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Flash vacuum pyrolysis of azolylacroleins and azolylbutadienes

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ABSTRACT

2-Aryl-5-acroleinyl-1,2,3,4-tetrazoles (**1a**–**d**) and 2-aryl-5-butadienyl-1,2,3,4-tetrazoles (**1e**–**g**) were subjected to flash vacuum pyrolysis. Acroleinyl derivatives resulted in nitrogen extrusion to give nitrilimines followed by ring closure to give the corresponding indazoles **3a**–**d** in good yields. On the other hand, butadiene derivatives underwent ring fragmentation to give *p*-substituted anilines without formation of the expected indazoles. Differences between thermal behaviour of 2-(4-chlorophenyl)-5-acroleinyl-1,2,3,4-tetrazole (**1c**) and 1-(4-chlorophenyl)-4-acroleinyl-1,2,3-triazole (**2**) were studied in details. DFT calculations have been used to examine the nitrilimine and carbene nature of the intermediates involved in the thermal reactions of azolyl derivatives.

1. Introduction

Flash vacuum pyrolysis (FVP) consists of subjecting a molecule to high temperature over a short period of time ($\sim 10^{-2}$ s). This process allows the acquisition of kinetic as well as unstable products and may be suitable for synthetic purposes or for the study of reaction mechanisms. FVP is used both as a single-step synthetic procedure and as a complement to a multistep synthesis. These reactions are generally clean and without solvent, so allow exploration of reactive species, such as carbenes, radicals, nitrenes and concerted reactions. Thus, FVP is an excellent technique for the study of intramolecular reactions, such as elimination, cyclization and generation of products that cannot be prepared in solution in thermal reactions. Several reviews concerning FVP have been reported[1] and a worldwide book concerning synthetic gas-phase transformations has also been published.[2] Many nitrogen heterocyclic compounds including pyrazoles, isoxazoles, triazines, triazoles and tetrazoles have been studied under thermal gas-phase conditions as an appropriate way to obtain new heterocycles.[3]

In the course of our pyrolytic studies we have focused on rings containing N—N double bonds, due to their ability to eliminate nitrogen, generating reactive species, which could undergo rearrangement to give monocyclic and fused *N*-heterocyclic compounds.

In particular, thermolysis of 1,5-disubstituted tetrazoles differs from that of the 2,5-disubstituted derivatives because nitrogen elimination in the former case produces nitrenes and carbodiimides that rearrange to pyrazoles,[4] thiadiazoles,[5] oxadiazoles[6] and triazoles[7] while in the latter gives nitrilamines.[8]

In this work, FVP methodology has been applied to prepare new acroleinylindazoles (**3a**–**d**) in good yields starting from 2-aryl-5-acroleinyltetrazole precursors **1a**–**d**. In contrast to this result, 2-aryl-5-butadienyltetrazoles **1e**–**g** afforded *p*-substituted anilines rather than indazoles. In addition, FVP reactions of 1-(4-chlorophenyl)-4-acroleinyl-1,2,3-triazole **2** were performed in order to assess the reactivity of tetrazole and triazole rings under similar thermal conditions (Fig. 1). Theoretical calculations concerning the assumed nitrilimine and carbene intermediates were also performed to understand the mechanism operating in the nitrogen elimination of azolyl derivatives **1** and **2**.

2. Results and discussion

Acroleinyltetrazoles (**1a**–**d**) and butadienyltetrazoles (**1e**–**g**) were prepared from 3-aryltetrazolo[1,5-*a*]pyridinium salts, whereas 1-(4-chlorophenyl)-4-acroleinyl-1,2,3-triazole (**2**) was prepared from 1,3-diaryl[1,2,3]triazolo[1,5-*a*]pyridinium salts according to a literature procedure.[9] In all cases the trans isomers of **1** and **2** were used in the thermal reactions. FVP reactions of these azolyl derivatives were performed in a Vycor glass reactor with

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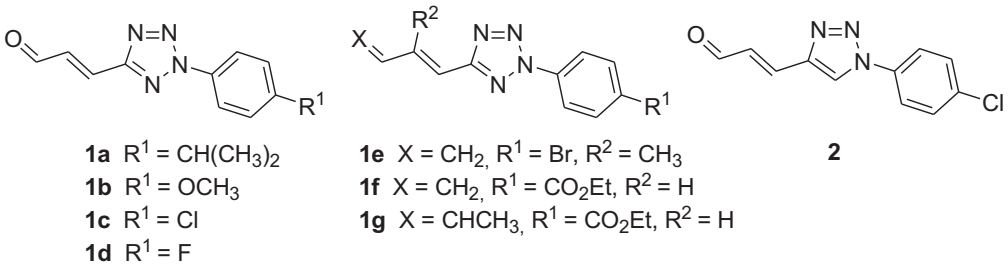
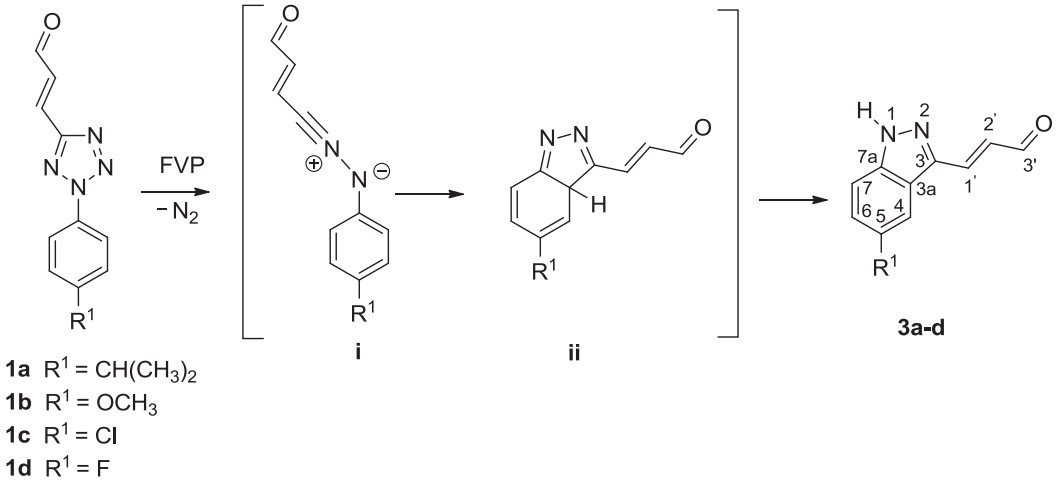


Fig. 1. Azolyl derivatives studied under FVP conditions.

pressures of $\sim 10^{-2}$ Torr and contact times of $\sim 10^{-2}$ s. In the case of substrate **1g** all efforts to achieve volatilization of the sample failed, and the low vapour pressure of this compound promoted decomposition in the sample probe without passage through the hot tube.

Gas-phase reactions of acroleinyltetrazoles (**1a**–**d**) were carried out between 250 and 370 °C (Scheme 1). These reactions were clean and 3-acroleinylindazoles (**3a**–**d**) were obtained in high yields (60–98%). The results are summarized in Table 1. In all cases, when a 100% conversion of the starting tetrazole was achieved, small amounts of two by-products: formylindenes **4** and indenes **5** were also detected (Scheme 2).



Scheme 1. Formation of 3-acroleinylindazole (**3**) by FVP starting from tetrazolylacrolein (**1**).

Table 1
FVP reactions of tetrazoles **1a**–**d**

Compound	R^1	T (°C)	% **1**	% **3**[a]	% **4**+**5**
1a	$CH(CH_3)_2$	350	38	62	—
		370	—	92	8
1b	OCH_3	250	55	28	17 (1:6)[b]
		280	5	60	35 (1:8)
		300	—	37	63 (1:12)
1c	Cl	250	39	61	—
		300	1	95	4
1d	F	250	27	73	—
		280	—	98	2

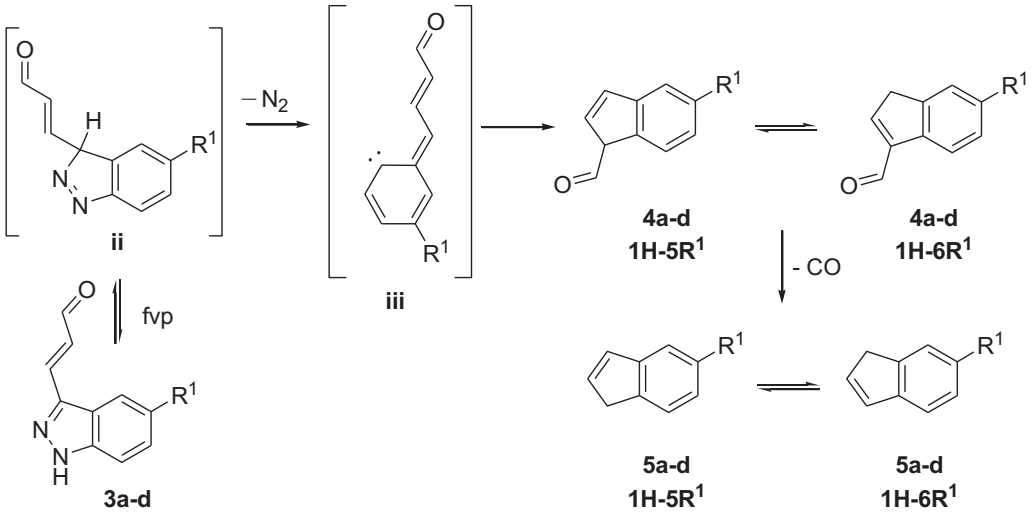
[a] Values determined by ^{1}H NMR spectroscopy.
[b] Total amount and relative ratio of indenes **4** and **5** determined by GC/MS.

The formation of indazoles **3a**–**d** could be rationalized by a nitrogen extrusion reaction in the starting tetrazole ring (Scheme 1). The intermediate proposed for these transformations is represented by the nitrilimine resonance structure (**i**), which initially undergoes a [1,5] dipolar cyclization with participation of one double bond of the phenyl ring to give 4*H*-indazoles (**ii**), which isomerizes to the more stable aromatic tautomers 1*H*-indazoles **3a**–**d**.

This intermediate (**i**) is, however, a flexible molecule, which can adopt its geometry depending on the reaction conditions.[8a,10] The generation of nitrilimines from 2,5-disubstituted tetrazoles has been previously studied in thermal[8a,10] and photochemical reactions.[11] Thermal studies in the gas and solution phase have shown that 2,5-disubstituted tetrazoles are usually less stable than 1,5-disubstituted ones,[12] and that the intermediate nitrilimine reacts according to the temperature, solvent and nature of the substituent in position 2 of the initial tetrazole. Thus, electron-withdrawing substituents decrease the energy barrier of the transformation of tetrazole into the nitrilimine intermediate. We also observed that the fluoroaryl derivative **1d** was completely transformed into **3d** at a reaction temperature lower than that used with the other substrates.

When the temperature is high enough, 3*H*-indazole (**ii**), i.e., the precursor of **3**, eliminates nitrogen to give 1*H*-indene-carbaldehyde **4** via carbene intermediates **iii** (Scheme 2). In general, loss of this second nitrogen molecule in indazoles requires high temperature (800 °C) as reported in case of pyrolysis of 3-phenyl-indazole to give fluorene.[10a] In our experiments, these reactions occurred at low temperatures (about 300 °C); therefore, thermal instability of indazoles **3a**–**d** could be ascribed to the electronic effect of an acroleinyl substituent. This behaviour resembles the transformation observed with nitrogen extrusion of 3-(2-furyl)-indazole, where benzofulvene derivatives were obtained at 400 °C.[10b]

In all cases, compounds **4a**–**d** were detected as a mixtures of 5-substituted-1*H*-indene-1-carbaldehyde (**1H-5R1**) and 6-substituted-1*H*-indene-3-carbaldehyde (**1H-6R1**), which were in equilibrium. Thermal isomerization of indenes is a well-known thermal reaction and the amount of each isomer depends on the reaction conditions.[13]



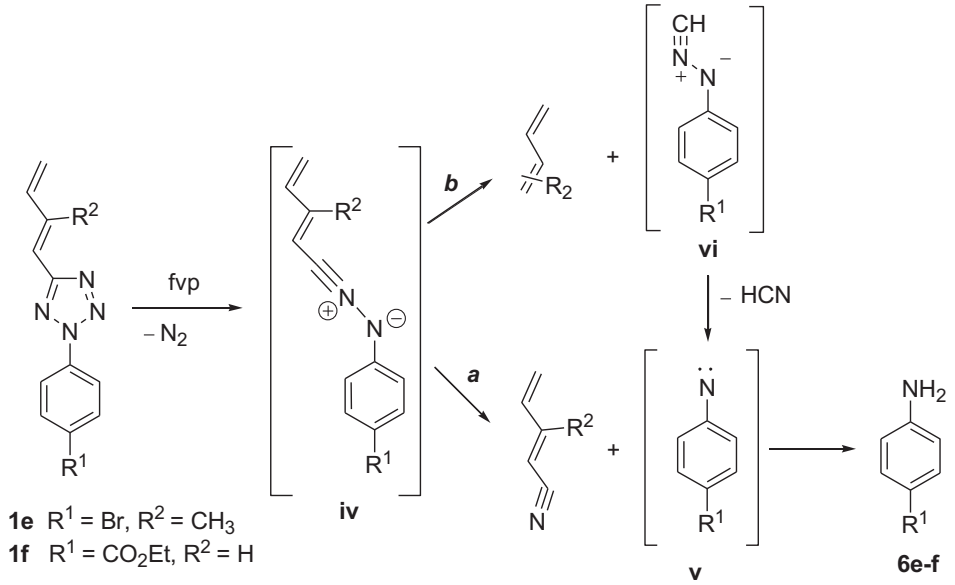
Scheme 2. Formation of indenes under FVP conditions.

Carbaldehydes **4** afforded decarbonylation to give indenes **5** under FVP conditions. A gas chromatography analysis of the mixture of indenes in the FVP of **1b** indicated that the ratio of **4b**/**5b** decreased as the temperature increased, the loss of CO being a favoured process under all thermal conditions (Table 1). In case of methoxy derivative **1b** formation of indenes became important giving a 63% yield of these products and only 37% of **3b** at 300 °C. This feature could be explained by the ability of the methoxy group to stabilize the carbene **iii** involved in the N_2 elimination reaction. Thus, the order of reactivity of **3a**–**d** is in concordance with the ability of the substituents to stabilize the positive charge density by resonance effect: OCH_3>Cl∼F>$CH(CH_3)_2$.

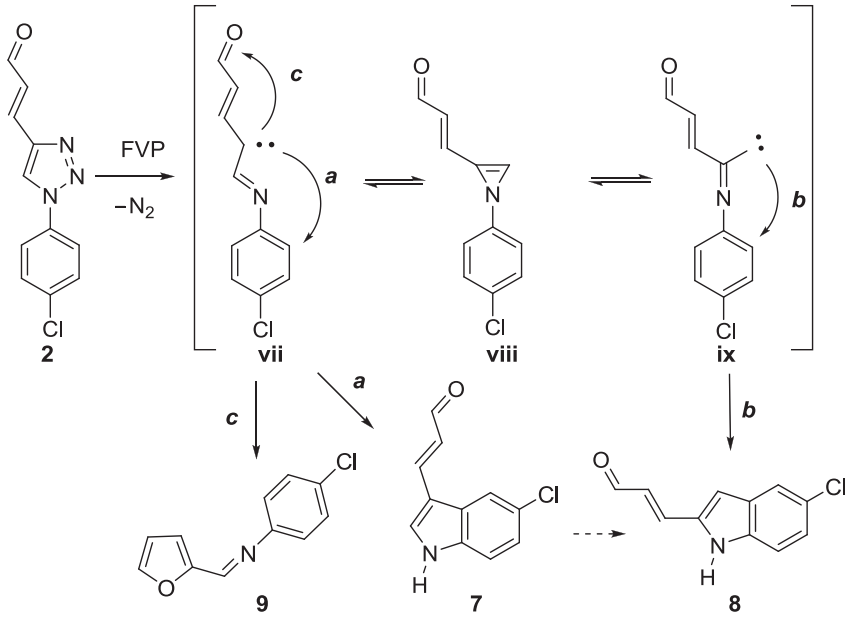
Gas-phase pyrolysis of butadienetetrazoles **1e**–**f** proceeded in a different fashion compared to that of acroleinyl derivatives **1a**–**d**. Thus, reactions performed at 200–400 °C afforded *p*-substituted anilines **6e**–**f** (<20% yield) as the main products without formation of the expected butadienylindazoles (Scheme 3). In the reaction mixture some volatile compounds including butadiene and unsaturated nitriles were also detected and their relative amount gradually increased with temperature. Fragmentation of nitrilimines **iv** could be attributed to a less stabilizing effect of the alkenyl substituent compared to the acroleinyl moiety also supported by results of calculations discussed below.

Formation of anilines **6e**–**f** could be rationalized by decomposition of the nitrilimines **iv** initially generated. Two possibilities can be proposed: either **iv** affords a conjugated nitrile and nitrene (**v**) by N–N bond fragmentation (pathway a in Scheme 3) or a C–C cleavage occurs to give a nitrilimine (**vi**), which also yields nitrene (**v**) by hydrogen cyanide elimination (pathway b). In both cases hydrogen abstraction by **v** may result in formation of anilines **6e**–**f**. It is known that nitrene species abstract hydrogen atoms to generate amines when a hydrogen radical source is available.[13] In our reactions, when toluene vapour was used as carrier gas bibenzyl was formed being an indicative of the presence of radicals in the reaction mixture.

Acroleinyltriazole **2**, a deaza-analogue of **1c**, was also subjected to investigation under FVP conditions. The first predictable observation was that a high furnace temperature (300–400 °C) was required for the transformation of **2**. Analysis of the pyrolysate at 400 °C indicated a mixture of isomeric indoles **7** and **8** (46%) and *N*-(furanylmethylene)aniline **9** (48%) as main products (Scheme 4). The thermal formation of indoles from 1,4-disubstituted-1,2,3-triazoles is a very well-known procedure.[14] However, there is no precedent for the thermal study of triazole containing acroleinyl substituents in the ring.



Scheme 3. FVP reactions of 2-aryl-5-butadienyl-1,2,3,4-tetrazoles **1e**,**f**.

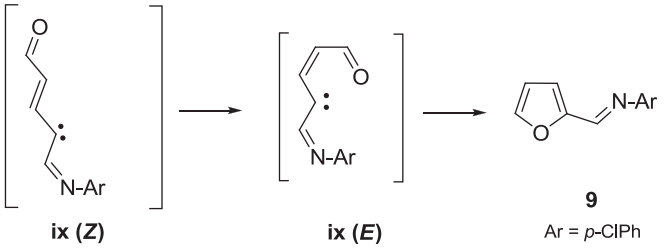


Scheme 4. FVP of 1-(4-chlorophenyl)-4-acroleinyl-1,2,3-triazole **2**.

The analysis of the mixture of 2- and 3-acroleinylindoles in the pyrolysate showed a preponderance of 3-substituted isomer **7** at all temperatures. As a result of the nitrogen elimination, obviously iminocarbene **vii** is formed first, and insertion of the carbene into the aromatic C–H bond can yield directly indole **7** (pathway a in Scheme 4). The formation of **8** through pathway b would require the intermediacy of 1*H*-azirine **viii** in the interconversion of iminocarbenes **vii** and **ix**. It was reported that the formation of the indole mixture could be ascribed to the intermediacy of 1*H*-azirines.[14b] Looking at the reactivity of azirine, a preponderance of 3-substituted indole **7** suggests that cyclization of **vii** to **7** (i.e., pathway a in Scheme 4) may be faster than formation of **ix** followed by cyclization to **8** (pathway b in Scheme 4). On the other hand, the thermal isomerization of 3-indole to 2-indole by a sigmatropic [1,5]-shift of a migratory group is well known.[14c] Although there is no information about the efficiency of acroleinyl moiety as a migrating group under thermal conditions, it cannot be discarded. Thus, formation of indole **8** could be rationalized in terms of the rearrangement of carbene **ix** and/or the rearrangement of indole **7**.

In addition, a very interesting finding was the presence of furanylmethylene-aniline (**9**) in the reaction mixture. This could be explained by the intermediacy of the iminocarbene **ix**. Thus, this initial intermediate could undergo a [1,5] dipolar cyclization in which the carbene carbon atom attaches to the carbonyl oxygen atom to form the five-membered furan ring (pathway c in Scheme 4). Similar rearrangements were observed in the pyrolysis of different triazoles to give oxazoles.[15] Experimental observations showed that furanyl derivative **9** could be detected by a careful GC/MS analysis, but it immediately underwent hydrolysis to 2-furaldehyde and 4-chloroaniline. In order to confirm the structure of **9**, *p*-chloroaniline was separately synthesized[25] from furfural and *p*-chloroaniline. Physical data of the synthesized **9** proved to be entirely identical to those of the product obtained in the FVP reactions.

Addition to the carbonyl oxygen atom (Scheme 4, route c), insertion into the aromatic C–H bond (route **a**), and insertion in the N=C double bond to give azirine **viii** are competitive reactions of iminocarbene **ix**. Such reactions are well known in gas-phase carbene chemistry.[16] The finding that pyrolysis of **2** at 350 °C afforded only indoles **7** and **8**, while **9** was absent suggests that the ring closure reaction of **ix** to form the furan derivative requires higher energy than the other rearrangements. In addition, interconversion of carbene **ix** (*Z*) to carbene **ix** (*E*) is necessary to achieve the orientation that allows overlapping between the oxygen lone pair of the carbonyl group and the empty p-orbital of the carbene (Scheme 5).



Scheme 5. Isomerization of carbene **ix** (*Z*) to carbene **ix** (*E*) under FVP conditions.

Z–*E* Isomerization of azolylalkenyl derivatives under FVP conditions has been described in the literature.[17] Although equilibrium between the *Z*- and *E*-alkenylindazoles could take place under gas-phase thermal conditions, we consider it would be minimal at the low temperature used herein. The alkenylindazole obtained in the pyrolysate was therefore the stable *Z*-configuration isomer. Previous calculations have also indicated that a minimal energy barrier is associated with this type of interconversion in iminocarbenes.[18]

The structures of the intermediates involved in the FVP reactions of **1** and **2** were calculated with the Gaussian03 program system,[19] using a DFT method with B3LYP/6-311++G (2df,pd) unrestricted valence basis set with polarization and diffuse function for all atoms. All geometries were optimized and characterized by vibrational analysis. Shielding values were calculated for the optimized geometries using the gauge including atomic orbitals method (GIAO).[20] Combination of the density-functional theory (DFT) and the GIAO method was used as an advantageous procedure for measuring chemical shielding properties.[21]

In order to understand the mechanism operating in our thermal reactions, the electronic structure of the nitrilimines (i.e., **i** in Scheme 1 and **iv** in Scheme 3, for the four possible representations see Fig. 3) involved in these transformations was calculated according to Mawhinney's previous theoretical studies.[22b] Thus,

three structures were considered: planar C_s and non-planar C_1 structures, and the cyclic species C (Fig. 2). C_s and C_1 electronic structures were therefore necessary to determine the effects of substitution on the flexibility of nitrilimine as described in the literature.[23] Based on the geometry of the YCN fragment, the C_s arrangement can be described as a combination of propargylic (Fig. 3, **a**) and allylic (**c**), while the C_1 structure posses the allenic (**b**) and carbenic form (**d**) as major contributors. Considering the CNN fragment, (**a**) and (**b**) structures can be described as linear units, while (**c**) and (**d**) are bent. However, it was determined that the angle values YCN and CNN are required for a proper description of the nitrilimine geometry involving all structures (**a**–**d**).[22b]

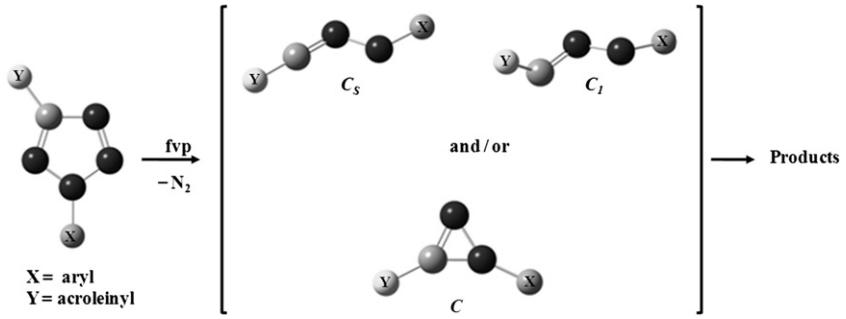


Fig. 2. Intermediates in the FVP reactions of acroleinyltetrazoles.

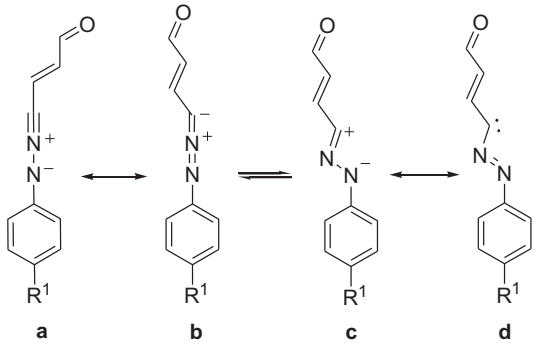
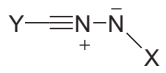


Fig. 3. Representation of nitrilimine **2** by propargyllic (**a**), allenic (**b**), allylic (**c**) and carbenic (**d**) structures.

The optimized parameters found in our calculations were compared with values previously described for other nitrilimines shown in Fig. 4: the parent formonitrilimine H–CNN–H (**10**), the borane derivative H–CNN–BH_2 (**11**), the diamine NH_2–CNN–NH_2 (**12**) and fluorinated derivatives F–CNN–F (**13**) and F–CNN–H (**14**). The results are summarized in Table 2.



10, X= Y= H
11, X= H, Y= BH_2
12, X= NH_2, Y= NH_2
13, X= F, Y= F
14, X= H, Y= F

Fig. 4. Some variously substituted nitrilimines for comparative purposes.

By analyzing the values of YCN and CNN angles it was clearly observed that the geometry of the intermediates corresponds to the planar C_s structure with a greater contribution of species **a**, **b** and **c**, showing a behaviour similar to that of borane derivative **11** described in the literature.[22a] These findings indicate that there was a poor contribution of carbenic species. We also found that the values of NNX angles were similar for all evaluated intermediates, independently of the *N*-aryl substitution. Table 2 shows that all intermediates from **1a**–**d**, C_s and C_1 structures corresponded to two stationary points that are almost isoenergetic, the energy difference between them being of only about 6 kcal between them. Intermediates **10**, **12**–**14**, on the other hand, were described as structures with more carbene character and, in these cases; C_s corresponded to a transition state (TS). The increase in the carbene character could be associated with a decrease in the YCN and CNN bond angles. The values of these angles described for **12** and **13** are typical of singlet carbenes.[22a]

On the other hand, the carbon absolute chemical shielding (σ_{iso} values) provides information on the nature of the carbenic structures.[22b] Carbenes generally present negative absolute chemical shielding values, such as the diamine derivative (NH_2–C–NH_2), which has a value of −62 ppm.[22b] However, our calculations showed high positive values of σ_{iso} (about 95 ppm) indicating a strong character of nitrilimines for the intermediates obtained from **1**. These findings were comparable to the experimental ^{13}C chemical shifts observed for stabilized nitrilimines,[24] ranging from 45 to 86 ppm, where, for example, ditritylnitrilimine, (Ph_3C–CNN–CPh_3) had the largest experimental value, 86 ppm. The predicted chemical shift (δ_{iso}) of the parent nitrilimine **10** is 66 ppm and C-substitution produces a deshielding of the nitrilimine carbon nucleus (Table 2).[24] This tendency agrees with our observations obtaining a decrease in σ_{iso} of about 30 ppm in the evaluated nitrilimines. The small difference observed in the deshielding of acroleinyl (**1a**–**d**) and butadienyl (**1f**) derivatives could be explained by a similar conjugated system in both intermediates.

In addition, Table 2 depicts the Highest Occupied Molecular Orbital (HOMO) of all calculated species. The carbon lone pair character is obvious in the HOMO from left to right and is consistent with the observed increase in carbene character.

Some calculations were also performed to provide information about the origin of the anilines **6e**–**f** in the thermal reaction of **1e**–**f**. Table 3 illustrates the bond distances of nitrilimine moiety for all compounds studied. All parameters, including the dihedral angle θYCN (Table 2), showed that nitrilimine (**iv**) from compound **1f**, was different and presented short Ar–N and N≡C bond distances and longer N–N and CC–C bond distances than nitrilimines formed from **1a**–**d**. The weakness of these bonds could indicate why the intermediates (**iv**) afforded anilines **6e**–**f** instead of the corresponding indazole rings (Scheme 3).

In view of these interesting findings we can estimate that in the FVP of butadienyltetrazoles (Scheme 3), both proposed ways (a and b) would take place. In the case of fragmentation b the

Table 2
Calculations data for nitrilimines from azolyl derivatives **1** compared to data reported in the literature for nitrilimines **10**–**14**

[a↔b↔c↔d] Y–CNN–X										
Y	Acrol.	Acrol.	Acrol.	Acrol.	H	Butad.	H	F	F	NH_2
X	*p*-FPh	*p*-ClPh	*p*-OCH_3Ph	*p*-*i*-pPh	BH_2	EtOC(O)	H	H	F	NH_2
From	(**1d**)[a]	(**1c**)[a]	(**1b**)[a]	(**1a**)[a]	(**11**)[b]	(**1f**)[a]	(**10**)[b]	(**14**)[b]	(**13**)[b]	(**12**)[b]
C_1	5.4	5.9	5.7	5.5	6.0	2.1	0	0	0	0
C_s	0	0	0	0	0	0	1.7 (TS)	14.5 (TS)	25.0 (TS)	12.0 (TS)
θYCN	179.2	179.2	179.4	179.3	177	176.6	133	123	117	117
θCNN	172.4	172.1	172.5	172.4	174	172.6	170	163	159	132
θNNX	117.6	117.6	117.8	117.6	—	117.3	—	—	—	—
H Contribution	a+b+c	a+b+c	a+b+c	a+b+c	a+b+c	a+b+c	a+b+c+d	b+c+d	b+c+d	b+d
σ_{iso}	95.7	95.5	94.7	95.3	124.0	96.4	122.0	76.0	−11.0	−53.0
δ_{iso}	92.3	92.5	93.3	92.7	64.0	91.6	66.0	112.0	199.0	241.0
HOMO										

[a] Zero-point energy corrected relatives energies (ΔE) in Kcal mol^{-1}, bond angles in θ degrees, absolute chemical shielding (σ_{iso}) and chemical shifts (δ_{iso}) in ppm reference to TMS, calculated with GIAO/6-311++G (2df,pd).
[b] From reference 22.

Table 3
Bond distances (Å) for all intermediates studied, calculated by B3LYP/6-311++G (2df,pd) method

Ar–N–Z≡C–CH=CH–CH=G (Z=N,C and G=O, CH_2)							
From	Ar–N	N–Z	Z≡C	ZC–C	C=C	CH–CH	CH=G
		N–N	N≡C	NN–C			CH=O
1c	1.405	1.256	1.178	1.394	1.364	1.460	1.222
1d	1.407	1.255	1.179	1.393	1.365	1.460	1.222
1a	1.408	1.254	1.179	1.392	1.336	1.458	1.223
1b	1.407	1.253	1.180	1.391	1.367	1.456	1.224
		N–N	N≡C	CC–C			$CH=CH_2$
1f	1.395	1.268	1.174	1.403	1.363	1.445	1.348
		N=C	C–C:	C:–C			CH=O
2	1.374	1.339	1.359	1.366	1.390	1.452	1.226

formation of nitrilimine (**vi**) could be supported by the long bond distance (1.403 Å) found for the simple C–C bond in the fragment ZC–C. On the other hand, the rupture a was corroborated by the formation of conjugated nitriles, which were detected by GC/MS analysis in the volatile fraction of the pyrolysate.

Besides, bond distance calculations for the carbenic intermediate allowed us to explain some features of the thermal reaction. Looking at the results in the last entry of Table 3 we can see that the N=C bond is longer than the N–N bond found for nitrilimine intermediates. However, the scission of this bond was not achieved and the formation of all products could be explained by the intermediacy of carbene species **viii** and their rearrangements. It was further observed that the similar short bond distances in the conjugated system for carbene species (**vii**) prevented fragmentation, thus allowing two competitive reactions: C–H aromatic insertion and C–O addition.

3. Conclusions

From a synthetic point of view, FVP of acroleinyltetrazoles (**1a**–**d**) proved to be an appropriate methodology to obtain the hitherto unknown acroleinylindazoles (**3a**–**d**).

In the thermal reactions of tetrazoles (**1a**–**f**) the nitrilimine nature rather than the carbenic character of the intermediate was proposed. Theoretical calculations showed that C_s structure was more stable than C_1 and *C* structures in the calculated intermediates.

4. Experimental part

4.1. General methods

FVP reactions were carried out in a Thermolyne 21100 furnace using a vycor glass of 30 cm long and a 1.2 cm i.d. reactor. Temperatures were 250–400 °C, pressures of 10^{-2} Torr, contact times were 10^{-2} s and sample amounts were 15–25 mg. After the experiments were completed, the pyrolysate was extracted with organic solvents and submitted to purification and conventional analysis (^{1}H NMR, ^{13}C NMR and GC/MS). Infrared spectra were recorded at room temperature with a Nicolet 5SXC-FT IR spectrometer. ^{1}H, ^{13}C NMR spectra were recorded on a Bruker FT-200 (^{1}H at 200, ^{13}C at 50 MHZ) spectrometer. Chemical shifts are reported in parts per million (ppm) downfield from TMS. Melting points are uncorrected. Gas chromatography/mass spectrometry (GC/MS) analyses were performed in a Shimadzu CG-MS-QP 5050A spectrometer equipped with a VF column, using Helium as eluent at a flow rate of 1.1 mL/min with a heating ramp of 15 °C/min from 50 °C to 280 °C. Mass spectra were obtained in electron impact mode (EI) with 70 eV ionization energy. Column and thin-layer chromatograms were performed on silica gel. The exact mass measurements were performed using a Q-TOF Premier mass spectrometer (Waters Corporation, 34 Maple St, Milford, MA, USA) in positive electrospray mode.

*4.1.1. (2E)-3-(5-Isopropyl-1H-indazol-3-yl)acrylaldehyde (**3a**).* This compound was obtained from FVP reaction of (2*E*)-3-[2-(4-isopropylphenyl)-2*H*-tetrazol-5-yl]acrylaldehyde (**1a**) at temperature 350–370 °C, yellow crystals, mp 127–129 °C; ν_{max} (KBr) 3147, 2958, 2820, 1686, 1452, 1379, 1360, 1352 cm^{-1}; δ_H (200 MHz acetone-d_6) 12.18 (s, 1H, NH), 9.87 (d, 1H, *J*=7.7 Hz, H3′), 7.97 (d, 1H, *J*=16.1 Hz, H1′), 7.94 (s, 1H, H4), 7.61 (dd, 1H, *J*=8.8 and 0.7 Hz, H7), 7.42 (dd, 1H, *J*=8.8 and 1.5 Hz, H6), 7.01 (dd, 1H, *J*=16.4 and 7.7 Hz, H2′), 3.13 (sep., 1H, *J*=6.9 Hz, CH *i*-Pr), 1.33 (d, 6H, *J*=6.9 Hz, 2 CH_3); δ_C (50 MHz acetone-d_6) 194.3, 161.3, 145.0, 144.4, 141.8, 141.4, 129.5, 127.4, 123.0, 117.6, 111.7, 35.0, 24.7; HRMS: MH^+, found 215.1178. $C_{13}H_{15}N_2O^+$ requires 215.1179.

*4.1.2. (2E)-3-(5-Methoxy-1H-indazol-3-yl)acrylaldehyde (**3b**).* This compound was obtained from FVP reaction of (2*E*)-3-[2-(4-methoxyphenyl)-2*H*-tetrazol-5-yl]acrylaldehyde (**1c**) at temperature 250–300 °C and was not isolated from the reaction mixture. Yellow thick oil; GC/MS: *m*/*z* (%)=202 (91) [M^+], 174 (87), 173 (100), 159 (72), 145 (22), 131 (45); ν_{max} (KBr) 3160, 2926, 2837, 1687, 1616,

1513, 1496, 1259, 1114 cm^{-1}; δ_H (400 MHz $CDCl_3$): 13.96 (s, 1H, NH), 9.76 (d, 1H, J=7.8 Hz, H3′), 7.83 (d, 1H, J=16.3 Hz, H1′), 7.45 (d, 1H, J=9.0 Hz, H7), 7.21 (dd, 1H, J=2.3 Hz, H4), 7.12 (dd, 1H, J=9.0 and 2.0 Hz, H6), 6.97 (dd, 1H, J=16.3 and 7.8 Hz, H2′), 3.90 (s, 3H, OCH_3); δ_C (100.6 MHz $CDCl_3$): 193.5, 156.3, 143.0, 142.9, 139.2, 138.6, 126.3, 125.4, 118.0, 112.3, 56.6; HRMS: MH^+, found 203.0816. $C_{11}H_{11}N_2O_2^+$ requires 203.0815.

*4.1.3. (2E)-3-(5-Chloro-1H-indazol-3-yl)acrylaldehyde (**3c**).* This compound was obtained from FVP reaction of (2*E*)-3-[2-(4-chlorophenyl)-2*H*-tetrazol-5-yl]acrylaldehyde (**1c**) at temperature 250–300 °C, brownish crystals, mp 106–107 °C; ν_{max} (KBr) 3146, 2847, 1654, 814 cm^{-1}. GC/MS: m/z (%)=206 (32)[M^+], 178 (100), 152 (26), 125 (11), 115 (27), 89 (19), 63 (28); δ_H (200 MHz DMSO-d_6) 14.00 (s, 1H, NH), 9.76 (d, 1H, J=8 Hz, H3′), 7.95 (s, 1H, H4), 7.80 (d, 1H, J=16 Hz, H1′), 7.50 (d, 1H, J=9 Hz, H7), 7.45 (dd, 1H, J=9 and 2 Hz, H6), 7.02 (dd, 1H, J=16.8 and 8 Hz, H2′); δ_C (50 MHz DMSO-d_6) 194.4, 143.6, 139.9, 135.6, 130.8, 128.6, 127.2, 122.3, 119.6, 112.7; HRMS: MH^+, found 207.0327. $C_{10}H_8ClN_2O^+$ requires 207.0325.

*4.1.4. (2E)-3-(5-Fluoro-1H-indazol-3-yl)acrylaldehyde (**3d**).* This compound was obtained from FVP reaction of (2*E*)-3-[2-(4-fluorophenyl)-2*H*-tetrazol-5-yl]acrylaldehyde (**1d**) at temperature 250–280 °C, colourless crystals, mp 91–92 °C; ν_{max} (KBr) 3090, 2850, 1720, 1641, 1275, 1217 cm^{-1}; δ_H (200 MHz DMSO-d_6) 13.96 (s, 1H, NH), 9.70 (d, 1H, J=7.8 Hz, H3′), 7.99 (d, 1H, J=16.1 Hz, H1′), 7.90 (dd, 1H, J=9.3 and 2.4 Hz, H8), 7.68 (dd,1H, J=9.3 and 4.4 Hz, H7), 7.34 (td, 1H, J=9.3 and J=2.4 Hz, H-6), 6.95 (dd, 1H, J=16.1 and 7.8 Hz, H2′); δ_C (50 MHz, DMSO-d_6) 194.2, 158.2 (J=236 Hz), 143.9, 140.1 (J=5 Hz), 138.4, 128.2, 121.1 (J=11 Hz), 116.1 (J=27 Hz), 112.6 (J=9 Hz), 104.7 (J=24 Hz). HRMS: MH^+, found 191.0618. $C_{10}H_8FN_2O^+$ requires 191.0615.

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Supplementary data

Supplementary data (general experimental procedures and data for compounds **7**, **8** and **9**) as well as computational data are found. Supplementary data related to this article can be found, in the online version, at doi:10.1016/j.tet.2011.11.034.

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