QSPR approach to the calculation of rate constants of homolysis of nitro compounds in different states of aggregation

3.* The solid phase

D. V. Sukhachev,[a] *T. S. Pivina,*[a]* *N. I. Zhokhova,*[b] *N. S. Zefirov,*[b] *and S. Zeman*[c]

[a]*N. D. Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences,*
47 Leninsky prosp., 117913 Moscow, Russian Federation.
Fax: +7 (095) 135 5328
[b]*Department of Chemistry, M. V. Lomonosov Moscow State University,*
Vorob'evy Gory, 119899 Moscow, Russian Federation.
Fax: +7 (095) 939 0126
[c]*University of Pardubice, CZ-532 10 Pardubice, Czech Republic.*
Fax: (042) 40 514 530

A method based on the QSPR approach is used for estimation and prediction of the rate constants of homolysis of C—C and C—N bonds of nitro compounds of different chemical classes in the solid phase.

Key words: QSPR approach; homolysis, nitro compounds, rate constants; solid phase.

Theoretical methods for calculating the parameters of thermal stability of organic nitro compounds are scarce and concern especially the activation energy of the homolysis of C—N and N—N bonds. These methods are usually based on semiempirical quantum-chemical calculations and can be applied to nitro compounds in the gas phase only.

The purpose of the present paper is to develop a theoretical method[1,2] for estimation and prediction of the key parameter of the thermal stability of nitro compounds — the rate constants of their homolysis — and to use this method for nitro compounds in the solid phase.

The correlation equations for nitro compounds of different chemical classes (aliphatic and aromatic nitro compounds, cyclic and acyclic nitramines, nitroesters, nitrates, *etc.*) were obtained on the basis of known experimental data.[3–24] We considered nitro compounds whose thermolysis involves homolytic cleavage of C—N or N—N bonds as the first step. For the data base we used the characteristics of nitro compounds obtained predominantly by a manometric method because of discrepancy of the activation parameters of thermolysis obtained by different experimental methods. As previously,[1,2] log *k* values were recomputed using the Arrhenius equation and the average temperature of homolysis of the nitro compounds studied (420 K).

"Structure—log *k*" correlation models were constructed for the data base consisted of 42 compounds, three of which were used for estimation of the prediction ability of the model.

An EMMA (Efficient Modelling of Molecular Activity)[25] program package developed by us was used for construction of "structure—property" regression models based on descriptors — quantitative structural characteristics. About 3000 descriptors were computed for each structure. A set of descriptors includes topological indices (molecular connectivity indices, indices of molecular shape, modified Wiener indices, *etc.*); information indices (SIC_i, TIC_i, CIC_i) that are functions of the charge distribution in molecules (atomic charges were calculated according to the Gastieger method[26]); indices based on electronegativities of atoms; indices based on substructures; *etc.*[28]

After the computed descriptors were analyzed and pairwisely highly correlated and low variable descriptors were removed a set of alternative models allowed us to calculate log *k* for nitro compounds from the training set with sufficient accuracy; models were constructed using some remaining descriptors. Finally, we selected models with the lowest prediction error of log *k* for three nitro compounds from the test set that was unused for previous construction of models. Since we had a rather small data base to enhance the reliability of log *k* prediction, two of the most stable regression models were selected (Eqs. (1) and (2)).

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* For Communication 2, see Ref. 1.

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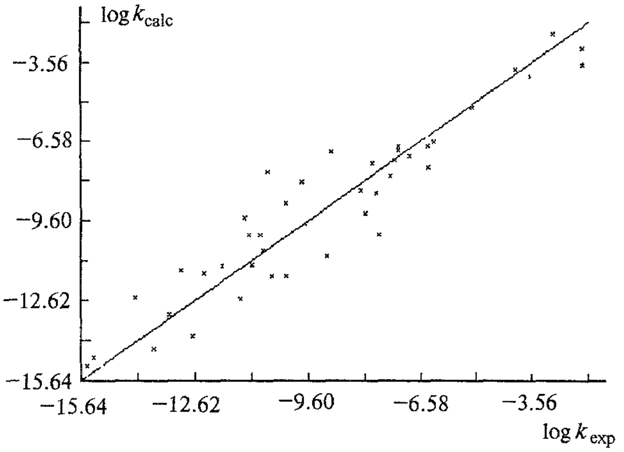


Fig. 1. Scattering diagram of experimental and calculated log *k* (model 1) for the training set consisting of 39 nitro compounds of different chemical classes.

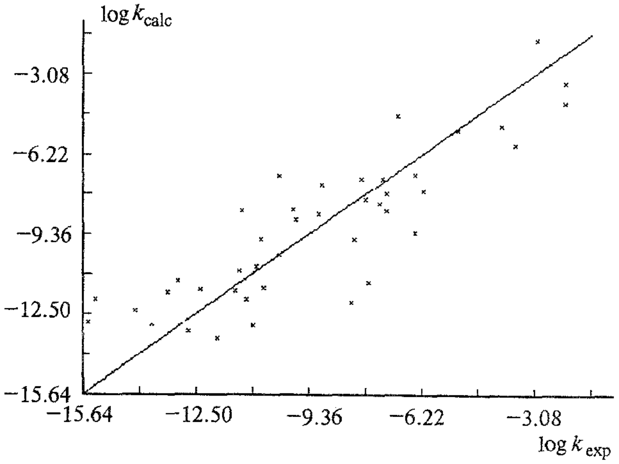


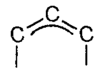
Fig. 2. Scattering diagram of experimental and calculated log *k* (model 2) for the training set consisting of 39 nitro compounds of different chemical classes.

The results of seaching for "structure—log *k*" correlations for these two models are shown in Figs. 1 and 2. Model 1 is constructed on the basis of 7 descriptors and is represented by the equation

$$\log k = -20.62 + 7.85(n^+/n^-)^2/N_{at} + 1.1S_{pol}/N_{at} + 0.003\sum p - 17.13\sum_{fr_1}(\min q) - 0.40\sum_{fr_2}(\max S_i) - 0.27\max(\sum_{fr_3} S_i) - 1.92\sum_{fr_4}(\min q), \quad (1)$$

$n = 39$, $R = 0.94$, $s = 1.3$, $F = 33.8$, $\Delta = 0.92$,

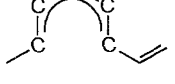
where n is the number of structures in the training set; R is the correlation coefficient; s is the standard deviation; F is the Fischer criterion; Δ is the average square error; N_{at} is the number of nonhydrogen atoms in the molecule (the sum is taken over all fragments (fr) in the molecule); n^+/n^- is the relation between positively and negatively charged atoms in the molecule (hydrogen is ignored)[26]; S_{pol} is the van der Waals surface of the atoms calculated as the sum of the van der Waals surfaces of Cl, O, and N atoms and of H atoms bonded to these atoms; Σp is the sum of nondiagonal elements in the matrix of weakening inductive effect parameters[28]; min$q$ is the smallest charge of atoms in fragment fr$_i$; maxS$_i$ is the highest value of electrotopological states[29] of atoms in fragment fr$_i$. Fragments used in the model are given below:



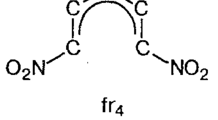
fr$_1$

—N—C—N—N—

fr$_2$



fr$_3$



fr$_4$

Model 2 is constructed on 3 descriptors and represented by the equation

$$\log k = -30.05 + 16.26\text{SDM/NB} + 17.82\text{Diff}\,\delta_\tau - 0.76\sum_{fr}(\max S_i), \quad (2)$$

$n = 39$, $R = 0.854$, $s = 1.87$, $F = 31.5$, $\Delta = 1.46$,

where SDM is the sum of differences of the electronegativities (according to Pouling) for all bonds in the molecule[30]; NB is the number of bonds in the molecule (hydrogen atoms are ignored); Diff δ_τ is the highest differences of the inductive parameter variation τ for all nonhydrogen atoms in the molecule.[28]

Both models allow one to separate out indices of molecular structure related to the atomic charges (indices $(n^+/n^-)^2/N_{at}$, SDM/NB, min$q$, maxS$_i$, *etc.*) and to the van der Waals surface of atoms as the most important descriptors. The presence of the latter descriptor in the model of "structure—log *k*" correlation for nitro compounds in the solid phase has an obvious physical meaning since this descriptor characterizes the effeciency of package of molecular crystals. Thus separated descriptors allow one to determine the important parameters of molecular structure that are in many ways responsible for the mechanism of the homolysis of chemical bonds during thermal decomposition of nitro compounds.

The results of log *k* calculation obtained by the best "structure—log *k*" models 1 and 2 for nitro compounds from the training set are represented in Table 1.

From comparison of the experimental and calculated data it follows that model 1 permits one to estimate the rate constants of homolysis of C—N and N—N bonds with higher accuracy than model 2.

The biggest errors in log *k* calculations were obtained for following nitro compounds (models 1 and 2, respectively): 1,3,5,7-tetranitro-1,3,5,7-tetraazacyclooctane — 2.00 and 1.61; α,β-bis(2,4,6-trinitrophenyl)-

Table 1. Experimental and calculated log *k* of homolysis of nitro compounds in the solid state (from the training set)

Compound	Empirical formula	−log*k*			References
		calculated		experimental	
		model 1	model 2		
1,4,5,8-Tetranitroso-1,4,5,8-tetraazadecaline	$C_6H_{10}N_8O_4$	2.5	1.7	3.0	3
1,5-Endomethylene-3,7-dinitroso-1,3,5,7-tetraazacyclooctane	$C_5H_{10}N_6O_2$	3.8	5.0	4.0	3
Methylenedinitramine	$CH_4N_4O_4$	3.6	4.1	2.2	4
Potassuim monomethylnitraminate	$KCH_3N_2O_2$	8.5	7.9	7.8	4
Potassuim ethylenedinitraminate	$K_2C_2H_4N_4O_4$	8.1	8.3	9.8	4
N,N-Dimethylnitramine	$C_2H_6N_2O_2$	9.6	8.7	9.7	5,6
1,3,5,7,9-Pentanitroazanonane	$C_5H_{12}N_{12}O_{12}$	4.0	5.8	3.6	4
1,4-Dinitro-1,4-diazacyclohexane	$C_4H_8N_4O_4$	7.9	8.1	7.4	7
1,3,5,7-Tetranitro-1,3,5,7-tetraazacyclooctane	$C_4H_8N_8O_8$	7.0	7.3	9.0	8,9
1,5-Endomethylene-3,7-dinitro-1,3,5,7-tetraazacyclooctane	$C_5H_9N_6O_4$	7.3	7.1	7.3	7
1,5-Diacetyl-3,7-dinitro-1,3,5,7-tetraazacyclooctane	$C_6H_{10}N_6O_8$	7.1	4.6	6.9	10
1,4-Dinitrotetrahydroimidazo-[4,5-*d*]imidazol-2,5(1*H*,3*H*)dione	$C_4H_2N_6O_6$	6.6	7.6	6.2	10
1-(Methylnitramino)-2,4,6-trinitrobenzene	$C_7H_5N_5O_8$	9.9	8.5	9.1	6
Pentaerythritol tetranitrate	$C_5H_8N_4O_{12}$	6.7	7.0	6.4	11
Hexanitroethane	$C_2N_6O_{12}$	3.0	3.4	2.2	11
3,3′-Dimethyl-2,2′,4,4′,6,6′-hexanitrodiphenyl	$C_{14}H_8N_6O_{12}$	9.3	9.5	8.1	12
2,2′,4,4′,6,6′-Hexanitrodiphenylmethane	$C_{13}H_6N_6O_{12}$	7.5	9.1	6.4	13,14
α,β-Bis(2,4,6-trinitrophenyl)ethane	$C_{14}H_8N_6O_{12}$	7.7	9.5	9.7	13,14
2,2′4,4′,6,6′-Hexanitrostilbene	$C_{14}H_6N_6O_{12}$	9.1	12.9	9.9	15
1,3,5-Trihydroxy-2,4,6-trinitrobenzene	$C_6H_3N_3O_9$	9.1	8.4	11.2	15,16
1,3-Diamino-2,4,6-trinitrobenzene	$C_6H_5N_5O_6$	9.4	9.7	11.3	15
1,3,5-Triamino-2,4,6-trinitrobenzene	$C_6H_6N_6O_6$	8.9	9.2	9.2	15
2,2′4,4′6,6′-Hexanitrooxanilide	$C_{14}H_6N_8O_{14}$	9.7	9.6	9.8	15
2,2′4,4′,6,6′-Hexanitrodiphenylamine	$C_{12}H_5N_7O_{12}$	11.1	11.9	11.1	13,14
3,3-Diamino-2,2′,4,4′,6,6′-hexanitrodiphenyl	$C_{12}H_6N_8O_{12}$	11.7	11.4	9.6	17
2,4,6-Tris(2,4,6-trinitrophenylamino)-1,3,5-triazine	$C_{21}H_9N_{15}O_{18}$	11.4	11.2	13.0	15
2,4,6-Tris(3-methyl-2,4,6-trinitrophenylamino)-1,3,5-triazine	$C_{24}H_{15}N_5O_{16}$	6.9	8.4	7.2	13,14
2,2′,4,4′,6,6′-Hexanitrodiphenylsulfide	$C_{12}H_4N_6O_{12}S$	11.6	7.0	9.2	18
2,2′,4,4′,6,6′-Hexanitrodiphenylsulfone	$C_{12}H_4N_6O_{13}S$	9.1	11.2	7.7	19
2,2′,2″,4,4′,4″,6,6′,6″-Nonanitro-*m*-terpenyl	$C_{18}H_5N_9O_{18}$	12.4	12.3	14.2	16
2,2′,2″,4,4′,6,6′,6″-Octanitro-*m*-terpenyl	$C_{18}H_6N_8O_{16}$	15.1	12.8	15.5	21
2,4,6-Tris(2,4,6-trinitrophenyl)-1,3,5-triazine	$C_{24}H_9N_9O_{18}$	14.7	11.9	15.3	21
1,4,5,8-Tetranitronaphthalene	$C_9H_4N_4O_8$	13.9	13.1	12.7	14,22
Benzotrifuroxane	$C_6N_6O_6$	11.6	11.5	12.4	23
1,3,7,9-Tetranitrodibenzo-1,3a,4,6a-tetraazapentalene	$C_{12}H_4N_8O_8$	14.1	12.8	13.7	15
1,3,8,9-Tetranitrodibenzo-1,3a,6,6a-tetraazapentalene	$C_{24}H_9N_9O_{18}$	11.3	13.4	11.9	15
1,3,7,9-Tetranitrophenothiazine-5,5-dioxide	$C_{12}H_5N_5O_{10}S$	13.1	11.6	13.3	15
Potassium picrate	$KC_6H_2N_3O_7$	12.5	11.6	11.4	19
Potassium 2,2',4,4',6,6'-hexanitrodiphenylaminate	$KC_{12}H_4N_7O_{12}$	8.4	12.0	8.2	7,13

ethane — 2.93 and 1.1; and 2,2',4,4',6,6'-hexanitrodiphenylsulfone— 2.43 and 3.56.

Ethylenenitramine (**1**), *trans*-1,4,5,8-tetranitro-1,4,5,8-tetraazadecaline (**2**), and 1,3,5-trinitro-1,3,5-triazacyclohexane (**3**) were selected as test compounds for estimation of the prediction ability of the models. For compound **1** the values of log *k* calculated by models 1, 2 and that experimentally obtained are −5.27, −5.20, and −5.2 (see Ref. 7), respectively. For compound **2** these values are −6.81, −7.70, and −7.9 (see Ref. 24), respectively. For compound **3** they are −7.44 (model 1), −7.9 (model 2), and −7.9 (see Ref. 18).

Good agreement between experimental and calculated values of the rate constants of homolysis for nitro compounds from the test set indicates a high prediction capability of the proposed "structure—log *k*" models. This proves the possibility of effective application of the QSPR method for the estimation and the prediction of studied parameter of thermal stability of nitro compounds of different chemical classes in the solid state.

Analyzing the QSPR approach for revealing the "structure—rate constant of homolysis" relationship for nitro compounds in different states of aggregation, the presence of descriptors related to the electrotopological state of the atoms in fragments should be noted in each model (see Refs. 1, 2, present paper). This permits one to select these indices as important descriptors determining the relationship between the molecular structure and the parameter studied. As a whole, the best "structure—log *k*" correlation was found for nitro compounds in the gas phase, where intermolcular interactions and effects of the crystal field are negligible.

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