

Carbathoxynitrene by α -Elimination.

Reactions with Hydrocarbons^{1,2}

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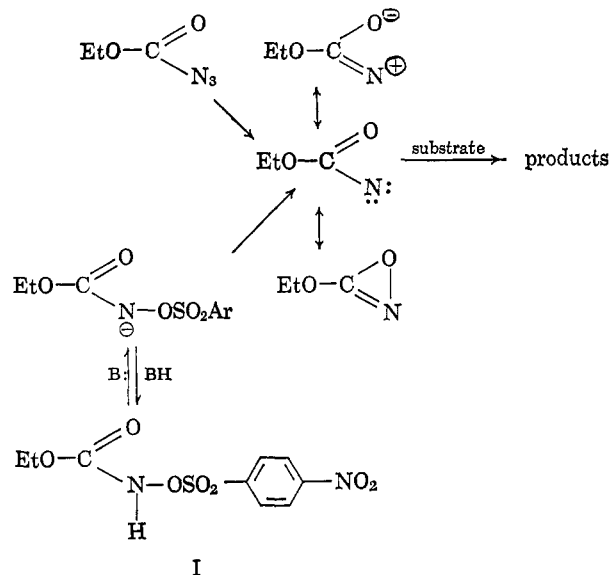
Carbathoxynitrene, EtOOCN , can be generated by α -elimination from the anion of *N-p*-nitrobenzenesulfonyurethan (I). The product mixtures produced with isopentane, cyclohexane, cyclohexene, and benzene are the same as those produced by photolytic decomposition of ethyl azidoformate in these substrates. Insensitivity toward dilution shows that the reactive intermediate is not in a vibrationally excited state.

Introduction

The transient formation of carbalkoxynitrene, ROCON , in the decomposition of alkyl azidoformates, ROCON_3 , has recently been reported.^{1,2,4-9} However, a general difficulty exists in determining the mechanism of any given decomposition of an azide. The same products might be formed by nitrenes and by azides,^{5,6,10} the mechanisms differing in whether the nitrogen is lost before or after attack on the substrate. For example, the formation of diethyl azodiformate in the decomposition of concentrated solutions of ethyl azidoformate^{11,12} is easily formulated as a nitrene reaction, but closer study seems to indicate that the whole azide group is involved. Also, some olefins accelerate the rate of decomposition of azides (presumably through interaction of the azide group with the double bond) while others do not.¹⁰ In the latter cases, loss of nitrogen prior to reaction with the olefin is assumed.^{6,10} In photolysis reactions, the rate of nitrogen evolution cannot be used as a criterion, because the light flux will determine this rate as long as quantum yield and experimental conditions remain constant.

To shed more light on the mechanism of the photolysis of ethyl azidoformate and on the nature of the presumed reactive intermediate, we have studied the base-induced decomposition of *N-p*-nitrobenzenesulfonyurethan (I), a compound that contains only a single nitrogen atom. α -Elimination of *p*-nitrobenzenesulfonate ion from the anion of I should lead to the same

carbathoxynitrene that is obtained from the azide (although the nitrenes should at least initially be of different vibrational energy). If, in a variety of substrates,



both the α -elimination and the azide routes gave identical product mixtures, a common intermediate would be indicated. In this paper, we wish to report such comparative studies with the substrates cyclohexane, isopentane, cyclohexene, and benzene.

Results and Discussion

N-p-Nitrobenzenesulfonyurethan (I) was prepared from *N*-hydroxyurethan and *p*-nitrobenzenesulfonyl chloride in 55% yield, together with *N,O*-di-*p*-nitrobenzenesulfonylhydroxyurethan (II). I is soluble in the more polar of organic solvents, and is converted to its anion by weak bases, such as sodium bicarbonate solution or triethylamine. The anion, in hydrocarbon solution, has a half-life of approximately 25 sec. at room temperature. Complete decomposition requires several hours in solutions that contain equimolar quantities of I and triethylamine because the equilibrium favors I over its anion. The N-H proton can be exchanged for deuterium with high recovery. The triethylammonium salt of I is isolable, but unstable at room temperature. It is a yellow solid. I decomposes in the presence of base, such as triethylamine, butylamine, or methoxide, to give the salt of *p*-nitrobenzenesulfonic acid and products resulting from attack of the nitrene EtOCON on the solvent or solvents, as described below. C-H bonds on carbons bearing electron-withdrawing substituents are attacked only slowly, so that dichloromethane and nitromethane can be used as solvents in most cases.

Solvolysis of I in boiling methanol is very slow. When 1 equiv. of benzoyloxy radicals was generated in

(1) Communicated in part: W. Lwowski, T. J. Maricich, and T. W. Mattingly, Jr., *J. Am. Chem. Soc.*, **85**, 1200 (1963).

(2) W. Lwowski and T. J. Maricich, *ibid.*, **86**, 3164 (1964).

(3) National Institutes of Health Predoctoral Fellow, 1963-1965; National Science Foundation Summer Fellow, 1963.

(4) W. Lwowski and T. W. Mattingly, Jr., *Tetrahedron Letters*, 277 (1962).

(5) W. Lwowski and T. W. Mattingly, Jr., *J. Am. Chem. Soc.*, **87**, 1947 (1965).

(6) T. J. Prosser, A. F. Marcantonio, and D. S. Breslow, *Tetrahedron Letters*, 2479 (1964); T. J. Prosser, A. F. Marcantonio, C. A. Genge, and D. S. Breslow, *ibid.*, 2483 (1964).

(7) M. F. Sloan, T. J. Prosser, N. R. Newburg, and D. S. Breslow, *ibid.*, 2945 (1964).

(8) R. J. Cotter and W. E. Beach, *J. Org. Chem.*, **29**, 751 (1964).

(9) R. Kreher and G. H. Bockhorn, *Angew. Chem.*, **76**, 681 (1964).

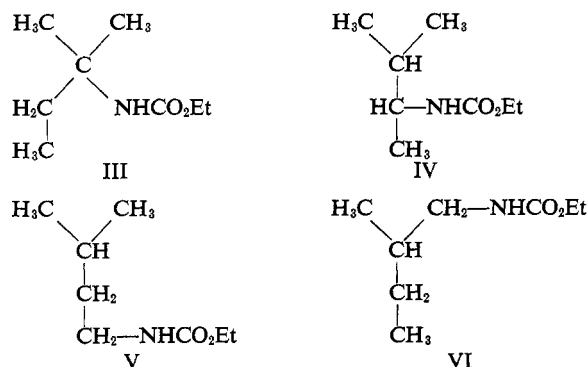
(10) P. Walker and W. A. Waters, *J. Chem. Soc.*, 1632 (1962).

(11) J. Hancock, *Tetrahedron Letters*, 1585 (1964).

(12) W. Lwowski, T. W. Mattingly, Jr., and T. J. Maricich, *ibid.*, 1591 (1964); W. Lwowski and E. Fabry, unpublished.

a boiling cyclohexane-benzene solution of I, all but 18% of it was recovered after over 5 hr. at reflux temperature. The reactions described below were carried out at room temperature in the presence of 1 equiv. of triethylamine.

Reaction with isopentane confirms the identity of the nitrene species generated in the azide photolysis and from I by α -elimination. The four urethans (III, IV, V, and VI) were formed from insertion into the tertiary, secondary, and two types of primary C-H



bonds. The urethans were separated by v.p.c. and identified by comparison of their retention times and infrared spectra with those of samples prepared from the corresponding amines and ethyl chloroformate. The two primary urethans, V and VI, were formed in the ratio of 1:2.2, indicating almost equal reactivity for the C-H bonds in the methyl groups. In the v.p.c. analyses, the sum of V + VI was determined.

The relative reactivities of the primary, secondary, and tertiary C-H bonds in isopentane were nearly the same for both reactions, as well as for the thermolysis of ethyl azidoformate.⁸ Dilution with dichloromethane to 38 mole % (44.5% by volume) of isopentane did not change the selectivity much, as is shown in Table I.

Table I. Reactivities of the C-H Groups in 2-Methylbutane toward Carbethoxynitrene^a

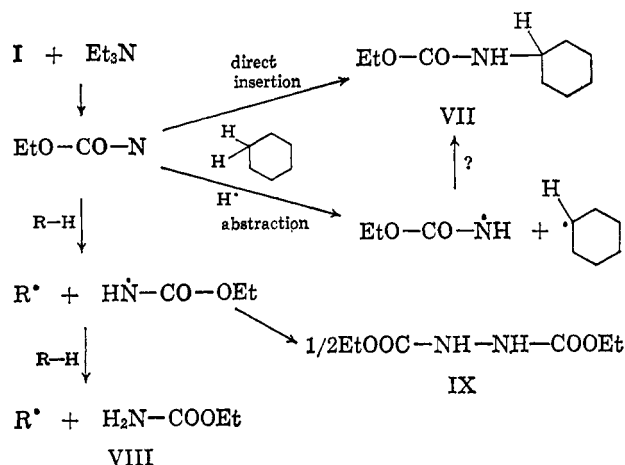
Type of C-H bond	In pure 2-methylbutane			In 44.5% 2-methylbutane-55.5% dichloromethane		
	3°	2°	1°	3°	2°	1°
CARBETHOXYNITRENE by α -elimination	27	11	1	25	8	1
Azide dec.	34	9	1	36	10	1
Relative error, %	+5	±10		±5	±10	

^a Corrected for the number of hydrogens.

The values were obtained by v.p.c. analysis and the products were identified by comparison with samples prepared by unambiguous syntheses. The data show that carbethoxynitrene is about ten times as selective, in the C-H insertion as is the corresponding carbene.¹³ Also, the nitrene must be in thermal equilibrium with its environment and not contain excess vibrational energy. If this were not so, dilution with dichloromethane ought to have a more drastic influence on the selectivity.

(13) W. von E. Doering, R. G. Buttery, R. G. Laughlin, and N. Chaudhuri, *J. Am. Chem. Soc.*, **78**, 3224 (1956); W. von E. Doering and H. Knox, *ibid.*, **83**, 1989 (1961).

Reaction with Cyclohexane. Base-induced decomposition of I in the presence of cyclohexane gave the same N-cyclohexylurethan (VII) that was obtained from the photolysis of ethyl azidoformate in cyclohexane. In heterogeneous solution (pure cyclohexane) the yield obtained was only 5.4%, but making the solution homogeneous by adding dichloromethane raised the yield to 20%. Variable quantities of ethyl carbamate (urethan, VIII) and diethyl hydrazodiformate (IX) were also found. The yield of IX increased with increasing rate of base addition, probably because faster addition provides a higher concentration of urethan radical, the presumed precursor of IX. Yields of IX up to 20% were obtained. The products are most easily explained by assuming a C-H insertion of the nitrene, accompanied by hydrogen abstraction and radical combination reactions. Cy-



clohexylurethan (VII) might be the product of a direct, one-step insertion into the C-H bond or the product of combination of a cyclohexyl radical with a urethan radical. The latter mechanism would also explain the formation of urethan (VIII) and diethyl hydrazodiformate (IX). However, the sum of our evidence (including the product distribution in the reaction of the nitrene with cyclohexene) makes us feel that the hydrogen abstraction reactions are independent of the C-H insertion. This matter is currently under investigation. Besides cyclohexane, the hydrogen donors in the formation of VIII and IX could be the triethylamine, triethylammonium ion, or the ethyl group in carbethoxynitrene. The triethylammonium ion is formed together with, and in the immediate vicinity of, the carbethoxynitrene; thus the chance of a reaction of the two is large. A high-boiling residue was always found when reaction mixtures from the triethylamine-induced decomposition of I were distilled. This will have to be studied further. A hydrogen atom is also abstracted by the nitrene from the monoprotonated N,N,N',N'-tetramethyl-*p*-phenylenediamine. Wurster's blue is formed in this case.

In order to learn more about the transition state of the C-H insertion reaction, a mixture of perdeuterio-cyclohexane and cyclohexane was treated with I and triethylamine. Cyclohexylurethan-*d*₁₁ and cyclohexylurethan were formed in a ratio corresponding to a kinetic isotope effect $k_H/k_D = 1.5 \pm 0.2$. Such a small isotope effect agrees with the very unsymmetrical transition state required in a one-step insertion. How-

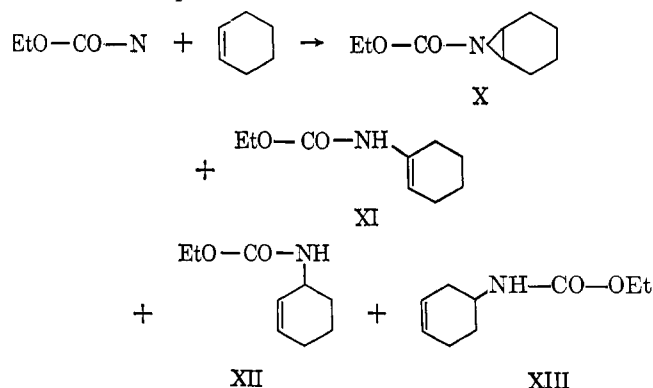
Table II. Comparison of Product Ratios and Yields in Reactions of Carbethoxynitrene with Cyclohexene

	Run no.						
	1	2	3	4	5	6	:CH ₂
Cyclohexene, mole %	20	38	33	100	100	24	100
Solvent (dichloromethane), mole %	80	62	67	0	0	76	0
Starting material	I	I	I, salt	I	EtO ₂ CN ₃	EtO ₂ CN ₃	CH ₂ N ₂
Product							
7-Carboethoxy-7-azabicyclo[4.1.0]-heptane (X)	1.00 (57) ^b	1.00	1.00 (37) ^b	1.00 (12) ^b	1.00 (56) ^b	1.00	[1.00]
1-Cyclohexenylurethan (XI)	0.014	<i>a</i>	0.03	<i>a</i>	0.02	0.03	[0.24]
3-Cyclohexenylurethan (XII)	0.09	0.16	0.19	0.16	0.16	0.13	[0.65]
4-Cyclohexenylurethan (XIII)	0.03		0.05		0.05	0.04	[0.65]
Triethylammonium <i>p</i> -nitrobenzenesulfonate (XIX)	(96) ^b	<i>a</i>	(90.3) ^b	93.5%

^a Not measured. ^b Values in parentheses are per cent yields.

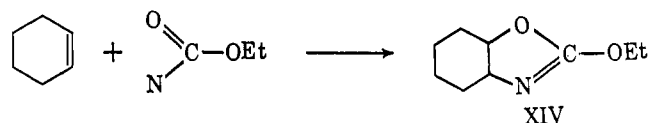
ever, the same result could be produced by a number of other causes and includes a secondary isotope effect of unknown magnitude. Further studies of the isotope effect are necessary.

Reaction of cyclohexene with the decomposing anion of I gave products of addition of carbethoxynitrene to the double bond and of its insertion into the three types of C-H bonds present. The product ratios were the same when the isolated triethylammonium salt of I was used and when the anion of I was generated *in situ*. Heterogeneous runs gave poor yields compared to runs kept homogenous by employing dichloromethane as solvent. The product ratios, however, were little affected. Representative runs are listed in Table II and compared with reaction mixtures from the photolysis of ethyl azidoformate in analogous cyclohexene-dichloromethane systems. Very similar product ratios are observed. For comparison, the column headed "CH₂N₂" gives the composition of the product mixture obtained from the analogous carbene reaction, employing diazomethane in pure cyclohexene. These products, of course, contain the entity CH₂ instead of NCOOEt; the data are taken from the literature.^{13,14} The differences between carbene and carbethoxynitrene reactions are drastic. Whereas the carbene inserts indiscriminately, the carbethoxynitrene exhibits a selectivity of 1:3:1 for the 4-, 3- (allyl)-, and 1- (vinyl) positions of cyclohexene. The ratio of double bond additions to C-H insertions is inverted, the nitrene giving more addition than insertion products.



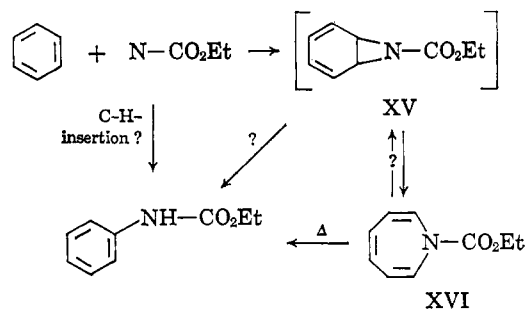
One might expect 2-ethoxy-4,5-cyclohexano- Δ^2 -oxazoline (XIV) to be formed by 1,3-cycloaddition. Despite

(14) K. Kopecky, G. S. Hammond, and P. A. Leermakers, *J. Am. Chem. Soc.*, **84**, 1015 (1962).



a thorough search, however, XIV could not be detected in the reaction mixtures from the nitrene reaction with cyclohexene. Reaction mixtures from the photolysis of ethyl azidoformate as well as from the α -elimination of I in cyclohexene were analyzed for XIV without detecting any; 0.5% could have been found easily. The aziridine X did isomerize to XIV during gas chromatography at 140° column temperature but not at 114°.

Benzene reacted with I and triethylamine to give a 50% yield of N-carbethoxyazepine (XVI), a trace of urethan (VIII) and less than 5% diethyl hydrazodiformate (IX). The azepine XVI was identified by its infrared, n.m.r., and ultraviolet spectra, which were the same as reported by Hafner,¹⁵ who had obtained XVI by photolyzing⁴ ethyl azidoformate in benzene. Hydrogenation of our product XVI gave N-carbethoxyhexamethylenimine, identical with a sample prepared from hexamethylenimine and ethyl chloroformate. The formation of XVI from I and base now establishes that the benzene ring is attacked by a one-nitrogen species (presumably carbethoxynitrene) rather than by an excited azide group. Our reaction mixtures contained some phenylurethan (XVII). This, however, need not be the product of a C-H insertion. N-Carbethoxyazepine readily isomerizes to phenylurethan, possibly *via* 7-carbethoxy-7-azabicyclo[4.1.0]heptadiene (XV), analogous to the rearrangement of tropylidene to toluene.¹⁸ The phenylurethan could also be formed from XV rather than from XVI.



(15) K. Hafner and C. König, *Angew. Chem.*, **75**, 89 (1963); *Tetrahedron Letters*, 1733 (1964).

(16) K. N. Klump and J. P. Chesick, *J. Am. Chem. Soc.*, **85**, 130 (1963).

Conclusions

The near identity of the reaction mixtures obtained in the photodecompositions of ethyl azidoformate and in the base-induced decompositions of I in various substrates allows the conclusion that a common intermediate is involved. This intermediate must be carbethoxynitrene. As discussed earlier,⁵ one must assume that it is formed in the singlet state from the azide decomposition. The α -elimination reaction of the anion of I will also form the nitrene in the singlet state. The possibility remains that the nitrene is converted to the triplet before it reacts. However, it seems quite likely that the observed reactions occur before such a change in multiplicity takes place. This problem is currently being studied. The identity of the reactive intermediate is indicated by several sets of data for the C-H insertion reaction. The constant ratio of olefin addition product to C-H insertion product in the cyclohexene case indicates that the same species (with the same electronic multiplicity) is involved in both addition and insertion.

Experimental

General Equipment and Techniques. Infrared spectra were obtained with a Perkin-Elmer Model 421 spectrometer. Nuclear magnetic resonance (n.m.r.) spectra were taken on a Varian A-60 spectrometer in 5 to 20% carbon tetrachloride solution with tetramethylsilane as internal standard. Peak positions are given in τ -units and peak shapes are denoted as follows: singlet (s), doublet (d), triplet (t), quartet (q), and multiplet (m). Ultraviolet and visible absorption spectra were taken on Cary spectrophotometers Models 11 and 14. Mass spectra were obtained with a Consolidated Model 70 mass spectrometer. Melting points are reported uncorrected. Vapor phase chromatograms (v.p.c.) were taken on Wilkens Aerograph Model A-90-P and A-90-P2 units. The following v.p.c. columns were used. Column A (4.5 ft. \times 0.25 in.) containing 20% 50 HB 2000 Ucon Polar oil stationary phase on 40-60 mesh crushed firebrick support; column B (5 ft. \times 0.25 in.) containing 20% 20M Carbowax stationary phase on 45-50 mesh Chromosorb W support; column C (5 ft. \times 0.25 in.) containing 20% XF 1150 Cyano Silicone oil stationary phase on 45-50 mesh Chromosorb W support; column D (5 ft. \times 0.25 in.) containing 20% 50 HB 2000 Ucon Polar oil stationary phase on 40-60 mesh crushed firebrick support; column E (5 ft. \times 0.25 in.) containing 20% GE-SF-96 Silicone oil stationary phase on 60-80 mesh crushed firebrick support; column F (5 m. \times 0.25 in.) containing 20% XF 1150 Cyano Silicone oil stationary phase on 45-50 mesh Chromosorb W support; column G (5 ft. \times 0.25 in.) containing 20% QF1-6500 Polar Silicone oil stationary phase on 40-60 mesh crushed firebrick support; column H (3 ft. \times 0.25 in.) containing 15% QF1-6500 Polar Silicone oil stationary phase on 50-60 mesh Anakrom ABS support. V.p.c. peak areas were measured with a planimeter to $\pm 2\%$. To obtain absolute yields, a calibration curve (weight injected vs. peak area) was first made using a standard solution of the pure material. Relative ratios of products for a given mixture were determined from relative peak areas, assuming that the detector response was the same for each compound.

Preparation of *N*-Hydroxyurethan. This compound was prepared by the method of Major, *et al.*,¹⁷ from hydroxylamine and ethyl chloroformate. Since *N*-hydroxyurethan occasionally decomposed on vacuum distillation, the ether concentrate, if yellow, was purified by suction filtration through a layer of activated charcoal. Yields ranged from 92 to 97% of theory, as compared to the reported yield (66%), b.p. 113-116° (3 mm.).

Preparation of *N*-*p*-Nitrobenzenesulfonylurethan (I). To a 5-l., three-necked, round-bottom flask containing 146.2 g. (1.39 moles) of *N*-hydroxyurethan dissolved in 2 l. of anhydrous ethyl ether was added slowly with stirring and ice cooling 307.7 g. (1.39 moles) of *p*-nitrobenzenesulfonyl chloride. A solution of 165.2 ml. (119.4 g., 1.18 moles, or 85.0% of 1 equiv.) of triethylamine in 200 ml. of ether was added slowly from an addition funnel at such a rate as to keep the mixture acidic at all times. After addition, the reaction mixture was stirred for 3 hr. and filtered to remove a precipitate containing the by-product II. The yellow ether filtrate was evaporated to dryness to yield a cream-white solid which was recrystallized from hot benzene. After concentrating the mother liquors several times, 223.3 g. (55.3% of theory) of I was obtained (varying in purity from 0.8 to 3.0° melting point range), m.p. 116.4-116.8°, infrared spectrum (in KBr) N-H at 3187 and C=O at 1697 cm^{-1} .

	N.m.r. spectrum, τ	
	in DCCl_3	in acetone
ethoxy CH_3	8.83 (t) (3.00 protons)	8.85 (t)
ethoxy CH_2	5.86 (q) (1.99)	5.80 (q) (2.26)
aromatic C-H	1.54 } (m) (5.01)	1.40 (q) (4.00)
N-H	1.54 }	-0.68 (s) (1.01)

Anal. Calcd. for $\text{C}_9\text{H}_{10}\text{N}_2\text{O}_7\text{S}$: C, 37.24; H, 3.47; N, 9.65. Found: C, 37.43; H, 3.34; N, 9.65.

I forms cream-white needle crystals. It is insoluble in cyclohexene, cyclohexane, hexane, water, carbon tetrachloride, tetrachloroethylene, fluorotrichloromethane, and 2,2,3-trichloroheptafluorobutane, moderately soluble in ethylene dichloride, benzene, and warm trichloroethylene, and soluble in ether, ethanol, nitromethane, chloroform, dichloromethane, dimethyl sulfoxide, acetone, ethyl acetate, methanol, *N,N*-dimethylformamide, and acetonitrile. I is insoluble in dilute aqueous hydrochloric acid but dissolves, with decomposition, in 10% aqueous sodium bicarbonate, triethylamine, and pyridine. I is stable at room temperature in the air. The ferric chloride (hydroxamic acid) test was negative.

Preparation of *N,O*-Di-*p*-nitrobenzenesulfonylhydroxyurethan (II). II was obtained as a by-product of the preparation of I. Much of it precipitates with the triethylammonium *p*-nitrobenzenesulfonate and remains when the precipitate is washed with water. The portion of II contained in the ether solution from the preparation of I can be isolated by recrystallizing the crude I from chloroform-cyclohexane. Up to a total of 31.4% yield of II was obtained. The total yields of I and II accounted for 86.7% of the *p*-nitrobenzenesulfonyl chloride used: m.p. 157.5-158.7°; infrared spectrum no N-H or O-H, aromatic C-H at 3109 and C=O at 1781 cm^{-1} .

(17) R. T. Major, F. Dürsch, and H. J. Hess, *J. Org. Chem.*, **24**, 431 (1959).

N.m.r. spectrum (in $\text{CH}_3\text{C}\equiv\text{N}$), τ	
ethoxy CH_3	8.94 (t) (3.1 ± 0.2 protons)
ethoxy CH_2	5.90 (q) (1.95)
aromatic C-H	1.65 (m) (8.0)

Anal. Calcd. for $\text{C}_{15}\text{H}_{13}\text{N}_3\text{O}_{11}\text{S}_2$: C, 37.90; H, 2.76; N, 8.84; mol. wt., 475.43. Found: C, 38.16; H, 2.68; N, 8.94; mol. wt., 490.

II forms small, cream-yellow, rhombic crystals. It is soluble in acetone, acetonitrile, nitromethane, dichloromethane, and dimethyl sulfoxide, moderately soluble in chloroform and benzene, slightly soluble in ether, and insoluble in water, hexane, and carbon tetrachloride.

Triethylammonium Salt of *N*-*p*-Nitrobenzenesulfonoyurethan. One gram of I was dissolved in 5 ml. of tetrahydrofuran, and the solution was cooled in an ice bath and brought near saturation by adding about 20 ml. of cyclohexane. Triethylamine (0.8 ml.) in 1 ml. of cyclohexane was then added. A yellow oil precipitated and crystallized on scratching. Filtration and pressing on paper gave a yellow powder, a sample of which decomposed violently after standing for 10 min. at room temperature in a closed vial. The decomposition of its solution in dichloromethane, as followed by the change in the ultraviolet spectrum, took about 3.5 hr. The salt is, however, stable enough to be handled and can be used for nitrene reactions (see cyclohexene reactions), although this does not seem to offer any advantages.

Exchange Reaction of I with Deuterium Oxide. A mixture of 0.30 g. of I, 10 ml. of 99.8% deuterium oxide, ca. 40 ml. of chloroform, and a trace of anhydrous potassium carbonate were shaken together for about 5 min. The chloroform solution was dried and concentrated to ca. 1 ml. I was crystallized by adding hexane. The infrared spectrum (in KBr) showed three new peaks at 2378, 1131, and 952 cm^{-1} , indicating the presence of an N-D bond. The rest of the spectrum corresponded to that of I, except for weakened N-H bands.

Attempted Decomposition of I in Dichloromethane-Cyclohexane. I (2.9 g.) was heated to reflux in a mixture of 150 ml. of dichloromethane and 15 ml. of cyclohexane for 11 days. Concentrating the solution and adding cyclohexane caused precipitation of essentially all the unchanged starting material.

Partial Solvolysis of I in Methanol. I (5.8 g.) was heated to reflux in 200 ml. of methanol for 20 hr. The solution became acidic. Concentrating and adding ether precipitated 0.49 g. of *p*-nitrobenzenesulfonic acid, identified by its infrared spectrum. From the filtrate, 3.58 g. of unreacted I was recovered.

Reaction of I with Benzoyl Peroxide. To explore the possibility of a radical mechanism for the formation of the products observed in the reactions of I and base in hydrocarbons, a solution of 1.16 g. (0.004 mole) of I and 0.48 g. (0.002 mole) of benzoyl peroxide in 250 ml. of a 3:2 mixture of cyclohexane and benzene was heated to reflux for 5.5 hr. A small amount of brown precipitate was filtered off. Cooling in an ice bath and adding 100 ml. of cyclohexane gave 0.76 g. of unreacted I; another 0.19 g. was obtained from the filtrate, so that 82% of I was recovered. Benzoic acid was isolated from the filtrate.

Reaction of I with Triethylamine and Isopentane in Dichloromethane. To a stirred, ice-cooled solution of 100 ml. of 99.7% pure isopentane and 50 ml. of dichloromethane was added slowly and alternately in small portions 14.50 g. (0.050 mole) of *N*-*p*-nitrobenzenesulfonoyurethan (I) and 7.70 ml. (5.57 g., 0.055 mole) of triethylamine (from a syringe). In the course of the addition of the reagents, which took 1 hr., 75 ml. more of dichloromethane was added to keep the solution homogeneous. However, after about 80% reaction, the triethylammonium *p*-nitrobenzenesulfonate salt began to precipitate from the yellow solution. After 1 more hr. of stirring, petroleum ether (b.p. 38–49°) was added to promote further precipitation of the salt, of which 13.65 g. (90.0% of theory) was filtered off. The filtrate was concentrated *in vacuo* and the products were isolated and analyzed by v.p.c. The products were shown to be identical with authentic samples by their infrared spectra and retention times on several columns. The relative peak areas from v.p.c. were averaged for three injections. On column A at 120° *t*-amylurethan (III) was isolated cleanly, but urethan (VIII) and 2-methyl-3-butylurethan (IV) came together. Diethyl hydroazodiformate separated well, but 2-methyl-4-butylurethan (V) and 2-methyl-1-butylurethan (VI) overlapped each other about 25%. The overlap of these two was about 15% at 107°. Nearly complete separation of V and VI was accomplished on column D at 102°. On column F at 125°, urethan, diethyl hydroazodiformate, III, and IV separated cleanly; however, V and VI, although separated from the other products, greatly overlapped.

A mixture of the four C_6H_{11} urethans was injected into several columns. In each case there was good separation of III and IV from the mixture of V and VI, but V and VI were difficult to separate. There was either no or poor separation on columns F, G, and B and on a 5 ft. \times 0.25 in. 20% didecyl phthalate on Chromosorb column. The best separation with still 5% overlap was on column D at 102°. The pre-

Relative ratios of products		
III	IV	V + VI
1.00	0.64	0.36
2.8	1.8	1.0

cision of the results are $\pm 5\%$ for III, V, and VI and $\pm 10\%$ for IV.

Reaction of I with Triethylamine in Isopentane. The procedure of the previous experiment was used with 100 ml. of isopentane, 7.25 g. (0.025 mole) of I, and 3.85 ml. (2.79 g., 0.028 mole) of triethylamine. The reaction was heterogeneous and was stirred for 7.5 hr. The salt was obtained in a yield of 7.17 g. (94.3% of theory). The yellow, oily concentrate was analyzed by v.p.c. as before to give the observed ratios of products.

Relative ratios of products		
III	IV	V + VI
1.00	0.79	0.33
3.0	2.4	1.0

Photodecomposition of Ethyl Azidoformate (XVIII) in Isopentane. A homogeneous solution of 5.76 g. (0.050 mole) of ethyl azidoformate (XVIII) in 150 ml. of 99.7% pure isopentane was irradiated in a quartz

vessel with 16 surrounding, medium-pressure, ultraviolet lamps (in a "Rayonet" photochemical reactor)⁵ for 11 hr. The vessel was fitted at the top with a reflux condenser and drying tube. Completion of the reaction was determined by the disappearance of the azide peak in the infrared spectrum of the reaction solution. The isopentane solution was concentrated and analyzed by v.p.c. as in the preceding two reactions.

Relative ratios of products		
III	IV	V VI
1.00	0.51	0.26
3.8	2.0	1.0

Photodecomposition of Ethyl Azidoformate (XVIII) in a Mixture of Isopentane and Dichloromethane. The same procedure and amount of XVIII as in the preceding reaction was used with a mixture of 70 ml. of isopentane and 88 ml. of dichloromethane. The reaction proceeded for 24 hr. and was analyzed by v.p.c. as before.

Relative ratios of products			
III	IV	V	VI
..	..	1.18	2.00
1.00	0.58	0.25	
4.0	2.3	1.0	

Pentylurethans III, IV, V,¹⁸ and VI¹⁹ were prepared from the corresponding amines and ethyl chloroformate and their identity was confirmed by their n.m.r. spectra. To a stirred, ice-cooled solution of 0.04 mole of the (commercially available) amines in 25 ml. of ether was added slowly a solution of 2.17 g. (0.02 mole) of ethyl chloroformate in 30 ml. of ether. After stirring overnight, the amine hydrochloride was filtered off and the product was distilled (see Table III).

Table III

	Compound			
	III	IV	V	VI
Infrared (in CCl ₄), cm. ⁻¹				
NH	3453	3455	3460	3462
CO	1724	1724	1723	1724
N.m.r. ^a (in CCl ₄), τ				
NH (m)	5.1	5.1	4.7	4.55
Ethoxy CH ₂ (q)	6.0	5.96 (2.0)	5.95 (2.0)	5.95 (2.0)
CH next to the N (m)	...	6.55 (0.98)	6.9 (1.7)	6.5-7.2 (1.96)
Other CH (m)	8.1-9.3	8.1-9.2	8.1-9.2	8.1-9.3

^a Peak areas in parentheses.

N-p-Nitrobenzenesulfonyurethan (I) with Triethylamine in Cyclohexane. To a suspension of 11.61 g. (0.04 mole) of I in 700 ml. of cyclohexane was added over 17 hr. 4.14 g. (0.041 mole) of triethylamine, at room temperature. After 2 more hr., most of the cyclohexane was evaporated. Starting I (11%) was recovered. Based on 89% reaction, 91.2% (9.89 g.) of the triethylammonium salt of *p*-nitrobenzenesulfonic acid (XIX) was obtained as a solid, insoluble in cyclohexane. Vapor phase chromatography of the liquid material on column D indicated the formation of $5.4 \pm 0.6\%$ of the theoretical amount of cyclohexylurethan

(VII) and 3.7% of urethan (VIII). These compounds were identified by comparison of their infrared spectra with those of authentic samples.

Reaction of I with Cyclohexane and Triethylamine in Dichloromethane Solution. To a stirred solution of 7.26 g. (0.025 mole) of I in 100 ml. of cyclohexane plus 200 ml. of dichloromethane was added over a period of 18 min. a solution of 2.78 g. (0.0275 mole) of triethylamine in 25 ml. of cyclohexane. The clear solution was kept at room temperature for 3 hr., then concentrated *in vacuo*, and the salt XIX was filtered (6.62 g. 87%). The oily residue was analyzed by v.p.c., which indicated the formation of 20.1% of the theoretical amount of cyclohexylurethan (VII). In some other runs, diethyl hydrazodiformate crystallized from the concentrate on standing. Its yield varied, depending on the rate of base addition and on concentration. A run using 50 ml. of cyclohexane plus 30 ml. of dichloromethane for 0.02 mole of I gave an 89% yield of the salt XIX, 9.7% of cyclohexylurethan (VII) (by chromatography on acid-washed alumina), and a 10.8% yield of diethyl hydrazodiformate.

Reaction of I with Triethylamine and 1:1 Cyclohexane-Perdeuteriocyclohexane in Dichloromethane and Nitromethane. Perdeuteriocyclohexane (0.2685 g., 0.00279 mole) was distilled from a vacuum line into a weighed reaction flask containing magnetic stirring bar and syringe cap. To this was added 0.2349 g. (0.00279 mole) of cyclohexane from a syringe, 1.00 ml. of dichloromethane, and 5.00 ml. of nitromethane. Next, 5.80 g. (0.020 mole) of I was added slowly from a spatula through a short condenser while simultaneously adding in proportionate amounts 3.08 ml. (2.22 g., 0.022 mole) of triethylamine from a syringe with ice cooling and stirring over a period of 1 hr. After stirring for an additional 15 min., the reaction was worked up to give 5.57 g. (91.3% of theory) of the salt XIX and *ca.* 0.1 g. of a mixture of deuterated and undeuterated cyclohexylurethans as shown by the infrared and n.m.r. spectra. The product ratio of cyclohexylurethan to the deuterated cyclohexylurethan was determined from the n.m.r. spectrum in the following way. In the n.m.r. the ethoxymethylene (two protons) was a clean quartet, which was used as an internal standard. Ten of the cyclohexyl protons were grouped with the three ethoxymethyl protons. Hence, if the product contained no deuterated cyclohexylurethan, this group would integrate to 13 compared with the two protons of the standard. If there was only the deuterated product, this would integrate to three. Hence, the actual result of 9.0 ± 0.2 gives a ratio of 6.0 to 4.0 ± 0.2 for H to D. This indicates a kinetic deuterium isotope effect of $K_H/K_D = 1.5 \pm 0.2$.

Reaction of I with Triethylamine and N,N,N',N'-Tetramethyl-*p*-phenylenediamine Dihydrochloride in Dichloromethane. To a stirred solution of 0.95 g. (0.004 mole) of N,N,N',N'-tetramethyl-*p*-phenylenediamine dihydrochloride (XX) and 1.12 ml. (0.81 g., 0.008 mole) of triethylamine in 50 ml. of dichloromethane was added a solution of 1.16 g. (0.004 mole) of N-*p*-nitrobenzenesulfonyurethan (I) in 25 ml. of dichloromethane. As soon as the first few drops of the solution of I was added the reaction mixture turned pale blue, and quickly became deep blue as the rest of the solution was added. The solution was ice cooled

(18) E. Custer, *Ber.*, 12, 1328 (1879).

(19) I. N. Denton and A. H. Lamberton, *J. Chem. Soc.*, 1655 (1955).

during addition. After stirring overnight at room temperature, the mixture was deep blue. The color could be extracted into water, indicating the formation of the Wurster's blue radical cation XXI and, thus, also indicating that a hydrogen abstraction had taken place. Wurster's salt was precipitated by adding ether and petroleum ether. The absorption spectrum of its aqueous solution showed a shoulder at about 517 and absorption maxima at 561 and 607 m μ . This is in tolerable agreement with Michaelis's values²⁰ of 530 (shoulder), 565, and 608 m μ .

Reactions of I with Cyclohexene and Triethylamine. The products from the cyclohexene reactions were identified by comparison with authentic samples obtained earlier.⁵

Run 1 (Table II). To a solution of 8.70 g. (0.03 mole) of I in 250 ml. of a mixture of 20 mole % of cyclohexene and 80 mole % of dichloromethane was added dropwise with stirring a solution of 3.33 g. (0.033 mole) of triethylamine in 50 ml. of the above mixture. The addition took 17 min. After 2 hr. and 40 min., 400 ml. of pentane was added to precipitate the triethylammonium *p*-nitrobenzenesulfonate. After concentrating the solution *in vacuo*, a total of 8.77 g. (96% yield) of the salt was obtained. The filtrate was concentrated further and analyzed by v.p.c., using column H at 114°. Yields were obtained by injecting known quantities of the aziridine (X) and comparing peak areas. The aziridine was formed in 57% yield; the ratio of X to the sum of cyclohexenyl 3- and 4-urethan was 1.00:0.12.

Alternative Work-up Procedure. After reaction, the solution was concentrated *in vacuo*, and enough water is added to dissolve the triethylammonium salt XIX. Pentane (about half the volume of the organic layer) was added to drive the salt into the water phase. The water layer was extracted twice with pentane, the organic layer twice with water. The combined, dried organic phases were concentrated *in vacuo* and distilled. The fraction boiling at 70–75° (0.5 mm.) was rather pure aziridine (X) according to its infrared spectrum. In a typical run, a 31% yield of X was obtained.

Run 2 was similar to run 1 except for the different solvent composition.

Run 3. A solution of 1.34 g. of the isolated triethylammonium salt of I in 40 ml. of cyclohexene and 50 ml. of dichloromethane (33 mole % cyclohexene) was kept at room temperature for 5 hr., then treated with pentane to precipitate 0.93 g. (90.3% yield) of the triethylammonium *p*-nitrobenzenesulfonate. V.p.c. analysis of the concentrated filtrate and identification of the v.p.c. fractions by their infrared spectra showed that the same products as in run I were formed. Aziridine (X) was formed in 37% of the theoretical yield; its ratio to the 1-, 3-, and 4-urethans was 1.00:0.03:0.19:0.05, respectively.

Run 4 (pure cyclohexene). To a stirred, heterogeneous mixture of 4.35 g. (0.015 mole) of I with 200 ml. of cyclohexene was added dropwise over the period of 1 hr. a solution of 3.03 g. (0.030 mole) of triethylamine in 50 ml. of cyclohexene. Stirring was continued

for 1 day and the mixture was filtered. The solids were washed with ether, from which 0.09 g. of I was recovered by recrystallization from hot chloroform and cyclohexane. The filtered cyclohexene solution, on standing for several days, gave some more precipitate, which was filtered and rinsed with ether. This ether solution gave 0.05 g. of diethyl hydrazodiformate, as identified by its infrared spectrum. The ether-insoluble solids from the two filtrations were identified as triethylammonium *p*-nitrobenzenesulfonate by their infrared spectra. They weighed 4.18 g. (93.5% yield). The cyclohexene solution was concentrated to give 1.211 g. of a concentrate which was analyzed by v.p.c. The ratio of aziridine (X) to cyclohexenyl-3- and -4-urethans to ethyl carbamate was 1.0:0.16:0.21. This corresponds to yields of 12, 2, and 5%, respectively.

Irradiation of Ethyl Azidoformate (XVIII) in Cyclohexene (Run 5). A solution of 0.58 g. (0.005 mole) of ethyl azidoformate (XVIII) in pure cyclohexene was irradiated as described⁵ for 3 hr. The mixture was concentrated and analyzed by v.p.c. at 114° on column H. The ratio of aziridine to the sum of cyclohexenyl-3- and -4-urethans was found to be 1:0.23. No oxazoline was found.

Irradiation of Ethyl Azidoformate in Cyclohexene–Dichloromethane (Run 6). A solution of 0.005 mole of ethyl azidoformate (XVIII) was irradiated in a mixture of 24 mole % cyclohexene and 76 mole % dichloromethane, otherwise as in run 5. The ratio of aziridine to cyclohexenyl-1-urethan to the sum of the 3- and 4-urethans was 1.00:0.03:0.17, respectively.

In the cyclohexene reactions, the product mixtures were analyzed by v.p.c. Column C separated X and XI cleanly, but XII and XIII overlapped and could be estimated with relative error of about 10%. Column G separated X and the oxazoline XIV cleanly (XIV was not present in the reaction mixtures unless produced by thermal rearrangement at 140°). XI was well separated, but XII and XIII formed one peak. The latter pair separated best on column F. A combination of separations on different columns had to be used.

cis-2-Ethoxy-4,5-cyclohexano- Δ^2 -oxazoline was formed when the 7-carbethoxy-7-azabicyclo[4.1.0]heptane (X) was subjected to too high a temperature in the gas chromatograph (e.g., at 140° but not at 114°). Pure aziridine, when injected at 144° column temperature on column G gave four peaks, the two major peaks having the shorter retention times. The first peak corresponded in its infrared and n.m.r. spectra to the oxazoline, the second to the aziridine (infrared only). The smaller peaks corresponded to the cyclohexenylurethans (by retention times only). Re-injection of the aziridine peak (at 144°) would again give the same peaks. The oxazoline was characterized by its infrared, n.m.r., and mass spectrum. The parent mass peak (at 68 and at 12.5 v. ionizing voltage) was at *m/e* 169 (mol. wt. calcd., 169.23). The infrared spectrum showed no NH or OH peaks, C=N at 1654, and C=O at 1245 cm⁻¹. The n.m.r. spectrum in CCl₄ showed signals for the ring CH₂ at τ 8.0–8.8; ethoxy group a triplet at 8.7 and a quartet at 5.82 (two protons). The signals at τ 8.0–8.7 corresponded to 11 protons (eight plus three). The ring C–H signals from the protons next to the N and the O

(20) L. Michaelis, M. P. Schubert, and S. Granick, *J. Am. Chem. Soc.*, **61**, 1981 (1939).

were found at 6.2 and 5.5, each corresponding to one proton. The sensitivity of the v.p.c. analysis at 114° was such that the oxazoline could have been detected if present as a 0.5% impurity relative to the aziridine (X).

Attempted Preparation of cis-2-Ethoxy-4,5-cyclohexano- Δ^2 -oxazoline. Preparation of 7-Carbethoxy-7-azabicyclo[4.1.0]heptane. *trans-2-Aminocyclohexanol* was prepared by a modification of the procedure of Osterberg and Kendall²¹ by treating *trans-2-chlorocyclohexanol* with ammonia at atmospheric pressure. This more convenient procedure gave only a 21% yield, as compared to 61% from the original procedure.

trans-2-Hydroxycyclohexylurethan. Ethyl chloroformate (14.7 g., 0.135 mole) in 25 ml. of benzene was added to a solution of 16.1 g. (0.140 mole) of *trans-2-aminocyclohexanol* in 75 ml. of water. To the shaken and cooled emulsion was added gradually a 5% aqueous solution of 5.60 g. (0.14 mole) of sodium hydroxide, and shaking was continued for 20 min. The organic layer was dried and evaporated to give 13.5 g. (51.5% of the theoretical yield) of *trans-2-hydroxycyclohexylurethan*, m.p. 57.0–58.0°. The infrared spectrum in CCl₄ showed OH at 3590, NH at 3448, and CO at 1699 cm⁻¹. The n.m.r. spectrum in CCl₄ gave NH at τ 4.2 (0.9), OH and ethoxy CH₂ at 5.9 (3.00); CH α to the NH and OH at 6.7 (1.96); and ring CH₂ at 7.6–9.0 (11.86).

trans-2-Tosyloxycyclohexylurethan. A solution of 5.43 g. (0.029 mole) of *trans-2-hydroxycyclohexylurethan* and 6.1 g. (0.032 mole) of *p*-toluenesulfonyl chloride in 30 ml. of pyridine was stirred at room temperature for 4 hr. Pouring into ice water gave an oil which quickly solidified on scratching. Crystallizing from hot cyclohexane–chloroform gave 7.66 g. of a compound, m.p. 104.8–105.8°, presumed to be the tosyloxy derivative. Reactions of this material with triethylamine in ethanol or dimethyl sulfoxide, and solvolysis in acetic acid, did not give the desired oxazoline.

7-Carbethoxy-7-azabicyclo[4.1.0]heptane (X). In an attempt to make the cyclohexanooxazoline (XIV) a solution of 1.71 g. (0.005 mole) of *trans-2-tosyloxycyclohexylurethan* and 0.56 g. (0.005 mole) of potassium *t*-butoxide in 50 ml. of *t*-butyl alcohol was stirred at room temperature for 3 hr. Addition of 20 ml. of dimethyl sulfoxide did not make the mixture completely homogeneous. It was stirred for 21 more hr., filtered, washed with 15 ml. of pentane, and diluted with another 50 ml. of pentane. The organic solution was shaken with 300 ml. of water, the water layer was extracted with pentane three times, and the combined pentane solutions were extracted with four portions of 100 ml. each of water. The dried pentane solution gave essentially pure 7-carbethoxy-7-azabicyclo[4.1.0]heptane in 96% of the theoretical yield (0.82 g.).

N-Carbethoxyazepine (XVI). To a suspension of 8.70 g. (0.030 mole) of I in 950 ml. of benzene was added slowly with stirring a solution of 4.62 ml. (0.033 mole) of triethylamine in 50 ml. of benzene. I dissolved be-

fore all the base had been added and the solution became bright yellow. Addition took 1.3 hr. and triethylammonium *p*-nitrobenzenesulfonate began to precipitate after 1.2 hr. After 3 hr., the solution was filtered and concentrated to precipitate more salt, which amounted to 7.78 g. (85.2% yield). The concentrated filtrate was chromatographed through acid-washed alumina, partially deactivated with 100 ml. of a 1:2 ethanol–hexane solution. Elution with benzene gave 2.48 g. (50% yield) of XVI. Diethyl hydrazoformate was eluted with chloroform. For purification by v.p.c., the best column proved to be E at 140°. The infrared spectrum (in CCl₄) of XVI showed no N–H or O–H, olefinic C–H at 3051 and 3033, C=O at 1717, and C=C at 1651 cm⁻¹. The ultraviolet spectrum (in *n*-hexane) gave λ_{\max} 210.0 m μ (log ϵ 4.37) and λ_{\max} 328.8 m μ (log ϵ 2.74). Literature values are (in *n*-hexane)¹⁵ λ_{\max} 208 m μ (log ϵ 4.44) and λ_{\max} 330 m μ (log ϵ 2.72).

N.m.r. spectrum (in CCl ₄), τ		
ethoxy CH ₃	8.71 (t)	(3.14 protons)
ethoxy CH ₂	5.81 (q)	(2.00)
ring protons	3.9–4.8 (m)	(5.74)

Rearrangement of N-Carbethoxyazepine to Phenylurethan. N-Carbethoxyazepine (XVI) was shown to rearrange at least to 10% to phenylurethan on v.p.c. column A at 150°. The phenylurethan obtained from this rearrangement was shown by its infrared spectrum to be identical with that of an authentic sample.

Catalytic Hydrogenation of N-Carbethoxyazepine to N-Carbethoxyhexamethylenimine. The hydrogenation of 0.018 g. of N-carbethoxyazepine (XVI) was carried out at atmospheric pressure with a suspension of ca. 0.1 g. of 5% platinum-on-charcoal catalyst in 5 ml. of absolute ethanol. Fast hydrogenation of the three olefinic bonds was followed by a much slower reaction, possibly reduction of the urethan.

The ethanol solution was filtered from the catalyst, concentrated, and analyzed by v.p.c. on column D. The major product was shown by its infrared spectrum to be identical with authentic N-carbethoxyhexamethylenimine.

Preparation of 7-Carbethoxyhexamethylenimine. To an ice-cooled, magnetically stirred, 100-ml. flask containing 3.55 g. (0.036 mole) of hexamethylenimine in 20 ml. of ether was added slowly from an addition funnel a solution of 1.17 ml. (1.95 g., 0.018 mole) of ethyl chloroformate in 50 ml. of ether. Immediately, a white solid began to precipitate. The mixture was stirred for 10.5 hr. and filtered. Hydrochloride (2.34 g., 96%) was obtained. The filtrate was concentrated to give 3 ml. of 7-carbethoxyhexamethylenimine which was purified by v.p.c. on column D. Infrared spectrum in CCl₄ showed C–H at 2984, 2935, and 2860; C=O at 1688 cm⁻¹; and no N–H.

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(21) C. Osterberg and E. Kendall, *J. Am. Chem. Soc.*, **42**, 2621 (1920).