Aqueous High-Temperature Chemistry of Carbo- and Heterocycles. Part 1. Introduction and Reaction of 3-Pyridylmethanol, Pyridine-3-carboxaldehyde, and Pyridine-3-carboxylic Acid

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Aqueous High-Temperature Chemistry of Carbo- and Heterocycles. 1. Introduction and Reaction of 3-Pyridylmethanol, Pyridine-3-carboxaldehyde, and Pyridine-3-carboxylic Acid

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A standard set of conditions for the study of the aquathermolysis of carbo- and heterocyclic compounds are defined. Pyridine and 3-methylpyridine are stable at 250 °C, but pyridine-3-carboxylic acid, pyridine-3-carboxaldehyde, and 3-pyridylmethanol all undergo cleavage to form pyridine with the release of CO_2, HCO_2H, and HCHO, respectively. These 3-substituted pyridines also all undergo reduction by HCO_2H and/or HCHO to give finally 3-methylpyridine. 3-Pyridylmethanol disproportionates to the aldehyde and 3-methylpyridine, and the aldehyde and methanol subsequently undergo an aldol-type condensation to afford bis(3-pyridyl)methane and 1,2-(bis-3-pyridyl)ethane after further transformations. The aqueous geochemical implications of this chemistry to maturation of source rock kerogens are discussed.

Introduction to the Present Series of Papers

Thermal transformations of organic compounds in aqueous environments are of great interest and importance. Most of the world's fossil fuel resources have been naturally formed and modified under such conditions; however, a detailed interpretation of the pathways is lacking. The potential economic incentives for conversion and upgrading of fossil fuels by aqueous treatment rather than by conventional hydrogen treatment is enormous. Despite this scientific and economic importance, published work on the chemical reactions of organic compounds in water at temperatures of 200–400 °C is sparse and fragmentary. It was to fill this gap in the literature that the investigations to be described in this and subsequent papers were planned and executed. The project is a joint collaboration between groups at the University of Florida and at Exxon Research and Engineering Co. The present series of papers will cover reactions of cyclic compounds, while a cognate series will deal mainly with aliphatic derivatives.

Soon after this work commenced it became apparent that a rich variety of reactions took place with many of the common organic functional groups in water at temperatures above 200 °C. Some of the reactions are purely thermal, but most require water as a reagent or catalyst. The latter type include acid–base, oxidation–reduction, condensation, and disproportionation reactions. In many cases trains of successive reactions were encountered and equilibria appeared to be established.

Introduction

This paper explains the general methods employed and reports the results obtained with a set of 3-pyridyl derivatives in which the 3-substituent in the pyridine ring contains a single carbon atom together with variable numbers of oxygen and hydrogen atoms.

Our main objective was to uncover the general pattern of reactivity of the common, naturally occurring functional groups. This was intended to provide a scientific base to allow an understanding of the geological formation of fossil fuel resources (diagenesis), of the generation of petroleum from these resources (catagenesis), and of how to modify fuel stocks intelligently. Given the above considerations, we approached the objective by successively focusing on relatively small groups of substituted compounds where information obtained from one of the groups would be of general value in interpreting reactions of other members of the group. For example, the family of organic carboxylic acids, aldehydes, and alcohols was chosen for these studies because it is probably the most prevalent redox system in organic resource materials and their precursors. During diagenesis of algal matter and other lower plant life, structures containing pyridine rings undergo transformations in an anoxic aqueous environment and are incorporated into the kerogen matrix. Pyridine compounds are the most abundant heteroatom containing species in oils produced from Green River oil shale by retorting and represent about 2% (by weight) of the total oil.[1] These molecules are also important components of oils generated from other oil shales. The rings found in the oil shale frequently contain one or two methyl groups and some have a longer alkyl side chain, and we postulate that they are largely derived by thermal cleavage of diarylethane cross-links in the kerogens.[2]

High-Temperature Water. High-temperature water provides a more favorable reaction medium than boiling water at atmospheric pressure for organics. The dielectric constant of water drops rapidly with temperature and water in equilibrium with its vapor has at 0, 200, and 300 °C dielectric constants that are respectively 88.4, 34.3, and 20.0.[3] This means that organic compounds become much

(1) Aczel, T., Ed. *Mass Spectrometric Characterization of Shale Oils*; ASTM Special Technical Publication No. 902; ASTM: Philadelphia, 1986.

(2) Scouten, C. G.; Siskin, M.; Rose, K. D.; Aczel, T.; Colgrove, S. G.; Pabst, R. E., Jr. *Prepr.—Am. Chem. Soc., Div. Pet. Chem.* **1986,** *10,* 295.

(3) Quist, A. S.; Marshall, W. L. *J. Phys. Chem.* **1965,** *69,* 3165.

more soluble as the water temperature is increased.[4,5]

The equilibrium pressure of water[6] rises to 576.6 psi at 250 °C and 2397.8 psi at 350 °C. The critical temperature of water is 374 °C. The temperatures used in most of the present work did not exceed 250 °C, and all these aqueous reactions were thus run in liquid water. On the other hand, the critical temperature of cyclohexane is 280 °C and we recognize that this could be lowered by the addition of the reactants. Hence it is possible that reactions at 250 °C may have been run under supercritical conditions.

Experimental Section

Experimental Approaches. Our standard procedure for initial experiments on a particular compound was heating it for 5 days (120 h) at 250 ± 5 °C. When less than 1% of reaction occurred, a subsequent run was carried out for shorter times at elevated temperature, e.g., 2–3 days at 350 ± 5 °C. Conversely, if more than 25% reaction was found over 5 days at 250 °C, then another run was carried out for, e.g., 1 day at 250 °C, or (if more than 80% had reacted) for even shorter reaction times at lower temperature, e.g., 1 day at 200 or 150 °C.

All reactions at 250 °C, or below, were carried out in a glass-lined 22-mL 303 SS screw cap Parr bomb. The reactions at higher temperatures were carried out in stainless steel tubing bombs (12.5 mL). Detailed description of the tubing bomb design and technique can be found elsewhere.[7] In both cases, heat was supplied by a fluidized sand bath.

In all aqueous reactions deoxygenated water was used; it was freshly prepared by bubbling nitrogen through distilled water for 1 h. The reaction mixtures were prepared under an inert atmosphere and blanketed with argon before each bomb was sealed. In all cases, parallel runs were carried out with cyclohexane in place of water, to identify thermal reactions. In consideration of the pressures building up inside the bombs, and to allow for the thermal expansion of water (25 vol % at 250 °C, 73 vol % at 350 °C), the amounts of the materials were chosen as 7.0 mL of water or cyclohexane, with 1.0 g of (99%+) pure compound being investigated. Reaction products were analyzed by GC and identified by GC/MS.

Experiments. Determination of the flame ionization detector (FID) response of all standard compounds was done on a Hewlett-Packard HP 5890 gas chromatograph equipped with FID and split injection port. A capillary column, "Supelco" SPB-1, 15 m long was used with a split ratio of 30:1.

The flow rates of helium carrier gas, hydrogen, and air for FID at room temperature were 5, 30 and 400 mL/min, respectively. The injector temperature was 200 °C. All injections were made with the use of a temperature program of 35 °C for 1 min, followed by heating at 20 °C/min up to 250 °C. The volume of the sample injected was 1 μL with a concentration of about 2 μg/μL.

The chemicals were from various sources (Aldrich, Fisher, Reilly Industries, Mallinckrodt, Kodak, TCI, Fluka). All starting materials were analyzed by GC before use and purified until the impurity level was well below 1%, and preferably below 0.1%. Standard solutions containing ca. 100 mg of each compound in 50 mL of ether or methanol were used to prepare a range of mixtures. These were examined on the MS system to ensure there was no peak overlap. The following workup procedure was applied to all the runs carried out with water. The reaction bombs were allowed to cool to room temperature, after which they were carefully opened in an inert atmosphere. When homogeneous aqueous solutions were produced, direct injection into the GC was possible. In all other cases the entire mixture was transferred into a jar equipped with a Teflon stir bar. The walls of the glass liner, the bomb, and the cap were rinsed with 10 mL of diethyl ether or CCl₄. In cases where appreciably water soluble hetero-

(4) Rabenau, A. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 1026.
(5) Gangoli, N.; Thodos, G. *Ind. Eng. Chem., Prod. Res. Dev.* **1977**, *16*, 208.
(6) Keenan, J. H.; Keyes, F. G. *Thermodynamic Properties of Steam*; Wiley: New York, 1936.
(7) Maa, P. S.; Neavel, R. C.; Vernon, L. W. *Ind. Eng. Chem. Process Des. Dev.* **1984**, *23*, 242.

Table I. Structure and Identification of Starting Materials and Products

no.	t_R, min	structure	mol wt	equiv wt	identification basis	response factor
1	0.50	PyH	79	79	Table II	0.80
2	1.00	3PyCH₃	93	93	Table II	0.83
3	2.01	3PyCHO	107	107	Table II	0.60
4	3.78	3PyCH₂OH	109	109	Table II	0.55
5	9.03	3PyCO₂H	123	123	Table II	0.25
6	9.27	3PyCH₂Py3	170	85	Table IV	0.68
7	10.54	3PyCH₂CH₂-Py3	184	92	Table IV	0.67
8	11.85	3PyCH=CHPy3	182	91	Table III	0.67

Table IV. Identification of Products from Mass Spectral Fragmentation Patterns

no.	compound	MW	fragmentation pattern m/z (% relative intensity, structure of fragment ion)
6	3PyCH₂Py3	170	170 (100, M); 169 (80, M – 1); 142 (20, M – HCN – H); 115 (20, M – 2HCN – H); 92 (15, 3PyCH₂)

cycles were used as starting materials, methanol was added to give a homogeneous mixture. This wash was then added to the reaction mixture in the jar. The jar was blanketed with a purge of argon and sealed. The contents were magnetically stirred overnight at ambient temperatures. After the phases were allowed to separate, the organic layer was separated and both layers were analyzed by GC. If an acid or a base that might damage the column, was present, the organics that remained in the aqueous phase were extracted with 2 × 5 mL of solvent (ether or CCl₄) and the organic phases were combined and analyzed by GC.

For cyclohexane reactions only 5 mL of cyclohexane was used to wash the liner and the inside of the bomb and that mixture was analyzed by GC. If, after the overnight stirring, solids were found, the entire mixture was centrifuged at 2000 rpm for 30 min in a sealed, argon-blanketed tube to facilitate separation. After separation of the liquid from the solid phase by pipetting, the solid was analyzed by GC, GC/MS, or MS and elemental analysis, IR, and NMR where applicable.

Conversion Yields and Material Balance. All conversions and yields are given in terms of moles as a percentage of moles of starting material. The GC peak areas were corrected for response factors[8] and then normalized. To achieve this, the area of each peak from the electronic integrator of the flame ionization detector signal was divided by its response factor to get the true area. For details on estimation of FID response factors see the Appendix. The conversion of the areas to molar units was done by use of an equivalent weight factor (Table I). The experiments were duplicated and found to be reproducible within ±5%.

Product Identification. Products were identified in most cases by MS. This was achieved at three levels of decreasing reliability:

(a) The first level was by direct comparison of the MS fragmentation pattern with that of the authentic compound obtained under essentially the same MS operating conditions. The major features of the MS are reported, together with a literature reference to the MS of the compound (if available) (Table II).

(b) The next level was by comparison of the MS fragmentation pattern with that for the same compound in a database or other literature source. In such cases the source of the reference spectrum is always given, and the major features of both the experimental and the reference spectra are recorded (Table III). Tables II and III are available as supplementary material (see paragraph at end of paper regarding supplementary material).

(c) The last level was by interpretation of the MS fragmentation pattern. Where the authentic compound was not available, and the spectrum had not been reported elsewhere, identification had to be based on the MS fragmentation pattern. In such cases the basis on which the assignment was made is explained (Table IV).

(8) Musumarra, G.; Pisano, D.; Katritzky, A. R.; Lapucha, A. R.; Luxem, J. F.; Murugan, R.; Siskin, M.; Brons, G. *Tetrahedron Comput. Methodol.* **1989**, *2*, 17.

Table V. Aquathermolysis of Pyridine-3-carboxylic Acid (5) and Its Sodium Salt

compound		3PyCO₂H (5)					3PyCO₂Na	
solvent		C_6H_{12}	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
additive (1 mol equiv)				HCO_2H	H_3PO_4	H_3PO_4		
temp, °C		250	250	250	200	250	150	200
time, h		120	120	120	24	120	24	24
no.	structure							
1	PyH	2.0	52.0	96.9	25.8	100	1.9	4.1
2	3PyCH₃			3.1	0.1		0.1	0.3
5	3PyCO₂H	98.0	48.0		74.0		98.0	95.6

Table VI. Aquathermolysis of Pyridine-3-carboxaldehyde (3) (3PyCHO)

	solvent	C_6H_{12}	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
	additive (1 mol equiv)		3PyCH₃		3PyCH₃	HCHO	HCHO	HCO_2H	HCO_2H	H_3PO_4	H_3PO_4
	temp, °C	250	250	250	250	200	250	200	250	200	250
	time, h	120	120	120	120	24	120	24	120	24	120
no.	structure										
1	PyH	0.7	0.7	53.2	16.7	7.3	55.5	2.6	7.0	2.2	87.0
2	3PyCH₃		19.4	8.1	43.5	31.5	26.3	47.0	38.9	0.1	13.0
3	3PyCHO	99.3	80.0	27.6	27.8	0.8	1.6	1.4	0.6	81.4	
4	3PyCH₂OH			2.2	5.7	51.2	4.5	49.0	32.3	0.2	
5	3PyCO₂H									16.0	
6	3PyCH₂Py3				3.3	1.1	4.0	5.1	7.7		
7	3PyCH₂CH₂Py3				5.6	2.2	5.2	6.9	13.4		
8	3PyCH=CHPy3				2.9						

Mass Spectral Assignments by Method C. In the case of bis(3-pyridyl)methane (6), the molecular ion was observed at m/z 170 of 100% relative intensity (r.i.). The next steps in the fragmentation pattern were a peak obtained by loss of a hydrogen atom at m/z 169 (80% r.i.) and two peaks from the loss of one or two molecules of HCN from the M − 1 ion (m/z 142 (20%) and m/z 115 (20%), respectively). A peak at m/z 92 (15% r.i.) due to 3PyCH₂⁺ was also observed.

Results and Discussion

The 3-Pyridyl System. An early objective was to define the behavior of the common single carbon functional groups attached to a benzenoid or heteroaromatic ring. We consider first the 3-pyridyl family, the interpretation of which is simpler than either that for the common phenyl compounds (where the ring is much more susceptible to electrophilic substitution) or those for the analogous 2- and 4-pyridyl series (where the α-CH of the functional group is more activated toward hydrogen loss).

Compounds studied were 3-methylpyridine, 3-pyridylmethanol, pyridine-3-carboxaldehyde, and pyridine-3-carboxylic acid, together with pyridine itself. Table I records gas chromatographic behavior of all the compounds encountered in this work, either as starting materials or as products. Results are collected in Tables V, VI, and VII, and the transformations are shown schematically in Scheme I. The products were identified by procedures a (Table II), b (Table III), or c (Table IV) as described above. Tables II and III have been deposited as supplementary material.

In addition to the thermolyses of the above single compounds in water and cyclohexane, some additional experiments were carried out: (a) certain compounds were taken in pairs; (b) certain compounds were heated with 1 mol equiv of formaldehyde, formic acid, or phosphoric acid; (c) certain compounds suspected of being products (and/or intermediates) were synthesized and studied (not done in the present paper, but in others of the series).

Pyridine and 3-Methylpyridine. These compounds are completely unreactive at 250 °C, and even at 350 °C for 3 days in water without any additives, no reaction products could be detected.

Pyridine-3-carboxylic Acid (5) (Table V). At 250 °C for 5 days in H₂O, 52% of decarboxylation to pyridine (1) is found. Water, which can act as an acid or a base (−log

Scheme I
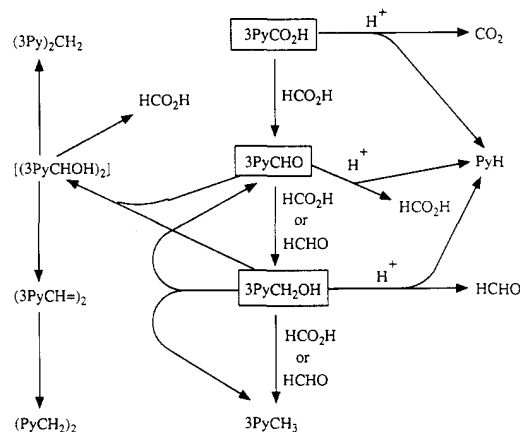
K_w = 11.20 at 250 °C),[9] clearly catalyzes this decarboxylation which probably occurs via the zwitterion as only 2.0% is found in cyclohexane. The decarboxylation reaction is catalyzed by the addition of 1 mol equiv of acid. It is complete in the presence of H₃PO₄ after 5 days at 250 °C and already well advanced after 1 day at 200 °C. The sodium salt also decarboxylates more rapidly than the free acid (Table V). Clearly a protonated nitrogen is a considerable advantage in this reaction through its stabilization of the intermediate C-3 anion which results from the loss of carbon dioxide. The carboxylate anion would react more rapidly than the un-ionised acid—the reaction of the sodium salt confirms this. Thus, it seems likely that for the simple aqueous solution of the acid decarboxylation takes place from the portion of the substrate that is in the zwitterion form. Addition of acid increases the proportion of the protonated form, and use of the salt increases the proportion of carboxylate anion available. In the presence of formic acid, a small but significant amount (3.1%) of reduction of 3-picoline (2) is observed, presumably via the intermediate formation of 3PyCHO and 3PyCH₂OH.

Pyridine-3-carboxaldehyde (3) (Table VI). Extensive kinetic studies have previously been made of the

(9) Marshall, W. L.; Franck, E. U. *J. Phys. Chem. Ref. Data* **1981**, *34*, 43.

Table VII. Aquathermolysis of 3-Pyridylcarbinol (4) (3PyCH₂OH)

no.	structure	C₆H₁₂	C₆H₁₂ 3PyCH₃	C₆H₁₂ 3PyCHO	H₂O	H₂O 3PyCH₃	H₂O 3PyCHO	H₂O HCHO	H₂O HCHO	H₂O HCO₂H	H₂O H₃PO₄	H₂O H₃PO₄	H₂O H₃PO₄
solvent additive (1 mol equiv)	temp, °C	250	250	250	250	250	250	250	250	250	150	200	250
	time, h	120	120	120	120	120	120	24	120	120	24	24	120
1	PyH	0.5	0.7	0.4	0.3	0.3	30.3	2.7	10.4	0.1	0.1	0.4	5.6
2	3PyCH₃	1.8	37.3	3.5	4.1	35.4	30.8	15.1	39.3	42.1	0.9	0.9	94.4
3	3PyCHO	2.4	2.0	58.5	2.3	0.6	21.1	5.6			0.5	3.2	
4	3PyCH₂OH	95.3	60.0	37.5	93.3	63.6	11.7	76.6	34.6	57.7	98.1	90.7	
5	3PyCO₂H											0.4	4.8
6	3PyCH₂Py3						2.7		4.2				
7	3PyCH₂CH₂Py3						3.3		11.6				

acid-catalyzed decarbonylation of aromatic aldehydes.[10] Reaction was shown to proceed via the hydrate and to give formic acid as the by-product. For pyridine-3-carbox-aldehyde, the dominant reaction in water is the formation of pyridine (53%) (and presumably formic acid). This reaction takes place to a small extent in cyclohexane and is strongly inhibited by 3-methylpyridine (2), unaffected by formaldehyde, and strongly catalyzed by phosphoric acid. The sequence in eq 1 follows the earlier studies and

$$\text{3PyCHO} \xrightarrow{i} \text{3PyCH(OH)}_2 \xrightarrow{ii} \xrightarrow{iii} + \text{HCO}_2\text{H} \quad (1)$$
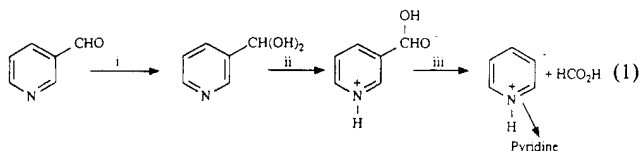
would explain all of this behavior. Water is needed for step i and in the presence of 3-methylpyridine, a stronger base, the pyridine nitrogen would not become protonated in step iii; this protonation would be strongly enhanced in acid media.

A considerable amount of 3-methylpyridine is also produced from pyridine-3-carboxaldehyde and water with a much smaller quantity of 3-pyridylmethanol (4) (2.2%). That the major source of the 3-methylpyridine is reduction of the aldehyde by the formic acid formed in eq 1 is strongly supported by the greater amount of 3-methyl-pyridine (38.9%) formed by pyridine-3-carboxaldehyde in the presence of formic acid. The reduction in the amount of pyridine formed from 3PyCHO/HCO₂H is probably not because of inhibition of the reaction of eq 1, but simply because of rapid reduction to 3PyCH₂OH and hence to 3PyCH₃. This behavior is even more marked in the ex-periment carried out at 200 °C for 1 day. In the pyri-dine-3-carboxaldehyde and formaldehyde experiments, the reduction is evidently slower, and eq 1 is not suppressed at 250 °C; however at 200 °C, a large amount of 3PyCH₂OH is formed by the reduction of 3PyCHO by HCHO.

The origins of the bimolecular compounds (numbers 6, 7, and 8 in Table VI) are discussed below.

3-Pyridylmethanol (4) (Table VII). The dominant reaction in water with 3-pyridylmethanol can be expressed as in eq 2, producing 3PyCH₃, 3PyCHO, and pyridine. In

$$\text{3PyCH}_2 \cdots \text{3Py—CH—O} \longrightarrow \text{3PyCH}_3 + \text{3PyCHO} \longrightarrow \text{PyH} + \text{HCO}_2\text{H} \quad (2)$$
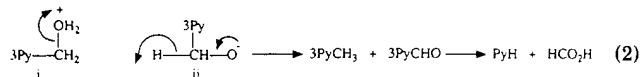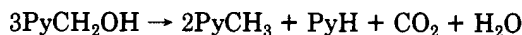
the presence of formic acid or formaldehyde, component ii is supplemented by these hydride ion donors (HCO₂⁻ and HCH(OH)O⁻) and the yield of 3-methylpyridine increases dramatically. The yield of pyridine also increases in the presence of formaldehyde but not formic acid: this occurs

because formaldehyde can also act as a hydride ion ac-ceptor, taking the place of component i in eq 2 to give first pyridine-3-carboxaldehyde. The acidic medium helps the decomposition 3-PyCHO → PyH + HCO₂H (autocatalytic) (cf. eq 1). In the strongly acidic H₃PO₄ medium, the products are 3-methylpyridine and pyridine, probably by a mechanism similar to eq 3
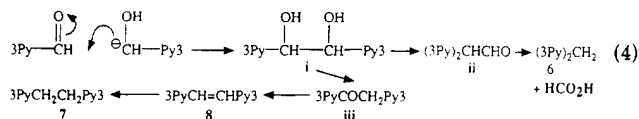
$$\xrightarrow{} + \text{HCHO} \xrightarrow{\text{3PyCH}_2\text{OH}} \text{3PyCH}_3 + \text{CO}_2 \quad (3)$$
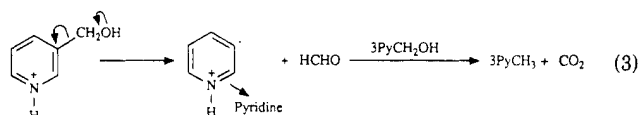
with overall stoichiometry

$$\text{3PyCH}_2\text{OH} \rightarrow \text{2PyCH}_3 + \text{PyH} + \text{CO}_2 + \text{H}_2\text{O}$$

The influence of 3-methylpyridine on the reactions of pyridine-3-carboxaldehyde and 3-pyridylmethanol is not clear. It dramatically increased the production of 3-methylpyridine from both substrates in cyclohexane and in water. Further investigations into this problem are currently under way.

Bimolecular Products. The bimolecular products (6-8) may reasonably be formed by a reaction sequence of the type shown in eq 4. In this sequence, compound

$$\text{3Py—CH} \cdots \text{CH—Py3} \xrightarrow{i} \text{3Py—CH—CH—Py3} \xrightarrow{ii} \text{(3Py)}_2\text{CHCHO} \rightarrow \text{(3Py)}_2\text{CH}_2 \quad (4)$$
$$\text{3PyCH}_2\text{CH}_2\text{Py3} \longleftarrow \text{3PyCH=CHPy3} \longleftarrow \text{3PyCOCH}_2\text{Py3} \quad \text{6, +HCO}_2\text{H}$$
$$\text{7} \qquad\qquad\qquad \text{8} \qquad\qquad\qquad \text{iii}$$

i is a common intermediate that undergoes a carbonium ion rearrangement to give ii or elimination of water to give iii. Aldehyde ii could reasonably be cleaved by hydroxide ion attack to give formic acid and bis(3-pyridyl)methane (6). Reduction of ketone iii would give compound 7 and/or 8.

The following evidence supports this mechanism: (a) 7 and 6 are always formed together and their ratio is ap-proximately constant at around 2. (b) Bimolecular prod-ucts are produced from 3PyCH₂OH only in the presence of 3PyCHO or HCHO (which can act as oxidizing reag-ents). (c) Bimolecular products are invariably produced from 3PyCHO, but especially in the presence of HCO₂H, which is an active reducing agent.

Conclusions

The results described in this study are directly appli-cable to understanding how kerogens mature and generate petroleum in an anoxic aqueous environment. Pyridine and methylpyridines are stable end products of matura-tion, and pyridine structures are common in kerogens and oils.[11] They are unreactive under aqueous conditions in the formation. Condensed products containing one and

(10) Schubert, W. M.; Kintner, R. R. In *The Chemistry of the Car-bonyl Group*; Patai, S., Ed.; Interscience: New York, 1966; pp 695–760.

(11) Siskin, M.; Scouten, C. G. Unpublished results.

two methylene groups between pyridyl moieties become major cross-links in kerogens. These are also unreactive under aqueous conditions but are cleaved during thermal treatment to generate methylated derivatives which predominate in the oil. During diagenesis oxygen functionalities such as acids, aldehydes, and alcohols are lost and condensations form methylene bridged cross-links. These reactions release water-soluble products such as carbon dioxide, formic acid, and formaldehyde. In the pore systems of oil-bearing rocks, the acids and aldehydes can act as acid catalysts and autocatalyze diagenesis and subsequent catagenesis chemistry. The aldehydes and alcohols also transfer hydride ions effecting the reduction of oxygen functionalities to alkyl groups and of polycyclic aromatics to their partially hydrogenated hydroaromatic derivatives. As will become clearer in subsequent papers in this series, these reactions are facilitated by the ionic strength of the medium and catalyzed by acidic and basic minerals in the geological formation and by generation of organic acids from the aqueous hydrolysis of, e.g., esters and of ammonia by hydrolysis of nitriles and amides.

Appendix. The Estimation of FID Response Factors

Summary. Extensive work in the field of aquathermolysis required the estimation of unknown response factors so that reaction products could be analyzed quantitatively by the GC/MS technique. We found no readily available and generally applicable published procedure that allowed us to do this. We therefore set out to present our results in a form that we now believe routinely allows a reliable estimation of response factors from molecular structures.[8]

Introduction. The flame ionization detector (FID) is the most widely used GC detector, having achieved great popularity in the early 1960s.[12-14] Rugged FIDs, relatively stable to small changes in operational parameters and with good sensitivity and linearity, are now available. The FID shows similar response factors for all hydrocarbons[15] and also responds to other analytes, while remaining unresponsive to permanent gases or carrier gas impurities. There are however, four key prerequisites to obtaining adequate quantitative analyses: careful sample preparation, precise sample injection, adequate resolution of the mixture, and use of a detector having a known and reliable linear response.[16] The major source of quantitative error when employing syringe injection arises from inaccuracies in delivering a precise and accurate sample volume onto the column. Fortunately, errors resulting from this problem may be overcome by the use of an internal standard. Another major source of error is the selective evaporation of components from the syringe needle, which of course is exacerbated by the use of a high-temperature injection port.[17] This is especially important when samples that contain components having a wide range of volatilities are being injected. Its significance increases when the injection volume is small relative to the needle capacity. To minimize all these problems, special injection techniques should be used (e.g., automatic on-column injection).

A problem that may arise, whenever a split-type injection device is used, is component discrimination that occurs on the basis of volatility caused by a change in split ratio. This seems to be a result of the change in pressure drop associated with the passage of the vaporized components into the column. There may be quite a large viscosity difference between the carrier gas and carrier gas plus sample vapor, and as the sample vapor enters the column, an increase in pressure drop and change in flow rate occur. This will cause a change in split ratio, and the bypass restricter is not exposed to sample vapor coincident with it entering the column or in a balanced manner. It is thought that the solvent vapor is probably the major cause of this effect.

There are three basic methods for processing data for quantitative analysis: the normalization method, the external standard method, and the internal standard method.[16] The normalization method is rarely employed because it requires that the detector gives the same response to all solutes. The internal standard method gives the most precise and accurate results but requires the selection of a standard that is resolved from all the sample constituents. Furthermore, the solutes of interest cannot, themselves, be selected as standards. The external standard method is a little less precise and accurate than the internal standard method but allows the solutes of interest themselves to be used as standards and makes no extra demands on the chromatographic resolution. However, different compounds have different detector responses; therefore, it is necessary to determine correction factors or the so-called response factors (RFs). Two important features of the FID are generally accepted: for hydrocarbons the FID response is proportional to the carbon number of the hydrocarbons, often called the "equal-per-carbon response", and the FID response of substituted hydrocarbons is always less than that of the parent hydrocarbon. The concept of the effective carbon number (ECN) was introduced many years ago[18] and has been proposed also for the calculation of response factors for compounds that cannot be obtained in pure form.[19]

An important factor that must be considered in the study of FID response factors is the performance of the GC instrument. In most earlier studies, packed columns and vaporization injection techniques were used. Accuracy and precision of peak areas were limited by the resolution obtained by use of packed columns. Bleeding of the stationary phase of the column commonly led to broadening and tailing of peaks and poor base lines. Discrimination against both low and high boiling point compounds occurs in the vaporization injection technique. These occurrences adversely affect the accurate evaluation of FID response factors for many compounds.

During the past few years the development of wall-coated capillary column (WCOT) GC (also called high-resolution GC) has resulted in improved quality GC analysis.[20] Also, the introduction of cold on-column injection into WCOT GC has minimized, or completely eliminated, the discrimination gainst both low and high boiling point compounds during sample injection.[21]

The RF value of a compound differs from instrument to instrument. Therefore, in the practical use of RFs for quantitative analysis, the RFs of standard compounds and samples must be determined on the same instrument and

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at the same operation conditions.

In the early 1960s several authors started to explain the mechanism of the response of flame ionization detectors,[18] the response of the detector to different functional groups,[22] and the relative molar response to hydrocarbons[23] or oxygenated aliphatic hydrocarbons.[12-14] However, W. A. Dietz first reported tabular GC responses for FID in 1967.[15] He gave no experimental details, but the correction factors appear to have been calculated by using an equation later utilized by McNair and Bonelli,[24] i.e.

$$RF = \frac{(wt \text{ of stand.})(area \text{ of compd})}{(wt \text{ of compd})(area \text{ of stand.})} \quad (A1)$$

and heptane with RF = 1.00 was used as a standard. The values so obtained are called "divisor RFs": the area of each peak is divided by the relative sensitivity (RF) and then normalized to obtain weight percent.

Recently (1985), J. T. Scanlon and D. E. Willis[19] summarized previous work and proposed the use of the ECN (effective carbon number) concept for the calculation of response factors for compounds not available in pure form. They defined RF as the inverse of eq A1, i.e.

$$RF = \frac{(area \text{ of stand.})(wt \text{ of compd})}{(area \text{ of compd})(wt \text{ of stand.})} \quad (A2)$$

This equation is based on a response factor of 1.0 for the standard (*n*-heptane) and the RFs so obtained are called "multiplier response factors"; i.e., each peak area has to be multiplied by the relative sensitivity (RF) and then normalized to obtain the weight percent. The relative weight response factor can be transformed to the relative molar response factor:

$$RF_{mol} = RF \frac{MW \text{ of stand.}}{MW \text{ of compd}} \quad (A3)$$

The ECN is calculated by

$$ECN_{compd} = \frac{ECN \text{ of stand.}}{RF_{mol} \text{ of compd}} \quad (A4)$$

or

$$ECN_{compd} = \frac{(MW \text{ of compd})(ECN \text{ of stand.})}{(MW \text{ of stand.})RF} \quad (A5)$$

Relative response factors for compounds whose ECN is known or can be calculated from the contributions of the various groups in the molecule are easy to obtain from the equation

$$RF = \frac{(MW \text{ of compd})(ECN \text{ of stand.})}{(MW \text{ of stand.})(ECN \text{ of compd})} \quad (A6)$$

Results and Discussion. The aim of this work was to quantitate the results obtained in the aqueous chemistry project and to understand better the relationships between molecular structure and the response of the flame ionization detector.

The response factors of a large variety of aliphatic, aromatic, and heteroatomic compounds were determined by GC/FID. These compounds cover a wide range of boiling points, molecular weights, and different substituents attached to the aromatic ring. The use of the ECN concept gave us large discrepancies between calculated and obtained response factors, especially for polar and/or high-boiling derivatives. Therefore, we have applied eq A1 for the calculations and have chosen hexane as a reference with RF = 1.00. The data have been treated by the partial least-squares (PLS) method, using as explanatory variables the molecular weight together with structural features such as the numbers of each element and of multiple bonds, functional groups, etc. As a result of the foregoing treatment, RF values can now be predicted from the PLS model parameter relationship and the details can be found elsewhere.[8]

Supplementary Material Available: Table II listing properties and mass spectral data of starting materials and Table III comparing experimental and literature mass spectral fragmentation data of products (2 pages). Ordering information is given on any current masthead page.

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