocyanate formation *via* Path B is also supported by studies[26] using ^{18}O-labelled mesitonitrile oxide (**2**, R = 2,4,6-Me$_3$C$_6$H$_2$) when the [18]O label was detected in the recovered sulfur dioxide.
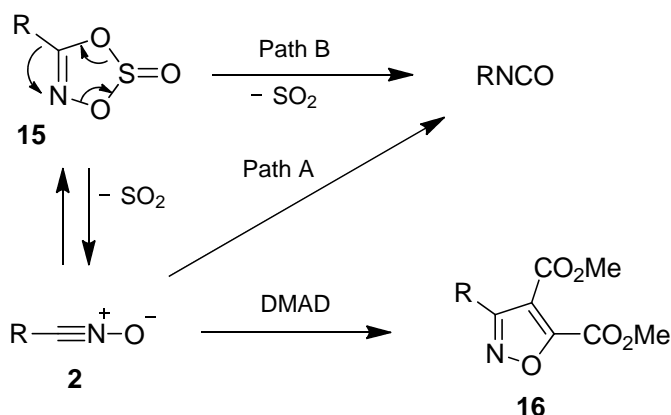
**Scheme 4.** [R = **a** Ph; **b** Me].

A similar approach can be used to convert nitrile oxides into isothiocyanates. Nitrile oxides react readily with several thiocarbonyl compounds to give 1,4,2-oxathiazole cycloadducts;[1] subsequent thermolysis results in the formation of the isothiocyanate and the oxygen analogue of the original thiocarbonyl compound.[27] Moreover, if the dipolarophile is a thioamide then the 5-amino-1,4,2-oxathiazole cycloadduct is of limited stability and the corresponding amide and isothiocyanate may be obtained directly.[27] Thus FVP of diphenylfuroxan **1a** at 550 ºC onto *N,N*-dimethylthioformamide afforded the cycloadduct **17** which decomposed on warming the pyrolysate to ambient temperature to form phenyl isothiocyanate and *N,N*-dimethylthioformamide (Scheme 5). The phenyl isothiocyanate was identified from its IR spectrum ($v_{max}$ 2050 cm$^{-1}$) and by reaction with aniline to yield *N,N'*-diphenylthiourea (49%).
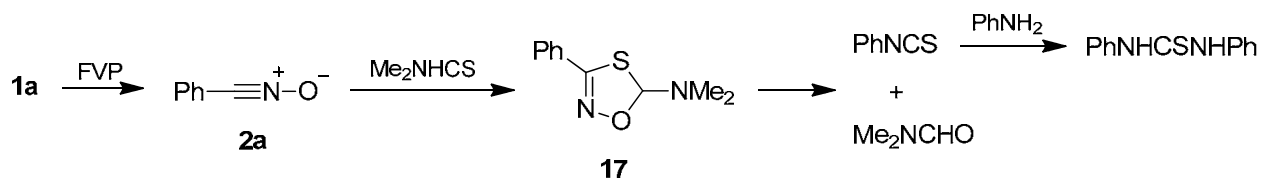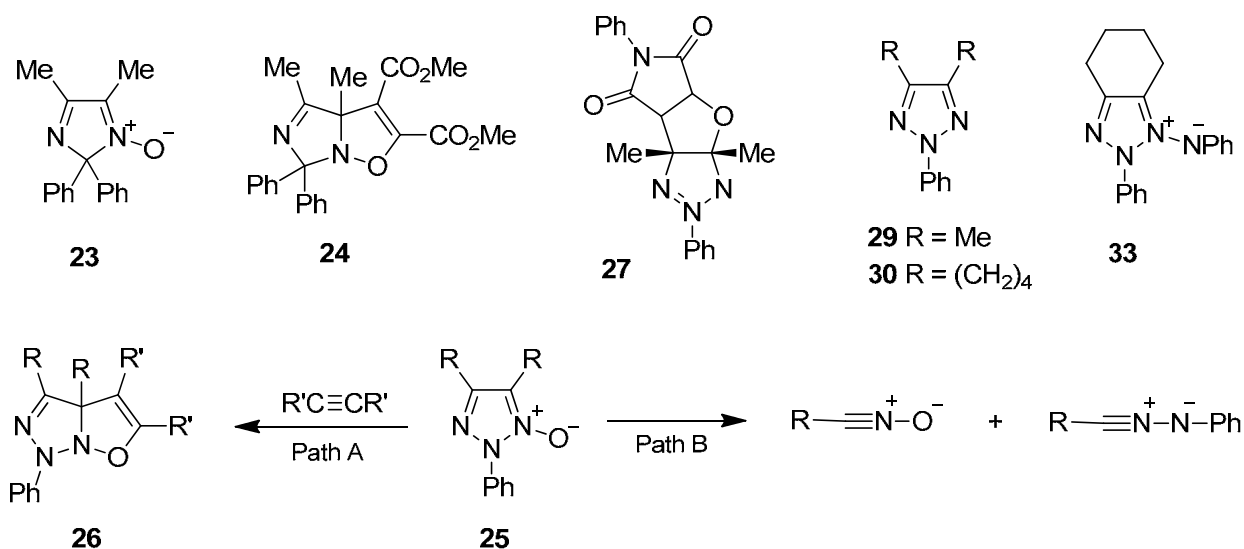


**Scheme 5**

As noted earlier, the temperatures required to achieve furoxan ring cleavage are markedly higher for simple dialkyl/aryl furoxans (>200 ºC) compared with ring-strained analogues such as the norbornane and trimethylene furoxans, **7** and **18** (50-120 ºC). It is also noteworthy that for the latter group there is more facile equilibration between the 1,2,5-oxadiazole 2- and 5-oxides,[2a,2g,11,28,29] presumably *via* the 1,2-dinitrosoalkene tautomer, *eg* **19**. These observations can be explained in terms of the relative weakness of the O(1)–N(2) bonds and the differing aromaticities of the furoxan rings. For example, the strained trimethylenefurazan **7** has a Bird aromaticity index $I_A$ = 20.9, whereas the less strained analogues **20** and **21** have $I_A$ values of 32.2

and 33.7 respectively.[30] By this measure the *N*-oxides (furoxans) are less stable than the parent furazans; thus diphenylfuroxan **1a** ($I_A$ = 48.9) is less aromatic than diphenylfurazan **22** ($I_A$ = 61.9).[31]

Furoxans are not the only heterocyclic *N*-oxides to behave like nitrones. The 2*H*-imidazole *N*-oxide **23** is reported to react with DMAD to afford the adduct **24**,[32] and nitrone-like behaviour has also been observed for the related 2,4,5-trisubstituted-1,2,3-triazole-1-oxides **25**. Two reaction pathways are also possible for the triazole *N*-oxides **25** (Scheme 6). Direct reaction of the dipolarophile with the nitrone unit C(5)=N(1)–O would give the isoxazolidine **26** (Path A), whereas fragmentation at N(1)–N(2) and C(4)–C(5), analogous to that observed for diaryl and dialkyl furoxans, would yield products derived from nitrile imides and nitrile oxides (Path B). Butler *et al*[33] investigated the reaction of several 1,2,3-triazole-1-oxides with electron-deficient dipolarophiles, but the nitrone cycloadducts were not themselves isolated. Instead rearrangement products were formed; for example tricyclic compound **27** was obtained from the reaction of *N*-phenylmaleimide with triazoline *N*-oxide **25a**. It was therefore of interest to examine the thermal stability of such triazoline *N*-oxides under FVP conditions.





**Scheme 6.** [R = **a** Ph; **b** Me].

The 2,4,5-triphenyl- and 4,5-dimethyl-2-phenyl-1,2,3-triazole 1-oxides **25a** and **25b** were chosen for investigation. These were prepared from benzil and diacetyl monooxime, respectively, *via* the corresponding phenylhydrazones, which on oxidation with aq CuSO₄/pyridine,[34] gave the triazole-1-oxides. Compared with the dialkyl and diaryl furoxans, the triazole *N*-oxides proved to be more stable. The 4,5-diphenyl compound **25a** was recovered unchanged after FVP at 650 ºC, but the dimethyl analogue **25b** proved to be somewhat less stable and above 600 ºC several decomposition products were observed. The pyrolysis products from FVP of compound **25b** at 650 ºC were condensed onto hex-1-ene in an attempt to trap any

acetonitrile oxide and *C*-methyl-*N*-phenyl nitrone that might have been generated. However, TLC analysis of the product mixture showed that none of the expected cycloadduct (5-butyl-3-phenyl-2-isoxazoline, **9a**) had been formed. Rather, in addition to unreacted starting material, a white crystalline solid was isolated, which was assigned the deoxygenated dimer structure **28** (Scheme 7) on the basis of its spectroscopic properties. The high-resolution mass spectrum (EI) gave a molecular ion *m/z* 344, corresponding to the molecular formula $C_{20}H_{20}N_6$ and a main fragment peak at *m/z* 172 ($C_{10}H_{10}N_3$), consistent with the proposed symmetrical structure. In the $^{13}C$ spectrum there were distinctive peaks for the carbons of the two equivalent triazole rings at 146.5 (C-4) and 143.5 ppm (C-5). There were also characteristic $^1H$ and $^{13}C$ NMR signals for the methyl substituents [$\delta_H$ 2.21 ppm, $\delta_C$ 9.9 ppm] and for the linking ethylidene unit [$\delta_H$ 3.10 ppm, $\delta_C$ 24.1 ppm]. For comparison, an authentic sample of 4,5-dimethyl-2-phenyl-1,2,3-triazole **29** was prepared by deoxygenation of the corresponding N-oxide **25b**. Its NMR data, together with those for compound **28** and for the tetramethylene analogue **30**[35] are shown in Table 3. The strong correlation between the data for compounds **28**, **29** and **30** provides good support for the proposed structure **28**.

**Table 3.** NMR chemical shifts for 2-phenyl-1,2,3-triazoles[a]

| Compound | $\delta_H$ / ppm | | | $\delta_C$ / ppm | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $CH_3$ | $CH_2$ | $C_6H_5$ | C(4) | C(5) | $CH_3$ | $CH_2$ | PhC | PhCH |
| **28** | 2.21 | 3.10 | 7.21-8.05 | 143.5 | 146.5 | 9.9 | 24.1 | 139.8 | 129.1 126.5 118.1 |
| **29** | 2.25 | - | 7.15-7.95 | 143.5 | 143.5 | 9.8 | - | 139.7 | 128.9 126.9 117.8 |
| **30**[b] | - | 2.82 | 7.29-7.99 | 145.6 | 145.6 | - | 23.1 | 140.1 | 129.1 126.5 118.2 |

[a]In $CDCl_3$; [b]data from ref 35.

A possible mechanism to account for the formation of compound **28** is shown in Scheme 7. This involves as the first stage formation of the *N*-hydroxyl tautomer **31**, followed by loss of OH under the FVP conditions to generate the resonance-stabilised radical **32**; subsequent dimerisation leads to the observed product, presumably in the gas phase. A similar mechanism has been invoked by George *et al*[36] to explain the formation of triazole **30** on irradiation of the triazole *N*-imide **33**. These results confirm that 1,2,3-triazole 1-oxides are more stable than the corresponding furoxans, an effect that can be attributed to the relative strength of the N–N bond compared with N–O, and also to the greater aromaticity of the 1,2,3-triazole nucleus ($I_A$ 109) compared with the corresponding 1,2,5-oxadiazole ($I_A$ 53).[30] A similar trend is expected for the

corresponding *N*-oxides, the latter being less aromatic.[31]
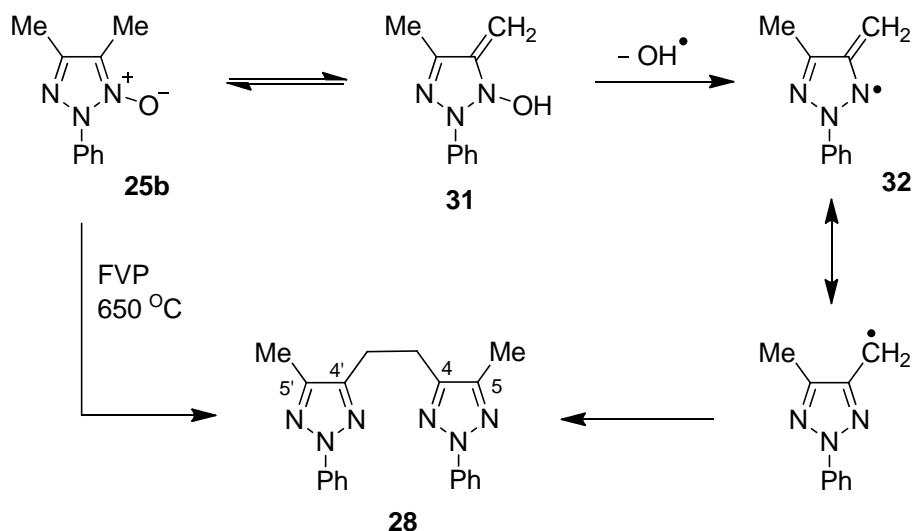


**Scheme 7**

In conclusion, these results show that the fragmentation of furoxans to nitrile oxides does not depend on special features such as ring strain or bulky substituents, and that the FVP technique gives excellent yields of cleavage products. It is also noteworthy that by using FVP a wider range of dipolarophiles can be employed compared with liquid-phase reactions. For short-lived nitrile oxides, such as acetonitrile oxide, FVP of the corresponding furoxan is a method of choice, the nitrile oxides being obtained in high yield from stable and readily accessible precursors. Isolation of acetonitrile oxide has also allowed the kinetics of its dimerisation to be studied, which showed that it is more stable than anticipated. One synthetic limitation of this approach, however, would be for low reactivity dipolarophiles when recombination back to the furoxan may dominate the desired cycloaddition reaction; in these cases generation by traditional methods in the presence of excess dipolarophile would remain the best approach. Using sulfur dioxide as the dipolarophile provides an efficient method for the conversion of the nitrile oxide fragments into the isomeric isocyanates. The 1,2,3-triazole 1-oxides examined proved to be much more stable and attempts to trap nitrile oxides from their decomposition were not successful.

## Experimental Section

**General.** The general methods and spectroscopic techniques were as recently reported.[9] Flash vacuum pyrolysis (FVP) experiments involved volatalisation of the furoxan (or triazole *N*-oxide) under rotary pump pressure through an electrically-heated silica tube (36 x 2.0 cm), arranged

horizontally and packed with 6 cm lengths of silica tube (7 mm o.d, 5 mm i.d.). The pyrolysate was condensed into a cold trap (*ca* −196 °C) containing an excess of the dipolarophile, and a further layer of the dipolarophile was then added. The reaction mixture was allowed to warm to room temperature under a nitrogen atmosphere and the entire pyrolysate dissolved in a solvent and removed from the trap. The results are summarised in Tables 1 and 2.

**Preparation of furoxans**

The furoxans were prepared by one of the following three methods:[11d]

*Method 1*. Dehydrogenation of the glyoxime using sodium hypochlorite after the method of Boyer.[12] **3,4-Diphenylfuroxan 9a**[37] (75%).

*Method 2*. Dimerisation of the nitrile oxide, generated by dehydration of the nitromethyl compound, as described by Mukaiyama and Hoshino.[13] **3,4-Dimethylfuroxan 9b**[13] (68%). **3,4-Diethylfuroxan 9c**[38] (40%).

*Method 3*. Dimerisation of the nitrile oxide, generated by dehydochlorination of the hydroximoyl chloride, as described by Boulton *et al.*[39] **3,4-Bis(4-methoxyphenyl)furoxan 9e**[14] (81%). **3,4-Bis(4-chlorophenyl)furoxan 9f**[39] (88%). **3,4-Bis(4-methylphenyl)furoxan 9g**[40] (70%).

**Preparation of 1,2,3-triazoles**

**2,4,5-Triphenyl-1,2,3-triazole 1-oxide (25a).** A solution of copper(II) sulfate (10.0 g, 40 mmol) in water (70 ml) was added over 1 h to a solution of benzil monooxime phenylhydrazone (5.0 g, 16 mmol) in pyridine (100 ml). The mixture was heated at reflux for 1½ h, cooled, and poured onto crushed ice. The resulting solid was extracted with toluene and dried (CaCl$_2$). The toluene was evaporated to leave the product (2.2 g, 44%), which was treated with activated charcoal/EtOH, and recrystallised from EtOH; mp 167 °C (lit.[33b] 168-169 °C); IR (Nujol): ν 1590 cm$^{-1}$ (C=N). Anal. Calcd. for C$_{20}$H$_{15}$N$_3$O: C, 76.7; H, 4.8; N, 13.4. Found: C, 76.5; H, 4.9; N, 13.4.

**4,5-Dimethyl-2-phenyl-1,2,3-triazole 1-oxide (25b).** A solution of copper(II) sulfate (25.0 g, 0.10 mol) in water (70 ml) was added over 1 h to a solution of diacetyl monooxime phenylhydrazone (9.6 g, 0.05 mol) in pyridine (250 ml). The mixture was heated at reflux for 1½ h, cooled, and poured onto crushed ice. The resulting solid was extracted with dichloromethane and dried (CaCl$_2$). The dichloromethane was evaporated to leave the product (6.7 g, 71%), which was treated with activated charcoal/EtOH, and recrystallised from EtOH to afford white needles; mp 87-89 °C (lit.[41] 92-93 °C); IR (Nujol): ν 1595 cm$^{-1}$ (C=N); $^{13}$C NMR (CDCl$_3$): δ 141.3, 135.5 (C-4,5), 129.0, 128.4, 124.5, 122.6 (ArC), 11.6, 7.6 (CH$_3$); MS (EI): *m/z* (%) 189 (M$^+$), 173 ([M-O]$^+$), 132 ( MeCNNPh$^+$).

**4,5-Dimethyl-2-phenyl-1,2,3-triazole (29).** A mixture of 4,5-dimethyl-2-phenyl-1,2,3-triazole 1-oxide **25b** (20.0 g, 10.6 mmol) and triethyl phosphite (10 ml) was heated at reflux under dry nitrogen until HPLC analysis showed that nearly all the triazole *N*-oxide had been consumed. The excess triethyl phosphite was removed by vacuum distillation and the residue poured onto crushed ice. Extraction with diethyl ether, drying (CaCl$_2$), and removal of the solvent gave a

yellow oil. Purification by chromatography (alumina, $CH_2Cl_2$) and vacuum distillation (75 ºC/0.01 mmHg) afforded the triazole **29** as a white solid (77%); mp 33-35 °C (lit.[41] 34-35 °C); ^{1}H NMR (CDCl$_3$): δ 7.95-7.15 (m, 5H, PhH), 2.25 (s, 3H, CH$_3$); ^{13}C NMR (CDCl$_3$): δ 143.5 (C-4,5), 139.7, 128.9, 126.2, 117.8 (ArC), 9.7 (CH$_3$); MS (EI): *m/z* (%) 173 (M[+]).

## Flash vacuum pyrolysis (FVP) of furoxans

### Preparation of 2-isoxazolines by FVP of furoxans

**Diethyl *trans*-3-phenyl-2-isoxazoline-4,5-dicarboxylate (13).** 3,4-Diphenylfuroxan **1a** (500 mg, 2.10 mmol) was sublimed (120 °C/10[-3] mmHg) and the vapour pyrolysed at 450 °C, and the pyrolysate condensed onto diethyl fumarate (0.8 g, 4.65 mmol) in toluene (5 ml). The reaction mixture allowed to warm to room temperature under dry nitrogen and the resulting solution examined by IR spectroscopy. Benzonitrile oxide was identified by the characteristic absorption at 2281 cm^{-1} and its disappearance was also monitored by IR. The toluene was removed *in vacuo* and TLC investigation of the residue showed the presence of a single product. Distillation afforded diethyl *trans*-3-phenyl-2-isoxazoline-4,5-dicarboxylate **13** (1.0 g, 82%) as a colourless liquid; bp 132 °C/0.1 mmHg (lit.[15] 158-160 °C/0.2 mmHg); IR (Nujol): ν 1595 (C=N), 1740 cm^{-1} (C=O); the ^{1}H and ^{13}C NMR spectra were indistinguishable from those of an authentic sample.

**5-Butyl-3-phenyl-2-isoxazoline (9a).** 3,4-Diphenylfuroxan **1a** (500 mg, 2.10 mmol) was pyrolysed at 550 °C and the pyrolysate condensed onto hex-1-ene (2.0 g, 23.8 mmol) in dry diethyl ether (5 ml). After warming to room temperature under dry nitrogen the solvent and unreacted hexene were removed *in vacuo* to leave 5-butyl-3-phenyl-2-isoxazoline **9a** (830 mg, 97%) as white platelets (from EtOH); mp 40-41 °C (lit.[42] 41 °C); the IR, ^{1}H and ^{13}C NMR spectra were indistinguishable from those previously reported.[9]

**5-Butyl-3-methyl-2-isoxazoline (9b).** 3,4-Dimethylfuroxan **1b** (300 mg, 2.63 mmol) was pyrolysed at 600 °C and the pyrolysate condensed onto hex-1-ene (4.4 g, 52.6 mmol). After warming to room temperature the unreacted hexene was removed *in vacuo* to leave the product (580 mg, 79%) as a yellow oil. Vacuum distillation yielded 5-butyl-3-methyl-2-isoxazoline **9b**; bp 40 °C/0.02 mmHg; the IR, ^{1}H and ^{13}C NMR spectra were indistinguishable from those previously reported.[9]

**5-Butyl-3-ethyl-2-isoxazoline (9c).** 3,4-Diethylfuroxan **1c** (400 mg, 2.80 mmol) was pyrolysed at 650 °C and the pyrolysate condensed onto hex-1-ene (10 fold excess). After warming to room temperature the unreacted hexene was removed *in vacuo* to leave a yellow liquid which, on vacuum distillation, afforded 5-butyl-3-ethyl-2-isoxazoline **9c** (830 mg, 96%); bp 45 °C/0.01 mmHg; ^{1}H NMR (CDCl$_3$): δ 4.45 (m, 1H, H-5), 2.98 (dd, $J_{4a,4b}$ = 16, $J_{4a,5}$ = 10 Hz, 1H, H-4a), 2.54 (dd, $J_{4b,4a}$ = 16, $J_{4b,5}$ = 8 Hz, 1H, H-4b), 2.33 (q, $J$ = 8 Hz, 2H, CH$_2$), 1.14 (t, $J$ = 8 Hz, 3H, CH$_3$), 0.8-1.8 (m, 9H, CH$_2$/CH$_3$); ^{13}C NMR (CDCl$_3$): δ 159.5 (C-3), 79.8 (C-5), 41.6 (C-4), 34.8, 27.4, 22.2, 22.1 (CH$_2$), 13.6, 11.0 (CH$_3$); HRMS (EI): Calcd. for $C_9H_{17}NO$: *M* 155.1310. Found: *m/z* 155.1315.

**5-Butyl-3-(4-methoxyphenyl)-2-isoxazoline (9e).** 3,4-Di(4-methoxyphenyl)furoxan **1e** (300 mg, 1.01 mmol) was pyrolysed at 500 °C and the pyrolysate condensed onto hex-1-ene (2.0 g, 23.8 mmol). After warming to room temperature under dry nitrogen the solvent and unreacted hexene were removed *in vacuo* to leave 5-butyl-3-(4-methoxyphenyl)-2-isoxazoline **9e** (350 mg, 75%) as white platelets (from EtOH/$H_2O$); mp 85 °C (lit.[9] 82-84 °C); the IR, ^{1}H and ^{13}C NMR spectra were indistinguishable from those previously reported.[9]

**5-Butyl-3-(4-chlorophenyl)-2-isoxazoline (9f).** 3,4-Di(4-chlorophenyl)furoxan **1f** (300 mg, 0.98 mmol) was pyrolysed at 600 °C and the pyrolysate condensed onto hex-1-ene (10 fold excess). HPLC analysis showed the presence of the product together with traces of unreacted starting material. After removal of the solvent and unreacted hexene the residue was purified by chromatography (silica, $CH_2Cl_2$) to yield a white solid that was recrystallised from MeOH/$H_2O$ to give 5-butyl-3-(4-chlorophenyl)-2-isoxazoline **9f** (420 mg, 90%); mp 73-74 °C (lit.[9] 73-74 °C); the IR, ^{1}H and ^{13}C NMR spectra were indistinguishable from those previously reported.[9]

**5-Dodecyl-3-(4-methylphenyl)-2-isoxazoline (9g).** 3,4-Di(4-methylphenyl)furoxan **1f** (200 mg, 0.78 mmol) was pyrolysed at 500 °C and the pyrolysate condensed onto tetradec-1-ene (1.5 g, 750 mmol) in dry diethyl ether. After removal of the solvent the residue was triturated with pentane and the resulting solid was collected by filtration and recrystallised from methanol to afford 5-butyl-3-(4-methylphenyl)-2-isoxazoline **9g** (380 mg, 77%); mp 75-77 °C; ^{1}H NMR (CDCl$_3$): δ 7.52 (d, *J* = 10 Hz, 2H, ArH), 7.18 (d, *J* = 10 Hz, 2H, ArH), 4.60 (m, 1H, H-5), 3.32 (dd, $J_{4a,4b}$ = 16, $J_{4a,5}$ 10 Hz, 1H, H-4a), 2.90 (dd, $J_{4,b4a}$ 16, $J_{4b,5}$ = 8 Hz, 1H, H-4b), 2.38 (s, 3H, CH$_3$), 0.7-1.9 (m, 25H, CH$_2$/CH$_3$); ^{13}C NMR (CDCl$_3$): δ 156.3 (C-3), 140.0, 129.3, 127.2, 126.5 (ArC), 81.3 (C-5), 40.1 (C-4), 35.4, 31.9, 29.7, 29.4, 25.6, 22.7 (15×CH$_2$), 21.4, 14.1 (CH$_3$). Anal. Calcd. for C$_{22}$H$_{35}$NO: C, 80.2; H, 10.6; N, 4.3. Found: C, 80.1; H, 10.8; N, 4.1.


**Preparation of isocyanates by FVP furoxans. General procedure**
Sulfur dioxide, dried by passing through a CaCl$_2$ drying tower, was dissolved in dry toluene (~5 ml) and the mixture co-distilled into the FVP cold trap. The furoxan was then sublimed/distilled through the pyrolysis tube (500-650 °C/10$^{-3}$ mmHg) and the pyrolysate condensed into the cold trap. A further layer of dry sulfur dioxide was then condensed into the trap and the mixture allowed to warm to room temperature. Dry toluene (~50 ml) was added and the mixture heated at reflux for 1-2 h. Any remaining sulfur dioxide was removed by passing dry nitrogen through the solution and the presence of the isocyanate established by GC and/or reaction with ethanol or aniline to form the urethane or urea derivatives, respectively. The results are summarised in Table 2.

**Phenyl isocyanate.** 3,4-Diphenylfuroxan **1a** (330 mg, 1.39 mmol) was pyrolysed at 500 °C and the pyrolysate condensed onto sulfur dioxide. GC analysis on 10% of the reaction mixture, using nitrobenzene as internal standard, showed the presence of phenyl isocyanate (2.59 mmol, 93%). Dry ethanol (10 ml) and triethylamine (5 drops) were added to the remainder of the reaction mixture and the resulting solution stirred for 24 h. The excess ethanol and the solvent were removed *in vacuo* and the residue vacuum distilled to afford ethyl phenylcarbamate (340 mg,

75%); mp and mixed mp 51-53 °C (lit.[43] 53 °C). The IR spectrum was indistinguishable from that of an authentic sample prepared from phenyl isocyanate and ethanol.

**4-Methylphenyl isocyanate.** 3,4-Di(4-methylphenyl)furoxan **1g** (500 mg, 1.86 mmol) was pyrolysed at 500 °C and the pyrolysate condensed onto sulfur dioxide. After heating under reflux in toluene the presence of the isocyanate was established by IR spectroscopy ($v$ 2250 cm$^{-1}$). GC analysis on 10% of the reaction mixture, using ethyl benzoate as internal standard, showed the presence of *p*-methylphenyl isocyanate (2.83 mmol, 76%). Freshly distilled aniline (excess) was added to the remainder of the reaction mixture and the resulting solution stirred for 12 h. The resulting precipitate of *N*-(4-methylphenyl)-*N′*-phenylurea was isolated by filtration and recrystallised from ethanol; mp 221-222 °C (lit.[43] 226 °C).

**4-Methoxyphenyl isocyanate.** 3,4-Di(4-methoxyphenyl)furoxan **1e** (200 mg, 0.67 mmol) was pyrolysed at 500 °C and the pyrolysate condensed onto sulfur dioxide. After warming to room temperature the mixture was examined by IR spectroscopy which showed the peaks attributable to sulfur dioxide [$v$ 2460, 1300, 1125 cm$^{-1}$], the isocyanate [$v$ 2265 cm$^{-1}$] and the 1,3,2,4-dioxathiazole *S*-oxide **15e** [$v$ 1243 cm$^{-1}$].[44] The solution was heated to reflux and the disappearance of **15e** monitored; the intensity of the absorption at 2265 cm$^{-1}$ decreased and that at 1243 cm$^{-1}$ increased, consistent with the reaction sequence proposed in Scheme 3. After the solution had been at reflux for 12 h, excess freshly distilled aniline was added and the mixture stirred at room temperature for 24 h. The solvent was removed *in vacuo* and the residue recrystallised from ethanol/water to give *N*-(4-methoxyphenyl)-*N′*-phenylurea (310 mg, 95%); mp 186-188 °C (lit.[45] 186-190 °C).

**Butyl isocyanate.** 3,4-Dibutylfuroxan **1h** (300 mg, 1.52 mmol) was pyrolysed at 600 °C and the pyrolysate condensed onto sulfur dioxide. HPLC analysis of the reaction mixture showed that all the starting material had been consumed. The solution was then heated at reflux for 3 h and on cooling the presence of butyl isocyanate demonstrated by an IR peak at 2260 cm$^{-1}$. An excess of aniline was added and the resulting solution stirred for 12 h. Work up of the mixture afforded *N*-butyl-*N′*-phenylurea as white needles (from CHCl$_3$/pentane); mp and mixed mp 128-129 °C (lit.[46] 130°C); the IR spectrum of the product was indistinguishable from that of an authentic sample prepared from aniline and butyl isocyanate.

**Methyl isocyanate.** 3,4-Dimethylfuroxan **1b** (650 mg, 5.70 mmol) was pyrolysed at 550 °C and the pyrolysate condensed onto sulfur dioxide. After 3 h at reflux, freshly distilled aniline (4 ml) was added and the solution heated at reflux for a further 10 minutes. *N*-Methyl-*N′*-phenylurea (930 mg, 54%) precipitated from the solution on cooling and was isolated as white platelets from ethanol; mp 149-150 °C (lit.[47] 152-152 °C); IR (Nujol): $v$ 3309, 3360 (N–H), 1700, 1650 (C=O); Anal. Calcd. for C$_8$H$_{10}$N$_2$O: C, 64.0; H, 6.7; N, 18.7. Found: C, 64.2; H, 6.7; N, 18.6. The toluene was evaporated from the filtrate and the residue distilled under vacuum (40 °C/0.05 mmHg) to give a yellow liquid. HPLC analysis, using diphenylfuroxan **1a** as internal standard, indicated the presence of dimethylfuroxan **1a** (0.85 mmol, 18%). Therefore the yield of *N*-methyl-*N′*-phenylurea, based on consumed furoxan, was 74%. In a parallel experiment the presence of methyl isocyanate was shown by an IR peak (in toluene) at 2270 cm$^{-1}$.

**Isolation of acetohydroxamic acid from the hydrolysis of 5-methyl-1,3,2,4-dioxathiazole 2-oxide (15b).** 3,4-Dimethylfuroxan **1b** (1.00 g, 8.77 mmol) was pyrolysed at 550 °C and the pyrolysate condensed onto sulfur dioxide. Diethyl ether and water were added and the reaction mixture shaken vigorously. A few drops were applied to a piece of filter paper saturated with aq. ferric chloride; an intense purple colour formed, consistent with the presence of the hydroxamic acid. The solvent was then removed *in vacuo* and the resulting yellow oil triturated with pentane to afford acetohydroxamic acid (0.80 g, 61%); mp 89-91 °C (lit.[48] 86-88 °C).

**FVP of 3,4-diphenylfuroxan in the absence of sulfur dioxide.** 3,4-Dimethylfuroxan **1b** (300 mg, 1.26 mmol) was pyrolysed at three temperatures (550, 700, 800 °C) and the pyrolysate condensed onto hex-1-ene (~2 ml). In each case the composition of the reaction mixture was analysed by GC using diphenyl ether as internal standard, and the isoxazoline **9a** isolated and its identity confirmed from its mp and mixed mp. The GC product yields were as follows:- 550 °C: 98% **9a**, <2% PhNCO; 700 °C: 95% **9a**, 4% PhNCO; 800 °C: 27% **9a**, 37% PhNCO. The pyrolysis at 800 °C proceeded with considerable charring.

**Preparation of phenyl isothiocyanate by FVP of 3,4-diphenylfuroxan.** 3,4-Diphenylfuroxan **1a** (400 mg, 1.69 mmol) was pyrolysed at 550 °C and the pyrolysate condensed onto *N,N*-dimethylthioformamide (1.5 g, 1.69 mmol) in dry diethyl ether (~2 ml). The mixture was allowed to warm to room temperature and, after standing for 3 h, examined by IR spectroscopy. The IR spectrum showed the presence of phenyl isothiocyanate (ν 2050 cm$^{-1}$) and the co-product *N,N*-dimethylformamide (ν 1685 cm$^{-1}$). Freshly distilled aniline was added and the mixture stirred for 24 h; the disappearance of the isothiocyanate was monitored by IR spectroscopy. *N,N'*-diphenylthiourea (380 mg, 49%) precipitated from the solution and was isolated as white platelets from an ethanol/water mixture; mp 152 °C (lit.[49] 152 °C). The IR spectrum was indistinguishable for that of an authentic sample prepared from phenyl isothiocyanate and aniline.

**Generation of alkanonitrile oxides**

**Acetonitrile oxide (2b).** 3,4-Dimethylfuroxan **1b** (0.5 g, 84.4 mmol) was pyrolysed at 600 °C and the pyrolysate condensed onto deuterochloroform (~2 ml) at -196 °C. A second layer of deuterochloroform was distilled into the cold trap to form a 'sandwich'. After warming under dry nitrogen to -78 °C (CO$_2$/Me$_2$CO slush bath), the resulting solution was transferred to NMR tubes for spectroscopic study; IR (CDCl$_3$): ν 2280 (CNO); the NMR spectra at -51 °C showed the presence of a ~5:1 mixture of acetonitrile oxide **2b** [δ$_H$ 2.26 ppm (CH$_3$); δ$_C$ 35.6 (t, $^1J$ 48±2 Hz, CN), 0.8 ppm (CH$_3$)] and unreacted 3,4-dimethylfuroxan **1b** [δ$_H$ 2.40, 2.21 ppm (CH$_3$); δ$_C$ 154.4 (C-4), 112.7 (C-3), 10.5, 6.9 ppm (CH$_3$)]. The spectra were unchanged after three days at -78 °C. After two days at room temperature the peaks for nitrile oxide **2b** had disappeared and only those for furoxan **1b** were detectable.

**Propionitrile oxide (2c)** was generated similarly by FVP of 3,4-diethylfuroxan **1c** at 600 °C; $^1$H NMR (CDCl$_3$, -45 °C): δ 2.61 (q, $J$ = 7.5 Hz, CH$_2$), 1.30 (t, $J$ = 7.5 Hz, CH$_3$); ); $^{13}$C NMR (CDCl$_3$, -45 °C): δ 39.1 (t, $^1J$ 42±2 Hz, CN), 11.0 ppm (CH$_2$, CH$_3$). After two days at room

temperature the peaks for nitrile oxide **2c** had disappeared and only those for furoxan **1c** were detectable; ^{1}H NMR (CDCl$_3$): δ 2.71 (q, $J$ = 7.5 Hz, CH$_2$), 2.55 (q, $J$ = 7.5 Hz, CH$_2$), 1.30 (t, $J$ = 7.5 Hz, CH$_3$), 1.18 (t, $J$ = 7.5 Hz, CH$_3$); ^{1}H NMR (CDCl$_3$): δ 158.5 (C-4), 116.5 (C-3), 19.0, 15.7, (CH$_2$), 10.6, 9.5 (CH$_3$).

**Dimerisation of acetonitrile oxide (2b) to 3,4-dimethylfuroxan (1b)**

The conversion of acetonitrile oxide **2b** into 3,4-dimethylfuroxan **1b** was monitored by ^{1}H NMR spectroscopy in CDCl$_3$ at 23.0±0.5 °C. A solution of **2b** in CDCl$_3$ was prepared by FVP of furoxan **1b** (0.5 g, 4.39 mmol) at 650 °C, as described above, and then stored at -78 °C. A portion of the acetonitrile oxide solution (0.50 ml) was added to an NMR tube containing dioxan (10.0 μl) as internal standard, and the NMR spectrum recorded at -40 °C in order to determine the initial concentrations. The reaction was then initiated by raising the temperature to 23 °C and spectra recorded at 5-minute intervals. After one hour the sample was allowed to warm to room temperature, left for two days, and the final spectrum then recorded. The formation of the furoxan, rather than the consumption of the nitrile oxide, was used to follow the progress of the reaction as the integral of the furoxan methyl signal at $\delta_H$ = 2.40 ppm could be measured more accurately than that of the nitrile oxide at $\delta_H$ = 2.26 ppm. The concentrations [$F_t$] of furoxan **2b** were measured at time 't' by comparison with the dioxan signal at $\delta_H$ = 3.75 ppm. A typical experiment gave the following values for time/minutes and [$F_t$]/mol.dm$^{-3}$: 0 [0.226], 5 [0.258], 10 [0.278], 15 [0.314], 20 [0.306], 25 [0.334], 30 [0.348], 35 [0.400], 40 [0.400], 45 [0.430], 50 [0.440], 55 [0.446], 2 days [0.696]. From a plot of [$F_\infty$ − $F_t$]$^{-1}$ $vs$ time $t$, the second order rate constant was determined as $k$ = 5.95±0.2 x 10$^{-4}$ mol$^{-1}$dm$^3$s$^{-1}$. A repeat experiment gave $k$ = 6.19±0.2 x 10$^{-4}$ mol$^{-1}$dm$^3$s$^{-1}$, giving a mean value of 6.1 ±0.2 x 10$^{-4}$ mol$^{-1}$dm$^3$s$^{-1}$.

**Flash vacuum pyrolysis (FVP) of 1,2,3-triazole 1-oxides**

**FVP of 2,4,5-triphenyl-1,2,3-triazole 1-oxide (25a).** 2,4,5-Triphenyl-1,2,3-triazole 1-oxide **25a** (500 mg, 1.60 mmol) was pyrolysed at 650 °C and the pyrolysate condensed onto diethyl fumarate (3.0 g) in sodium dried toluene (5 ml). On warming the solution was examined by IR spectroscopy, which showed no peak at ~2330 cm$^{-1}$ attributable to benzonitrile oxide. The toluene and diethyl fumarate were removed *in vacuo*. TLC and ^{1}H NMR spectroscopy showed the presence of unreacted **25a**; diethyl *trans*-3-phenyl-2-isoxazoline-4,5-dicarboxylate **13** was not detectable.

**FVP of 4,5-dimethyl-2-phenyl-1,2,3-triazole 1-oxide (25b).** 4,5-dimethyl-2-phenyl-1,2,3-triazole 1-oxide **25b** (250 mg, 1.32 mmol) was pyrolysed at 650 °C and the pyrolysate condensed onto hex-1-ene (5 ml). After warming to room temperature the hexene was removed *in vacuo* to leave a brown oil. TLC examination showed the presence of five components, one of which was the starting material. Comparison of the R$_f$ values with that of authentic 5-butyl-3-methyl-2-isoxazoline showed that it was not present. Chromatography (alumina, Et$_2$O/pentane) gave a brown solid (85 mg) which was recrystallised from methanol to yield 1,2-di(5-methyl-2-phenyl-1,2,3-triazol-4-yl)ethane **28** (37%) as white platelets; mp 138-139 °C; ^{1}H NMR (CDCl$_3$): δ 8.05-

7.21 (m, 10H, PhH), 3.10 (s, 4H, CH$_2$), 2.21 (s, 6H, CH$_3$); $^1$C NMR (CDCl$_3$): δ 146.5, 143.5 (C-4,5), 139.8, 129.1, 126.5, 118.1 (ArC), 24.1 (CH$_2$), 9.8 (CH$_3$); MS (EI): $m/z$ (%) 345 (M$^+$+1, 18), 344 (M$^+$, 83), 185 (16), 173 (15), 172 (100), 91 (27), 77 (18); HRMS (EI): Calcd. for C$_{20}$H$_{20}$N$_6$: $M$ 344.1749. Found: $m/z$ 344.1745.

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