AN ABSTRACT OF THE THESIS OF

Timothy Dean Ziebarth (Name of student) for the Doctor of Philosophy (Degree)

in Chemistry(Organic) (Major) presented on 22 November 1972 (Date)

Title: REACTIVE INTERMEDIATES IN THE TETRACYCLO-[3.3.0.$0^{2,7}$.$0^{4,6}$]OCTANE, THE TETRACYCLO[3.3.0.$0^{2,4}$.$0^{3,7}$]-OCTANE, AND RELATED RING SYSTEMS CONTAINING THE NORBORNANE SKELETON

Abstract approved
Dr. Peter K. Freeman

The base induced thermal decompositions of tricyclo-[3.2.1.$0^{3,6}$]octan-2-one p-toluenesulfonyl hydrazone and the and the corresponding N-d isomer were studied under a variety of reaction conditions. The two resulting hydrocarbons tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane and tetracyclo[3.3.0.$0^{2,4}$.-$0^{3,7}$]octane were identified as being derived from either 2-carbenatricyclo[3.2.1.$0^{3,6}$]octane in a ratio of 1.6:1, or from an ionic precursor, either the 2-tricyclo[3.2.1.$0^{3,6}$]-octyl carbonium ion, or the corresponding diazo compound, in a ratio of 20:1. An ether, formed when this reaction was induced by methoxide ion, was identified as exo-2-methoxytricyclo[3.2.1.$0^{3,6}$]octane by independent synthesis,

and was shown not to be derived from the carbene intermediate.

The structure of tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane was established by an alternate synthesis via key intermediate cis-2,7-bicyclo[3.3.0]octadiene. Preparation of the monoepoxide of cis,cis-1,3-cyclooctadiene followed by treatment with lithium diethylamide in ether resulted in stereospecific formation of cis-bicyclo[3.3.0]oct-7-ene-endo-2-ol. Conversion of this alcohol to endo-2-acetoxy-cis-bicyclo-[3.3.0]oct-7-ene followed by gas phase pyrolysis gave the required diene. Photolysis of this diene in either pentane or ether solution with an unfiltered high-pressure Hg vapor lamp gave exclusively tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane in an overall yield of 10% from cyclooctadiene.

The thermal stabilities of tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]-octane and tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane in the gas phase were investigated. Whereas the former isomer gave quantitative conversion to cis-2,7-bicyclo[3.3.0]octadiene with a rate constant of 0.074 ± 0.004 hr^{-1} at 301°, the latter gave several products, mainly a 78:22 mixture of 2,6- and 2,7-cis-bicyclo[3.3.0]octadiene, in addition to polymer, with a rate constant for dissappearance of starting material of k = 0.023 ± 0.002 hr^{-1} at 317°.

Pseudo first order rate constants for the dissappearance of tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane and tetracyclo-[3.3.0.$0^{2,4}$.$0^{3,7}$]octane upon treatment with an 0.08 N solution of sulfuric acid in glacial acetic acid were

$k = 0.90 \pm 0.01$ min^{-1} and $k = 0.0367 \pm 0.0006$ min^{-1} respectively. Both tetracyclic isomers yielded mainly exo-2-acetoxytricyclo[3.2.1.$0^{3,6}$]octane.

Free radical chlorination of tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane with t-butyl hypochlorite in CCl_4 at 40^{o} gave two major products, in the ratio of 16:58, and identified as 1-chloro- and 3-chlorotetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane by a combination of spectral and chemical evidence. Attempted reduction of the major isomer with tri-n-butyltin hydride resulted in ring fragmentation to give a mixture of 2,6- and 2,7-cis-bicyclo[3.3.0]octadiene.

Free radical chlorination of tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane with t-butyl hypochlorite in CCl_4 at 40^{o} gave four major products, in the approximate ratio of 4:2:1:1, and were identified as 1-chloro-, syn-6-chloro-, and anti-6-chlorotetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane, and exo-8-chlorotetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane by a combination of spectral and chemical evidence. The latter product was found to be derived from anti-6-chlorotetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]-octane via a trishomocyclopropenyl radical rearrangement, as evidenced by isolation of both [3.3.0.$0^{2,4}$.$0^{3,7}$] and [3.3.0.$0^{2,7}$.$0^{4,6}$] parent hydrocarbons from tri-n-butyltin hydride reductions of mixtures of the two minor chlorides.

An investigation of the physical and chemical properties of symmetrical tricyclo[3.3.0.$0^{3,7}$]octane was conducted in order to define the strain energy, and to relate the [3.3.0.$0^{3,7}$] ring system to norbornane. The ir, ^{1}H nmr, and

the ^{13}C-^{1}H satellite nmr spectra of tricyclo[3.3.0.$0^{3,7}$]-octane revealed that the methylene positions carry as much angle strain as cyclobutane. Calculation of an internal methylene C-C-C internuclear angle of 95° based on the ^{13}C-^{1}H spectrum allowed calculation of the coordinates of all atoms in the molecule, and revealed a severe nonbonded interaction between neighboring methylene hydrogens (2.06 Å).

Gas phase pyrolysis of tricyclo[3.3.0.$0^{3,7}$]octane gave exclusively cis-2-bicyclo[3.3.0]octene with a first order rate constant of $1.9 \pm 0.1 \times 10^{-5}$ sec^{-1} at 297°. Using the pyrolysis of cis-bicyclo[3.2.0]heptane as a model to approximate the frequency factor, the activation energy for pyrolysis of tricyclo[3.3.0.$0^{3,7}$]octane was calculated to be 53 kcal/mole.

Photochlorination of tricyclo[3.3.0.$0^{3,7}$]octane with chlorine in benzene gave exclusively 2-chlorotricyclo-[3.3.0.$0^{3,7}$]octane, a structure identified by observation of one proton α to chlorine in the nmr spectrum coupled with reduction of this chloride to the parent hydrocarbon using tri-n-butyltin hydride.

The rates of hydrogen abstraction from tricyclo-[3.3.0.$0^{3,7}$]octane by t-butoxy radical at 40° relative to both cyclohexane ($k/k_{cyclohexyl}$ per hydrogen = 0.30 ± 0.03) and adamantane ($k/k_{2\text{-adamantyl}}$ per hydrogen = 0.9 ± 0.2) were determined, and were compared to the rates of hydrogen abstraction from norbornane ($k_{7\text{-norbornyl}}/k_{cyclohexyl}$ per hydrogen = 0.11 ± 0.02; $k_{1\text{-norbornyl}}/k_{cyclohexyl}$ per

hydrogen = 0.076 ± 0.007). Observation of a significant amount of bridgehead hydrogen abstraction from norbornane (1.55 ± 0.09% at 40^0 in CCl_4) when t-butoxy radical is the abstracting agent was unprecedented, and was compared to the much smaller amount of C-1 abstraction observed (0.30 ± 0.04% at 40^0 in CCl_4) when chlorine atom was the abstracting agent.

Solvolysis of 2-chlorotricyclo[3.3.0.$0^{3,7}$]octane in 80% aqueous ethanol gave both exo-2-tricyclo[3.2.1.$0^{3,6}$]-octanol and exo-2-ethoxytricyclo[3.2.1.$0^{3,6}$]octane, in addition to rearranged chloride exo-2-chlorotricyclo-[3.2.1.$0^{3,6}$]octane by internal return, with a calculated anchimeric assistance of 10^8. These results indicated that the large degree of strain present in the [3.3.0.$0^{3,7}$] ring system could be relieved by a facile Wagner-Meerwein rearrangement to the [3.2.1.$0^{3,6}$] ring system.

Based on the observed formation of bridgehead substituted products as a result of free radical chlorination of tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane and tetracyclo[3.3.0.$0^{2,4}$.-$0^{3,7}$]octane, and the trishomocyclopropenyl radical rearrangement observed in both free radical chlorination and in reduction of the [3.3.0.$0^{2,4}$.$0^{3,7}$] ring system, an investigation of the free radical reactivity of a number of bridged polycyclic hydrocarbons was conducted in order to determine the generality of these two phenomena.

Photochlorination of exo,exo-tetracyclo[3.3.1.$0^{2,4}$.-

$0^{6,8}$]nonane with t-butyl hypochlorite in CCl_4 at 40° gave 1-chloro- and 2-chlorotetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane in a ratio of 76:24, and a per mole rate of hydrogen abstraction of 0.33 ± 0.02 relative to cyclohexane.

Photochlorination of <u>exo,endo</u>-tetracyclo[3.3.1.$0^{2,4}$.-$0^{6,8}$]nonane with t-butyl hypochlorite in CCl_4 at 40° gave 1-chloro- and 6-chloro-<u>exo,endo</u>-tetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]-nonane, and <u>endo</u>-9-chloro-<u>exo</u>-tetracyclo[4.3.0.0^{2,4}.$0^{5,7}$]-nonane, in a ratio of 34:16:42, and a per mole rate of hydrogen abstraction of 1.62 ± 0.15 relative to cyclohexane. The latter chloride arose as a result of trishomocyclopropenyl radical rearrangement resulting from C-9 hydrogen abstraction from substrate [3.3.1.$0^{2,4}$.$0^{6,8}$] hydrocarbon.

Photochlorination of deltacyclane with t-butyl hypochlorite in CCl_4 at 40° gave <u>exo</u>-8-chloro-, <u>endo</u>-8-chloro-, 5-chloro-, and 1-chlorodeltacyclane in a ratio of 61:11:17:11, and a per mole rate of hydrogen abstraction of 0.83 ± 0.07 relative to cyclohexane.

Photochlorination of pentacyclo[4.3.0.0^{2,4}.$0^{3,8}$.$0^{5,7}$]-nonane with t-butyl hypochlorite in CCl_4 at 40° gave almost exclusively (86%) 2-chloropentacyclo[4.3.0.0^{2,4}.$0^{3,8}$.$0^{5,7}$]-nonane with a per mole rate of hydrogen abstraction of 0.24 ± 0.04 relative to cyclohexane. The structure of this product was determined by deuteration experiments, including chlorination of 4,5-dideuteriopentacyclo[4.3.0.0^{2,4}.$0^{3,8}$.-$0^{5,7}$]nonane and reduction of the major photochlorination product with t-BuOD and sodium in THF to give 2-deuterio-

pentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane.

The results of these investigations were coupled with the hydrogen abstraction rates for tetracyclo[3.3.0.$0^{2,4}$.-$0^{3,7}$]octane ($k/k_{cyclohexane}$ per mole = 0.36 ± 0.03), tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane ($k/k_{cyclohexane}$ per mole = 0.35 ± 0.03), <u>exo</u>-tricyclo[3.2.1.$0^{2,4}$]octane, and <u>endo</u>-tricyclo[3.2.1.$0^{2,4}$]octane, and norbornane, and interpreted to indicate that 1) a cyclopropane ring, oriented in an <u>exo</u> fashion at C-2 and C-3 of a norbornane ring, is responsible for a six fold enhancement in the rate of C-1 bridgehead hydrogen abstraction by t-butoxy radical, whereas a corresponding <u>endo</u> cyclopropyl moiety is ineffectual, 2) trishomocyclopropenyl anchimeric assistance to hydrogen abstraction from the <u>anti</u>-C-8 position in <u>endo</u>-tricyclo-[3.2.1.$0^{2,4}$]octane, and other hydrocarbons containing this relationship, is a general phenomenon, and can give rate accelerations of up to 100, and 3) that abstraction of a secondary nortricyclyl type hydrogen by a t-butoxy radical occurs with an anchimeric assistance of about six. Lack of facile hydrogen abstraction from C-9 in pentacyclo-[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane was attributed to an unfavorable charge interaction between the oxygen atom in the t-butoxy radical and the bent C-C orbital of the cyclopropane ring in the transition state.

Reactive Intermediates in the Tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane, the Tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane, and Related Ring Systems Containing the Norbornane Skeleton

by

Timothy Dean Ziebarth

A THESIS
submitted to
Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

June 1973

APPROVED:

Redacted for Privacy

Professor of Chemistry
in charge of major

Redacted for Privacy

Chairman of Department of Chemistry

Redacted for Privacy

Dean of the Graduate School

Date thesis is presented Nov 22, 1972

Typed by Neita DeJong for Timothy Dean Ziebarth

ACKNOWLEDGEMENTS

The author would like to express his appreciation to the following for moral and financial assistance given over the last eight years: Dr. J. Jutila, Department of Botany and Microbiology, Montana State University; Dr. P. W. Jennings, Department of Chemistry, Montana State University; Dr. R. B. Kinnel, Hamilton College; fellow graduate students Tom Hardy and Brian Stevenson; the authors parents, wife, and family; a special debt of gratitude is owed Dr. P. K. Freeman for his help and guidance during the period of graduate training; the National Science Foundation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

REACTIVE INTERMEDIATES IN THE TETRACYCLO-[3.3.0.0^{2,7}.0^{4,6}]OCTANE, THE TETRACYCLO[3.3.0.0^{2,4}.0^{3,7}]-OCTANE, AND RELATED RING SYSTEMS CONTAINING THE NORBORNANE SKELETON

Introduction

This thesis is divided into three parts. The first two describe the synthesis and chemistry of three novel polycyclic bridged hydrocarbons, tetracyclo[3.3.0.0^{2,7}.0^{4,6}]-octane, tetracyclo[3.3.0.0^{2,4}.0^{3,7}]octane, and tricyclo-[3.3.0.0^{3,7}]octane, all of which were first prepared in our laboratories in a continuing program devoted to the synthesis and chemistry of small ring systems.

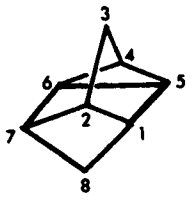
Part III describes a study of free radical hydrogen abstraction from bridged polycyclic hydrocarbons containing the norbornane skeleton. This research stemmed from observations made concerning the free radical reactivity of the three hydrocarbons in Parts I and II, and <u>exo</u>- and <u>endo</u>-tricyclo[3.2.1.0^{2,4}]octane which were studied by R. S. Raghavan.

Part I

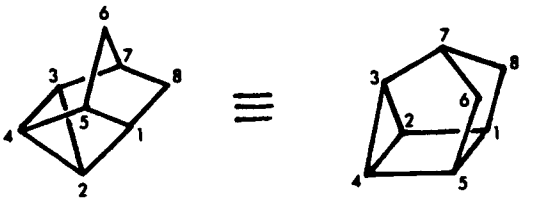
SYNTHESIS AND CHEMISTRY OF TETRACYCLO[3.3.0.0^{2,7}.0^{4,6}]OCTANE AND TETRACYCLO[3.3.0.0^{2,4}.0^{3,7}]OCTANE

Introduction

The two title hydrocarbons 1 and 2 are interesting for a number of reasons. Both have C_s symmetry. Isomer 1 contains one unique and two equivalent norbornyl rings as well as cyclopropyl, cyclobutyl, nortricyclyl, bicyclo[2.1.1]-hexyl, endo-tricyclo[3.1.1.0^{2,4}]heptyl, and exo-tricyclo-[3.1.1.0^{2,4}]heptyl moieties. Tetracyclic 2 also contains two equivalent norbornyl rings in conjunction with cyclo-propyl, cyclobutyl, bicyclo[2.1.0]pentyl, and two equivalent endo-tricyclo[3.2.1.0^{2,4}]octyl moieties. These included ring systems are all of current interest and an assessment of their relative contribution to the overall chemistry of 1 and 2 could be made by a thorough study of these hydrocarbons.

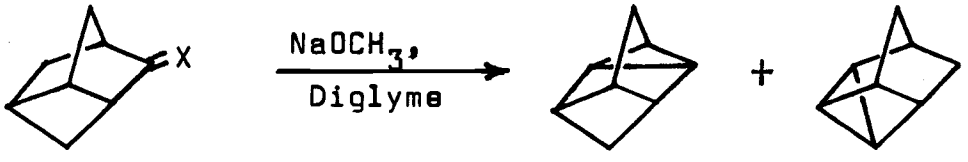


1



2

The first synthesis of the [3.3.0.$0^{2,7}$.$0^{4,6}$] and the [3.3.0.$0^{2,4}$.$0^{3,7}$] ring systems was reported by Freeman, Rao, and Bigam (1), who observed concurrent formation of parent hydrocarbons 1 and 2 in a yield ratio of 30:15 in the base induced thermal decomposition of tricyclo[3.2.1.$0^{3,6}$]octan-2-one p-toluenesulfonylhydrazone 3-NNHTs. This tosylhydrazone was prepared by extending the previously reported

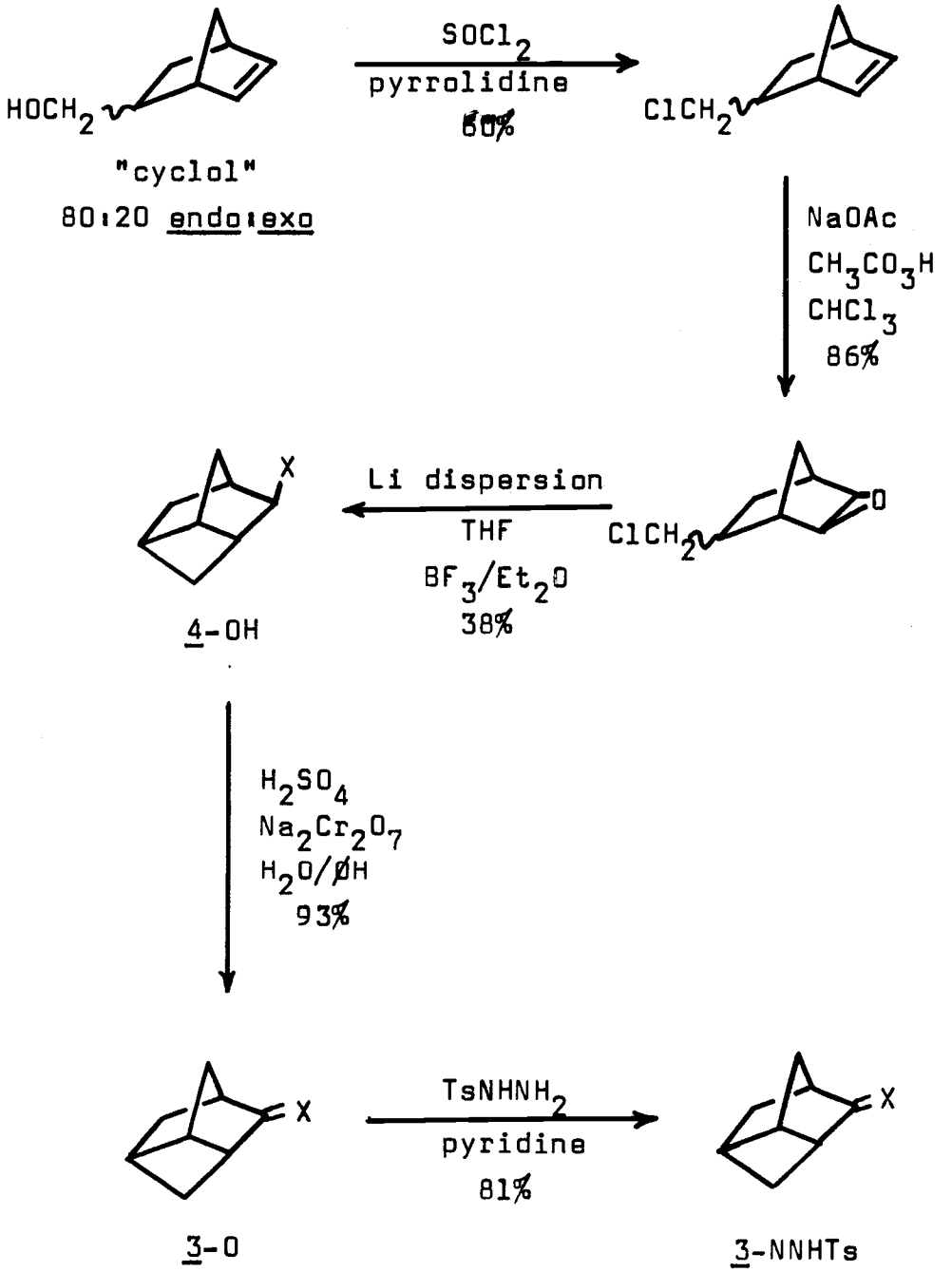


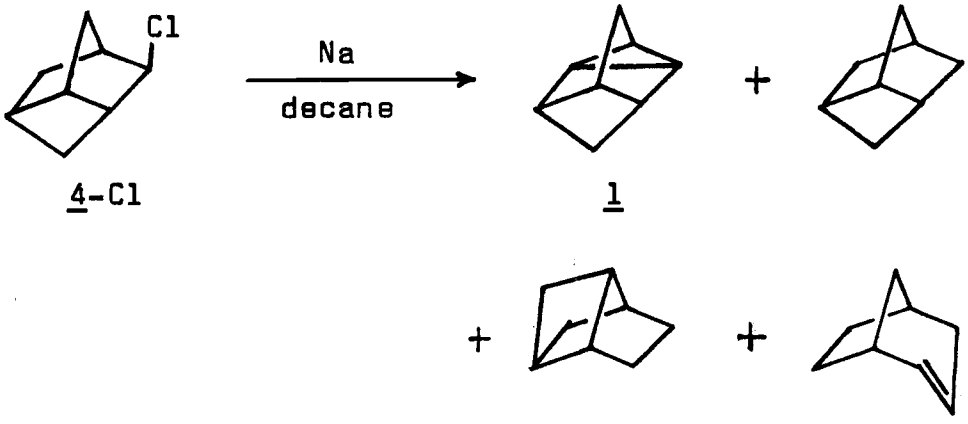
3-NNHTs 1 2

synthesis of 2-tricyclo[3.2.1.$0^{3,6}$]octanol 4-OH (2) via oxidation to ketone 3-O and subsequent conversion to the desired derivative 3-NNHTs (Scheme I). The structures of the two tetracyclic products were deduced from detailed nmr spin decoupling data (1,3) in conjunction with hydrogenolysis experiments (1,3) described later.

Rao (3) also observed the formation of 1 as a minor product in both the treatment of 4-Cl with sodium in decane

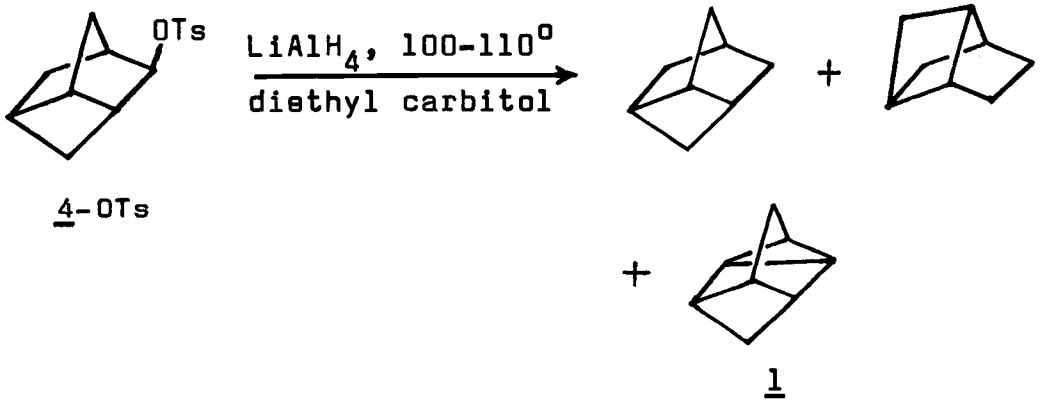
Scheme I


HOCH2
SOCl2
pyrrolidine
60%
ClCH2
"cyclol"
80:20 endo:exo
NaOAc
CH3CO3H
CHCl3
86%
X
Li dispersion
THF
BF3/Et2O
38%
O
ClCH2
4-OH
H2SO4
Na2Cr2O7
H2O/ØH
93%
X
TsNHNH2
pyridine
81%
X
3-O
3-NNHTs



4-Cl 1

(2% yield) and the solvolysis of 4-OTs in bis-(2-ethoxyethyl)-ether at 100-110° in the presence of lithium aluminum hydride (4% yield). Neither of the latter two reactions are partic-

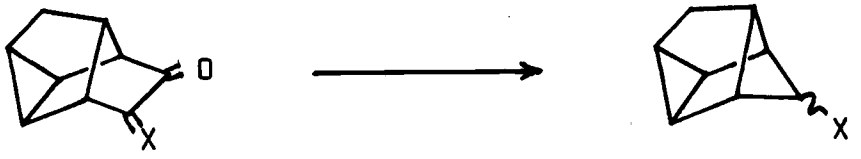


4-OTs 1

ularly impressive as viable synthetic routes to 1.

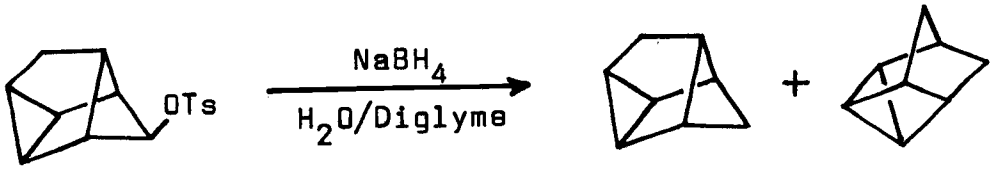
Subsequent to these initial observations by Rao, only two articles have appeared which provide alternate syntheses for 1, 2, or substituted 1 or 2. Coates and Yano (4) reported

the preparation of exo- and endo-C-8 substituted 1 by Wolff rearrangement of deltacyclanone 5-H_2 derived diazoketone 5-N_2 to give a mixture of epimeric acids 6-CO_2H. Subsequent ketonization to give 6-$COCH_3$ followed by Bayer-Villiger oxidation and lithium aluminum hydride reduction gave epimeric alcohols 6-OH. Conversion of exo-6-OH to the tosylate



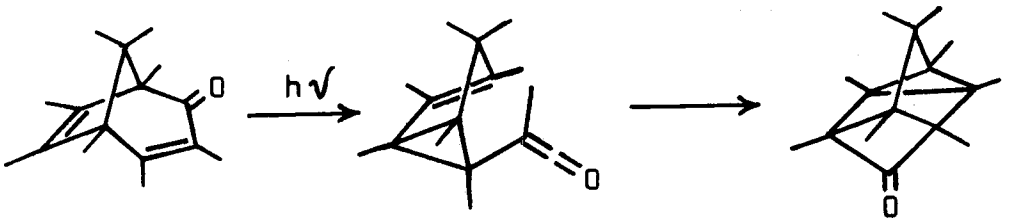
5 6

exo-6-OTs followed by solvolysis in 65% aqueous diglyme containing sodium borohydride afforded a 36:64 mixture of 1 and 2 in 17% yield.



exo-6-OTs 1 2

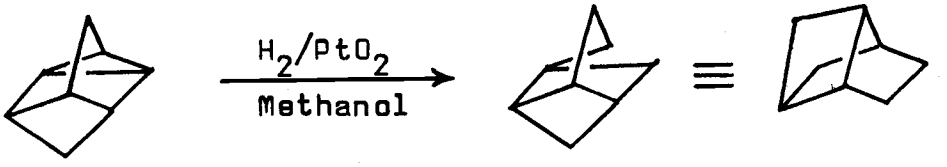
Another communication (5) described the novel photoisomerization of 7 to 9, presumably via ketene 8. This synthesis of the [3.3.0.$0^{2,7}$.$0^{4,6}$] ring system is limited, however, since it only occurs for permethylated substrate 7,



7 8 9

less substituted homologues of 9 having given either starting diene, or polymer upon irradiation in the absence of trapping agents (6).

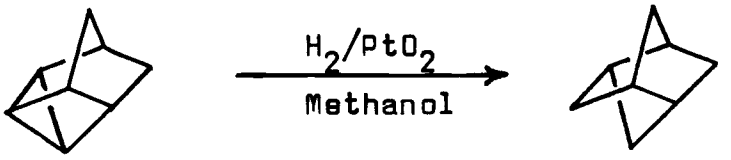
Evidence defining the chemistry of the title ring systems is limited. Rao observed that hydrogenolysis of 1 with Adam's catalyst in methanol resulted in exclusive formation of 10 (1,3), the unexpected regioselectivity apparently due to steric hindrance to C-5-C-6 bond cleavage imposed by the C-8 methylene bridge. Tetracyclic 2, on the other hand,



1 10

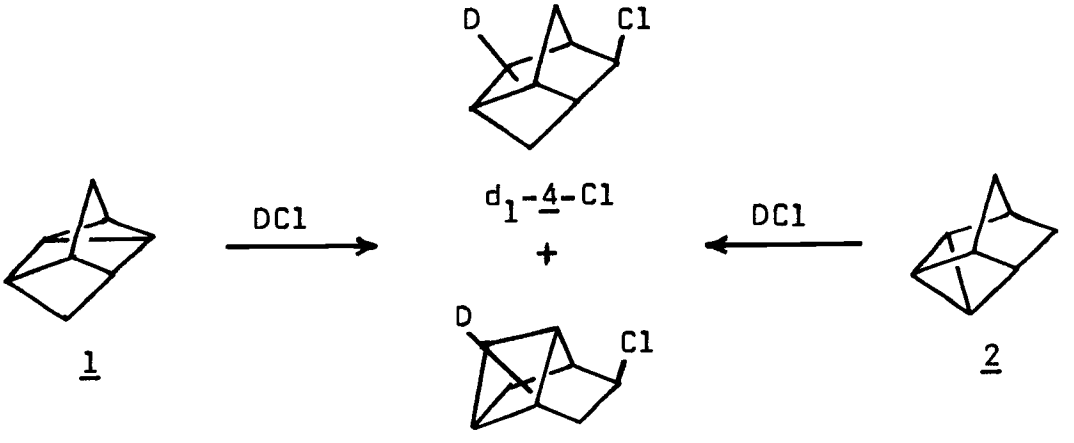
behaved predictably upon similar treatment, suffering fission of the C-2-C-4 bond (a transannular bond of a bicyclo[2.1.0]pentane moiety and thus subject to facile

cleavage (7)) to yield tricyclo[3.3.0.$0^{3,7}$]octane 11, an unusually symmetric hydrocarbon whose physical properties and chemistry are the subject of Part II of this thesis.



2 11

Rao (3) also identified the major production from addition of DCl to both 1 and 2 as d_1-4-Cl. The minor product observed in each case was tentatively assigned structure 12. The implications of related observations are



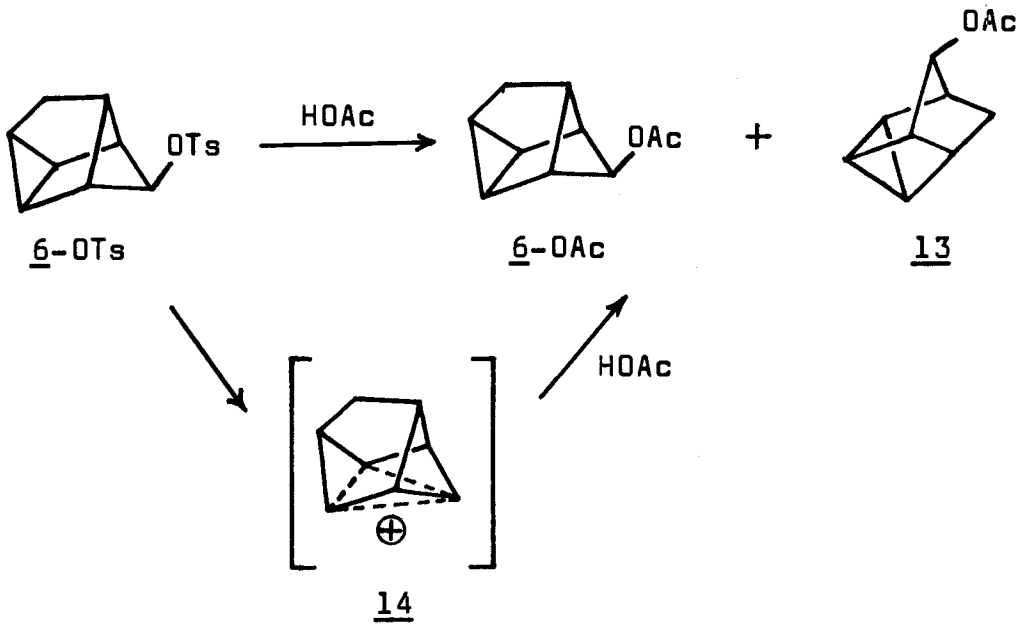
1 2

12

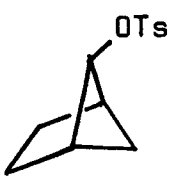
discussed in the results section in conjunction with the electrophilic addition of acetic acid to both 1 and 2.

The most recent study defining the chemistry of 1 and 2

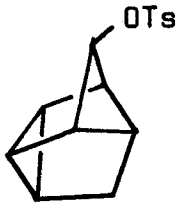
is that by Coates and Yano (4) who observed that solvolysis in acetic acid of exo-6-OTs gave exo-6-OAc as well as a rearrangement product 13 with considerable anchimeric assistance to ion formation (10^6 relative to exo-5-bicyclo[2.1.1]-hexyl tosylate 15 at 75^o(8)). This evidence suggested the



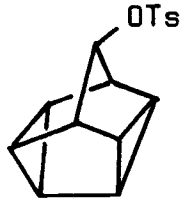
intermediacy of delocalized ion 14, an assertion reinforced by the formation of hydrocarbons 1 and 2 via the hydride trapping experiment described above. These results were deemed compatable with previous observations in other systems which can form the trishomocyclopropenyl cation (9) on solvolysis; the decreased reactivity of exo-6-OTs relative to 16 (10) or 17 (11) was ascribed to an increased restriction of the movement of the two cyclopropane carbons towards the incipient carbonium ion center in the transition state.



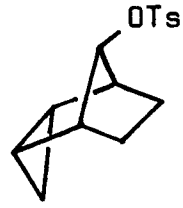
15



6-OTs



16



17

$k_{rel}^{25^o}$	(1.0)	10^6	10^7-10^9	10^{11}-10^{12}

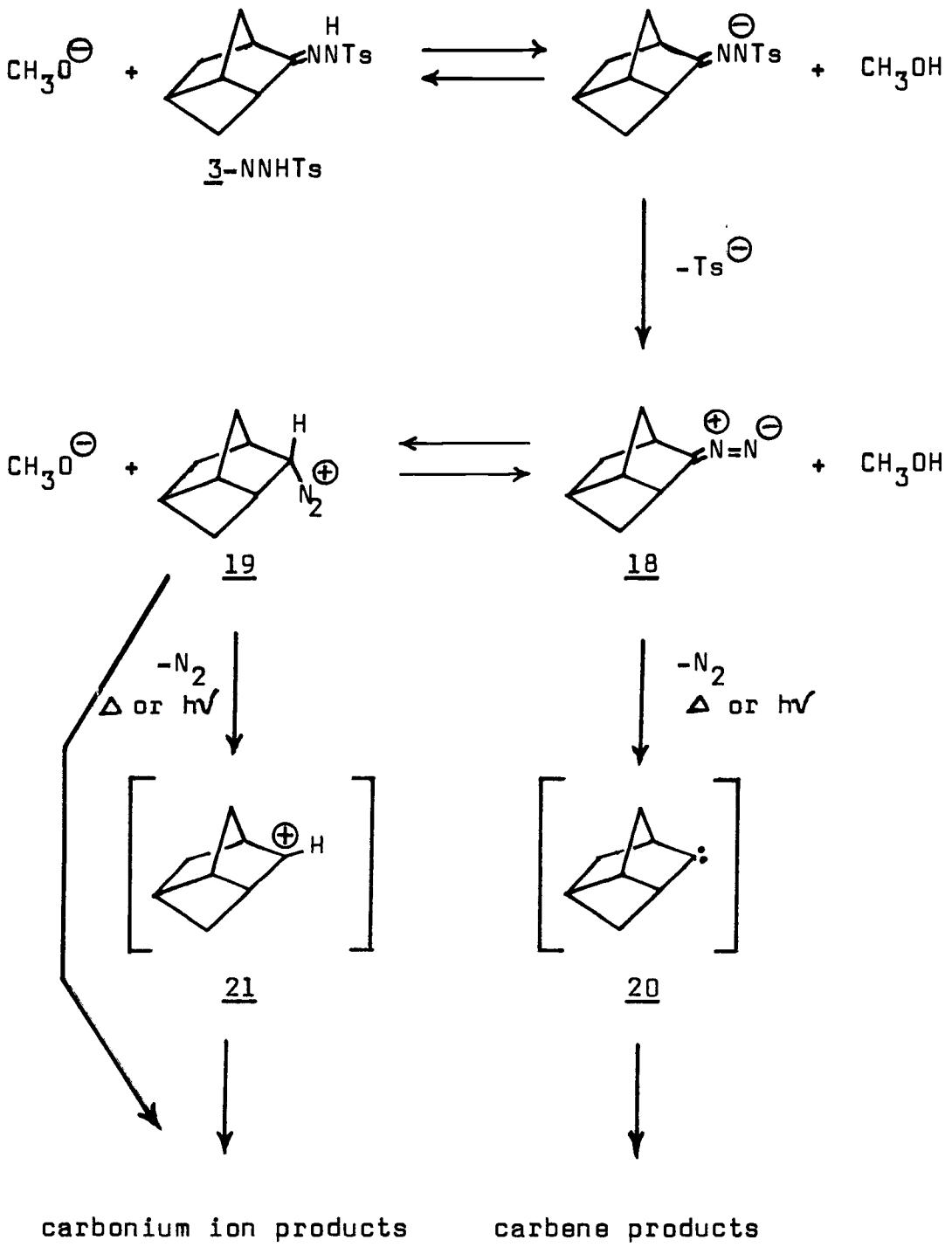
As a result of these introductory studies, three areas required further investigation. First, since the best available method for production of 1 and 2 remained the base catalyzed decomposition of tosylhydrazone 3-NNHTs, a reaction known to proceed via different mechanisms depending upon a number of reaction variables (12 - 17), a full mechanistic description of this process was in order. Second, the current best synthetic route to 1 and 2 (Scheme I) was only tentatively acceptable (4% and 2% overall yield of 1 and 2, respectively, in six steps from commercially available cyclol); the low yield and the lack of exclusive formation of 1 or 2 suggested attempts at alternate synthetic routes. Third, except as outlined above, a great deal of the chemistry of the two title hydrocarbons remained unexplored.

Before presenting our results concerning these three areas of interest, some further background pertaining to the base catalyzed decomposition of tosylhydrazones in general is in order. The favored mechanism for this reaction is shown in Scheme II using 3-NNHTs as an example of a typical tosylhydrazone. This formulation was offered by Shapiro, Duncan, and Clopton (15) based on their own observations as well as those of Powell and Whiting (12), Nickon and Werstiuk (16), Friedman and Shechter (18), and DePuy and Froemsdorf (19) in the camphor system, coupled with the work of Friedman and Shechter (20) and Wiberg and Lavanish (21) with cyclopropanecarboxaldehyde tosylhydrazone.

The key features of this mechanism are: 1) loss of p-toluenesulfinate anion in the rate determining step; 2) a rapid equilibrium between diazo 18 and diazonium ion 19 intermediates, the required proton furnished by a) the conjugate acid of the base employed, b) unreacted tosylhydrazone, or c) solvent; 3) loss of nitrogen by diazo compound 18 to form carbene 20; and 4) loss of nitrogen by diazonium ion 19 to form free carbonium ion 21, or an E_2 type elimination to form carbonium ion like products.

We have several reservations concerning the Shaprio mechanism outlined in Scheme II. First, the only evidence for assertion 1) above, offered by Powell and Whiting (12), is that cyclohexanone and camphor tosylhydrazones react at

Scheme II


CH3O⊖
+
H
NNTs
3-NNHTs
⊖
NNTs
+ CH3OH
-Ts⊖
CH3O⊖
+
H
N2⊕
19
⊕
N=N⊖
18
+ CH3OH
-N2
Δ or hν
-N2
Δ or hν
⊕
H
21
20
carbonium ion products
carbene products

the same rate with nearly identical activation energies. Since in their opinion formation of a carbene from diazo compound should be "anchimerically assisted" in the case of camphor tosylhydrazone, they concluded that the rate determining step must precede this fragmentation. There is simply no evidence for this argument. Furthermore, their contention that frequent isolation of diazo compounds reflects a rate determining loss of p-toluenesulfinate anion is erroneous.

Second, there is considerable doubt whether a diazo compound can be protonated by weak proton donors such as methanol (22).

There is also the fact, not mentioned in any published results, that sodium methoxide (the most commonly used base for effecting tosylhydrazone decompositions) is not appreciably soluble in aprotic solvents such as diglyme and diethyl carbitol.

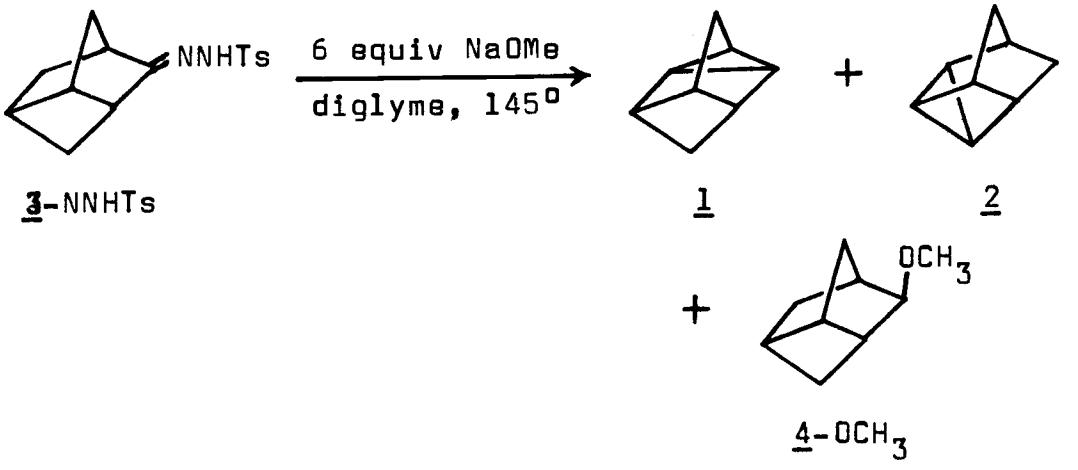
The suggested equilibrium between 18 and 19 must therefore be considered heterogeneous, if it occurs at all, and the overall mechanism viewed with some skepticism, although it is useful, since it successfully describes a wide variety of results (12-21, 23).

Results and Discussion

In order to define the precursor(s) of tetracyclic isomers 1 and 2 in the base catalyzed decomposition of tosylhydrazone 3-NNHTs, two sets of experiments were conducted. The first (summarized in Table I) was designed to distinguish between carbene and carbonium ion products by performing the decomposition under a selected variety of reaction conditions.

The tosylhydrazone used in the following studies was prepared by the method outlined in Scheme I, as described by Sauers and coworkers (2) and Rao (3).

Decomposition of 3-NNHTs under aprotic conditions similar to those previously reported (1) gave hydrocarbons 1 and 2 (Run 1, Table I), plus a heretofore unobserved ether in 22% yield. This ether was identified as exo-2-methoxytricyclo[3.2.1.$0^{3,6}$]octane 4-OCH_3 by independent synthesis



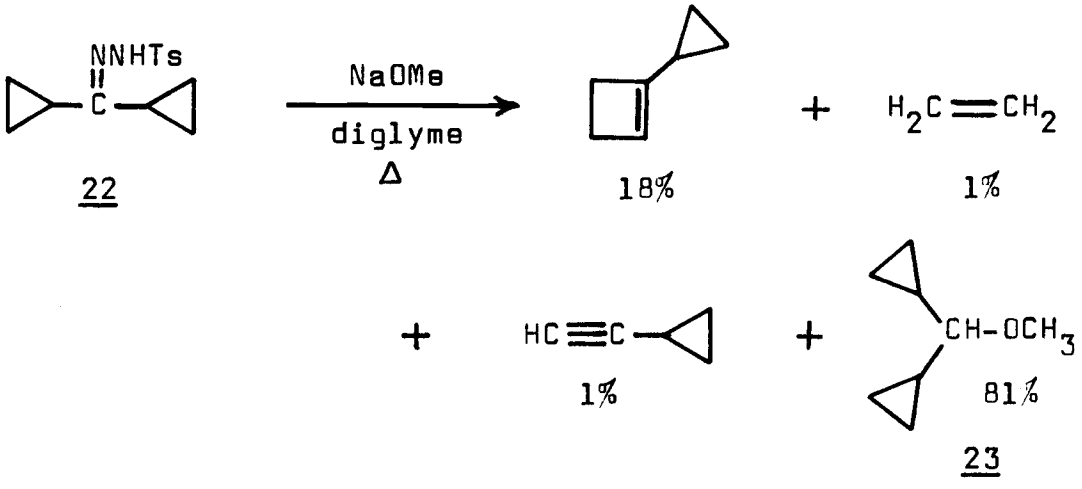
3-NNHTs 1 2 4-OCH_3

Table I. Dependence of product composition on reaction conditions in the decomposition of N-substituted tricyclo[3.2.1.$0^{3,6}$]octan-2-one p-toluenesulfonyl hydrazone 3-NNRTs.

Run	R	Conditions	equiv/base	[1]/[2]	% yield 1+2	% yield 4-OMe	% yield 4-OiPr
1	H	Diglyme, 145°	6/NaOMe	1.96	50	22	
2	H	Diglyme, 145°	1.25/NaH then 6/NaOMe	2.07	24	none	
3	H	Diethyl Carbitol, 145°	6/NaOMe	2.01	29	17	
4	H	Ethylene Glycol, 145°	6/NaOMe	22.4	8	3	
5	Li	200°	-	1.64	78		
6	Li	160°	-	1.63	76		
7	Li	Diglyme, hν, 20°	-	2.03	3		
8	H	Diglyme, 145°	8/Al(OiPr)$_3$	18	13		44

from corresponding alcohol 4-OH as described in the experimental section.

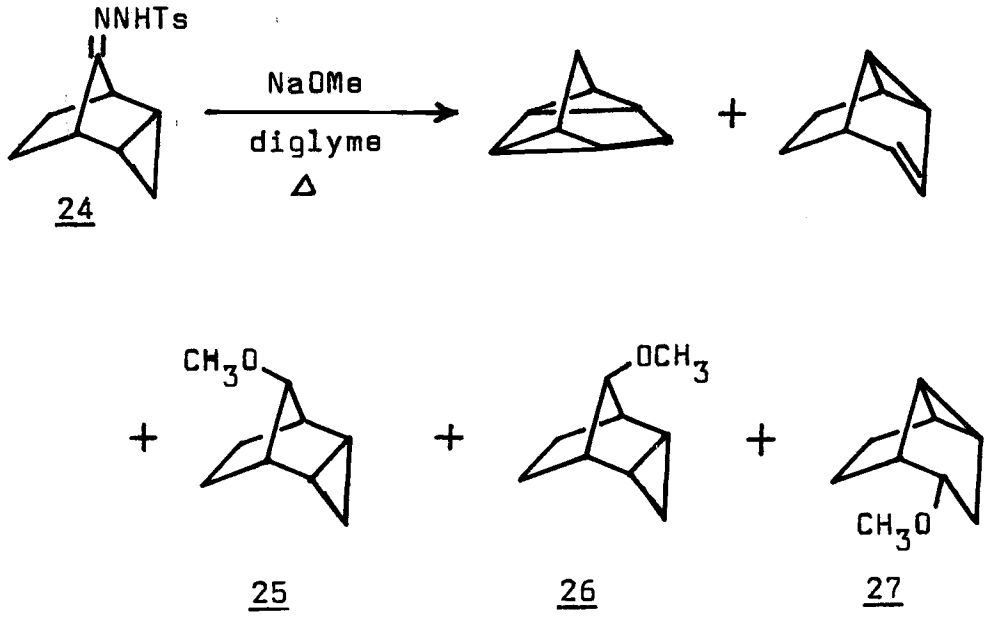
Previous observations of intermolecular products in the Bamford-Stevens reaction when conducted under aprotic conditions have only been made in this laboratory: in 1969, formation of ether 23 was observed as the major product of the methoxide ion induced decomposition of tosylhydrazone 22 (24),



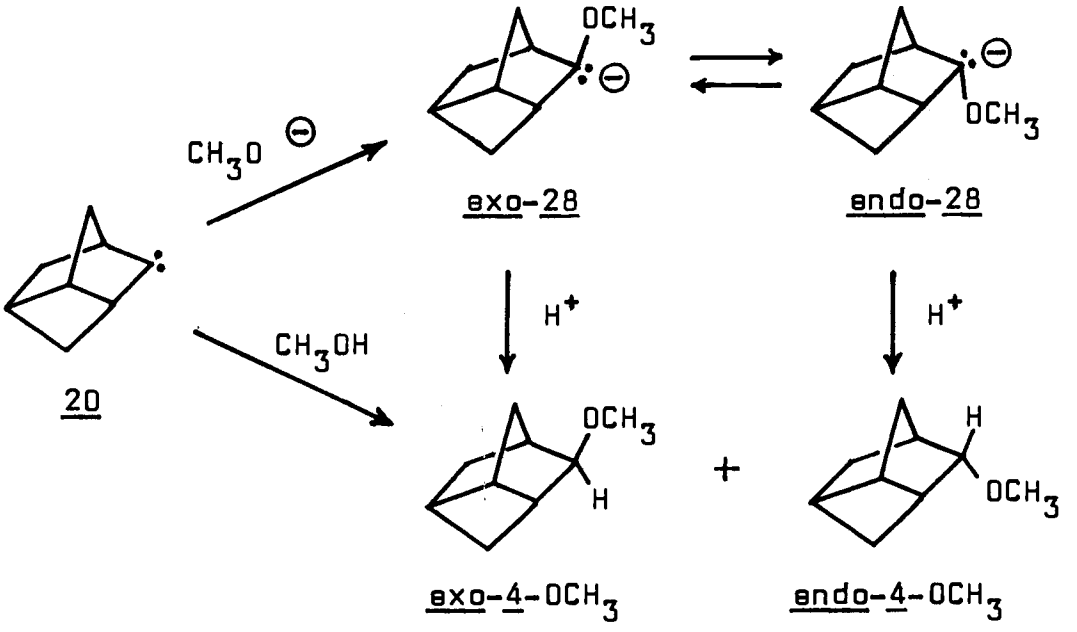
22

23

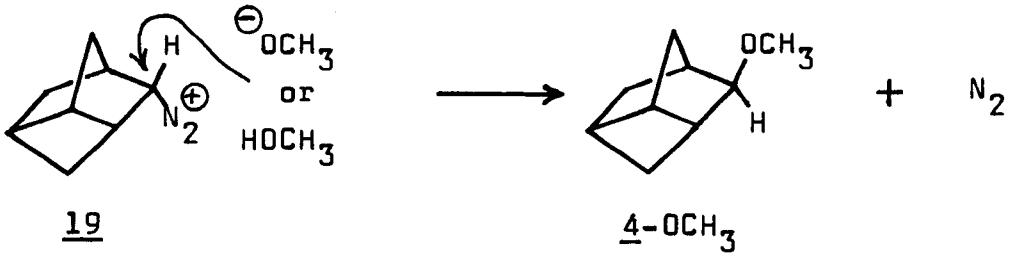
and in 1971, Freeman, Raghavan, and Kuper reported the formation of methyl ethers 25, 26, and 27 in the decomposition of tosylhydrazone 24 (25).



Four distinct pathways for ether formation are postulated. The first is by reaction of a free carbene with either the methoxide ion or methanol of neutralization, the stereochemistry of the product determined in the former case either by the relative stabilities of anions exo-28 and endo-28 and/or the relative rates of protonation of exo-28 and endo-28, and in the latter case by the steric interaction of methanol with the substrate carbene 20.



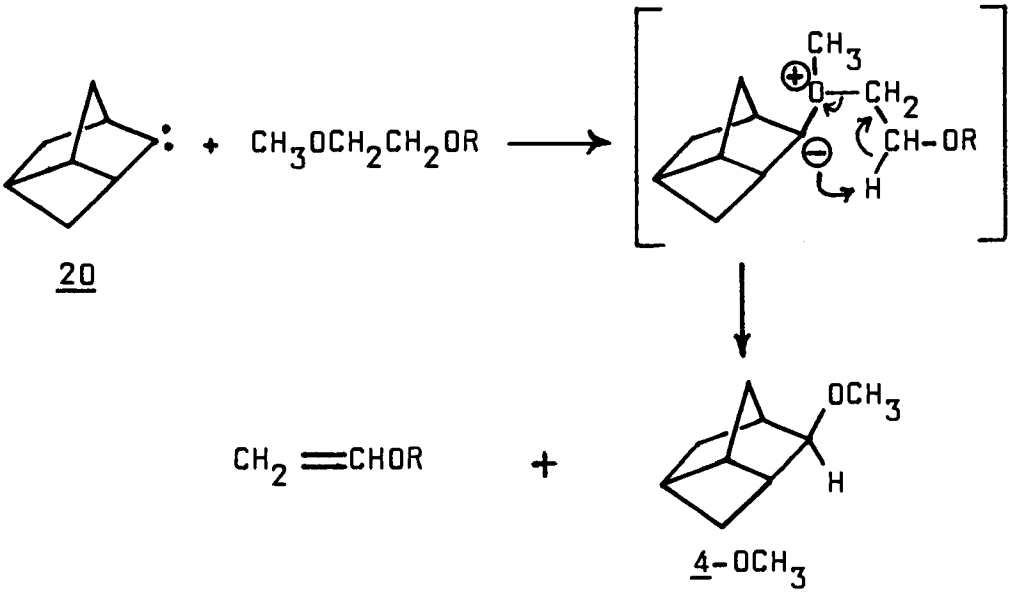
The second discrete mechanism is reaction of methoxide ion or methanol with diazonium ion 19, the stereochemistry of the product being determined by the stereochemistry of ion 19.



The third possible pathway for formation of ethers in an aprotic Bamford-Stevens reaction is via capture of methanol or methoxide ion by carbonium ion 21, the stereochemistry of the resulting ether determined by steric

accessibility of the two faces of the incorporated sp^2 carbon.

A fourth mechanism would entail reaction of bivalent intermediate 20 with the solvent diglyme via an intermediate ylide, in a manner analogous to previous examples (26).



20

4-OCH_3

Identification of the mechanism responsible for formation of ether 4-OCH_3 was accomplished by experiments summarized as Runs 2 and 3 in Table I. Lack of ether formation under conditions of high methoxide ion concentration and no proton source (Run 2) in concert with the observation of methyl rather than ethyl ether in Run 3 rule out a carbene precursor for 4-OCH_3. A carbonium ion or diazonium ion mechanism is therefore indicated. This conclusion is similar to that derived in a totally different way from data describing the decomposition of tosylhydrazone 24 (25).

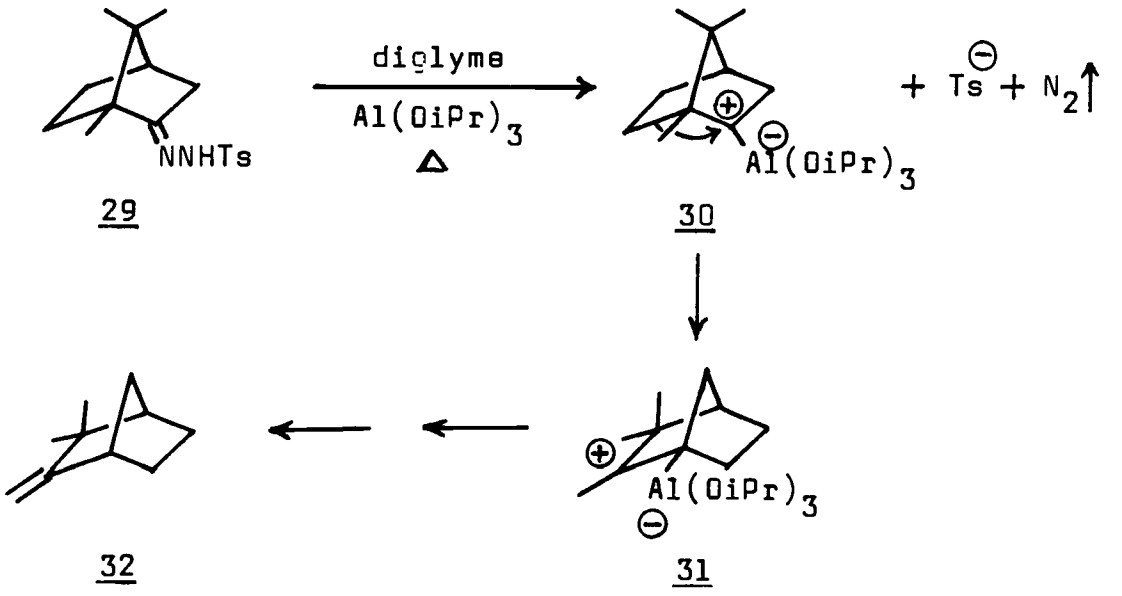
With the products of Run 1 identified, it was clear

that even when conducted under typical carbene conditions (15,23) the Bamford-Stevens reaction incorporated a substantial ionic component, at least in the system in question. Diazo compound 18 was therefore generated and decomposed in the absence of a proton source both thermally (Runs 2, 5, and 6) and photolytically (Run 7), both in the presence of (Runs 2 and 7) and in the absence of (Runs 5 and 6) solvent. From these experiments it is clear that bivalent intermediate 20 produces both 1 and 2 in a ratio of 1.64:1 via intramolecular insertion, a ratio independent of moderate changes in temperature and mode of generation, but curiously dependent upon the presence of solvent. The latter observation can be explained either by considering the solvent as a proton source, or by invoking the interesting possibility of a solvation effect on either the carbene insertion step, or the free energy of the carbene itself.

The effect of a highly protic medium on the reaction course was investigated by performing the decomposition of 3-NNHTs in ethylene glycol (Run 4) (17). Both tetracyclic isomers were produced, but with vastly increased preference for formation of 1 and a lower overall yield. Apparently a new product determining intermediate had been formed which, according to the mechanism in Scheme II, must be either diazonium ion 19 or carbonium ion 21.

Shapiro found (15) that he could duplicate product ratios observed under highly protic reaction conditions in

the decomposition of camphor tosylhydrazone 29 by performing the reaction in an aprotic medium using aluminum isopropoxide as the required base. This phenomenon he attributed to the formation of carbenoid 30 which, upon Wagner-Meerwein



29 30 31 32

rearrangement to 31 and elimination, gave camphene 32, the typical carbonium ion product in the camphor system. Run 8 provided similar reaction conditions for the substrate under study, and indeed, resulted in a 1 to 2 ratio similar to Run 4. This observation correlates with the results obtained by Rao (3) for the reaction of 4-Cl with sodium in decane, a reaction which can also produce a carbenoid intermediate (27).

In order to verify the conclusions drawn from the data in Table I, a second set of experiments was conducted, the results of which are summarized in Table II. Based on the

Table II. Decomposition of N-d_1-Tricyclo[3.2.1.$0^{3,6}$]octan-2-one p-toluenesulfonyl hydrazone 3-NNDTs in tetraglyme at 160° with various equivalents of sodium methoxide.

Run	equivalents NaOMe[a]	% 1 formed[b]	% 2 formed[b]	% d_1 1[c]	% d_1 2[c]
1	0.48	86	14	46 ± 4[d]	30 ± 6
2	1.07	87	13	31 ± 2	15 ± 2
3	1.97	78	22	16 ± 2	7 ± 2
4	3.16	69	31	5 ± 1	2[e]
5	11.62	62	38	3 ± 1	2 ± 1

[a]Relative to the amount of tosylhydrazone 3-NNDTs. [b]Average relative percent as determined by weighing respective peak areas obtained in triplicate from vpc analysis. [c]Inability to remove the P-1 peak at lowest operable electron energy resulted in an approximate correction based on the observation of 15 ± 1% P-1 in 1 and 17 ± 1% P-1 in 2. [d]Errors are average deviations from three analyses. [e]Only one run.

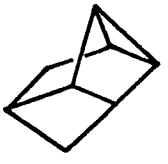
mechanism in Scheme II, replacement of hydrogen by deuterium on the nitrogen of tosylhydrazone 3-NNHTs (the only proton source if the decomposition is performed in an aprotic solvent) should yield carbonium ion products containing one atom of deuterium. Moreover, by altering the ratio of sodium methoxide to tosylhydrazone, a shift in product ratio and deuterium content should occur.

The results of this study reveal that under high methoxide ion concentration (or effective ion concentration since the reaction solution is heterogeneous), the product ratio of 1 to 2 is identical to that of Runs 1, 2, and 3 of Table I, and neither hydrocarbon contains deuterium, indicating a bivalent precursor for both.

At low sodium methoxide levels (Run 1, Table II), the product ratio shifts to favor formation of 1 and both isomers contain deuterium. This observation correlates with the decomposition performed in the highly protic solvent ethylene glycol.

In conclusion, the results of these experiments indicate that both tetracyclic coproducts of the base induced decomposition of tosylhydrazone 3-NNHTs can be formed from two distinct intermediates. Whereas carbene 20 makes little choice between formation of 1 or 2, the ionic precursor of these isomers favors formation of 1 by a factor of about 20:1.

The observed insertion pattern of bivalent intermediate 20 provides interesting new evidence bearing on the steric requirements for such intramolecular processes. Previous experiments (28) have been interpreted to indicate a preference for coplanarity of the Cα-Cβ bond with the C-H into which the carbene will ultimately insert (angle ∅ in Table III). Analyzed in this manner, 2-carbenatricyclo[3.2.1.$0^{3,6}$]-octane 20 is predicted to give predominate insertion at C-4 to yield 2, and approximately equal preference for insertion at C-8 and C-7 to yield 1 and unobserved tetracyclic product 33. Although the effect of the differences in angles ∅ could be modified somewhat by the relative strain in the transition

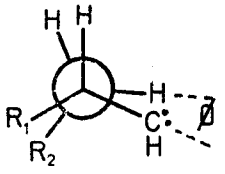


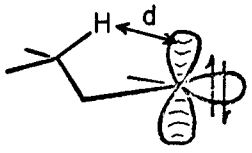
33

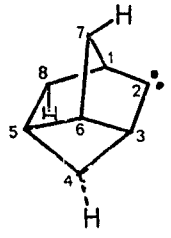
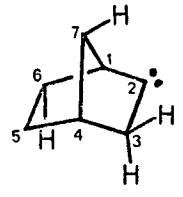
states encountered during product formation, Hammond's postulate indicates that such differences would be small. Clearly a simple analysis of bond angles is insufficient for systems in which the geometry of both carbene orbitals and labile C-H bond are fixed.

A better explanation for the insertion pattern found can be made based on the following two assumptions: first,

Table III. Selected interorbital distances and angles for 2-carbenanorbornane and 2-carbenatricyclo[3.2.1.$0^{3,6}$]-octane.





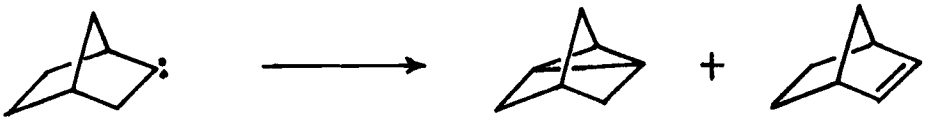
Carbene	Migrating H	Angle, Ø[a,b]	Distance d, Å[c,d]
	C_4 endo	30°	1.46 ± 0.04
	C_8 endo	54°	1.54
	C_7 syn	60°	1.81
	C_6 endo	54°	1.53
	C_3 exo = C_3 endo	(38°)[e]	1.97
	C_7 syn	60°	1.73

[a]Angles Ø measured as prescribed by Richey and Hill (28) using Dreiding models. [b]Estimated error = ± 3°. [c]Distance d measured from the nucleus of the hydrogen listed to a point 1.54 Å from the nucleus of the divalent carbon along the axis of the vacant p orbital using Dreiding models. [d]Estimated error = ± 0.04 Å. [e]The angle between the vacant p orbital at C-2 and the exo or endo C-3-H bond.

the carbene generated is an sp^2 hybrid with the p orbital vacant (29); second, the preference for hydride migration or C-H insertion is determined on the basis of proximity of adjacent hydrogens to the empty p orbital of the divalent carbon.

Analyzed in this manner (Table III), intermediate 20 is predicted to give approximately equal amounts of C-4 and C-8 insertion, and far less of isomer 33. This prediction, when modified by the realization that 2 contains a bicyclo-[2.1.0]pentyl moiety and 1 does not, is indeed correlative with the empirical insertion pattern.

This type of analysis can be applied not only to remote C-H insertion, but to the process commonly called hydride migration as well. For example, the preference for C-6 rather than C-3 insertion by 2-carbenanorbornane 34 (30) is somewhat puzzling, since β hydride migration is normally preferred over remote C-H insertion in aliphatic carbenes (29). The interorbital distances defined above and presented



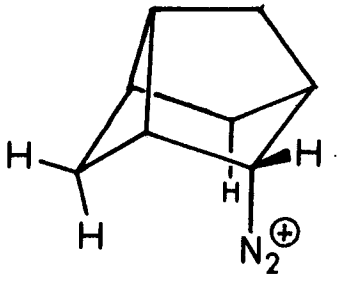
34 99.5% 0.5%

in Table III, however, successfully predict that for 2-norbornylidene, transannular insertion to form the nortricyclene

ring skeleton should be preferred over olefin formation.

Of final interest in this investigation is the discrepancy between the insertion pattern for carbene 20 and the products formed from ionic intermediates 19 or 21. Although they are different in overall charge, both bivalent 20 (in the singlet state) and trivalent 21 presumably have an sp^2 carbon at the reactive site and form products by electrophylic attack using the empty p-orbital at Cα.

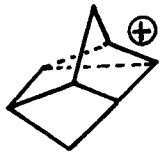
Two explanations are favored. The first is to assume that Nickon and Werstiuk (16) were correct in asserting that a diazonium ion is the only ionic intermediate formed in the Bamford-Stevens reaction; the hydrocarbon products arise from this intermediate by a preferred concerted syn elimination of H^+ and N_2. Models indicate that in 21, only the axial C-8-H bond remains syn-periplanar with the C-N_2^+ bond, the C-4 hydrogen having been distorted from true axial direction in the cyclohexyl moiety in 21 by both its inclusion in a



19

four membered ring, and the C-7 methylene bridge. Thus such syn-elimination as was postulated (16) would occur to form 1 in preference over 2.

The second rationale for the discrepancy is to assume that the transition states for product formation from the ionic precursor of 1 and 2 are more sensitive to product free energies than the analogous transition states from bivalent intermediate 20, and, therefore, that the ionic intermediate is more stable than 20. Carbonium ion 21 could fill this role, since it is formed under acetolysis conditions with an estimated $10^{2.8}$ anchimeric assistance (2), presumably as a result of interaction of the C-1-C-8 bond with the developing positive charge. It is interesting that the

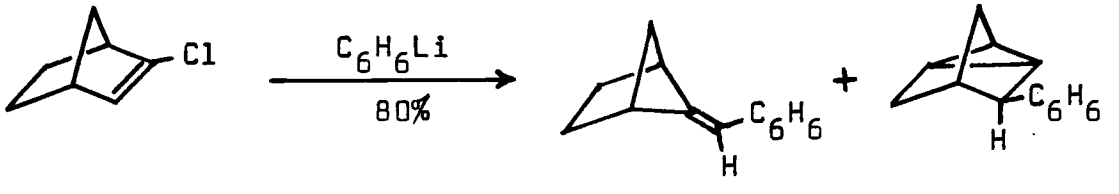


21

C-2-C-8 internuclear distance would be reduced in such an intermediate giving a second reason for favoring deprotonation from C-8 rather than C-4 to form 1 rather than 2. This type of deprotonation has been observed in the norbornyl system (31).

Since both the tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octyl 1 and the tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octyl 2 ring systems (1) were first prepared in this laboratory, we were naturally interested in providing unambiguous alternative (and if possible more efficient) synthetic routes to both isomers. Concentrating first on hydrocarbon 1, the availability of deltacyclanone 5-N_2 (32) and its homo-relationship to the desired ring system suggested an approach (Scheme III) involving ring contraction via the corresponding α-diazoketone. Significant progress in this reaction scheme had been made, when the successful completion of an analogous synthesis was published (4) thus confirming the identity of 1.

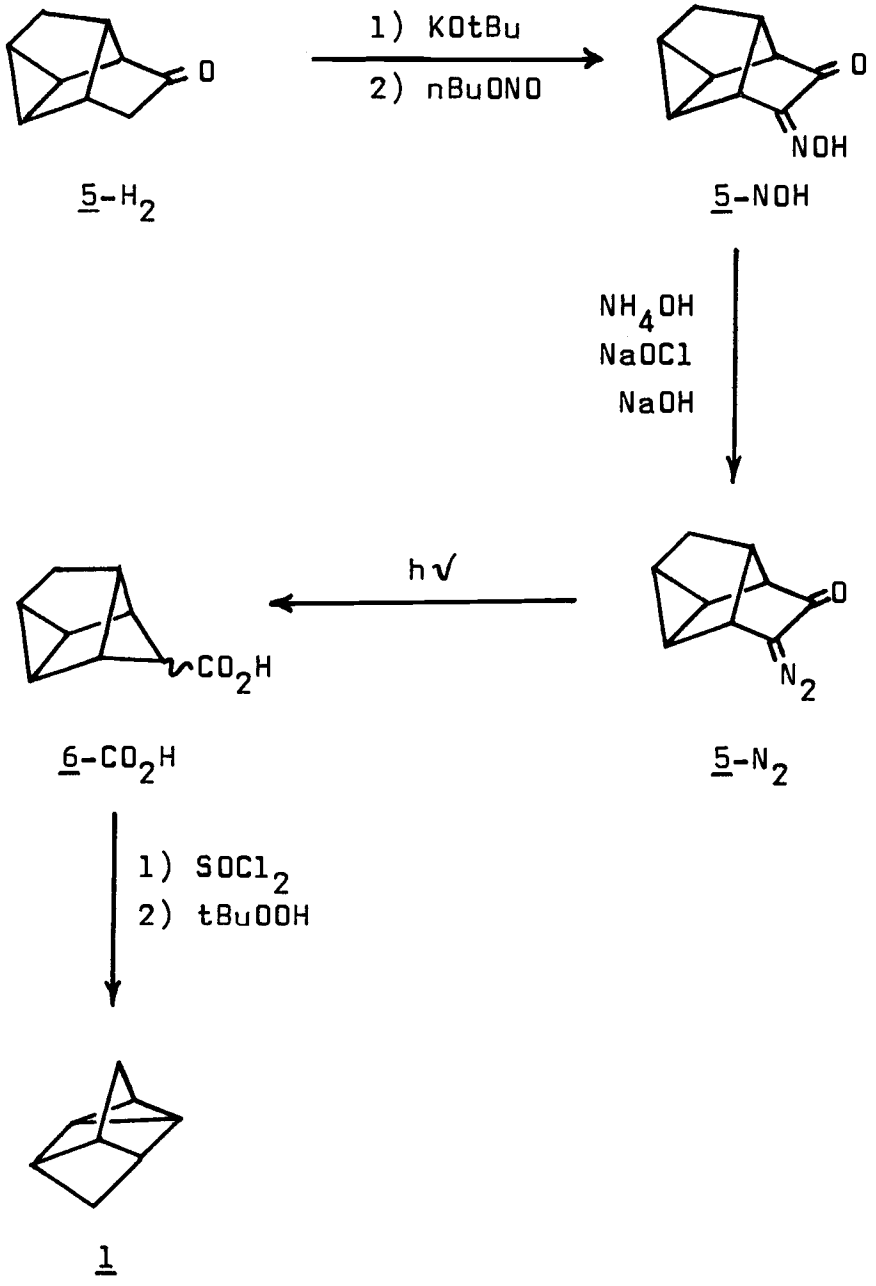
Concurrently with the above experiments we were also exploring a second method of preparing 1. In 1970, Gassman and Atkins (33) reported a novel ring contraction in the norbornyl system upon treatment of 2-chloronorbornene (35)

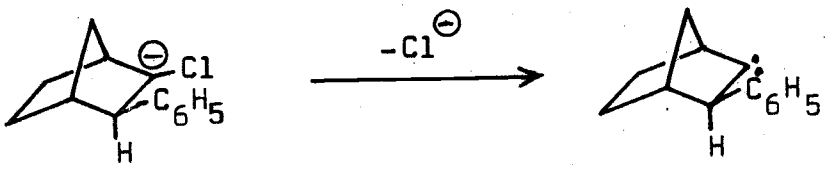


35 5 : 1

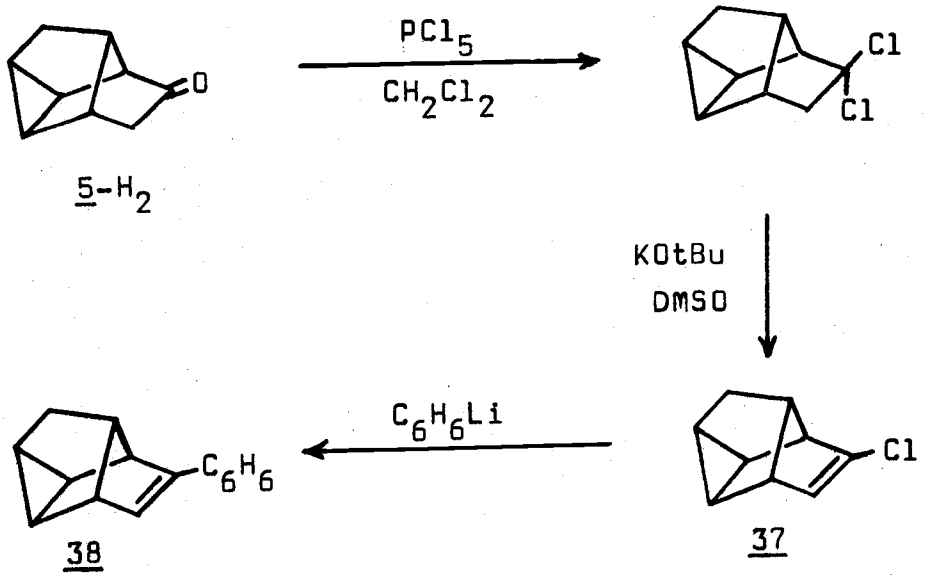
with phenyllithium. They assigned this result to the formation of bivalent intermediate 36, although 2-norbornylidene

Scheme III


1) KOtBu
2) nBuONO
NH4OH
NaOCl
NaOH
hν
5-H2
5-NOH
5-N2
6-CO2H
1) SOCl2
2) tBuOOH
1

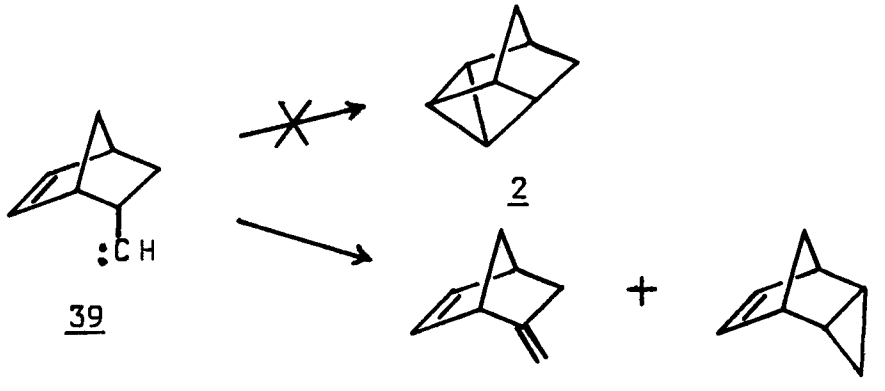


generated by conventional means (34) normally yields nortricyclyl products. In the deltacyclyl ring system, transannular insertion would be prevented, leaving ring contraction as the only alternative to an analogously produced intermediate. Unfortunately, preparation of the required vinyl chloride 37 followed by treatment with phenyllithium yielded exclusively olefin 38. No evidence for ring contraction was noted.



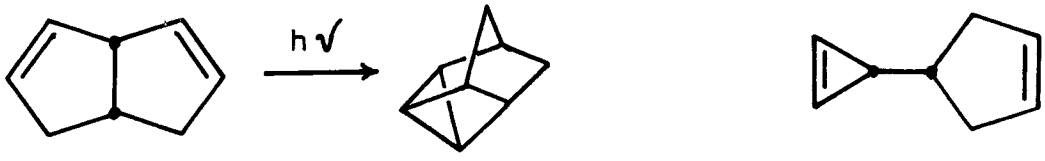
If indeed bivalent intermediates are formed in these reactions, they must be carbenoid in nature, and in the norbornane system prefer ring contraction over transannular insertion and hydride migration, but, because of additional product strain in the deltacyclane system, the reaction is limited to hydride migration.

Our efforts to develop a viable synthesis of tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2 have been considerably more successful. An inital attempt included generation of bivalent intermediate 39, the projected intramolecular addition to have yielded 2 directly (35). Unfortunately, only products arising from hydrogen migration (40) and endo-C-3-H insertion (41) were observed. The failure of 39 to form 2 is in agreement with the results of Kirmse and Grossman (36) who found that separation of the bivalent carbon from the olefinic function by two carbon atoms prevented intramolecular addition in open chain alkenylcarbenes.



39 2 40 41

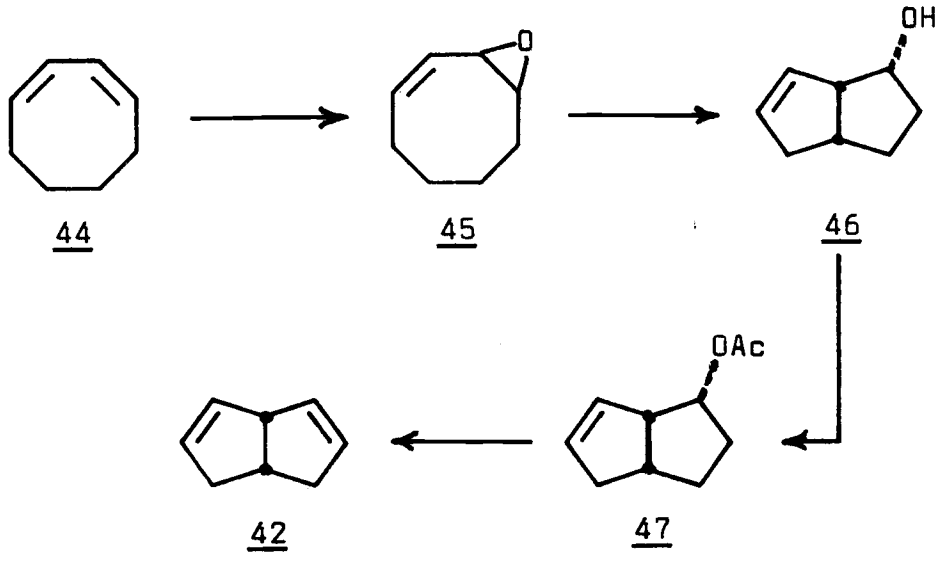
The photochemical synthesis we developed relies on the intramolecular $[_{\pi}2_s + _{\pi}2_s]$ cycloaddition (37) of diene 42. This method was chosen for formation of 2 because of the success of similar photolytic reactions (38), the apparent proximity of the two olefinic functions in 42 (Dreiding models indicate a C-2-C-8 internuclear distance of 2.56 Å), and the lack of a reasonable synthesis of alternative photolytic precursor 43.



42 2 43

Synthesis of key intermediate 42 was accomplished as shown in Scheme IV. Monoepoxidation of commercially available cis, cis-1,3-cyclooctadiene 44 and subsequent treatment of 45 with lithium diethylamide in ether yielded exclusively alcohol 46 by transannular carbene insertion (39). Formation of acetate 47 by treatment of 46 at reflux with acetic anhydride, followed by gas phase pyrolysis, yielded required diene 42 in an overall yield of 45%.

Scheme IV

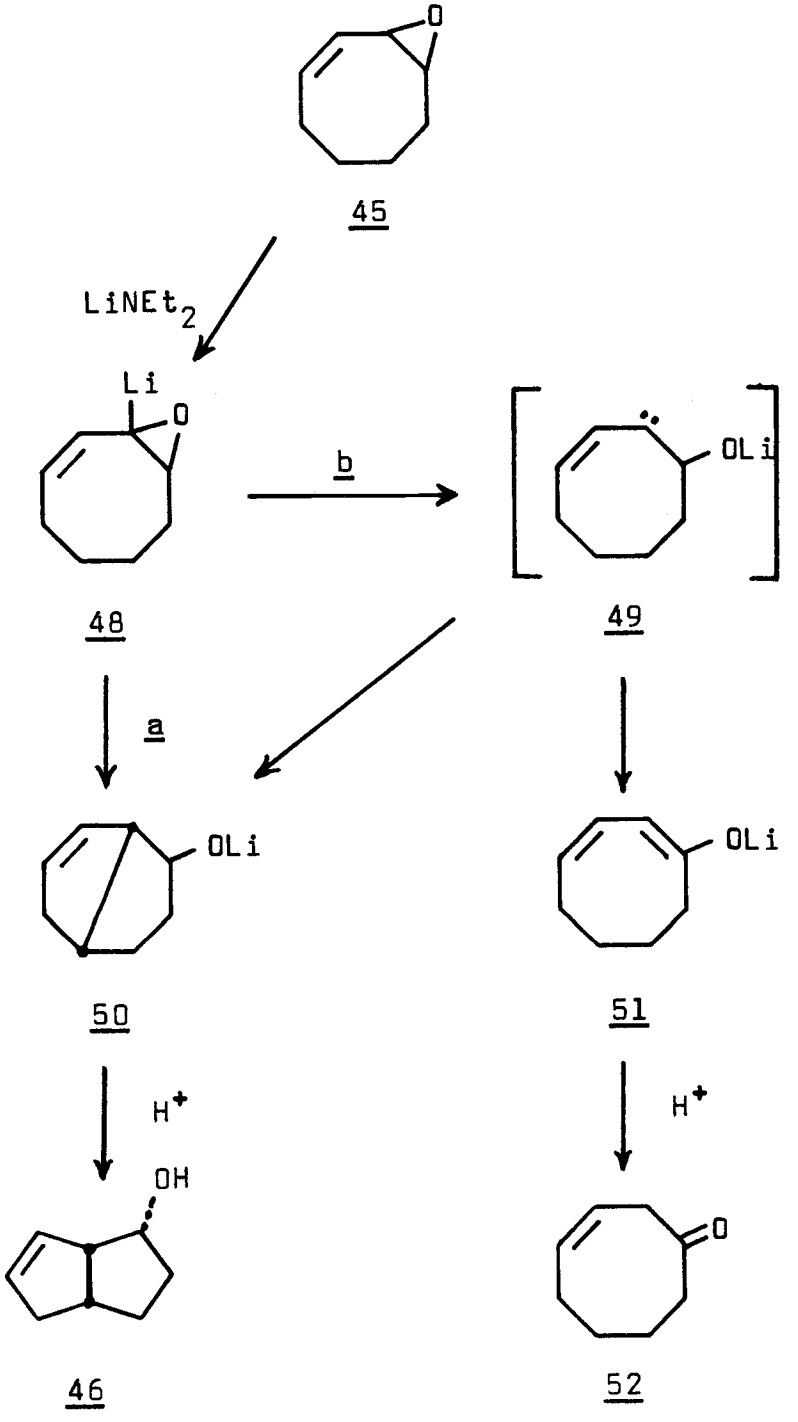


44 45 46 47 42

Two aspects of this synthetic scheme deserve further comment. First, the remarkable regio- and stereoselectivity displayed in the reaction of 45 with lithium diethylamide in refluxing ether has been credited to conformational stability of allylic lithioepoxide 48 (40), followed by a concerted elimination-insertion mechanism (path a, Scheme V) (39-41).

Formation of ketone 52 was also observed although data did not allow explicit assignment of its source (40). An alternative mechanism (path b, Scheme V) is more appealing, since both observed products derive from common intermediate 49. Preference for remote rather than β C-H insertion would result from rigidity imposed by delocalization of the unpaired electrons on the bivalent carbon. In such a

Scheme V



conformation, Dreiding models indicate proximity of transannular hydrogen to the empty carbene orbital, and concurrent near-orthogonality of the same orbital with the β C-H bond. The observed increased preference for formation of 46 relative to 52 is attributed to the lower reaction temperature employed.

Second, pyrolytic elimination of acetic acid from acetate 47, a reaction generally accepted to proceed by a unimolecular cis-elimination mechanism in the gas phase (42), yielded exclusively 2,7-diene 42. This substantiates the assigned (43) trans-configuration of the acetoxy group to the C-1 bridgehead hydrogen.

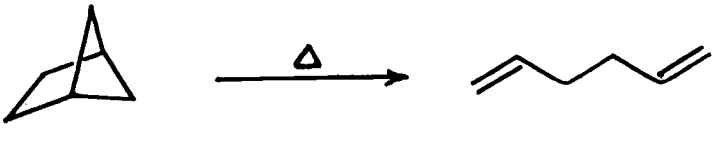
The photolytic ring closure of diene 42 to tetracyclo-[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2 was studied in some detail. Photolysis in pentane resulted in tetracyclic hydrocarbon formation at a rate twice that in ether. However, periodic removal of side products was necessary for completion of the reaction (43). Furthermore, attempts to obtain a ratio of 2:42 greater than 0.5 were unsuccessful. Irradiation in ether, on the other hand, resulted in a corresponding yield ratio of 1.6, proceeded to this point without filtration, and resulted in a higher absolute yield (22% vs. 8%) of desired adduct 2. Irradiation in the gas phase produced no reaction, irradiation in acetone and in the presence of benzophenone resulted in rapid loss of starting material with no concomitant production of 2, presumably due to oxetane

formation (44), and attempts to catalyze the reaction by CuCl (no 1:1 adduct of CuCl:42 could be obtained by the reported method for formation of CuCl:1,5-cyclooctadiene adduct (45)) were unsuccessful.

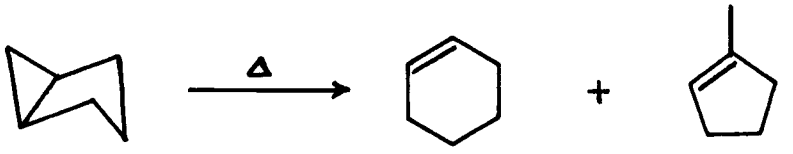
Overall, the yield of tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2 based on commercially available 1,3-cyclooctadiene 44 was 10%. This synthetic route has provided proof for the structure of the minor insertion product of 3-NNHTs, and greatly facilitated the investigations of the chemistry of 2 and 11 reported below, and in Part II of this thesis.

The gas phase pyrolytic behavior of both tetracyclic isomers 1 and 2 was studied with an aim toward examining thermal stabilities and primary modes of strain relief in each ring system.

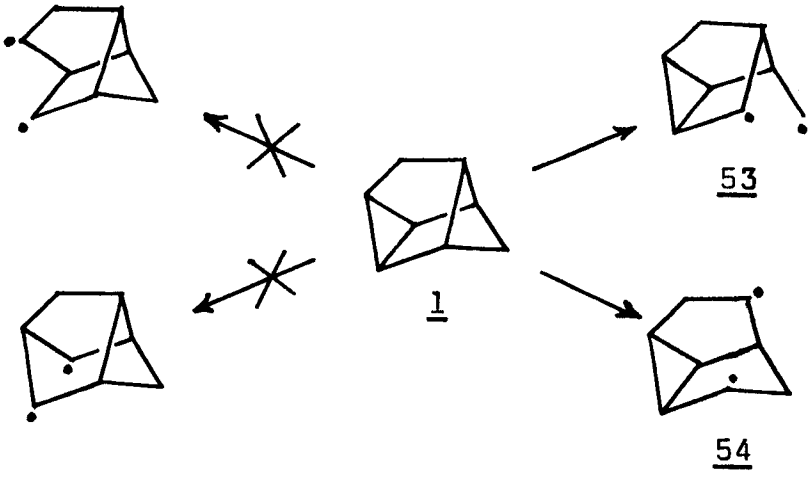
Tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane 1 was stable for three days at 295° but was 83% reacted after 89.5 hr at 320°. The first order rate constant for disappearance of 1 ($k = 6 \times 10^{-6}$ sec^{-1} at 317°) was nearly identical to that for the gas phase pyrolysis of bicyclo[2.1.1]hexane (46) ($k = 3 \times 10^{-6}$ sec^{-1} at 305°), but far greater than for pyrolysis of



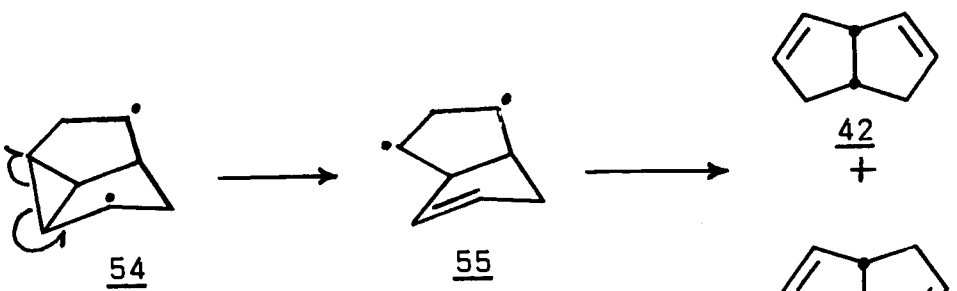
bicyclo[3.1.0]hexane to either cyclohexene ($k = 1.4 \times 10^{-8}$ sec^{-1} at 320^{o}) or methylcyclopentene ($k = 4.5 \times 10^{-9}$ sec^{-1} at 320^{o}) (47).



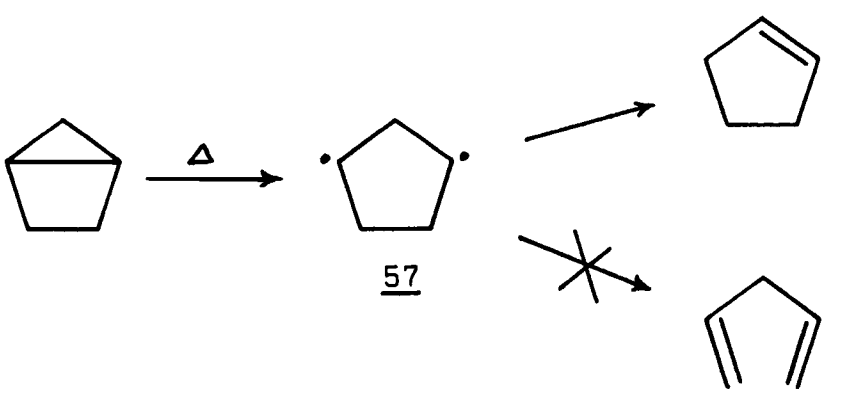
Since the $[3.3.0.0^{2,7}.0^{4,6}]$ ring structure contains both [2.1.1] and [3.1.0] skeletons, the rate data suggest that cleavage of either the C-1-C-2 or C-1-C-8 bond occurs preferentially over C-4-C-5 or C-5-C-6 bond fission in the rate determining step. Formation of diradical 54 would be preferred over intermediate 53 on the basis of primary vs. secondary radical stability.



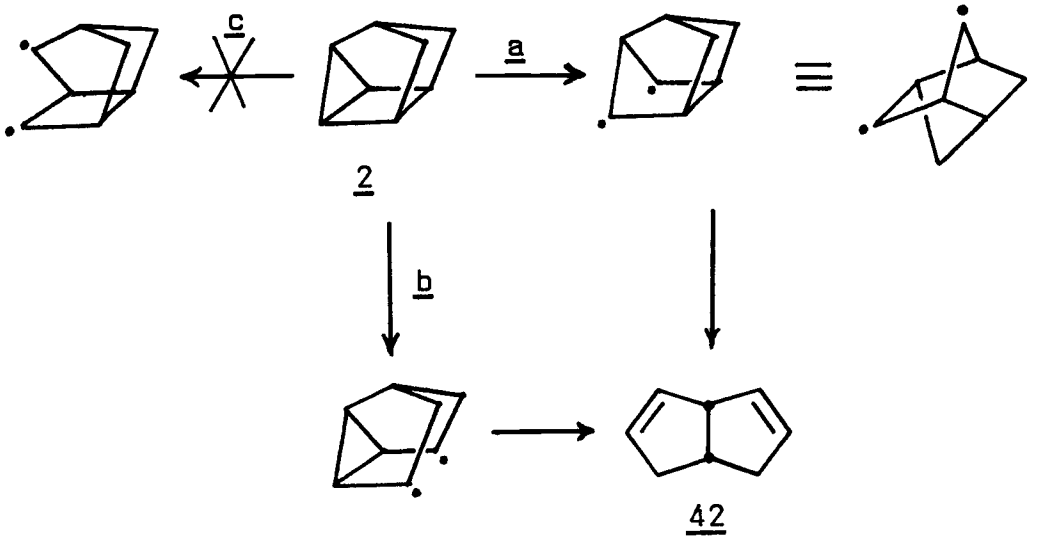
The contents of the pyrolysate resulting from thermolysis of 1 support this contention. The major isolable product was identified as a mixture of 2,6- and 2,7-cis-bicyclo[3.3.0]octadiene 42 and 56 by comparison of the ir and nmr spectra of this mixture to those of authentic samples (48). These olefins arise from diradical 54 as shown below. Formation of a cyclopentenyl moiety from 1,3-diradical 55



is analogous to the observed behavior of parent diradical 57, which forms cyclopentene rather than divinylmethane (49). Olefins 42 and 56 were not interconverted upon heating to 305° for 24 hours (48).



Tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2, although of remarkable stability for its compactness, was less stable than isomer 1. At 295°, 2 was two-thirds converted to a single product in only 13.5 hours. The first order rate constant for pyrolysis of 2 (2.05×10^{-5} sec^{-1} at 301°) is 25 times less than that for formation of cyclopentene from bicyclo[2.1.0]hexane (49) ($k = 5.6 \times 10^{-4}$ sec^{-1} at 301°), but 10^3 times more than for formation of cyclohexene from bicyclo[3.1.0]hexane (47). It would therefore seem that cleavage of the C-2-C-4 bond (path a) would be favored over cleavage of the C-2-C-3 bond (path c) in 2, since the former is a transannular bond of a [2.1.0] moiety.



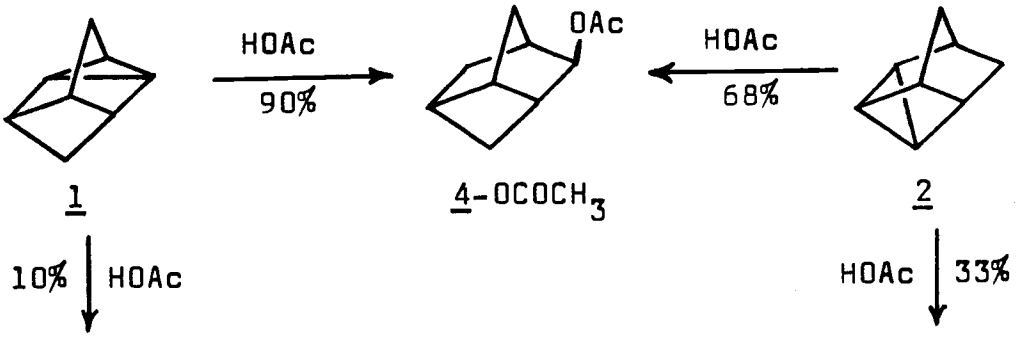
Although this hypothesis was substantiated by identification of the exclusive reaction product as diene 42, it should be noted that cleavage of the C-1-C-5 cyclobutyl bond (path b) also leads to 42. Either route would explain why the rate for pyrolysis of 2 is less than for bicyclo[2.1.0]pentane, since path a forms a diradical which has both trivalent carbons at the methylene position of a tricyclo[3.3.0.$0^{3,7}$]octyl ring system and thus would be expected to be highly strained due to angle distortion (see Part II of this thesis), and path b involves fission of a bond less strained that the one that, presumably, is broken in the rate determining step for pyrolysis of bicyclo[2.1.0]pentane (49).

Our interest in the development of a synthetic route to tricyclo[3.3.0.$0^{3,7}$]octane 11 (see Part II of this thesis and ref. 50) lead to an investigation of the electrophilic addition of acetic acid to the cyclopropyl moiety of both tetracyclic isomers 1 and 2. Acid catalyzed addition of acetic acid to three membered rings in a variety of substrates has been well studied by LaLonde and others (51-53). The mode of ring scission has been attributed to two factors, the strain associated with the molecule (52), and the production of the most stable carbonium ion (53), and can occur with or without the intervention of carbonium ions, depending upon the ring system incorporating the cyclopropyl moiety. Furthermore, it has been demonstrated that although the

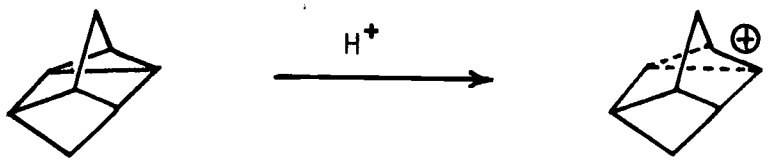
stereochemistry of initial addition of the electrophile H^+ cannot be predicted (51-53), the second step (nucleophilic addition of AcO^-) always proceeds via inversion (54) if a free carbonium ion is not formed.

With this background in mind, we subjected a mixture of 1 and 2 to an 0.08 N H_2SO_4 in glacial acetic acid solution, and observed the rates of disappearance of each isomer relative to a non-reactive internal standard. Surprisingly, tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane 1 reacted at a rate 25 times as fast as tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2. These results were unexpected since isomer 2 underwent both hydrogenolysis (1,3) and thermal rearrangement (see above) much more readily than 1. The factors controlling the rate determining steps in these reactions are clearly different.

The major product formed from acetic acid addition to both 1 and 2 was 4-$OCOCH_3$. This result was expected based on the DCl addition reactions performed by Rao (3). The minor product(s) formed in each case were not identified.

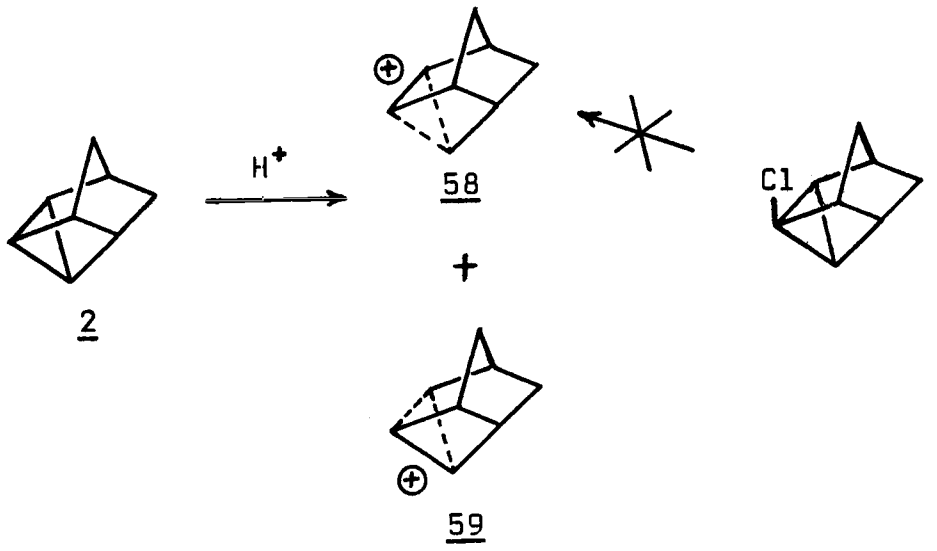


Since the greater reactivity of 1 relative to 2 in electrophilic addition is opposite that expected based on ring stability, the rates must be determined by resultant transition state free energies. It is interesting to note that nonclassical ion 21, the existence of which has been demonstrated (2), is formed directly by corner protonation of 1, but cannot be formed by simple protonation of 2 without



1 21

more extensive bond reorganization. Of the two nonclassical ions formed by protonation of 2, no evidence was found for 58 upon solvolysis of 2-chlorotricyclo[3.3.0.$0^{3,7}$]octane even though reorganization to the [3.2.1.$0^{3,6}$] system occurred (see Part II), and 59 is of unknown stability.

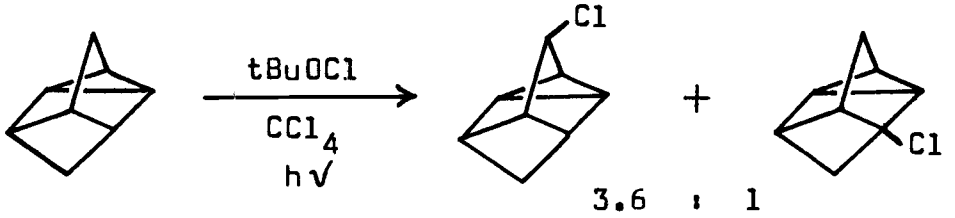


2 58 59

Since the bulk of our work concerning the [3.3.0.$0^{2,7}$.$0^{4,6}$] and the [3.3.0.$0^{2,4}$.$0^{3,7}$] ring systems was conducted prior to the report (4) of the carbonium ion interconversion of these systems, we were aiming at such a study ourselves because of the very trishomocyclopropenyl relationship observed. Photochlorination appeared promising as a means of functionalizing ring systems 1 and 2 to create solvolyzable chlorides. Initial experiments using chlorine as the chain transfer agent, however, failed to give monochlorides, since the rate for substitution was at least 100 times less than the rate for electrophilic addition to the cyclopropyl moiety in each ring system. We therefore turned to the chlorinating agent t-butyl hyprochlorite, since it does not add to three membered rings (55).

Photochlorination of tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane 1 with t-butyl hypochlorite in carbon tetrachloride yielded

two major and three minor monochlorides in a ratio of 7:16:3:58:8 by vapor phase chromatographic analysis. A parent ion mass corresponding to a molecular formula of C_8H_9Cl and lack of olefinic absorptions in ir and nmr spectra indicated that both major isomers were tetracyclic.



1 60 61

+ 3 unidentified minor chlorides

The 16% component contained no protons α to chlorine in the nmr, defining it as a bridgehead chloride. Substitution at C-2 and C-4 was ruled out because there are two distinct geminal couplings of 6 and 12 Hz. in the nmr spectrum of this component (Figure 1). Of the two remaining bridgehead positions, C-5 was excluded since the endo-C-8 proton (identifiable because of its distinct 6 Hz. geminal coupling in both this monochloride and in parent hydrocarbon 1) appears 70 Hz. downfield from its chemical shift in parent hydrocarbon 1. Theory (56) predicts for angles ∅ as defined below, the

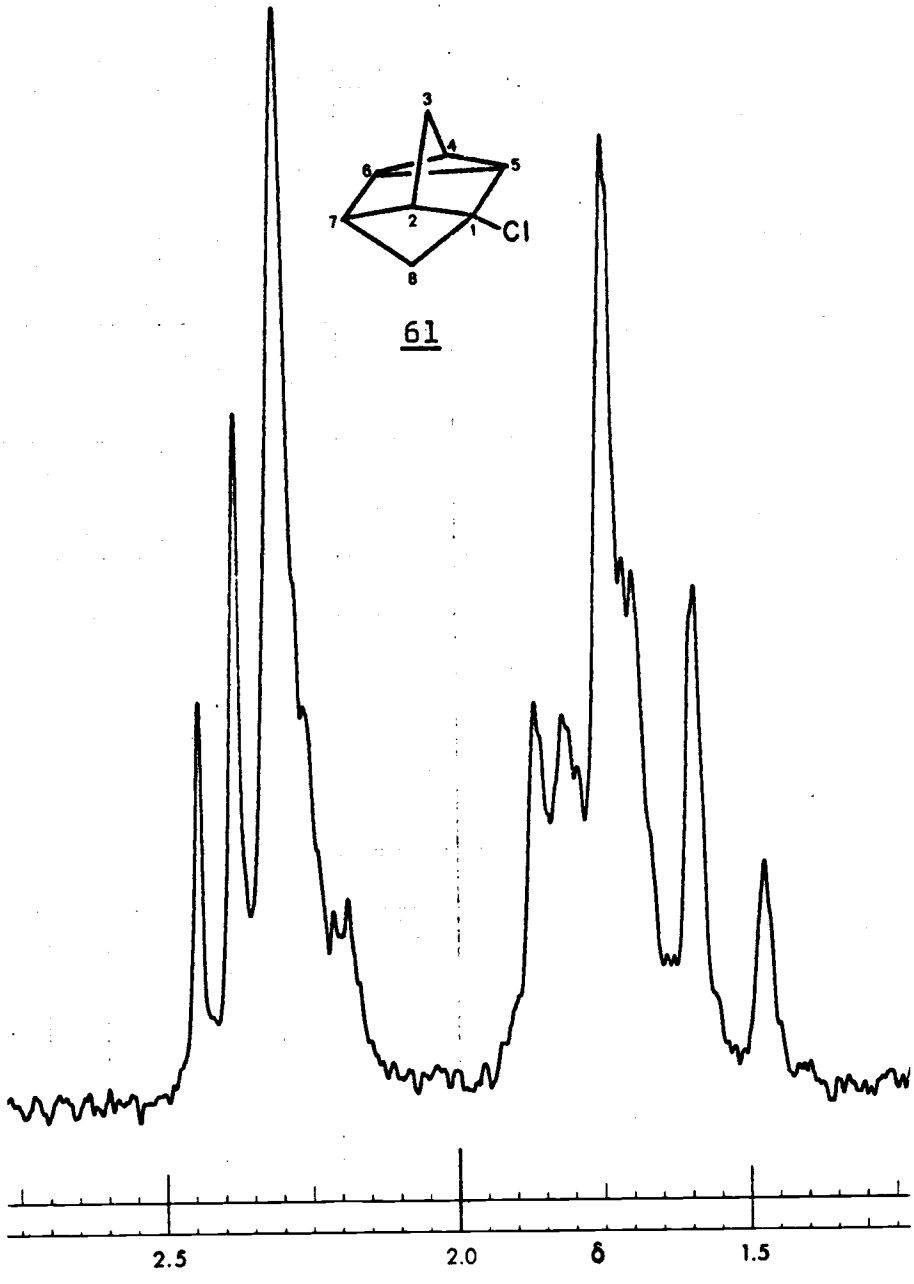
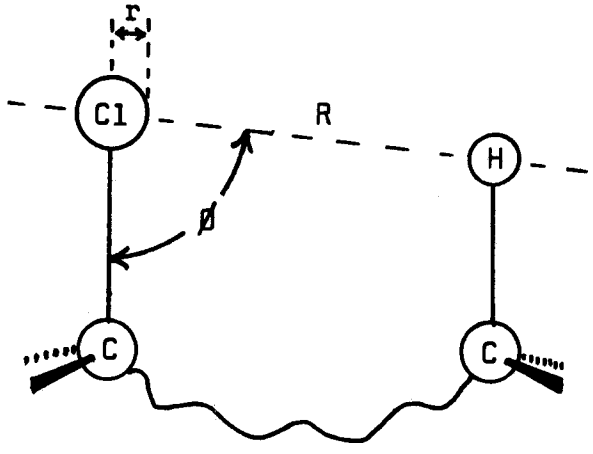


Figure 1. 100 MHz nmr spectrum (CCl_4) of 1-chlorotetracyclo-[3.3.0.$0^{2,7}$.$0^{4,6}$]octane 61.



following relationships will hold for $R \gg r$ where R is the internuclear halogen-hydrogen distance, r is the Van der Waals radius of the halogen, $\Delta\sigma$ is the screening constant, and $\Delta\chi$ is a constant:

$$\Delta\sigma = 0 \qquad \phi = 54^{\circ}\ 45'$$

$$\Delta\sigma > 0 \qquad \phi > 54^{\circ}\ 45'$$

$$\Delta\sigma < 0 \qquad \phi < 54^{\circ}\ 45'$$

$$\Delta\sigma = \Delta\chi\,(1 - 3\cos^2\phi)/3\,R^3$$

models indicate an angle ϕ of 50° for a C-5 halogen-*endo*-C-8 hydrogen interaction, but only 34° for a C-1 halogen-*endo*-C-8 hydrogen relationship. This anisotropic field effect, in combination with the inductive deshielding effect of a halogen atom (57) defines this product as 1-chlorotetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane **61**.

The major product of the photochlorination of **1** was

readily identified as 3-chlorotetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]-octane 60 by observation of a proton α to chlorine in the nmr spectrum of 60 (Figure 2) at 4.05 δ in addition to at least three other unique protons. Substitution at C-8 would yield a structure containing only two unique protons other than the one α to chlorine.

Verification of these two product structures was attempted by subjecting them to free radical reduction by tri-n-butyltin hydride (TBTH) (58) using azobisisobutyronitrile chain initiation. Although 61 gave no reduction, the major chloride 60 gave 3% of parent hydrocarbon 1 (identified by vpc retention time only) and 97% of a mixture of dienes 42 and 56. The latter two products can arise by fragmentation reactions outlined in Scheme VI.

The discrepancy between the behavior of radical 62 when formed from hydrogen atom abstraction by t-butoxy radical at 40^{0} and the behavior of 62 when formed by chlorine atom abstraction by the tri-n-butyltin radical at 100^{0} must be due to a change in thermal stability of radical 62, since chain transfer should occur more rapidly in the latter case (for R• + tBuOCl = RCl + tBuO•, $k = 3.8 \times 10^{5}$ $M^{-1}sec^{-1}$ at 40^{0} where R• = cyclohexyl (59); for R• + nBu_3SnH = RH + nBu_3Sn•, $k = 3 \times 10^{5}$ $M^{-1}sec^{-1}$ at 25^{0} where R• = t-butyl (60)).

Of the three minor chlorides produced in this reaction, two were tetracyclic whereas the third (the 8% component) contained an olefinic absorption in the ir. The former two

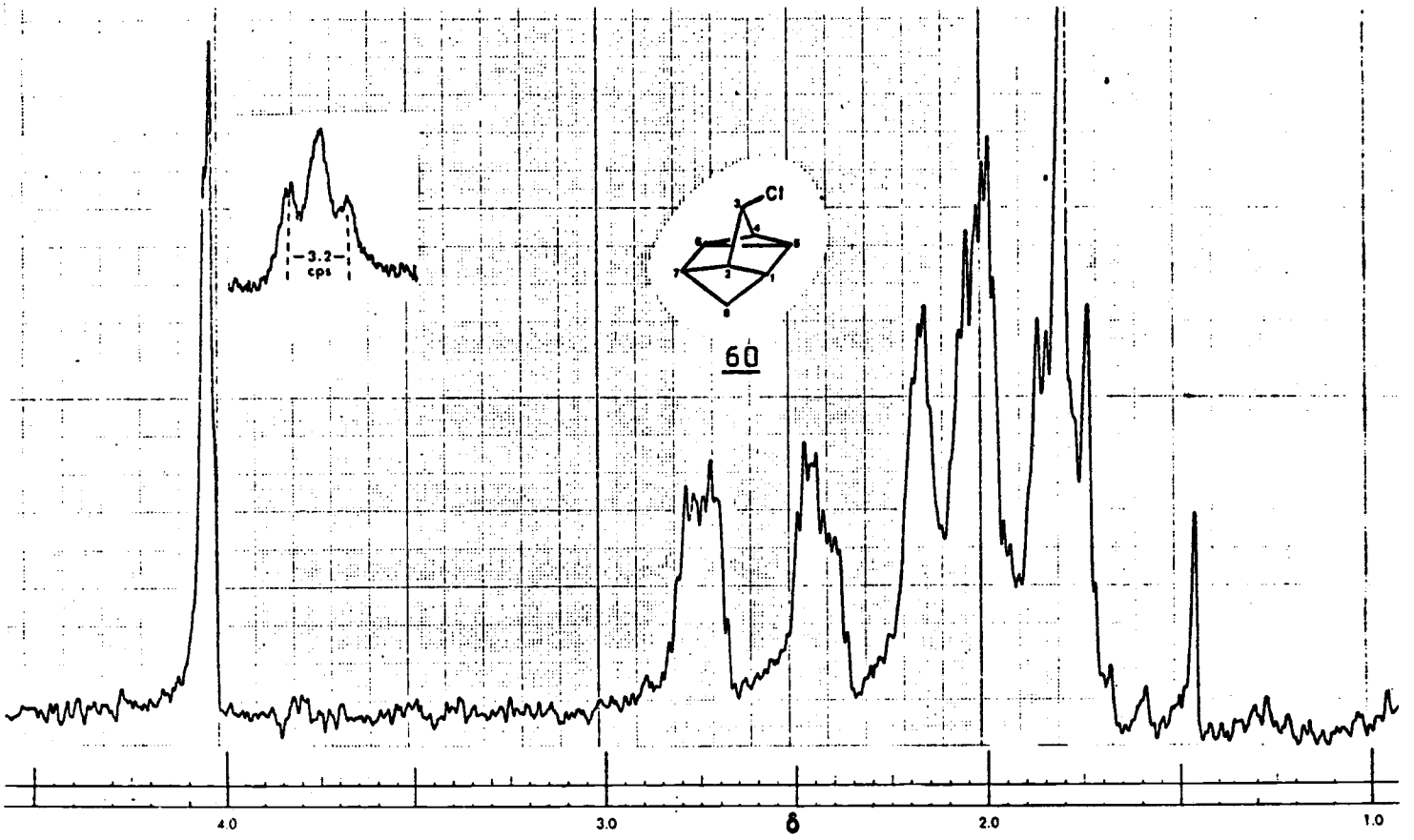
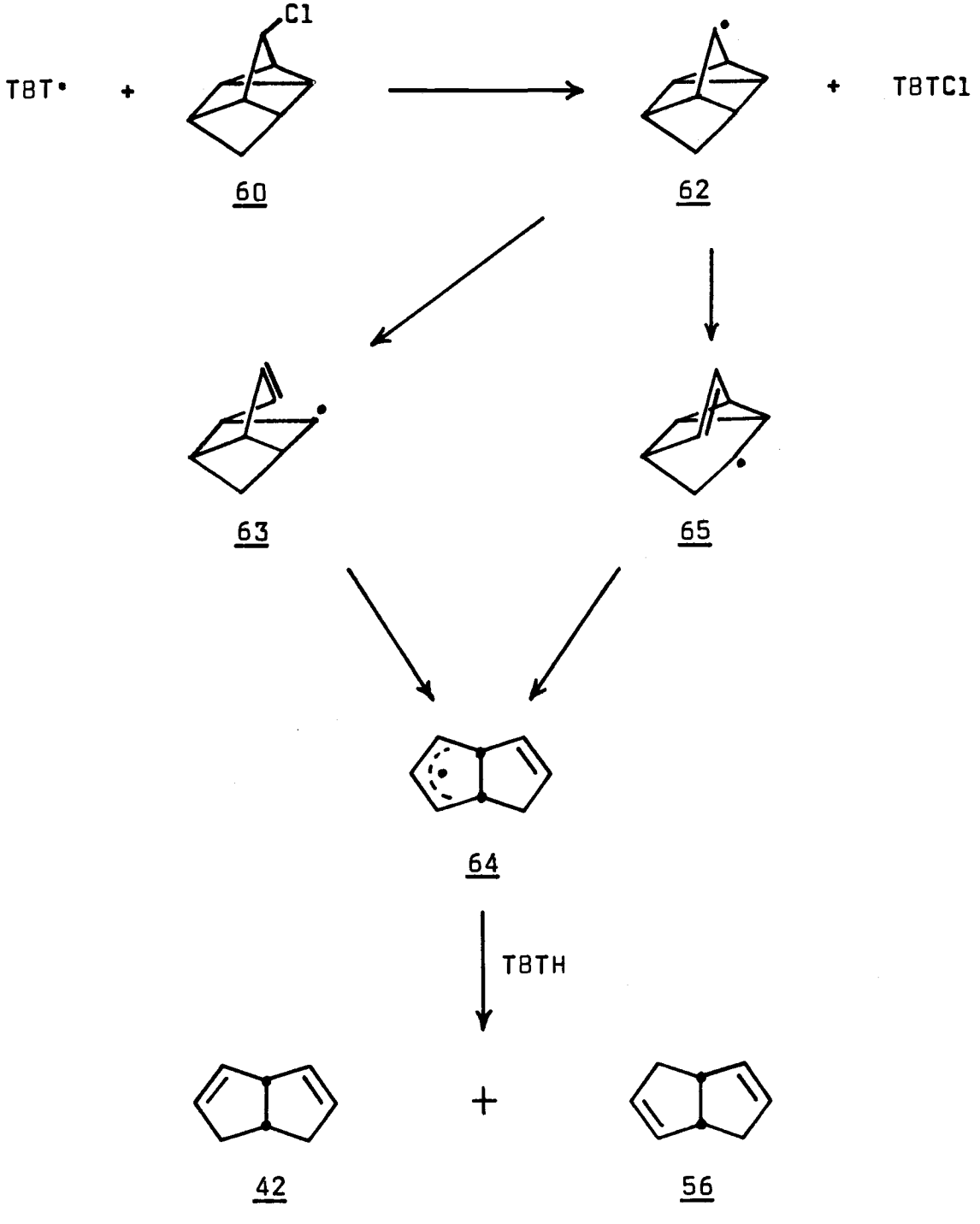


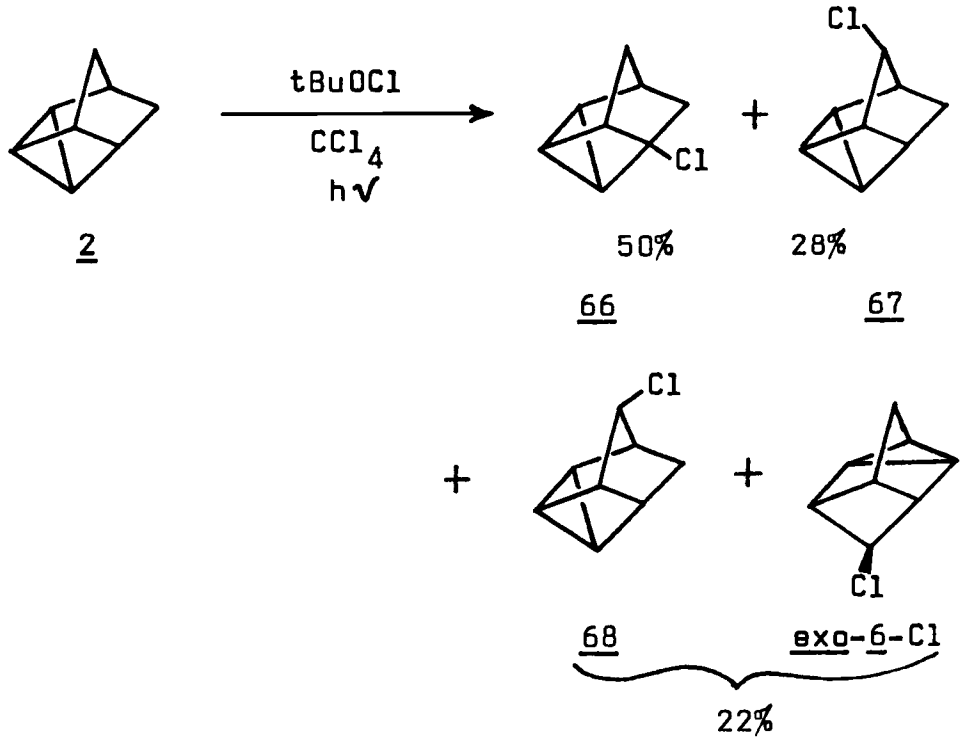
Figure 2. 100 MHz nmr spectrum (CCl_4) of 3-chlorotetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane 60.

Scheme VI



could be any of the five unidentified monochloro derivatives of parent hydrocarbon 1. The latter could result from trapping of an intermediate in the fragmentation of radical 62 as outlined in Scheme VI. Appearance of the C=C stretching frequency for this chloride at 1615 cm^{-1} suggests that this product is derived by chain transfer of radical 64.

Photochlorination of tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane with t-butyl hypochlorite in carbon tetrachloride yielded four monochlorides. Ir and nmr spectral analyses in conjunction with molecular formulas of C_8H_9Cl as indicated by parent ion masses of 140 and 142 suggested that all components were tetracyclic and not olefinic.



2 → 66 (50%) + 67 (28%) + 68 + exo-6-Cl (22%)

Treatment of the major monochloride with TBTH yielded only parent hydrocarbon 2 in 10% yield. Lack of any protons α to chlorine and three magnetically non-equivalent protons in the nmr spectrum of this component (Figure 3) identified it as a bridgehead chloride in the [3.3.0.$0^{2,4}$.$0^{3,7}$] system other than those derived by C-3 or C-7 substitution.

Comparison of the nmr spectrum of this monochloride to that of parent hydrocarbon 2 reveals that the proton at C-3 is shifted downfield only 10 Hz. in the chloride and has an unaltered splitting pattern, and that protons at C-2 and C-4 are either absent, or shifted downfield by at least 50 Hz. These observations define this product as 1-chlorotetracyclo-[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 66.

The 28% product resulting from the photochlorination of 2 yielded parent hydrocarbon 2 (73%) and a mixture of octadienes 42 and 56 (27%) upon reduction with TBTH. Since the nmr spectrum of this chloride contains one proton α to chlorine (Figure 4), the observed fragmentation must arise from radical 69 via a mechanism similar to that observed in the [3.3.0.$0^{2,7}$.$0^{4,6}$] ring system (Scheme VI).

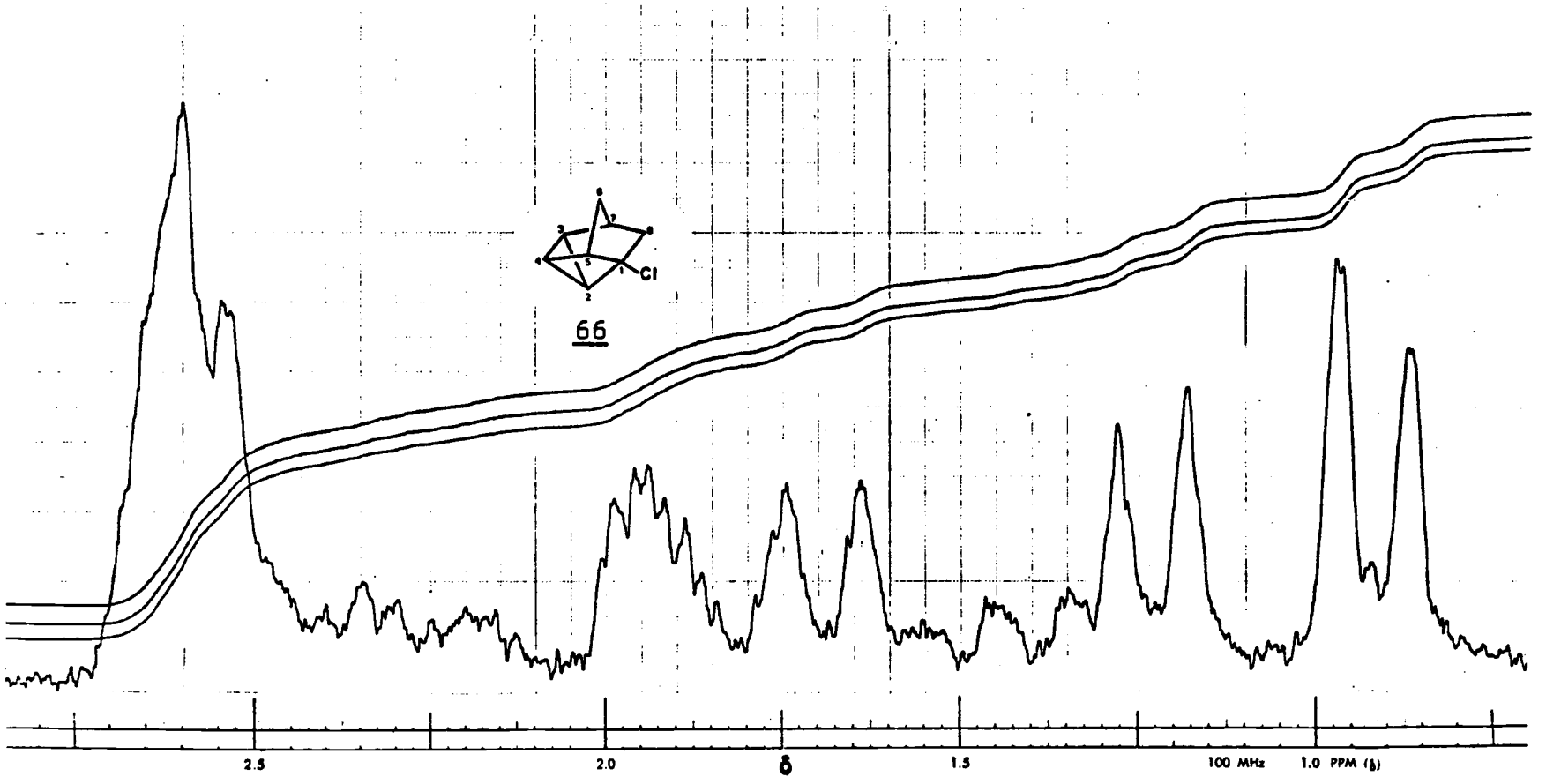


Figure 3. 100 MHz nmr spectrum (CCl_4) of 1-chlorotetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 66.

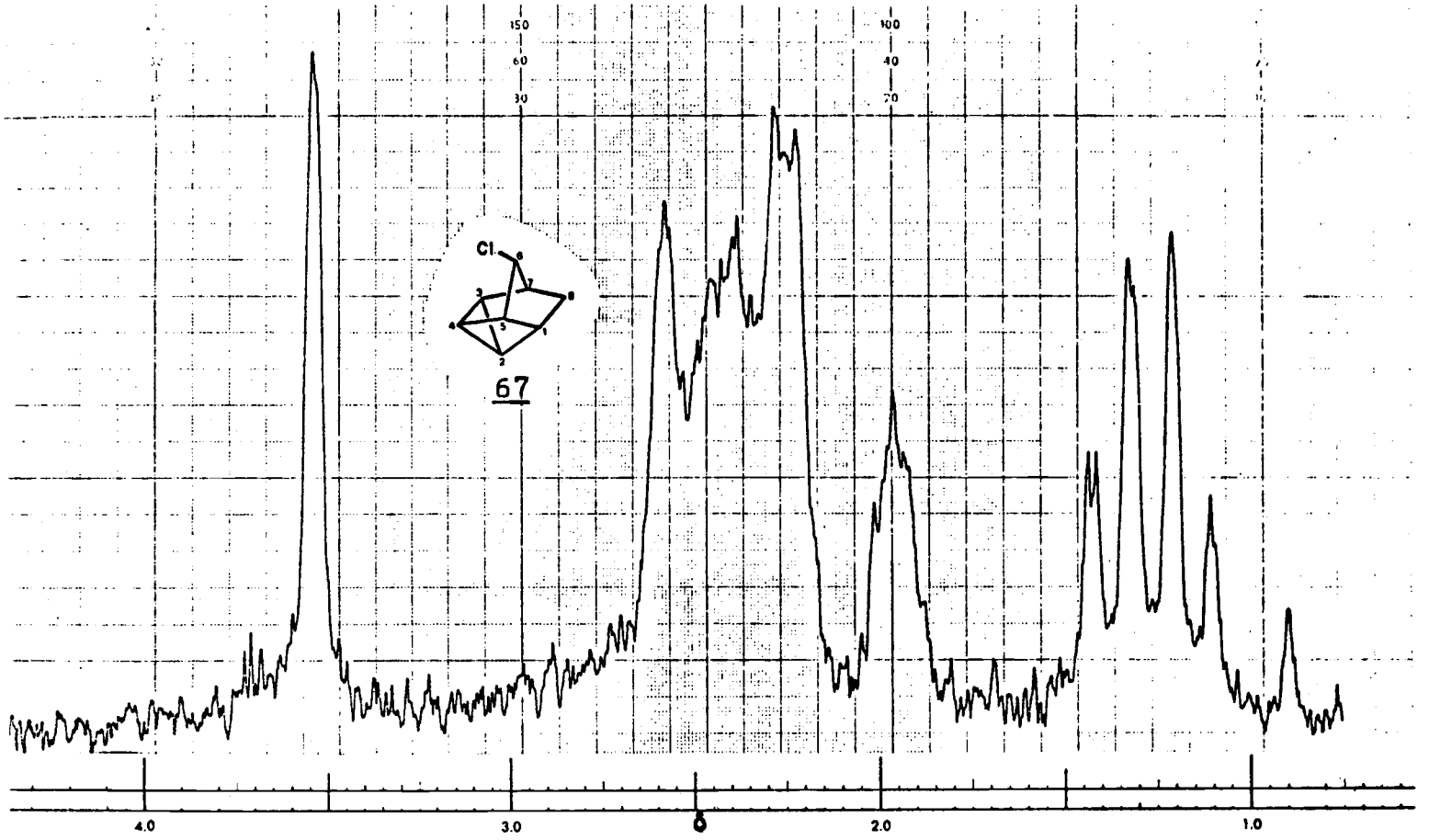
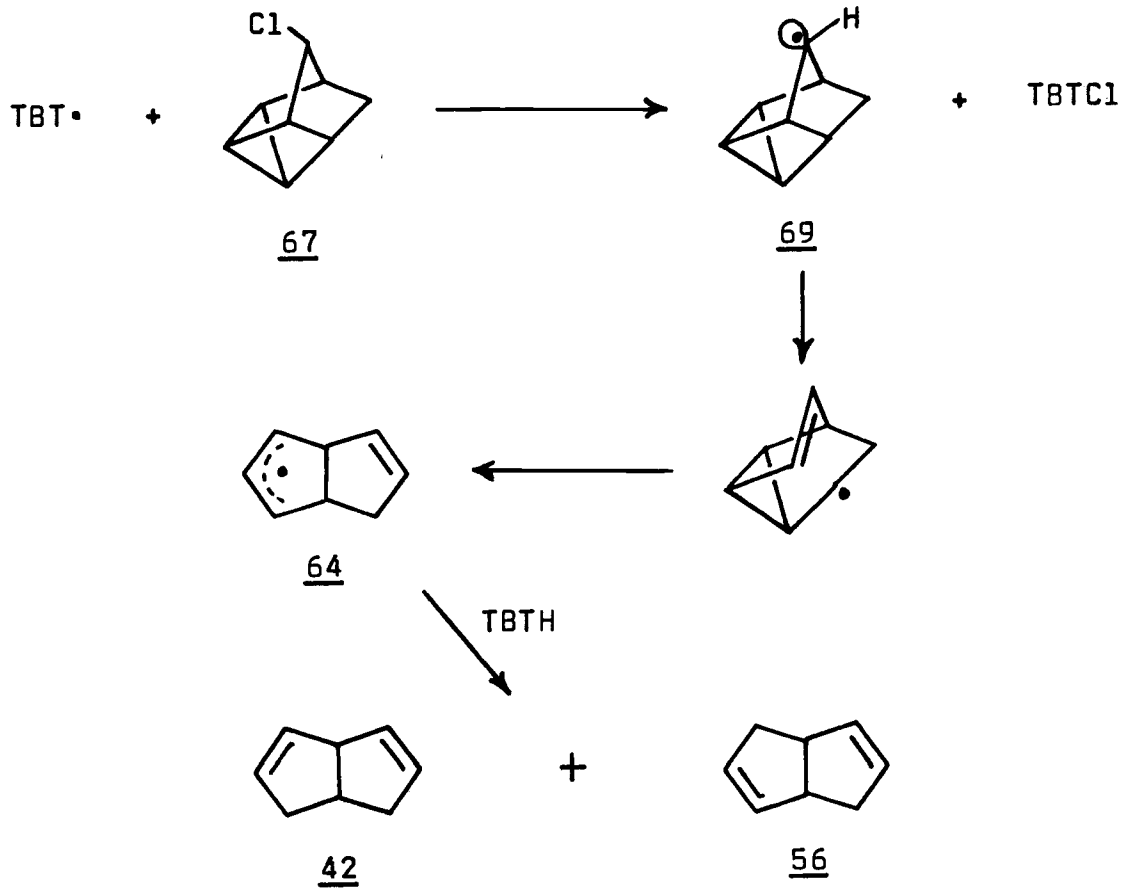


Figure 4. 100 MHz nmr spectrum (CCl_4) of <u>syn</u>-6-chlorotetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]-octane <u>67</u>.



Definition of the stereochemistry of the chlorine atom in this monochloride was effected by observation of a 14 ± 4% nuclear Overhauser signal enhancement (61) in the nmr signal of the anti-C-6 proton relative to the syn-C-6 proton by irradiation of the proton α to chlorine. The magnitude of this nuclear Overhauser effect is less than the predicted enhancement based on an internuclear H-H distance of 2.20 A^{o} (measured from a Dreiding model) and the work of Bell and Saunders (62) who observed a linear relationship between internuclear distance and the magnitude of this effect.

However, the 14% signal enhancement was observed without rigorous degassing, as is necessary to obtain correlation with theory. Saturation occurred at all Rf energies when oxygen was removed from the sample of 67.

Supporting this assignment is the observation of a singlet for the proton α to chlorine in the nmr spectrum of 67. In the parent hydrocarbon, the anti protons appear as singlets, whereas the syn protons are coupled to the unique bridgehead proton by 2.3 Hz (3).

Vapor phase chromatographic and nmr analyses revealed that the 22% product from the photochlorination of 2 was actually a mixture of two isomers in about equal proportions (Figure 5). The presence of two protons α to chlorine (a singlet at 3.95 δ and a doublet with J = 2 Hz at 3.72 δ) indicated that at least one of these isomers must be a rearrangement product, since in hydrocarbon 2 there are only two diastereotopic secondary positions and substitution at one of these led to chloride 67 identified above.

Reduction of this chloride mixture with TBTH yielded hydrocarbon 1 (70%), hydrocarbon 2 (10%), and a mixture of dienes 42 and 56 (20%) when conducted at 60° with photoinitiation, whereas at 100° without irradiation, 2 was the major product (70%) with minor amounts of 1 (10%) and diene mixture 42 + 56 (20%) also observed. This interesting result suggests that both [3.3.0.$0^{2,7}$.$0^{4,6}$] and [3.3.0.$0^{2,4}$.$0^{3,7}$] ring systems are present in this mixture. Recalling the trishomocyclo-

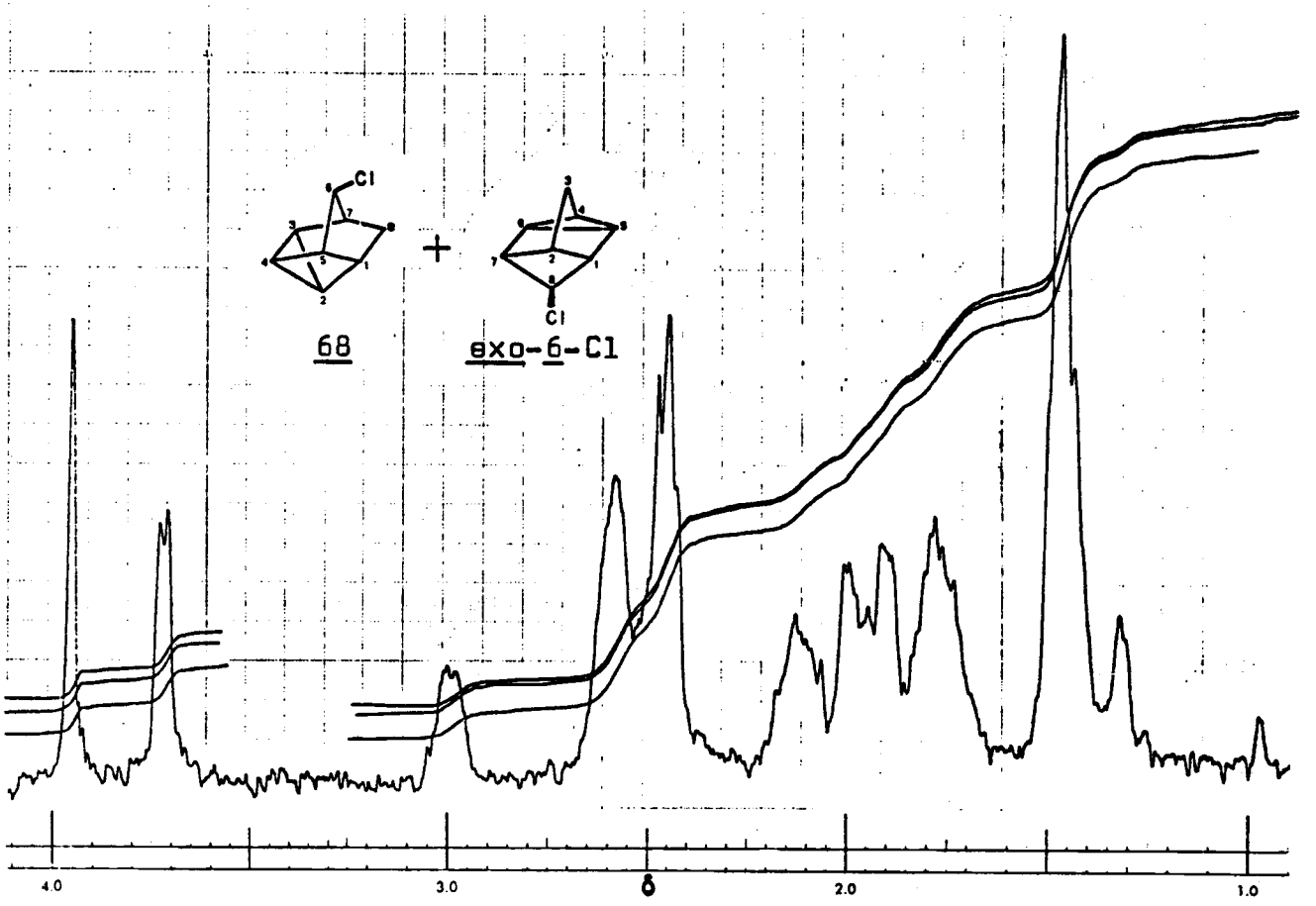
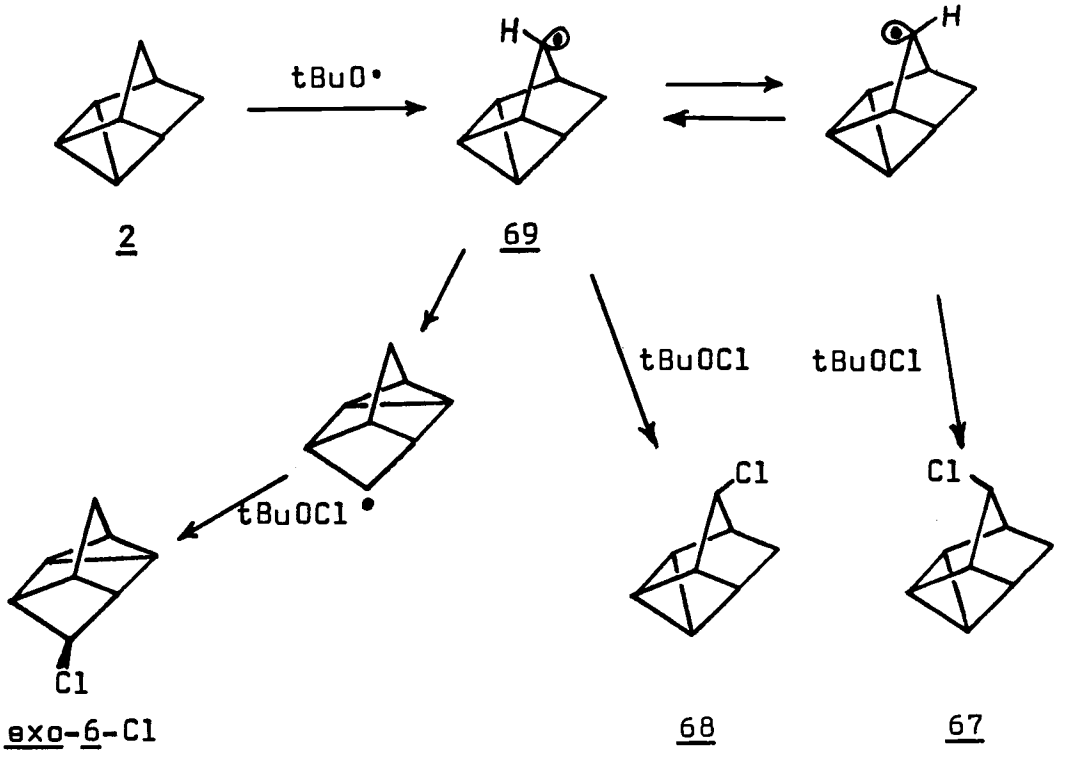


Figure 5. 100 MHz nmr spectrum (CCl_4) of a mixture of exo-8-chlorotetracyclo-[3.3.0.$0^{2,7}$.$0^{4,6}$]octane exo-6-Cl and anti-6-chlorotetracyclo[3.3.0.-$0^{2,4}$.$0^{3,7}$]octane 68.

propenyl relationship between hydrocarbons 1 and 2, a logical choice for the composition of this mixture would be anti-6-chlorotetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 68 and exo-8-chlorotetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane exo-6-Cl, the latter having been formed by rearrangement of initially formed radical 69, or by rearrangement after product formation

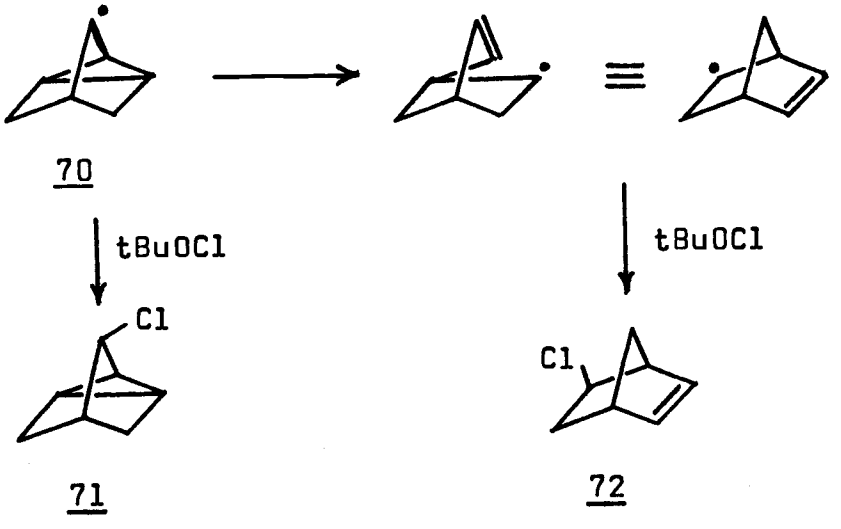


either in the reaction solution or during vpc collection. The TBTH reductions performed on the mixture of 68 and exo-6-Cl suggest that indeed a radical-radical rearrangement is involved.

The nmr spectrum of this mixture is consistent with these structure assignments. Coates and Yano (4) report a singlet for the proton α to hydroxy in exo-6-OH, and in

parent hydrocarbon 2, the equivalent syn-C-6 and C-8 protons appear as doublets with a coupling of 2.3 Hz (3). The remainder of the spectrum was readily assignable on this basis (see experimental section).

Identification of the major products from the free radical chlorination of hydrocarbons 1 and 2 revealed a number of interesting phenomena. First, formation of radical 62 may have been accompanied by rearrangement to 63 in a manner analogous to the 2-nortricyclyl radical 70 which undergoes rapid rearrangement to give a mixture of 2-chloronortricyclene 71 and exo-2-chloronorborn-5-ene 72 upon chain transfer with t-butyl hypochlorite (63). Second, and perhaps



70

71

72

most interesting, is the observation of bridgehead chloride formation in the [2.2.1] system of 2 and the [2.1.1] system

of 1. These observations are unprecedented, since bridgehead hydrogen abstraction has not been observed in norbornane (64-66) or bicyclo[2.1.1]hexane (67). This unusual behavior prompted, in part, the study reported in Part III of this thesis. Third, since alkyl radical rearrangements are rare (68) the observation of a trishomocyclopropenyl radical rearrangement is novel. Part III of this thesis is designed in part to build on these results by determining not only the generality of such behavior, but the possibility of anchimeric assistance for hydrogen abstraction. Further discussion of these points is deferred to Part III.

Experimental

All melting points were determined using a Büchi melting point apparatus. All melting points, boiling points, and reaction temperatures reported are unstandardized unless otherwise stated. Microanalyses were performed by Alfred Bernhardt, Mikroanalytisches Laboratorium, 5251 Elbach über Engelskirchen, Fritz-Pregl-Strasse 14-16, West Germany, or Chemalytics, Inc., 2330 S. Industrial Park Dr., Tempe, Ariz., 85282. Infrared spectra were recorded on a Beckman Model IR-8 Infrared Spectrophotometer, unless stated otherwise. Nmr spectra were recorded on a Varian Associates A-60 or HA-100 Nmr Spectrometer. Routine mass spectra were obtained using an Atlas CH7 Mass Spectrometer. High resolution mass spectra were determined by the Department of Chemistry, University of Oregon, Eugene, Ore., 97403.

Vapor phase chromatographic analyses and collections were carried out using either an F and M Model 700 or an Aerograph Model A-90-P Chromatograph equipped with thermal conductivity detectors. Injector and detector ports were generally operated at 200°, except when analyzing and collecting alkyl halides, when the temperature was reduced to 120° and the injector port lined with pyrex glass tubing. Columns employed were made with aluminum tubing and contained the following:

A. 32' x 1/4" 20% Carbowax 20M + 2% XF 1150 on 30/60 Chromasorb P(AW)

B. 23' x 1/4" 13% TCEP on 30/60 Chromasorb P(AW)

C. 17' x 1/4" 10% TCEP on 70/80 Anakrom ABS

D. 10' x 1/4" 10% β,β'-oxydipropionitrile on 30/60 Chromasorb P(AW)

E. 6' x 1/4" 10% Carbowax 20M on 70/80 Anakrom ABS

F. 8' x 1/4" 15% Carbowax 20M + 2% XF-1112 on 30/60 Chromasorb P(AW)

G. 20' x 1/8" 10% β,β'-oxydipropionitrile on 30/60 Chromasorb P(AW)

H. 20' x 1/8" 13% TCEP on 30/60 Chromasorb P(AW)

I. 30' x 1/8" 5% TCEP on 70/80 Anakrom ABS

J. 30' x 1/8" 5% Carbowax 20M on 70/80 Anakrom ABS

K. 9' x 1/8" 5% Carbowax 20M on 70/80 Anakrom ABS

Product ratios and percentage yields calculated from chromatographic data are based on relative peak areas and were corrected, when necessary, for differences in molecular weight by the method of Eastman (69). Peak areas were determined by electronic integration using a Hewlett-Packard Model 3373-B integrator unless stated otherwise.

Solvents used in tosylhydrazone decompositions were distilled from lithium aluminum or calcium hydride and stored over 4Å molecular sieves, but only for short periods,

since peroxides formed upon prolonged standing. Tert-butyl hypochlorite was prepared by a standard procedure (70), distilled, and either used at once, or stored in the dark at -20° in sealed, degassed ampoules. Tri-n-butyltin hydride was prepared and distilled by the method of Kuivila (71) and stored at 5° in the dark.

Decomposition of Tricyclo[3.2.1.$0^{3,6}$]octan-2-one p-Toluenesulfonylhydrazone 3-NNHTs in Sodium Methoxide-Diglyme. In a dry 25 ml flask fitted with a reflux condenser and nitrogen inlet, a mixture of 1.00 g (3.45 mmol) of tosylhydrazone 3-NNHTs, 1.12 g (21.7 mmol, 6 equiv) of sodium methoxide, and 15 ml of dry diglyme were stirred at ambient temperature for 1 hr under a nitrogen atmosphere. The flask was then plunged into a 145° oil bath and held at that temperature for 3 hours. Initially a red-brown color appeared which dissipated after ca 15 min leaving a pale milky-pink suspension. Allowing the mixture to cool followed by dilution with an equal volume of pentane and subsequent extraction with five aliquots of water yielded a pentane extract which was dried over anhydrous Na_2SO_4 and concentrated by distillation of the pentane through a 10 cm Vigreaux column. The residue was analyzed by vpc on column K, and contained three components.

The first two were identified as tetracyclo[3.3.0.$0^{2,7}$.-$0^{4,6}$]octane 1 and tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2 in a

yield ratio of 33:17 (determined by quantitative gas chromatography relative to a norbornane internal standard introduced after product isolation) by comparison of ir and nmr spectra to those of authentic samples (1,3).

The third component was identified as exo-2-methoxytricyclo[3.2.1.$0^{3,6}$]octane 4-OCH_3 by ir and nmr spectral comparison with spectra of an authentic sample.

Anal. Calcd. for $C_9H_{14}O$: C, 78.21; H, 10.21. Found: C, 78.04; H, 10.09.

Preparation of exo-2-Methoxytricyclo[3.2.1.$0^{3,6}$]octane 4-OCH_3. In a sealed reaction vessel were stirred 0.15 g (1.23 mmol) of exo-tricyclo[3.2.1.$0^{3,6}$]octan-2-ol 4-OH, 0.56 g (2.4 mmol) of Ag_2O, 0.34 g (3.6 mmol) of methyl iodide, and 2 ml of dimethylformamide at ambient temperature for 5 days with exclusion of light. Dilution of the resulting solution with 1:1 pentane:ether (5 ml) followed by extraction with 5 aliquots H_2O yielded, after solvent removal at reduced pressure, a residue which contained two components by vpc analysis on column F.

The minor component (30%) was identified as starting alcohol 4-OH; the major component (70%) had ir and nmr spectra consistent with the assigned structure, exo-2-methoxytricyclo[3.2.1.$0^{3,6}$]octane 4-OCH_3, and was formed in 65% yield based on unreacted alcohol: ir (CCl_4) ν = 2959, 2875, 2833, 1449, 1366, 1199, 1120, 1106, 1094, 1078, 971

cm^{-1}; nmr (100 MH_z, CCl_4) δ = 3.24 (s, 1H), 3.17 (s, 3H), 2.74 (broad s, $w_{\frac{1}{2}}$ = 9 Hz, 1H), 2.60 (broad s, $w_{\frac{1}{2}}$ = 7 Hz, 1H), 2.18 (m, 3H), 1.80 (doublet of doublets, J = 11, 1.7 Hz, 1H), 1.56 (doublet of multiplets, J = 11 Hz, 1H), 1.36 (s, 1H), 1.23 (s, 1H), 1.12 (m, 1H).

Preparation of N-d_1-Tricyclo[3.2.1.$0^{3,6}$]octan-2-one p-Toluenesulfonylhydrazone 3-NNDTs. Deuterium exchange was effected by vigorously shaking 3.0 g (10.3 mmol) of tosylhydrazone 3-NNHTs, 25 ml $CHCl_3$, 30 ml of 99.8% D_2O, and a catalytic amount of sodium methoxide in a 125 ml separatory funnel. Monitoring the amount of N-H vs N-D by observation of the 3.1 μ band in the infrared revealed that a maximum d_1 incorporation occurred after only a few minutes — continued shaking caused a diminution of the amount of N-D due to exchange of the chloroform proton. Precipitation of the tosylhydrazone by pentane addition yielded 1.74 g (6 mmol, 58%) of 3-NNDTs, mp 156-157° d. Quantitative ir analysis using the resolved C=N stretching absorption at 6.0 μ as an internal standard in comparison to the N-H stretching frequency at 3.1 μ indicated 68% deuterium incorporation at the desired position. Mass spectral analysis at 16 eV likewise revealed 68 $\pm$ 3% d_1 incorporation, determined from 9 scans.

Preparation of N-Lithiotricyclo[3.2.1.$0^{3,6}$]octan-2-one *p*-Toluenesulfonylhydrazone 3-NNLiTs. The tosylhydrazone lithium salt was prepared by addition of one equiv of methyllithium (1.95 M in ether) to tosylhydrazone 3-NNHTs in ether under nitrogen in a glove bag, followed by vacuum removal of solvent at room temperature with swirling of the solution such that the salt forms a thin coat on the inside of the reaction vessel. The last traces of ether were very difficult to remove, but extended subjection of the salt to less than 0.01 mm Hg while warming to 40° in the dark seemed moderately effective. No attempt was made to separate the tosylhydrazone lithium salt from the lithium bromide (one equiv per mole of methyllithium) present in the commercial methyllithium solution used.

Decomposition of Tricyclo[3.2.1.$0^{3,6}$]octan-2-one *p*-Toluenesulfonylhydrazone 3-NNHTs in Sodium Methoxide-Ethylene Glycol. Decomposition of 1.00 g (3.45 mmol) of tosylhydrazone 3-NNHTs was effected under conditions in all respects identical to those above, except that ethylene glycol (distilled from sodium) was substituted for diglyme as the solvent. Isolation and analysis of the resulting product mixture was also done in a fashion identical with the diglyme decomposition. Ether 4-OCH_3 was found in only 2.0% yield, and a mixture of hydrocarbons 1 and 2 in the ratio of 90:4 was found in 7.8% yield using an internal

norbornane reference. Two additional peaks, eluting before 1 or 2, were found in 0.13% and 0.36% yield in order of elution, and were not identified.

Decomposition of N-Lithiotricyclo[3.2.1.$0^{3,6}$]octan-2-one p-Toluenesulfonylhydrazone 3-NNLiTs in the Absence of Solvent. A reaction vessel containing the lithium salt 3-NNLiTs was connected to a trap, cooled to -78° in a dry ice-isopropanol bath, and the system evacuated to 0.01 mm Hg. Immersion of the flask in a 200° silicone oil bath for 1 hr yielded a clear trap pyrolysate which was analyzed in the same manner as the two preceeding decomposition product mixtures. Hydrocarbons 1 and 2 were found in a ratio of 59:36 in a 74% yield in addition to an unidentified component, in 4% yield, which eluted after both 1 and 2 on column G (this component was not present when the same reaction was carried out at 160°). A small amount of colorless liquid was noted remaining in the 200° reaction vessel in addition to a tan solid.

Photolysis of N-Lithiotricyclo[3.2.1.$0^{3,6}$]octan-2-one p-Toluenesylfonylhydrazone in Diglyme. The lithium salt was prepared by addition of 1.1 equiv of methyl lithium (2.13 M in ether) to tosylhydrazone 3-NNHTs dissolved in diglyme. Irradiation of the resulting suspension in a quartz reaction vessel, equipped with a magnetic stirrer, a cold finger,

and $CaCl_2$ drying tube, with a 450 W Hanovia high pressure mercury lamp for five hr at a distance of one in, followed by dilution with pentane and extraction several times with water, yielded a solution which was analyzed by vpc as in the above thermal decompositions of 3-NNHTs. Both tetracyclic C_8 hydrocarbons 1 and 2 were formed, in a ratio of 33:67, but in only 3% yield as determined by an internal norbornane standard. The low yield was attributed to a low conversion of tosylhydrazone salt to hydrocarbon due to the heterogeneity of the mixture.

Decomposition of Tricyclo[3.2.1.$0^{3,6}$]octan-2-one *p*-Toluenesulfonylhydrazone 3-NNHTs in Aluminum Isopropoxide-Diglyme. Decomposition of 0.88 g of tosylhydrazone 3-NNHTs was effected under conditions in all respects identical to those for the methoxide-diglyme experiment above, except that 8 equiv of freshly distilled aluminum isopropoxide was substituted for sodium methoxide as the base. Isolation and analysis, also as above, indicated a very low yield (5%) of the two tetracyclic isomers 1 and 2 in the ratio of 18:1. The two volatile peaks observed in the ethylene glycol decomposition were again noticed in similar relative yields.

Decomposition of Tricyclo[3.2.1.$0^{3,6}$]octan-2-one _p_-Toluenesulfonylhydrazone _3_-NNHTs in Sodium Methoxide-_bis_-(2-Ethoxyethyl) Ether. Decomposition and analysis of 0.68 g of tosylhydrazone _3_-NNHTs under conditions identical to those for the methoxide-diglyme decomposition above, except for a change in solvent to _bis_-(2-ethoxyethyl) ether, gave ether _4_-OCH_3 in 17% yield, and hydrocarbons _1_ and _2_ in the ratio of 2:1 in 29% yield.

Decomposition of N-d_1-Tricyclo[3.2.1.$0^{3,6}$]octan-2-one _p_-Toluenesulfonylhydrazone _3_-NNDTs with Various Equivalents of Sodium Methoxide. In a 15 ml round-bottomed flask fitted with nitrogen inlet and condenser, were mechanically stirred 0.290 g (1.0 mmol) of tosylhydrazone _3_-NNDTs, 5 ml of tetraglyme, and various amounts of sodium methoxide at room temperature for 15 min. The entire apparatus was lowered into a 160 $\pm$ 5° oil bath and held there for 30 min. After cooling, the pot was diluted with pentane, filtered, washed six times with water, dried over anhydrous Na_2SO_4, and reduced in volume by distillation of the pentane through a 10 cm Vigreaux column. Vpc analysis on column J connected directly to an Atlas CH-7 mass spectrometer operated at 13 eV gave ratios of _1_ to _2_ and percent deuterium incorporation reported in Table II. The values reported are the average and average deviation of three scans of each sample.

Preparation of cis, cis-1,3-Cyclooctadiene Monoxide 45.

Epoxidation was effected by modification of previously reported methods for monoepoxidation of dienes (72). To a stirred solution of 70.0 g (0.636 mol) of cis, cis-1,3-cyclooctadiene in 250 ml of reagent grade chloroform cooled to 5^{o} in an ice bath, was added, dropwise, over a 90 min period, 100 ml of commercial 40% peracetic acid containing 10 g of anhydrous sodium acetate. After an additional 3.5 hr stirring at 5^{o}, the solution was allowed to warm slowly to room temperature overnight. The resulting cloudy suspension was poured into a two phase solution of 500 ml of ether and 500 ml of water containing 120 g of sodium carbonate. The aqueous layer was separated and washed once with 5% $NaHCO_3$, once with water, once with saturated NaCl, and dried over anhydrous $MgSO_4$. Subsequent filtration and distillation through a 40 cm spinning band column yielded 60.0 g (0.484 mol, 77%) of cis, cis-1,3-cyclooctadiene monoxide 45, bp 74-75^{o} at 13 mm Hg; ir, ν = 3030, 2940, 2880, 1650, 1450, 843, 812 cm^{-1}; nmr (100 MHz, CCl_4) δ = 5.70 (doublet of doublets, J = 12, 5.5 Hz, 1H), 5.50 (doublet, J = 12 Hz, 1H), 3.25 (doublet, J = 4 Hz, 1H), 2.92 (multiplet, 1H), 2.4-1.2 (complex multiplet, 8H).

Preparation of endo-2-cis-Bicyclo[3.3.0]oct-7-enol 46.

The method previously reported for synthesis of 46 involved use of lithium metal to obtain lithium diethylamide, and

refluxing ether to effect conversion of epoxide 45 to alcohol 46 (40). Although this procedure was followed initially, we observed that use of commercial methyllithium and lower reaction temperatures lead to a simpler and cleaner reaction as described below.

An ethereal solution of lithium diethylamide was prepared by dropwise addition of 12.9 g (0.176 mol) of dry diethylamine (distilled from CaH_2 and stored over 4Å molecular sieves) to a stirred solution of 0.176 mol of methyllithium in 300 ml of anhydrous ether (prepared from a commercial 2.13 M solution), cooled to 5° by an ice bath with exclusion of atmospheric moisture.

To this solution was added over a 2 hr period 20.0 g (0.159 mol) of monoepoxide 45 dissolved in 50 ml of ether. The temperature was maintained at less than 5° during addition. (A pilot run proved this addition to be extremely exothermic.) After an additional 2 hr at 5°, the solution was allowed to warm to room temperature and stirred for an additional 4 hr. (A pilot run monitored by vpc using column E indicated that reaction to a single volatile product was complete after this time period, but was only 60% complete after stirring for 2 hr at 5°.) The resulting pale yellow solution was then decanted into a separatory funnel and extracted with five aliquots of saturated NH_4Cl (caution, the first extraction is exothermic). The ether solution was then dried over anhydrous $MgSO_4$, filtered, and distilled on a 40

cm spinning band column, resulting in isolation of 15.4 g (77% yield) of pure alcohol 46, bp 64-65° at 5 mm Hg which exhibits ir and nmr absorptions as previously reported (40).

Preparation of endo-2-cis-Bicyclo[3.3.0]oct-7-enyl Acetate 47. Heating a solution of 3.0 g (2.42×10^{-2} mol) of alcohol 46, 3.5 g (3.42×10^{-2} mol) of acetic anhydride, and 0.4 g of sodium acetate at reflux for 2 hr, followed by dilution with ether, extraction with 5% $NaHCO_3$ until no more CO_2 was evolved, and drying over sodium sulfate-potassium carbonate, yielded 3.80 g (95%) of crude acetate upon removal of solvent at reduced pressure. This acetate was of sufficient purity (>99% by vpc analysis on column K and nmr analysis) to be used in subsequent reactions without further purification: ir (neat) ν = 3080, 2980, 2860, 2885, 1728, 1615, 1375, 1240, 1052, 714 cm^{-1}; nmr (100 MHz, CCl_4) δ = 5.68 (doublet of doublets, J = 6, 2 Hz, 1H), 5.38 (doublet of doublets, J = 6, 2 Hz, 1H), 5.01 (doublet of triplets, J = 6, 6 Hz, 1H), 3.35 (m, 1H), 2.66 (m, 2H), 1.96 (s, 3H), 2.2-1.3 (m, 5H).

Anal. Calcd. for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.40; H, 8.78.

Preparation of cis-2,7-Bicyclo[3.3.0]octadiene 42. Acetate 47 (2.2 g, 0.0132 mol) was pyrolyzed by dropwise addition onto a 40 cm pyrex column packed with pyrex glass

beads heated to 475° in a slow nitrogen flow. The product was trapped directly into a receiver cooled to -78°, diluted with pentane, washed once with water, once with 5% $NaHCO_3$, once with saturated NaCl, and dried over anhydrous Na_2SO_4. Subsequent removal of solvent by distillation through a 10 cm Vigreaux column, followed by distillation of the residue yielded 1.12 g (0.0106 mol, 80% based on acetate lost) of diene 42, and 0.30 g of recovered acetate 47. The product was pale yellow; a colorless sample having an identical ir spectrum was obtained by chromatography on alumina with pentane elution. The ir spectrum of 42 was identical to that previously reported (48); nmr (100 MHz, CCl_4) δ = 5.54 (m, 4H), 3.66 (doublet of multiplets, J = 7.5 Hz, 1H), 3.1-2.5 (complex multiplet, 2H), 2.55 (doublet of multiplets, J = 7.5 Hz, 1H), 2.04 (doublet of multiplets, J = 15 Hz, 2H).

Preparation of Tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2. A: Photolysis in Pentane. A stirred solution of 2.45 g (2.29 x 10^{-2} mol) of diene 42 in 250 ml of olefin free pentane was purged with nitrogen for 30 min, then irradiated under nitrogen with an unfiltered 450 W Hanovia high-pressure mercury lamp using a water-cooled quartz probe. Monitoring the reaction by vpc on column G indicated a buildup of a new volatile component at the rate of about 1% per hr. At the end of 16 hr, however, conversion stopped. The solution, somewhat yellow and containing a solid material, was passed

through a short alumina column, the resulting clear solution repurged and irradiated again as above. The new volatile component again grew at the rate of 1% per hour until it was 35% of the starting diene after 40 hr total irradiation. Further manipulation of the solution as above produced no further increase in the ratio of product to starting diene 42. The yield of 2 as indicated by an internal vpc reference was 8%.

The product was isolated by removal of ca 99% of the pentane by distillation through a 40 cm spinning band column, followed by extraction of the residue with an equal volume of saturated $AgNO_3$. Vpc analysis of this procedure indicated no loss of product relative to an internal norbornane standard, whereas diene 42 was completely removed. The resulting pentane solution was subjected to preparative gas chromatography on column D, the single product being identified as desired hydrocarbon 2. Unreacted diene 42 was recovered by dilution of the $AgNO_3$ solution with a 10 fold volume of water and extraction by pentane.

B: Photolysis in Ether. A solution of 2.50 g (2.43×10^{-2} mol) of diene 42 was taken up in 250 ml of commercial anhydrous ether, purged with nitrogen, and irradiated as described above. Monitoring the reaction indicated conversion of 42 to 2 at a rate of 0.5% per hr until the ratio of 42:2 was 38:62 as measured by vpc integration. The resulting yellow solution was concentrated by distillation of the ether

through a 40 cm Vigreaux column, the residue yielding pure 2 by the method described in A above. The yield as determined by an internal norbornane vpc reference was 35%.

Gas Phase Pyrolysis of Tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2. In a pyrex ampoule, prepared by washing with 28% NH_4OH and drying at >100° for 30 hr, were placed 28.6 mg (0.27 mmol) of hydrocarbon 2 vpc collected using column F. The tube was flushed with nitrogen, frozen, evacuated, and sealed. Heating the tube for 13.5 hr at 295.2° (NBS calibrated) resulted in a clear liquid pyrolysate, which contained only two components in a 1.8:1 ratio as determined by vpc analysis on column G. The minor constituent of the pyrolysate was identified as unreacted 2 by ir analysis of a sample purified by vpc using column F. The major constituent was identified as cis-bicyclo[3.3.0]octa-2,7-diene 42 by ir and nmr comparison with data of an authentic sample.

Gas Phase Pyrolysis of Tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane 1. Hydrocarbon 1 was pyrolyzed using the same equipment and technique as for the pyrolysis of of 2 above. The resulting dark amber pyrolysate, which gave a black precipitate upon dilution with pentane, was analyzed by vpc on column G, using an added norbornane internal reference; the presence of eight volatile components was revealed. Six of these were less than 4% in yield and were not identified.

The remaining two in 17% and 32% yields were identified by ir and nmr analyses as starting hydrocarbon 1, and a 78:22 mixture of 2,6- and 2,7-cis-bicyclo[3.3.0]octadiene 42 and 56 (51) respectively. The total yield of volatile products was 65%, indicating a substantial amount of polymerization, in concert with the observed color of the pyrolysate. Three attempts failed to yield a colorless pyrolysate.

Rate of Gas Phase Pyrolysis of Tetracyclo[3.3.0.$0^{2,4}$-.$0^{3,7}$]octane 2. A mixture of hydrocarbon 2 and n-decane, both purified by vpc using column F, was divided into several 3 μl aliquots in pyrex tubes. These tubes were frozen, evacuated, sealed, then pyrolyzed for various lengths of time at 301° (NBS calibrated). The resulting colorless pyrolysate in each tube was then gas chromatographically analyzed by multiple injection on column G, the molar ratio of internal reference n-decane, product 42, and starting hydrocarbon 2 determined by electronic integration of the respective peaks.

The resulting data were plotted by computer using a linear least squares program. First order rate constants determined were: disappearance of starting hydrocarbon 2; $k = 0.074 \pm 0.004$ hr^{-1}, correlation coefficient = -0.995; appearance of product 42; $k' = 0.071 \pm 0.006$ hr^{-1}, correlation coefficient = -0.985.

Rate of Gas Phase Pyrolysis of Tetracyclo[3.3.0.$0^{2,7}$.-$0^{4,6}$]octane 1. The rate constant for disappearance of hydrocarbon 1 at 317° (standardized) was calculated to be k = 0.023 ± .002 hr^{-1}, correlation coefficient = -0.984, and was obtained in a manner identical to the corresponding rate constant for pyrolysis of 2 reported above.

Addition of Acetic Acid to Tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]-octane 1. A mixture of 85 mg (0.80 mmol) of hydrocarbon 1, vpc collected from column A, in 0.5 ml of 0.08 N H_2SO_4 in glacial acetic acid was allowed to react for 30 min at 25°. At the end of this time period, the solution was diluted with pentane, extracted with two aliquots of water, once with $NaHCO_3$, and dried over anhydrous Na_2SO_4. The pentane was removed by distillation, yielding 90 mg (68%) of a mixture of acetates. Vpc analysis of this mixture on columns F and H showed two peaks in the ratio of 90:10. Preparative gas chromatography using column F revealed the minor component to be 2-tricyclo[3.2.1.$0^{3,6}$]octanol 4-OH by comparison of its nmr spectrum to that of an authentic sample prepared as described in the text. An nmr spectrum of the major vpc component revealed two protons α to acetoxy, δ = 4.63 (s) and δ = 4.92 (d, J = 6 Hz), in the ratio of 90:10 respectively. The spectrum from 1 to 3 δ was essentially identical to that of an authentic sample of exo-2-acetoxytricyclo[3.2.1.$0^{3,6}$]-octane 4-$OCOCH_3$, prepared by the method of Sauers, Parent,

and Damle (2), identifying this as the major product from acetic acid addition to 1. No further evidence as to the structure of the minor product was obtained, since it proved inseparable from 4-$OCOCH_3$ on several vpc columns.

Addition of Acetic Acid to Tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]-octane 2. A solution of 26.3 mg (0.246 mmol) of hydrocarbon 2 vpc collected from column A and ca 200 μl of 0.08 N H_2SO_4 in glacial acetic acid was allowed to react for 3 hr at 25°. Subsequent dilution with pentane, water and $NaHCO_3$ extraction, drying over anhydrous Na_2SO_4, and distillation of the pentane left 36.3 mg (89%) of a mixture of acetates. Vpc analysis of this mixture on column F revealed three components in the ratio of 68:5:27, the first having a retention time equal to that of 4-$OCOCH_3$, the two minor components of different retention time than the minor component observed in the acetic acid addition to 1 reported above. Preparative separation of the major component from the other two lead to its identification as 4-$OCOCH_3$ by comparison of its nmr spectrum to that of an authentic sample. The mixture of minor components was subjected to nmr analysis, and revealed a doublet at δ = 4.94, J = 6 Hz, and a singlet at δ = 4.16 in the ratio of 7:1 for protons α to acetoxy, and olefinic absorptions at δ = 5.78 (d, J = 9 Hz) and 5.43 (d, J = 9 Hz) equal in area to the 4.94 doublet. No further evidence as to the identity of these components was obtained.

Kinetics of Acetic Acid Addition to Tetracyclo[3.3.0.-$0^{2,7}.0^{4,6}$]octane 1 and Tetracyclo[3.3.0.$0^{2,4}.0^{3,7}$]octane 2. A mixture of hydrocarbons 1, 2, and norbornane was injected into an 0.08 N H_2SO_4 in glacial acetic acid solution maintained at 25 ± 1°. At appropriate time intervals, 0.5 ml aliquots were withdrawn and quenched by addition with shaking to a two phase solution of 5 ml of H_2O and 0.5 ml pentane. The pentane layer was analyzed for hydrocarbon content by vpc on column A. Percentages of each tetracyclic isomer remaining were determined relative to the norbornane internal standard by multiple injection.

The data showed that isomer 1 had a half life of about 20 sec, while 2 took *ca* 8 minutes to reach 50% of its starting concentration. The data was analyzed by computer using a linear least squares analysis, and gave first order plots for the disappearance of each isomer: hydrocarbon 1, k = 0.90 ± 0.01 min^{-1}, correlation coefficient = -0.9997; hydrocarbon 2, k = 0.0367 ± 0.0006 min^{-1}, correlation coefficient = -0.998.

Chlorination of Tetracyclo[3.3.0.$0^{2,7}.0^{4,6}$]octane 1 with t-Butyl Hypochlorite. A 4 molal solution of 75.0 mg (0.71 mmol) of 1 and 90 μl (1 equiv) of t-BuOCl in CCl_4 was irradiated in a sealed pyrex tube at 39.85 ± 0.15° (standardized) with a 275 W sunlamp at a distance of 8 in for one hr. To the resulting solution was added 10.0 mg (0.084 mmol)

cyclohexyl chloride as an internal reference, and the mixture analyzed by vpc on columns C, H, and I. No less than six components in addition to the cyclohexyl chloride and unreacted hydrocarbon were observed in the ratio of 7:16:3:58:8:8 in an overall yield of 34%. Components eluting after these peaks, although numerous, amounted to no more than 5% in yield.

The first five components had m/e = 140 and 142, corresponding to tetracyclic monochlorides. The last peak had m/e = 174, 176, and 178 as well as ions at m/e = 139 and 141, which corresponded to parent tetracyclic dichloride and P-Cl masses.

The seven percent component, in addition to an m/e corresponding to C_8H_9Cl, had ir absorptions at ν = 3085, 3001, 2879, 1447, 1342, 1269, 1194, 1090, 1050, 1083, 1021 cm^{-1}. The three percent component also had a molecular weight corresponding to a molecular formula of C_8H_9Cl, and had ir absorptions at ν = 3103, 2031, 2959, 2880, 1338, 1264, 966, 944, and 700 cm^{-1}. These two components were not identified further.

The 16% component was identified as 1-chlorotetracyclo-[3.3.0.$0^{2,7}$.$0^{4,6}$]octane 61 by the spectral analysis summarized below and detailed in the text: ir (CCl_4) ν = 3078, 3001, 2966, 2890, 2863, 1445, 1318, 1268, 1194, 1160, 1090, 1066, 990, 944, 918, and 874 cm^{-1}; nmr (Figure 1) (100 MHz, CCl_4) δ = 2.40 (d, J = 6 Hz, 1H, exo-C-8), 2.35-2.15 (m,

3H, C-2, C-7, and endo-C-8), 1.95-1.65 (m, 4H, C-4, C-5, C-6, and syn-C-3), 1.52 (d, J = 12 Hz, 1H, syn-C-3).

Anal. Calcd. for C_8H_9Cl: m/e = 140.039. Found: m/e = 140.039.

The major product was identified as 3-chlorotetracyclo-[3.3.0.$0^{2,7}$.$0^{4,6}$]octane 60 by a combination of spectral and chemical evidence outlined below, in the following experiment, and in the discussion: ir (CCl_4) ν = 3085, 2994, 2891, 1339, 1318, 1276, 1249, 1229, 1205, 1147, 1047, 1037, 982, 961, 939, 847, and 650 cm^{-1}; nmr (Figure 2) (100 MHz, CCl_4) δ = 4.05 (t, J = 1.6 Hz, 1H, C-3), 2.75 (m, 1H, C-2), 2.45 (m, 1H, C-4), 2.15 (m, 1H, C-7, anti to chlorine), 2.00 (m, 2H, C-1, syn to chlorine, and exo-C-8), 1.80 (m with a protruding doublet with coupling of 7 Hz, 3H, C-5, C-6, and endo-C-8).

Anal. Calcd. for C_8H_9Cl: C, 68.34; H, 6.45. Found: C, 68.22; H, 6.62.

The 8% monochloride, in addition to a mass corresponding to a molecular formula C_8H_9Cl, had the following ir absorptions: ν = 3085, 2983, 2959, 2873, 1617, 1450, 1320, 1287, 1267, 1219, 1195, 1039, 948, 912, 854, 847, 828, 706, 681, and 654 cm^{-1}.

Reduction of Chlorides with TBTH. Chloride reductions reported in this and the following two parts of this thesis were conducted in two ways:

Method A: Thermal Initiation: A mixture of alkyl halide, ca 1.5 equiv TBTH, a catalytic amount of AIBN, and, if necessary, cyclohexane as a solvent, was sealed under N_2 in a pyrex ampoule and heated to 100° in an oil bath. Time of thermolysis and analytical procedures varied, and are reported for the individual experiments. The resulting solutions were invariably colorless.

Method B: Photoinitiation: A mixture of required reactants was prepared as in the thermal initiation procedure above, and heated to 60° in an oil bath with irradiation from a 275 W sunlamp at a distance of about 8 in for 5 hr. The resulting solutions were consistently yellow, and were analyzed as individually reported.

Reduction of 3-Chlorotetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane 60 by TBTH. Eight mg of chloride 60 were reduced by Method A using a 24 hr reaction time. Subsequent dilution of the product mixture with pentane and analysis by vpc on column F revealed two volatile peaks in the ratio of 3:97, and no chloride. The minor product had a vpc retention time equal to parent hydrocarbon 1, but was not identified further. The major product was identified as a 78:22 mixture of 2,6- and 2,7-cis-bicyclo[3.3.0]octadiene 42 and 56 by comparison of ir and nmr to those of authentic samples (48).

Attempted Reduction of 1-Chlorotetracyclo[3.3.0.$0^{2,7}$.-$0^{4,6}$]octane 61 by TBTH. Treatment of chloride 61 by Method A for 5 days resulted in an essentially quantitative recovery of starting material and no hydrocarbon production as determined by vpc analysis.

Chlorination of Tetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2 with t-Butyl Hypochlorite. A 4 molal solution of 0.141 g (1.33 mmol) of hydrocarbon 2 and 159 μl (ca 1 equiv) of t-BuOCl in CCl_4 was irradiated in a sealed pyrex ampoule at 39.85 $\pm$ 0.15° (standardized) with a 275 W sunlamp at a distance of 8 in for one hr. To the resulting solution was added 10.5 mg of cyclohexyl chloride as an internal reference and the mixture analyzed by vpc on columns C, H, and I. Three peaks with m/e 140 and 142 corresponding to monochlorides were observed in the ratio of 50:22:28 in an overall yield of 28%. The 22% component had a peak shape indicating that it was a mixture of two components. Dichlorides were not observed in greater than 10% overall yield.

The major component was identified as 1-chlorotetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 66 by a combination of spectral and chemical analysis described below, in the discussion section, and in the following TBTH reduction: ir (CCl_4) ν = 3104, 3020, 2982, 2891, 1439, 1343, 1248, 1250, 1220, 1058, 1020, and 682 cm^{-1}; nmr (Figure 3) (100 MHz, CCl_4) δ = 2.73-2.43 (m, 4H, C-2, C-4, C-5 and C-7), 2.02-1.83 (m, 1H, C-3),

1.69 (d, J = 10 Hz, 1H, syn-C-8), 1.23 (d, J = 10 Hz, 1H, syn-C-6), 0.92 (d, J = 10 Hz, 2H, anti-C-6 and C-8).

Anal. Calcd. for C_8H_9Cl: m/e 140.039. Found: m/e 140.040.

The 22% component, although a mixture, was treated as a single component, since preparative vpc separation proved unsuccessful. This peak was assigned as a mixture of anti-6-chlorotetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 68 (chloride 8 in the nmr assignments below) and exo-8-chlorotetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane exo-6-Cl (chloride A in the nmr assignments below) by a combination of spectral and chemical evidence outlined below, in the following reduction experiments, and in the discussion section above: ir (CCl_4, collective) ν = 3096, 3030, 2976, 2890, 1448, 1287, 1261, 973, 951, 911, 701, and 656 cm^{-1}; nmr (Figure 5) (100 MHz, CCl_4) δ = 3.95 (s, $w_{\frac{1}{2}}$ = 2Hz, 1AH, endo-C-8), 3.72 (d, J = 2 Hz, 1BH, syn-C-6), 2.99 (broad m, $w_{\frac{1}{2}}$ = 8 Hz, 1BH, C-7), 2.58 (broad s, $w_{\frac{1}{2}}$ = 9 Hz, 2BH, C-1 and C-5), 2.53-2.38 (m, 2AH, C-1 and C-7, and 1BH, C-4), 2.20-2.05 (m, 1AH, C-2), 2.04-1.85 (m, protruding doublet, J = 9 Hz, 2BH, syn-C-8 and C-2), 1.95-1.65 (m, 1AH, C-4, and 1BH, C-3), 1.52-1.40 (m, 4AH, C-3, C-5, and C-6), 1.37 (d, J = 9 Hz, 1BH, anti-C-8).

Anal. Calcd. for C_8H_9Cl: m/e 140.039. Found: m/e 140.036.

The 28% component was identified as syn-6-chlorotetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 67 by normal spectral analysis,

a nuclear Overhauser experiment, and TBTH reduction discribed below and in the discussion: ir (CCl_4) ν = 3104, 3058, 3010, 2915, 1444, 1297, 1279, 954, 688, and 652 cm^{-1}; nmr (Figure 4) (100 MHz, CCl_4) δ = 3.47 (s, $w_{\frac{1}{2}}$ = 5 Hz, 1H, C-6), 2.58-2.45 (m, 1H, C-7), 2.43-2.08 (m, 4H, C-1, C-2, C-4 and C-5), 2.00-1.76 (m, 1H, C-3), 1.28 (doublet of doublets, J = 10, ca 2 Hz, 1H, syn-C-8), 1.04 (d, J = 10 Hz, 1H, anti-C-8).

Anal. Calcd. for C_8H_9Cl: m/e 140.039. Found: m/e 140.040.

Reduction of 1-Chlorotetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]octane-66 by TBTH. Using method A, 7.2 mg of chloride 66 were heated for 5 days. Dilution of the resulting solution with pentane followed by preparative vpc isolation, using column F, of the single volatile component, in addition to a large amount of unreacted chloride (estimated to be 90%), identified this product as parent hydrocarbon 2 by comparison of an ir spectrum and vpc retention time with those of an authentic sample.

Reduction of syn-6-Chlorotetracyclo[3.3.0.$0^{2,4}$.$0^{3,7}$]-octane 67 by TBTH. Application of Method A for 24 hr gave approximately 80% conversion of 7.0 mg of chloride 67 to two volatile components in the ratio of 100:37 which were isolated by preparative vpc using column F. The ir spectrum of the major product was identical to that of an authentic

sample of hydrocarbon 2. The minor product had an ir spectrum identical to that of 2,6-cis-bicyclo[3.3.0]octadiene 56 (48). It was estimated that as much as 20% of the 2,7-isomer 42 could have been present.

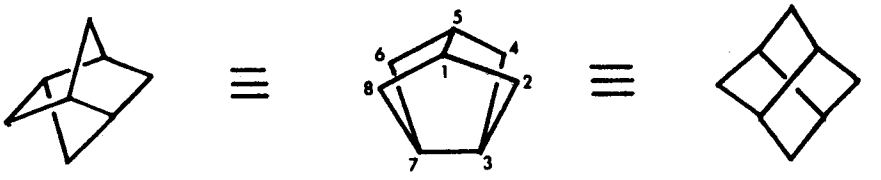
Reduction of the Mixture of anti-6-Chlorotetracyclo-[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 68 and exo-8-Chlorotetracyclo[3.3.0.-$0^{2,7}$.$0^{4,6}$]octane exo-6-Cl by TBTH. Method A: reduction of 6.0 mg of a mixture of chlorides 68 and exo-6-Cl for 5 days followed by vpc analysis using column F gave three volatile peaks in the ratio of 10:70:20, having retention times equal to 1, 2, and 42 and/or 56 respectively. Preparative vpc followed by ir analysis confirmed the identity of the major product as hydrocarbon 2. Method B: reduction of 7.0 mg of a mixture of chlorides 68 and exo-6-Cl followed by vpc analysis using column F revealed three components in the ratio of 70:10:20 having retention times equal to 1, 2 and 42 and/or 56 respectively. Preparative vpc followed by ir analysis identified the 70% component as hydrocarbon 1, and the 20% component as 2,6-diene 56 which could have contained up to 30% of the 2,7 isomer 42.

PART II

SYNTHESIS AND CHEMISTRY OF TRICYCLO[3.3.0.$0^{3,7}$]OCTANE

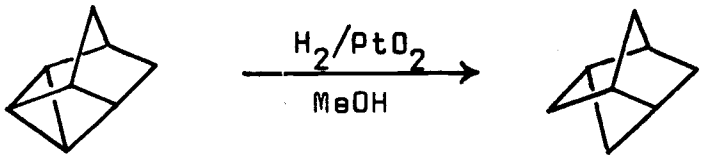
Introduction

The tricyclo[3.3.0.$0^{3,7}$]octyl ring system is most intriguing because of its overall D_2d symmetry, the inclusion of the most twisted norbornane ring of record, and its bisnor relationship to adamantane.



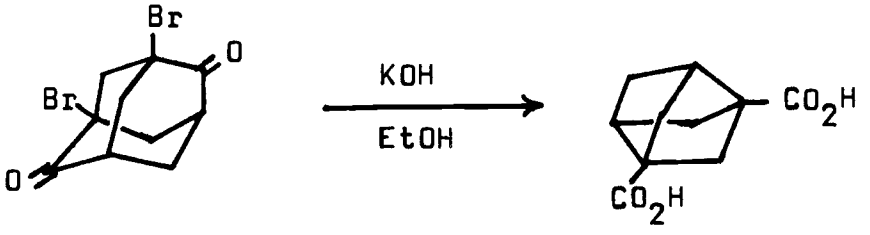
11

Four unique syntheses of the [3.3.0.$0^{3,7}$] ring system have been reported. The first, by Freeman, Rao, and Bigam (1), yielded parent hydrocarbon 11 via catalytic hydrogenation of 2 as discussed in Part I of this thesis. The



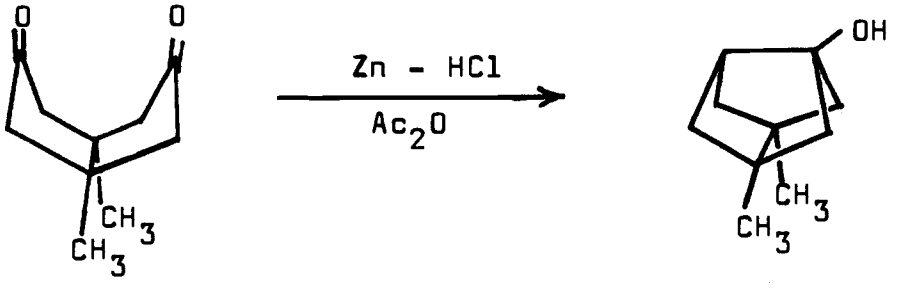
2 11

second utilized an interesting double Favorskii reaction to yield tricyclo[3.3.0.$0^{3,7}$]octane-1,3-dicarboxylic acid 73 (74). A third entry to the ring system was accomplished by reduction of dione 74 with zinc and hydrochloric acid in



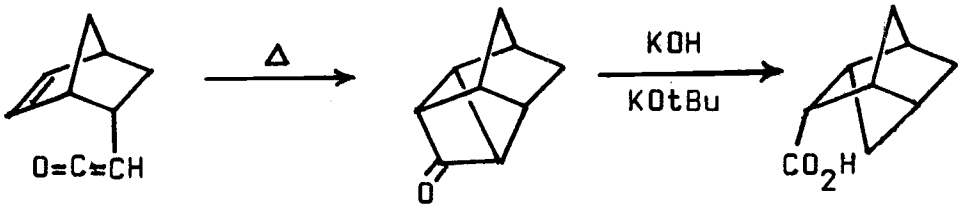
73

acetic anhydride to give alcohol 75 (75). The fourth



74 75

consisted of an intramolecular thermal ketene olefin [$_{\pi}2_s$ + $_{\pi}2_a$] cycloaddition followed by base cleavage of the resulting ketone 76 to yield carboxylic acid 77 (76).

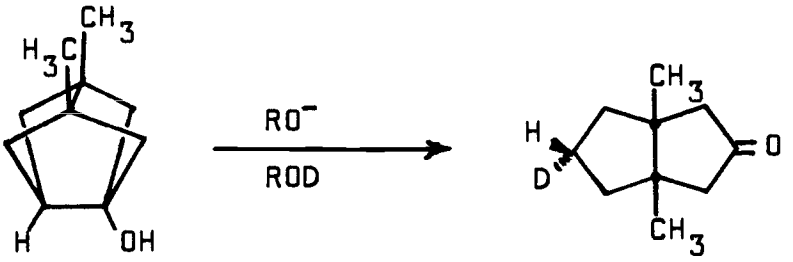


76 77

Data describing the chemical properties of the tricyclo-[3.3.0.$0^{3,7}$]octyl ring system are limited. Vogt, Suter, and Hoover (74) observed that generation of the 1-tricyclo[3.3.-0.$0^{3,7}$]octylcarbinyl carbonium ion 78 gave the 1-noradamantyl carbonium ion 79 via ring expansion analogous to other bridgeheadcarbinyl carbonium ions (77). Borden, Cabell, and

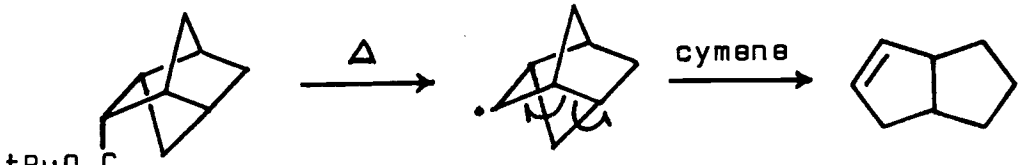
78 79

Ravindranathan (75) also report a facile reaction of one of the zero carbon bridges in this ring system; they have demonstrated that treatment of bridgehead alcohol 75 with t-BuOD or d_2-ethylene glycol and the corresponding potassium alcoholate gave stereospecific cleavage to 80 with >98% retention of configuration. This is exactly opposite of the results



75 80

found by Nickon for the base catalyzed ring opening of nortricyclanol (78), the reason for the discrepancy being at present unclear. Finally, Sauers and Kelly (76) observed that production of the secondary free radical 82 by decomposition of perester 81 resulted in homolysis of a neighboring zero carbon bridge to yield olefin 83.

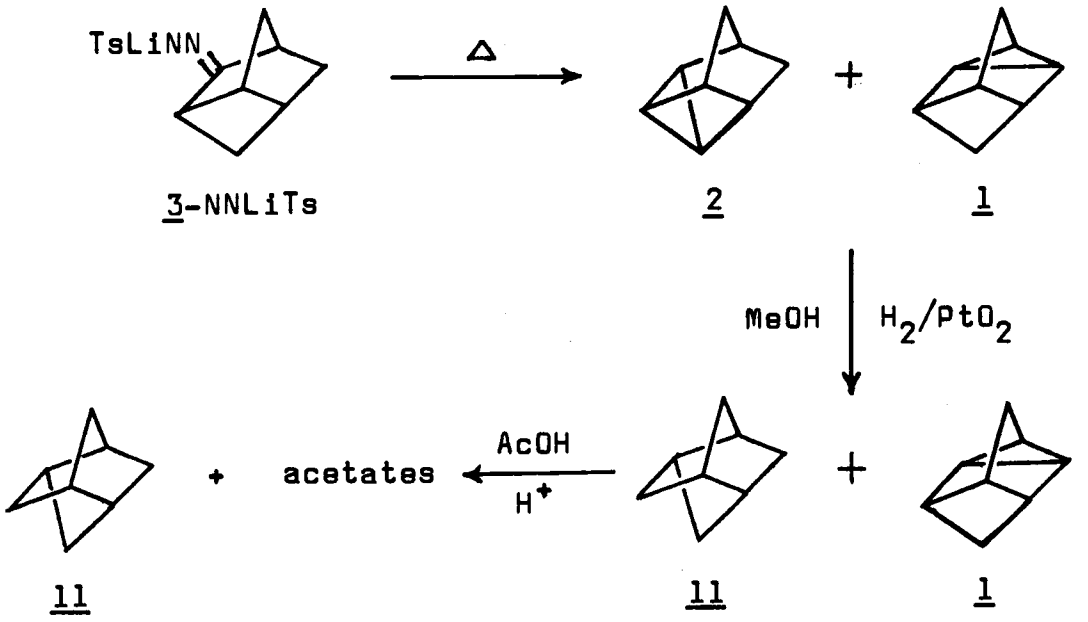


81 82 83

It is apparent from these initial studies that the chemistry of the [3.3.0.$0^{3,7}$] ring system may be dominated by strain relief achieved by cleavage of one of the transannular bonds.

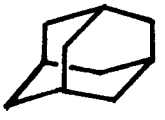
Results and Discussion

Tricyclo[3.3.0.$0^{3,7}$]octane 11, a colorless, amorphous solid, mp 105.0-105.5^{o} (1) which readily sublimes at room temperature and pressure, was obtained for use in the following studies exclusively by hydrogenation of tetracyclo-[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2. Prior to the development of the synthetic method reported in Part I, the only available route to 2 was by the method in Scheme I, coupled with the carbenoid decomposition of the resultant tosylhydrazone 3-NNHTs. For preparative runs, the dry lithium salt pyrolysis was the method of choice because of the yield (Table I). Pure 11 was obtained by capitalizing on the rapid rate of hydrogenolysis of 2 compared to coproduct 1, followed by chemical separation of 1 as a mixture of acetates.



Of primary interest was an assessment of the strain energy and its disbursement in the tricyclo[3.3.0.$0^{3,7}$]octyl ring system. Observation of CH and CH_2 stretching vibrations as well as the CH_2 scissoring deformation at significantly higher frequencies (ca 30 cm^{-1}) than corresponding absorptions in cyclohexane and adamantane (see Table IV) indicate substantial strain at both methylene and bridgehead positions (79-81), due at least in part to increased s character in the exocyclic bonds (82), and possibly to non-bonded steric interactions (83). Although a precise calculation of the strain energy in 11 is impossible based solely on these observations, it appears from the correlative data in Table IV that the methylene positions in 11 carry as much angle strain as does cyclobutane.

Table IV. Ir C-H stretching and bending vibrations in selected cyclic and polycyclic hydrocarbons.[a]

compound	stretching vibrations			methylene scissoring deformation	Ref
	CH_2		CH		
	ν_{as}	ν_s			
	3103	3024			79
	2990	2900			81
	2952	2866			79
	2927	2854		1452	79,b
	2930	2852	2907		b
	2975[c]	2894	2942	1481	b
R_3CH			2890		84

[a]All frequencies were calibrated using a polystyrene reference. [b]This thesis. [c]This value represents the center band of a broad three peak envelope.

Consideration of the proton and ^{13}C-^{1}H satellite nmr spectra of 11 (summarized in experimental section and Table V) allows a more accurate assessment of the strain in the $[3.3.0.0^{3,7}]$ ring system. It has been demonstrated that the ^{13}C-^{1}H coupling constant is approximately a linear function of the amount of s-character in the carbon orbital from which the C-H bond is formed (85), an expected result since only s

$$\% \text{ s character } \rho \times 5 = J_{^{13}C-^{1}H}(Hz) \qquad \text{eq. 1}$$

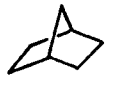
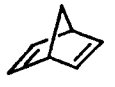
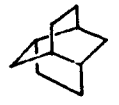
atomic states have finite electron density at the nucleus. It has further been demonstrated (86, 87) that ^{13}C-^{1}H coupling is a function of interorbital C-C-C angle (ϕ_o) and

$$\text{local } C_2v \text{ symmetry} \qquad J = \frac{250(1 + \cos\phi_o)}{1 - \cos\phi_o} \qquad \text{eq. 2}$$

$$\text{local } C_3v \text{ symmetry} \qquad J = \frac{500(1 + 2\cos\phi_o)}{1 - \cos\phi_o} \qquad \text{eq. 3}$$

of the internuclear bond angle (ϕ_n). These two phenomena

Table V. Nmr chemical shifts and $J_{^{13}C-^{1}H}$ coupling constants of selected cyclic and polycyclic hydrocarbons.

Compound	$\omega(\delta)$ Bridgehead	$\omega(\delta)$ Methylene	$J_{^{13}C-^{1}H}$ (Hz) Bridgehead	$J_{^{13}C-^{1}H}$ (Hz) Methylene	Ref
				161	86
				134	86
				128	86
				123	86
	2.19		142		95;96
				136	87
	1.78	1.78	120	120	95;97
	4.00		160		94
	2.45	1.84	164	144	46;91
	2.53	<u>exo</u> 1.59 <u>endo</u> 0.87			93
	1.63	1.35			92
	2.28	1.32	143	132	

$$\phi_o = 0.1340\,\phi_n + 94.83 \qquad \text{eq. 4}$$

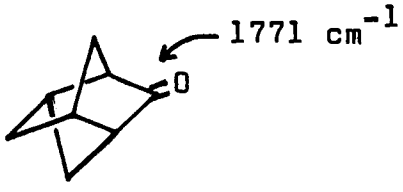
indicate that 1) with increased angle bending there is a corresponding increase in orbital bending, and 2) the hybridization of an exocyclic C-H bond is a function of the internal C-C-C bond angle. Therefore a comparison of ^{13}C-^{1}H coupling constants in 11 to those of other ring systems (Table V) should reveal relative angle strain, of primary importance in the overall molecular strain energy (88-90).

Considering first the bridgehead position, the data in Table V indicates that the s character of the C-1-H bond in 11 (ρ = 28.6%), and therefore the strain energy due to angle bending, is much more than that in adamantane (ρ = 25.0%), less than that in highly distorted cubane (ρ = 32.0%) and bicyclo[1.1.1]pentane (ρ = 32.8%), and approximately equal to that in norbornane (ρ = 28.4%). This analogy is verified by comparison of the bridgehead C-1-H chemical shifts, a value also dependent upon the hybridization of the carbon atom in the absence of diamagnetic anisotropy, medium and self-association effects (98), none of which should be important at the relatively isolated bridgehead positions in carbon tetrachloride solvent.

The ^{13}C-^{1}H coupling constants for the methylene position in 11 (ρ = 26.4%) reveals as much angle distortion as in cyclobutane (ρ = 26.8%) but considerably less than in

bicyclo[1.1.1]pentane (ρ = 28.8%). The ^{1}H chemical shifts are of little value in substantiating these observations due to non-bonded interactions (cf exo vs endo methylene hydrogens in bicyclo[2.1.1]pentane, Table V).

The nmr data describing 11 allows calculation of a 95° C-1-C-2-C-3 bond angle (local C_2v symmetry) using equations 2 and 4. This compares with the corresponding value of 93° calculated from the carbonyl stretching frequency of 84 (99) using the procedure described by Halford et al (100), and a C-1-C-7-C-4 angle of 96° in norbornane (101) to which 11 is related.



Furthermore, the coordinates of all atoms in 11 can be calculated (Table VI) based on five assumptions: 1) C-C bond lengths of 1.559 Å, selected because of the apparent similarity of the C-1-C-2 bond in 11 to the C-1-C-7 bond of norbornane (101) and substantial p character in the endocyclic transannular bonds as indicated by the ^{13}C-^{1}H nmr data; 2) C-H bond lengths of 1.115 Å (101); 3) an H-C-H bond angle of 110° (101); 4) a C-1-C-2-C-3 bond angle of 94°, the average of the two empirical values quoted above; and 5)

Table VI. Calculated Cartesian coordinates of atoms in tricyclo[3.3.0.$0^{3,7}$]octane 11.

Atom	x	y	z
C-1	0	-0.780	+0.998
C-2	+1.142	-1.142	0
C-3	+0.780	0	-0.998
C-4	+1.142	+1.142	0
C-5	0	+0.780	+0.998
C-6	-1.142	+0.142	0
C-7	-0.780	0	-0.998
C-8	-1.142	-1.142	0
H-9	0	-1.291	+1.989
H-10	+1.029	-2.083	-0.440
H-11	+2.083	-1.029	+0.440
H-12	+1.291	0	-1.989
H-13	+2.083	+1.029	+0.440
H-14	+1.029	+2.083	-0.440
H-15	0	+1.291	+1.989
H-16	-1.029	+2.083	-0.440
H-17	-2.083	+1.029	+0.440
H-18	-1.291	0	-1.989
H-19	-2.083	-1.029	+0.440
H-20	-1.029	-2.083	-0.440

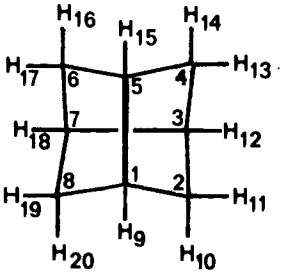
Assumptions:

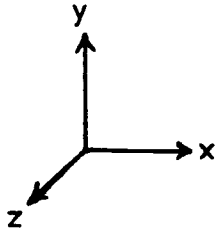
C-C = 1.559 Å

C-H = 1.115 Å

$C_1-C_2-C_3$ ∠ = 94°

H-C-H ∠ = 110°





assumption of local C_3v symmetry when calculating the coordinates of methine hydrogens.

From these coordinates, the intramolecular distances and angles summarized in Figure 6 were calculated. Of particular interest is the small distance between remote methylene hydrogens, and the effect of the "extra" methylene bridge on the angles at the bridgehead in 11 relative to norbornane (Figure 7).

The coordinate calculations were verified by assuming local C_3v symmetry at C-1 in 11, then using equations 3 and 4 to calculate an internal angle of 100° based on the appropriate empirical $^{13}C-^{1}H$ coupling constant (Table V). This value is identical within experimental error to the average of the three internal angles at C-1 calculated from the coordinates in Table VI.

Turning our attention to the chemistry of the tricyclo-[3.3.0.$0^{3,7}$]octyl ring system, we first investigated the thermal stability of parent hydrocarbon 11. At 297° in the gas phase, conversion of 11 to a single product occurred with a half life of 10.3 hours. This product was identified as cis-2-bicyclo[3.3.0]octene 83 by alternate synthesis from known alcohol 46 (40) as outlined below.

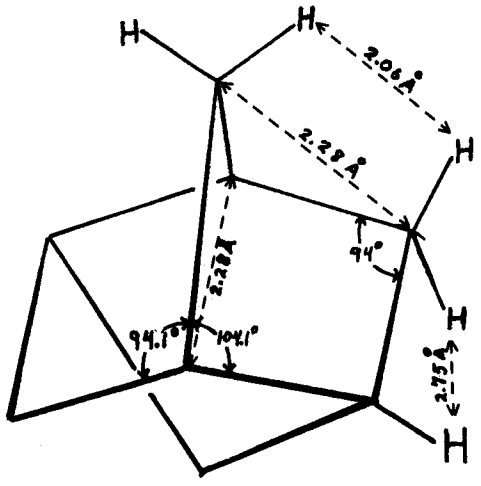


Figure 6. Calculated bond angles and internuclear distances in tricyclo[3.3.0.$0^{3,7}$]octane 11.

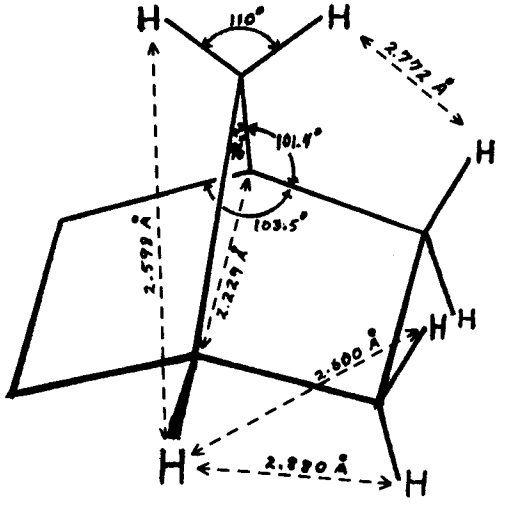
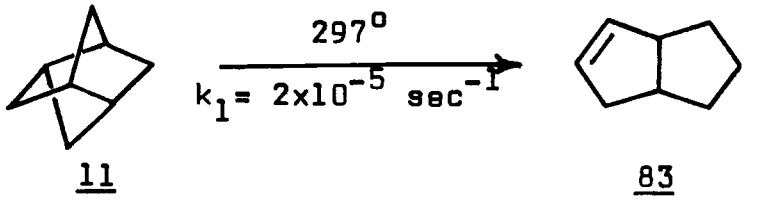
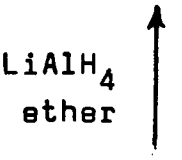
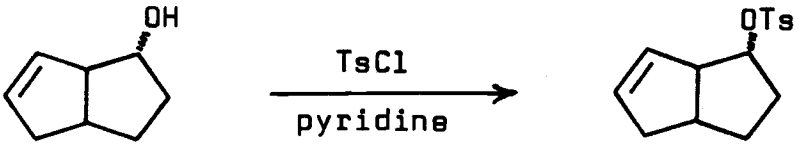


Figure 7. Bond angles and internuclear distances in norbornane (101).



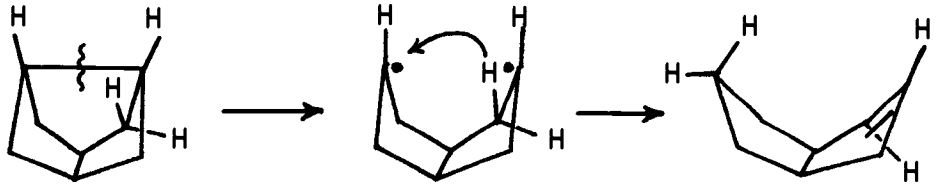
11 83





46 85

The most probable mechanism for the observed thermal rearrangement of 11 is initial homolysis of a transannular bond, followed by intramolecular hydrogen atom transfer.



11 83

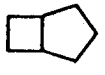
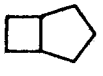
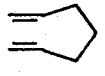
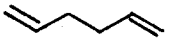
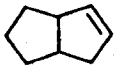
The fragmentation must occur in two steps, since there are no geometrically obtainable transition states for a concerted process which would be allowed by Woodward-Hoffman rules (37).

As in Part I of this thesis, the first order rate constant for pyrolysis of 11 ($1.9 \pm 0.1 \times 10^{-5}$ sec^{-1} at 297°)

can be used to obtain an estimate of the activation energy for fission of the [3.3.0.$0^{3,7}$] ring system. The most appropriate model to approximate the required frequency factor would be the thermal rearrangement of bicyclo[3.3.0]octane to cyclooctene since both reactions would generate remote secondary radicals. Unfortunately, no pertinent data is available for this reaction. Alternatively, value of $10^{15.4}$ was used, the pre-exponential factor observed for the pyrolyses of bicyclo[3.2.0]heptane (102). This number, along with the observed first order rate constant, allowed calculation of an activation energy for the conversion of 11 to 83 of 53 kcal/mole. Comparison to activation energies for pyrolysis of other polycyclic hydrocarbons (Table VII) proves this value to be low, indicating substantial strain relief accompanying the cleavage of the C-1-C-5 bond in 11.

More specifically, appproximation of the observed cleavage as a dissociation of two isopropyl groups (dissociation energy = 77.5 kcal/mole (103)) allows estimation of the total strain in the [3.3.0.$0^{3,7}$] system as follows: the strain relief afforded by conversion of the [3.3.0.$0^{3,7}$] system to a [3.3.0] system would be 77.5 - 53 = 25 kcal/mole; since the [3.3.0] system itself contains ca 13 kcal/mole of strain energy (89), the total strain energy in 11 would be 25 + 13 = 38 kcal/mole! This is more than double the strain energy of norbornane (17.55 kcal/mole (89)), but less than that in bicyclo[2.1.1]hexane (44.64 kcal/mole(90)).

Table VII. Products, rate constants, activation energies, and frequency factors for the gas phase pyrolyses of selected polycyclic hydrocarbons.

Reactant	Product	log A	k (sec^{-1})	Temp	E_a(kcal/mole)	Ref
		14.1			46	49
					52	49
		13.4			36	49
		13.3			57	47
					61	47
	C_2H_4 + 				61	102
		15.4			64	102
		15.5			56	104
			3×10^{-6}	305		46
			3×10^{-5}	305		46
			2×10^{-5}	297	53	

This simple calculation does not distinguish between the various factors which contribute to ring strain, and neglects any difference in strain energy between the generated diradical and a saturated bicyclo[3.3.0]octyl system. The calculated strain energy released in cleavage of the first transannular bond in 11 (25 kcal/mole) is approximately equal to the strain energy in cyclobutane (27 to 29 kcal/mole (89, 90)), which indicates that the [3.2.0] system was an adequate choice as a model to approximate the preexponential factor. Even if the true frequency factor is 10^2 different than the one chosen, this would only lower or raise the calculated strain energy in 11 by 5 kcal/mole, which still leaves it twice as strained as norbornane.

Photochemical chlorination of tricyclo[3.3.0.$0^{3,7}$]-octane 11 was carried out with chlorine in dry benzene at -5^{o}. Vapor phase chromatographic analysis indicated the presence of only one monochloride. The nmr spectrum (Figure 8, one proton α to chlorine and no olefinic protons) and ir spectrum (no absorption in the 1550 - 1750 cm^{-1} region or greater than 3002 cm^{-1}) are consistent with the assignment of structure as 2-chlorotricyclo[3.3.0.$0^{3,7}$]octane 86. Verification was obtained by free radical reduction of chloride 86 with tri-n-butyltin hydride which resulted in predominant formation (95%) of parent hydrocarbon 11. The minor product observed in this reaction was tentatively

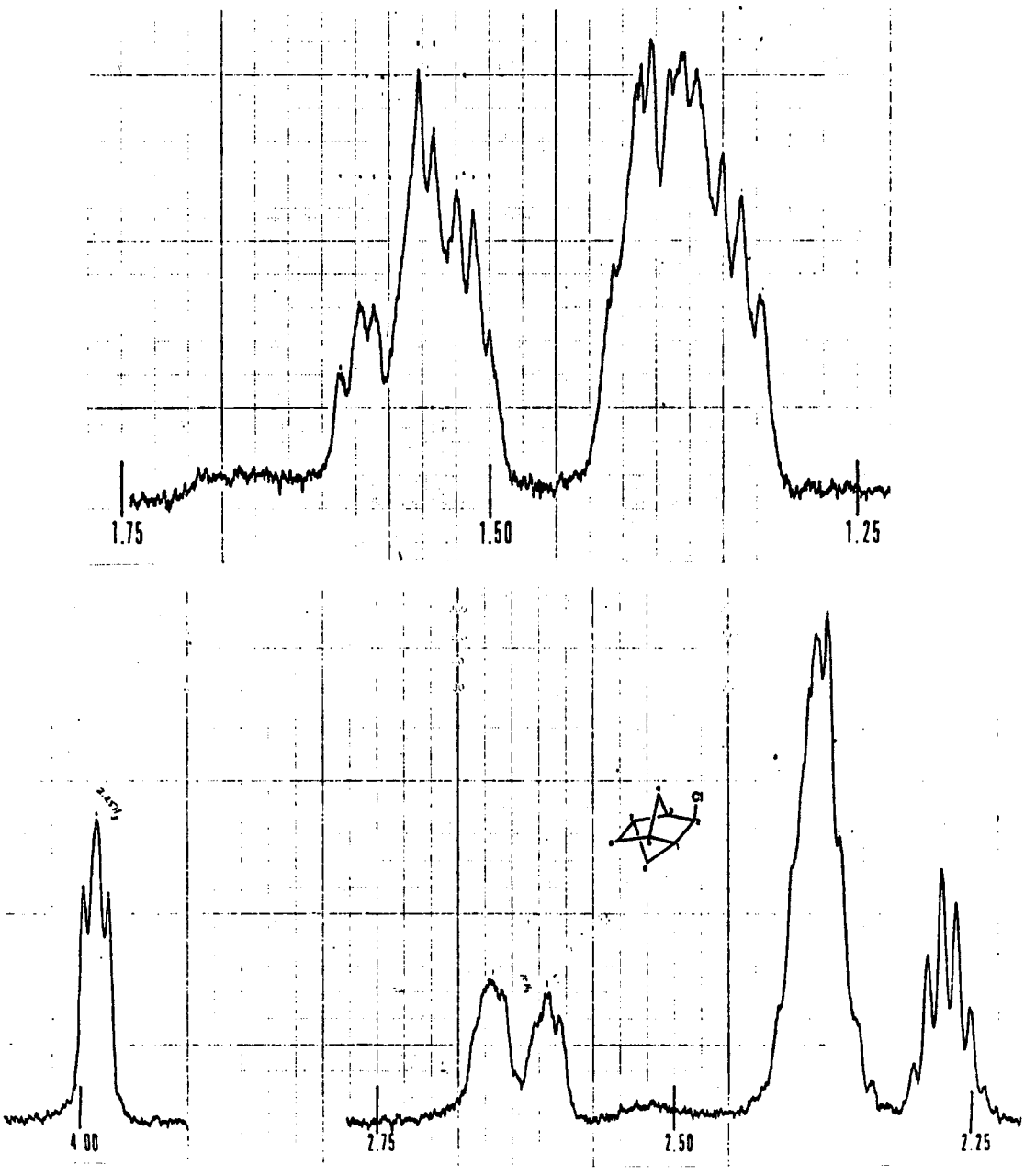
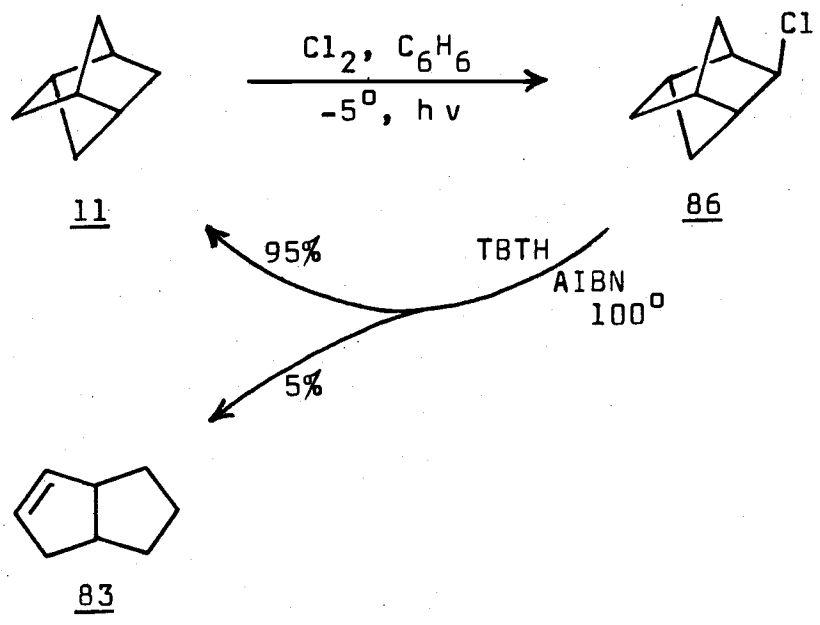


Figure 8. 220 MHz nmr spectrum (CCl_4) of 2-chlorotricyclo-[3.3.0.$0^{3,7}$]octane 86.



identified as 83, arising from β-fission of the 2-tricyclo-[3.3.0.0^{3,7}]octyl radical 82 leading to the bicyclo[3.3.0]oct-6-ene-3-yl radical, as observed by Sauers (76) in the thermal decomposition of perester 81. No evidence for analogous ring opening in the photochemical chlorination of 11 was uncovered. The behavior of the 2-tricyclo[3.3.0.0^{3,7}]octyl radical 82 under the various conditions studied is in accord with the greater rate of chain transfer of alkyl radicals in both t-butyl hypochlorite chlorinations and TBTH reductions (see chain transfer constants quoted in Part I) relative to perester decompositions in aromatic solvents (DH^{o} tBuO-Cl = 40 kcal/mole (107) whereas DH^{o} $C_6H_5CH_2$-H = 85 kcal/mole (103), indicating that chain transfer of any radical should occur much more rapidly for tBuOCl than for toluene).

Lack of formation of 1-chlorotricyclo[3.3.0.$0^{3,7}$]octane in the free radical chlorination of 11, although unfortunate from a synthetic standpoint, was not surprising. Contrary to early theoretical arguments (108) which predicted that the most favorable hybridization for a methyl radical is sp^3, it has been suggested on more empirical grounds that sp^2 is preferred (109). The latter postulate appears correct, since restricted geometry at bridgehead positions mitigates against facile formation of radical intermediates at such sites in norbornane (64-66) and bicyclo[2.1.1]hexane (67) upon subjection of these hydrocarbons to free radical hydrogen abstraction. Since the bridgehead position in the [3.3.0.$0^{3,7}$] system bears at least as much strain as that in norbornane, it would not be predicted to be reactive toward radical substitution.

On the other hand, since the regioselectivity of free radical substitution in hydrocarbons depends ultimately on the relative ease of hydrogen atom abstraction from the various incorporated positions, and since the methylene positions in 11 carry as much or more angle strain as the C-7 position of norbornane, it is somewhat curious that a modest amount of C-1 abstraction did not occur. Apparently there is enough difference between the flexibility at C-1 and C-2 in 11 such that formation of an sp^2 like transition state in the latter can occur, albeit reluctantly, whereas at the former center, this is not the case. These observations certainly

bolster the arguments favoring an sp^2 rather than an sp^3 hybridization for free radicals at carbon centers.

Further assessment of the importance of strain and rigidity in the formation of free radicals in the tricyclo-[3.3.0.$0^{3,7}$]octane system is, as alluded to above, dependent upon determination of the relative reactivity of the incorporated C-H bonds to those of related, well studied systems. We therefore turned to an investigation of the free radical reactivity of 11 relative to cyclohexane, norbornane, and adamantane.

The abstraction agent of choice was t-butyl hypochlorite because of ease of handling, and the availability of anticipated products. The accepted mechanism (59) for the reaction of hydrocarbons with t-butyl hypochlorite in carbon tetrachloride solvent where R = alkyl (110) is:

$$(CH_3)_3COCl \xrightarrow[\text{heat}]{h\nu \text{ or}} (CH_3)_3CO\cdot + Cl\cdot$$

$$(CH_3)_3CO\cdot + RH \longrightarrow (CH_3)_3COH + R\cdot$$

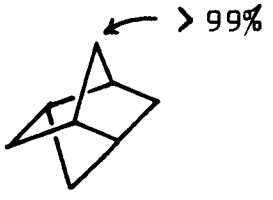
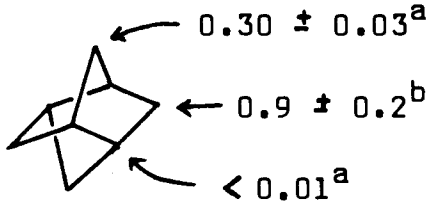
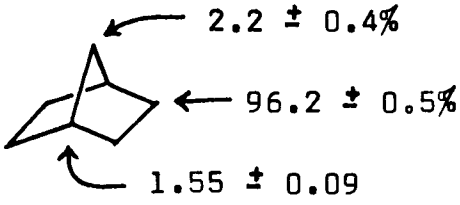
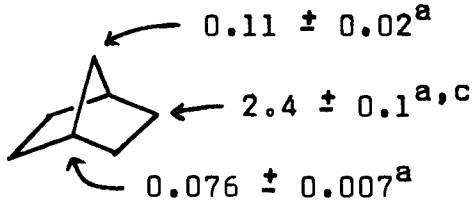
$$R\cdot + (CH_3)_3COCl \longrightarrow RCl + (CH_3)_3CO\cdot .$$

Following the method of Walling and Jacknow (111) tricyclo[3.3.0.$0^{3,7}$]octane 11 and norbornane were allowed to

compete with cyclohexane for the t-butoxy radical at 40°. Product studies were also performed under conditions identical to the competition studies. The resulting substitution patterns, as well as the per bond relative rates of hydrogen atom abstraction are presented in Table VIII.

Tricyclo[3.3.0.$0^{3,7}$]octane 11 behaved entirely as expected based on the photochlorination experiment discussed above; reaction of 11 with t-butyl hypochlorite at 40° gave only methylene substitution. Reaction of norbornane with t-butyl hypochlorite on the other hand, revealed a surprise. While substitution at the C-2 and C-7 positions occurred to the degree expected based on earlier work using chlorine in dichloromethane (65), we found, in addition, almost as much substitution at the bridgehead (1.6%) as at C-7 (2.2%) when the reaction was conducted at 40°! To verify the apparent difference between chlorine and t-butyl hypochlorite as chlorinating agents, norbornane was photolytically chlorinated with chlorine in refluxing CCl_4 (77°), conditions favoring non-selective hydrogen atom abstraction (112). As noted by Kooyman and Vegter (65), significant amounts of C-7 substitution occurred (3.3 ± 0.1%), but only careful scrutiny of the product mixture by vapor phase chromatography (an analytical tool not used by Kooyman and Vegter) revealed a 0.30 ± 0.04% relative yield of bridgehead substitution. We also carried out the chlorination of norbornane with t-butyl hypochlorite at 80° with photoinitiation, observing bridge-

Table VIII. Substitution patterns and relative rates for hydrogen abstraction from norbornane and tricyclo[3.3.0.$0^{3,7}$]octane 11 by the t-butoxy radical.

Substitution Pattern	Relative Rate of Hydrogen Abstraction
	> 99%
	0.30 ± 0.03[a] 0.9 ± 0.2[b] < 0.01[a]
	2.2 ± 0.4% 96.2 ± 0.5% 1.55 ± 0.09
	0.11 ± 0.02[a] 2.4 ± 0.1[a,c] 0.076 ± 0.007[a]

[a]Relative to cyclohexane; per hydrogen; at 39.85 ± 0.15°; *ca* 1 molal solutions in CCl_4. [b]Relative to 2-adamantyl; per hydrogen; 39.85 ± 0.15°; in CCl_4. [c]Assuming *exo* hydrogen abstraction only.

head substitution to the extent of 2.7%, in line with the expected decreased selectivity of the t-butoxy radical at elevated temperatures, and chlorination of 11 with Cl_2 in CCl_4 at ambient temperature, again observing greater than 99% methylene regioselectivity for free radical formation.

The difference between chlorine and t-butyl hypochlorite as chlorinating agents is therefore real, and indeed most intriguing, since the selectivity for bridgehead vs C-7 hydrogen abstraction (Table IX) is opposite that predicted based upon earlier work which found t-butoxy radical to be more selective than chlorine atom, at least when choosing between primary, secondary, and tertiary hydrogens (Table X). A closer analysis of these two radical chlorinating agents is therefore in order.

Both chlorine atom and t-butoxy radical have been classified as electrophilic radicals (116) because of the fact that they abstract a hydrogen from cyclohexane faster than from toluene (see Table X), and because the ρ value for hydrogen abstraction from a number of substituted toluenes is -0.66 for abstraction by chlorine atom (117) and -0.83 for abstraction by t-butoxy radical (111). These facts have been generally interpreted as indicating that the usual selectivity displayed by chlorine and t-butoxy radicals (Table X) is almost entirely due to the differences in their electrophilicities.

Recently, however, Zavitsas and Pinto (118) found that

Table IX. Relative rates of hydrogen abstraction from norbornane by t-butoxy radical and chlorine atom.[a]

Type of Hydrogen	tBuO· 40°[b]	Cl· 77°[c]	tBuO· 77°[d]
2-norbornyl	21.9 ± 0.2	14.6 ± 0.1	13
7-norbornyl	(1.00)	(1.00)	(1.00)
1-norbornyl	0.73 ± 0.05	0.091 ± 0.012	0.75

[a]All rates are per hydrogen, in CCl_4. [b]Average ± average deviation of 6 runs. [c]Average ± average deviation of 3 runs. [d]Only one run.

Table X. Relative rates of hydrogen abstraction from selected hydrocarbons by t-butoxy radical and chlorine atom.[a]

Type of Hydrogen	tBuO· 40°	Cl· 25°
primary	1	1
secondary	8	3.6
tertiary	44	4.2
cyclohexyl	15	2.5
α-tolyl	10	1.3[b]
ref	113	112,114,115

[a]All rates are per hydrogen, in CCl_4. [b]At 40°.

removal of chain transfer by chlorine atoms (a process which can interfere with alkoxy chains when hydrogen abstraction occurs from benzylic positions (110)) from t-butyl hypochlorite chlorination of substituted toluenes gave a ρ value for this reaction of only -0.41. Thus, the polar effect may not be responsible for the selectivity difference between chlorine and t-butoxy radicals.

Examination of the energetics of the two chain transfer processes sheds considerably more light on the matter. Hydrogen abstraction by chlorine atom (ΔH = -3.6 kcal/mole for abstraction of a 1-norbornyl hydrogen, DH^{o} 1-norbornyl = 99.4 kcal/mole (119) and DH^{o} HCl = 103.0 kcal/mole (103)) and hydrogen abstraction by t-butoxy radical (ΔH = -5.9 kcal/mole for abstraction of a 1-norbornyl hydrogen using DH^{o} tBuOH = 105.3 kcal/mole (120)) are both exothermic reactions. Hammond's postulate therefore indicates that the transition states encountered should resemble reactants more than products and that at the transition state the substrate undergoing hydrogen abstraction should resemble product radical more in the case of abstraction by chlorine atom than for abstraction by t-butoxy radical. Since both C-7 and C-1 positions resist rehybridization because of angle strain, polar effects, whatever their relative magnitude, should be inoperative. Therefore, since more bond breaking occurs in hydrogen abstraction by chlorine radical, this process should occur less readily than for abstraction by t-butoxy

radical, in agreement with the results obtained (Table IX).

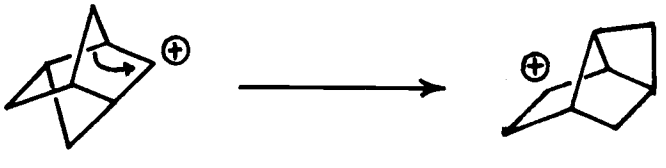
Analysis of the relative abstraction rates in Table VIII reveals that the methylene position in 11 is less reactive than the methylene position of cyclohexane by an amount approximately equal to that of cyclobutane (55), but three times as reactive as the C-7 position of norbornane. The latter observation is surprising, since models as well as the physical data described earlier suggest that the C-2 position of 11 is more strained than the C-7 position of norbornane. The reason for this apparent anomaly is suggested to result from a severe non-bonded repulsive interaction of neighboring methylene hydrogens (2.06 Å) in 11 not present in norbornane. Strain energy thus caused would be relieved in the transition state leading to hydrogen atom abstraction, since rehybridization is occurring.

The bridgehead position of 11 behaves as expected based on the ^{13}C nmr work since it is less reactive than the bridgehead of norbornane by a minimum of about 8 fold.

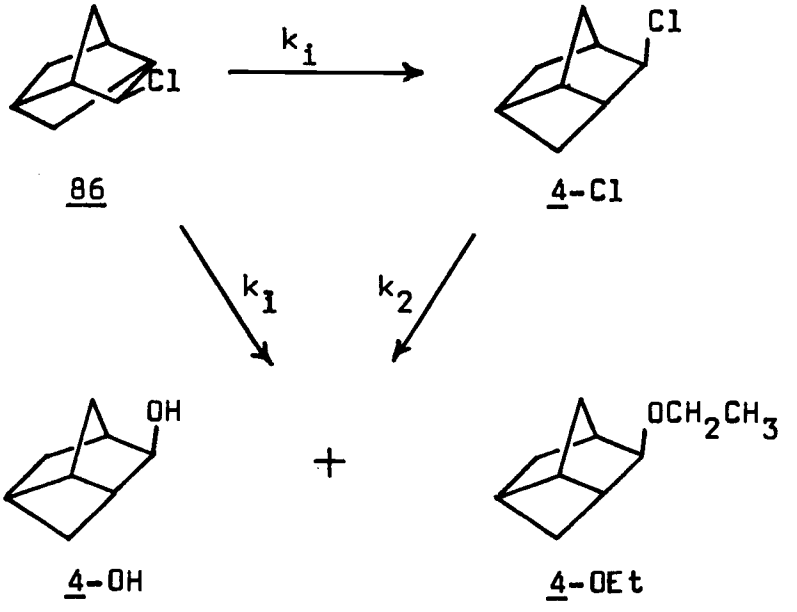
Prompted by the bisnor relationship of tricyclo[3.3.0.-$0^{3,7}$]octane to adamantane, we extended our free radical studies to include the relative reactivity of these two symmetrical hydrocarbons toward hydrogen abstraction by t-butoxy radical. Data resulting from an experiment performed analogously to the cyclohexane competition studies are

included in Table VIII. The substitution pattern of adamantane is similar to that observed by Koch and Gleicher (66) for hydrogen abstraction by trichloromethyl radical, the preference for bridgehead over methylene substitution having been attributed by these authors to a combination of the electronic preference for tertiary vs secondary radical formation and the unfavorable torsional interaction in the sp^2 like transition state. The somewhat baffling near equality of methylene hydrogen abstraction rates in these two hydrocarbons must be due to a combination of steric acceleration in the case of 11, and torsional strain introduction in adamantane.

Turning our attention from free radical chemistry, we felt that the strain present in the [3.3.0.$0^{3,7}$] system and its relationship to the norbornyl system would make an investigation of a carbonium ion intermediate at the methylene position in 11 of interest. A priori, a Wagner-Meerwein shift, analogous to that undergone by the 2-norbornyl carbonium ion, or ring cleavage analogous to the behavior of the tricyclo[3.3.0.$0^{3,7}$]octyl free radical 82 (76) was expected.



Solvolysis of chloride 86 in 80% aqueous ethanol at 85.4 ± 0.1° resulted in behavior reminiscent of that noted by Winstein, Young, and Goering (121) concerning the solvolysis of γ,γ -dimethylallyl chloride which was found to rearrange to the more stable tertiary isomer. After only 10 hours (Figure 9) vapor phase chromatographic analysis showed almost no initial chloride left, although only about half of the theoretical amount of hydrogen chloride had been liberated. Product analysis showed indeed a second chloride 4-Cl was being formed via internal return in addition to solvolysis products 4-OH and 4-OCH_2CH_3.



Using the kinetic method of Young, Winstein, and Goering (121), the rate constants for isomerization of 86 to 4-Cl and for solvolysis of 86 and 4-Cl were determined (Table XI).

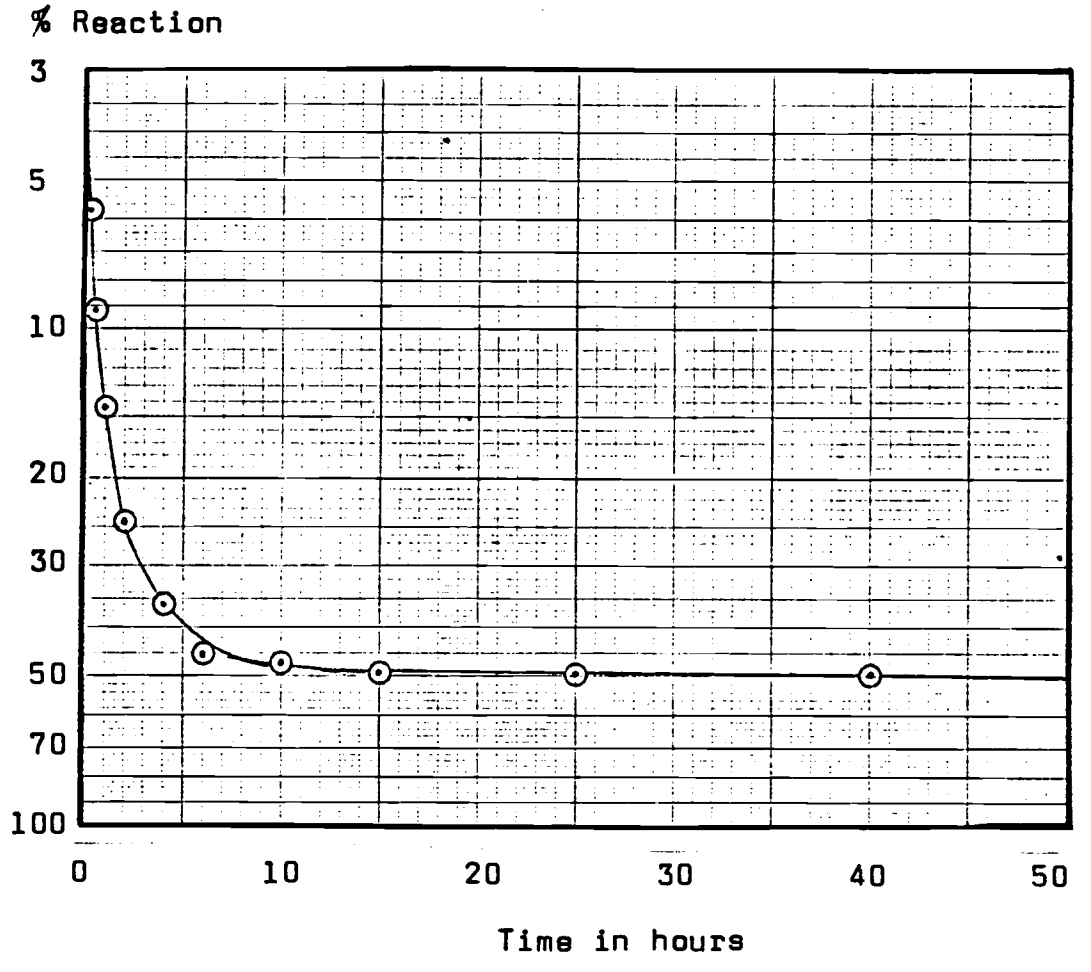
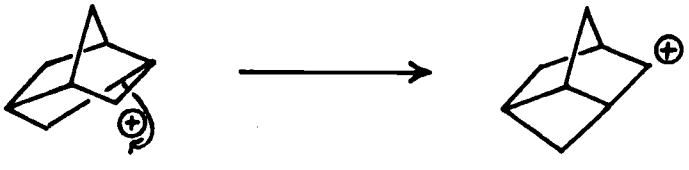


Figure 9. Kinetic data from solvolysis of 2-chlorotricyclo[3.3.0.$0^{3,7}$]octane 86 expressed as % reaction vs time.

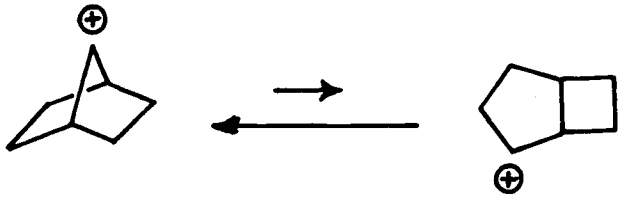
Table XI. Rate constants for chloride solvolyses and rearrangement.

chloride	Temp	rate constant (hr^{-1})
86	85.4 ± .1	k_1 0.20
86	85.4	k_i 0.16
4-Cl	85.4	k_2 5.1×10^{-4}
exo-2-norbornyl	85.0 ± .1	0.14 (122)

The solvolysis of chloride 86 proceeds at essentially the same rate as that for exo-2-norbornyl chloride, and since models as well as the spectral data presented earlier reveal that the geometry of the 2-tricyclo[3.3.0.$0^{3,7}$]octyl position resembles the 7-norbornyl position much more closely than the 2-norbornyl position, a rate enhancement of ca 10^8 is indicated (123). The large degree of strain present in the [3.3.0.$0^{3,7}$] system is revealed by the facile Wagner-Meerwein rearrangement which takes place during solvolysis, a process which is formally a cyclopentyl to cyclobutylmethyl conversion.



Making the assumptions that the same intermediate is formed in the solvolyses of 86 and 4-Cl and that return to 4-Cl is favored over return to 86 by a factor of 100 or greater, the standard free energy of the cyclobutyl form 4-Cl is at least 7 kcal/mole less than that for the cyclopentyl form 86. This contrasts with the situation which prevails for ionization of 7-norbornyl substrates, where the cyclopenty form (2.2.1) is more stable than the cyclobutyl form (3.2.0) by about 14 kcal/mole (122). Thus, to the degree that the



transition state for solvolysis of 86 resembles the tricyclo-[3.2.1.$0^{3,6}$]octane system, the enhanced rate may be rationalized by the greater stability of the [3.2.1.$0^{3,6}$] skeleton and the reduced angle strain at C_α for the developing carbonium ion center.

Recent investigations of the reactivity of strained carbon-carbon single bonds with Ag(I) (105) and Rh(I) (106) suggested attempts at rearrangement of the tricyclo[3.3.-0.$0^{3,7}$]octyl ring system with these catalysts. Unfortunately, treatment of 11 at elevated temperatures with either

saturated $AgClO_4$ in benzene or $[Rh(norbornadiene)Cl]_2$ in chloroform was ineffectual, indicating a lack of sufficient strain energy in the ring system, or a considerable steric hindrance towards attack by either cataly t.

Concluding the chemistry of tricyclo[3.3.0.$0^{3,7}$]octane, it can be said that the physical properties and reactivity of this ring system are largely determined by the high degree of incorporated strain energy. Of particular interest is the disparity between the modes of strain relief for positively charged ion and uncharged trivalent radical 2-tricyclo[3.3.0.$0^{3,7}$]octyl intermediates. The preference for fragmentation relative to alkyl migration by the radical intermediate is in accord with the fact that 1,2-alkyl shifts in carbon radicals are unknown (68,124) whereas 1,2-alkyl (or Wagner-Meerwein) shifts in carbonium ion intermediates are common.

EXPERIMENTAL SECTION

General. The general techniques and equipment described in the experimental section of Part I of this thesis were used, except as noted.

Preparation of Tricyclo[3.3.0.$0^{3,7}$]octane 11. The pyrolysate from the thermal decomposition of 3-NNLiTs (Part I experimental) was dissolved in a 10 fold molar excess of anhydrous methanol and hydrogenated at 1 atm in the presence of Adam's catalyst. Uptake of hydrogen to about 40 mole % (the per cent of isomer 2 in the pyrolysate) was rapid over a 1 hr period. The resulting suspension was diluted with pentane, filtered, then washed five times with water. After drying over anhydrous Na_2SO_4, the clear solution was concentrated by distillation of the pentane through a 10 cm Vigreaux column.

Separation of desired 11 from the contaminating tetracyclic hydrocarbon 1 was accomplished either by preparative GLC on columns H, D, or F, or by stirring the concentrate from the hydrogenolysis in 0.08 N H_2SO_4 in glacial acetic acid, followed by dilution with pentane and extraction with five aliquots of water. The resulting solution was dried over Na_2SO_4 and the pentane removed by distillation through a 10 cm Vigreaux column. The residue was chromatographed on

a short alumina column with pentane elution. Pure 11 obtained in this manner had ir and nmr spectra identical to those previously reported (1,3).

IR Spectra of Cyclohexane, Adamantane, and Tricyclo-[3.3.0.$0^{3,7}$]octane 11. Ir spectra used for comparison of the C-H bending and stretching modes in these compound were obtained on a Perkin-Elmer Model 621 Infrared Spectrophotometer. The 1400 - 1600 cm^{-1} and the 2800 - 3100 cm^{-1} regions were scanned using the 10.4 cm^{-1}/cm linear drive. a polystyrene absorption band within each region being recorded simultaneously with each spectrum for reference. The calibrated absorption bands observed are recorded in the text, Table IV.

^{13}C-^{1}H Satellite Spectrum of Tricyclo[3.3.0.$0^{3,7}$]-octane 11. A sample of 11 of sufficient purity for determination of the ^{13}C-^{1}H satellites was obtained by vpc collection, reinjection, and collection on column E. Using a Varian Associates Model HA-100 NMR Spectrometer in conjunction with a time averaging computer, the satellites were observed with $J_{^{13}C-^{1}H}$ (CH_2) = 132.0 ± 0.7 Hz, $w_{\frac{1}{2}}$ = 4.3 Hz and $J_{^{13}C-^{1}H}$ (CH) = 142.5 ± 0.7 Hz, $w_{\frac{1}{2}}$ = 7.5 Hz, the values reported being the average and standard deviation of nine scans on three separately isolated samples of 11.

Pyrolysis of Tricyclo[3.3.0.$0^{3,7}$]octane 11. A mixture of 5 mg of 11 and ca 10 μl of n-decane, both vpc collected from column D, was divided between six pyrex tubes which had been rinsed with 28% NH_4OH and dried at 175° for 24 hr. The tubes were cooled in dry ice-isopropanol, evacuated, and sealed. Four tubes were pyrolyzed at 297 ± 1.5° (NBS calibrated), a fifth saved back for a t = 0 point, the sixth being discarded. At appropriate intervals, each tube was cooled, refrozen in dry ice-isopropanol, opened, and analyzed by vpc using column G. Integrals were obtained by electronic integration. Only one peak other than that corresponding to 11 and n-decane was observed; the resultant data are presented in tabular form below:

	Integrated relative areas			
Time	n-decane	11	83	(11+83)/n-decane
0 hr	(1.00)	1.25	-	1.19
3	"	1.06	0.293	1.30
6	"	0.813	0.408	1.22
9	"	0.693	0.585	1.28
12	"	0.536	0.755	1.29

As indicated by the last column in this table and the equality of the two rate constants calculated below, no substantial polymerization occurred. A plot of $\log[\underline{11}]/[\underline{11}]_0$ vs time using a linear least squares computer analysis gave a straight line with a slope corresponding to $k = 0.070 \pm 0.002\ hr^{-1}$ with a correlation coefficient of -0.997; a similar plot of $\log([\underline{83}]_\infty - [\underline{83}]/[\underline{83}]_\infty)$ vs time gave $k' = 0.072 \pm 0.004\ hr^{-1}$ with a correlation coefficient of -0.995.

The product from the gas phase pyrolysis was identified via a preparative scale run on *ca* 20 mg of 11 using the procedure described above, omitting the internal reference n-decane. After 10.5 hr at 305° (uncalibrated), vpc analysis indicated about 60% conversion to a single product ($t_{\frac{1}{2}}$ = 9 hr), which was vpc collected from column D, and had nmr and ir spectra identical to those of an authentic sample of 83 prepared as described below.

Preparation of *cis*-2-Bicyclo[3.3.0]octene 83. Tosylate 85 was formed over a 3 day period at 5° from 5.0 g (0.0403 mol of alcohol 46 and 15 g (0.0788 mol) of freshly recrystallized tosyl chloride in dry pyridine. The resulting pink solution was poured into 350 ml of ice water and extracted with 3 aliquots of ether. The combined organic extracts were washed twice with 3 M HCl, once with water, and dried over Na_2SO_4-K_2CO_3. Removal of solvent at reduced pressure resulted in isolation of 11.5 g (100%) of an oil. Several recrystalli-

zations from pentane resulted in crystal formation, but with severe loss of yield. The crude oil had an ir spectrum (neat, ν = 3077, 2976, 1600, 1357, 1176, 994, 903, 814, 715, 688, 667 cm^{-1}) showing the characteristic arylsulfonate bands, and the requisite olefinic absorptions, and was therefore used as such in the subsequent reduction.

To a stirred suspension of 100 ml of anhydrous ether and 2.71 g (0.0714 mol) of lithium aluminum hydride was added, dropwise, over a 1.5 hr period a solution of 10.0 g (0.0357 mol) of tosylate 85 dissolved in 50 ml of anhydrous ether. After refluxing an additional 2 hr, the excess $LiAlH_4$ was killed by cooling in an ice bath and adding saturated NH_4Cl. The solution was neutralized with 6 N HCl, the aqueous layer separated and washed twice with ether. The combined ether layers (200 ml) were extracted with water, saturated NaCl, and dried over K_2CO_3-Na_2SO_4. Removal of the ether by distillation through a spinning band column, followed by distillation of the residue, afforded 3.38 g (88%) of pure alkene 83, bp (760 mm Hg) 140-142°. Ir and nmr spectra of 83, identical to those of a previously reported sample (125), were: ir (neat) ν = 3078, 2976, 2890, 1613, 1445, 703 cm^{-1}; nmr (100 MHz, CCl_4) δ = 5.47 (m, 2H), 3.10 (broad, 1H), 2.75-2.35 (m, 2H), and 2.15-1.15 (m, 7H).

Chlorination of Tricyclo[3.3.0.$0^{3,7}$]octane 11 with Chlorine in Benzene. A solution of 0.50 g (0.046 mol) of

11 in 20 ml of 0.29 M chlorine in anhydrous benzene was cooled to -5° and irradiated for one hr with direct sunlight. The resulting colorless solution was then boiled briefly to expel HCl. Vpc analysis on column B indicated the presence of only one volatile component. Distillation of the benzene at atmospheric pressure, followed by vacuum distillation yielded 0.50 g (76%) of 2-chlorotricyclo[3.3.0.$0^{3,7}$]octane 86; m/e (70 eV) 142 and 144; ir (neat) ν = 3002, 2919, 1486, 1313, 1292, 935, 855, 821, 747 cm^{-1}; nmr (Figure 8) (220 MHz, CCl_4) δ = 3.97 (t, J = 2.3 Hz, 1H), 2.36 (m, 3H), 2.15 (sextet, J = 2.8 Hz, 1H), 1.54 (m, 2H), 1.36 (m, 3H).

Anal. Calcd. for $C_8H_{11}Cl$: C, 67.36; H, 7.78. Found: C, 67.30; H, 7.77.

Reduction of 2-Chlorotricyclo[3.3.0.$0^{3,7}$]octane 86 with TBTH. A solution of 1.9 mg (0.0133 mmol) of chloride 86, 4.4 mg (0.015 mol) of tri-n-butyltin hydride, 1 mg of AIBN, and ca 20 μl of spectral grade cyclohexane was sealed in a glass tube and heated 12 hr at 100°. Vpc analysis on column G showed two volatile peaks in the ratio of 95:5. The major component was collected and had an ir spectrum identical to that of an authentic sample of tricyclo[3.3.0.-$0^{3,7}$]octane 11. The minor component was not unambiguously identified, but had a retention time identical to that of an authentic sample of cis-2-bicyclo[3.3.0]octene 83,

prepared as above.

Chlorination of Norbornane with t-Butyl Hypochlorite. A solution of 19.1 g (0.20 mol) of norbornane, 10.7 g (0.111 mol) of t-BuOCl, and 80 ml of CCl_4 in a pyrex reaction vessel, equipped with reflux condenser and magnetic stirrer, was heated to reflux, then irradiated for one hr with a 275 W sunlamp. Removal of the solvent and unreacted norbornane by distillation at reduced pressure left a residue of 7.6 g (52%). Vpc analysis on column H indicated the presence of one major and four minor components in ratios of 2.7:91.5:0.3:1.1:4.4 as determined by electronic integration. The major component had an unresolved shoulder estimated to be approximately equal in size to the 2.7% component.

The first component was identified as 1-chloronorbornane by ir and nmr spectral comparison of a vpc collected sample with an authentic sample prepared by the method of Bixler and Niemann (126). The second major component was identifed by nmr and ir analysis of a vpc collected sample as a 7.8:1 mixture of exo:endo-2-chloronorbornane. This stereochemical ratio is in line with previous investigations of the 2-norbornyl free radical (127). The 3% shoulder appearing on this major peak was isolated by treatment of an aliquot of the crude monochloride mixture with $AgNO_3$ in 80% aqueous ethanol. Pentane extraction ultimately revealed by vpc analysis that neither the 2.7% component (1-chloronorbornane) nor this

shoulder decreased in size, while the 2-chloronorbornane peak nearly vanished. Preparative vpc resulted in identification of this product as 7-chloronorbornane by ir comparison to a published spectrum (128) in a relative yield of 3.6%.

The last three minor components eluting after the identified norbornyl chlorides were not identified, but presumably arose from the t-BuOCl because they were absent in the corresponding chlorination with chlorine described below.

Chlorination of Norbornane with Chlorine in CCl_4.

A 4 molal solution of norbornane in CCl_4 was brought to reflux, and Cl_2 was bubbled in with irradiation by a 275 W sunlamp until a maximum of 2% reaction had occurred, as determined by vpc analysis. After boiling briefly to expel HCl, the solution was analyzed by vpc on column H. The three observed components were identified as exo- plus endo-2-chloronorbornane (96.4 $\pm$ 0.1%) and 7-chloronorbornane (3.3 $\pm$ 0.1%) as determined by ir analysis of samples vpc collected from a preparative scale run, and 1-chloronorbornane (0.30 $\pm$ 0.04%) by coinjection with an authentic sample on column H. The product ratios and errors are the average and average deviation of three separate chlorinations.

Chlorination of Norbornane with t-Butyl Hypochlorite: Relative Rate Product Study. A solution 1.29 m norbornane and 0.30 m t-butyl hypochlorite in CCl_4 was sealed in a pyrex ampoule and irradiated at 39.85 ± 0.15° (NBS calibrated) for 2 hr. Subsequent vpc analysis on column H revealed the presence of 1-chloro-, 7-chloro-, and 2-chloronorbornane in the ratio of 1.6:2.2:96.2.

Reaction of Tricyclo[3.3.0.$0^{3,7}$]octane 11 with t-Butyl Hypochlorite in CCl_4. A solution of 36 mg (0.34 mmol) of hydrocarbon 11 and 41 μl (1 equiv) of t-BuOCl were dissolved in CCl_4 to ca 4 molal, the tube sealed and irradiated at 39.85 ± 0.15° (standardized) with a 275 W sunlamp at a distance of 8 in. The resulting solution was subjected to preparative vpc on column C, and yielded 10.4 mg (22%) of 2-chlorotricyclo[3.3.0.$0^{3,7}$]octane 86. No other product of greater than 1% was observed by vpc analysis on column H.

Reaction of Tricyclo[3.3.0.$0^{3,7}$]octane 11 with Chlorine in CCl_4. In a pyrex tube were placed 3 mg of 11 and 50 μl of CCl_4. At ambient temperature, a dilute solution of Cl_2 in CCl_4 was added dropwise with irradiation with a 275 W sunlamp. Monitoring the reaction by vpc using column H demonstrated that up to 50% conversion of 11 to 86, no other chloride was formed in greater than 1% relative yield.

Relative Rates of Hydrogen Atom Abstraction. Relative rate data were obtained by the method of Walling and Jacknow (111). Reference and chlorination runs, both performed in replicate, were prepared from single stock solutions of hydrocarbons in CCl_4 and were treated identically, except for the exclusion of t-BuOCl in the former. The solutions were prepared ca 1 molal in each hydrocarbon and t-BuOCl. Photolyses were carried out at 39.85 ± 0.15° (standardized) with irradiation from a 275 W sunlamp at a distance of 8 in. Analysis was performed on column H by vpc with the aid of an electronic integrator. The resultant per mole relative reaction rates, determined by the method of Huyser (129) are summarized below:

Compound	Reference	k/k_{ref}	number of runs
norbornane	cyclohexane	0.82 ± 0.03	6
11	cyclohexane	0.20 ± 0.02	6
11	adamantane	0.17 ± 0.04	8

The products resulting from chlorination of adamantane were identified from combined rate runs as 1-chloro- and 2-chloroadamantane in a relative yield of 7:3 by comparison

of vpc retention times on column I to those of authentic samples.

Preparation of 2-Ethoxytricyclo[3.2.1.$0^{3,6}$]octane 4-OEt. To a solution of 2 g (0.0161 mol) of alcohol 4-OH in 15 ml of anhydrous ether was added portionwise 0.677 g (0.0161 mol) of sodium hydride. After heating at reflux for 24 hr, 2.15 g (0.0161 mol) of ethyl iodide in 15 ml of anhydrous ether was added dropwise and the resulting solution stirred at reflux for 45 hr. After cooling to room temperature, water was added, the resulting organic layer dried over anhydrous $MgSO_4$, and the ether removed at reduced pressure. The residue was subjected to preparative vpc on column E, the two volatile peaks, observed in the ratio of 95:5, identified as starting alcohol 4-OH by ir and nmr analysis, and desired ether 4-OCH_2CH_3; ir (0.1 mm, CCl_4) ν = 2976, 2874, 1250, 1111, 862, 694 cm^{-1}; nmr (100 MHz, CCl_4) δ = 3.38 (quartet, J = 7 Hz, 2H), 3.34 (s, 1H), 2.74 (broad s, $w_{\frac{1}{2}}$ = 8 Hz, 1H), 2.57 (broad s, $w_{\frac{1}{2}}$ = 7 Hz, 1H), 2.16 (m, 2H), 1.78 (d, J = 11 Hz, 2H), 1.70-1.45 (m, 1H), 1.38 (s, 1H), 1.30-1.10 (m, 2H), 1.11 (triplet, J = 7 Hz, 3H).

Anal. Calcd. for $C_{10}H_{16}O$: C, 78.89; H, 10.60. Found: C, 78.87; H, 10.43.

Solvolysis of 2-Chlorotricyclo[3.3.0.$0^{3,7}$]octane 86.

A solution which was 0.029 M chloride 86 and 0.028 M p-xylene in 80% aqueous ethanol was sealed at -70° into pyrex tubes in 3 ml aliquots. The ampoules were submerged in an 85.4 ± 0.1° (NBS calibrated) oil bath. At appropriate intervals the solutions were analyzed both titrimetrically and gas chromatographically by freezing to -70°, allowing the ampoules to warm to room temperature, and removing 2.955 ± 0.003 ml of the solution. These aliquots were diluted with 20 ml of water and titrated with standardized 0.022 M NaOH using a Beckman Model 72 pH meter. The resulting titers are given in Table XII. Immediately after titration, each sample was extracted with 25 ml of pentane, the pentane solution extracted with three aliquots of water, dried over anhydrous Na_2SO_4, and the bulk of the pentane removed by distillation through a 10 cm Vigreaux column. The resulting residues from Runs #3 - #8 were analyzed on column B and showed four volatile peaks in addition to the internal p-xylene reference. These components were identified by vpc collection from column B as 4-Cl, starting chloride 86, ether 4-OCH_2CH_3, and alcohol 4-OH by comparison as described above. Using p-xylene as an internal reference, peak areas for chlorides 86 and 4-Cl resulted in F values (121) summarized in Table XII.

Table XII. Kinetic data from solvolysis of 2-chlorotricyclo[3.3.0.$0^{3,7}$]octane 86 in 80% aqueous ethanol at 85.4 ± 0.1°.

Run	Time hr	[HCl] x 10^2 N	% Reaction[a]	F[b]
1	0.00	0.00	0.0	1.000
2	0.25	0.43	5.8	-
3	0.50	0.68	9.2	0.861
4	1.00	1.07	14.4	0.757
5	2.00	1.81	24.4	0.592
6	4.00	2.67	36.1	0.347
7	6.00	3.36	45.4	0.175
8	10.00	3.49	47.2	0.051
9	15.00	3.68	49.7	-
10	25.00	3.66	49.5	-
11	42.00	3.74	50.6	-
12	91.00	3.84	51.9	-
13	144.50	3.92	53.0	-

[a][HCl] at time = , 7.40 x 10^{-2} N as calculated from the amount of chloride solvolyzed. [b]F values were determined by vpc analysis on column B; relative peak areas were obtained by the method of weighing.

Part III

FREE RADICAL HYDROGEN ABSTRACTION FROM BRIDGED POLYCYCLIC HYDROCARBONS CONTAINING THE NORBORNANE SKELETON

Introduction

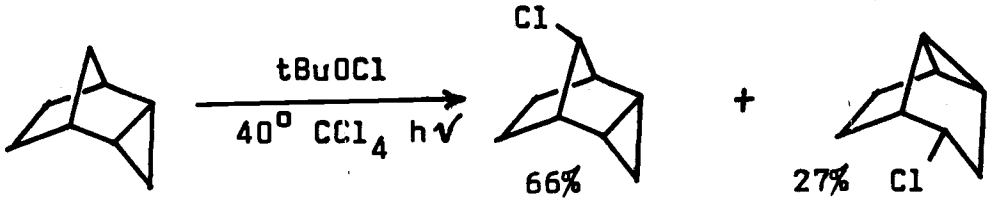
A number of unprecedented observations concerning free radical hydrogen atom abstraction from bridged polycyclic hydrocarbons have recently been made in our laboratories. Several of these unique results are described in Parts I and II of this thesis, and are summarized as follows: 1) contrary to earlier studies which found norbornane unreactive toward free radical hydrogen abstraction at the bridgehead position (64-66), we observed substitution at C-1 to an approximately equal extent as C-7 substitution when t-butoxy radical is the abstracting agent; 2) free radical hydrogen abstraction from tetracyclo[3.3.0.0^{2,4}.0^{3,7}]octane 2 gave predominate C-1 substitution, formally a bridgehead position of a [2.2.1] moiety; and 3) free radical hydrogen abstraction from tetracyclo[3.3.0.0^{2,7}.0^{4,6}]octane 1 resulted in a large amount of substitution at C-1, formally a bridgehead position of a [2.1.1] moiety, historically as unreactive in such reactions as norbornane (67).

Still another example of unexpected bridgehead free radical reactivity arose as a result of the efforts of R. S. Raghavan who observed (130, 131) that photochlorination of exo-tricyclo[3.2.1.$0^{2,4}$]octane 87 gave substantial C-1 substitution. Since the ethano bridge in this system should

87 79% 17%

88

equal in reactivity that in norbornane, the data in Table VIII describing norbornane, and the per mole relative rate of hydrogen abstraction of 87 as determined by Raghavan (130), make it possible to calculate a six fold rate enhancement for free radical hydrogen abstraction from the bridgehead position in 87 relative to C-1 in nobornane. Perhaps most intriguing is the fact that Raghavan observed (130, 131) no such bridgehead substitution in the endo isomer 89, suggesting that the effect of the cyclopropyl moiety is quite sensitive to geometry. However, the rapid rate of hydrogen



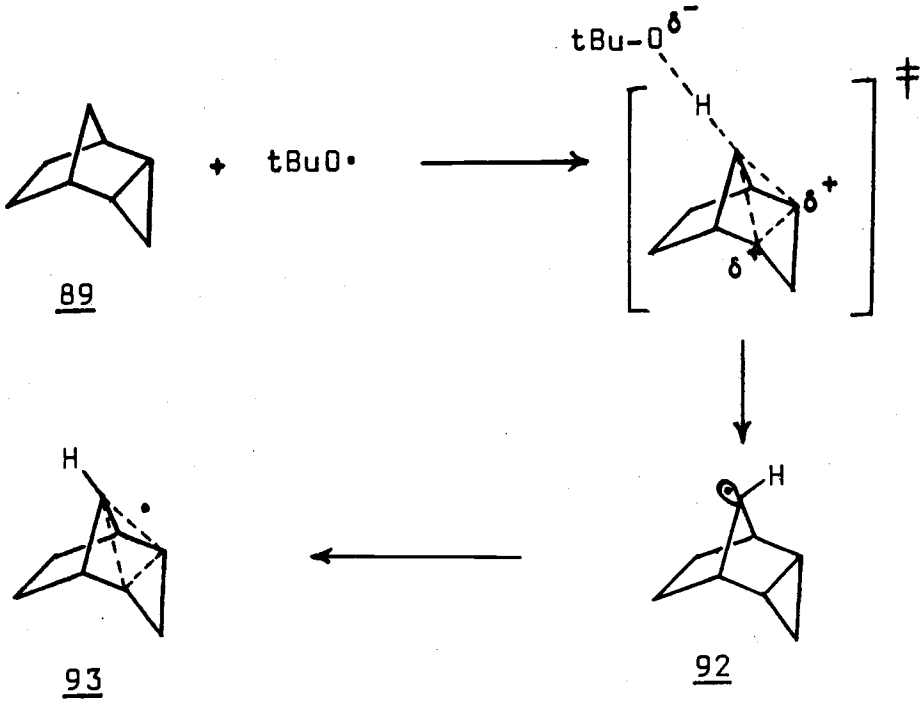
89 90 91

abstraction from the methylene bridge of 89 (eleven times faster than hydrogen abstraction from cyclohexane (130)) may have obscured observation of bridgehead substitution, since substitution in the ethano bridge of 89 was also not observed (the predominate unidentified monochloride from this reaction was 5% in relative yield (130, 131)). Therefore, unambiguous assignment of enhanced bridgehead reactivity due to the exo cyclopropyl moiety was foiled.

Considered in concert, then, the above observations indicated that the cyclopropane rings included in the substrate hydrocarbons were in some way stereospecifically activating the bridgehead positions to free radical hydrogen abstraction. This possibility was certainly worth further investigation.

The unusual regio- and stereoselectivity displayed by the t-butoxy radical in abstracting hydrogen from tetracyclo-[3.3.0.$0^{2,4}$.$0^{3,7}$]octane 2 (Part I) and endo-tricyclo-[3.2.1.$0^{2,4}$]octane 89 (130, 131) were also inconsistent with the free radical substitution pattern in norbornane. The

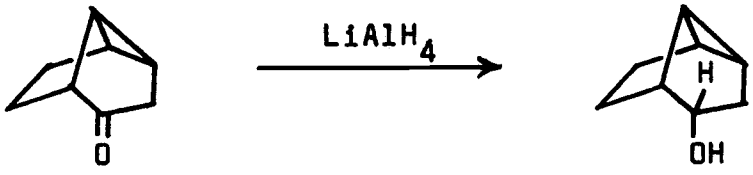
predominant formation of 90 and 91 from 89 was attributed (131) to trishomocyclopropenyl anchimeric assistance to hydrogen abstraction in the transition state, followed by formation of localized pyramidal radical 92 which can rearrange to a second intermediate 93. This duality of intermediates is necessary in order to explain the decrease in the



89 92 93

ratio of 90:91 when the concentration of the chain transfer agent was reduced. Product 90 stereochemistry was assumed controlled by steric effects, whereas exclusive formation of the endo isomer 91 was attributed to transannular interaction of the cyclopropyl moiety with the radical center, as in intermediate 93, since the exo side of the [3.3.0.$0^{2,8}$] ring system is the most sterically accessible based on the reduction of ketone 94 to endo alcohol 95 with greater than 99%

stereoselectivity (132). Similar rearrangement and product



stereochemistry was observed for tetracyclic hydrocarbon 2, although the first formed pyramidal radical, 69 in this case, was also trapped after inversion to form syn- chloride 67, presumably because of steric interference to chain transfer of anti radical 69. In this case, however, stereospecific formation of rearranged chloride exo-6-Cl could not be attributed to non-classical radical formation, since endo attack at C-4 in the [3.2.1.$O^{3,6}$] system is sterically blocked.

The possibility of trishomocyclopropenyl anchimeric assistance to hydrogen atom abstraction therefore existed. The rate data in Part II describing norbornane coupled with the abstraction rates obtained by Raghavan (130) indicated a 100 fold acceleration for anti-C-8 hydrogen abstraction in 89 relative to a C-7 hydrogen in norbornane. A thorough study of this phenomenon was therefore in order, since non-classical rate accelerations in free radical chemistry have not been previously observed.

The research described below was therefore directed at

answering three questions. First, since the clearest example of enhanced bridgehead reactivity hinged on the identity of chloride 88, and since this product had been identified solely on the basis of its reduction to parent hydrocarbon 87 and its nmr spectrum (130, 131), could an unambiguous proof of its structure by an alternate synthesis be provided? Second, is the enhancement of reactivity of bridgehead hydrogens to free radical abstraction by a β cyclopropyl moiety a general phenomenon, and if so, what role does the relative stereochemistry of the three membered ring and incipient radical play? Third, is the anchimeric acceleration for anti-C-8 hydrogen abstraction from 89 observable in other systems containing the possibility of trishomocyclopropenyl delocalization?

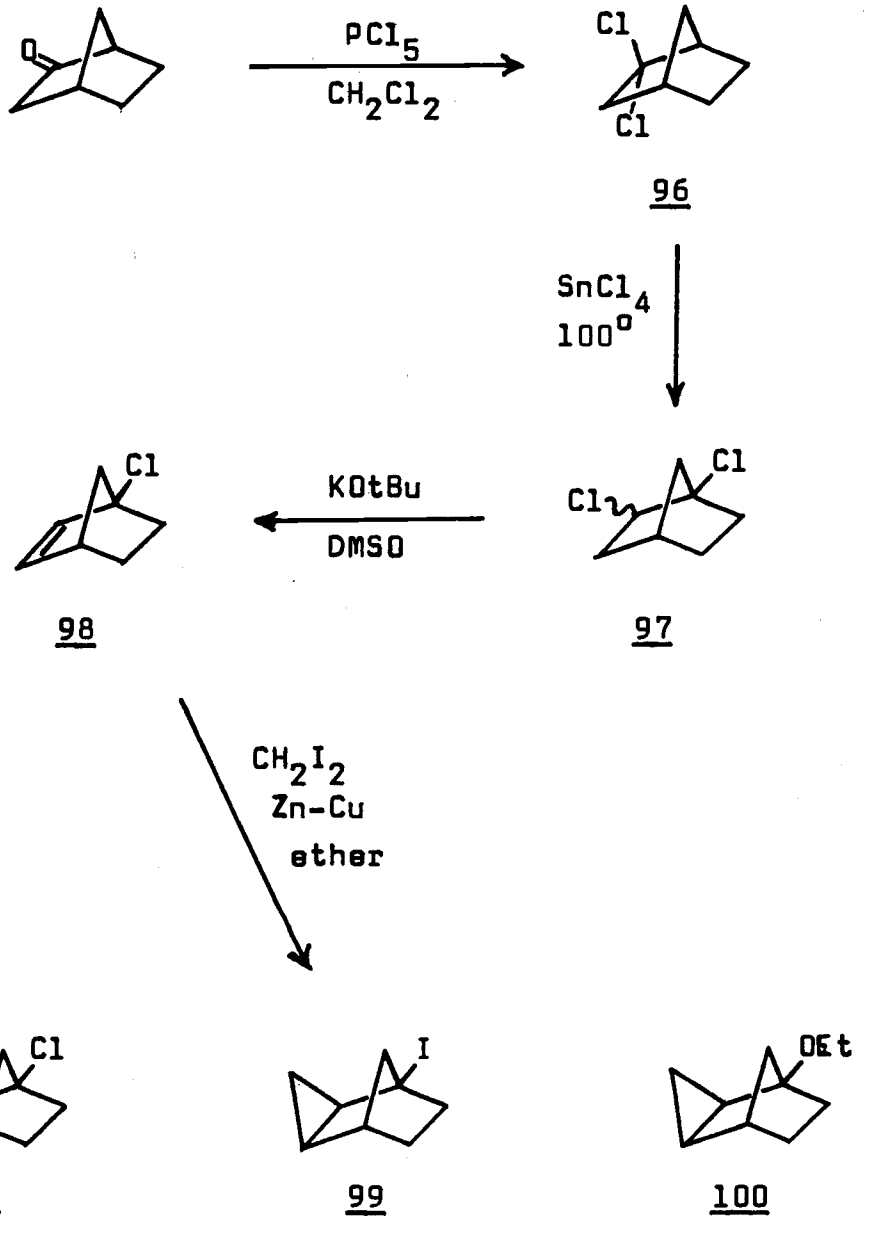
Results and Discussion

Synthesis of 1-chlorotricyclo[3.2.1.$0^{2,4}$]octane 88 was accomplished as shown in Scheme VII. Preparation of 1-chloronorbornane 98 was effected by the method of Fry and Farnham (132) using anhydrous stannic chloride as the Lewis acid necessary for rearrangement of gem-dichloride 96. Reaction of 98 with the Simmons-Smith reagent yielded adduct 88 with >94% exo stereoselectivity. The nmr and ir of this chloride were identical to those of the 17% product of the photochlorination of hydrocarbon 87 (130, 131).

Formation of the corresponding bridgehead iodide 99 and ether 100 was attributed to a competitive exchange process catalyzed by the zinc-copper couple (133). Since no proton source was available, reduction to hydrocarbon 87 was foiled, and apparently the intermediate radical, anion, or alkylzinc halide reacted with zinc iodide, methylene iodide, or solvent ether.

With the structure of key bridgehead chloride 88 confirmed, we forged ahead with an investigation aimed at defining the scope and mechanism of enhanced bridgehead free radical reactivity. In designing this study, we kept in mind the possibility of also observing trishomocyclopropenyl anchimeric assistance to hydrogen atom abstraction, and chose hydrocarbons which could serve to elucidate the mechanism of

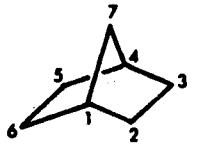
Scheme VII

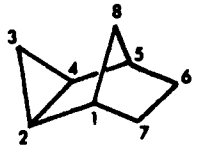

O
PCl5
CH2Cl2
Cl
Cl
96
SnCl4
100°
Cl
Cl
Cl
KOtBu
DMSO
98
97
CH2I2
Zn-Cu
ether
Cl
I
OEt
88
99
100

both phenomena.

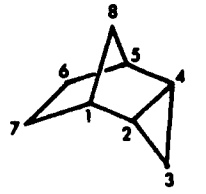
We felt that the set of polycyclic hydrocarbons shown in Figure 10 would best serve this dual purpose. Norbornane (Part II) and exo- and endo-tricyclo[3.2.1.$0^{2,4}$]octanes 87 and 89 (130, 131) had already been characterized in terms of relative reactivities and substitution patterns in hydrogen abstraction by t-butoxy radical. Products from the chlorination of tetracyclic hydrocarbons 1 and 2 (Part I) had been determined, but not their relative reactivities. Fenwick (134) had made a preliminary observation of the abstraction pattern from deltacyclane 103, although a reexamination of his product structure proofs showed them to be erroneous. Kuper (135) chlorinated exo, exo-tetracyclo-[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane 101 with t-butyl hypochlorite, but was incorrect in his product structure assignment, as discussed below. Hydrocarbons 102 and 104 were known, but no pertinent chlorination studies had been reported.

The experimental objective was therefore clear. First, products from photochlorination of 101-104 must be characterized in order to define the hydrogen abstraction patterns in these ring systems. Second, the reactivities of hydrocarbons 1, 2, and 101-104 towards t-butyl hypochlorite must be determined relative to some common standard, preferably cyclohexane. With the results from these experiments in hand, we would therefore be able to calculate relative reactivities of each carbon-hydrogen bond in all nine ring

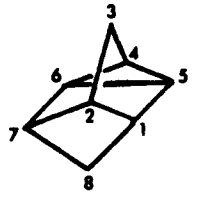




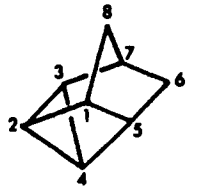
87



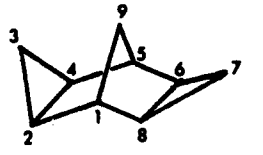
89



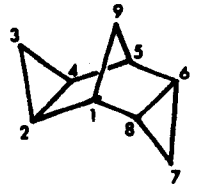
1



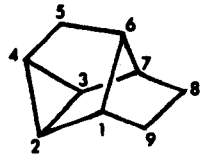
2



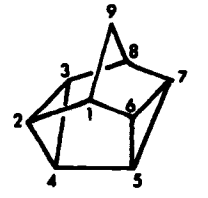
101



102



103

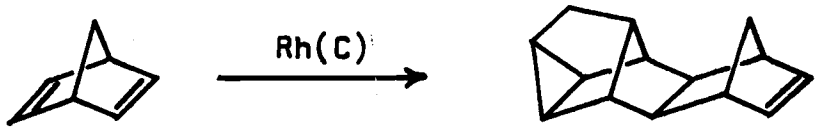


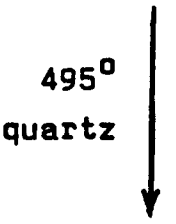
104

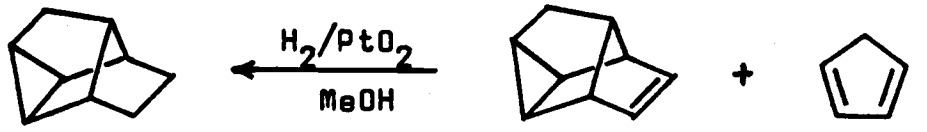
Figure 10. Bridged polycyclic hydrocarbons.

systems, and hopefully be able to interpret them in terms of the rate accelerating phenomena discussed above.

Syntheses of 1 and 2 were described in Part I. Deltacyclane 103 was prepared, as described below, by catalytic hydrogenation of deltacyclene 105 (136). Pentacyclo[4.3.0-

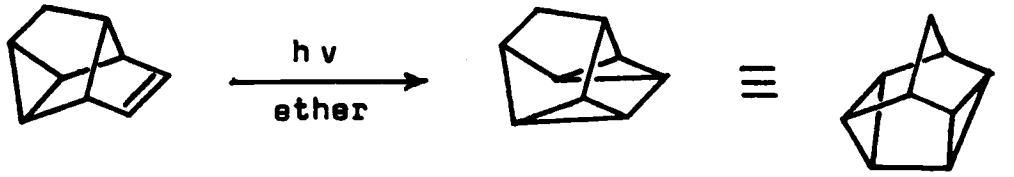






103 105

.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 104 was synthesized by photoisomerization of deltacyclene 105 as prescribed by Freeman and Balls



105 104

(137). Tetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]nonanes 101 and 102 were prepared by a reported method (138), via Simmons-Smith reaction of norbornadiene (139), and purified by chromatography on a 3' 10% $AgNO_3$ on Silicar column with pentane elution. The diexo isomer prepared in this manner was >99% free of the exo, endo isomer. The sample of 102 used in the following studies, however, was only 86% pure as determined by ir and nmr analyses, the contaminant being a 14% impurity of the diexo isomer 101.

Since calculation of per bond relative reactivities is dependent upon the regioselectivity displayed in the hydrogen abstraction step, we were concerned about using simple product studies for a variety of reasons. First, even at low conversion levels of hydrocarbon to chloride, extraneous facile chlorination of one or more of the initially formed monochlorides could bias the product ratios such that they no longer reflect the true abstraction pattern. Second, the possibility of radical rearrangements such as those observed by Poutsma in the nortricyclyl-norbornene system (63) and Freeman, Raghavan, and Fenwick in the endo-tricyclo[3.2.1.-$0^{2,4}$]octyl system (131) must be considered. Third, the possibility of product rearrangement in the reaction solutions or during analysis by vapor phase chromatography must also be assessed.

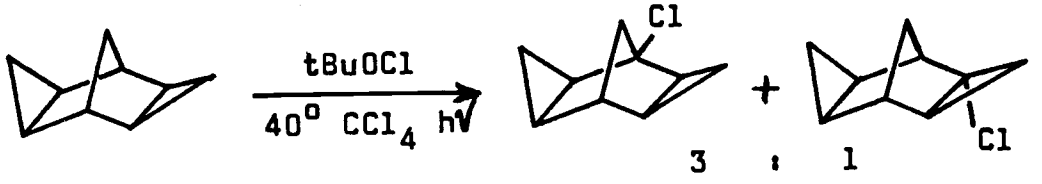
To eliminate these difficulties, a set of control experiments was performed on each substrate by 1) varying the hydrocarbon:t-butyl hypochlorite ratio in order to determine the product monochloride composition extrapolated to zero percent conversion, 2) varying the absolute concentration of chain transfer agent in order to reveal the presence of radical rearrangements (63, 130, 131), 3) subjecting product chlorides to photolytic reaction conditions for various lengths of time in order to determine product stabilities, and 4) testing all monochlorides, collected by vpc, to check for rearrangement during analysis and collection. The results of each of these studies is discussed with the individual chlorination experiments.

Photochlorination of exo, exo-tetracyclo[3.3.1.$0^{2,4}$.-$0^{6,8}$]nonane 101 with t-butyl hypochlorite in CCl_4 at 40° gave predominately two monochlorides in the ratio of 3:1. Kuper (135) reported only one monochloride formed and assigned its structure as the anti-3-chloro derivative 106. This was

106

clearly in error, however, since no proton α to chlorine

was present in the nmr spectrum of his product, nor in the nmr spectrum of either of the products we observed. Reduction of the two monochlorides with TBTH identified each as containing the exo, exo-[3.3.1.$0^{2,4}$.$0^{6,8}$] skeleton. Since there are only two unique tertiary positions in this ring system, the chlorides were readily identified as 107 and 108 on the basis of the symmetry in the nmr spectra (Figures 11 and 12).



101 107 108

Dilution experiments revealed that the ratio of C-1 to C-2 abstraction was 3.2:1, and that no radical rearrangements were occurring. Control studies proved both products stable to reaction, analysis, and collection conditions.

We were naturally delighted to observe a large amount of C-1 hydrogen abstraction from 101, and no C-9 substitution, in concert with the observations of Raghavan for the [3.2.1.-$0^{2,4}$] system (130). Abstraction from the C-2 position in 101 was expected, since these cyclopropyl methine hydrogens are attached to carbon atoms not governed by Bredt's rule.

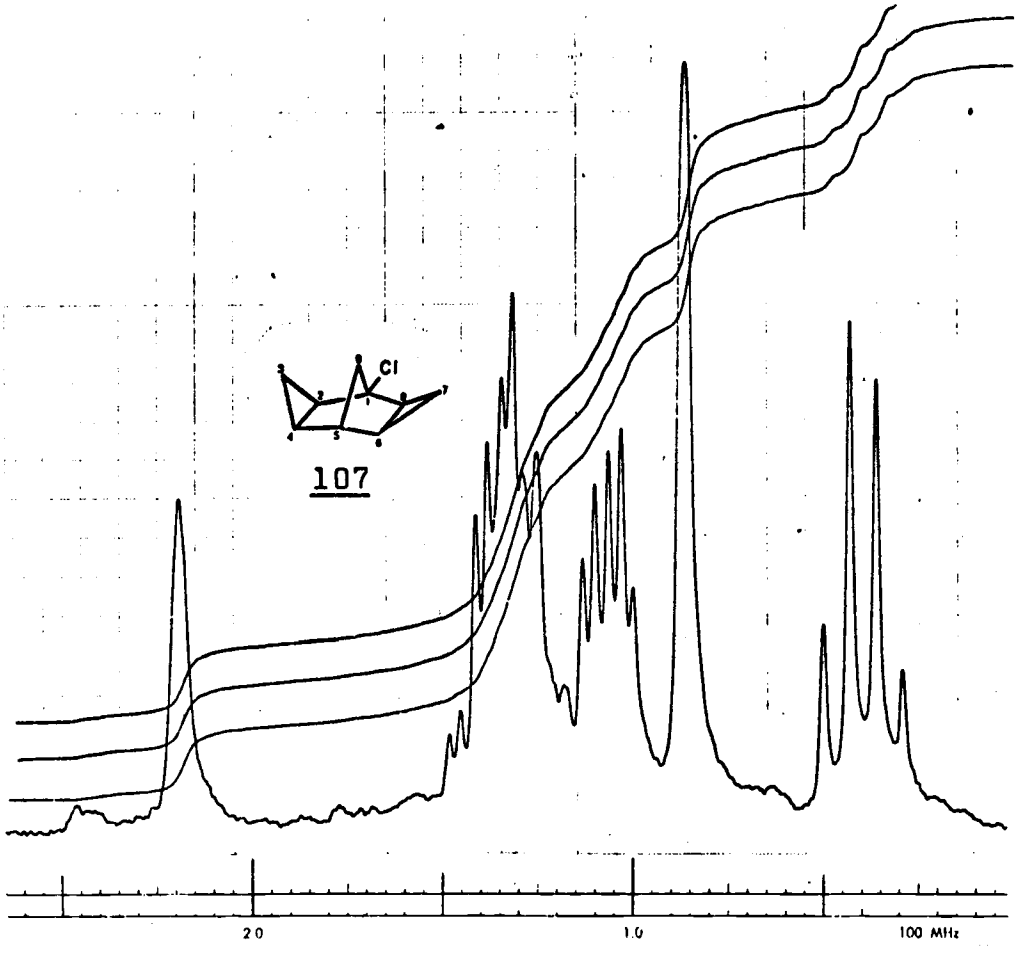


Figure 11. 100 MHz nmr spectrum (CCl_4) of exo,exo-1-chlorotetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane 107.

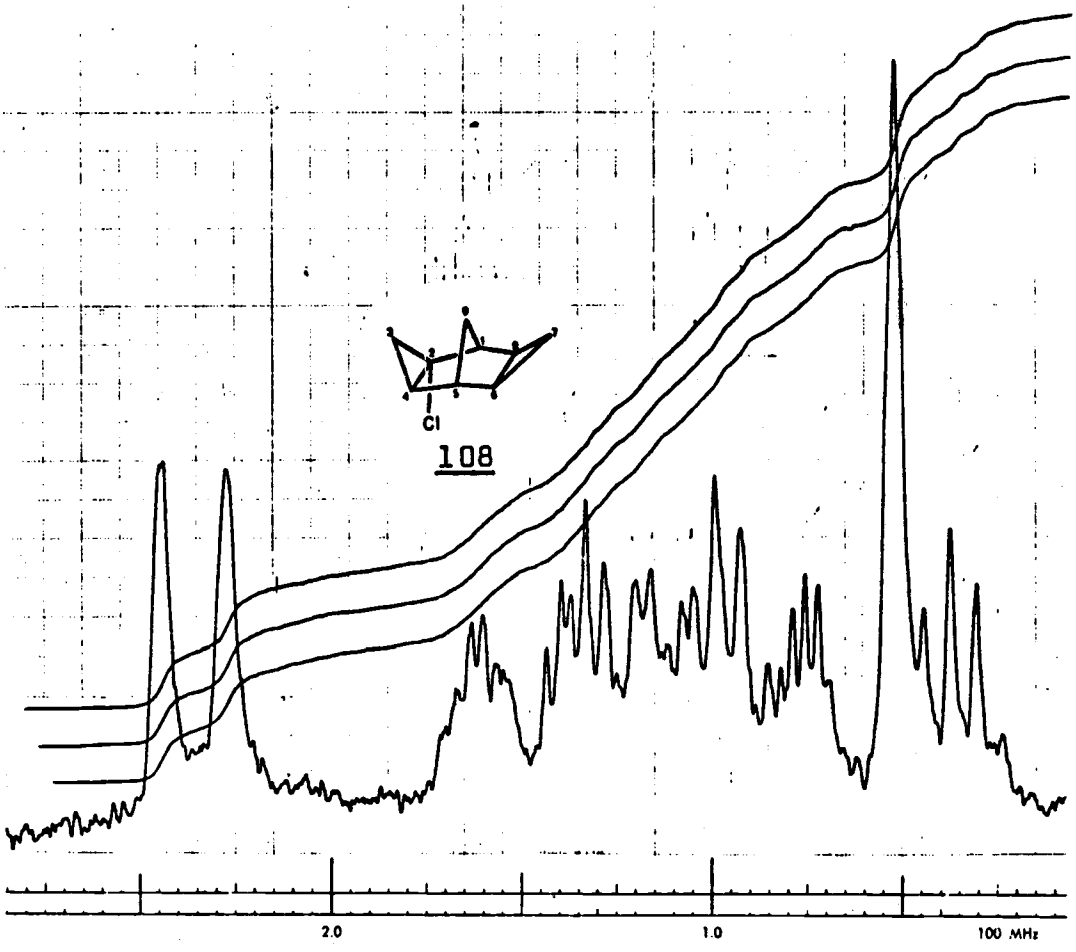
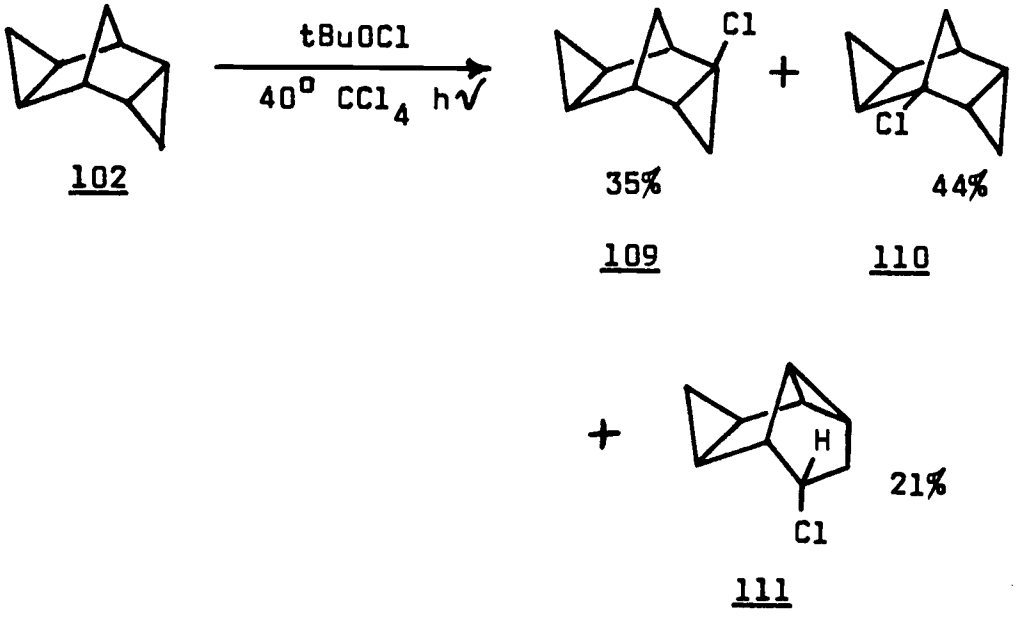


Figure 12. 100 MHz nmr spectrum (CCl_4) of exo,exo-2-chloro-tetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane 108.

Photochlorination of exo, endo-tetracyclo[3.3.1.$0^{2,4}$.-$0^{6,8}$]nonane 102 with t-butyl hypochlorite in CCl_4 at 40^o gave three major monochlorides in the ratio of 35:21:44. Two minor components, shown to be secondary rearrangement products as described below, were unidentified.



102 35% 44%

109 110

+ 21%

111

The 35% component was a C_9H_{11} tetracyclic tertiary chloride containing the exo, endo-[3.3.1.$0^{2,4}$.$0^{6,8}$] ring skeleton as indicated by mass spectral analysis, lack of olefinic absorptions in ir and nmr spectra, absence of a proton α to chlorine in the nmr spectrum (Figure 13), and reduction by TBTH to yield exclusively hydrocarbon 102. Of the three unique tertiary positions in 102, only substitution of either type of cyclopropyl methine hydrogen would

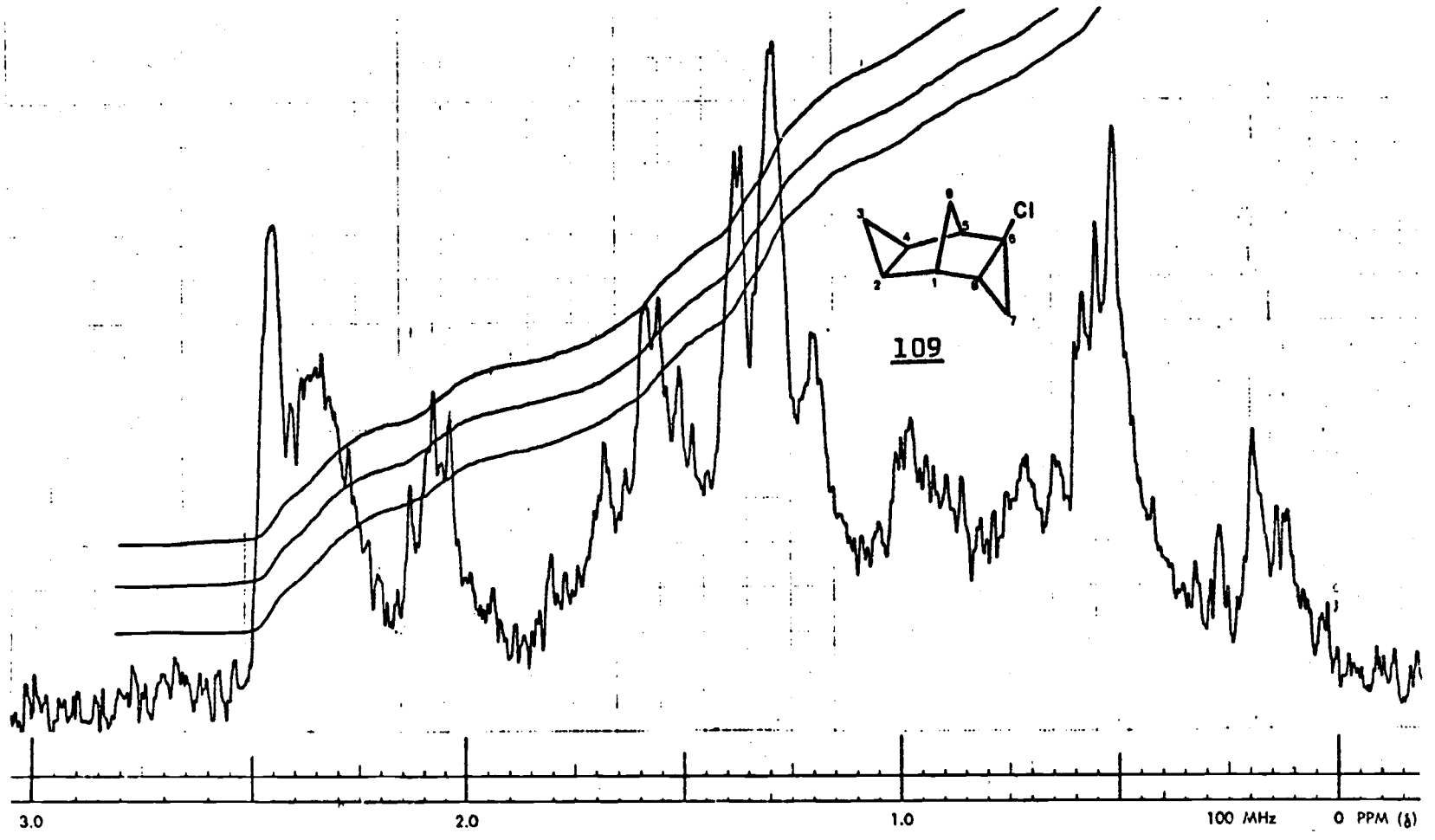


Figure 13. 100 MHz nmr spectrum (CCl_4) of <u>exo,endo</u>-6-chlorotetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]-nonane <u>109</u>.

leave two bridgehead protons at C-1 and C-5, as observed in the nmr spectrum (Figure 13). Furthermore, since these two bridgehead protons have different peak widths suggesting that they have different coupling patterns, and since the upfield cyclopropyl hydrogen at δ -0.07, assigned to the anti-C-3 proton, has not collapsed from a quartet (as it is in parent hydrocarbon 102) to a triplet, this product must be exo, endo-6-chlorotetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane 109 rather than the corresponding C-2 isomer. Substitution at C-6 rather than C-2 would be predicted, since traditionally exo attack on a norbornane ring is preferred over endo attack.

The 44% component was likewise a tertiary chloride in the exo, endo-[3.3.1.$0^{2,4}$.$0^{6,8}$] ring system for the same reasons as the 35% component. The nmr spectrum of this major chloride (Figure 14) revealed only one bridgehead proton, and an intact exo cyclopropyl moiety. The structure of this product is therefore readily assignable as exo, endo-1-chlorotetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane 110.

The 21% product, although a C_9H_{11} monochloride lacking olefinic absorptions in ir and nmr spectra, did not contain the [3.3.1.$0^{2,4}$.$0^{6,8}$] skeleton, as evidenced by production of a hydrocarbon other than 101 or 102 upon reduction with TBTH. The nmr spectrum of this chloride (Figure 15) was strikingly similar in the δ 2.0-4.5 region to that of chloride 91, obtained by Raghavan (130, 131) as a result of rearrangement

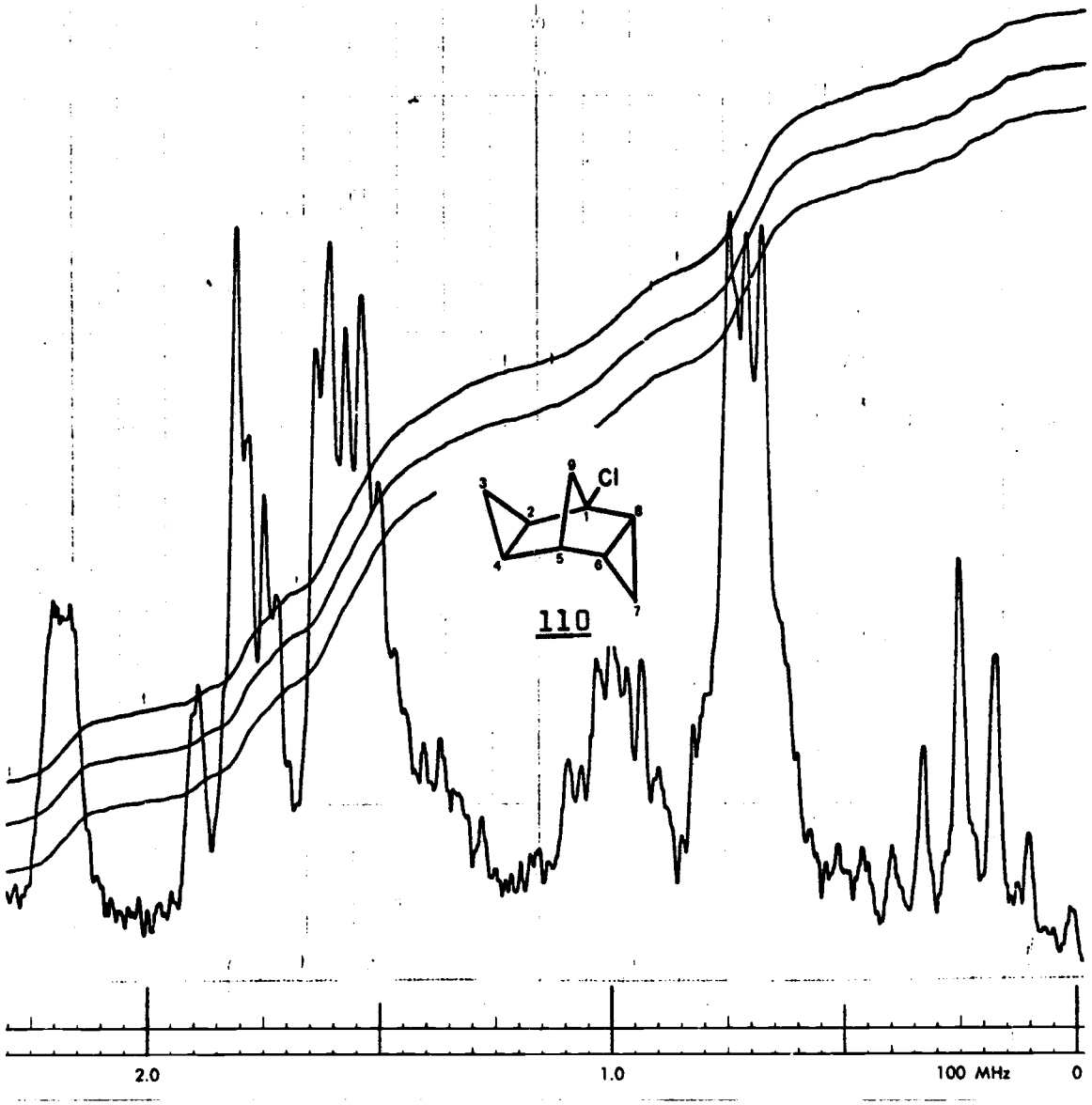


Figure 14. 100 MHz nmr spectrum (CCl_4) of exo,endo-1-chlorotetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane 110.

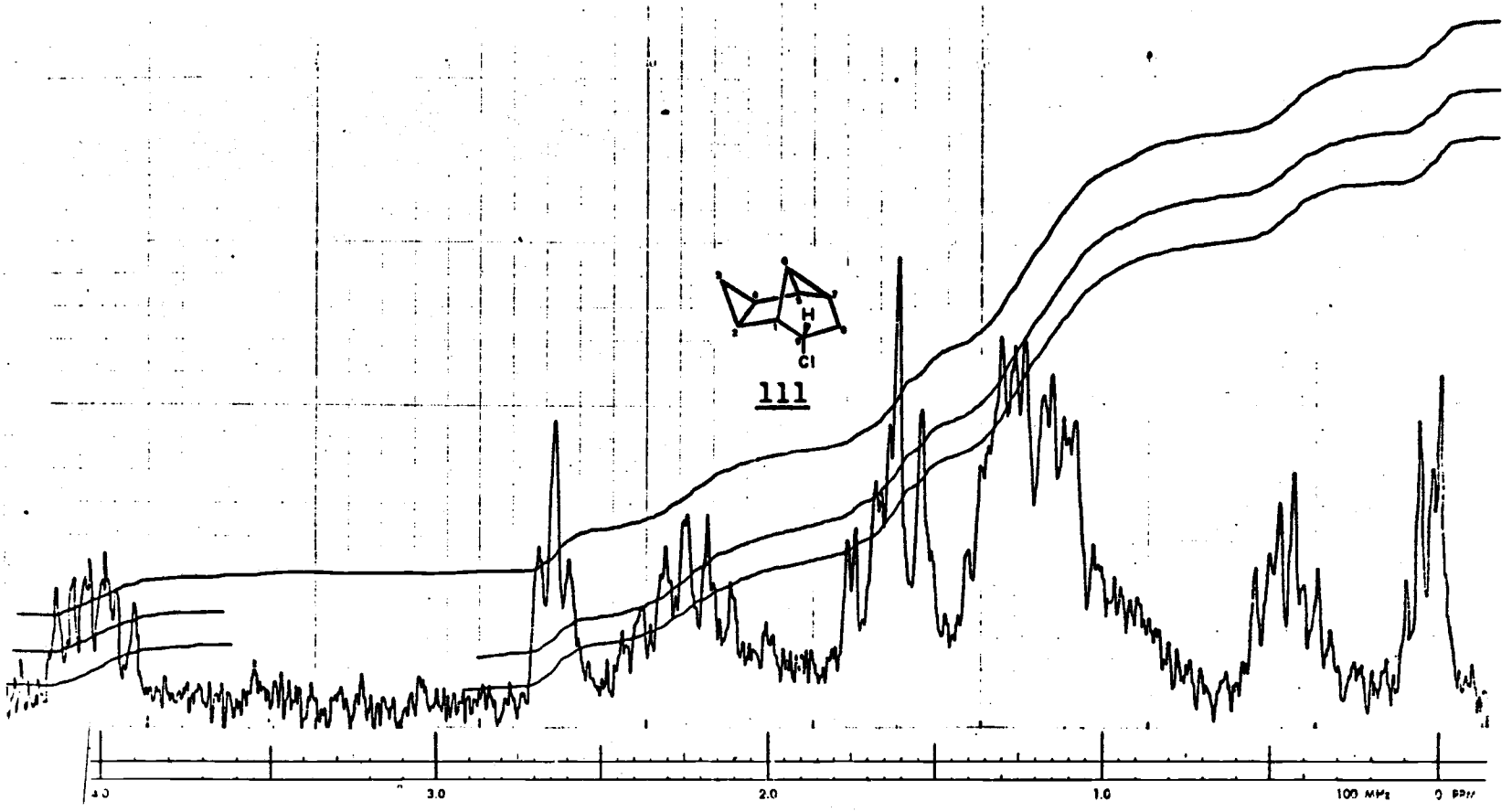
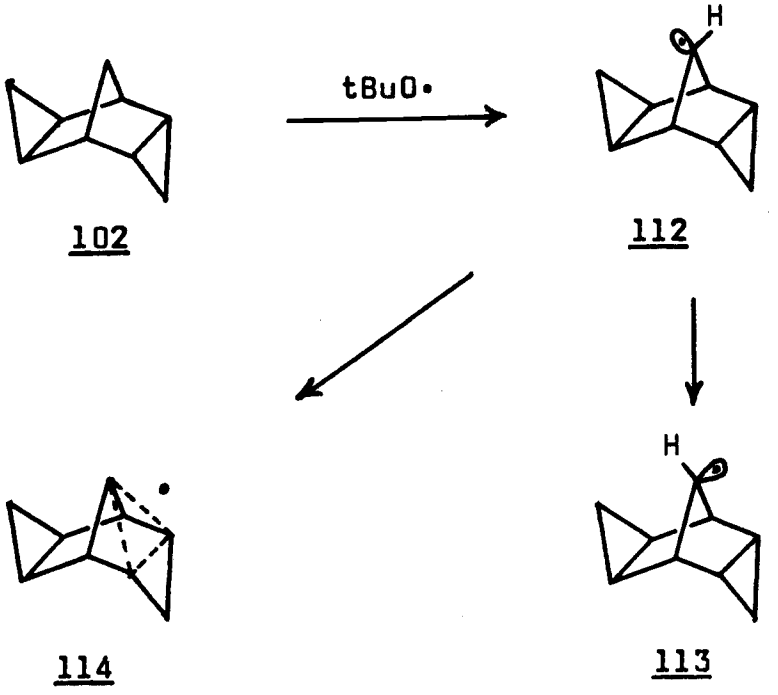


Figure 15. 100 MHz nmr spectrum (CCl_4) of <u>endo</u>-9-chloro-<u>exo</u>-tetracyclo[4.3.0.$0^{2,4}$.$0^{5,7}$]-nonane <u>111</u>.

and chain transfer of the endo-8-tricyclo[3.2.1.$0^{2,4}$]octyl radical 92. Since an endo-tricyclo[3.2.1.$0^{2,4}$]octyl moiety exists in 102, abstraction from C-9, followed by a trishomocyclopropenyl rearrangement, would yield nonclassical radical 114 which, upon chain transfer with t-butyl hypochlorite, would yield chloride 111. Reduction by TBTH would then give



102 112 114 113

tetracyclo[4.3.0.$0^{2,4}$.$0^{5,7}$]nonane 115. The nmr spectra of this chloride (Figure 15) and its corresponding reduction product 115 (Figure 16) are readily assignable on this basis

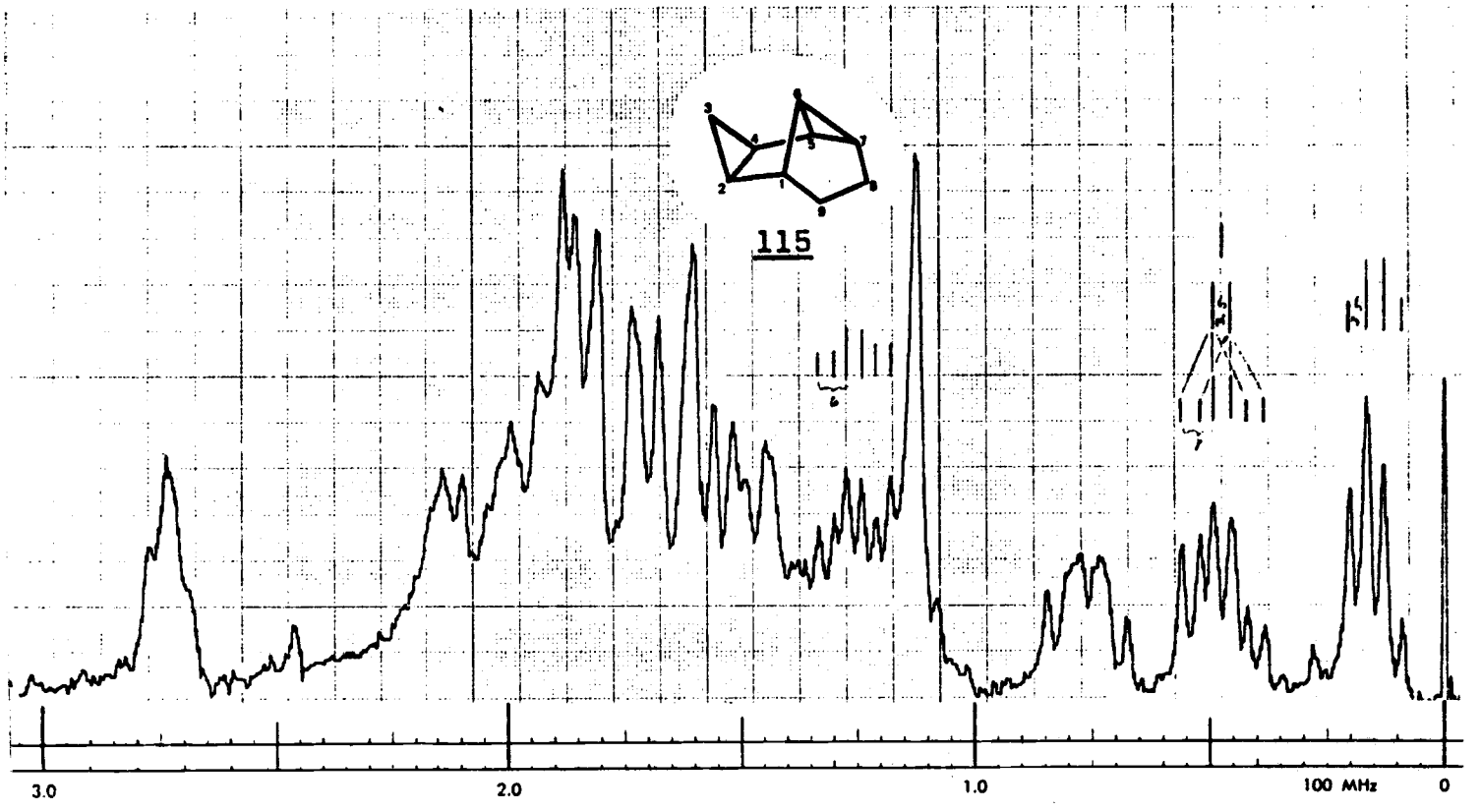
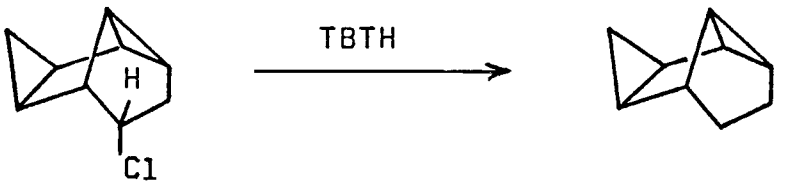


Figure 16. 100 MHz nmr spectrum (CCl_4) of <u>exo</u>-tetracyclo[4.3.0.$0^{2,4}$.$0^{5,7}$]nonane <u>115</u>.



111 115

(see experimental section). The observed change in the exo-cyclopropyl methylene splitting pattern in the nmr spectra of 102 and 115 when the $[3.3.1.0^{2,4}.0^{6,8}]$ system is converted to the $[4.3.0.0^{2,4}.0^{5,7}]$ system is consistent with the fact that the severe nonbonded C-3-H-C-9-H interaction in 102 (1.36 Å) is relieved when rearrangement to 115 occurs (C-3-H-C-6-H = 3.04 Å).

Irradiation of a typical chlorination mixture of t-butyl hypochlorite for 0.5, 4, and 15 hours proved the two minor unidentified vpc peaks as secondary products arising from photolytic rearrangement of chloride 111, since a sample of the 30 min. reaction mixture was unchanged after 24 hours without irradiation. Dilution experiments, summarized in Table XIII, showed that the yield of chloride 109 remained constant upon decrease in percent conversion of hydrocarbon to chloride, and that rearranged isomer 111 was the major product at low t-butyl hypochlorite dilutions. The apparent rearrangement of the radical precursor to chloride 110 to a second product (as evidenced by the constancy of the composition of 110 plus the unknown) is unexplained. It is evident,

in any case, that the hydrogen abstraction ratio from 102 by t-butoxy radical should be based on a common source for both chloride 110 and the unknown rearrangement product.

Table XIII. Dilution experiments with exo,endo-tetracyclo-[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane 102.

Run	molality [102]	molality [tBuOCl]	relative % 109	relative % 110	relative % 111	relative % unknown
1	0.79	0.27	16	14	42	21
2	0.79	0.55	17	19	42	13
3	0.79	0.82	20	27	33	9

The behavior of the exo,endo-[3.3.1.$0^{2,4}$.$0^{6,8}$] system toward hydrogen abstraction is consistent with the observations of Raghavan in the [3.2.1.$0^{2,4}$] system, since a tris-homocyclopropenyl rearrangement has occurred as a result of C-9 methylene hydrogen abstraction. Failure to observe formation of a chloride resulting from chain transfer at C-9 (either 112 or 113) is not surprising, since the exo-cyclopropane not present in the [3.2.1.$0^{2,4}$] system would mitigate

against facile chain transfer of classical radical 112 and hinder pyramidal radical inversion to 113 because of the steric effect of the syn cyclopropyl hydrogen. Thus rearrangement to nonclassical radical 114 competes more favorably than in the simpler [3.2.1.$0^{2,4}$] system. As noted by Raghavan, rearranged chloride 111 appears to have been formed stereospecifically, and indeed contrary to the expected steric ease of approach to the C-9 carbon of the [4.3.0.$0^{2,4}$.$0^{5,7}$] skeleton, based on the preference for endo alcohol production upon treatment of ketone 94 with lithium aluminum hydride. Models reveal no reason why the extra methylene bridge in 115 should alter this steric approachability. Radical 114 must therefore be delocalized.

It is interesting to find that we now observe a large amount of C-1 bridgehead hydrogen abstraction, whereas none was found in the endo-[3.2.1.$0^{2,4}$] system. It is difficult to judge at this point, however, whether abstraction at C-1 has been enhanced in this ring system over that studied by Raghavan, or if C-9 abstraction has been slowed by the proximity of the syn-C-3 cyclopropyl hydrogen. A final judgement on this matter can only be made on the basis of relative rate data discussed below.

Since the structures of the major products from the t-butyl hypochlorite chlorination of tetracyclic isomers

1 and 2 had already been determined (see Part I), definition of the true hydrogen abstraction pattern from each hydrocarbon awaited only dilution experiments and determination of relative rates.

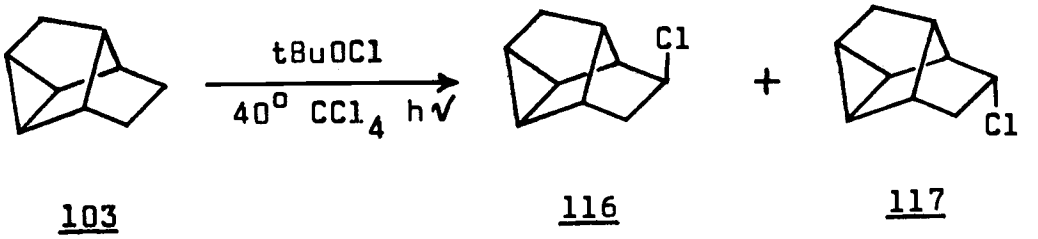
Looking first at tetracyclo[3.3.0.$0^{2,7}$.$0^{4,6}$]octane 1, we found that the relative yield of the two unidentified tetracyclic monochlorides increased dramatically upon continued irradiation of a typical reaction solution, defining these as secondary products. The remaining two major tetracyclic chlorides 60 and 61, as well as the unidentified olefinic product, were formed in a ratio of 16:52:5 in a dilution experiment at low levels of conversion of hydrocarbon to chloride. No rearrangements of products or radicals, other than the fragmentation which formed the olefinic monochloride, were detected under reaction conditions, or upon vpc analysis and collection. No significant change in the concentration of olefinic product with dilution was detected.

Dilution experiments performed on hydrocarbon 2 in reaction with t-butyl hypochlorite revealed that at low conversion of 2 to monochloride, the ratio of products was 45:25:30 for 66, 68 plus exo-6-Cl, and 67 respectively. Although the yields of 66, 67, and 68 plus exo-6-Cl remained relatively constant upon dilution of the t-butyl hypochlorite, the ratio of 68 to exo-6-Cl varied irreproducibly from 0.8 to 1.8, therefore suggesting that these two monochlorides can inter-

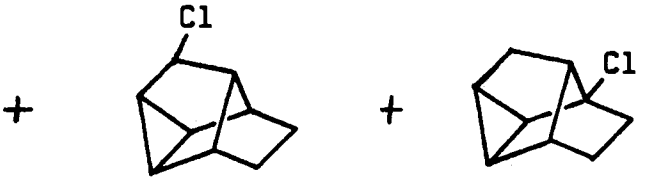
convert under analysis conditions. However, since exo-6-Cl is presumed to arise by a trishomocyclopropenyl rearrangement of radical 69, the combined yield of 68 and exo-6-Cl serves in defining the hydrogen abstraction pattern from 2.

Control experiments demonstrated that chloride 67 was stable to reaction and analytical conditions, that chloride 66 was somewhat unstable to reaction conditions, having decreased from about 45% to about 38% relative yield over a 16 hr period. Any judgement as to the interconvertability of 68 and exo-6-Cl under reaction conditions was thwarted due to the problems with vpc stability.

Photochlorination of deltacyclane 103 with t-butyl hypochlorite in CCl_4 was reported by Fenwick (134) to have yielded two monochlorides in the ratio of 52:48 in a 54% yield. The 52% component he identified as exo-8-chlorodeltacyclane 116 by alernate synthesis and reduction to parent hydrocarbon with TBTH. The 48% component was shown not to be endo-8-chlorodeltacyclane 117 by nmr and ir comparison to an authentic sample, although reduction of this monochloride with TBTH did yield exclusively parent hydrocarbon 103, and the reported nmr spectrum did contain one proton α to chlorine at 4.10 δ. Fenwick concluded that this component must therefore be 5-chlorodeltacyclane 118.



103 116 117



118 119

A reappraisal of the nmr spectrum of the 48% component revealed that one additional peak α to chlorine at ca 4.2 δ had gone unnoticed, perhaps because it is split into a multiplet. We therefore felt a reevaluation of this reaction was necessary.

Chlorination of 103 with t-butyl hypochlorite in CCl_4 at 40° yielded not two, but three components, as determined by vpc analysis in conjunction with parent ion masses corresponding to C_9H_{11} monochlorides, in the ratio of 11:61:28 in an overall yield of 37%, a ratio unaltered by dilution of the t-butyl hypochlorite ratio relative to deltacyclane.

The major component had ir and nmr spectra identical to the authentic sample of exo-8-chlorodeltacyclane 116 prepared by Balls (140).

The 28% component had ir and nmr spectra identical to

the minor product reported by Fenwick (134); i.e. two protons α to chlorine in the nmr, one a multiplet from δ 4.19-4.32, the other a broadened singlet at δ 4.12, in the ratio of 1:1.6. This mixture again gave only hydrocarbon 103 upon reduction. These observations define this peak as a mixture of endo-8-chlorodeltacyclane 117 and 5-chlorodeltacyclane 118. The exo-endo stereospecificity of chain transfer at C-8 in 103 is therefore ca 6:1, in accord with previous observations of the stereospecificity of chain transfer of the 2-norbornyl free radical (127).

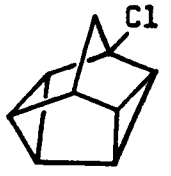
The 11% component, unobserved by Fenwick, exhibited no olefinic absorptions in ir or nmr spectra, and no protons > 2.20 δ; reduction with TBTH gave only 103. This component must therefore be a bridgehead chloride in the [4.3.0.$0^{2,4}$.-$0^{3,7}$] ring system. Observation of at least three unique protons in the nmr spectrum of this componenet (Figure 17) rules out C-4 or C-6 substitution. Of the two remaining possibilities, isomer 119, 1-chlorodeltacyclane, appeared most consistent with a three proton nmr absorption centered at δ 1.20 due to the cyclopropyl hydrogens, although unequivocal proof of this assignment was not developed.

Preparative chlorination of pentacyclo[4.3.0.$0^{2,4}$.-$0^{3,8}$.$0^{5,7}$]nonane 104 with t-butyl hypochlorite in CCl_4 at 40° yielded three monochlorides in the approximate ratio of 8:1:1 as determined by vapor phase chromatographic analysis.

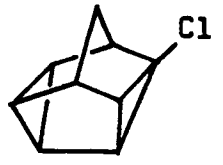
Figure 17. 100 MHz nmr spectrum (CCl_4) of 1-chlorodeltacyclane 119.

Dilution studies detected no free radical rearrangements, and indicated a hydrogen abstraction ratio of 86:7:7. Control experiments proved all three componenets stable to reaction, analysis, and collection conditions.

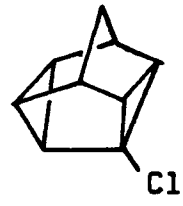
The major product was pentacyclic, as dictated by a molecular formula C_9H_9Cl, and lack of olefinic absorptions in ir and nmr spectra. Since reduction of this chloride with TBTH gave hydrocarbon 104, and since no absorption above 2.85 δ in the corresponding nmr spectrum (Figure 18) was observed, this chloride must contain the [4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$] skeleton substituted at one of the three unique bridgehead positions. Appearance of a well resolved broadened two proton singlet, a single proton complex absorption, and two three proton multiplets in the nmr spectrum of this chloride could be consistent with any of the three possible structures 120-122, even after comparison of these features to the methylene,



120



121



122

C-1 and C-8 bridgehead, and cyclopropyl methine hydrogens in parent hydrocarbon 104 (Figure 19) and in diacid 123 (141). (Nmr assignments for parent hydrocarbon 104 were made by

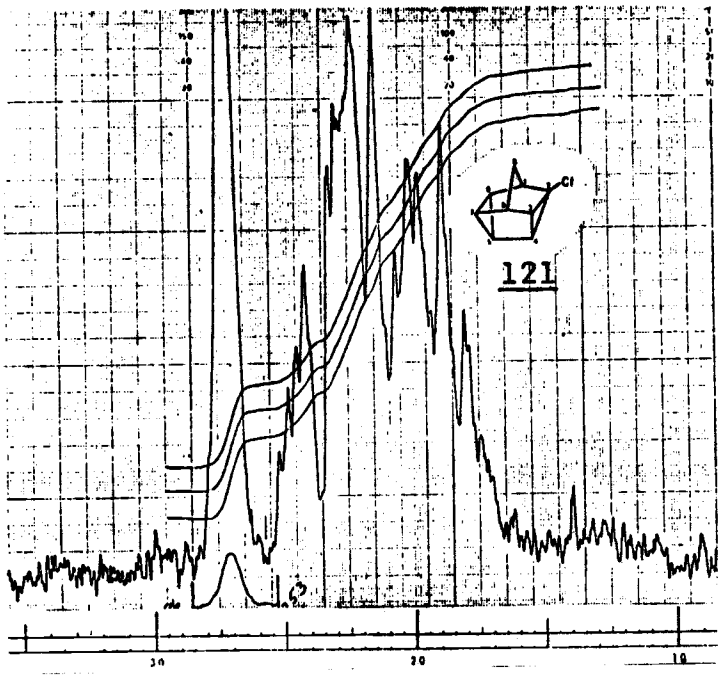


Figure 18. 100 MHz nmr spectrum (CCl_4) of 2-chloropentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 121.

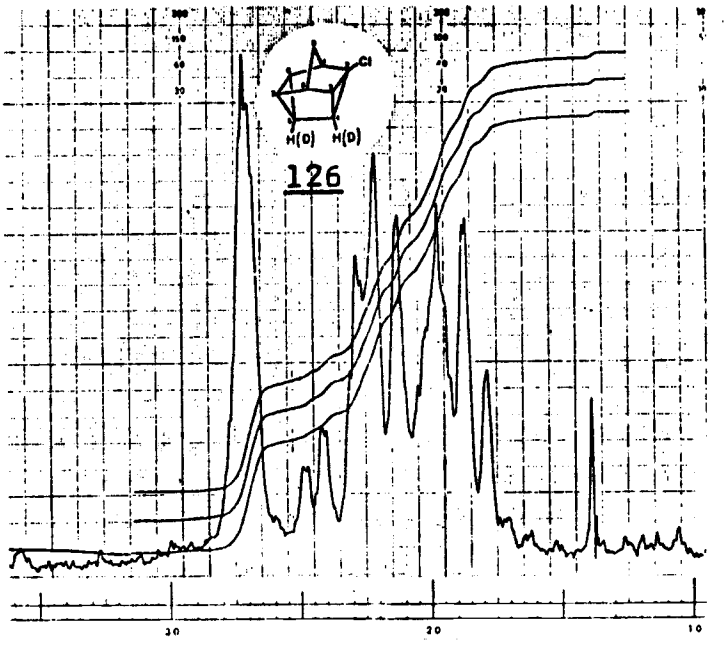


Figure 21. 100 MHz nmr spectrum (CCl_4) of C-4 and C-5 deuterio substituted 2-chloropentacyclo[4.3.0.-$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 126.

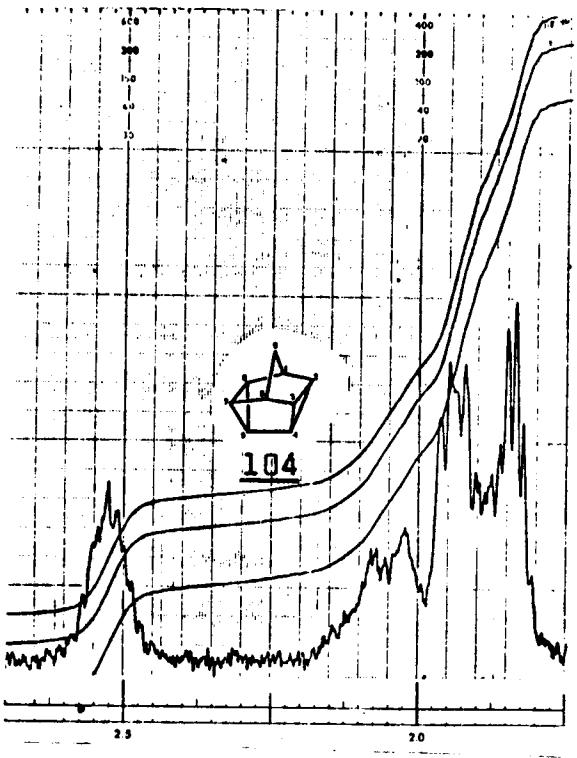


Figure 19. 100 MHz nmr spectrum (CCl_4) of pentacyclo-[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 104.

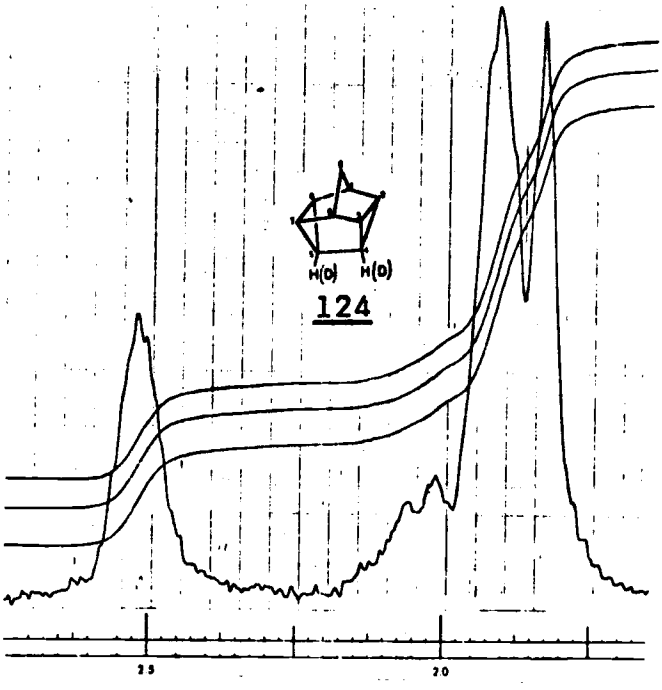
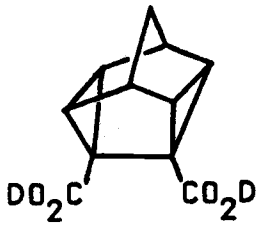
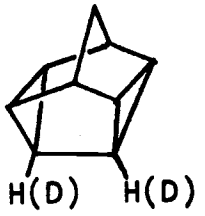


Figure 20. 100 MHz nmr spectrum (CCl_4) of C-4 and C-5 deuterio pentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 124.

comparison with the nmr spectrum of deuterated hydrocarbon, 124 (Figure 20) prepared as described below, and with the nmr spectrum of diacid 123 (141).)

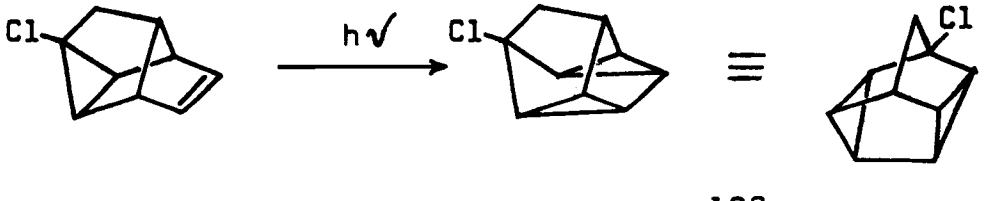


123

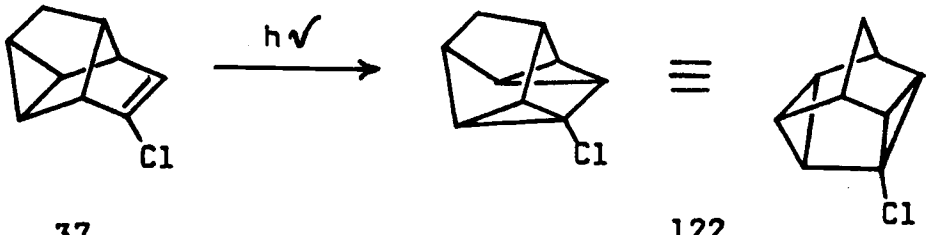


124

Attempts to synthesize possible products 120 and 122 by photocyclization of appropriately substituted monochloro deltacyclanes 125 and 37, in a manner analogous to the syntheses of parent hydrocarbon 104, and diacid 123, were unsuccessful.

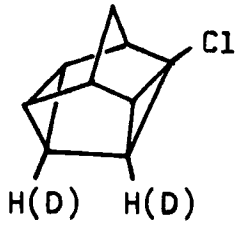


125 120



37 122

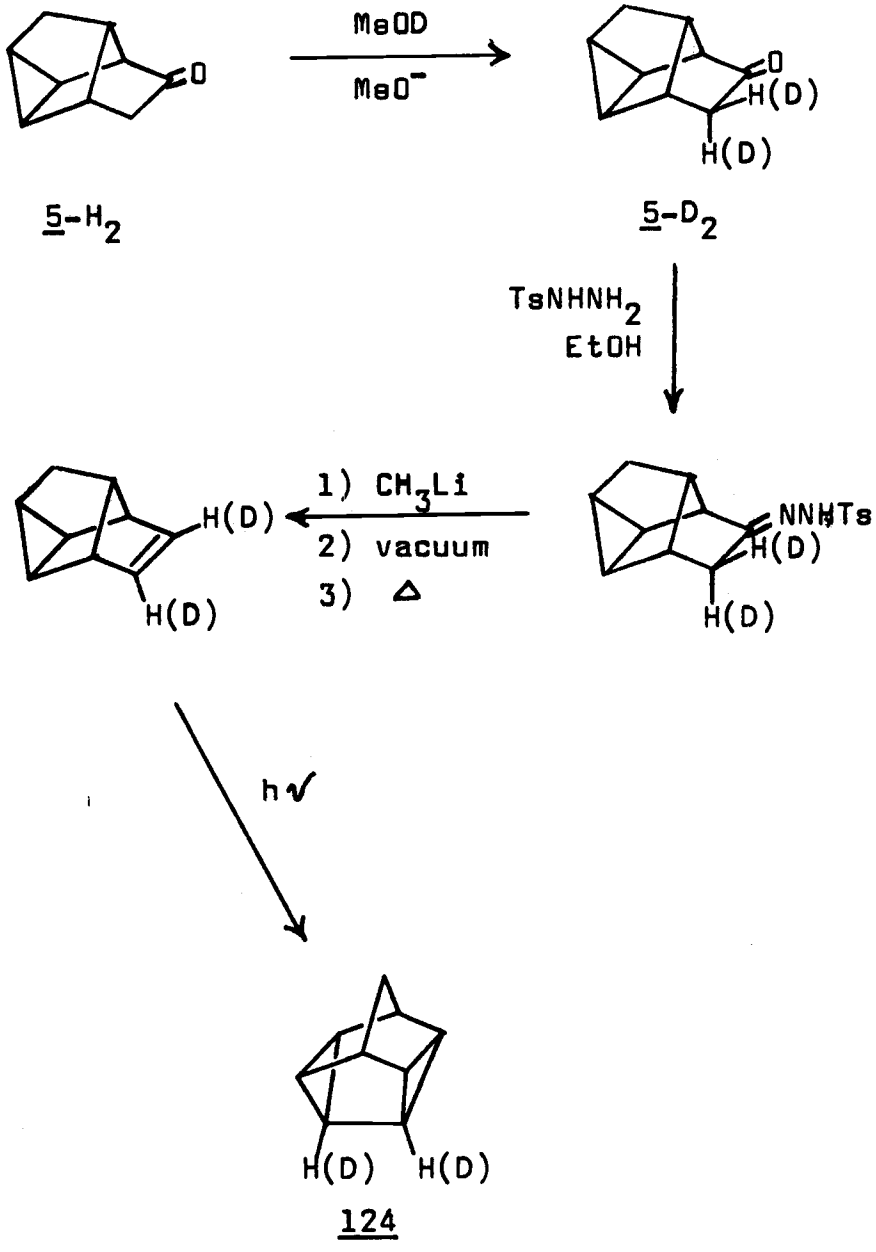
We therefore turned to a set of experiments, designed to unambiguously define the position of the chlorine atom in the unidentified monochloride in question, by replacing selected hydrogens with deuterium. Preparation of pentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane containing 1.13 atoms deuterium at the C-4 and C-5 positions, as shown in Scheme VIII, followed by photochlorination of resulting hydrocarbon 124 with t-butyl hypochlorite again yielded one major monochloride. The nmr spectrum of this product (Figure 21) was similar to that of the undeuterated isomer, except that 1) the single proton multiplet was now a half proton doublet of doublets with J = 7 and 2 Hz, 2) half a proton had been lost in the downfield three proton group, and 3) considerable simplification was observed in the upfield three proton signal. Appearance of half of the incorporated deuterium in the one odd proton multiplet rules out structure 120; simplification of the splitting pattern of this proton upon deuterium substitution further rules out structure 122.



126

The remaining possibility, chloride 121 (or 126),

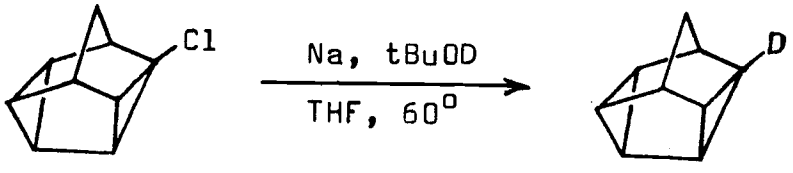
Scheme VIII



5-H_2 5-D_2 124

readily explains all features of these nmr observations. The two proton signal is due to the bridgehead C-1 and C-8 protons. Near equality of their chemical shifts is in accord with the observed effect of C-2 chloride substitution on the bridgehead protons in norbornane (both bridgehead protons appear at 2.38 δ in the nmr spectrum of exo- and endo-2-chloronorbornanes prepared in Part II). The one proton signal is due to the C-4 proton which 1) is shifted downfield relative to the companion C-5 proton by the inductive effect of the chlorine atom, 2) appears as half a proton in the deuterated isomer 126, and 3) collapses to a doublet of doublets when the companion C-5 position is deuterated, an expected splitting pattern since cis cyclopropyl protons have coupling constants of about 7 Hz (142) and Coates (10) demonstrated a C-4-anti-C-9 coupling of 2 Hz in the $[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]$ ring system. The remaining deuterated position falls under the downfield three proton multiplet, as must the C-3 proton. The C-6 and C-7 protons lie in the upfield three proton signal, and indeed display a simplified splitting pattern, when the one proton to which they are coupled (C-5) is partially replaced by deuterium. Remaining, and quite apparent in the spectra, are two one proton doublets which are generally uneffected by deuterium substitution, and are assigned to the syn- and anti-geminally coupled C-9 methylene protons.

Verification of this structure assignment was obtained via three experiments. First, reduction of deuterated chloride 126 with TBTH yielded hydrocarbon 124 which had lost none of its deuterium, as determined by mass spectral analysis. However, a large isotope effect for hydrogen abstraction, coupled with the low conversion of hydrocarbon to chloride in this reaction, could mask significant deuterium loss. This was discredited by observing that unreacted hydrocarbon 124 in the photochlorination also was unchanged in deuterium content. Second, reduction of chloride 121 with sodium and deuterated t-butanol in THF gave deuterated pentacyclo[4.3.-0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 127 which had a different ir spectrum than that of 124, and an nmr spectrum (Figure 22) consistent with the incorporation of one deuterium at one of the four equivalent methine positions. Third, observation of a 3 Hz decrease in the width at half height of the resolved



121 127

downfield two proton signal in a 60 MHz nmr spectrum of 126 relative to a 100 MHz spectrum of 126 is consistent with a peak width due to two chemically non-equivalent protons rather

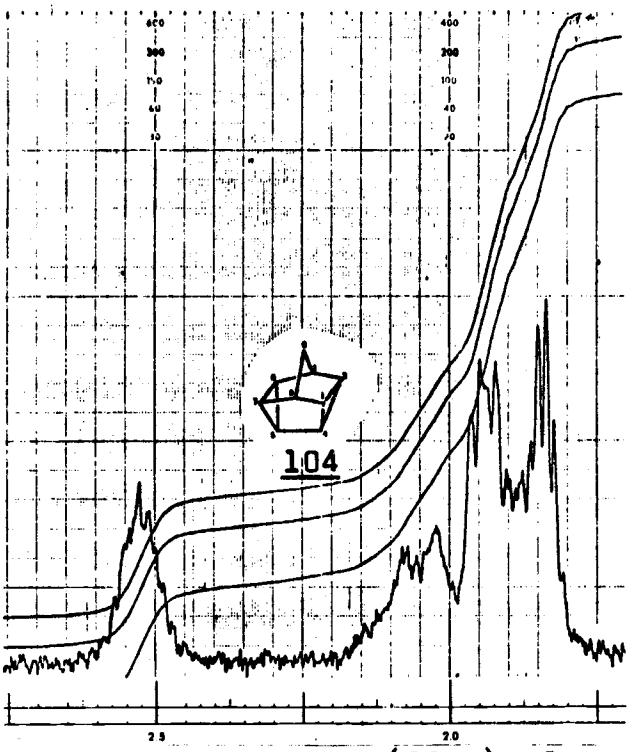


Figure 19. 100 MHz nmr spectrum (CCl_4) of pentacyclo-[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 104.

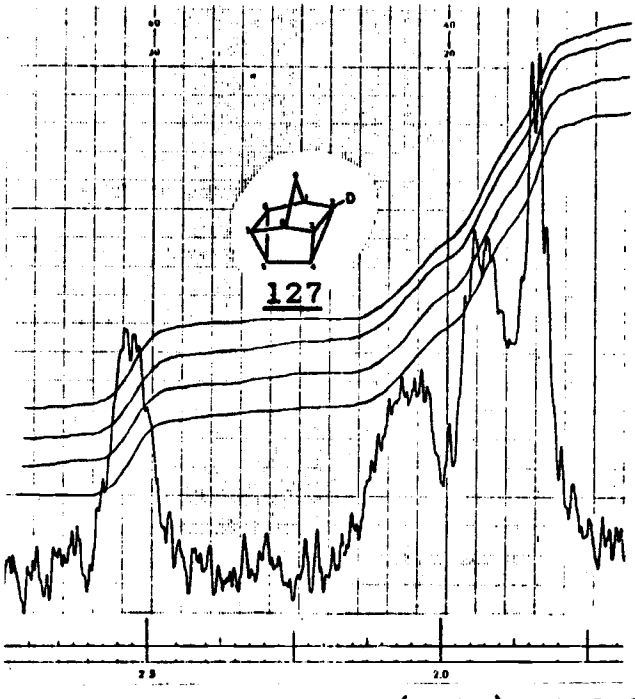


Figure 22. 100 MHz nmr spectrum (CCl_4) of C-2 deuterio pentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 127.

than to coupling of two equivalent protons.

The first of the two minor monochlorides produced upon photochlorination of 104 eluted coincidentally with the major product 120 on preparative vpc columns and was therefore never obtained in sufficient quantity to characterize. The second minor product had a parent ion mass, and ir and nmr spectra consistent with a C_9H_9 pentacyclic monochloride. No absorptions greater than δ 2.63 in the nmr spectrum of this component (Figure 23) indicated that it was also a tertiary chloride. Observation of a single proton absorption with a complex splitting pattern, a two proton singlet, and an apparent two proton triplet with coupling of 8 Hz is consistent only with isomer 122 as assigned in the experimental section.

The product structures resulting from t-butyl hypochlorite chlorination of each of the bridged polycyclic hydrocarbons in Figure 10, coupled with dilution and control experiments, defined the hydrogen abstraction patterns by t-butoxy radical for each ring system, and are summarized in Figure 24.

We next determined per mole reactivities of the hydrocarbons in Figures 10 and 24 by allowing each to compete with cyclohexane for the t-butoxy radical using the method of Walling and Jacknow (111), and as described in the

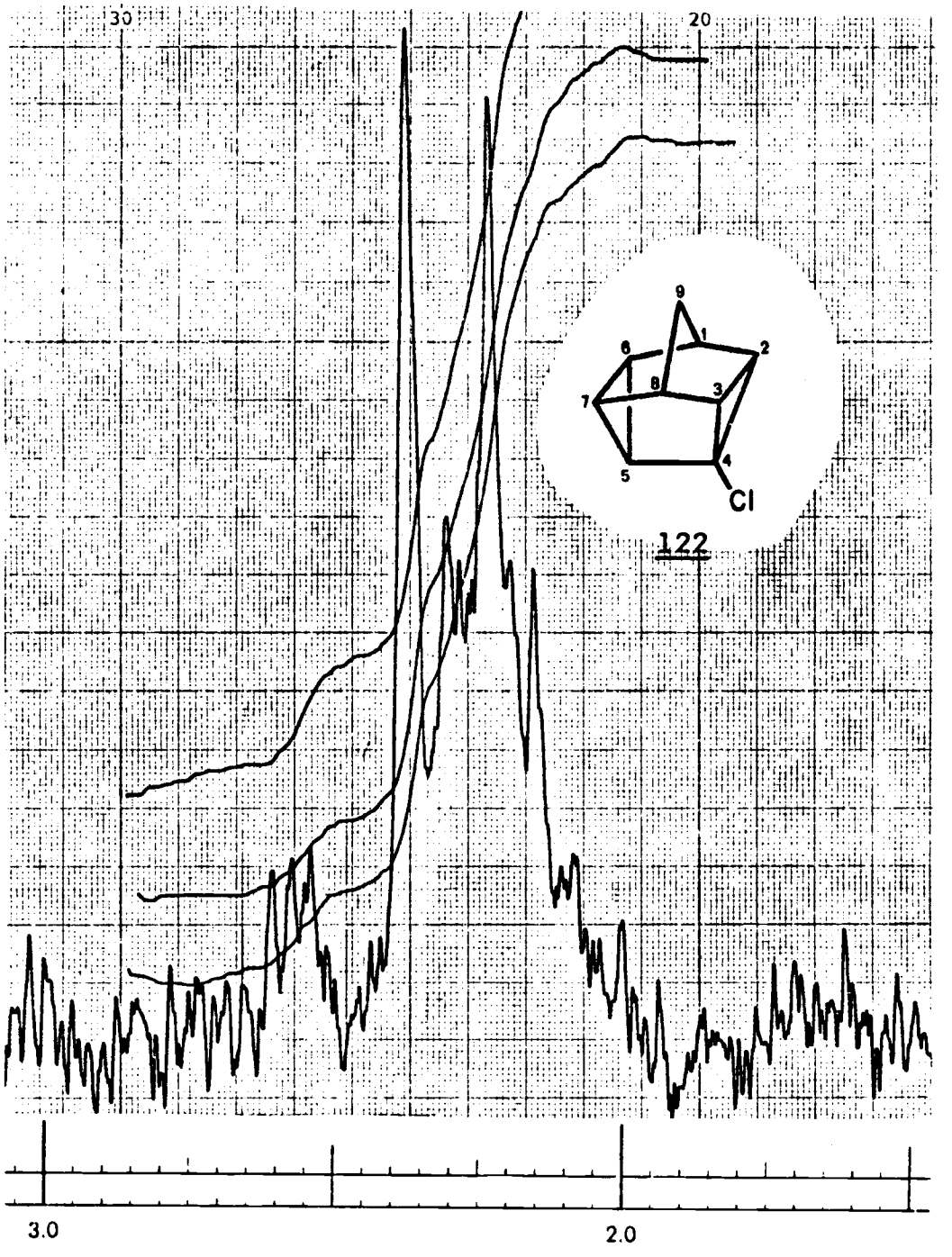


Figure 23. 100 MHz nmr spectrum (CCl_4) of 4-chloropentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 122.

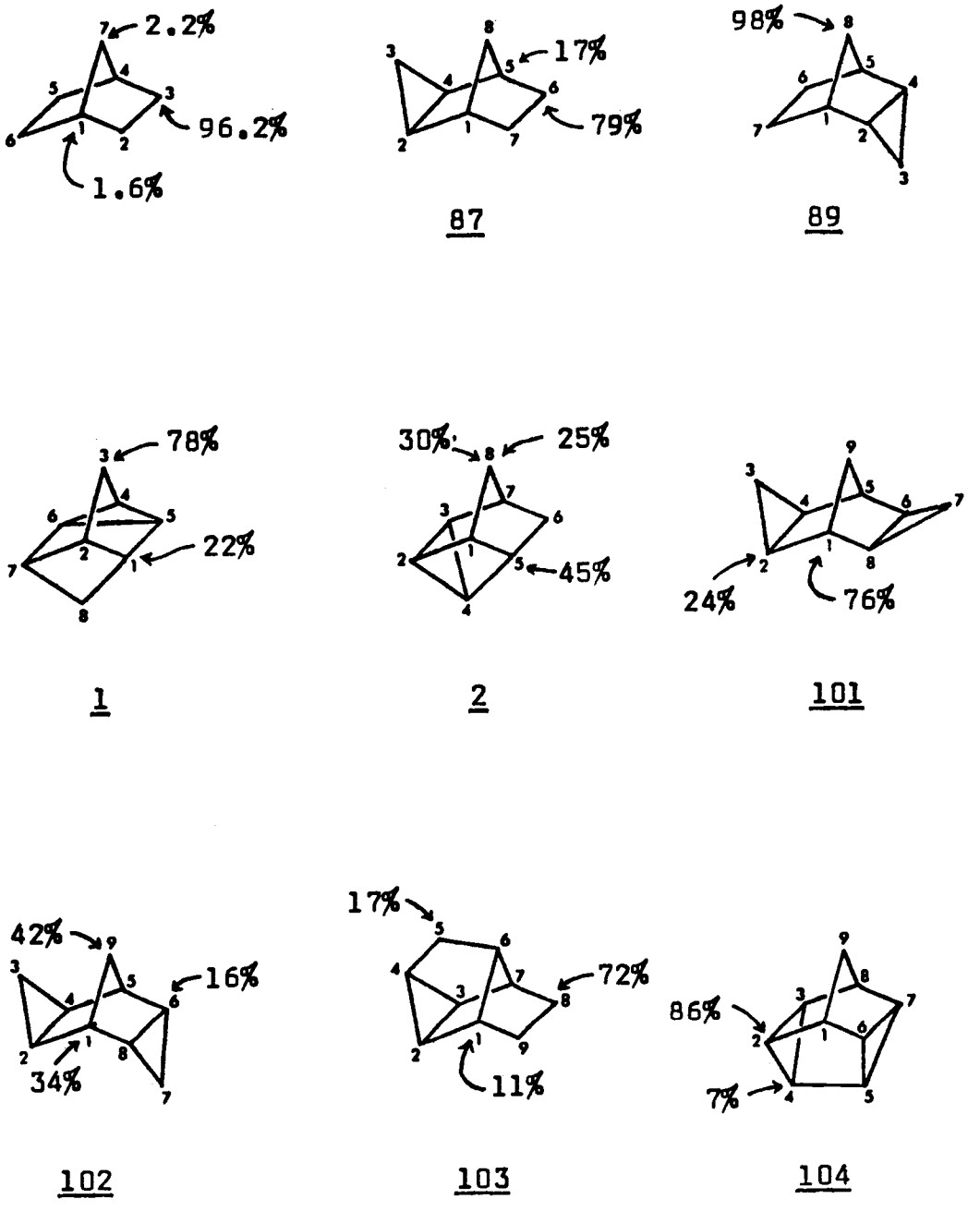


Figure 24. Regioselectivity of hydrogen abstraction by t-butoxy radical from selected polycyclic hydrocarbons at 40^{o} in CCl_4.

experimental section of Part II for the competition between tricyclo[3.3.0.$0^{3,7}$]octane 11 and cyclohexane. The critical reaction parameters and the resulting relative reactivities are presented in Table XIV.

Finally, coupling the abstraction patterns in Figure 24 with the per mole relative reactivities in Table XIV allowed calculation of the reactivity of each type of hydrogen in each of the hydrocarbons in Figure 10 relative to a cyclohexyl hydrogen. For comparative purposes, the hydrogens were broken up into several types related to the 1-norbornyl bridgehead position (Tables XV and XVI), the 2-norbornyl position (Table XIX), the 7-norbornyl position (Tables XVII and XVIII), and tertiary cyclopropyl positions (Table XX) not related to norbornane. Two tabulations were made for both 1-norbornyl and 7-norbornyl type positions, since, by product identification, the rates in Tables XV and XVII are known within error limits, but where no corresponding product was observed, we could only calculate an upper limit to reactivity (Tables XVI and XVIII) based on either the largest unidentified product observed in that particular chlorination, (rates given as less than or equal to a limiting value) or the assumption that we could observe any minor product of greater than 1% (rates given as less than a limiting value).

Before discussing the individual hydrogen abstraction

Table XIV. Critical reaction parameters and resulting relative reactivities for reaction of selected polycyclic hydrocarbons with t-butoxy radical in CCl_4.

Hydrocarbon	Runs	Rate[a]	[cyclohexane][b]	[hydrocarbon][b]	[tBuOCl][b]
	6	0.82 ± 0.03[c]	0.65	0.76	0.91
	3	0.41[d] ± 0.04[e]	1.1	1.7	1.1
	3	0.92[d] ± 0.03[e]	1.1	1.7	1.1
	6	0.35 ± 0.03[c]	1.05	1.18	1.06
	6	0.36 ± 0.03[c]	0.70	0.63	0.54
	6	0.33 ± 0.02[c]	0.70	0.84	0.46
	6	1.62 ± 0.15[c]	0.76	0.52	0.47
	5	0.83 ± 0.07[c]	0.84	0.83	0.86
	6	0.24 ± 0.04[c]	0.68	0.84	0.87

[a]Per mole, relative to cyclohexane. [b]Molality. [c]Standard deviation. [d]Determined by Raghavan (130). [e]Average

Table XV. Defined relative rates of 1-norbornyl type hydrogen abstraction from selected polycyclic hydrocarbons by t-butoxy radical at 40° in CCl_4.

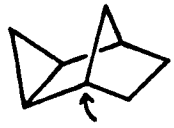
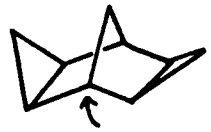
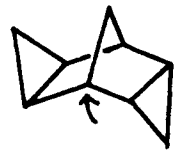
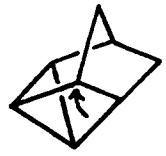
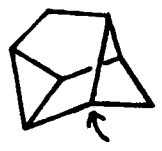
hydrocarbon	$k/k_{cyclohexyl}$ per H	k_{rel}
	0.076 ± 0.007	(1.00)
	0.52 ± 0.02	6.8 ± 0.7
	1.5 ± 0.1	20 ± 2
	3.3 ± 0.3	43 ± 6
	0.42 ± 0.06	5.5 ± 0.9
	0.97 ± 0.08	13 ± 2
	0.46 ± 0.04	6.1 ± 0.8

Table XVI. Limited relative rates of 1-norbornyl type hydrogen abstraction from selected polycyclic hydrocarbons by t-butoxy radical at 40° in CCl_4.

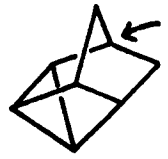
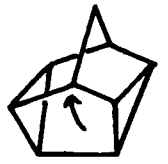
hydrocarbon	$k/k_{cyclohexyl}$ per H	k_{rel}
	0.076 ± 0.007	(1.00)
	≦ 0.11	≦ 1.4
	≦ 0.043	≦ 0.6
	< 0.1	< 1.3
	< 0.043	< 0.6
	≦ 0.1	≦ 1.3

Table XVII. Defined relative rates of 7-norbornyl type hydrogen abstraction from selected polycyclic hydrocarbons by t-butoxy radical at 40° in CCl_4.

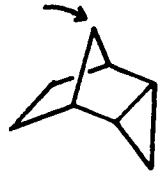
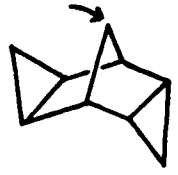
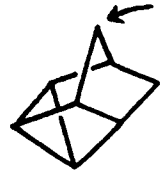
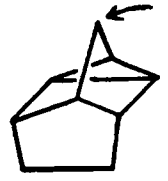
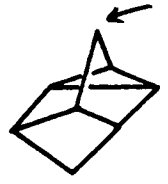
hydrocarbon	$k/k_{cyclohexyl}$ per H	k_{rel}
	0.11 ± 0.02	(1.00)
	11.0 ± 0.4	100 ± 18
	8.2 ± 0.8	75 ± 14
	1.2 ± 0.1	10.9 ± 2
	0.85 ± 0.07	8 ± 1
	1.6 ± 0.1	15 ± 3

Table XVIII. Limited relative rates of 7-norbornyl type hydrogen abstraction from selected polycyclic hydrocarbons by t-butoxy radical at 40° in CCl_4.

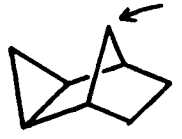
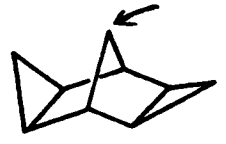
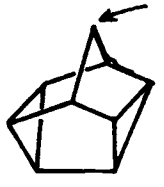
hydrocarbon	$k/k_{cyclohexyl}$ per H	k_{rel}
	0.11 ± 0.02	(1.00)
	$\leq$ 0.1	$\leq$ 0.9
	$\leq$ 0.06	$\leq$ 0.5
	$\leq$ 0.1	$\leq$ 0.9

Table XIX. Relative rates of 2-norbornyl type hydrogen abstraction from selected polycyclic hydrocarbons by t-butoxy radical at 40° in CCl_4.

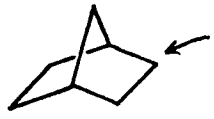
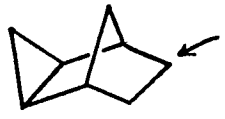
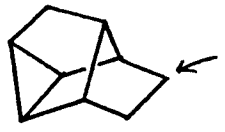
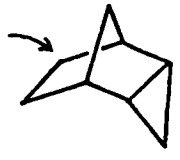
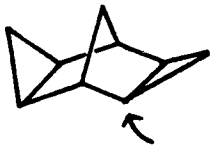
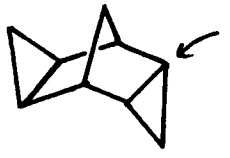
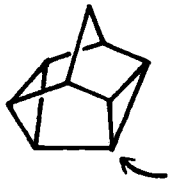
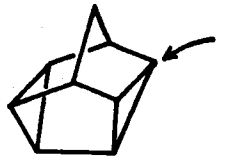
hydrocarbon	$k/k_{cyclohexyl}$ per H	k_{rel}
	2.4 ± 0.2	(1.00)
	2.4 ± 0.1	1.0 ± 0.1
	3.6 ± 0.3	1.5 ± 0.2
	≦ 0.11 ± 0.01	≦ 0.046 ± 0.003

Table XX. Relative rates of tertiary hydrogen abstraction from selected polycyclic hydrocarbons by t-butoxy radical at 40° in CCl_4.

hydrocarbon	$k/k_{cyclohexyl}$ per H	k_{rel}
	0.24 ± 0.02	(1.00)
	1.5 ± 0.15	6 ± 1
	0.10 ± 0.01	0.4 ± 0.1
	1.2 ± 0.1	5 ± 1

patterns and their implications, a few general observations are in order.

At the outset, it should be understood that the magnitude of the rate effects being discussed are extremely small. The largest rate enhancement observed is only a hundred fold, and an activation energy difference of 2.8 kcal/mole or an activation entropy of only 9 eu could be causal. Therefore, very minor structural changes, changes too small to be readily observable in carbonium ion chemistry because of the large activation energies involved, must be considered when correlation of the abstraction rates in Tables XV - XX is attempted.

Several factors can effect the activation energy of free radical hydrogen abstraction. Of primary importance is the exothermicity of the reaction, which in turn is determined by the C-H bond energy if a common chain transfer agent is used. Also of primary importance, eepecially when an attempt is made (as is done in the following discussion) to relate only those hydrogens which formally should have equivalent dissociation energies, are steric, resonance, field effects. Since, in the absence of special features, polarization in the transition state for hydrogen abstraction by t-butoxy radical should be inoperative at the C-1 and C-7 positions in norbornane (see discussion of this point in Part II), and since carbon tetrachloride was used as solvent in the study

reported here, inductive and solvent effects should not be important in determining relative rates.

The importance of steric factors in determining activation energies is magnified by a consideration of the structure of the transition state. Although the C-H-X bond angle, where X is the abstracting agent, is usually considered to be 180^{o}, the incipient H-O-tBu bond must be angular, therefore making attack by the C-H bond on the t-butoxy radical similar to S_N2 displacement at a neopentyl carbon, a process which is extremely difficult (143) and would thus be sensitive to the steric bulk of the attacking hydrocarbon.

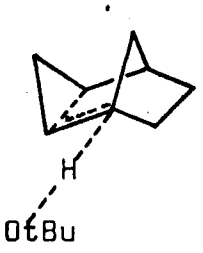
Viewed in this manner, two seemingly unrelated pieces of data can be rationalized. First, the activation energy for tertiary hydrogen atom attack on chlorine atom (0.1 kcal/mole (144)) is less than for attack on t-butoxy radical (4.9 kcal/mole (120)). Second, Stuart-Briegleb models indicate that the C-1 position in norbornane is much more accessible than the C-7 position because of interference by the exo methylene hydrogens, thus suggesting the prediction that a greater C-1:C-7 abstraction ratio from norbornane will be observed when t-butoxy radical is being attacked than when norbornane attacks a chlorine atom. This prediction is in accord with the results in Part II.

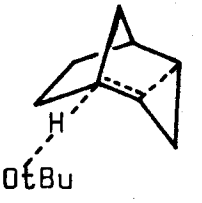
The data describing norbornane and hydrocarbons 87,

103, 1, 89, 104, and C-1 abstraction from 2 in Tables XV and XVI indicate that a cyclopropane ring oriented in an exo fashion, and adjacent to the bridgehead positions in each ring system, is responsible for a six to seven fold increase in the rate of C-1 hydrogen atom abstraction by t-butoxy radical relative to norbornane, whereas an endo cyclopropyl moiety increases the rate by less than a factor of 1.4. Introduction of a second exo-cyclopropane ring does give additional rate enhancement (hydrocarbon 101) although not a six fold rate increase, since there is also a concomitant increase in the strain energy in the ring system which need not be proportional to the number of three membered rings incorporated. The unpredicted facile abstractions from C-1 in 102 and 2 are anomalous, and are apparently due to additional factors not related to the general stereospecific effect noted.

The enhanced bridgehead free radical reactivity of 87 relative to 89 might be attributed to delocalization in the transition state of electron density from the transannular cyclopropane bond (the backside of the orbital comprising this bond is approximately syn-periplanar to the bridgehead C-H bond in both exo and endo ring systems) into the C-H bond being broken. Such delocalization would favor abstraction of a hydrogen adjacent to an exo cyclopropyl moiety relative to a proton adjacent to an endo cyclopropyl moiety

because the former would result in partial cis double bond character in a six membered ring, whereas in the latter case, the incipient double bond would be formed in the trans configuration in the cyclohexane ring.



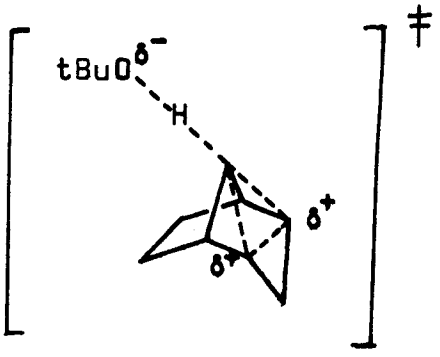


An alternative explanation (equally helpless at explaining the abstraction rates at C-1 in 102 and 2) is afforded by noting that introduction of an exo cyclopropyl moiety into the norbornane ring removes the exo protons which are nearly eclipsed (145) with the bridgehead hydrogen, and which interfere somewhat with t-butoxy radical attack at C-1. Introduction of an endo cyclopropyl moiety does not remove this interaction, and in fact bends the exo hydrogen out and down so that it blocks C-1 attack by t-butoxy radical even more effectively than in norbornane.

In conclusion, it can be said that neither explanation is totally satisfying, in that two pieces of data are not explained. Usually such occurrences are not due to specific anomalies, but are simply an indication that the theory to which they are anomalous is imperfect. The data in Tables

XV and XVI do, however, provide a broad base from which to extract, with additional experimentation, an improved rationalization for the enhanced bridgehead reactivities observed.

Interpretation of the 7-norbornyl type hydrogen abstraction rates in Tables XVII and XVIII is considerably easier. The data describing norbornane and hydrocarbons 89, 102, 2, 87, and 101 demonstrate that rate acceleration due to trishomocyclopropenyl charge delocalization in the transition state for C-7 hydrogen abstraction by t-butoxy radical is a general phenomenon. Polar effects need not be washed out in these cases, since rehybridization to a pentavalent carbon, as is necessary in the proposed nonclassical transition state, should actually be favored by the restricted bond angle.

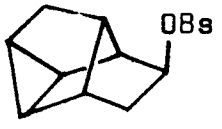


The unexpected low reactivity of the C-9 position in pentacyclic hydrocarbon 104 is readily understood, since charge separation such as would be necessary in a delocalized transition state would place the partially negative oxygen atom in a region of space already occupied by the high electron

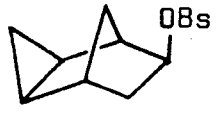
density of the bent cyclopropane bond.

Hydrocarbons 1 and 103 are unrelated to the trishomocyclopropenyl problem, but are in themselves intriguing, since a planar radical formed at the 7-norbornyl type position in these substrates is in the most stable bisected orientation to the included cyclopropyl moiety (146). The rates of abstraction from these positions is therefore enhanced relative to norbornane, and are close in reactivity to the enhancement observed for primary hydrogen abstraction from methylcyclopropane (55).

The data in Table XIX show that no nonclassical anchimeric assistance to hydrogen atom abstraction from the exo-2-norbornyl type positions in 87 or 103 occurs. This contrasts with the substantial rate accelerations observed for solvolysis of corresponding exo-brosylate 128 (147) and exo-brosylate 129 (148). The low reactivity of the C-6 and C-7 hydrogens in 89 is anomalous.



128



129

EXPERIMENTAL SECTION

General. The general techniques and equipment described in the experimental section of Part I of this thesis were used.

Simmons-Smith Reaction of 1-Chloronorbornene 98. To a refluxing solution of 1.00 g (7.8 mmol) of 1-chloronorbornene 98 in 10 ml of anhydrous ether, under nitrogen, were added in three aliquots, over a 36 hr period, a total of 9 g of methylene iodide and 3 g of zinc-copper couple (prepared from zinc dust and cupric acetate) (150). At the end of this period, the solution was diluted with pentane, washed with saturated NH_4Cl, and dried over K_2CO_3-Na_2SO_4. Removal of the pentane by distillation through a 10 cm Vigreaux column yielded a residue which was analyzed by vpc using column F, and was found to contain, in addition to a 10% recovery of starting chloride, three additional components in a yield ratio of 2:17:22. Aliquots removed during the course of the reaction indicated an even rate of buildup of the 2% and the 17% component, while the 22% component increased in area only near the end of the 36 hr reaction period. The products were isolated by preparative vpc and identified as described below. No other peaks in greater than 1% yield were observed.

The 2% component was identified as 1-ethoxy-exo-tricyclo[3.2.1.$0^{2,4}$]octane 100 by analysis of the ir, nmr, and mass spectra detailed below. The ir band at 1602 cm^{-1} appears to be anomalous as an olefinic absorption, since there is no other evidence for unsaturation: m/e 152; ir (CCl_4) ν = 3098, 3030, 2983, 2890, 1602, 1462, 1389, 1343, 1320, 1297, 1208, 1190, and 1137 (very strong) cm^{-1}; nmr (100 MHz, CCl_4) δ = 3.51 (quartet, J = 7 Hz, 1H, ethoxy methylene), 3.39 (quartet, J = 7 Hz, 1H, ethoxy methylene), 2.05 (broad s, $w_{\frac{1}{2}}$ = 8 Hz, 1H, C-5), 1.90-1.65 (m, 1H, exo-C-7), 1.65-1.30 (m, 4H, protruding peaks with J = 9Hz, C-8 and endo-C-7), 1.30-1.00 (m, 1H, exo-C-6), 1.15 (triplet, J = 7 Hz, 3H, ethoxy methyl), 0.95-0.40 (m, 4H, C-2, syn-C-3, C-4, and endo-C-7), 0.10 (doublet of triplets, J = 7, 7 Hz, 1H, anti-C-3).

Anal., Calcd. for $C_{10}H_{16}O$: m/e 152.120. Found: m/e 152.120.

The 17% component was identified as 1-chloro-exo-tricyclo[3.2.1.$0^{2,4}$]octane 88 by comparison of its ir spectrum to that of the sample reported by Raghavan (130, 131).

The 22% component gave a yellow precipitate when treated with $AgNO_3$ in 80% aqueous acetone, and formed exo-tricyclo-[3.2.1.$0^{2,4}$]octane 87 upon treatment with TBTH at 80° for 12 hr. This evidence, in conjunction with the spectral data detailed below, define this component as 1-iodo-exo-tricyclo-[3.2.1.$0^{2,4}$]octane 99: ir (CCl_4) ν = 3105, 1048, 2984, 2891,

1482, 1455, 1319, 1271, 1221, 1197, 1114, 1079, 1039, 995, 960, 943, 894, 869 cm^{-1}; nmr (100 MHz, CCl_4) δ = 2.05-1.85 (m, 3H, C-5 and C-8), 1.85-1.10 (m, 5H, exo- and endo-C-6 and C-7, C-2), 1.00-0.75 (m, 1H, C-4), 0.46 (doublet of triplets, J = 3.5, 7 Hz, 1H, syn-C-3), 0.17 (doublet of triplets, J = 7, 7 Hz, 1H, anti-C-3).

Anal. Calcd. for $C_8H_{11}I$: C, 41.05; H, 4.74. Found: C, 40.85; H, 4.60.

Photochlorination of exo, exo-Tetracyclo[3.3.1.$0^{2,4}$.-$0^{6,8}$]nonane 101 with t-Butyl Hypochlorite in CCl_4. A 4 molal solution of 187 mg (1.57 mmol) of hydrocarbon 101 and 187 μl (ca 1 equiv) of tBuOCl in CCl_4 was sealed in a pyrex ampoule and irradiated one hr at 39.85 $\pm$ 0.15° (standardized) with a 275 W sunlamp at a distance of 8 in. Vpc analysis of the resulting solution using column C and 9.8 mg of chlorocyclohexane as an internal reference indicated the presence of six volatile peaks, in the ratio of 0.5:22:3:0.5:71:3, in an overall yield of 9%. The same internal standard indicated that most of the starting hydrocarbon was unreacted. Heavier components comprised no more than 1% in total yield.

Both the 71% and the 22% component gave only parent hydrocarbon 101 upon reduction with TBTH by Method A. This observation, coupled with the lack of a proton α to chlorine in the nmr spectrum of each isomer, indicated that both mono-

chlorides resulted from tertiary C-H substitution. Since there are only two such positions in the di<u>exo</u>-[3.2.1.$0^{2,4}$.-$0^{6,8}$] ring system, the major isomer was readily identified as <u>exo</u>, <u>exo</u>-1-chlorotetracyclo[3.2.1.$0^{2,4}$.$0^{6,8}$]nonane <u>107</u>, since all protons appeared in pairs, except for a single downfield absorption due to the C-5 bridgehead proton, in the nmr spectrum of this component (Figure 11), and no precipitate was formed upon treatment of <u>107</u> with $AgNO_3$ at 80° for two days: m/e 154 and 156; ir (CCl_4) $\sqrt{}$ = 3105, 059, 2956, 1500, 1449, 1311, 1209, 1187, 1090, 1045, 991, 914, 836, and 706 cm^{-1}; nmr (Figure 11) (100 MHz, CCl_4) δ = 2.19 (s, $w_{\frac{1}{2}}$ = 5 Hz, 1H, C-5), 1.50-1.20 (m, 4H, C-2, C-4, C-6, and C-8), 1.07 (doublet of triplets, J = 3.5, 7 Hz, 2H, <u>syn</u>-C-3 and C-7), 0.86 (s, $w_{\frac{1}{2}}$ = 4 Hz, 2H, C-9), and 0.40 (doublet of triplets, J = 7, 7 Hz, 2H, <u>anti</u>-C-3 and C-7).

<u>Anal.</u> Calcd. for $C_9H_{11}Cl$: m/e 154.055. Found: m/e 154.055.

The 22% component was also readily identified as <u>exo</u>, <u>exo</u>-2-chlorotetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane <u>108</u>, since there were at least five non-equivalent protons apparent in the nmr spectrum of this isomer (Figure 12): m/e no parent ion observed, but a P-Cl peak at 119 was prominent; ir (CCl_4) $\sqrt{}$ = 3104, 3049, 2994, 1502, 1449, 1314, 1271, 1250, 1194, 1128, 1088, 1046, 1040, 1011, 983, 939, 859 cm^{-1}; nmr (Figure 12) (100 MHz, CCl_4) δ = 2.44 (s, $w_{\frac{1}{2}}$ = 5.5 Hz, 1H,

C-1), 2.27 (s, $w_{\frac{1}{2}}$ = 5.5 Hz, 1H, C-5), 1.62 (m, 1H, C-4), 1.50-0.85 (complex m, 4H, syn and anti-C-3, C-6, and C-8), 0.76 (doublet of triplets, J = 3.5, 7 Hz, 1H, syn-C-7), 0.52 (s, $w_{\frac{1}{2}}$ = 5 Hz, 2H, C-9), and 0.34 (doublet of triplets, J = 7, 7Hz, 1H, anti-C-3).

Anal. Calcd. for C_9H_{11}: m/e 119.086. Found: m/e 119.088.

Photochlorination of exo, endo-Tetracyclo[3.3.1.$0^{2,4}$.-$0^{6,8}$]nonane 102 with t-Butyl Hypochlorite in CCl_4. A 4 molal solution of 68 mg (0.58 mmol) of hydrocarbon 102, containing a 16% impurity of the corresponding diexo isomer 101 as determined by nmr analysis, and 69 μl (ca 1 equiv) of t-BuOCl in CCl_4 was sealed in a pyrex ampoule and irradiated one hr at 39.85 $\pm$ 0.15° (standardized) with a 275 W sunlamp at a distance at 8 in. Vpc analysis of the resulting solution using column C and 5.6 mg of chlorocyclohexane as an internal reference indicated the presence of three major components which had parent ion masses corresponding to tetracyclic C_9H_{11} monochlorides. The combined yield of these three products, observed in a ratio of 35:21:44, was 27%. A small peak formed in 2% yield, which eluted just after the monochlorides, had a large mass spectral peak at m/e of 153 and 155, indicating that it was a dichloride of molecular formula $C_9H_{10}Cl_2$. Products eluting later on column C comprised no more than 20%

of the total volatile chlorides. Unreacted hydrocarbon was collected, analyzed by nmr, and was found to contain 20% of the contaminating isomer 101. No absorptions were found in either the ir or the nmr spectra of any of the three monochlorides which corresponded to the two monochloro derivatives 107 and 108 of the contaminating diexo isomer 101.

The 35% product had parent masses of 154 and 156, no olefinic absorptions in the ir or nmr spectra, no protons α to chlorine in the nmr (Figure 13), and gave exclusively parent hydrocarbon 102 upon reduction with TBTH by Method B, indicating that this component was a bridgehead monochloride in the exo, endo-[3.3.1.$0^{2,4}$.$0^{6,8}$] system. Observation of a single cyclopropyl proton at 0.19 δ and two unique bridgehead protons at 2.45 and ca 2.30 δ in the nmr spectrum of this monochloride (Figure 13) define its structure as either 2- or 6-chloro-exo, endo-tetracyclo[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane. The discussion of this spectrum presented in the text indicated that this product is the C-6 substituted isomer 109; m/e 154 and 156; ir (CCl_4) ν = 3097, 3040, 2995, 1488, 1430, 1319, 1261, 1118, 1108, 1050, 1040, 1032, and 900 cm^{-1}; nmr (Figure 13) (100 MHz, CCl_4) δ = 2.45 (broad s, $w_{\frac{1}{2}}$ = 6 Hz, 1H, C-1), 2.40-2.20 (m, 1H, C-5), 2.20-1.95 (m, 1H, endo-C-7), 1.80-1.10 (m, 4H, C-6, C-8, and both C-9), 1.10-0.40 (m, 3H, syn-C-3, C-4, exo-C-7), 0.19 (triplet, J = 7 Hz, 1H, anti-C-3).

Anal. Calcd. for $C_9H_{11}Cl$: m/e 154.055. Found: m/e 154.055.

The 44% product also had parent ion masses of 154 and 156, no olefinic absorptions in ir or nmr spectra, no protons α to chlorine in the nmr (Figure 14), and gave exclusively parent hydrocarbon 102 upon reduction with TBTH by Method B. Observation of a single bridgehead proton at 2.18 δ, and one cyclopropyl proton (a doublet of triplets, J = 7, 7 Hz) at 0.20 δ, define this product as exo, endo-1-chlorotetracyclo-[3.3.1.$0^{2,4}$.$0^{6,8}$]nonane 110: m/e 154 and 156; ir (CCl_4) ν = 3105, 3040, 2994, 1487, 1437, 1316, 1193, 1080, 1042, 1019, 971, 901, and 704 cm^{-1}; nmr (Figure 14) (100 MHz, CCl_4) δ = 2.18 (broad m, $w_{\frac{1}{2}}$ = 9 Hz, 1H, C-5), 1.98-1.30 (m, an apparent doublet protruding with J = 7 Hz, 5H, C-6, endo-C-7, C-8, and both C-9), 1.10-0.85 (m, 1H, C-2), 0.85-0.55 (m, coupling of 7 Hz apparent, 3H, syn-C-3, C-4, exo-C-7), 0.20 (doublet of triplets, J = 7, 7 Hz, anti-C-3).

Anal. Calcd. for $C_9H_{11}Cl$: m/e 154.055. Found: m/e 154.059.

The 21% product had parent ion masses of 154 and 156, and contained no olefinic absorptions in the ir or nmr spectra, but did have one proton α to chlorine in the nmr spectrum (Figure 15) at 4.05 δ (a doublet of triplets with J = 4, 8.5 Hz), but did not give hydrocarbon 102 upon TBTH reduction (see following experiment). The spectral analysis

presented in the discussion defined this rearranged C_9H_{11} monochloride as endo-9-chloro-exo-tetracyclo[4.3.0.$0^{2,4}$.-$0^{5,7}$]nonane 111: m/e 154 and 156; ir (CCl_4) ν = 3059, 2965, 2899, 1449, 1338, 1296, 1276, 1234, 1027, 919, 908, 711, and 682 cm^{-1}; nmr (Figure 15) (100 MHz, CCl_4) δ = 4.05 (doublet of triplets, J = 4, 8.5 Hz, 1H, C-9), 2.64 (doublet of doublets, J = 4.5, 4.5 Hz, 1H, C-1), 2.47-2.40 (m, 2H, exo and endo-C-8), 1.80-1.50 (m, 3H, C-5, C-6, and C-7), 1.45-1.05 (m, 2H, C-2 and C-4), 0.58-0.31 (doublet of triplets, J = 4, 7 Hz, 1H, syn-C-3), 0.08 (doublet of triplets, J = 7, 4 Hz, 1H, anti-C-3).

Anal. Calcd. for $C_9H_{11}Cl$: m/e 154.055. Found: m/e 154.056.

Reduction of endo-9-Chloro-exo-Tetracyclo[4.3.0.$0^{2,4}$.-$0^{5,7}$]nonane 111 by TBTH. Reduction of chloride 111 with TBTH using Method B gave a single volatile product in quantitative conversion, as determined by vpc analysis on column H. Collection of this hydrocarbon followed by ir and nmr analyses as described below and in the discussion section defined this product as exo-tetracyclo[4.3.0.$0^{2,4}$.$0^{5,7}$]nonane 115: ir (CCl_4) ν = 3058, 2967, 2890, 1456, 1445, 1333, 1299, 1024, and 720 cm^{-1}; nmr (Figure 16) (100 MHz, CCl_4) δ = 2.74 (triplet, J = 4 Hz, 1H, C-1), 1.26 (doublet of triplets, J = 3.5, 6 Hz, 1H, C-4), 0.77 (m, 1H, syn-C-3), 0.48 (doublet

of triplets, J = 3.5, 7 Hz, C-2), 0.15 (quartet, J = 3.5 Hz, 1H, anti-C-3), 2.30-1.05 (m, 7H, hydrogens on C-5 to C-9).

Photochlorination of Deltacyclane 103 with t-Butyl Hypochlorite in CCl_4. A 4 molal solution of 146 mg (1.22 mmol) of deltacyclane 103 and 146 μl (ca 1 equiv) of t-BuOCl in CCl_4 was sealed in a pyrex tube and irradiated at 39.85 ± 0.15° (NBS calibrated) for 1 hr with a 275 W sunlamp at a distance of 8 in. To the resulting solution were added 9.8 mg of chlorocyclohexane as an internal standard, and the mixture analyzed by vpc on column C. Three peaks in the ratio of 11:61:27 were observed in an overall yield of 37%. Preparative vpc using column C, followed by TBTH reduction of each peak using Method B, resulted in formation of only deltacyclane 103 from all components.

The 61% component was identified as exo-8-chlorodeltacyclane 116 by ir and nmr comparison to an authentic sample prepared by Balls (140). The 27% component, whose analysis and ir properties were described by Fenwick (134), was identified as a 1.6:1 mixture of 5-chlorodeltacyclane 118 and endo-8-chlorodeltacyclane 117 as described in the discussion section. The following spectral properties of this mixture are added to those of Fenwick (134): m/e 154 and 156; nmr (100 MHz, CCl_4) δ = 4.32-4.19 (m, exo-CHCl proton in 117) and 4.12 (s, $w_{\frac{1}{2}}$ = 4 Hz, CHCl proton in 118) in relative areas

of 1:1.6, and complex absorptions from 2.73-0.92 δ.

Anal. Calcd. for $C_9H_{11}Cl$: m/e 154.055. Found: m/e 154.052.

The 11% component was tentatively identified as 1-chlorodeltacyclane 119 as described in the discussion, although we wee unable to unequivocably rule out a possible structure of 2-chlorodeltacyclane: m/e 154 and 156; ir (CCl_4) ν = 3095, 2967, 2891, 1466, 1446, 1349, 1302, 1278, 1079, 1056, 996, 984, 965, 934, 915, 903, and 882 cm^{-1}; nmr (Figure 17) (100 MHz, CCl_4) δ = 2.20-2.07 (m, 1H, C-6), 2.07-1.70 (m, 6H, protruding doublet with J = 10.5 Hz, exo- and endo-C-8 and C-9, C-7, and anti-C-5), 1.60 (d, J = 10.5 Hz, syn-C-5), 1.30-1.10 (m, 3H, C-2, C-3, and C-4).

Anal. Calcd. for $C_9H_{11}Cl$: m/e 154.055. Found: m/e 154.055.

Photochlorination of Pentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]-nonane 104 with t-Butyl Hypochlorite in CCl_4. A 4 molal solution of 0.157 g (1.33 mmol) of hydrocarbon 104 and 159 μl (ca 1 equiv) of t-BuOCl in CCl_4 was sealed in a pyrex tube and irradiated at 39.85 ± 0.15° (standardized) with a 275 W sunlamp for one hour at a distance of 8 in. Analysis of the resulting solution revealed the presence of three monochlorides in the ratio of 81:10:9 in an overall yield of 9%, as determined by the addition of 14 mg of chlorocyclohexane internal

reference and vpc analysis on column H. Less volatile peaks which had mass spectra consistent with C_9 dichlorides were observed, but in less than 1% combined yield.

The 10% component eluted too close to the major product to be isolated in sufficient quantity or purity to be characterized. The 9% component was identified as 4-chloropentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 122 by the spectral analysis presented in the discussion section and summarized below: m/e 152 and 154; ir (CCl_4) ν 3078, 2994, 2959, 2881, 1321, 1297, 1177, 1079, 989, 934, 881, and 644 cm^{-1}; nmr (Figure 23) (100 MHz, CCl_4) δ = 2.63-2.49 (m, $w_{\frac{1}{2}}$ = 10 Hz, 1H, C-5), 2.38 (s, $w_{\frac{1}{2}}$ = 3.5 Hz, 2H, C-1 and C-8), 2.34-2.07 (m, 6H, protruding triplet, J = 8 Hz, assigned to syn- and anti-C-9).

Anal. Calcd. for C_9H_9Cl: m/e 152.039. Found: m/e 152.036.

The major product gave only parent hydrocarbon 104 in 30% conversion after 6 hr by TBTH reduction Method A. Spectral analysis coupled with extensive deuteration experiments, described below and correlated in the discussion section, identifed this product as 2-chloropentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 121: m/e 153 and 154; ir (CCl_4) ν = 3077, 3011, 2984, 2875, 1351, 1314, 1302, 1054, 1040, 961, 934, 896, and 674 cm^{-1}; nmr (Figure 18) (100 MHz, CCl_4) δ = 2.73 (broad s, $w_{\frac{1}{2}}$ = 9 Hz, 2H, C-1 and C-8), 2.53-2.35 (m, 1H, C-4),

2.35-2.09 (m, protruding doublet with J = 9Hz, 3H, C-3, C-5, and syn-C-9), 2.09-1.67 (m, protruding doublet, J = 9 Hz, 3H, C-6, C-7, and anti-C-9).

Anal. Calcd. for C_9H_9Cl: C, 79.38; H, 5.94. Found: C, 70.70; H, 5.95.

Preparation of Deuterated Pentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.-$0^{5,7}$]nonane 124. A solution of deltacyclanone 5-H_2 (5.0 g, 37.3 mmol) prepared by the method of Freeman, Balls, and Brown (32), and CH_3OD (40 ml, ca 99%) prepared as prescribed by Streitwieser, Verbit, and Stang (149), was heated at reflux for 20 hr with a catalytic amount of $NaOCH_3$. The methanol was then removed at reduced pressure, and a fresh 40 ml CH_3OD aliquot was added, and the solution again heated at reflux for 20 hr. After removal of the methanol by distillation, the residue was diluted with pentane, washed with water, dried over Na_2SO_4-K_2CO_3, and distilled to yield 4.24 g (85%) deuterated deltacyclanone 5-D_2. Nmr analysis indicated the presence of 1.33 atoms deuterium at the α methylene position.

Conversion of 5-D_2 to the corresponding tosylhydrazone by the method of Freeman and Balls (137), followed by thermal decomposition of the lithium salt using the procedure described in Part I for the dry salt pyrolysis of 3-NNLiTs, yielded a pyrolysate which was diluted with ether, and photolyzed by the method of Freeman and Balls (137), to give deuterated

pentacyclic hydrocarbon 124. Nmr analysis of deltacyclene, which was vpc collected from the dry salt pyrolysate, indicated the presence of 1.3 atoms deuterium in the vinyl position. Nmr analysis of resultant pentacyclic hydrocarbon 124 indicated that about 1.1 atoms deuterium had been incorporated. Low voltage mass spectral analysis on both deuterated and undeuterated pentacyclic hydrocarbons gave the following relative intensities: 104; m/e (12.1 eV, average ± standard deviation on 10 scans); P-1, 12.3 ± 0.7; P, 41.4 ± 1.2; P+1, 4.3 ± 0.3; 124; m/e (12.1 eV, average ± standard deviation on 10 scans); P-1, 0.16 ± 0.01; P, 1.00 ± 0.06; P+1, 2.10 ± 0.04; P+2, 1.02 ± 0.06; P+3, 0.10 ± 0.01. The P-1 peak could not be reduced to less than 29% of the parent peak in parent hydrocarbon 104. Assuming no deuterium is lost in the P to P-1 fragmentation, this data indicates the following species are present in the sample of 124: d_0 = 15 ± 2; d_1 = 58 ± 7; d_2 = 27 ± 3. Total incorporation was 1.1 ± 0.1 atoms deuterium: ir (CCl_4) ν = 3058, 2994, 2950, 2865, 2283, 1299, 894, 676, and 653 cm^{-1}; nmr (Figure 20) (100 MHz, CCl_4) δ = 2.59-2.43 (m, 2H, C-1 and C-8), 2.19-1.98 (m, ca 1H, residual C-4 and C-5), 1.98-1.86 (m, 4H, C-2, C-3, C-6 and C-7), 1.86-1.76 (m, 2H, C-9).

Photochlorination of Deuterated Pentacyclo[4.3.0.-$0^{2,4}.0^{3,8}.0^{5,7}$]nonane 124 with t-Butyl Hypochlorite in CCl_4.

Chlorination of 130 mg of hydrocarbon 124 by the same procedure as that used for chlorination of 104 yielded three products in the approximate ratio 8:1:1 as determined by vpc analysis on column F. The major product 126 had an nmr spectrum (Figure 21) consistent with the assigned structure as described in the discussion: ir (CCl_4) ν = 3077, 3012, 2874, 2294, 1339, 1333, 1314, 1285, 1266, 1250, 1227, 1148, 1083, 1049, 1040, 1031, 969, 900, 714, 685, 668, 661, and 647 cm^{-1}; nmr (Figure 21) (100 MHz, CCl_4) δ = 2.72 (m, 2H, C-1 and C-8), 2.45 (doublet of doublets, J = 2, 7 Hz, 0.5H, residual C-4), 2.35-2.08 (m, protruding doublet with J = 9 Hz, 2.5 H, C-3, residual C-5, and syn-C-9), 2.08-1.75 (m, protruding doublet with J = 9 Hz, 3H, C-6, C-7, and anti-C-9).

Unreacted hydrocarbon 124 was recovered by preparative vpc and analyzed for deuterium content using the mass spectrometer: m/e (12.1 eV, relative intensities are averages ± standard deviations on 10 scans); P-1, 0.18 ± 0.02; P, 1.00 ± 0.05; P+1, 2.00 ± 0.06; P+2, 0.99 ± 0.03; P+3, 0.09 ± 0.01. The ir spectrum of this sample was identical to that of starting material 124.

Reduction of Deuterated 2-Chloropentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 126 with TBTH. Using Method A, 19 mg of chloride 126 was reduced with TBTH over a 3 day period. Vpc collection of resultant hydrocarbon 124 from column F followed

by mass spectral analysis revealed the following: m/e (12.1 eV, relative intensities are the average ± standard deviations on 10 scans); P-1, 0.18 ± 0.01; P, 1.00 ± 0.07; P+1, 2.07 ± 0.10; P+2, 1.01 ± 0.06; P+3, 0.10 ± 0.01.

Reduction of 2-Chloropentacyclo[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]-nonane 121 with Sodium and Deuterated t-Butanol in THF. A solution of 5.2 mg (0.034 mmol) of chloride 121 was taken up in a solution of 15 μl of anhydrous THF and 25 μl of t-BuOD (98+%, prepared by the method of Young and Guthrie (73) and analyzed by nmr) and added to 60^{o} to an excess of freshly cut sodium (flaked with a hammer) in anhydrous THF with exclusion of moisture. After 5 hr, the suspension was diluted with pentane and centrifuged. Subjection of the resulting supernatant to preparative vpc using column F showed a single volatile component (2.1 mg, 52% yield), other than pentane, THF, and excess t-BuOD, which had a retention time equal to that of authentic 104, and the following ir and nmr spectra: ir (CCl_4) ν = 3058, 2994, 2950, 2865, 2278, 1299, 1285, 900, 887, 653, and 641 cm^{-1}; nmr (Figure 22) (100 MHz, CCl_4) δ = 2.59-2.43 (m, 2H, C-1 and C-8), 2.19-1.98 (m, 2H, C-4 and C-5), 1.98-1.86 (m, 3H, C-3, C-6, and C-7), 1.86-1.76 (m, 2H, C-9).

Dilution Experiments. The following procedure was used for all dilution experiments described in the discussion

section. A solution of 38.4 mg (0.32 mmol) of hydrocarbon 104 in 360 mg of CCl_4 was divided between 6 tubes as follows: tubes 1-4, 50 μl of solution; tubes 5 and 6, 25 μl of solution. An additional 50 μl of CCl_4 was then added to tubes 4 and 5. Each ampoule was then charged with tBuOCl, in amounts recorded in Table XXI below, sealed, and irradiated for 2 hr at 39.85 ± 0.15° with a 275 W sunlamp at a distance of 8 in. Tube 6 was irradiated for a total of 6 hr. Subsequent vpc analysis of the resulting solutions using column H gave the relative yields of products 121, 122, and the unidentified peak as shown in Table XXI. Major chloride 121 and the unknown were porly resolved. The analysis order was tube 1, 2, 5, 4, 3, then 6.

Relative rates of hydrogen abstraction. The procedure described by Walling and Jacknow (111), and detailed in Part II for the competition experiment between 11 and cyclohexane, was followed. Vpc analysis of the resulting solutions, performed by alternating analysis of reference and sample runs, gave relative peak areas for reference norbornane and polycyclic hydrocarbon, typified by the data in Table XXII for the relative rate of hydrogen abstraction from 104. Per mole relative reactivities were calculated by the method of Huyser (129) using the following equation, where R = reference cyclohexane, H = polycyclic hydrocarbon (e.g. 104), and the

Table XXI. Dilution experiments with pentacyclo[4.3.0.-$0^{2,4}.0^{3,8}.0^{5,7}$]nonane 104.

Tube	µl tBuOCl	molality [104]	molality [tBuOCl]	relative % 121	relative % unknown	relative % 122
1	2	0.90	0.25	86	7	7
2	4	0.90	0.49	84	9	7
3	6	0.90	0.99	80	11	9
4	4	0.41	0.23	82	8	10
5	2	0.27	0.15	89	5	6
6	2	0.90	0.49	85	7	8

$$k/k_o = \frac{\log [H]_o/[H]}{\log [R]_o/[R]}$$

concentrations are the average of the concentrations recorded in Table XXII. Errors were determined from standard deviations using standard propogating techniques (151).

Table XXII. Rate data for chlorination of pentacyclo-[4.3.0.$0^{2,4}$.$0^{3,8}$.$0^{5,7}$]nonane 104 with t-butyl hypochlorite in CCl_4 at 40^{o}.

Reference Runs[a]	Sample Runs[b]	relative concentrations[c] cyclohexane	104
1		0.0958	0.1228
	1	0.0329	0.0949
2		0.0955	0.1248
	2	0.0344	0.1004
3		0.0956	0.1219
	3	0.0336	0.0987
4		0.0949	0.1242
	4	0.0327	0.0969
5		0.0954	0.1283
	5	0.0334	0.0914
6		0.0951	0.1238
	6	0.0329	0.0951
average		0.0954	0.1243
	average	0.0333	0.0962
standard deviation		0.0003	0.0022
	standard deviation	0.0006	0.0032

[a]No tBuOCl added. [b]tBuOCl added. [c]CCl_4 was used as the internal reference, since it has been shown to be at least 10^4 less reactive than tBuOCl as a chain transfer agent (59).

BIBLIOGRAPHY

1. P. K. Freeman, V. N. M. Rao, and G. E. Bigam, Chem. Commun., 511 (1965).

2. R. R. Sauers and R. A. Parent, J. Org. Chem., 28, 605 (1963); R. R. Sauers, R. A. Parent, and S. B. Damle, J. Amer. Chem. Soc., 88, 2257 (1966); C. Weston, Ph.D. Dissertation, Rutgers University, 1968.

3. V. N. M. Rao, Ph.D. Dissertation, University of Idaho, 1965.

4. R. M. Coates and K. Yano, Tetrahedron Lett., 2289 (1972).

5. H. Hart and G. M. Love, J. Amer. Chem Soc., 93, 6266 (1971).

6. O. L. Chapman, M. Kane, J. D. Lassila, R. L. Loeschen, and H. E. Wright, ibid., 91, 6856 (1969).

7. R. Criegee and A. Rimmelin, Ber., 90, 414 (1957).

8. K. B. Wiberg, R. A. Fenoglio, V. Z. Williams, Jr., and R. W. Ubersax, J. Amer. Chem. Soc., 92, 568 (1970).

9. S. Winstein and J. Sonnenberg, ibid., 83, 3235 (1961); 83, 3244 (1961).

10. R. M. Coates and J. L. Kirkpatrick, ibid., 92, 4883 (1970).

11. J. S. Haywood-Farmer and R. E. Pincock, ibid., 91, 3020 (1970).

12. J. W. Powell and M. C. Whiting, Tetrahedron, 7, 305 (1959).

13. P. Clarke, M. C. Whiting, G. Papenmeier, and W. Reusch, J. Org. Chem., 27, 3356 (1962).

14. R. H. Shapiro, Tetrahedron Lett., 3401 (1966).

15. R. H. Shapiro, J. H. Duncan, and J. C. Clopton, J. Amer. Chem. Soc., 89, 471 (1967); 89, 1442 (1967).

16. A. Nickon and N. H. Werstiuk, ibid., 88, 4543 (1966); 94, 7081 (1972).

17. J. H. Bayless, L. Friedman, F. B. Cook, and H. Shechter, ibid., 90, 531 (1968).

18. L. Friedman and H. Shechter, ibid., 81, 5512 (1959); 83, 3159 (1961).

19. C. H. DePuy and D. H. Froemsdorf, ibid., 82, 634 (1960).

20. J. A. Smith, H. Shechter, J. Bayless, and L. Friedman, ibid., 87, 659 (1965); F. Cook, H. Shechter, J. Bayless, L. Friedman, R. L. Foltz, and R. Randall, ibid., 88, 3870 (1960).

21. K. B. Wiberg and J. M. Lavanish, ibid., 88, 5272 (1966).

22. M. Reusch, M. W. DiCarlo, and L. Traynor, J. Org. Chem., 26, 1711 (1961).

23. W. Kirmse, "Carbene Chemistry," 2nd Ed., Academic Press, New York and London, 1971, pp. 1, 29-34.

24. T. D. Ziebarth and P. K. Freeman, unpublished results.

25. P. K. Freeman, R. S. Raghavan, and D. G. Kuper, J. Amer. Chem. Soc., 93, 5288 (1971).

26. H. M. Frey and M. A. Voisey, Trans. Faraday Soc., 64, 954 (1968).

27. W. Kirmse and W. von E. Doering, Tetrahedron, 11, 266 (1960); P. S. Skell and A. P. Krapcho, J. Amer. Chem. Soc., 83, 754 (1961); W. Kirmse, Angew. Chem Int. Ed. Engl., 4, 1 (1965).

28. H. G. Richey, Jr. and E. A. Hill, J. Org. Chem., 29, 421 (1964); W. Kirmse and G. Wächterhäuser, Tetrahedron, 22, 63 (1966); H. Babad, W. Flemon, and J. B. Wood, J. Org. Chem., 32, 2871 (1967); M. Rey, R. Begrich, W. Kirmse, and A. S. Dreiding, Helv. Chim. Acta., 51, 1001 (1968).

29. Ref. 23, Ch. 5.

30. P. K. Freeman, D. E. George, and V. N. M. Rao, J. Org. Chem., 29, 1682 (1964).

31. G. A. Olah, A. Commeyras, and C. Y. Lui, J. Amer. Chem. Soc., 90, 3882 (1968).

32. P. K. Freeman, D. M. Balls, and D. J. Brown, J. Org. Chem., 33, 2211 (1968).

33. P. G. Gassman and T. J. Atkins, J. Amer. Chem. Soc., 92, 5810 (1970).

34. Ref. 23, p. 247.

35. P. K. Freeman and K. B. Desai, J. Org. Chem., 36, 1554 (1971).

36. W. Kirmse and D. Grossman, Chem. Ber., 99, 1746 (1966).

37. R. B. Woodward and R. Hoffmann, Angew. Chem. Int. Ed. Engl., 8, 781 (1969).

38. W. Eberbach and H. Prinzbach, Helv. Chim. Acta, 50, 2490 (1967); J. Meinwald and B. E. Kaplan, J. Amer. Chem. Soc., 89, 2611 (1967).

39. A. C. Cope, H. H. Lee, and H. E. Petree, ibid., 80, 2849 (1958); A. C. Cope, G. A. Berchtold, P. E. Peterson, and S. H. Sharman, ibid., 82, 6370 (1960).

40. J. K. Crandall and L. H. Chang, J. Org. Chem., 32, 532 (1967).

41. J. K. Crandall and L. H. Chang, ibid., 32, 435 (1967).

42. C. H. DePuy and R. W. King, Chem. Rev., 60, 431 (1960).

43. R. Srinivasan, J. Amer. Chem. Soc., 85, 3048 (1963).

44. N. J. Turro, D. M. Pond, D. R. Morton, and J. C. Dalton in "Annual Survey of Photochemistry," vol. 3, Wiley and Sons, New York, London, Sidney, and Toronto, 1971, pp. 67-70.

45. J. H. Van de Hende and W. C. Baird, J. Amer. Chem. Soc., 85, 1009 (1963).

46. K. B. Wiberg and D. S. Connor, ibid., 88, 4437 (1966).

47. H. M. Frey and R. C. Smith, Trans. Faraday Soc., 58, 697 (1962).

48. W. von E. Doering and W. R. Roth, Tetrahedron, 19, 715 (1963).

49. C. Steel, R. Zand, P. Hurwitz and S. G. Cohen, J. Amer. Chem. Soc., 86, 679 (1964).

50. P. K. Freeman, R. B. Kinnel, and T. D. Ziebarth, Tetrahedron Lett., 1059 (1970).

51. R. T. LaLonde, J. Org. Chem., 27, 2275 (1962); R. T. LaLonde and M. A. Tobias, J. Amer. Chem. Soc., 85, 3767 (1963); R. T. LaLonde and J. J. Batelka, Tetrahedron Lett., 445 (1964); R. T. LaLonde, J. Ding, and M. A. Tobias, J. Amer. Chem. Soc., 89, 6651 (1967); R. T. LaLonde and A. D. Debboli, Jr., J. Org. Chem., 35, 2657 (1970); A. Nickon and J. H. Hammons, J. Amer. Chem. Soc., 86, 3322 (1964); A. Nickon, H. Kwasnick, T. Swartz, R. O. Williams and J. B. DiGiorgio, ibid., 87, 1615 (1965); J. H. Hammons, E. K. Probasco, L. A. Saunders, and E. J. Whalen, J. Org. Chem., 33, 4493 (1968).

52. R. T. LaLonde and L. S. Forney, J. Amer. Chem. Soc., 85, 2767 (1963).

53. G. Büchi, M. S. van Wittenau, and D. M. White, ibid., 81, 1968 (1959); R. T. LaLonde and M. A. Tobias, ibid., 85, 3771 (1963).

54. S. J. Cristol, W. Y. Linn, and A. R. Dahl, ibid., 92, 4013 (1970); S. J. Cristol, J. K. Harrington, J. C. Morrill, and B. E. Greenwald, J. Org. Chem., 36, 2773 (1971).

55. C. Walling and P. S. Fredericks, J. Amer. Chem. Soc., 84, 3326 (1962).

56. J. A. Pople, W. G. Schneider and H. J. Bernstein, "High-resolution Nuclear Magnetic Resonance," McGraw-Hill, Inc., New York, Toronto, and London, 1959, pp. 176-180; H. Spiesecke and W. G. Schneider, J. Chem. Phys., 35, 722 (1961).

57. A. A. Bothner-By and J. A. Pople, Ann. Rev. Phys. Chem., 16, 43 (1965).

58. H. G. Kuivila, Accounts Chem. Res., 1, 299 (1968).

59. A. A. Zavitsas and J. D. Blanch, J. Amer. Chem. Soc., 94, 4603 (1972).

60. J. W. Wilt, S. N. Massie, and R. B. Dabek, J. Org. Chem., 35, 2803 (1970).

61. J. H. Noggle and R. E. Schirmer, "The Nuclear Overhauser

Effect; Chemical Applications," Academic Press, New York, 1971, p. 1.

62. R. A. Bell and J. K. Saunders, Can. J. Chem., 48, 1114 (1970).

63. M. L. Poutsma, J. Amer. Chem. Soc., 87, 4293 (1965).

64. C. Walling and M. F. Mayahi, ibid., 81, 1485 (1959).

65. E. C. Kooyman and G. C. Vegta, Tetrahedron, 4, 382 (1958).

66. V. R. Koch and G. J. Gleicher, J. Amer. Chem. Soc., 93, 1657 (1971).

67. R. Srinivasan and F. I. Sonntag, ibid., 89, 407 (1967).

68. R. Kh. Freidlina, in "Advances in Free Radical Chemistry," vol. I, Logos Press, London, 1965, Ch. 6.

69. R. Eastman, J. Amer. Chem. Soc., 79, 4243 (1957).

70. H. M. Teeter and E. W. Bell, Org. Syn. Coll. Vol. IV, 125 (1963).

71. H. G. Kuivila and O. F. Beumel, Jr., J. Amer. Chem. Soc., 83, 1246 (1961).

72. N. Heap and G. H. Whitham, J. Chem. Soc. (B), 164 (1966); M. Korach, D. R. Nielsen, and W. H. Rideoat, Org. Syn., 42, 50 (1962).

73. A. T. Young and R. D. Guthrie, J. Org. Chem., 35, 853 (1970).

74. B. R. Vogt, S. R. Suter, and J. R. E. Hoover, Tetrahedron Lett., 1609 (1968).

75. W. T. Borden, V. V. M. Cabell, and R. Ravindranathan, J. Amer. Chem. Soc., 93, 3800 (1971).

76. R. R. Sauers and K. W. Kelly, J. Org. Chem., 35, 3286 (1970).

77. R. R. Sauers and D. H. Ahlstrom, ibid., 32, 2233 (1967); K. B. Wiberg and B. R. Lowry, J. Amer. Chem.Soc., 85, 3188 (1963).

78. A. Nickon, J. L. Lambert, S. J., R. O. Williams, and N. H. Werstiuk, ibid., 88, 3354

79. E. K. Plyler and N. Acquista, J. Research Nat'l. Bur. Standards, 43, 37 (1949).

80. J. D. Roberts and V. C. Chambers, J. Amer. Chem. Soc., 73, 5030 (1951); H. W. Thompson and W. T. Cave, Trans. Faraday Soc., 47, 946, 951 (1951).

81. S. E. Wiberley, S. C. Bunce, and W. H. Bauer, Anal. Chem., 32, 217 (1960).

82. C. A. Coulson, "Valence," Oxford, Clarendon Press, London, 1952, p. 200; M. Davies, "Infra-Red Spectroscopy and Molecular Structure," Elsevier Publishing Co., Amsterdam, London, New York, 1963, p. 244.

83. D. Kivelson, S. Winstein, P. Bruck, and R. L. Hansen, J. Amer. Chem Soc., 83, 2938 (1961).

84. C. N. R. Rao, "Chemical Applications of Infrared Spectroscopy," Academic Press, New York and London, 1963, p. 132.

85. N. Muller and D. E. Pritchard, J. Chem. Phys., 31, 768, 1471 (1959); J. N. Shoolery, ibid., 31, 1427 (1959); N. Muller, ibid., 36, 359 (1962); C. Juan and H. S. Gutowsky, ibid., 37,2198 (1962).

86. C. S. Foote, Tetrahedon Lett., 579 (1963).

87. K. Mislow, ibid., 1415 (1964).

88. C. A. Coulson, "Valence," Oxford, Clarendon Press, 1952, pp. 204-6.

89. P. v. R. Schleyer, J. E. Williams, and K. R. Blanchard, J. Amer. Chem. Soc., 92, 2377 (1970).

90. N. L. Allinger, M. T. Tribble, M. A. Miller, and D. H. Wertz, ibid., 93, 1637 (1971).

91. E. F. Mooney and P. H. Winson, "Annual Review of NMR Spectroscopy," vol. 2, ed. E. F. Mooney, Academic Press, New York and London, 1969, pp. 187-9.

92. H. W. Whitlock, J. Amer. Chem. Soc., 84, 3412 (1962).

93. R. Srinivasan, ibid., 83, 2590 (1961).

94. P. E. Eaton and T. W. Cole, Jr., ibid., 86, 962 (1964).

95. H. Conroy, "Advances in Organic Chemistry," eds. R. A. Raphael, E. C. Taylor, and H. Wynberg, vol. II, Interscience Publishers, Inc., New York, 1960, p. 288-9.

96. K. Tori, R. Munevuki, and H. Tanida, Can. J. Chem., 41, 3146 (1963).

97. R. C. Fort, Jr. and P. v. R. Schleyer, J. Org. Chem., 30, 789 (1965).

98. J. W. Emsley, "High Resolution Nuclear Magnetic Resonance Spectroscopy," Pergamon Press, New York, 1966, p. 1020.

99. R. R. Sauers and B. R. Sickles, Tetrahedron Lett., 1067 (1970).

100. J. O. Halford, J. Chem. Phys., 24, 830 (1956); R. Zbinden and H. K. Hall, J. Amer. Chem. Soc., 82, 1215 (1960).

101. J. F. Chiang, C. F. Wilcox, Jr., and S. H. Bauer, ibid., 90, 3149 (1968).

102. R. J. Ellis and H. M. Frey, J. Chem. Soc., 4184 (1964).

103. S. W. Benson, J. Chem. Ed., 42, 502 (1965).

104. R. Srinivasan and A. A. Levi, J. Amer. Chem. Soc., 86, 3756 (1964).

105. L. A. Paquette, Accounts Chem. Res., 4, 280 (1971).

106. H. Hogeveen and H. C. Volger, Chem. Commun., 1133 (1967); L. Cassar, P. E. Eaton, and J. Halpern, J. Amer. Chem. Soc., 92, 3515 (1970).

107. W. A. Pryor, "Free Radicals," McGraw-Hill, New York, 1966, pp. 1, 122.

108. J. W. Linnett and A. J. Poe, Trans. Faraday Soc., 47, 1033 (1951); A. D. Walsh, J. Chem. Soc., 2296 (1953).

109. E. L. Eliel, "Stereochemistry of Carbon Compounds," McGraw-Hill, New York, 1963, Ch. 13.

110. C. Walling and J. A. McGuinness, J. Amer. Chem. Soc., 91, 2053 (1969).

111. C. Walling and B. B. Jacknow, ibid., 82, 6108 (1960).

112. G. A. Russell, ibid., 80, 4987 (1958).

113. C. Walling and W. Thaler, ibid., 83, 3877 (1961).

114. G. A. Russell, ibid., 80, 4997 (1958).

115. R. F. Bridger and G. A. Russell, ibid., 85, 3754 (1963).

116. E. S. Huyser, "Free-Radical Chain Reactions," Wiley-Interscience, New York, London, Sidney, and Toronto, 1970, pp. 77-85; C. Walling, "Free Radicals in Solution," Wiley and Sons, New York and London, 1957, p. 365; Ref. 122, p. 171.

117. G. A. Russell and R. C. Williamson, J. Amer. Chem. Soc., 86, 2357 (1964); C. Walling and B. Miller, ibid., 79, 4181 (1957).

118. A. A. Zavitsas and J. A. Pinto, ibid., 94, 7390 (1972).

119. W. C. Danen, T. J. Tipton, and D. G. Saunders, ibid., 93, 5186 (1971).

120. A. A. Zavitsas, ibid., 94, 2779 (1972).

121. W. G. Young, S. Winstein, and H. L. Goering, ibid., 73, 1958 (1951).

122. J. D. Roberts, W. Bennett, and R. Armstrong, ibid., 72, 3329 (1950).

123. S. Winstein, M. Shatavsky, C. Norton, and R. B. Woodward, ibid., 77, 4183 (1955); P. v. R. Schleyer, M. M. Donaldson, W. E. Watts, ibid., 87, 375 (1965).

124. E. S. Huyser, "Free-Radical Chain Reactions," Wiley-Interscience, New York, London, Sidney, and Toronto, 1970, p. 235-6.

125. D. E. George, Ph.D. Dissertation, University of Idaho, 1962.

126. R. L. Bixler and C. Niemann, J. Org. Chem., 23, 742 (1958).

127. P. D. Bartlett, G. N. Fickes, F. C. Haupt, and R. Helgeson, Accounts Chem. Res., 3, 177 (1970).

128. J. D. Roberts, J. Amer. Chem. Soc., 76, 5692 (1954).

129. E. S. Huyser, ibid., 82, 394 (1960).

130. R. S. Raghavan, Ph.D. Dissertation, Oregon State University, 1972.

131. P. K. Freeman, R. S. Raghavan, and G. L. Fenwick, J. Amer. Chem. Soc., 94, 5101 (1972).

132. A. J. Fry and W. B. Farnham, J. Org. Chem., 34, 2314 (1969).

133. T. F. Corbin, R. C. Hahn, and H. Shechter, Org. Syn., 44, 30 (1964).

134. G. L. Fenwick, Ph.D. Dissertation, University of Idaho, 1969.

135. D. G. Kuper, Ph.D. Dissertation, University of Idaho, 1965.

136. T. J. Katz, J. C. Carnahan, Jr., and R. Boecke, J. Org. Chem., 32, 1301 (1967).

137. P. K. Freeman and D. M. Balls, ibid., 32, 2354 (1967).

138. H. C. Volger, H. Hogeveen, and M. M. P. Gaasbeek, J. Amer. Chem. Soc., 91, 218, 2137 (1969).

139. H. E. Simmons and R. D. Smith, ibid., 81, 4256 (1959); S. D. Koch, R. M. Kliss, D. V. Lopiekas, and R. J. Wineman, J. Org. Chem., 26, 3122 (1961).

140. D. M. Balls, Ph.D. Dissertation, University of Idaho, 1968.

141. C. F. Huebner, E. Donoghue, L. Dorfman, E. Wenkert, W. E. Streth, and S. W. Donelly, Chem. Commun., 419 (1966).

142. L. M. Jackman and S. Sternhell, "Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry," Pergamon Press, New York, 1969, p. 272.

143. A. Streitwieser, Jr., "Solvolytic Displacement Reactions," McGraw-Hill, New York, 1962, p. 24-5.

144. Ref. 124, p. 105.

145. P. v. R. Schleyer, J. Amer. Chem. Soc., 89, 699, 701 (1967).

146. N. L. Bauld, J. D. McDermed, C. E. Hudson, Y. S. Rim, J. Zoeller, Jr., R. D. Gordon, and J. S. Hyde, ibid., 91, 6666 (1969).

147. P. K. Freeman, D. M. Balls, and J. N. Blazevich, ibid., 92, 2051 (1970).

148. A. K. Colter and R. C. Musso, J. Org. Chem., 30, 2462 (1965).

149. A. Streitwieser, Jr., L. Verbit, and P. Stang, ibid., 29, 3706 (1964).

150. E. LeGoff, J. Org. Chem., 29, 2048 (1964).

151. W. J. Blaedel and V. W. Meloche, "Elementary Quantitative Analysis," Harper and Row, New York, 1963, p. 640.