

1995

# Isomerization and Chelation Studies of Dangling Phosphine Complexes of Group 6

Zhongjiang Jia

*Eastern Illinois University*

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Isomerization and Chelation Studies of  
Dangling Phosphine Complexes of Group 6  
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BY

Zhongjiang Jia

**THESIS**

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Dangling Phosphine Complexes of Group 6

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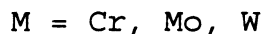
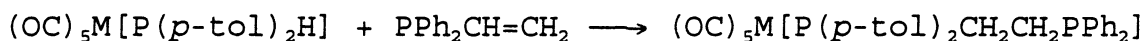
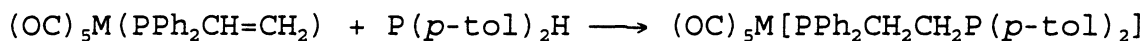


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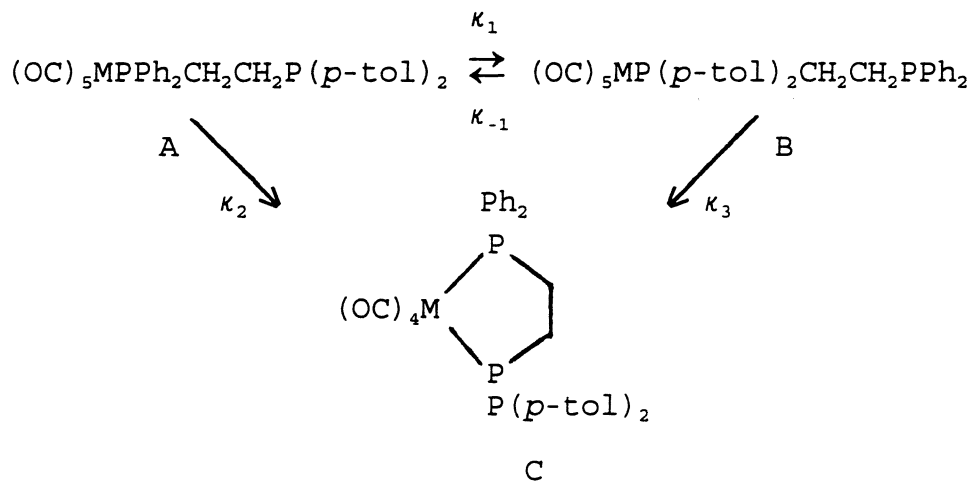
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# ABSTRACT

Vinyl addition reactions, catalyzed by 2,2'-azobis(isobutyronitrile) (AIBN), have been used to prepare six pentacarbonyl complexes of group 6, each of which contains a dangling  $\text{Ph}_2\text{PCH}_2\text{CH}_2\text{P}(p\text{-tol})_2$  ligand.



Each of the six complexes undergoes slow isomerization and chelation at 55 °C in perdeuterated toluene:



The reactions were monitored by  $^{31}\text{P}\{^1\text{H}\}$  NMR spectroscopy. The isomerization reactions are reversible in solution, while the chelated products form irreversibly with the loss of carbon monoxide. The rate constants,  $\kappa_1$  and  $\kappa_{-1}$ , have

been determined for the three pairs of linkage isomers. Equilibrium constants for the chromium and tungsten isomerization reactions were determined from the rate constants. The molybdenum isomerization reactions were sufficiently fast to allow the equilibrium constant to be determined directly. In addition, rate constants  $\kappa_2$  and  $\kappa_3$ , were determined for the chromium and molybdenum chelation reactions. The rate of chelation for the tungsten complexes was too slow to determine. Rate constants and equilibrium constants are shown below:

M	$\kappa_1$ $10^8 \text{ s}^{-1}$	$\kappa_{-1}$ $10^8 \text{ s}^{-1}$	$\kappa_2$ $10^8 \text{ s}^{-1}$	$\kappa_3$ $10^8 \text{ s}^{-1}$	$K_{\text{eq}}$
Cr	1.22	0.65	1.15	1.24	1.88
Mo	759	387	29.6	30.3	1.96
W	2.31	0.97	---	---	2.38

Rate constants for the isomerization and chelation of the chromium complexes are nearly the same, consistent with dissociative (D) mechanisms for each reaction. Rate constants for isomerization of the molybdenum and tungsten complexes are much larger than those for chelation, suggestive of an associative component in the former reaction. Even so, bond-breaking would appear to be more important than bond-making. Thus, the isomerization is best described as proceeding through an interchange dissociative mechanism ( $I_D$ ).

## Dedication

To my parents, my wife, and my son.

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## I. Introduction

Even though the first tertiary phosphine complexes were made in 1857 by Hofmann<sup>1</sup>, phosphine coordination chemistry did not begin to boom until the 1960s. Several reasons accounted for the development of this area:

(1) Phosphine complexes were found to play a major role in homogeneous catalysis and organic synthesis.

(2) Phosphines are soft ligands capable of stabilizing low oxidation state transition metal complexes.

(3) New bonding theories were developed to describe the metal-phosphine bond.

(4) Many new phosphine ligands and their complexes were synthesized.

(5) Sophisticated <sup>31</sup>P NMR techniques were developed that allowed easy characterization of new compounds.

Today, phosphines are among the most important ligands in organometallic chemistry.

### 1. Metal-Phosphine Bonding

Following bonding theory that had been proposed for metal carbonyl complexes,<sup>2</sup> Chatt<sup>3,4</sup> offered the first accepted scheme for the metal-phosphorus bond. He suggested that the lone pair of the phosphorus ligand is donated into an empty metal orbital to form a  $\sigma$  bond, while the filled metal d orbitals donate electron density to the empty phosphorus 3d orbitals ( $\pi$  back-bonding). For metal



carbonyls,  $\pi$  back-bonding is formed between the filled metal d orbitals and the empty antibonding orbitals ( $\pi^*$ ) of the carbonyl.

The metal-phosphine bonding theory was supported by several observations. First, no complex formation takes place when  $\text{PF}_3$  is mixed with  $\text{BF}_3$  or  $\text{AlCl}_3$ , Lewis acids that do not possess d electrons.<sup>3</sup> Two stable compounds,  $(\text{PF}_3)_2\text{PtCl}_2$  and  $(\text{PF}_3\text{PtCl}_2)_2$ , were obtained, however, with  $\text{PtCl}_2$ . Second,  $\text{PF}_3$ , but not  $\text{NF}_3$  which has no empty d orbitals of low energy, combines with hemoglobin in a way that is analogous to  $\text{CO}$ .<sup>5</sup> The  $\pi$  back-bonding mechanism also accounted for the *trans*-influence of phosphine ligands.

However, the nature of  $\pi$  back-bonding theory has been modified in recent times. It has been argued that the 3d orbitals on phosphorus are too high in energy and too diffuse to engage in directional bonding.<sup>6</sup> Ellis et al<sup>7</sup> examined the electronic structures of  $\text{PH}_3$ ,  $\text{P}(\text{CH}_3)_3$ , and  $\text{PF}_3$  with the aid of self-consistent multipolar  $X\alpha$  calculations and concluded that the  $\pi$ -acceptor orbital on phosphorus mostly consists of phosphorus 3p character which has the effect of directing the empty  $\pi$  orbital in the direction of the lone pair. For qualitative understanding, Marynick<sup>8</sup> demonstrated that d orbitals on phosphorus are not necessary for  $\pi$  back-bonding by using approximate and ab initio molecular orbital theory. Structural evidence that P-X bond lengths increase with decreasing M-P distances supported a

new proposal that the phosphorus 3d and P-X  $\sigma^*$  orbitals hybridize to form the  $\pi$ -acceptor orbitals.<sup>9</sup> However, Ernst et al<sup>10</sup> observed that the Ti-P(OEt)<sub>3</sub> bond length (2.472 Å) is significantly shorter than the Ti-PMe<sub>3</sub> bond length (2.550 Å), while the bond strengths follow the opposite order, a result which can not be explained by the  $\pi$ -bonding mechanism alone. Therefore, a possible explanation for the observed trend in M-P bond lengths (M-PF<sub>3</sub> < M-P(OR)<sub>3</sub> < M-PR<sub>3</sub>) seems to be that increasing electronegativity of the phosphine substituents causes contraction of the phosphorus lone pair orbital.<sup>10</sup> This explanation allows bond shortening without involving additional bonding interactions.

## 2. Electronic Effects of Phosphine Ligands

It was of great interest to determine how the electron donor-acceptor properties of phosphine ligands would change with different substituents on phosphorus. Infrared spectroscopy of phosphine substituted metal carbonyls has enabled the study of electronic effects based on the carbonyl frequencies and force constants. The donor strengths of various ligands have been compared.<sup>11-15</sup> Tolman<sup>16</sup> has proposed a substituent additivity rule based on the A<sub>1</sub> carbonyl stretching frequency of Ni(CO)<sub>3</sub>L.

The C-O stretching frequency shifts in substituted metal carbonyl complexes were interpreted in terms of the  $\pi$ -bonding ability of L.<sup>15</sup> <sup>31</sup>P NMR studies of <sup>183</sup>W-<sup>31</sup>P coupling

constants in  $R_3PW(CO)_5$  complexes also have been interpreted in terms of the W-P  $\pi$  bonding.<sup>17</sup> However, Angelici suggested that  $\sigma$  bonding, not  $\pi$  bonding, is largely responsible for the strength of the W-L bond based on the results of infrared studies<sup>11</sup> and equilibrium studies<sup>18</sup>.

It is clear that the more electron-withdrawing substituents give higher CO stretching frequencies, while the better  $\sigma$  donor phosphine ligands will lead to a greater  $W(d\pi) \rightarrow CO(\pi^*)$  back-donation and lower CO stretching frequencies. However, it is very difficult to say to what extent the  $\pi$ - or  $\sigma$ -bonding properties of phosphine ligands are responsible for the C-O frequency shift.

Some researchers have attempted to separate  $\sigma$  and  $\pi$  effects indirectly by using the different CO stretching force constants for carbonyls cis and trans to L in  $LM(CO)_5$ <sup>19</sup> or directly by using photoelectron spectroscopy (PES)<sup>20,21</sup>. The  $\sigma$  donor ability of phosphine ligands can be quantitatively measured in terms of the basicity of the phosphine as the equilibrium constant in the reaction of  $H^+$  with  $PR_3$ , which is determined by  $\sigma$  bonding not  $\pi$  bonding. The  $pK_a$  values of a number of phosphine ligands have been determined by titration.<sup>22-24</sup> However, the employment of  $pK_a$  values as a measure of  $\sigma$ -donor ability faces two problems. First,  $pK_a$  values are dependent upon the interactions between the phosphorus and the hard acid,  $H^+$ , rather than a soft acid such as a low-valent metal center.<sup>25</sup> Second,  $pK_a$

values are sensitive to solvation energies of the phosphine ligands.<sup>26</sup> In addition, the  $pK_a$  values were challenged by the results from the gas-phase photoelectron spectroscopy (PES).<sup>26</sup> In the gas phase, the order of the electron donor ability is:  $PPh_3 > PPh_2Me > PPhMe_2 > PMe_3$ , while the order of basicity is reversed in solution. The lower basicity of  $PPh_3$  was rationalized in terms of the lower solvation energy of the bulkier ion  $[PPh_3H]^+$  compared to  $[PMe_3H]^+$  and is therefore due primarily to steric rather than electronic effects.<sup>26</sup> It has also been observed that the binding strength of the  $PX_3$  ligands to the titanium centers correlated well with the steric effects of the  $PX_3$  groups.<sup>10</sup> Considering  $\sigma$ ,  $\pi$ , and steric properties of phosphine ligands, Giering et al<sup>25,27,28</sup> developed an analytical method—the quantitative analysis of ligand effects (QALE). They separated the phosphine ligands into two classes, pure  $\sigma$ -donor ligands and  $\sigma$ -donor/ $\pi$  acceptor ligands, and concluded that  $pK_a$  values are still reasonable measures of the  $\sigma$ -donor ability for those ligands that are pure  $\sigma$ -donor ligands.

### 3. Steric Effects of Phosphine Ligands

As mentioned above,<sup>26</sup> some experimental results can not be explained by electronic effects alone. The steric effects must be taken into account. However, not much attention was devoted to steric effects until the 1970s.<sup>29,30</sup> By conducting ligand-competition experiments, Tolman ranked

24 ligands to give a stability series which did not correlate with the electronic properties of the phosphine ligands. Thereafter, Tolman used atomic models to define a quantitative steric effect parameter—the ligand cone angle,  $\theta$ , which did correlate well with the stability data. The ligand cone angle was measured by the apex angle of a cone centered on the metal. Since the introduction of the cone angle, it has been shown that many chemical and spectroscopic properties of organometallic complexes correlate with ligand cone angles.<sup>30</sup> However, there are some limitations in the measurement of the cone angles. First, even symmetric ligands do not have cylindrical symmetry. The ligands are not rigid, and can mesh into one another. Second, the measurement of the cone angles is based on a 2.28 Å M-P bond length and on tetrahedral angles about phosphorus both of which vary in real molecules.<sup>10</sup> Other definitions and arguments about the ligand cone angle have been presented but will not be discussed here.<sup>31,32</sup>

#### 4. Mechanism of Chelation and Substitution

Conventionally there are two extreme mechanisms, dissociative and associative (corresponding to  $S_N1$  and  $S_N2$  reactions), for chelation and ligand substitution. A number of investigations<sup>33</sup> have shown that the reaction of  $M(CO)_6$  with monodentate ligands involves a rate-determining dissociative step and the enthalpy of the activation has

been found to correlate with the mean M-CO bond energy. For the reactions of  $\text{NiL}_4$  with  $\text{L}'$  and of  $\text{Ni}(\text{CO})_4$  with  $\text{L}$ , Tolman<sup>29</sup> suggested that the mechanism is probably a dissociative process involving three-coordinate intermediates. The purported reason for a dissociative process is that a five-coordinate intermediate would require nickel to exceed an 18-electron inert gas configuration and be more crowded with too many ligands.<sup>29</sup> The mechanism of the chelation process was also shown to be primarily dissociative.<sup>34,35</sup> The existence of the five-coordinate ion  $\text{LM}(\text{CO})_4^+$  ( $\text{M}=\text{Cr}, \text{Mo}, \text{W}$ ) in mass spectra<sup>35</sup> and the synthesis<sup>36</sup> of a five-coordinate complex  $(\text{OC})\text{Mo}(\text{Ph}_2\text{PCH}_2\text{CH}_2\text{PPh}_2)_2$  seem to support the  $\text{S}_{\text{N}}1$  process in six-coordinate group 6 metal complexes.

In summary, there are some trends<sup>34-36</sup> for the chelation of  $\text{R}_2\text{P}(\text{CH}_2)_n\text{PR}_2\text{M}(\text{CO})_5$  ( $\text{M}=\text{Cr}, \text{Mo}, \text{W}$ ;  $n=1-3$ ).

(1) The rate of chelation decreases as the chain length increases.

(2) Bulky phosphorus substituents,  $\text{R}$ , favor chelation.

(3) The rate of chelation decreases in the order  
 $\text{Mo} > \text{Cr} > \text{W}$ .

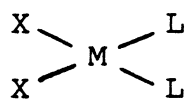
(4) The principal enthalpy requirement for activation is M-CO bond stretching, although the ring strain in the complex formed contributes.

(5) The principal entropy contribution to activation appears to come from the entropy change associated with the free end of the phosphine ligand, although steric effects

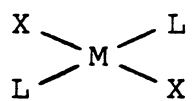
also contribute.

## 5. Isomerization

Isomerization in phosphine complexes is an old topic. The most familiar example is the *cis-trans* isomerism in  $\text{MX}_2\text{L}_2$  complexes of Pd and Pt.<sup>37</sup>

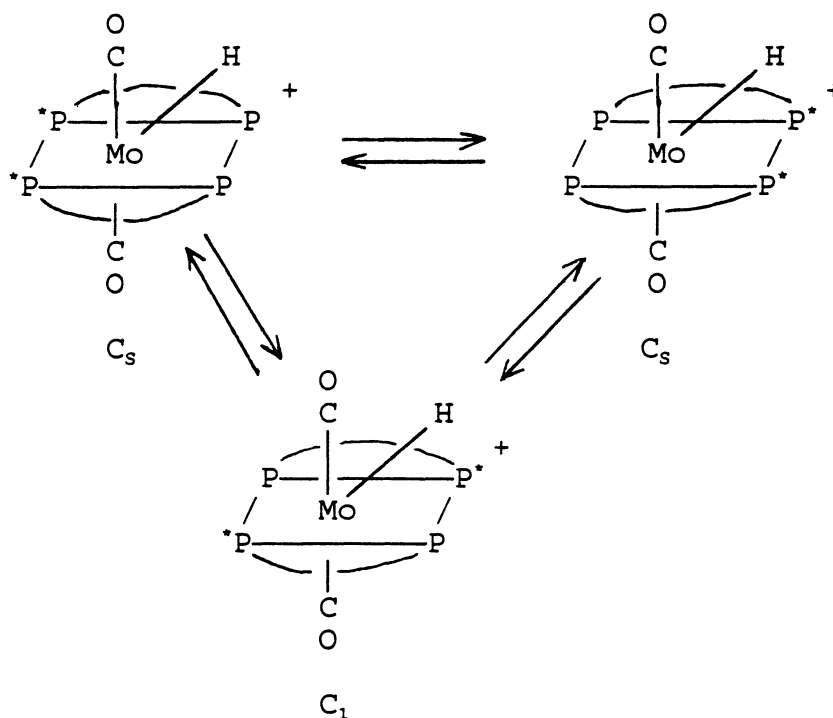


*cis-*



*trans-*

Some geometrical isomers can also be formed by the chelation of two unsymmetrical diphosphine ligands.<sup>38-40</sup> The isomerization can be easily followed by  $^1\text{H}$  NMR or  $^{31}\text{P}\{^1\text{H}\}$  NMR.



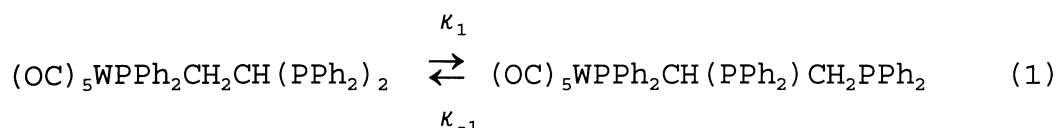
(Taken from reference 40)

However, only a few examples of linkage isomerism involving non-ring systems have been studied. Verkade et al<sup>41</sup> have synthesized both linkage isomers,  $\text{Fe}(\text{CO})_4\text{P}(\text{OCH}_2)_3\text{P}$  and  $\text{Fe}(\text{CO})_4\text{P}(\text{CH}_2\text{O})_3\text{P}$ , by irradiation of  $\text{Fe}(\text{CO})_5$  with the bicyclic phosphorus ligand  $\text{P}(\text{OCH}_2)_3\text{P}$ . In this instance chelation is not possible because of the rigid geometry of the ligand. Only one isomer, with the smaller  $\text{PO}_3$  end coordinated, was obtained from the reaction of  $\text{P}(\text{OCH}_2)_3\text{P}$  with  $(\text{C}_6\text{H}_5\text{NH}_2)\text{W}(\text{CO})_5$  [or with  $\text{Cr}(\text{CO})_6$  or  $\text{Mo}(\text{CO})_6$  under uv radiation].<sup>42</sup> Grim et al<sup>43</sup> have observed linkage isomers of the type  $(\text{OC})_5\text{WP}-\text{P}'$  and  $(\text{OC})_5\text{WP}'-\text{P}$  from the reaction of  $\text{Ph}_2\text{PCH}_2\text{CH}_2\text{PMePh}$  or  $\text{Ph}_2\text{PCH}_2\text{CH}_2\text{PPh}(i\text{-Pr})$  with  $(\text{C}_6\text{H}_5\text{NH}_2)\text{W}(\text{CO})_5$ , but no evidence was reported for them existing in equilibrium. In addition, the isomers were not separated. In general, the favored order of stability for phosphorus group coordination is  $\text{R}_2\text{P} > \text{RPhP} > \text{Ph}_2\text{P}$  ( $\text{R} = \text{alkyl}$ ), which is both the steric order and the order of ligand basicity. Groups such as  $i\text{-Pr}$  that have large steric requirement can lead to a reversal:  $\text{Ph}_2\text{P} > \text{Ph}(i\text{-Pr})\text{P}$ .

More recently, Keiter et al<sup>44</sup> have reported the isomerization of  $(\text{OC})_5\text{WPPH}_2\text{CH}_2\text{CH}(\text{PPh}_2)_2$ , which was believed to be the first experimental evidence for exchange of the terminal and coordinated phosphorus groups in pentacarbonyl complexes of group 6 metals. The  $-\text{PPh}_2$  groups on the end of  $-\text{CH}(\text{PPh}_2)_2$  are more favorable for coordination than the  $-\text{PPh}_2$  group on the other end, in a ratio of 5:1 at 25 °C. The



mechanism of the isomerization was suggested to be a 1,4-metal-phosphorus shift involving a pseudo-seven-coordinate transition state because a five-coordinate intermediate could not be trapped with  $\text{PPh}_3$ . The latest work<sup>45</sup> on the kinetics and equilibrium of this isomerization reaction has shown that



$\Delta H = -13.6$  kJ/mol,  $\Delta S = -32.5$  J/mol·K;  $\kappa_1 = 1.20 \times 10^{-6}$  sec<sup>-1</sup>,  $\kappa_{-1} = 1.92 \times 10^{-7}$  sec<sup>-1</sup> at 10 °C. The forward process is enthalpy driven, while the reverse process is entropy driven.

Isomerization reactions for Cr and Mo complexes are under investigation.<sup>45</sup>

Connor et al<sup>35</sup> found that dangling diphosphine complexes  $(\text{Me}_2\text{PCH}_2\text{CH}_2\text{PMe}_2)\text{M}(\text{CO})_5$  (M=Cr, Mo, W) do not undergo rapid intramolecular exchange between the two phosphorus groups. So far, no work has been done on the isomerization of dangling diphosphine pentacarbonyl complexes of group 6 metals.

## 6. Unsymmetrical Diphosphines

Diphosphine ligands can be classified roughly into two types: symmetrical  $\text{R}_2\text{P}(\text{CH}_2)_n\text{PR}_2$  and unsymmetrical  $\text{R}_2\text{P}(\text{CH}_2)_n\text{PR}'\text{R}''$ . By the nature and the length of the backbone connecting the two phosphorus groups, they can be further divided into four classes: (a) one-carbon backbones ( $n=1$ );

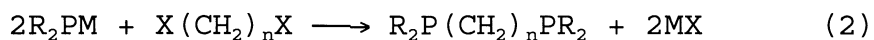
(b) two- and three-carbon backbones ( $n=2, 3$ ); (c) longer backbones ( $n \geq 4$ ); and (d) rigid backbones, such as  $R_2PC \equiv CPR_2$ , which prevent chelation.

The first diphosphine complexes contained  $Et_2PCH_2CH_2PEt_2$  and were synthesized by Wymore and Bailar in 1960.<sup>46</sup> After that, many diphosphine ligands and their complexes were prepared. Among them  $PPh_2CH_2CH_2PPh_2$  (dppe) is the most widely used chelating ligand. Because of its ability to form bridged binuclear complexes,  $PPh_2CH_2PPh_2$  (dppm) has also been widely investigated in catalysis studies.<sup>36</sup>

The electronic and steric properties of diphosphines can be modified systematically by changing the substituents on the phosphorus. Unsymmetrical diphosphines have been of interest for several reasons: (a) solubilities of the complexes<sup>38</sup> may be increased; (b) mechanistic studies are easier to monitor with  $^{31}P\{^1H\}$  NMR<sup>34,40</sup>; and (c) homogeneous catalysis and asymmetric synthesis can be studied.<sup>47</sup> In this thesis we will mainly focus on the synthesis of unsymmetrical diphosphine ligands and their complexes.

#### a. Synthesis of Unsymmetrical Ligands

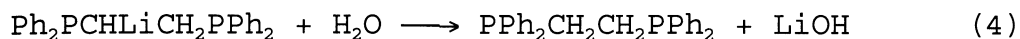
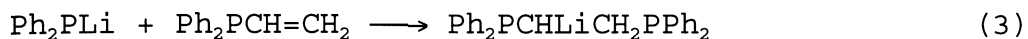
Most of the symmetrical diphosphines are synthesized by the reaction<sup>48</sup>:



(R= alkyl or aryl; M= alkali metal; X= halogen; and  $n= 1-5$ )

The metal organophosphides can be made by metallation of a secondary phosphine<sup>46</sup> or by cleavage of triphenylphosphine<sup>49</sup>.

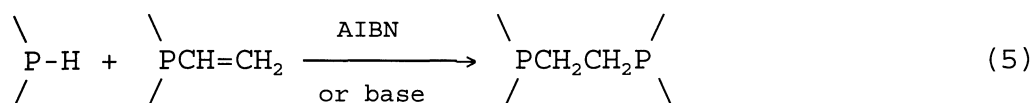
The synthesis of unsymmetrical diphosphines has proved to be more difficult. In 1967, Keiter<sup>50</sup> synthesized bis-(1,2-diphenylphosphino)ethane (dppe) with a new method:



This method was used to synthesize some new unsymmetrical diphosphine ligands by changing the metal organophosphide.<sup>51</sup> Grim et al<sup>43</sup> have employed a similar method to produce many unsymmetrical diphosphine ligands,  $\text{PPh}_2\text{CH}_2\text{CH}_2\text{PBu}_2$  and  $\text{PPh}_2\text{CH}_2\text{CH}_2\text{PRPh}$ , where R=methyl, ethyl, *n*-propyl, isopropyl, *sec*-butyl, isobutyl, and *n*-amyl. The complexes of group 6 metal carbonyls with these unsymmetrical diphosphine ligands have been synthesized and characterized by <sup>1</sup>H NMR, <sup>31</sup>P{<sup>1</sup>H} MNR, and IR.<sup>43,52</sup>

By a variation of Keiter's method, King et al<sup>53-55</sup> synthesized many novel polytertiary phosphine and arsine ligands by the direct addition of phosphorus-hydrogen and arsenic-hydrogen bonds across the carbon-carbon double bonds of vinylphosphines or the carbon-carbon triple bonds of ethynylphosphines in the presence of a base catalyst such as phenyllithium or potassium *tert*-butoxide. Some metal

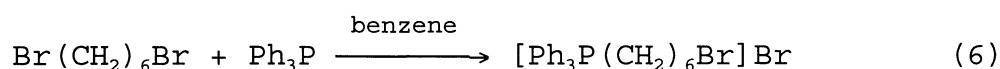
complexes of polytertiary phosphines have been synthesized and characterized by  $^{31}\text{P}\{^1\text{H}\}$  NMR.<sup>56</sup> Meek et al<sup>57,58</sup> found that the addition reaction is equally productive when a free-radical catalyst is used instead of the base catalyst. The free-radical catalyzed addition has the advantage of not requiring a solvent and can be carried out at modest temperature.

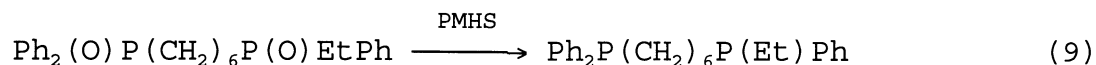
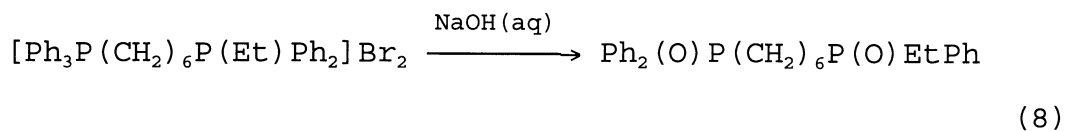
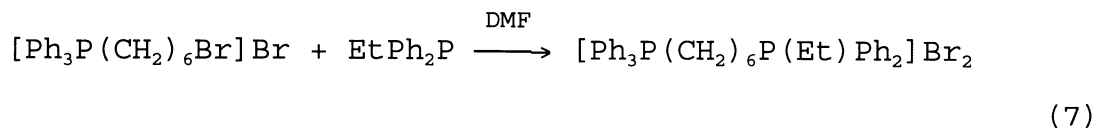


(AIBN = 2,2'-azobisisobutyronitrile)

Other methods have also been developed to synthesize the unsymmetrical diphosphine ligands. Grim et al<sup>59</sup> have synthesized the unsymmetrical diphosphines,  $\text{Ph}_2\text{P}(\text{CH}_2)_3\text{PR}^1\text{R}^2$ , by two routes: reaction of 3-chloropropyldiphenylphosphine with lithium diorganophosphides; or, reaction of the Grignard reagent,  $\text{Ph}_2\text{P}(\text{CH}_2)_3\text{MgCl}$ , with diorganochlorophosphines. This was the first example of the synthesis a Grignard reagent of a phosphinoalkyl compound.

McAuliffe et al<sup>47</sup> have prepared the ligand,  $\text{Ph}_2\text{P}(\text{CH}_2)_6\text{P}(\text{Et})\text{Ph}$ , by a novel synthetic route shown in eq 6-9.





DMF= dimethylformamide; PMHS= poly(methylhydrosiloxane)

The key step in the synthesis is the formation of the phosphonium salt with triphenylphosphine in a nonpolar solvent. This method allows the synthesis of novel diphosphines with long backbones, such as  $\text{Ph}_2\text{P}(\text{CH}_2)_n\text{PR}_2$ ,  $\text{Ph}_2\text{P}(\text{CH}_2)_n\text{P}(\text{R})\text{Ph}$ , and  $\text{Ph}(\text{R})\text{P}(\text{CH}_2)_n\text{P}(\text{R})\text{Ph}$  ( $\text{R}=\text{alkyl}$ ). Some of these have been ligands of interest in homogeneous catalysis and asymmetric synthesis.<sup>47</sup>

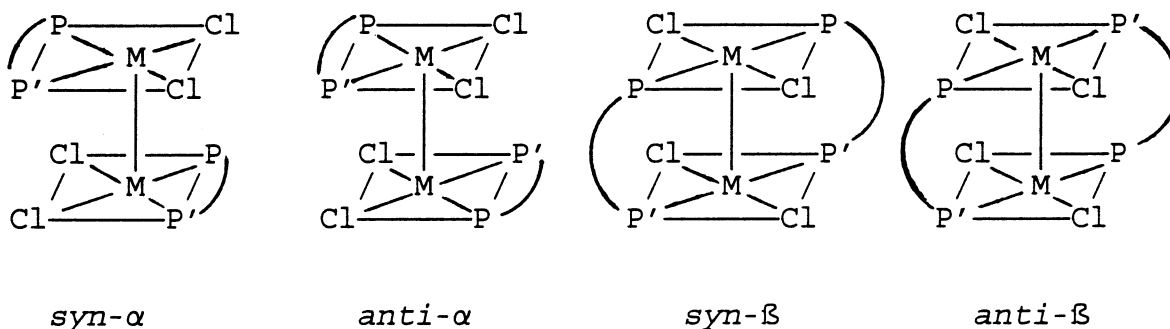
#### b. Ditolyl Derivatives

Because 1-(diphenylphosphino)-2-(di-*p*-tolylphosphino)-ethane,  $\text{Ph}_2\text{PCH}_2\text{CH}_2\text{P}(\text{p-CH}_3\text{C}_6\text{H}_4)_2$  (dpdt) was used in our work, a special survey of this ligand has been conducted.

In 1981, Kapoor et al<sup>60</sup> first synthesized the ligand dpdt by the reaction of diphenylvinylphosphine with di(*p*-toyl) phosphine in the presence of potassium *tert*-butoxide. A number of chelated complexes of the types  $(\text{OC})_4\text{M}(\text{dpdt})$  ( $\text{M}=\text{Cr}, \text{Mo}, \text{W}$ ) and  $\text{M}(\text{dpdt})\text{X}_2$  ( $\text{M}=\text{Ni}(\text{II}), \text{Pd}(\text{II}), \text{Pt}(\text{II})$ ;  $\text{X}=\text{Cl},$

Br, I, NCS) have been synthesized. However, no  $^{31}\text{P}\{^1\text{H}\}$  NMR data were reported.

The ligand dpdt has not been used frequently. The second case, which was also the last, is found in Cotton and Kilagawa's work.<sup>38</sup> Because of the insolubility of  $\alpha$ - and  $\beta$ - $\text{Mo}_2\text{X}_4(\text{dppe})_2$ , it is very difficult to investigate the isomerization of  $\alpha$ - to  $\beta$ - $\text{Mo}_2\text{X}_4(\text{dppe})_2$ . Therefore, dpdt was used to synthesize *anti*- and *syn*- $\alpha$ - $\text{Mo}_2\text{X}_2(\text{dpdt})_2$  which are very soluble in  $\text{CH}_2\text{Cl}_2$ . In addition to increasing the solubility, dpdt also creates more isomers: *syn*- $\alpha$ -, *anti*- $\alpha$ -, *syn*- $\beta$ -, and *anti*- $\beta$ -, instead of only  $\alpha$ - and  $\beta$ - isomers for dppe.



Other analogous ligands of dpdt have also been synthesized. 1-(diphenylphosphino)-2-(di-*m*-tolylphosphino)ethane,  $\text{Ph}_2\text{PCH}_2\text{CH}_2\text{P}(\textit{m}\text{-CH}_3\text{C}_6\text{H}_4)_2$  (pmt-pf), was first synthesized by King and Kapoor<sup>61</sup> in 1972 by a base catalyzed addition of di-*m*-tolylphosphine to diphenylvinylphosphine. Later on, Kapoor et al<sup>62</sup> synthesized the same kind of chelated complexes analogous to

those described on page 14 (see reference 60) using the ligand pmt-pf. Again, no  $^{31}\text{P}\{^1\text{H}\}$  NMR data were reported.

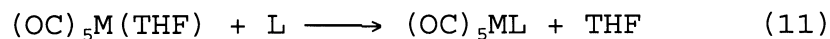
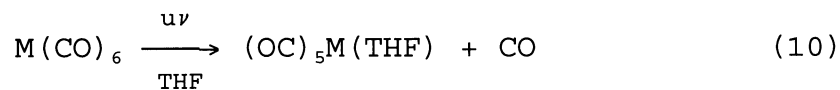
In addition three diphosphine ligands of the type  $\text{Ph}_2\text{PCH}_2\text{CH}_2\text{PR}_2$  ( $\text{R} = m\text{-FC}_6\text{H}_4, p\text{-FC}_6\text{H}_4, m\text{-CF}_3\text{C}_6\text{H}_4$ ) have been synthesized by Kapoor et al<sup>63</sup> using King's vinyl addition method<sup>52</sup>. These ligands improve the solubility characteristics of transition metal complexes and allow the use of  $^{19}\text{F}$  NMR in characterization of the complexes.

## 7. Synthesis of Dangling Diphosphine Complexes

Because diphosphine ligands can form chelated and bridged complexes readily, the synthesis of dangling diphosphine complexes becomes more difficult. Potential methods are summarized as follows:

### a. Strohmeier's Method ( Photolysis )

Starting materials can be prepared by the method of Strohmeier, first used in 1969.<sup>64</sup> By irradiation of group 6 metal hexacarbonyls in the presence of excess tetrahydrofuran (THF), a mono-substituted intermediate complex can be formed, in which the THF can be easily substituted by the phosphine ligand.



Keiter et al<sup>65,66</sup> have synthesized the complexes  $(OC)_5MPPh_2H$  and  $(OC)_5MPPh_2CH=CH_2$  ( $M=Cr$  and  $W$ ) by Strohmeier's method in very good yields. Strohmeier's method has not been used directly for the synthesis of the dangling diphosphine complexes.

b. Angelici's Method ( Aniline substitution )

Anilinepentacarbonyltungsten(0),  $PhNH_2W(CO)_5$  can be prepared by the irradiation of  $W(CO)_6$  and a three- to fivefold excess of aniline in tetrahydrofuran.<sup>11</sup> The method has not been shown to be useful for the synthesis of  $(PhNH_2)Cr(CO)_5$  or  $(PhNH_2)Mo(CO)_5$ .

The displacement of aniline from  $(PhNH_2)W(CO)_5$  by phosphine ligands occurs readily in a stirred solution of benzene or toluene at room temperature.<sup>18a</sup>



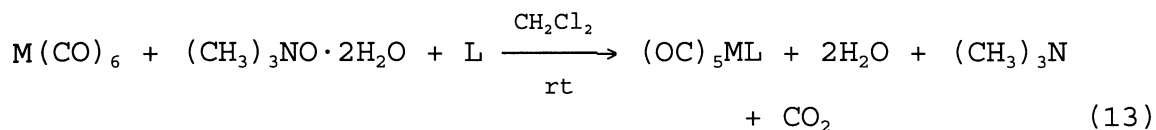
Keiter and Shah<sup>67</sup> prepared the complexes  $(OC)_5WPPh_2(CH_2)_nPPh_2$  ( $n=1,2$ ) by this method. The complex  $(OC)_5W(dppe)$  was prepared from a 3:1 mole ratio of  $dppe$  and  $(Ph_2NH_2)W(CO)_5$ , while a 1:1 mole ratio gives the dimetallic complex  $(OC)_5WPPh_2CH_2CH_2PPh_2W(CO)_5$  as the dominant product.

Grim et al have used the method with unsymmetrical diphosphines.<sup>43</sup> The dangling phosphine product is a mixture of two linkage isomers.<sup>43</sup> The ratio of the two isomers



depends on the electronic and steric differences of the two phosphorus groups.

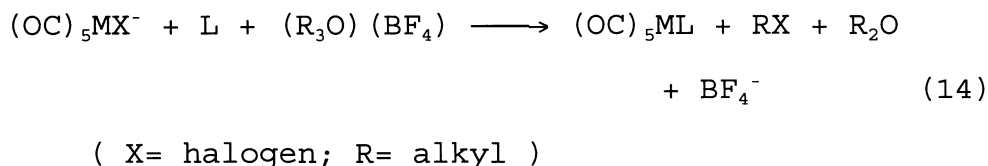
c. Oxidative Decarbonylation of  $M(CO)_6$



The carbonyl groups in  $M(CO)_6$  can be removed by oxidation with trimethylamine N-oxide  $[(CH_3)_3NO]$ .<sup>68</sup> For monodentate phosphine ligands, some di- and tri-substituted complexes may form in this reaction.

Hor et al<sup>69</sup> have prepared the complexes  $(OC)_5M[PPh_2(CH_2)_n PPh_2]$  ( $n=2, 3, 4$ ;  $M=Cr, Mo$ ) in low yields (13-42%) by adding  $(OC)_5M(CH_3CN)$  prepared in situ from  $M(CO)_6$  and  $(CH_3)_3NO$  in  $CH_3CN$  or a  $CH_3CN/THF$  mixture. The monobridged dimer is the major by-product. The use of a slight excess of the diphosphine improves the yield of the dangling diphosphine complexes.

d. Lewis Acid-Assisted Nucleophilic Substitution

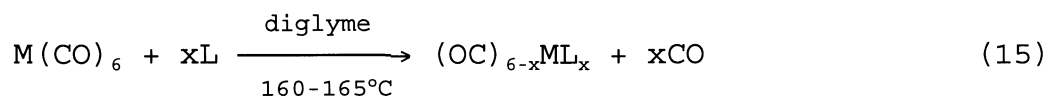


These reactions were carried out by adding a solution of

$[(\text{Et})_3\text{O}]\text{BF}_4$  in  $\text{CH}_2\text{Cl}_2$  to a stirred mixture of  $\text{Et}_4\text{N}[(\text{CO})_5\text{MI}]$  and diphosphine ligand dissolved in  $\text{CH}_2\text{Cl}_2$  in a mole ratio of 1:1:1.<sup>35</sup> This reaction occurs very rapidly at room temperature. The starting materials  $\text{Et}_4\text{N}[(\text{CO})_5\text{MI}]$  ( $\text{M}=\text{Cr}, \text{Mo}, \text{W}$ )<sup>70</sup> and  $(\text{R}_3\text{O})(\text{BF}_4)$  ( $\text{R}=\text{Me}^{71}$  or  $\text{Et}^{72}$ ) are established chemical reagents.

This method was originally designed to provide specific syntheses of complexes containing neutral monodentate ligands, such as  $\text{PH}_3\text{Cr}(\text{CO})_5$ .<sup>73</sup> Connor et al<sup>35</sup> extended this method to the synthesis of dangling diphosphine and phosphine/arsine complexes  $\text{LM}(\text{CO})_5$  [ $\text{M}=\text{Cr}, \text{Mo}, \text{W}$ ;  $\text{L}=\text{Me}_2\text{PCH}_2\text{CH}_2\text{PMe}_2$  (dmpe),  $\text{PPh}_2(\text{CH}_2)_n\text{PPh}_2$  ( $n=1-3$ ),  $\text{PPh}_2\text{CH}_2\text{CH}_2\text{AsPh}_2$  (ape)] and reported yields of >70%. In a 1977 paper from our research group it was shown that this method does not work well. For ape, the only product reported by Connor is the one in which the ligand is bonded through the phosphorus atom.

#### e. Thermal Reactions



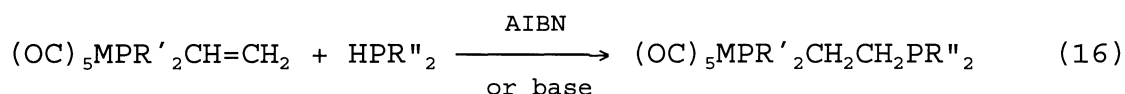
( $\text{L}=\text{phosphine}$ ; diglyme=bis-2-methoxyethyl ether)

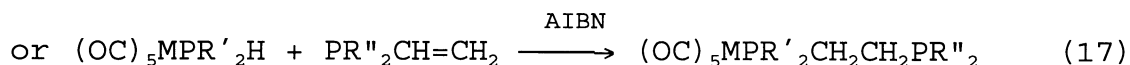
The reactions were carried out by refluxing a mixture of the starting materials in diglyme.<sup>74</sup> The value of  $x$  depends primarily on the product desired and, to a lesser extent, on

the nature of ligand and the reaction time.<sup>74</sup> A slight deficiency of ligand favors the formation of mono-substituted complexes. Other solvents can also be used, such as monoglyme,<sup>17</sup> *n*-hexane, *n*-heptane, and *n*-decane<sup>75</sup>. This method seems very useful for the synthesis of (OC)<sub>5</sub>MoPPh<sub>2</sub>CH=CH<sub>2</sub> (97%) and (OC)<sub>5</sub>MoPPh<sub>2</sub>H (73%)<sup>66</sup> which are the key starting materials in method (f). However, when diphosphine ligands were used, chelated complexes were the dominant products.<sup>43</sup>

#### f. Vinyl Addition Reaction (Keiter's Method)

All the methods mentioned above have limitations for synthesizing dangling diphosphine complexes. In particular, phosphine-bridged complexes tend to form if vacant coordination sites become available. In addition, reactions at higher temperatures tend to give chelated products. Further, these methods do not allow control of which end of an unsymmetrical diphosphine ligand becomes coordinated to the metal. This problem arises when one uses an already synthesized unsymmetrical diphosphine ligand. Keiter<sup>76</sup> has resolved this problem by reversing the procedure that was generally used before, i.e. one phosphorus group is coordinated before the other is connected to the carbon backbone.





The former reaction can be carried out under free-radical or base-catalyzed conditions. However, the latter reaction can only proceed under free-radical conditions. In the presence of base, the latter reaction will only give the chelated complex. The mechanism proposed to account for this observation involves the formation of the intermediate *cis*-(OC)<sub>4</sub>M(PR''<sub>2</sub>CH=CH<sub>2</sub>)(PR'<sub>2</sub><sup>-</sup>) followed by intramolecular cyclization.<sup>44,65</sup>

## 8. Purpose of This Work

Following the interesting discovery that (OC)<sub>5</sub>WPPh<sub>2</sub>CH<sub>2</sub>CH(PPh<sub>2</sub>)<sub>2</sub> undergoes isomerization readily at room temperature, the question arose as to how general such reactions are. In particular, we wanted to find out whether simpler systems such as (OC)<sub>5</sub>WPPh<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub> undergo equally rapid exchange. We have used variable temperature <sup>31</sup>P{<sup>1</sup>H} NMR experiments to look for evidence of exchange of bound and unbound phosphorus groups.

We have employed the unsymmetrical diphosphine, PPh<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>P(*p*-tol)<sub>2</sub> (dpdt), to make the two phosphorus ends nonequivalent. The ligand dpdt was used because P(*p*-tol)<sub>2</sub> and PPh<sub>2</sub> are different electronically, but are the same sterically (same cone angle). We have prepared six novel dangling phosphine complexes of the types

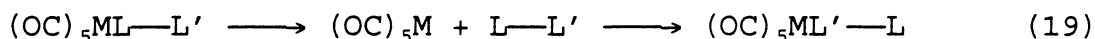
$(OC)_5MPPh_2CH_2CH_2P(p\text{-tol})_2$  and  $(OC)_5MP(p\text{-tol})_2CH_2CH_2PPh_2$  ( $M = Cr, Mo, W$ ). This allowed us to monitor the isomerization of each linkage isomer.



(  $M = Cr, Mo, W$  )

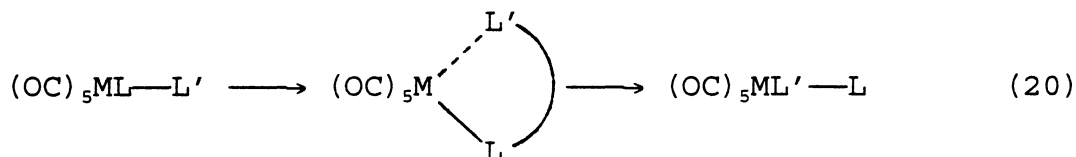
We have attempted to obtain equilibrium constants and rate constants of isomerization for these complexes.

One can envision two basic mechanisms for isomerization. A dissociative mechanism (D) involves the formation of a five-coordinate intermediate.



If there is some rate dependence on the incoming nucleophile, but bond-breaking is more important than bond-making the mechanism is called interchange dissociative,  $I_D$ .

The other basic mechanism is associative (A) and is analogous to an  $SN_2$  reaction.



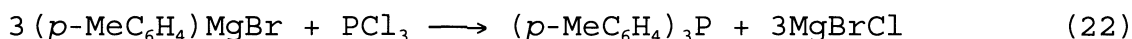
If bond-making is more important than bond-breaking the mechanism is called interchange associative,  $I_A$ .

In this work we have attempted to determine the mechanism of isomerization from the kinetic data collected.

## II. Results and Discussion

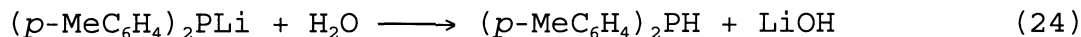
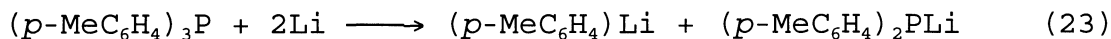
### 1. Synthesis of Phosphine Ligands

Tri-(*p*-tolyl)phosphine was synthesized by the general method of the Grignard reaction.<sup>1b,77</sup>



The addition of I<sub>2</sub> activates the Mg surface and the MgI<sub>2</sub> thus formed will bind the last traces of water in the reaction mixture.<sup>78</sup> The melting point of tri-(*p*-tolyl)-phosphine in this work (145-146 °C) is similar to that reported by Allman and Goel's work (145-148 °C).<sup>24</sup> For comparison, the properties of some tritolylphosphine analogues taken from Allman and Goel's work<sup>24</sup> are summarized in Table 1. The <sup>31</sup>P{<sup>1</sup>H} NMR spectrum of (*p*-MeC<sub>6</sub>H<sub>4</sub>)<sub>3</sub>P is shown in Figure 1.

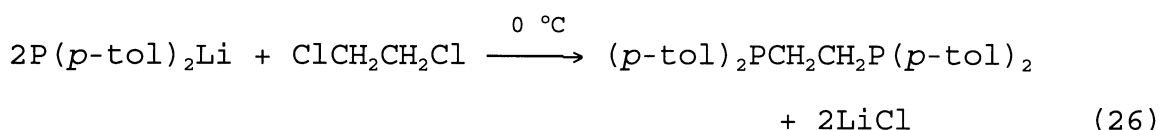
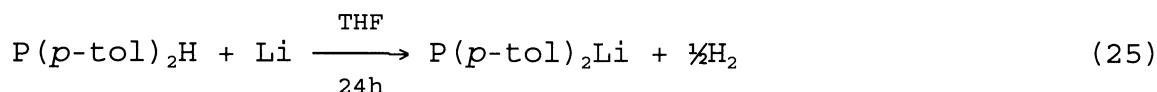
The cleavage of tri-(*p*-tolyl)phosphine to lithium di-(*p*-tolyl)phosphide and *p*-tolyllithium, followed by hydrolysis and distillation, gave di-(*p*-tolyl)phosphine in good yield.



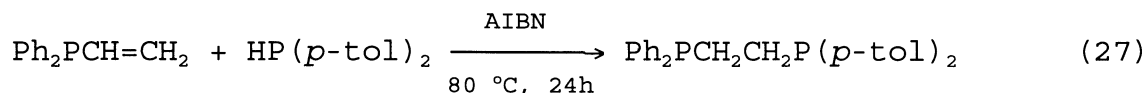
The properties of some ditolylphosphine analogues from the literature are summarized in Table 2. The <sup>31</sup>P{<sup>1</sup>H} NMR

spectrum of  $(p\text{-MeC}_6\text{H}_4)_2\text{PH}$  is shown in Figure 2.

The reaction of lithium di-(*p*-tolyl)phosphide with 1,2-dichloroethane gave the symmetrical diphosphine,  $(p\text{-tol})_2\text{PCH}_2\text{CH}_2\text{P}(p\text{-tol})_2$ , in low yield (11.8%). The  $^{31}\text{P}\{^1\text{H}\}$  NMR spectrum is shown in Figure 3.



The free-radical addition of di-(*p*-tolyl)phosphine to diphenylvinylphosphine gave a high yield (94.4%) of unsymmetrical diphosphine (dpdt). The  $^{31}\text{P}\{^1\text{H}\}$  NMR spectrum of  $(p\text{-tol})_2\text{PCH}_2\text{CH}_2\text{PPh}_2$  (dpdt) is shown in Figure 4.



The melting point of dpdt in our work (108-109 °C) is similar to that in reference [38] (112.0-112.5 °C), but is very different from that in reference [60] (81-82 °C). The properties of some relatives of dpdt are summarized in Table 3.

For the above mentioned phosphines, the  $^{31}\text{P}$  chemical shift depends mainly on the electronic properties and the

position of the substituents on the phenyl group. In general, the  $\text{CH}_3\text{C}_6\text{H}_4$  group makes the ligand more basic, causes an upfield  $^{31}\text{P}$  chemical shift, and makes the boiling and melting points higher than does a  $\text{C}_6\text{H}_5$  group. For the same kind of substituent, it seems that the order of basicity is : para- > meta- > ortho-, while the  $^{31}\text{P}$  chemical shift is in the order of meta- > para- > ortho-. For diphosphines, the  $^{31}\text{P}$  chemical shift of one phosphorus does not vary much when the substituents of the phenyl group of the other phosphorus group are changed. Likewise, the P-P coupling constants show little variation, indicating that the two phosphorus groups, separated by three bonds, do not have much electronic influence on each other.

## 2. Synthesis of $(\text{OC})_5\text{ML}$ (M=Cr, Mo, W; L=PPh<sub>2</sub>H, P(*p*-tol)<sub>2</sub>H, PPh<sub>2</sub>CH=CH<sub>2</sub>)

Three methods, photolysis,<sup>65,66</sup> oxidative decarbonylation, and thermal substitution,<sup>81</sup> were used for the synthesis of monosubstituted tungsten and chromium complexes (see Introduction). However, oxidative decarbonylation, using  $\text{Me}_3\text{NO}$  as an initiator, gave disubstituted molybdenum complexes,  $\text{M}(\text{CO})_4\text{L}_2$ , as dominant products. Monosubstituted molybdenum complexes were synthesized by thermal reaction in monoglyme or toluene<sup>81</sup>. Diglyme was avoided to avoid formation of *trans*- $\text{M}(\text{CO})_4\text{L}_2$ .<sup>65</sup> The  $^{31}\text{P}\{^1\text{H}\}$  NMR spectra of  $(\text{OC})_5\text{MP}(\textit{p}\text{-tol})_2\text{H}$  (M=Cr, Mo, W) are shown in Figures 5-7.



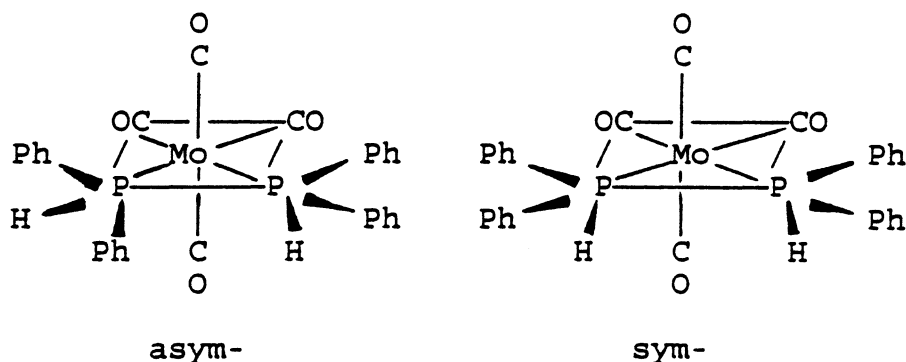
The properties of  $(OC)_5ML$  complexes are given in Table 4. The  $^{31}P$  chemical shifts of complexes  $(OC)_5ML$  with the same phosphine ligand are in the order  $Cr > Mo > W$ .

The infrared spectra of complexes  $(OC)_5ML$  are characterized by the  $A_1^{(1)}$ ,  $A_1^{(2)}$ , and E modes expected for local  $C_{4v}$  symmetry.<sup>14</sup> The  $A_1^{(1)}$  and E modes show in the same C-O absorption band because of accidental degeneracy or near degeneracy. Because the molecule is not rigorously of  $C_{4v}$  symmetry, the forbidden  $B_1$  mode was also observed as a weak band. The IR spectra of  $(OC)_5MP(p\text{-tol})_2H$  ( $M=Cr, Mo, W$ ) are shown in Figures 8-10. The IR data are given in Table 5.

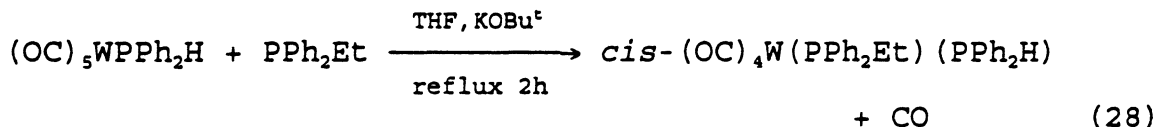
### 3. Disubstituted Complexes

The compound *cis*- $(OC)_4W[P(p\text{-tol})_2H]_2$  was obtained as a by-product from the synthesis of  $(OC)_5WP(p\text{-tol})_2H$ . The  $^{31}P\{^1H\}$  NMR spectrum is shown in Figure 11. In addition, *cis*- $(OC)_4Mo(PPh_2CH=CH_2)_2$  was the dominant product obtained by oxidation decarbonylation, a method frequently used for the synthesis of monosubstituted complexes. The  $^{31}P\{^1H\}$  NMR spectrum of *cis*- $(OC)_4Mo(PPh_2CH=CH_2)_2$  is shown in Figure 12. Keiter et al<sup>65</sup> have synthesized the complexes *trans*- $(OC)_4M(PPh_2CH=CH_2)_2$  ( $M=Cr, Mo, W$ ) and *cis*- $(OC)_4W(PPh_2H)_2$  by thermal reactions in diglyme, but the complex *cis*- $(OC)_4W(PPh_2CH=CH_2)_2$  was not synthesized successfully. Smith and Thompson<sup>81</sup> have synthesized *cis*- $(OC)_4Mo(PPh_2H)_2$  (mp 95-98 °C) which was found to exist in two configurations in the

solid state: symmetric and asymmetric.



The complex *cis*-(OC)<sub>4</sub>W(PPh<sub>2</sub>Et)(PPh<sub>2</sub>H) was prepared by the base catalyzed reaction as described in the literature.<sup>65,83</sup> The <sup>31</sup>P{<sup>1</sup>H} NMR spectrum is shown in Figure 13.



The *cis* complexes have C<sub>2v</sub> symmetry and the infrared spectra are characterized by the B<sub>1</sub>, B<sub>2</sub>, A<sub>1</sub><sup>(1)</sup>, and A<sub>1</sub><sup>(2)</sup> vibrational modes. B<sub>1</sub> and B<sub>2</sub> modes overlap to form one band (Figures 14-16). The A<sub>1</sub><sup>(1)</sup> band often appears as a shoulder on the very strong B<sub>1</sub> and B<sub>2</sub> bands and as a result the frequency of this band is often difficult to measure. The IR data are listed in Table 6. Other properties of these complexes are given in Table 7.

The melting points and <sup>31</sup>P chemical shifts of the complexes are in the order of *trans*- > *cis*- > mono-. The

infrared spectra can also be used to distinguish between di- and mono-substituted or *cis*- and *trans*- complexes which have different symmetries and different CO stretching frequencies.

From Tables 4 and 7, the  $^{183}\text{W}$ - $^{31}\text{P}$  coupling constants decrease in the order  $\text{PPh}_2\text{CH}=\text{CH}_2 > \text{PPh}_2\text{H} > \text{P}(p\text{-tol})_2\text{H}$ , which corresponds with the decreasing electronegativity order of the substituents on phosphorus.<sup>84</sup> The Fermi contact term is believed to be the main contributor to the coupling interactions.<sup>85</sup>

#### 4. Dangling Diphosphine Complexes

Six novel dangling diphosphine complexes were synthesized by Keiter's free-radical vinyl addition reaction (see introduction).<sup>76</sup> The  $^{31}\text{P}\{^1\text{H}\}$  NMR and IR spectra are shown in Figure 17-30. The melting points and  $^{31}\text{P}\{^1\text{H}\}$  NMR data are given in Table 8. The IR data are listed in Table 9.

The melting points of the diphosphine complexes with the  $\text{PPh}_2$  group coordinated are higher than those of the complexes with the  $\text{P}(p\text{-tol})_2$  group coordinated, which is the reverse of that found for  $(\text{OC})_5\text{MPPPh}_2\text{H}$  and  $(\text{OC})_5\text{MP}(p\text{-tol})_2\text{H}$  ( $\text{M}=\text{Cr}, \text{Mo}, \text{W}$ ). The  $^{31}\text{P}$  chemical shifts of the coordinated phosphorus groups are in the order of  $\text{Cr} > \text{Mo} > \text{W}$ , while those of the uncoordinated phosphorus groups are insensitive to the metals. The phosphorus-phosphorus coupling constants

are in the order of  $W > Mo > Cr$ , which is opposite to that of the chelated complexes of diphenylphosphinite,  $PPh_2(CH_2)_nOPPh_2$  ( $n=1$  or  $2$ ).<sup>87</sup> Among the complexes the molybdenum one has the highest CO stretching frequency.

## 5. Diphosphine Oxide Complexes

Keiter et al.<sup>88</sup> have isolated the complex,  $(OC)_5WPPH_2CH_2CH_2P(O)Ph_2$ , which decomposes at 170-175 °C. Three diphosphine dioxides of the type  $PPh_2P(O)CH_2CH_2P(O)PhR$  ( $R= Me, Et, i-Pr$ ) were synthesized by Grim et al.<sup>43</sup> Some  $^{31}P\{^1H\}$  NMR data of diphosphine oxide complexes, which were not isolated, were obtained in the course of our experimentations and are included in Table 10 for completeness. The diphosphine oxide complexes have large downfield  $^{31}P$  chemical shifts and large phosphorus-phosphorus coupling constants. The large phosphorus-phosphorus coupling constants, compared to non-oxides, were accounted for by consideration of the change in oxidation state (+3 to +5) and by the increasing s character in the phosphorus bonds.<sup>43</sup>

## 6. Chelated Complexes

The chelated complexes can be prepared easily by refluxing a mixture of  $M(CO)_6$  and diphosphine in a solvent.<sup>43,60,62</sup> In preparing the dangling diphosphine complexes by Keiter's free-radical vinyl addition

reaction,<sup>76</sup> the chelated complex of molybdenum formed at high temperature. The  $^{31}\text{P}\{^1\text{H}\}$  NMR and IR spectra of  $(\text{OC})_4\text{Mo}(\text{dpdt})$  are shown in Figure 31 and 32. The melting points and  $^{31}\text{P}\{^1\text{H}\}$  NMR data are summarized in Table 11. The IR data are summarized in Table 12.

The unusual large downfield  $^{31}\text{P}$  chemical shifts of the chelated complexes were explained by ring strain.<sup>35</sup> However, the much more strained four-membered rings show much less downfield  $^{31}\text{P}$  chemical shifts.<sup>87</sup> Grim et al<sup>52,87</sup> also observed that the phosphorus-phosphorus coupling constants in chelated complexes of  $\text{Ph}_2\text{PCH}_2\text{OPPh}_2$  and  $\text{Ph}_2\text{P}(\text{CH}_2)_n\text{PPhR}$  ( $n = 1, 2$ ;  $\text{R} = \text{Me}, \text{Et}, i\text{-Pr}$ ) contain contributions of coupling both through the backbone and through the metal center ( $|J_{\text{PP}}| = J_{\text{PP}}^{\text{b}} + J_{\text{PP}}^{\text{m}}$ ). The sign of  $J_{\text{PP}}^{\text{b}}$  is opposite to that of  $J_{\text{PP}}^{\text{m}}$  and this fact accounts for the observed small coupling constants. The average observed values of  $J_{\text{PP}}$  for  $[\text{Ph}_2\text{P}(\text{CH}_2)_2\text{PPhR}]\text{M}(\text{CO})_4$  are 12, 5, and 4 Hz for  $\text{M} = \text{Cr}, \text{Mo},$  and  $\text{W}$ , respectively,<sup>52</sup> which is similar to our results.

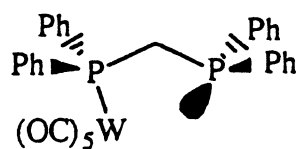
## 7. Variable Temperature $^{31}\text{P}\{^1\text{H}\}$ NMR Experiments of Compounds $(\text{OC})_5\text{W}(\text{dppe})$ and $(\text{OC})_5\text{W}(\text{dppm})$

If the exchange between the coordinated and uncoordinated phosphorus groups in  $(\text{OC})_5\text{WPh}_2\text{CH}_2\text{CH}_2\text{PPh}_2$  is fast enough, a time-averaged spectrum will be observed, in which the tungsten-phosphorus satellites disappear or become

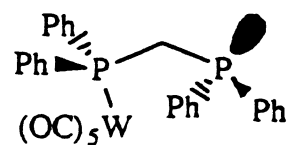
much smaller in magnitude, and the two doublets may collapse into a single line. However, the variable temperature  $^{31}\text{P}\{^1\text{H}\}$  NMR experiments (Table 13) show that the pattern and chemical shifts of the  $^{31}\text{P}\{^1\text{H}\}$  NMR spectrum at room temperature (Figure 33) remains the same as those at high temperature (Figure 34). Therefore, it can be concluded that the exchange between the two phosphorus groups is too slow to be detected over the temperature range of 30-80 °C.

It needs to be pointed out that oxidation of the terminal phosphine took place during the experiment because the NMR tube was not sealed completely (Figure 35). In addition, the reaction of compound  $(\text{OC})_5\text{W}(\text{dppe})$  with the solvent (or some impurity in the solvent) was also significant. However, chelation was not observed below 80 °C.

In contrast, the  $^2J_{\text{PP}}$  values of  $(\text{OC})_5\text{WPPH}_2\text{CH}_2\text{PPh}_2$  change from 122.4 to 110.6 Hz over the range of -50 to 70 °C, while the  $^1J_{\text{WP}}$  values change insignificantly (Figures 36 and 37, Table 14). In addition, the  $^{31}\text{P}$  chemical shifts of the two phosphorus groups move downfield somewhat with increasing temperature. The change of  $^2J_{\text{PP}}$  with temperature does not mean that the two phosphorus groups are undergoing exchange. It has been shown that the temperature can affect  $^2J_{\text{PP}}$  by changing the conformation of diphosphine ligands.<sup>89</sup> The compound  $(\text{OC})_5\text{W}(\text{dppm})$  may exist in two conformations A and B.<sup>90</sup>



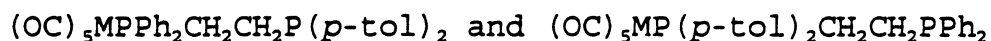
A



B

Conformation A, in which the phosphorus lone pair is directed toward the W-P bond, may give rise to larger value of  $^2J_{PP}$  than B in which the phosphorus lone pair is directed away from the W-P bond. The phosphorus lone pair in A may interact with the C group which is close to it to make conformation A more stable at room temperature. When the temperature is increased, the weak interaction between the phosphorus lone pair and CO will be broken allowing the C-P bond to rotate freely.

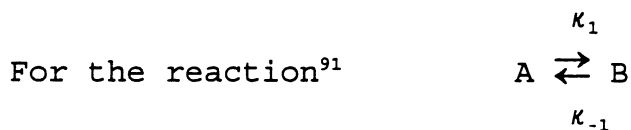
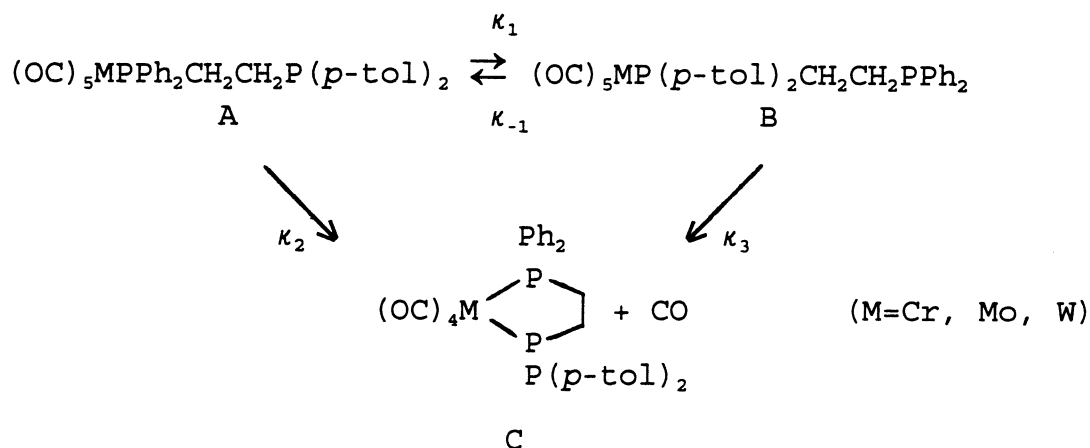
#### 8. Isomerization Studies of Compounds



(M= Cr, Mo, W)

Even though rapid exchange between the two phosphorus groups in compounds  $(OC)_5WPPH_2(CH_2)_nPPH_2$  ( $n=1,2$ ) was not observed, isomerization of the title compounds in solution could be followed with  $^{31}P\{^1H\}$  NMR spectroscopy (Figure 38). In addition, the chromium and molybdenum compounds undergo chelation to some extent. Chelation of tungsten complexes in  $(CD)_3C_6D_5$  was insignificant within the time of investigation. The reactions, carried out at 55 °C, are shown in Scheme 1.

# Scheme 1



the rate of disappearance of A is given by

$$- \frac{d[A]}{dt} = \kappa_1[A] - \kappa_{-1}[B] \quad (29)$$

From stoichiometry:  $[A]_0 + [B]_0 = [A] + [B] = [A]_{eq} + [B]_{eq}$  (30)

at equilibrium:  $\frac{[B]_{eq}}{[A]_{eq}} = K = \frac{\kappa_1}{\kappa_{-1}}$  (31)

Substitution of equation (30) and (31) into the differential equation (29) gives

$$- \frac{d[A]}{dt} = (\kappa_1 + \kappa_{-1}) ([A] - [A]_{eq}) \quad (32)$$

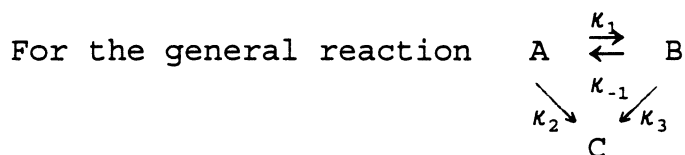
Integration of equation (32) gives

$$\ln([A] - [A]_{eq}) = -(\kappa_1 + \kappa_{-1})t + \ln([A]_0 - [A]_{eq}) \quad (33)$$

To solve this problem, the equilibrium constant K should be known. For molybdenum compounds, the isomerization is relatively fast and the equilibrium constant can be easily



measured:  $1.96 \left( \frac{[B]_{eq}}{[A]_{eq}} \right)$  at  $55^\circ\text{C}$  in  $(\text{CD}_3)\text{C}_6\text{D}_5$ . The plot of  $\ln([A]/[A]_0 - [A]_{eq}/[A]_0)$  vs time for molybdenum compound is shown in Figure 39. For tungsten and chromium compounds, however, it takes a very long time to reach equilibrium because the isomerizations are extremely slow. In addition, the occurrence of chelation for the chromium complex makes the analysis more complicated. It is possible, however, to obtain all rate constants and equilibrium constants from a detailed analysis.



The rate equations are

$$\frac{d[A]}{dt} = -(\kappa_1 + \kappa_2)[A] + \kappa_{-1}[B] \quad (34)$$

$$\frac{d[B]}{dt} = \kappa_1[A] - (\kappa_{-1} + \kappa_3)[B] \quad (35)$$

$$\frac{d[C]}{dt} = \kappa_2[A] + \kappa_3[B] \quad (36)$$

which can be solved by the literature method.<sup>92</sup>

From eq (35), [A] can be solved as

$$[A] = \frac{1}{\kappa_1} \frac{d[B]}{dt} + \frac{\kappa_{-1} + \kappa_3}{\kappa_1} [B] \quad (37)$$

Differentiation followed by substitution into eq (34) gives

$$\frac{d^2[B]}{dt^2} + (\kappa_1 + \kappa_{-1} + \kappa_2 + \kappa_3) \frac{d[B]}{dt} + (\kappa_1\kappa_3 + \kappa_2\kappa_{-1} + \kappa_2\kappa_3)[B] = 0 \quad (38)$$

It is assumed that [B] is of the form  $e^{rt}$ ; thus substitution of  $[B]=e^{rt}$  into eq (38) generates the characteristic equation

$$r^2 + (\kappa_1 + \kappa_{-1} + \kappa_2 + \kappa_3)r + \kappa_1\kappa_3 + \kappa_2\kappa_{-1} + \kappa_2\kappa_3 = 0 \quad (39)$$

$$\text{in which } 2r_{\pm} = -(\kappa_1 + \kappa_{-1} + \kappa_2 + \kappa_3) \pm [(\kappa_1 + \kappa_{-1} + \kappa_2 + \kappa_3)^2 - 4(\kappa_1\kappa_3 + \kappa_2\kappa_{-1} + \kappa_2\kappa_3)]^{1/2} \quad (40)$$

The general solution for [B] is given as

$$[B] = C_+ e^{r_+ t} + C_- e^{r_- t} \quad (41)$$

where  $C_+$  and  $C_-$  are arbitrary constants.

Substitution of eq (41) into eq (37) gives

$$\kappa_1[A] = C_+(r_+ + \kappa_{-1} + \kappa_3)e^{r_+ t} + C_-(r_- + \kappa_{-1} + \kappa_3)e^{r_- t} \quad (42)$$

in which  $C_+$  and  $C_-$  can be found from the simultaneous solution of equations (43) and (44).

$$[B]_0 = C_+ + C_- \quad (43)$$

$$\kappa_1[A]_0 = C_+(r_+ + \kappa_{-1} + \kappa_3) + C_-(r_- + \kappa_{-1} + \kappa_3) \quad (44)$$

If  $[B]_0 = 0$  and  $[C]_0 = 0$ , the exact solutions are given as

$$[A] = \frac{-(r_- + \kappa_1 + \kappa_2)[A]_0}{r_+ - r_-} e^{r_+ t} + \frac{(r_+ + \kappa_1 + \kappa_2)[A]_0}{r_+ - r_-} e^{r_- t} \quad (45)$$

$$[B] = \frac{\kappa_1[A]_0}{r_+ - r_-} (e^{r_+ t} - e^{r_- t}) \quad (46)$$

$$\begin{aligned} [C] = & \frac{[(r_- + \kappa_1)\kappa_2 - \kappa_1\kappa_3]}{r_+(r_+ - r_-)} [A]_0(1 - e^{r_+ t}) \\ & + \frac{[\kappa_1\kappa_3 - (r_+ + \kappa_1)\kappa_2]}{r_-(r_+ - r_-)} [A]_0(1 - e^{r_- t}) \end{aligned} \quad (47)$$

As  $r_+t$  and  $r_-t$  are very small in our case, the terms of  $e^{r_+t}$  and  $e^{r_-t}$  can be simplified as  $1 + r_+t$  and  $1 + r_-t$ , respectively. Substitution of  $e^{r_-t} = 1 + r_-t$  and  $e^{r_+t} = 1 + r_+t$  into equations (45), (46), and (47) followed by rearrangement gives the simpler forms

$$[A]/[A]_0 = 1 - (\kappa_1 + \kappa_2)t \quad (48)$$

$$[B]/[A]_0 = \kappa_1 t \quad (49)$$

$$[C]/[A]_0 = \kappa_2 t \quad (50)$$

If the isomerization is started with pure isomer B, similarly the equations of concentration vs time are given as

$$[B]/[B]_0 = 1 - (\kappa_{-1} + \kappa_3)t \quad (51)$$

$$[A]/[B]_0 = \kappa_{-1}t \quad (52)$$

$$[C]/[B]_0 = \kappa_3 t \quad (53)$$

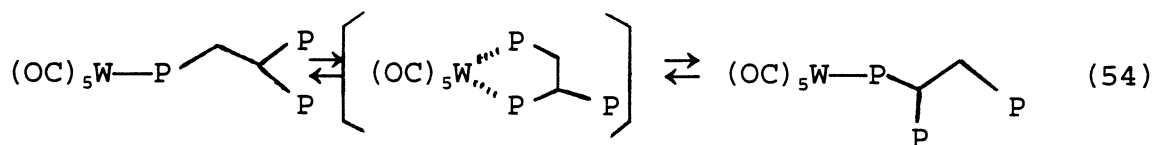
Therefore, the rate constants,  $\kappa_1$ ,  $\kappa_2$ ,  $\kappa_{-1}$ , and  $\kappa_3$ , can be obtained for the isomerization and chelation reactions if one starts with pure isomer A and with pure isomer B. The plots of concentration with time give good straight lines (Figures 40-46, 48, 50-55;  $r \geq 0.9$ ). When the Napierian logarithm of concentration is used, the disappearance of the starting isomer with time is a straight line (Figure 47), while the appearance of the product isomer with time follows a curve (Figure 49). In eq (48), the term  $1 - (\kappa_1 + \kappa_2)t$  approximately equals  $e^{-(\kappa_1 + \kappa_2)t}$ , while the term in eq (49),  $\kappa_1 t$ , can be written as  $e^{\kappa_1 t} - 1$ . Therefore, when the logarithm is applied, eq (48) will give a straight line and eq (49) will

generate a curve. The rate constants are given in Table 15.

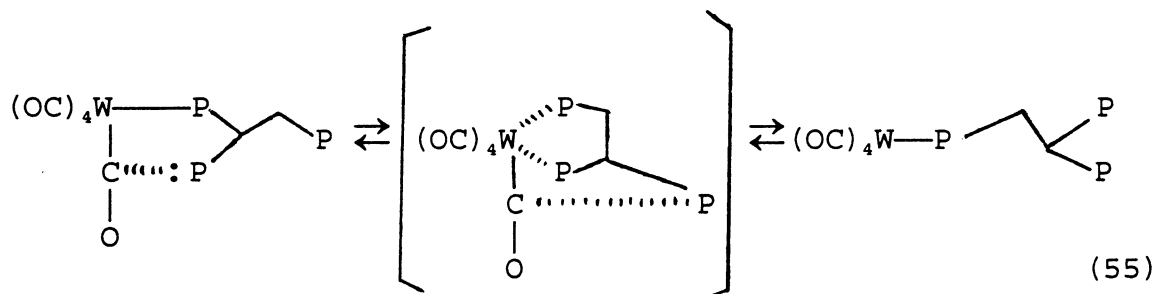
The rates of isomerization follow the order of  $\text{Mo} \gg \text{W} > \text{Cr}$ , while the rates of chelation are in the order of  $\text{Mo} \gg \text{Cr} > \text{W}$  which is consistent with the order of the first CO dissociation energy in  $\text{M}(\text{CO})_6$  [ $\text{W}(47.8) > \text{Cr}(45.3) > \text{Mo}(40.3)$ : kcal/mol].<sup>93</sup> This provides evidence for a dissociation pathway for chelation. Such a pathway is consistent with Connor's chelation studies<sup>34</sup> involving  $(\text{OC})_5\text{ML}$  [ $\text{L} = ((\text{cyclo-C}_6\text{H}_{11})\text{PCH})_2$ ].

In all of the cases, the rate of isomerization of A,  $(\text{OC})_5\text{MPPh}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-tol})_2$ , is faster than that of B,  $(\text{OC})_5\text{MP}(p\text{-tol})_2\text{CH}_2\text{CH}_2\text{PPh}_2$  ( $\text{M} = \text{Cr}, \text{Mo}, \text{W}$ ) because the *p*-tol group is a better  $\sigma$ -donor than the Ph group [e.g.  $\text{P}(p\text{-tol})_3$ ,  $\text{pK}_a = 3.84$ ; and  $\text{PPh}_3$ ,  $\text{pK}_a = 2.73$ ].<sup>24</sup> In other words the less stable  $(\text{OC})_5\text{MPPh}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-tol})_2$  dissociates faster than the more stable  $(\text{OC})_5\text{MP}(p\text{-tol})_2\text{CH}_2\text{CH}_2\text{PPh}_2$ . In addition, the tolyl end is more nucleophilic than the phenyl end of the phosphorus and therefore any contribution from an associative mechanism would be consistent with the observed rates.

The rates of isomerization of compounds A and B ( $\text{M} = \text{Cr}, \text{W}$ ;  $10^{-8} \text{ s}^{-1}$  at  $55^\circ \text{C}$ ) are very much slower than those of compounds  $(\text{OC})_5\text{WPPh}_2\text{CH}_2\text{CH}(\text{PPh}_2)_2$  and  $(\text{OC})_5\text{WPPh}_2\text{CH}(\text{Ph}_2)\text{CH}_2\text{PPh}_2$  ( $10^{-4}$  and  $10^{-5} \text{ s}^{-1}$  at  $55^\circ \text{C}$ )<sup>45</sup> which are believed to have a significant associative component.



The question arises, why is the above reaction four orders of magnitude faster than the isomerization of  $(\text{OC})_5\text{WPPH}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-tol})_2$ ? The answer may lie in the number of dangling phosphine arms. In the tri-tertiary phosphine one arm may interact with the carbon of a metal carbonyl which in turn weakens the M-P bond, allowing the third phosphorus group to swing in and displace the bound phosphorus.



The complex,  $(\text{OC})_5\text{WPPH}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-tol})_2$ , does not have a third arm to displace the bound phosphorus or interact with the metal carbonyl. Thus, the bound metal-phosphorus bond is not weakened and dissociation or exchange with another phosphine is not favorable.

By plotting the equation,  $\ln \kappa = -(E_a/R)T^{-1} + b$ , it can be estimated that the first-order rate constants at 55 °C for the dissociation<sup>34</sup> of  $\text{PPh}_3$  from  $\text{Cr}(\text{CO})_5\text{PPh}_3$  and the chelation<sup>34</sup> of  $(\text{OC})_5\text{Cr}(\text{dcpe})$  [ $\text{dcpe} = ((\text{cyclo-C}_6\text{H}_{11})\text{PCH})_2$ ] are  $2 \times 10^{-9} \text{ s}^{-1}$  and  $2.4 \times 10^{-8} \text{ s}^{-1}$  respectively, which are similar to those of the isomerization and the chelation of compounds

$(OC)_5CrPPh_2CH_2CH_2P(p-tol)_2$  and  $(OC)_5CrP(p-tol)_2CH_2CH_2PPh_2$ .

Therefore, the isomerization and chelation for compound  $(OC)_5CrPPh_2CH_2CH_2P(p-tol)_2$  and  $(OC)_5CrP(p-tol)_2CH_2CH_2PPh_2$  may also proceed by the dissociative mechanism. For molybdenum and tungsten compounds, however, the isomerization is an order of magnitude faster than chelation, suggesting an associative component.

The rate of chelation for compound  $(OC)_5MPPhCH_2CH_2P(p-tol)_2$  is slower than that for compound  $(OC)_5MP(p-tol)_2CH_2CH_2PPh_2$  ( $M=Cr, Mo, W$ ) because the  $P(p-tol)_2$  group, with its greater basicity, can make the transition state more stable than can the  $PPh_2$  group.<sup>95</sup>

In conclusion we have measured the rates of isomerization and chelation of three pairs of linkage isomers. These rates suggest that isomerization and chelation proceed by a dissociative mechanism (D) in the case of the chromium isomers. Reactions for molybdenum and tungsten are best described as taking place by a dissociative interchange mechanism (ID).

Equilibrium constants (Table 15) in all cases establish that  $(OC)_5MP(p-tol)_2CH_2CH_2PPh_2$  is more stable than  $(OC)_5MPPh_2CH_2CH_2P(p-tol)_2$ . Variable temperature studies are underway to determine  $\Delta H$  and  $\Delta S$  for these reactions as well as activation parameters.

Table 1. Properties of Tritolylphosphine Analogues  
(from Allman and Goel's work<sup>24</sup>)

Ligand	pK <sub>a</sub>	mp (°C)	δ <sub>p</sub> (ppm) <sup>a</sup>
P[4-(CH <sub>3</sub> ) <sub>2</sub> NC <sub>6</sub> H <sub>4</sub> ] <sub>3</sub>	8.65	265-270	-11.7
P(4-CH <sub>3</sub> OC <sub>6</sub> H <sub>4</sub> ) <sub>3</sub>	4.57	135-137	-10.6
P(4-CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub> ) <sub>3</sub>	3.84	145-148 (145-146) <sup>b</sup>	- 8.3 (-7.5) <sup>c</sup>
P(3-CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub> ) <sub>3</sub>	3.30	103-104	- 5.3
P(2-CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub> ) <sub>3</sub>	3.08	125-127	-27.8
P(C <sub>6</sub> H <sub>5</sub> ) <sub>3</sub>	2.73	80	- 6.3
P(4-FC <sub>6</sub> H <sub>4</sub> ) <sub>3</sub>	1.97	80-81	- 9.3
P(4-ClC <sub>6</sub> H <sub>4</sub> ) <sub>3</sub>	1.03	100-101	- 8.7

<sup>a</sup> CH<sub>2</sub>Cl<sub>2</sub>/C<sub>6</sub>D<sub>6</sub> 9:1 (v/v)  
except where noted

<sup>b</sup> this work

<sup>c</sup> this work (CDCl<sub>3</sub>)

Table 2. Properties of Ditolylphosphine Analogues

Ligand	b.p (°C)	δ <sub>p</sub> (ppm)	<sup>1</sup> J <sub>PH</sub> (Hz)
HP(2-CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub> ) <sub>2</sub> <sup>a</sup>	104-106/0.1 mmHg	-59.1	219
HP(3-CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub> ) <sub>2</sub> <sup>a</sup>		-40.3	214
HP(4-CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub> ) <sub>2</sub>	(110/0.1 mmHg) <sup>b</sup> (124-126/1.2 mmHg) <sup>c</sup>	-43.0 <sup>a</sup> (-42.0) <sup>b</sup>	212 <sup>a</sup> (218.4) <sup>b</sup>
HP[4-(CH <sub>3</sub> ) <sub>3</sub> CC <sub>6</sub> H <sub>4</sub> ] <sub>2</sub> <sup>a</sup>		-43.9	212
HP( <i>p</i> -FC <sub>6</sub> H <sub>4</sub> ) <sub>2</sub> <sup>d</sup>	110-113/2.0 mmHg	-44.0	219.7
HP( <i>m</i> -FC <sub>6</sub> H <sub>4</sub> ) <sub>2</sub> <sup>d</sup>	115-118/2.5 mmHg	-40.9	220.4
HP(C <sub>6</sub> H <sub>5</sub> ) <sub>2</sub>	150-154/11 mmHg <sup>e</sup>	-40.7 <sup>f</sup>	216 <sup>f</sup>

<sup>a</sup> reference 79 (neat solution) <sup>b</sup> this work (CDCl<sub>3</sub>)

<sup>c</sup> reference 38 <sup>d</sup> reference 63 (CDCl<sub>3</sub>) <sup>e</sup> reference 49

<sup>f</sup> reference 80 (neat solution)

Table 3. Properties of Some Diphosphines

Ligand	mp (°C)	$\delta_{\text{PPh}_2}$ (ppm)	$\delta_{\text{PR}'}$ (ppm)	$^3J_{\text{PP}}$ (Hz)
$\text{PPh}_2\text{CH}_2\text{CH}_2\text{PPh}_2$	139-140 <sup>a</sup>	-13.2 <sup>b</sup>		
$\text{PPh}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-tol})_2$ <sup>c</sup>	108-109	-12.1	-14.2	34.6
$(p\text{-tol})_2\text{PCH}_2\text{CH}_2\text{P}(p\text{-tol})_2$ <sup>c</sup>	148-149		-14.0	
$\text{PPh}_2\text{CH}_2\text{CH}_2\text{P}(m\text{-CH}_3\text{C}_6\text{H}_4)_2$	95 <sup>d</sup>			
$\text{PPh}_2\text{CH}_2\text{CH}_2\text{P}(m\text{-FC}_6\text{H}_4)_2$ <sup>e</sup>	92-93	-12.1	-11.1	34.8
$\text{PPh}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-FC}_6\text{H}_4)_2$ <sup>e</sup>	93-94	-12.2	-14.5	35.0
$\text{PPh}_2\text{CH}_2\text{CH}_2\text{P}(m\text{-CF}_3\text{C}_6\text{H}_4)_2$ <sup>e</sup>	88-89	-12.2	-11.2	35.1

<sup>a</sup> reference 53    <sup>b</sup> reference 51    <sup>c</sup> this work ( $^{31}\text{P}\{^1\text{H}\}$  NMR in  $\text{CDCl}_3$ )    <sup>d</sup> reference 61    <sup>e</sup> reference 63 ( $^{31}\text{P}\{^1\text{H}\}$  NMR in  $\text{C}_6\text{H}_6$ )

Table 4. Properties of  $(\text{OC})_5\text{ML}$ 

Complex	mp (°C)	$\delta_{\text{P}}$ (ppm) <sup>a</sup>	$J_{\text{PH}}$ (Hz)	$J_{\text{WP}}$ (Hz)
$(\text{OC})_5\text{CrPPh}_2\text{H}$	60-61 <sup>b</sup>	32.9 <sup>b</sup>	340 <sup>c</sup>	
$(\text{OC})_5\text{MoPPh}_2\text{H}$	74-75.5 <sup>b</sup>	6.7 <sup>b</sup>	330 <sup>c</sup>	
$(\text{OC})_5\text{WPPh}_2\text{H}$	90-91 (91-93) <sup>d</sup>	-13.2 (-13.7) <sup>d</sup>	345.3 (334.9) <sup>d</sup>	229.3 (229.6) <sup>d</sup>
$(\text{OC})_5\text{CrP}(p\text{-tol})_2\text{H}$	91-92	30.9	338.2	
$(\text{OC})_5\text{MoP}(p\text{-tol})_2\text{H}$	81-82	4.5	332.3	
$(\text{OC})_5\text{WP}(p\text{-tol})_2\text{H}$	89-90	-15.5	332.3	227.5
$(\text{OC})_5\text{CrPPh}_2\text{CH}=\text{CH}_2$	54-55 (58-59) <sup>b</sup>	47.9 (47.4) <sup>b</sup>		
$(\text{OC})_5\text{MoPPh}_2\text{CH}=\text{CH}_2$	57-58 <sup>b</sup>	29.3 <sup>b</sup>		
$(\text{OC})_5\text{WPPh}_2\text{CH}=\text{CH}_2$	59-60 (64-65) <sup>d</sup>	11.9 (11.4) <sup>d</sup>		239.3 (239.4) <sup>d</sup>

<sup>a</sup>  $\text{CDCl}_3$     <sup>b</sup> reference 66    <sup>c</sup> reference 81    <sup>d</sup> reference 65



Table 5. IR Data of (OC)<sub>5</sub>ML (CH<sub>2</sub>Cl<sub>2</sub>, cm<sup>-1</sup>)

Complex	A <sub>1</sub> <sup>(2)</sup>	B <sub>1</sub>	(E+A <sub>1</sub> <sup>(1)</sup> )
(OC) <sub>5</sub> CrPPh <sub>2</sub> H <sup>a</sup>	2078	1993	1953
(OC) <sub>5</sub> MoPPh <sub>2</sub> H <sup>a</sup>	2074	1992	1950
(OC) <sub>5</sub> WPPh <sub>2</sub> H	2075 2077 <sup>b</sup>	1985 <sup>b</sup>	1942 1947 <sup>b</sup>
(OC) <sub>5</sub> CrP( <i>p</i> -tol) <sub>2</sub> H	2066	1984	1943
(OC) <sub>5</sub> MoP( <i>p</i> -tol) <sub>2</sub> H	2075		1948
(OC) <sub>5</sub> WP( <i>p</i> -tol) <sub>2</sub> H	2074		1940
(OC) <sub>5</sub> CrPPh <sub>2</sub> CH=CH <sub>2</sub>	2064	1983	1941
(OC) <sub>5</sub> MoPPh <sub>2</sub> CH=CH <sub>2</sub> <sup>c</sup>	2074	1991	1949
(OC) <sub>5</sub> WPPh <sub>2</sub> CH=CH <sub>2</sub>	2072	1979	1939

<sup>a</sup> reference 82 (CHCl<sub>3</sub>)<sup>b</sup> reference 65 (CHCl<sub>3</sub>)<sup>c</sup> reference 66 (CHCl<sub>3</sub>)Table 6. IR Data of *cis*-(OC)<sub>4</sub>ML<sub>2</sub> (CH<sub>2</sub>Cl<sub>2</sub>, cm<sup>-1</sup>)

Complex	A <sub>1</sub> <sup>(2)</sup>	A <sub>1</sub> <sup>(2)</sup>	(B <sub>1</sub> +B <sub>2</sub> )
<i>cis</i> -(OC) <sub>4</sub> W(PPh <sub>2</sub> H) <sub>2</sub> <sup>a</sup>	2020	1917	1903
<i>cis</i> -(OC) <sub>4</sub> W[P( <i>p</i> -tol) <sub>2</sub> H] <sub>2</sub>	2021		1906
<i>cis</i> -(OC) <sub>4</sub> Mo(PPh <sub>2</sub> CH=CH <sub>2</sub> ) <sub>2</sub>	2022		1907, 1883
<i>cis</i> -(OC) <sub>4</sub> W(PPh <sub>2</sub> Et)(PPh <sub>2</sub> H)	2019 (2023) <sup>b</sup>	(1922) <sup>b</sup>	1901, 1877 (1903) <sup>b</sup>

<sup>a</sup> reference 65 (CHCl<sub>3</sub>)<sup>b</sup> reference 83 (CHCl<sub>3</sub>)

Table 7. Properties of Disubstituted Complexes

Complex	mp (°C)	$\delta_p$ (ppm)	$^1J_{PH}$ (Hz)	$^1J_{2WP}$ (Hz)	$^2J_{PP}$ (Hz)
<i>cis</i> -(OC) <sub>4</sub> W(PPh <sub>2</sub> H) <sub>2</sub>	88-90	-2.8	342	224.1	
<i>cis</i> -(OC) <sub>4</sub> W[P(p-tol) <sub>2</sub> H] <sub>2</sub>	138-139	-4.4	336.6	223.8	
<i>cis</i> -(OC) <sub>4</sub> Mo(PPh <sub>2</sub> CH=CH <sub>2</sub> ) <sub>2</sub>	93-94	29.3			
<i>trans</i> -(OC) <sub>4</sub> Mo(PPh <sub>2</sub> CH=CH <sub>2</sub> ) <sub>2</sub> <sup>b</sup>	148-150	41.8			
<i>cis</i> -(OC) <sub>4</sub> W(PPh <sub>2</sub> Et)(PPh <sub>2</sub> H)	130-130.5	2.4 (1.4) <sup>c</sup> (PPh <sub>2</sub> H)	335 <sup>c</sup>	230.1 (230) <sup>c</sup> [ $^1J_{WP}$ (PPh <sub>2</sub> H)]	16.7
	(128-129) <sup>c</sup>	14.8 (14.1) <sup>c</sup> (PPh <sub>2</sub> Et)	7.9 <sup>c</sup> ( $^3J_{PH}$ )	225.7 (226) <sup>c</sup> [ $^1J_{WP}$ (PPh <sub>2</sub> Et)]	(17) <sup>c</sup>

<sup>a</sup> CDCl<sub>3</sub>    <sup>b</sup> reference 65    <sup>c</sup> reference 83

Table 8. Properties of Dangling Diphosphine Complexes

Complex	mp (°C)	$\delta_{\text{W-P}}$ (ppm)	$\delta_{\text{P}}$ (ppm) <sup>a</sup>	$^3J_{\text{PP}}$ (Hz)	$^1J_{2\text{WP}}$ (Hz)
(OC) <sub>5</sub> WPPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> PPh <sub>2</sub>	112-115 (116-117) <sup>b</sup>	13.4 (11.4) <sup>c</sup>	-12.2 (13.7) <sup>c</sup>	37.5 (37.2) <sup>c</sup>	239.4 (240.0) <sup>c</sup>
(OC) <sub>5</sub> CrPPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P( <i>p</i> -tol) <sub>2</sub>	133-134	50.5	-13.6	35.1	
(OC) <sub>5</sub> MoPPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P( <i>p</i> -tol) <sub>2</sub>	130	31.7	-13.6	37.0	
(OC) <sub>5</sub> WPPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P( <i>p</i> -tol) <sub>2</sub>	143-144	13.6	-13.7	37.6	239.3
(OC) <sub>5</sub> CrP( <i>p</i> -tol) <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> PPh <sub>2</sub>	103-104	48.4	-11.8	35.0	
(OC) <sub>5</sub> MoP( <i>p</i> -tol) <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> PPh <sub>2</sub>	90-91	29.7	-11.8	35.9	
(OC) <sub>5</sub> WP( <i>p</i> -tol) <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> PPh <sub>2</sub>	111-112	11.5	-12.0	38.0	238.4

<sup>a</sup> CDCl<sub>3</sub>      <sup>b</sup> reference 67      <sup>c</sup> reference 86

Table 9. IR Data of Dangling Diphosphine Complexes  
(CH<sub>2</sub>Cl<sub>2</sub>, cm<sup>-1</sup>)

Complex	A <sub>1</sub> <sup>(1)</sup>	B <sub>1</sub>	(E+A <sub>1</sub> <sup>(1)</sup> )
(OC) <sub>5</sub> WPPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> PPh <sub>2</sub>	2071 (2074) <sup>a</sup>	1982 (1986) <sup>a</sup>	1937 (1940) <sup>a</sup>
(OC) <sub>5</sub> CrPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P( <i>p</i> -tol) <sub>2</sub>	2063	1983	1939
(OC) <sub>5</sub> MoPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P( <i>p</i> -tol) <sub>2</sub>	2073	1989	1945
(OC) <sub>5</sub> WPPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P( <i>p</i> -tol) <sub>2</sub>	2071	1981	1937
(OC) <sub>5</sub> CrP( <i>p</i> -tol)CH <sub>2</sub> CH <sub>2</sub> PPh <sub>2</sub>	2062	1982	1937
(OC) <sub>5</sub> MoP( <i>p</i> -tol) <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> PPh <sub>2</sub>	2072	1989	1943
(OC) <sub>5</sub> WP( <i>p</i> -tol) <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> PPh <sub>2</sub>	2071	1981	1936

<sup>a</sup> reference 67 (CHCl<sub>3</sub>)

Table 10. <sup>31</sup>P{<sup>1</sup>H} NMR Data of Diphosphine Oxide Complexes  
(CDCl<sub>3</sub>)

Complex	δ <sub>P-W</sub> (ppm)	δ <sub>P-O</sub> (ppm)	<sup>3</sup> J <sub>PP</sub> (Hz)	<sup>1</sup> J <sub>WP</sub> (Hz)
(OC) <sub>5</sub> WPPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P(O)Ph <sub>2</sub>	13.6 <sup>a</sup> 13.3 <sup>b</sup>	33.1 <sup>a</sup> 31.6 <sup>b</sup>	47.5 <sup>a</sup> 48.8 <sup>b</sup>	239.9 <sup>a</sup> 241.5 <sup>b</sup>
(OC) <sub>5</sub> WPPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P(O)( <i>p</i> -tol) <sub>2</sub>	13.8	32.4	48.1	
(OC) <sub>5</sub> WP( <i>p</i> -tol) <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P(O)Ph <sub>2</sub>	11.8	32.2	48.0	
(OC) <sub>5</sub> CrPPh <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P(O)P( <i>p</i> -tol) <sub>2</sub>	50.8 <sup>c</sup>	28.1 <sup>c</sup>	46.4 <sup>c</sup>	

<sup>a</sup> in (CDCl<sub>2</sub>)<sub>2</sub>

<sup>b</sup> reference 86

<sup>c</sup> in C<sub>6</sub>D<sub>5</sub>(CD<sub>3</sub>)

Table 11. Properties of Chelated Complexes ( $\text{CDCl}_3$ )

Complex	mp ( $^{\circ}\text{C}$ )	$\delta_{\text{PPh}_2}$ (ppm)	$\delta_{\text{P}(\text{tol})_2}$ (ppm)	$J_{\text{PP}}$ (Hz)	$^1J_{\text{WP}}$ (Hz)
$(\text{OC})_4\text{Cr}(\text{dpdt})$	(118-119) <sup>a</sup>	80.8 <sup>b</sup>	78.6 <sup>b</sup>	11.3 <sup>b</sup>	
$(\text{OC})_4\text{Mo}(\text{dpdt})$	147-148 (132) <sup>a</sup>	55.8	53.6	5.7	
$(\text{OC})_4\text{W}(\text{dpdt})$	(165) <sup>a</sup>	41.1	39.1	5.6	
$(\text{OC})_4\text{W}(\text{dppe})$	(206-207) <sup>c</sup>	41.3 (40.1) <sup>c</sup>			230.2 (231) <sup>c</sup>

<sup>a</sup> reference 60      <sup>b</sup> in  $\text{C}_6\text{D}_5(\text{CD}_3)$       <sup>c</sup> reference 87

Table 12. IR Data of Chelated Complexes ( $\text{cm}^{-1}$ )

Complex	$A_1^{(2)}$	$A_1^{(1)}$	$B_1$	$B_1$
$(\text{OC})_4\text{Cr}(\text{dpdt})$ <sup>a</sup>	2030	1898	1890	1855
$(\text{OC})_4\text{Mo}(\text{dpdt})$	2021 <sup>b</sup> (2010) <sup>a</sup>	1909 <sup>b</sup> (1910) <sup>a</sup>	1882 <sup>b</sup> (1855) <sup>a</sup>	(1840) <sup>a</sup>
$(\text{OC})_4\text{W}(\text{dpdt})$ <sup>a</sup>	2005	1930	1910	1880
$(\text{OC})_4\text{W}(\text{dppe})$ <sup>c</sup>	2019	1922	1909	1897

<sup>a</sup> reference 60 (KBr)      <sup>b</sup> this work ( $\text{CH}_2\text{Cl}_2$ )

<sup>c</sup> reference 87 ( $\text{ClCH}_2\text{CH}_2\text{Cl}$ )

Table 13. Variable Temperature  $^{31}\text{P}\{^1\text{H}\}$  NMR Data of  
 $(\text{OC})_5\text{W}(\text{dppe}) [(\text{CDCl}_2)_2]$

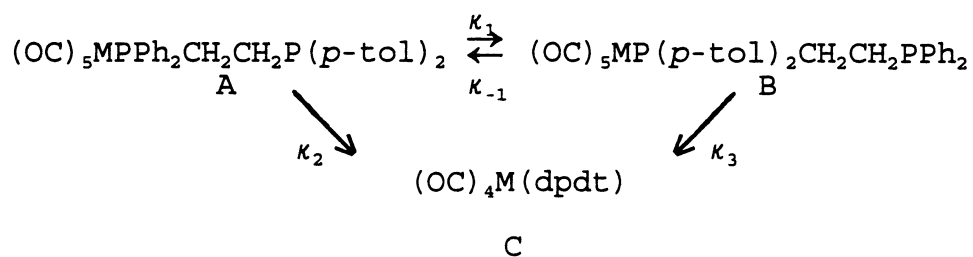
T (°C)	$\delta_{\text{P-W}}$ (ppm)	$\delta_{\text{P}}$ (ppm)	$^1\text{J}_{\text{WP}}$ (Hz)	$^3\text{J}_{\text{PP}}$ (Hz)
30	13.3	-11.6	238.5	36.7
50	13.3	-11.5	237.2	36.7
65	13.3	-11.3	239.3	35.9
80	13.4	-10.9	241.6	36.6

Table 14. Variable Temperature  $^{31}\text{P}\{^1\text{H}\}$  NMR Data of  
 $(\text{OC})_5\text{W}(\text{dppm}) [\text{C}_6\text{D}_5(\text{CD}_3)]$

T (°C)	$\delta_{\text{P-W}}$ (ppm)	$\delta_{\text{P}}$ (ppm)	$^2\text{J}_{\text{PP}}$ (Hz)	$^1\text{J}_{\text{WP}}$ (Hz)
-50	11.2	-23.7	122.4	245.5
-30	11.2	-23.6	121.0	245.3
-10	11.2	-23.6	119.0	
10	11.2	-23.6	116.6	
30	11.2	-23.5	114.0	
50	11.3	-23.4	111.7	246.9
70	11.4	-23.2	110.6	246.5
room <sup>a</sup>	10.0	-24.8	106.2	245.6 ( $^3\text{J}_{\text{WP}}$ 6.3)

<sup>a</sup> reference 86 ( $\text{CDCl}_3$ )

Table 15. Kinetic Data of Isomerization and Chelation at 55°C.



M	solvent	$k_1$ $10^8 \text{ s}^{-1}$	$k_{-1}$ $10^8 \text{ s}^{-1}$	$k_2$ $10^8 \text{ s}^{-1}$	$k_3$ $10^8 \text{ s}^{-1}$	$K_{\text{eq}} = k_1 / k_{-1}$
Cr	$(\text{CD}_3)\text{C}_6\text{D}_5$	1.22	0.65	1.15	1.24	1.88
Mo	$(\text{CD}_3)\text{C}_6\text{D}_5$	759	387	29.6	30.3	1.96
W	$(\text{CD}_3)\text{C}_6\text{D}_5$	2.31	0.97			2.38
W	$\text{CDCl}_3$	2.03	1.25	0.32	0.46	1.62

Figure 1.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of P(p-tol),

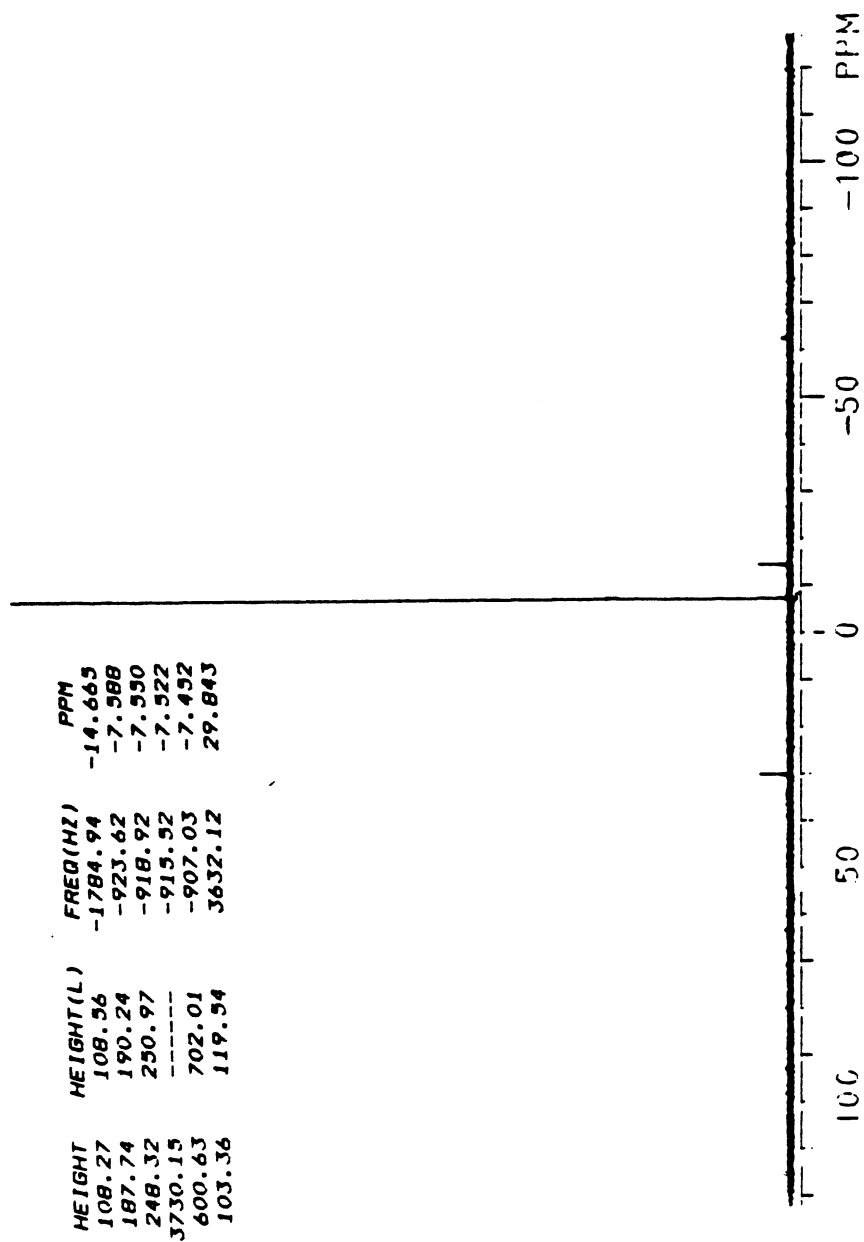




Figure 2.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of P(p-tol) $_2$ H

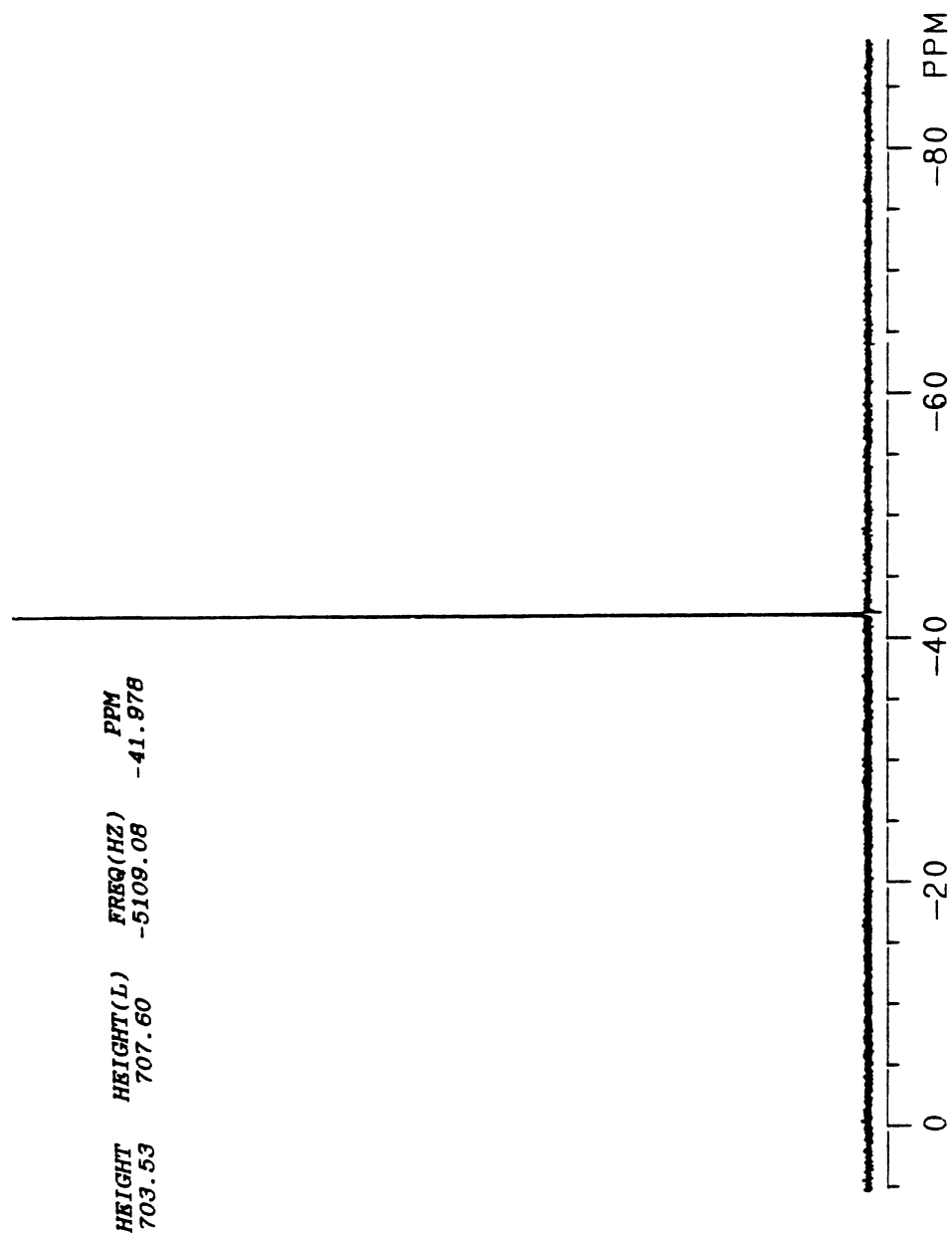


Figure 3.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
(*p*-tol) $_2\text{PCH}_2\text{CH}_2\text{P}$ (*p*-tol) $_2$  (dpdt)

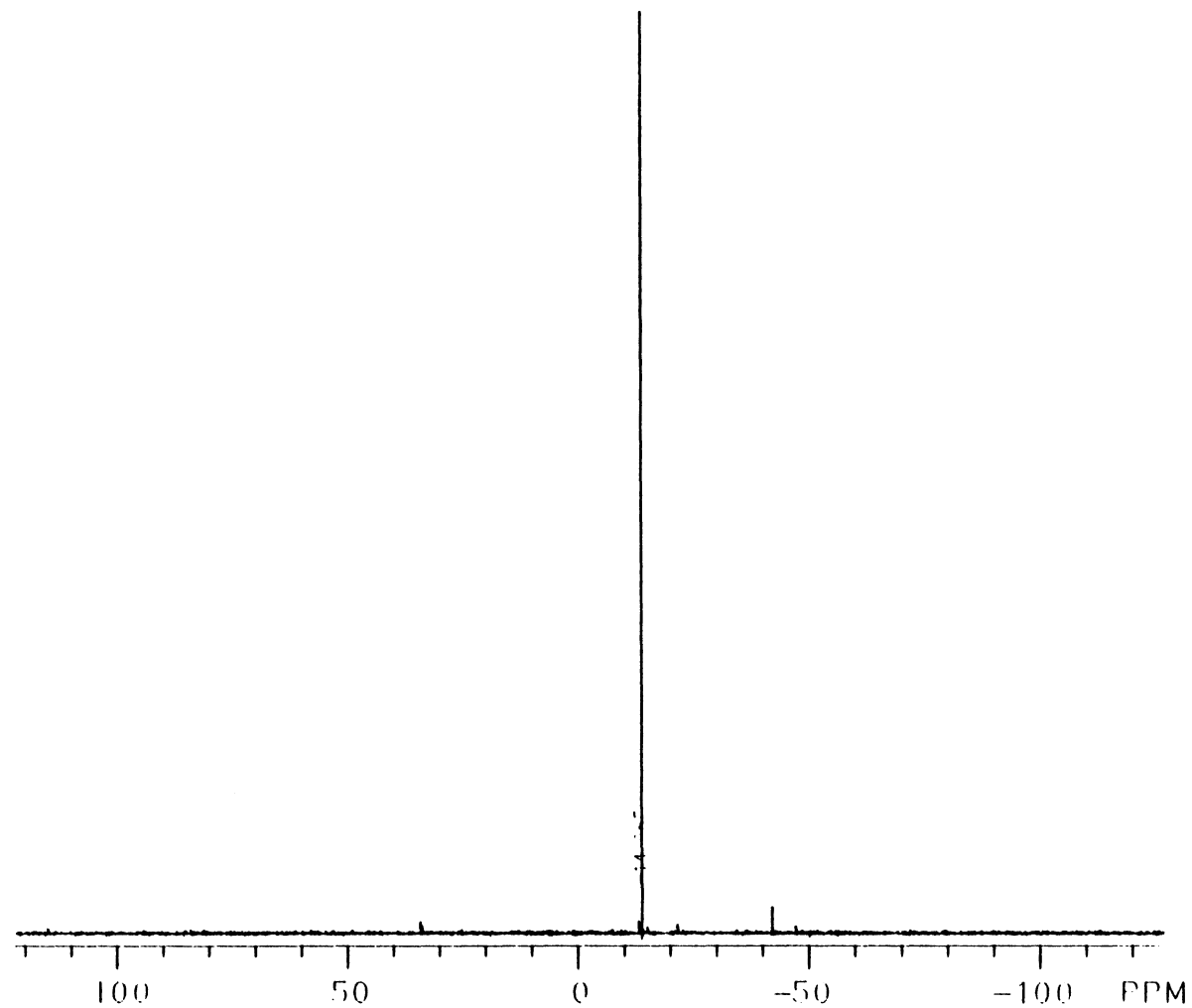


Figure 4.  $^1\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $\text{PPh}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-tol})_2$

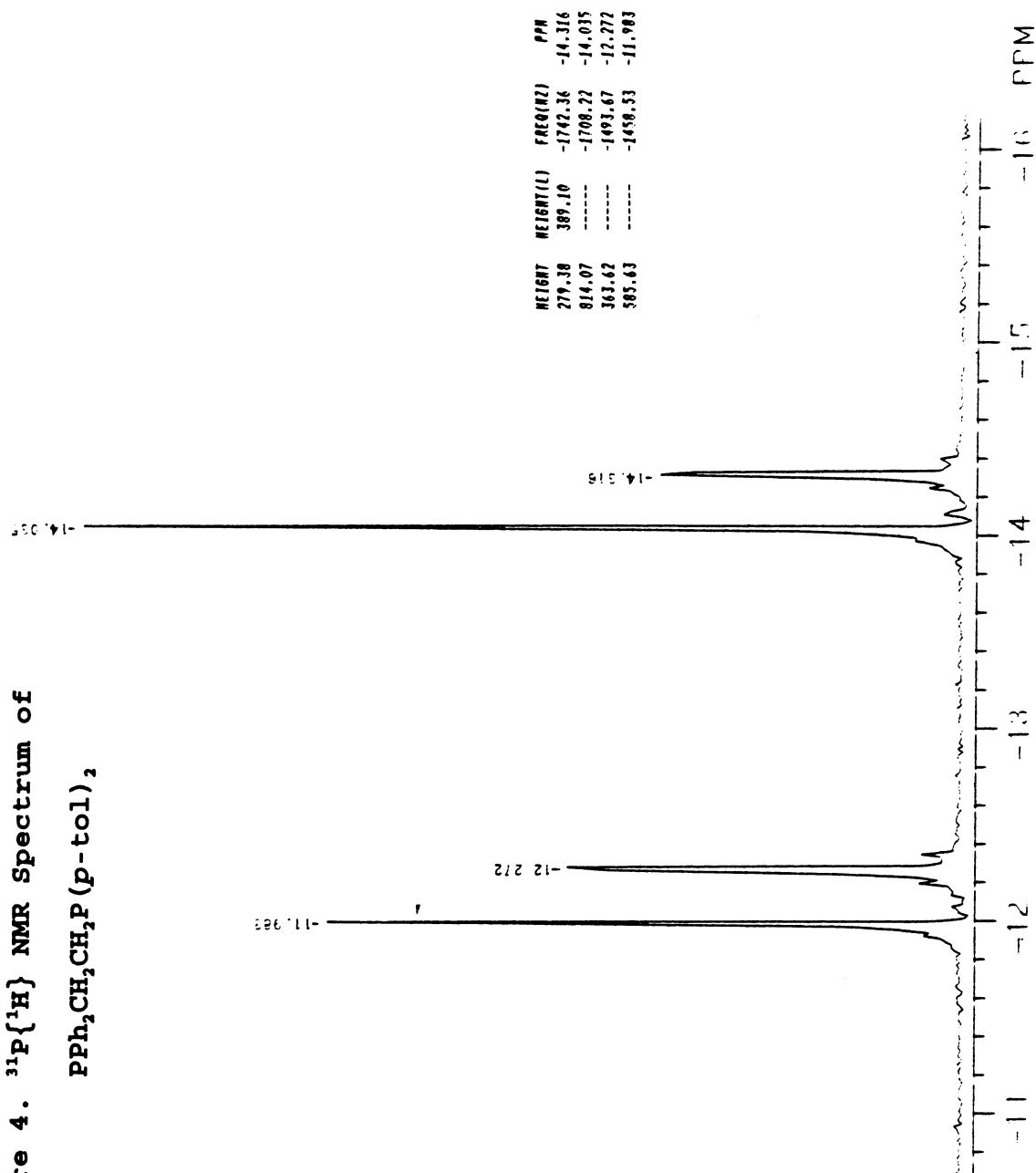


Figure 5.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{CrP}(\text{p-tol})_2\text{H}$

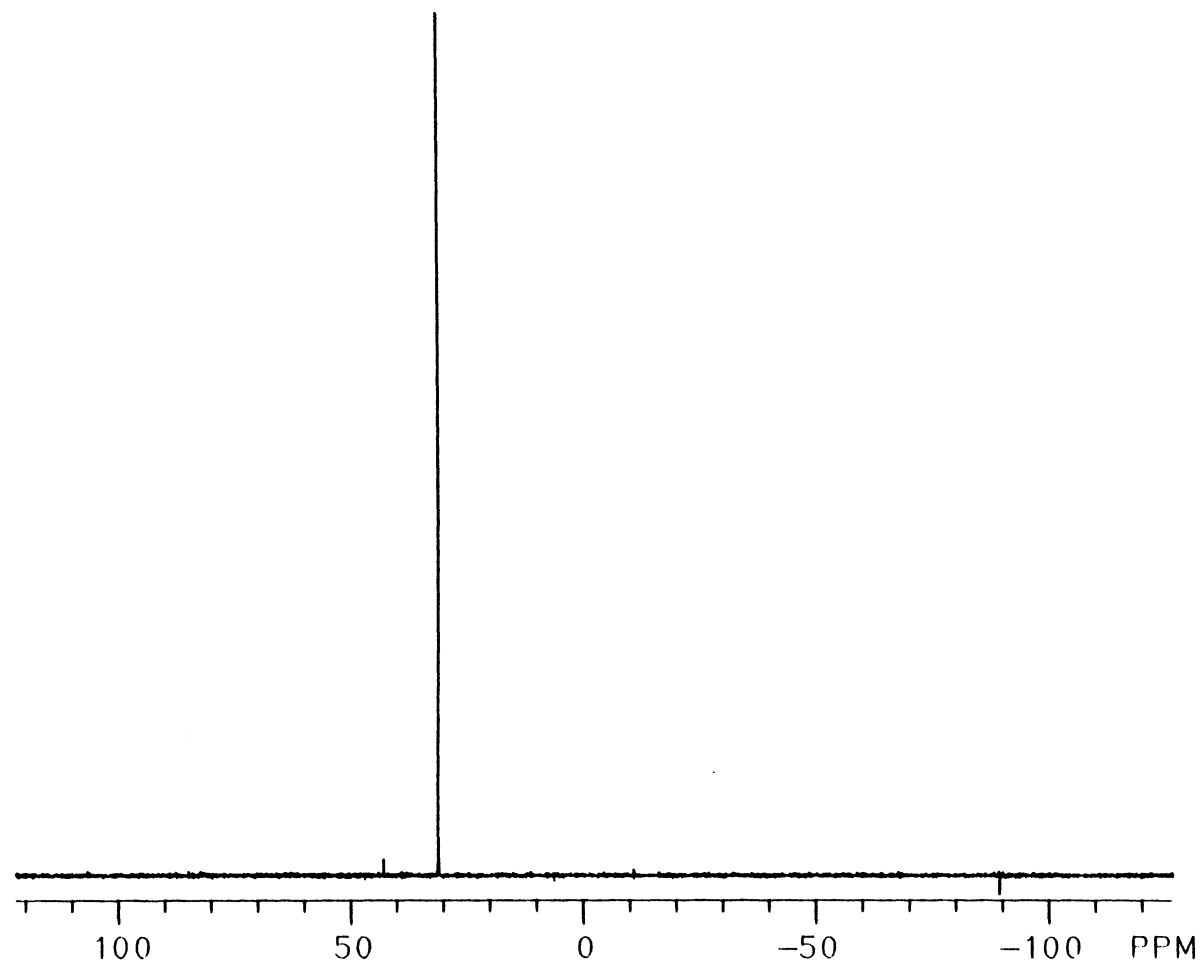


Figure 6.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{MoP}(\text{p-tol})_2\text{H}$

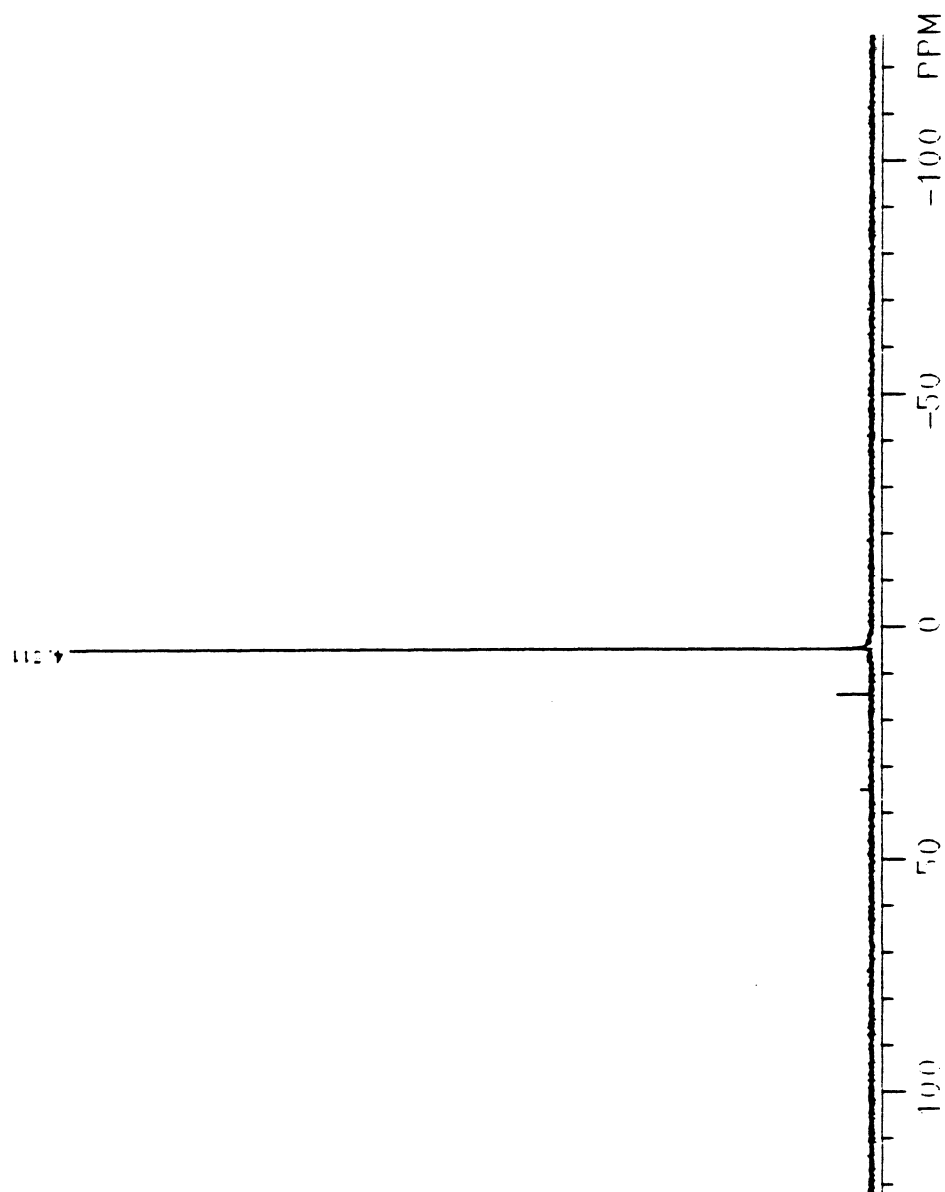


Figure 7.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{WP}(\text{p-tol})_2\text{H}$

HEIGHT	HEIGHT(L)	FREQ(HZ)	PPM
106.30	185.87	-1885.98	-16.399
1289.27	-----	-1880.99	-15.455
76.05	-----	-1766.32	-14.512

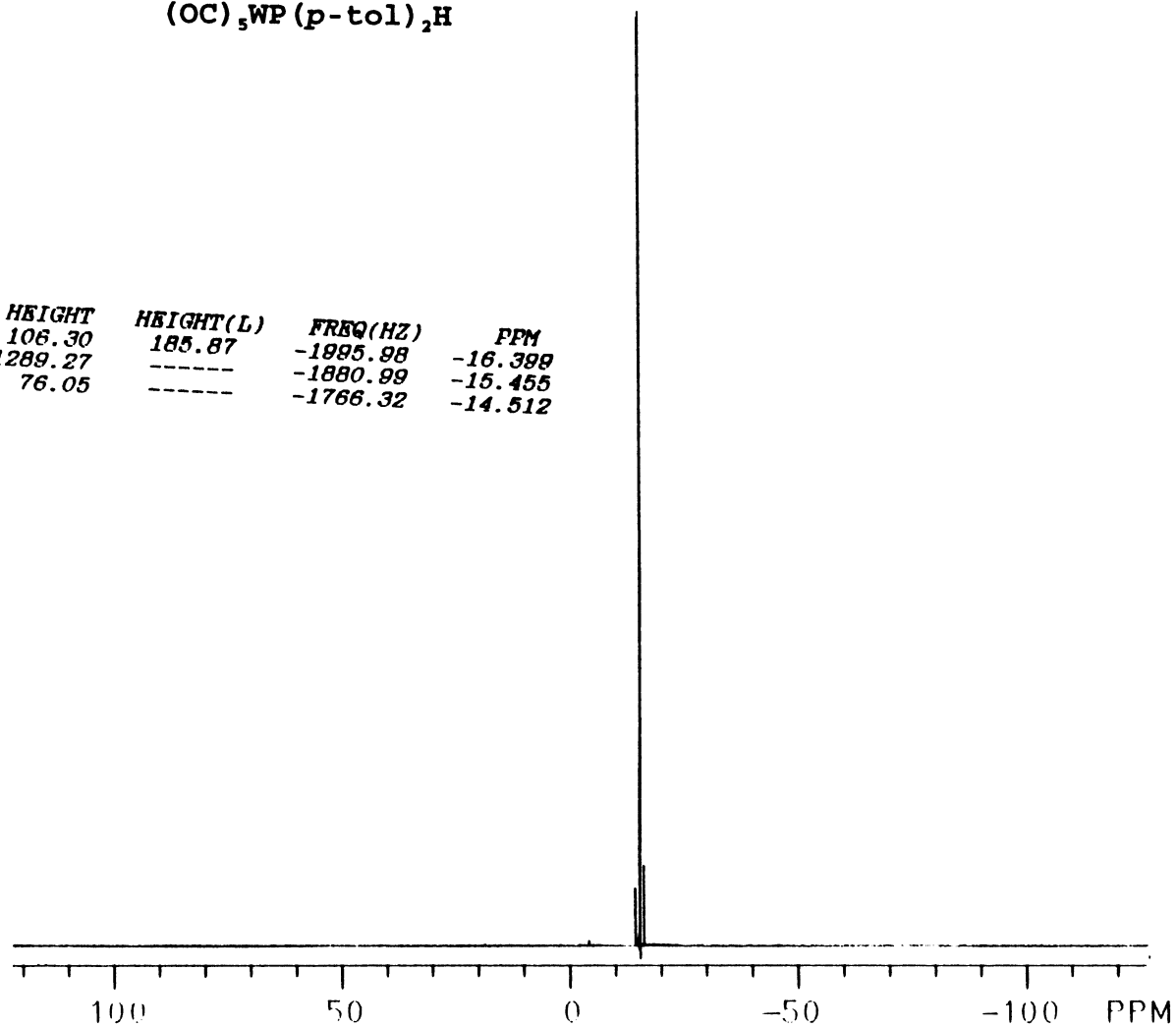


Figure 8. IR Spectrum of (OC)<sub>5</sub>CrP(p-tol)<sub>2</sub>H

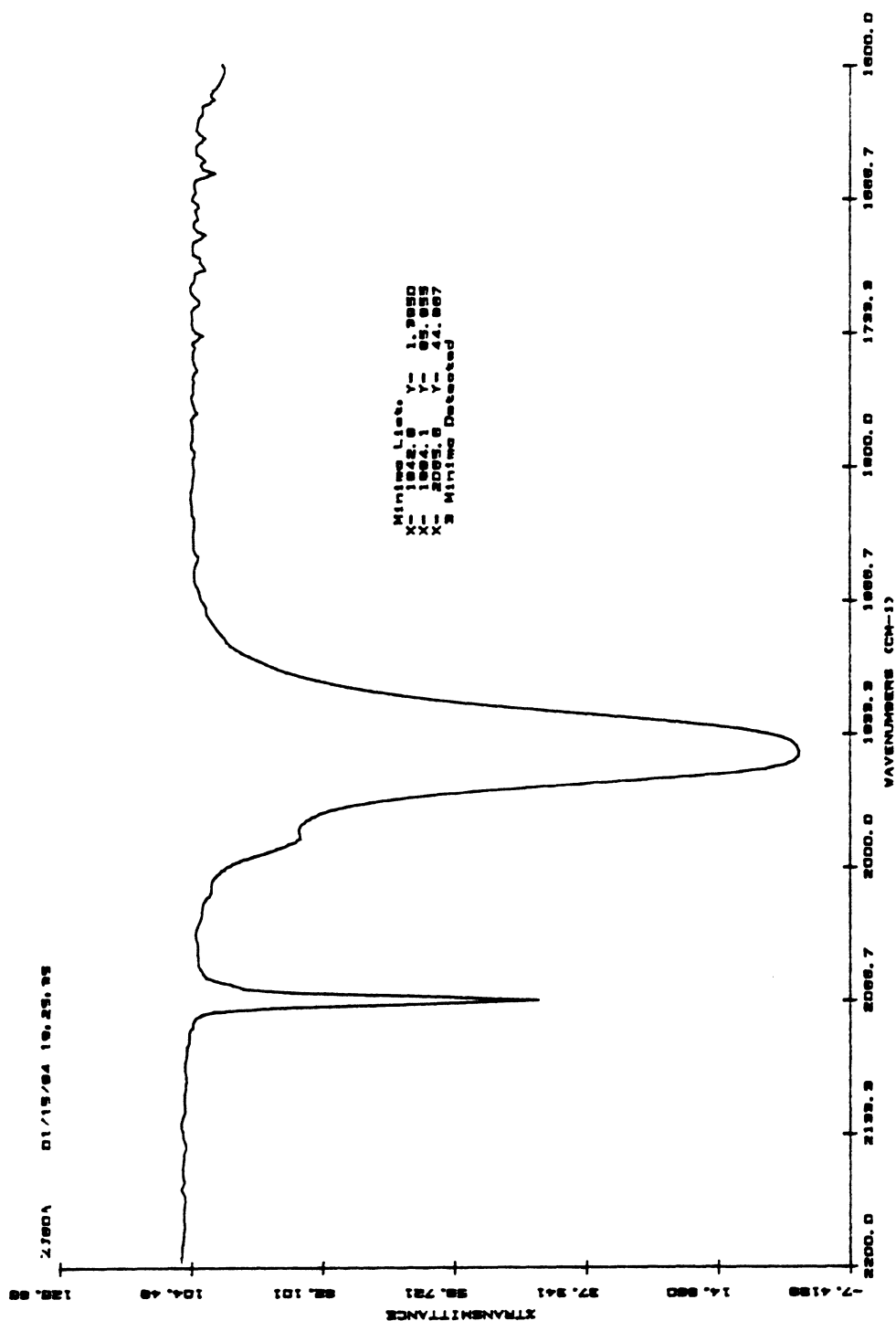


Figure 9. IR Spectrum of (OC)<sub>5</sub>MoP(*p*-tol)<sub>2</sub>H

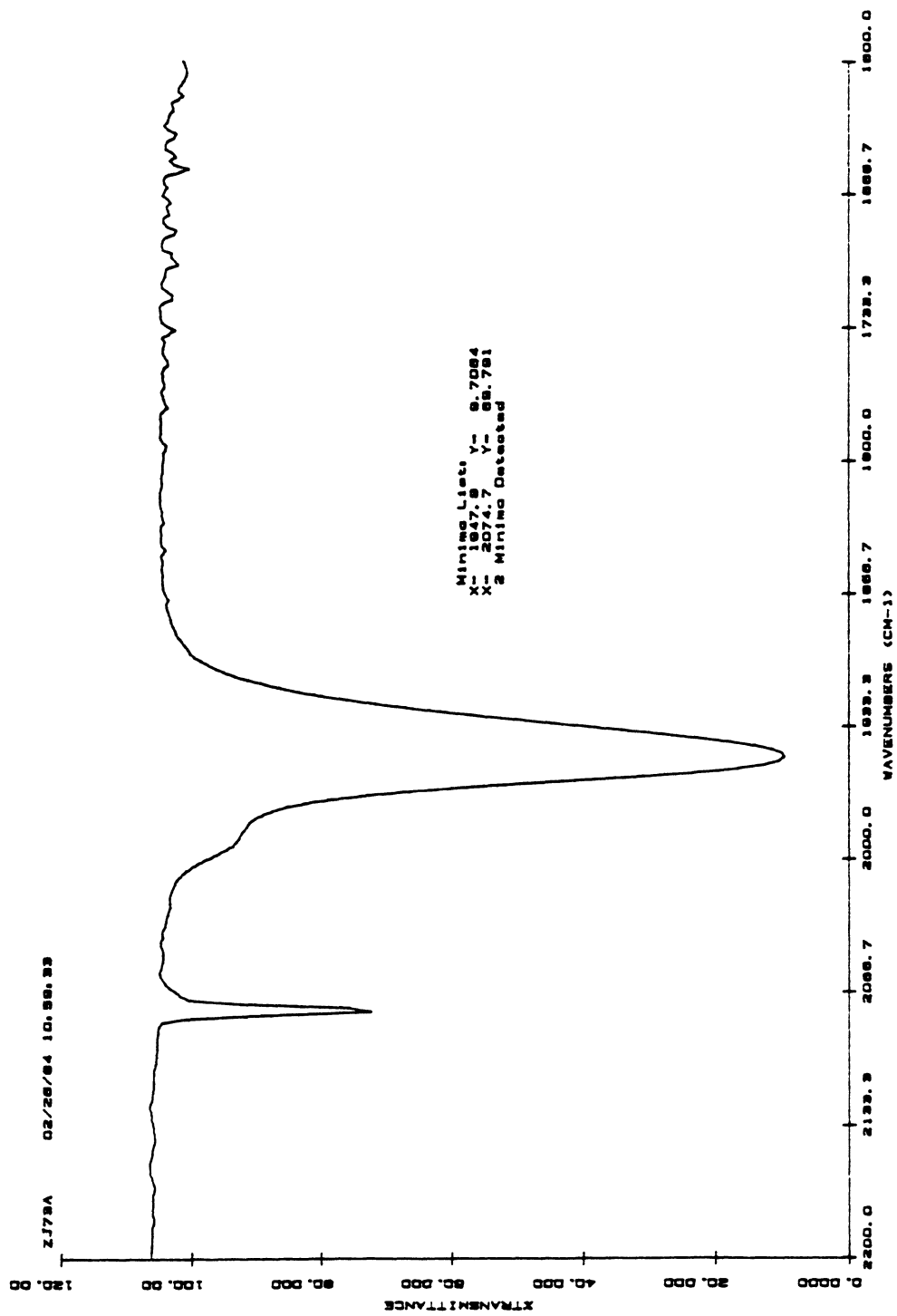






Figure 11.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
*cis*-(OC)<sub>4</sub>W[P(*p*-tol)<sub>2</sub>H]<sub>2</sub>

HEIGHT	HEIGHT(L)	FREQ(HZ)	PPM
139.38	-----	-639.94	-5.258
707.99	709.09	-527.06	-4.330
164.49	-----	-416.14	-3.419

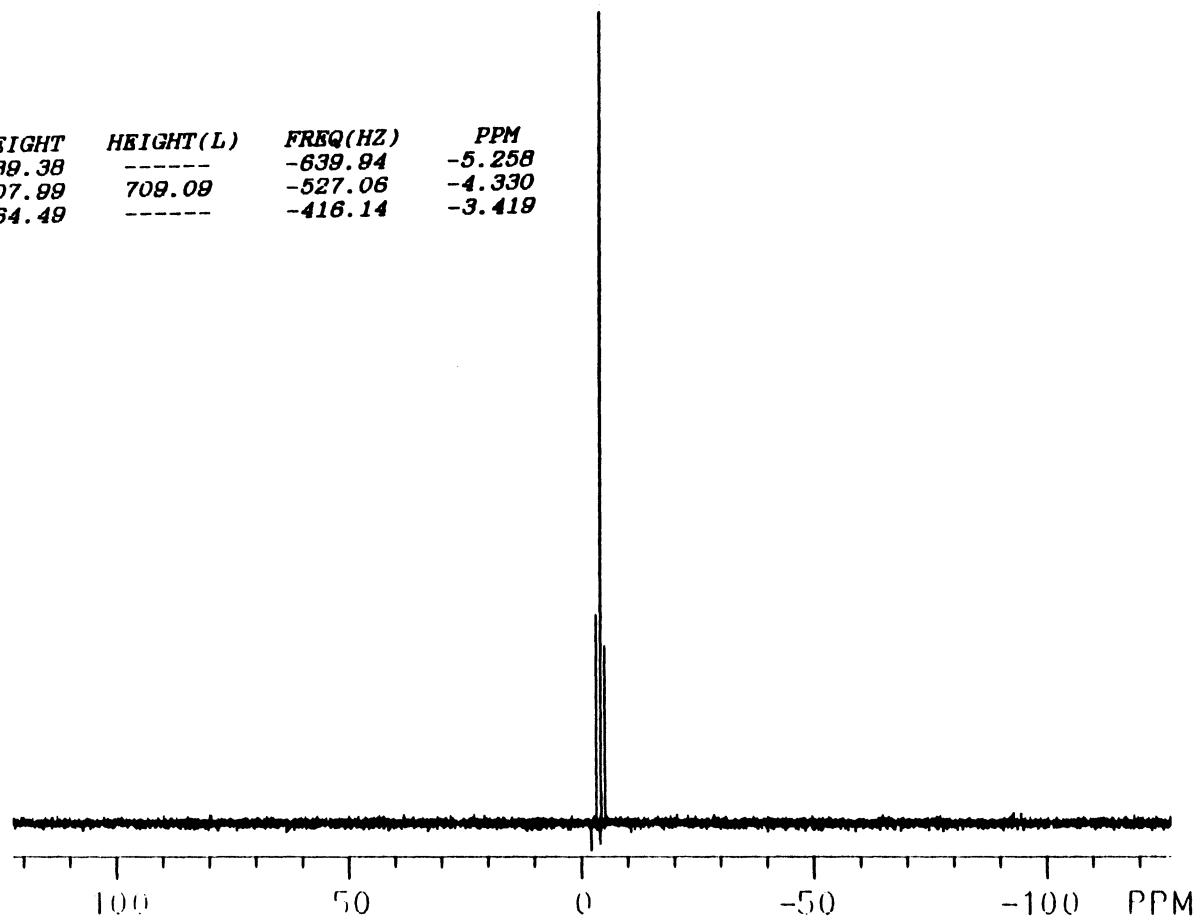


Figure 12.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $\text{cis} - (\text{OC})_4\text{Mo}(\text{PPh}_2\text{CH}=\text{CH}_2)_2$

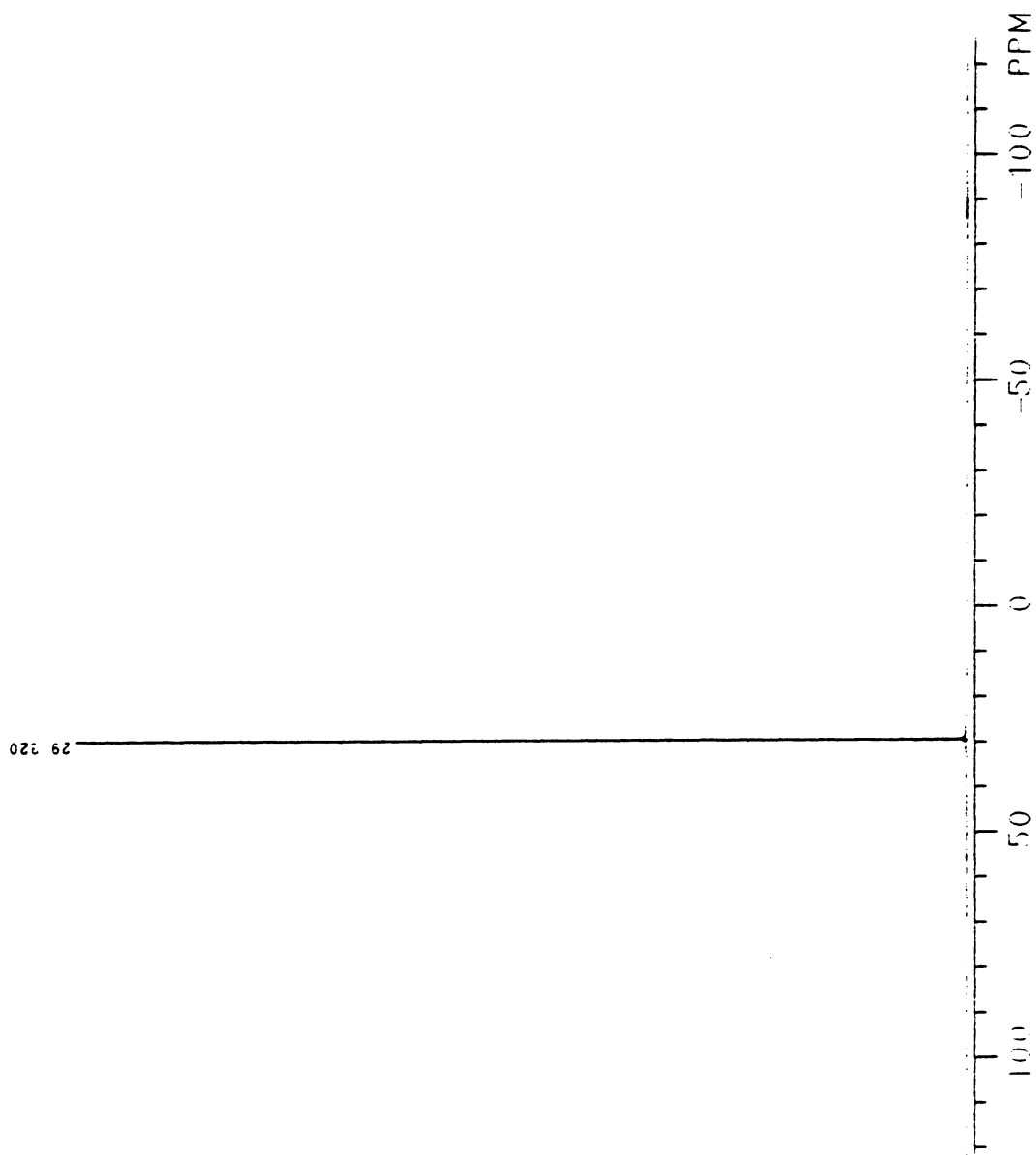


Figure 13.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
*cis* - (OC) $_4$ W(PPh $_3$ Et) (PPh $_3$ H)

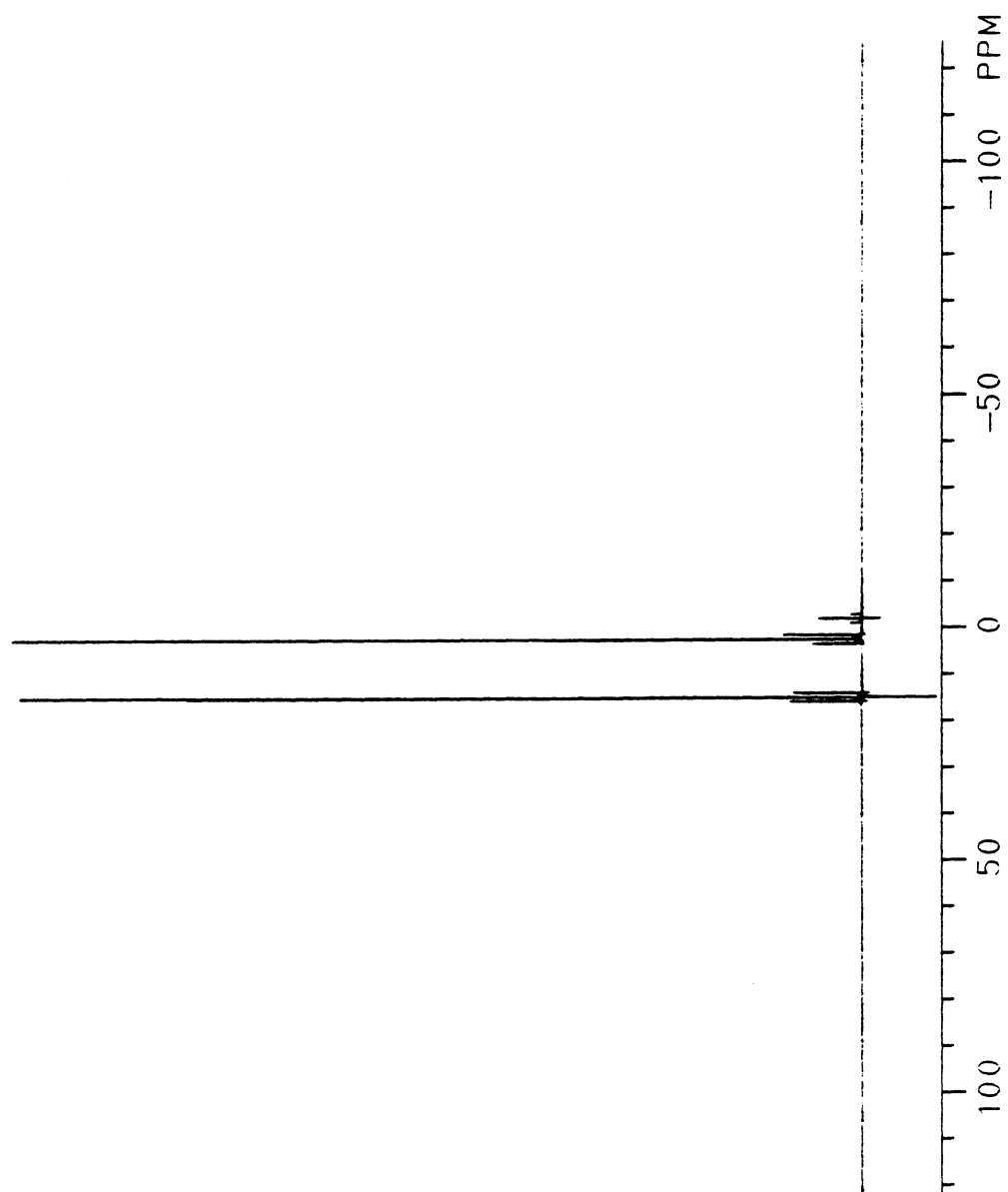


Figure 14. IR Spectrum of *cis*-(OC)<sub>4</sub>W[P(p-tol)<sub>2</sub>H]<sub>2</sub>

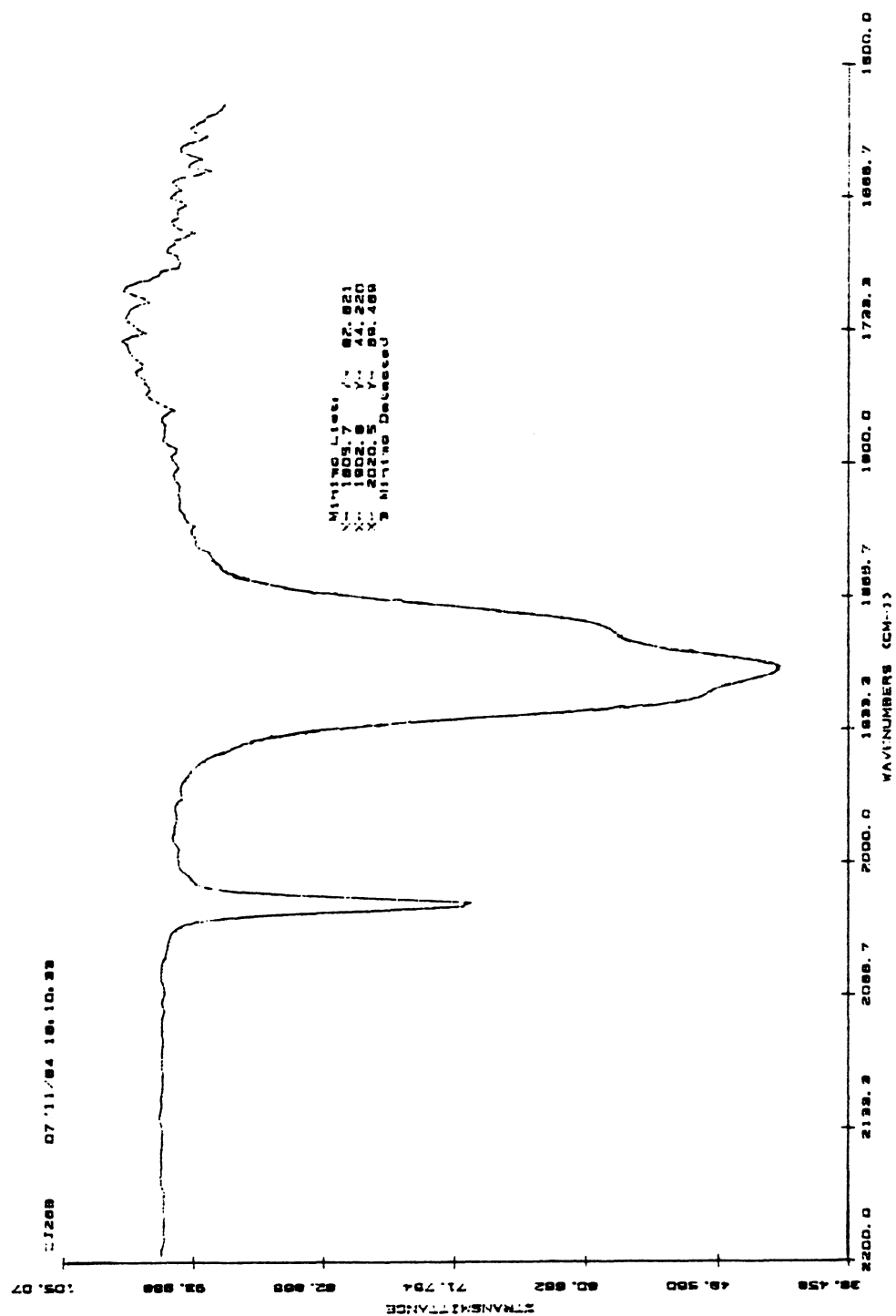


Figure 15. IR Spectrum of *cis*-(OC)<sub>4</sub>Mo(PPh<sub>2</sub>CH=CH<sub>2</sub>)<sub>2</sub>

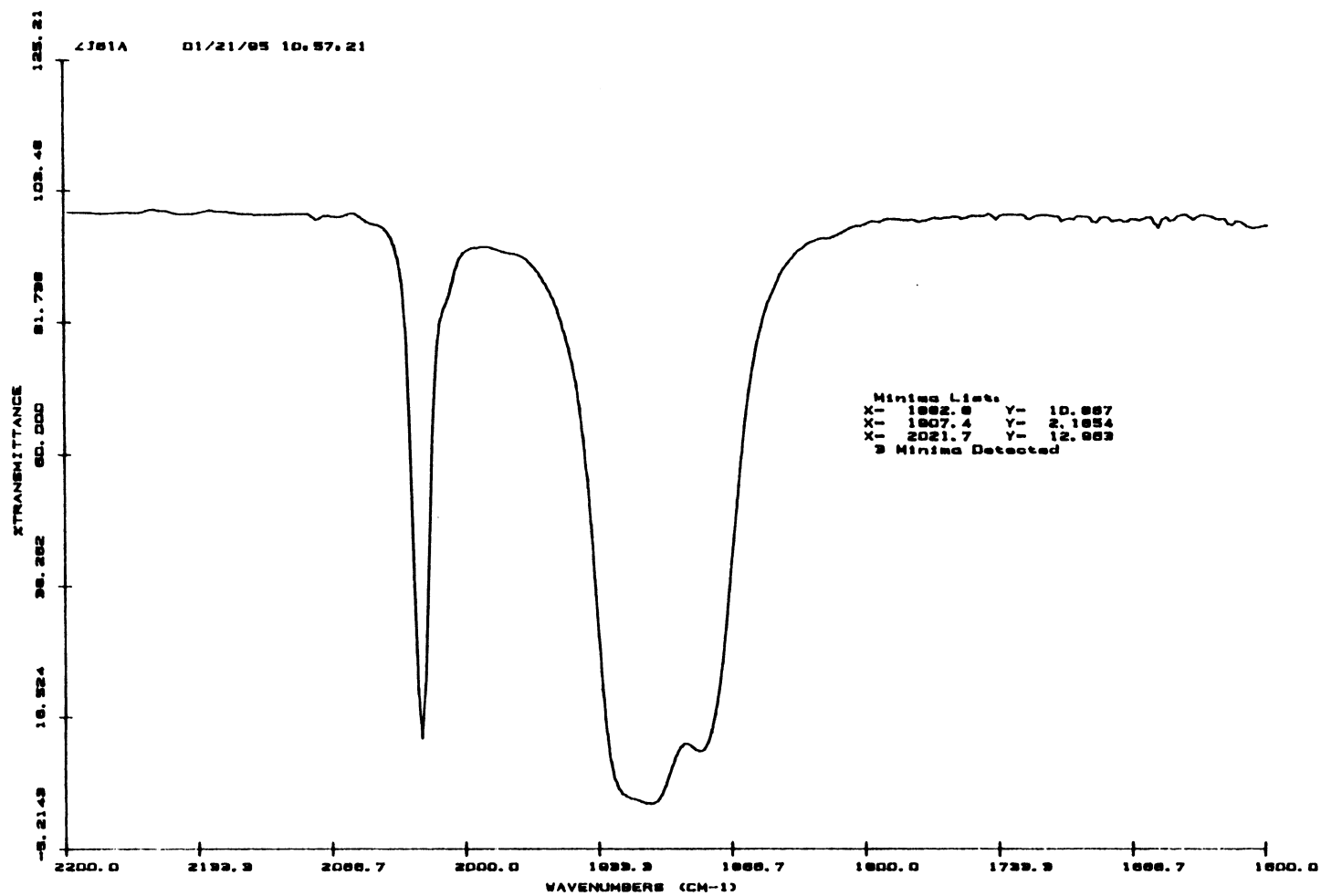


Figure 16. IR Spectrum of *cis*-(OC)<sub>4</sub>W(PPh<sub>2</sub>Et)(PPh<sub>2</sub>H)

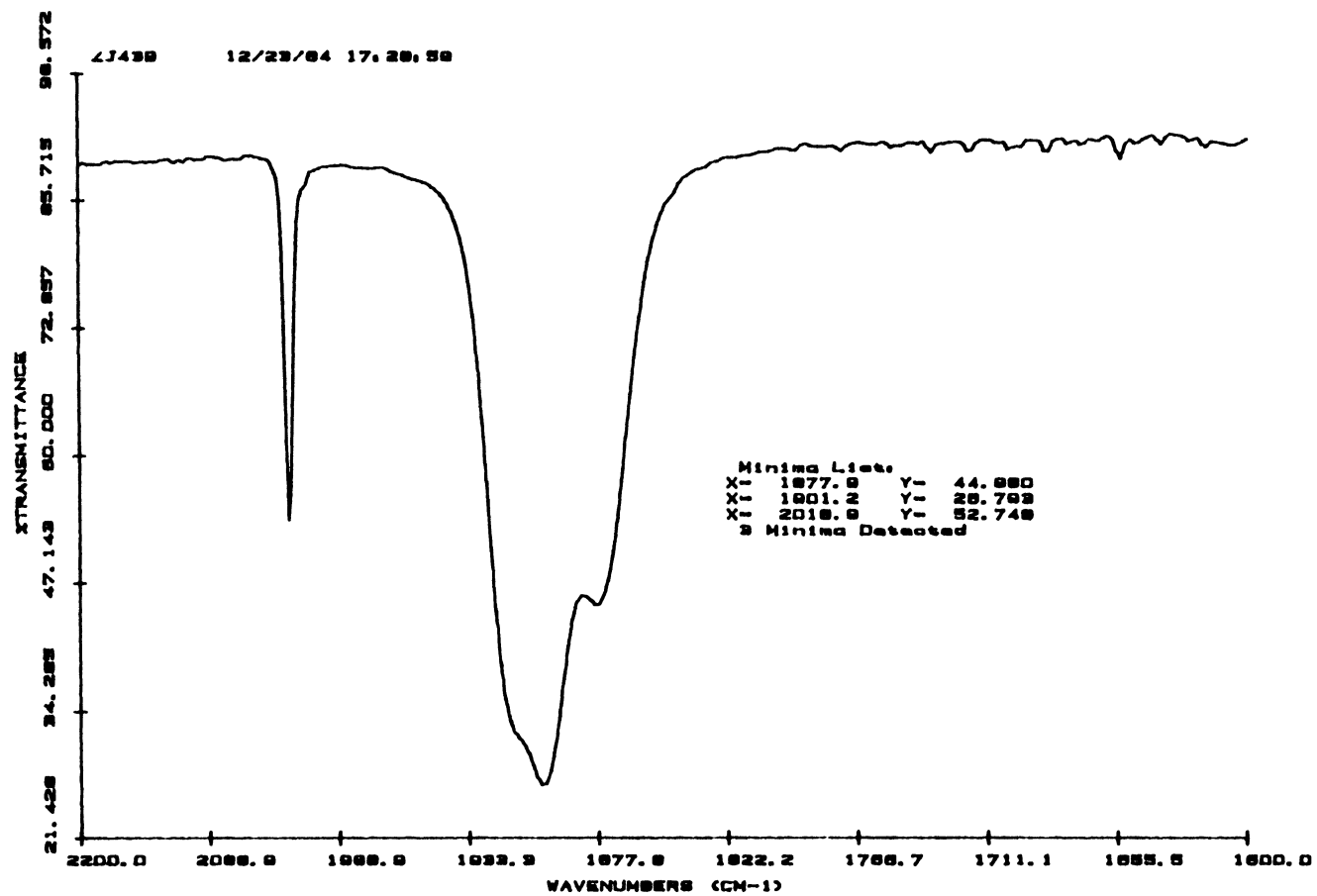


Figure 17.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{WPPh}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-tol})_2$

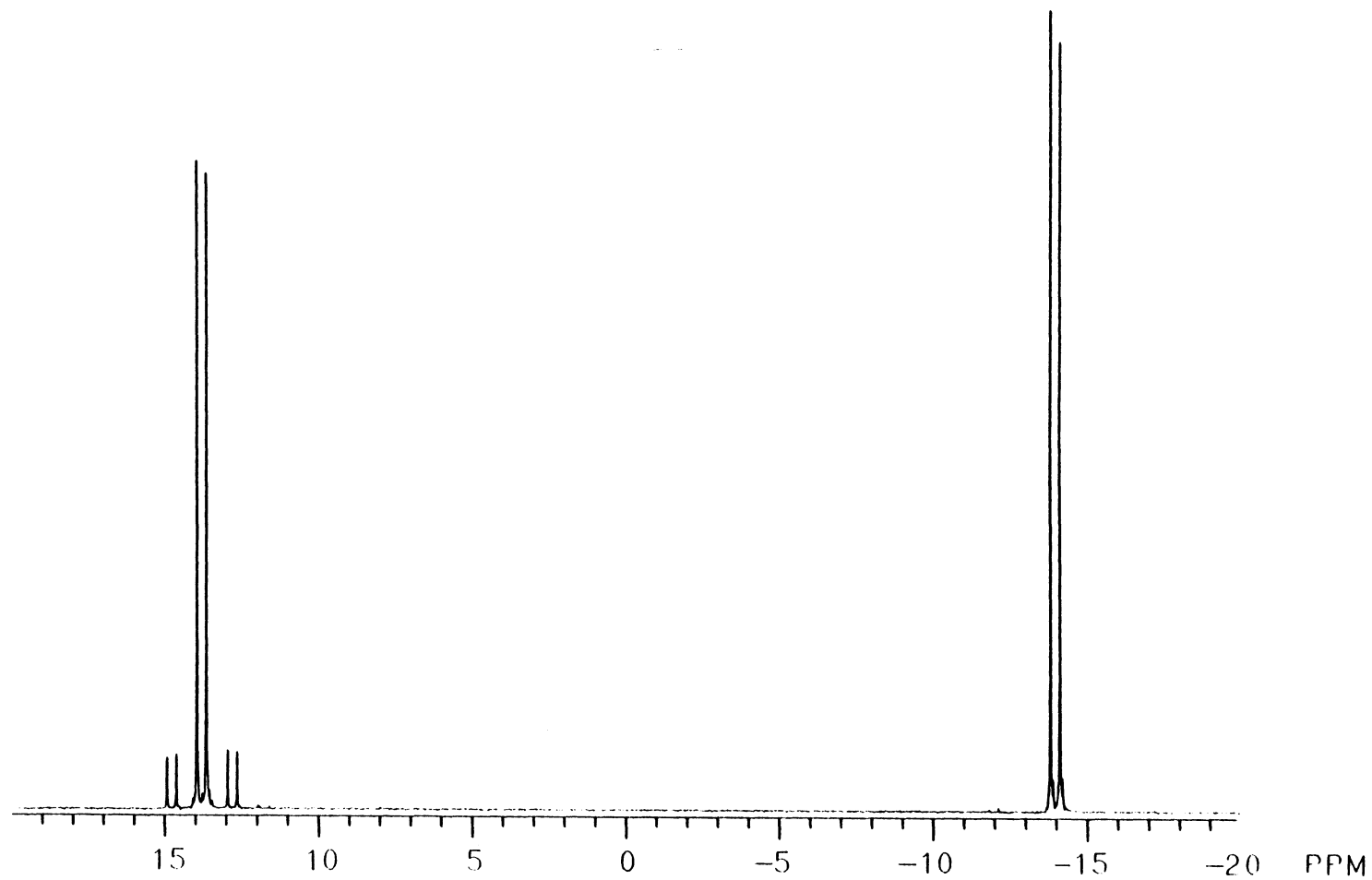




Figure 18. IR Spectrum of  $(OC)_3WPPH_2CH_2CH_2P(p-tol)_2$

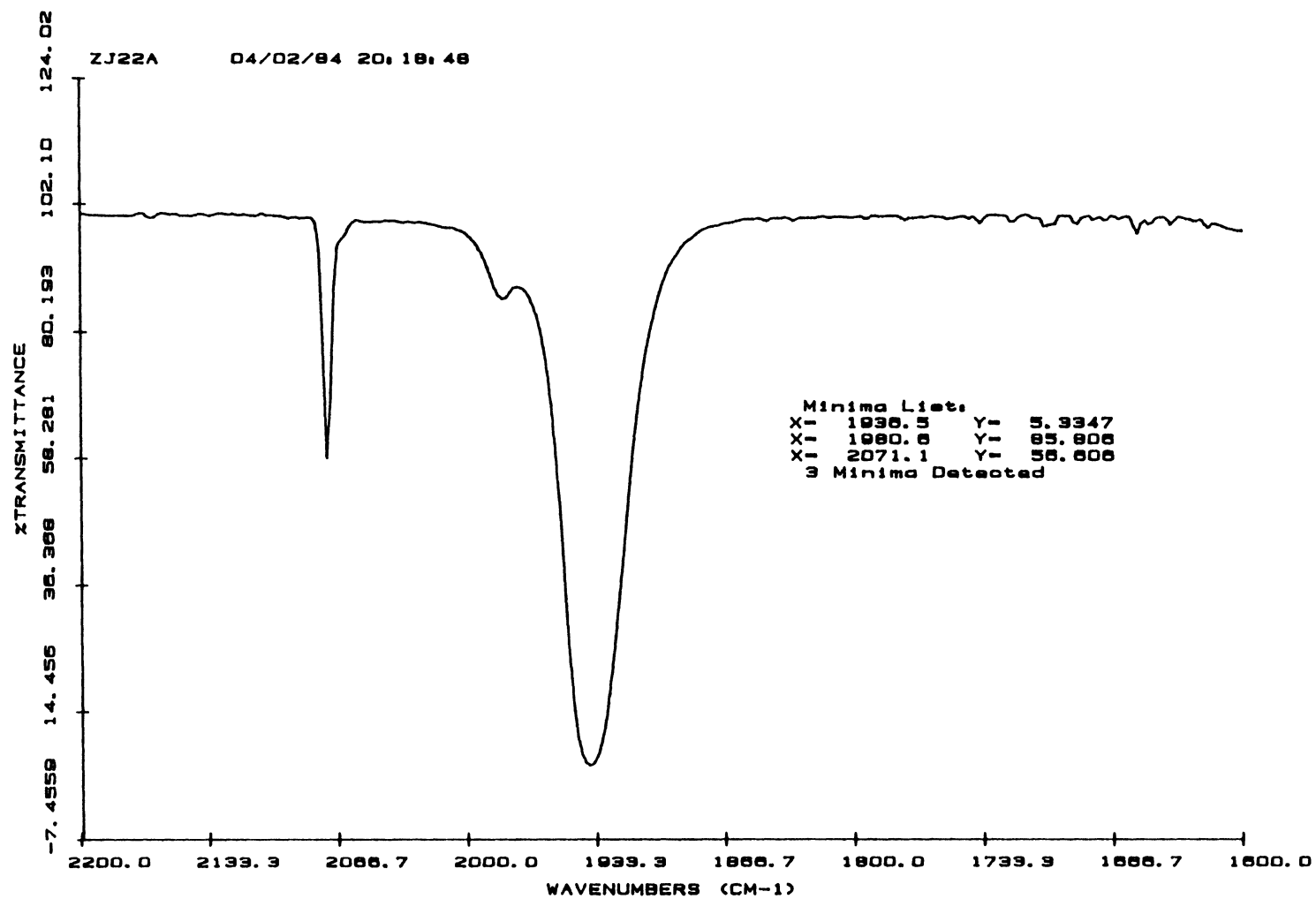


Figure 19.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{WP}(p\text{-tol})_2\text{CH}_2\text{CH}_2\text{PPh}_2$

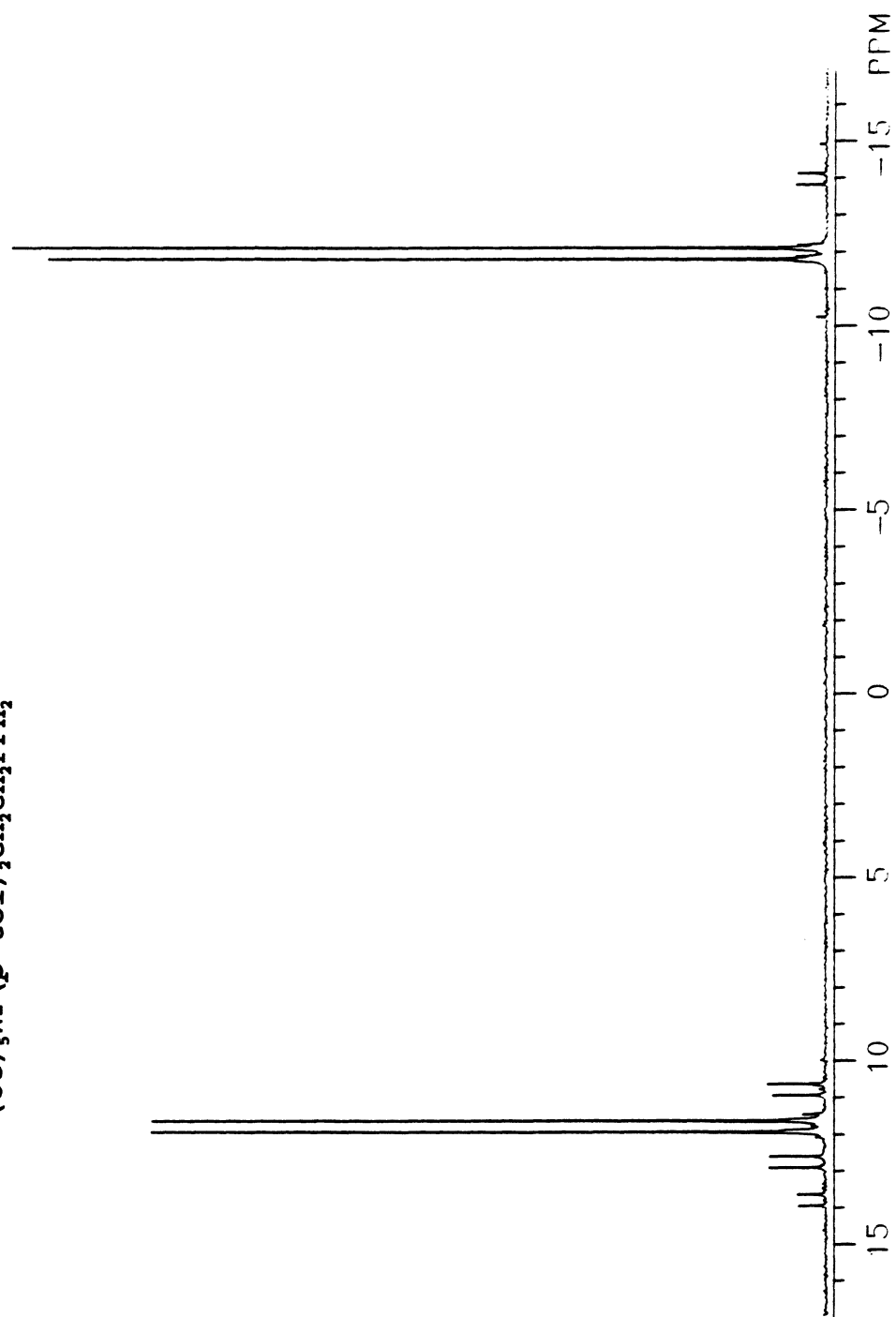


Figure 20. IR Spectrum of (OC)<sub>3</sub>WP(p-tol)<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>

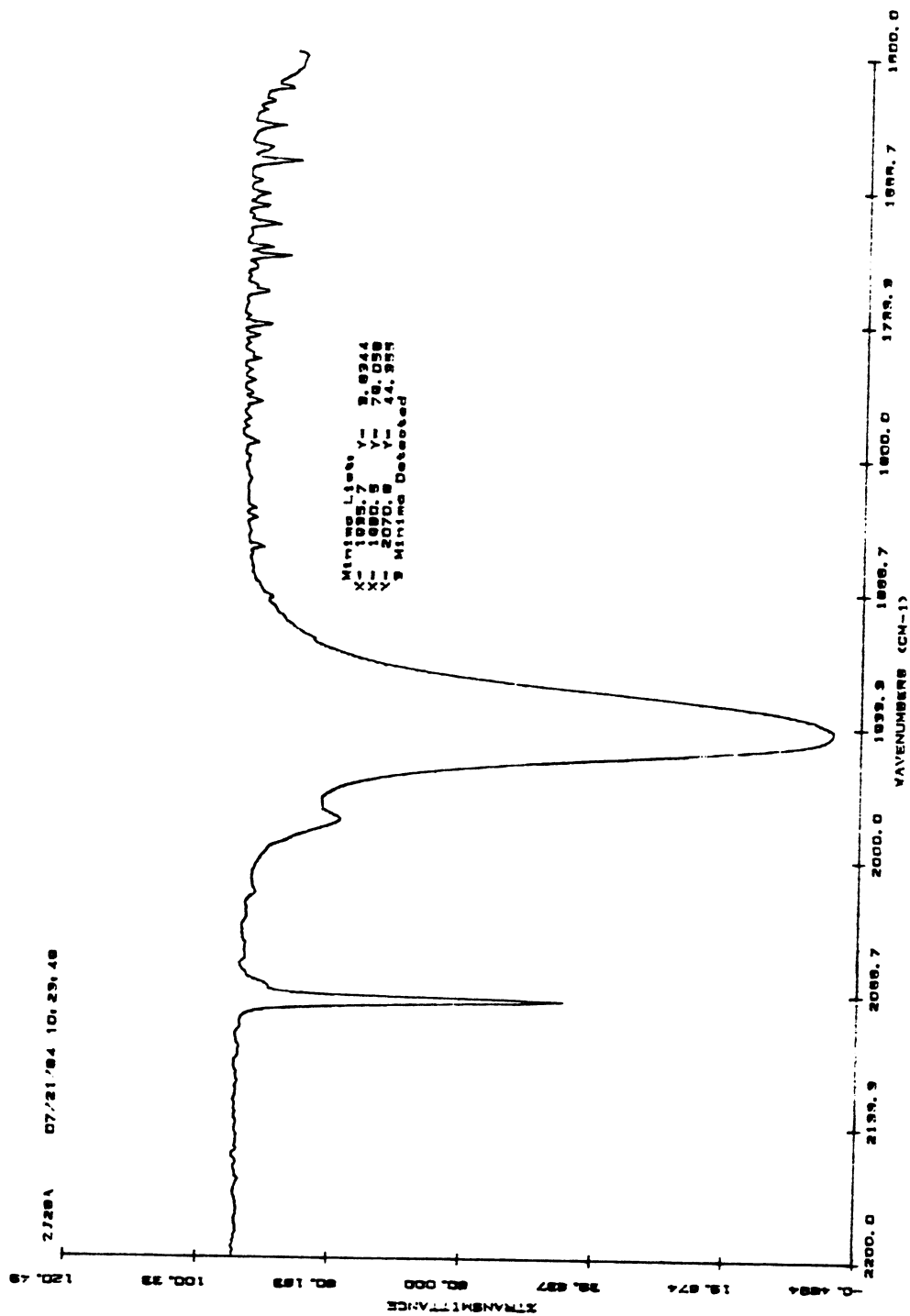


Figure 21.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{CrPPh}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-tol})_2$

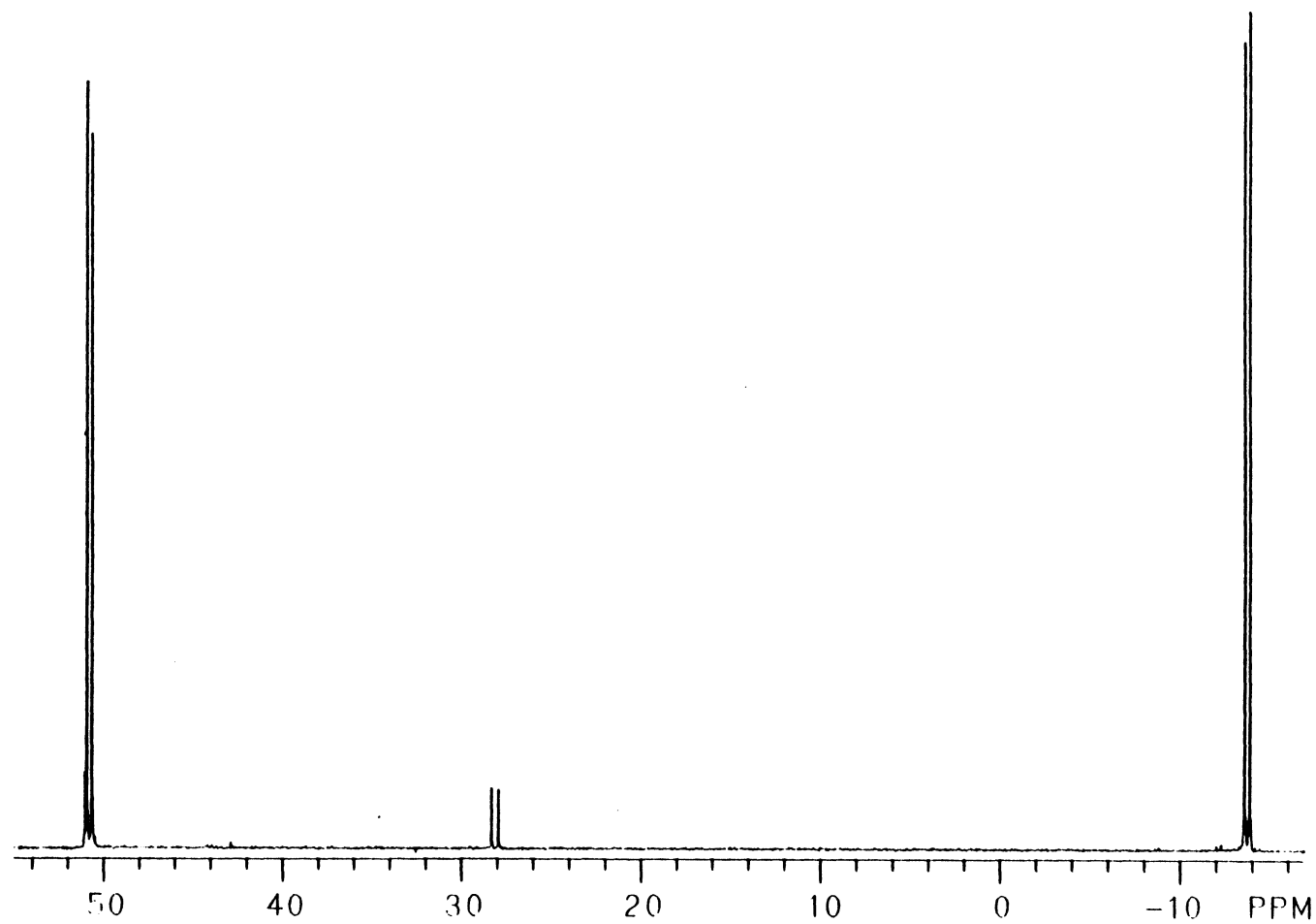


Figure 22. IR Spectrum of  $(OC)_5CrPPh_2CH_2CH_2P(p-tol)_2$

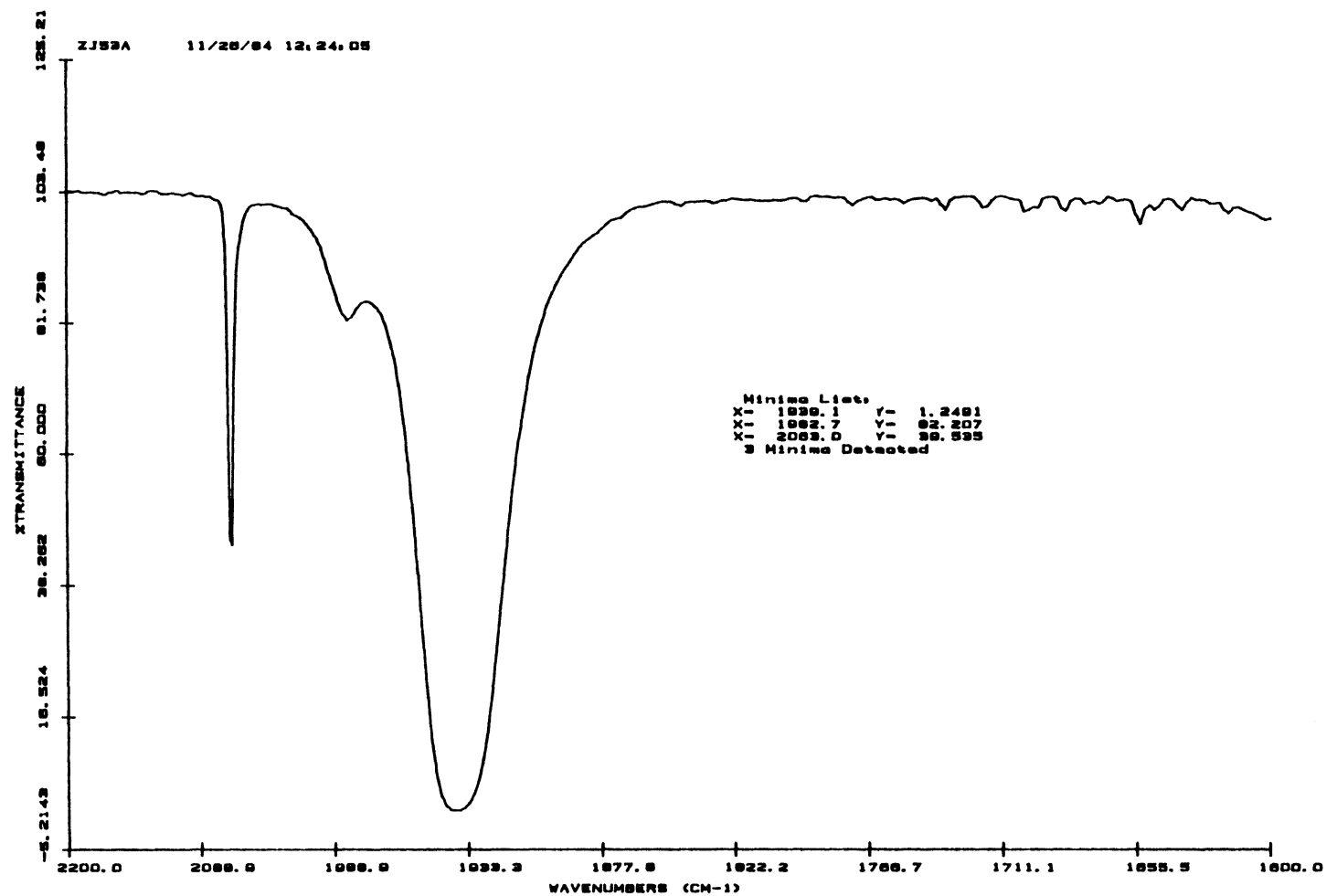


Figure 23.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{CrP}(p\text{-tol})_2\text{CH}_2\text{CH}_2\text{PPh}_2$

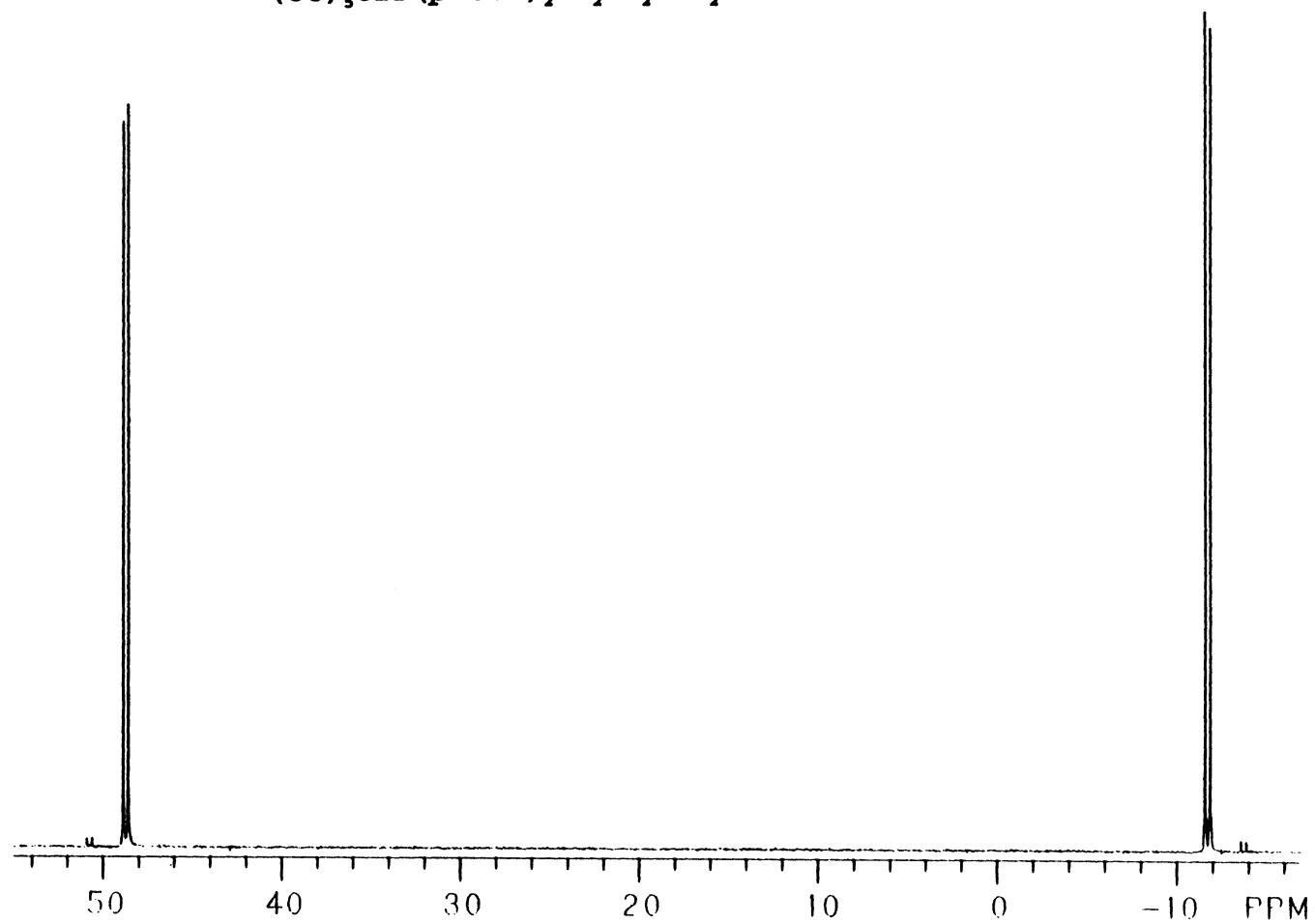




Figure 25.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{MoPPh}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-tol})_2$

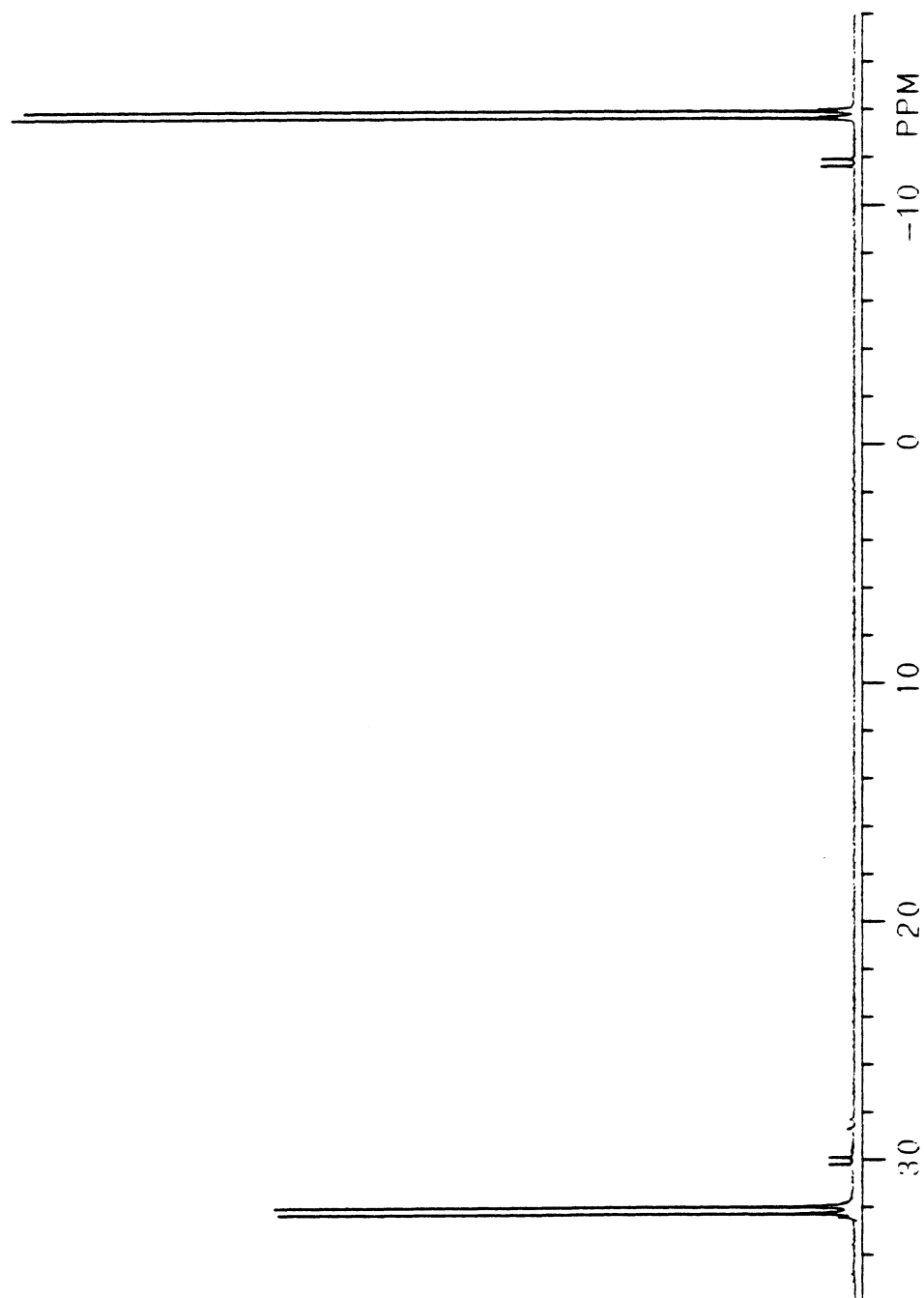




Figure 26. IR Spectrum of  $(OC)_5MoPPh_2CH_2CH_2P(p-tol)_2$

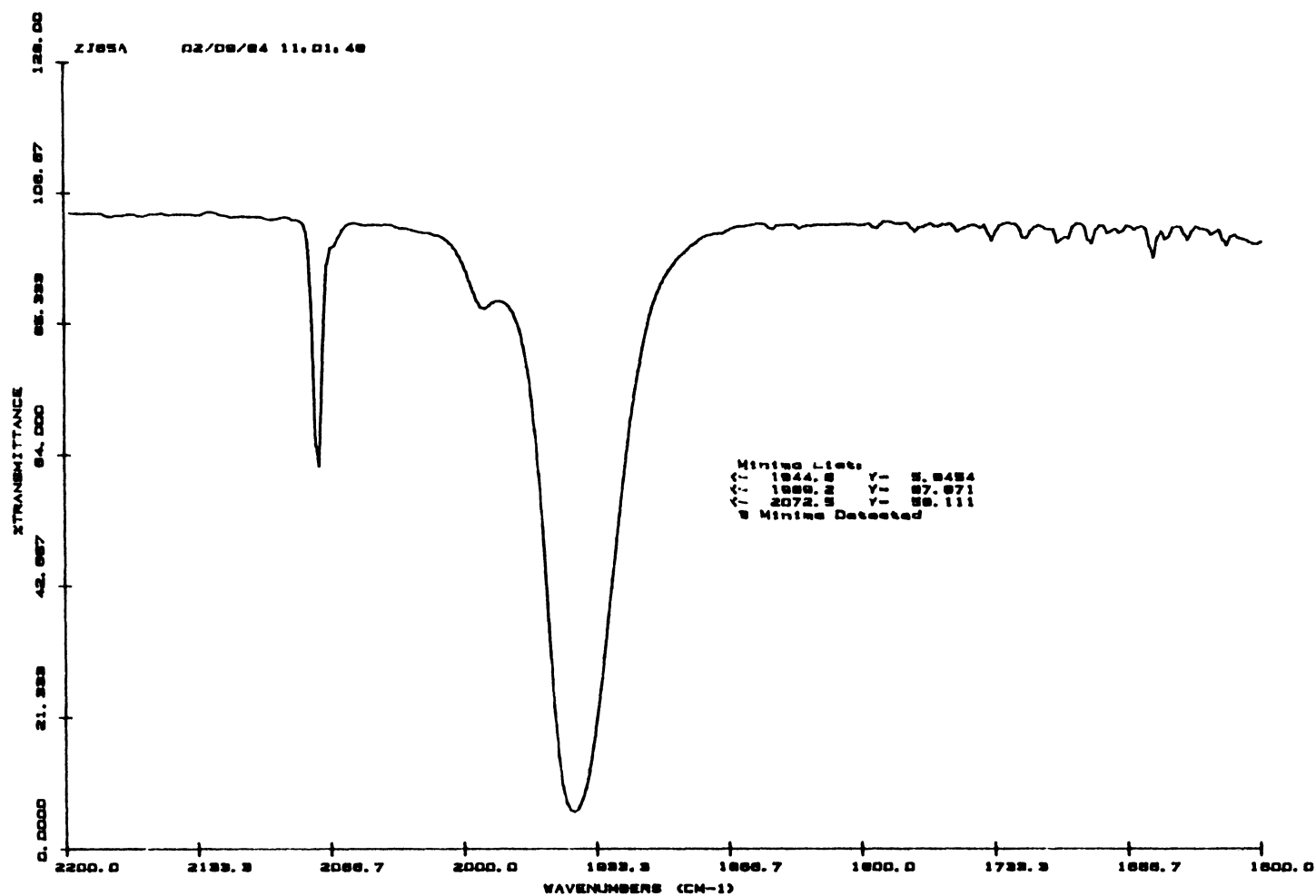


Figure 27.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_3\text{MoP}(\text{p-tol})_2\text{CH}_2\text{CH}_2\text{PPh}_2$

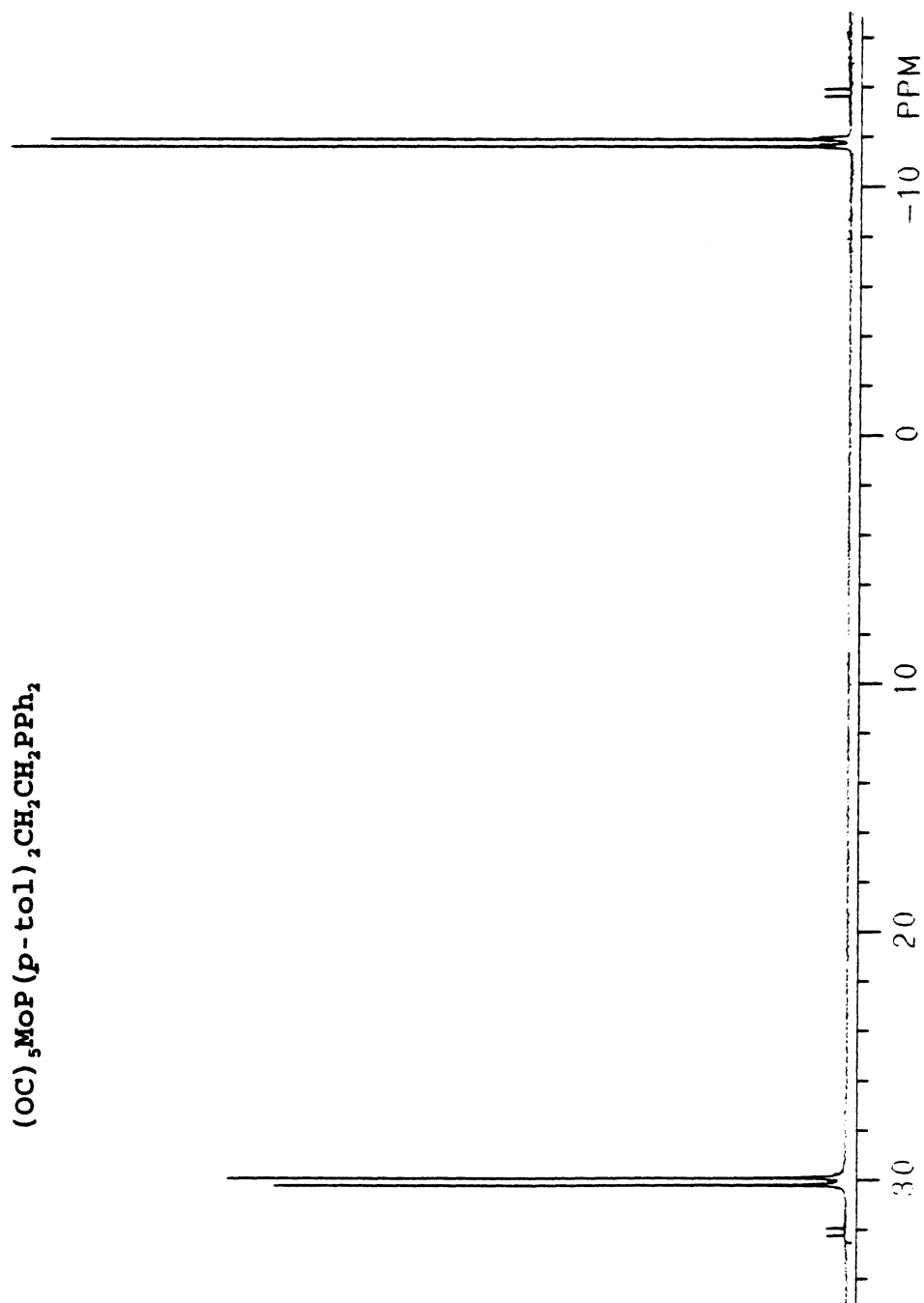


Figure 28. IR Spectrum of  $(OC)_3MoP(p\text{-tol})_2CH_2CH_2PPh_2$

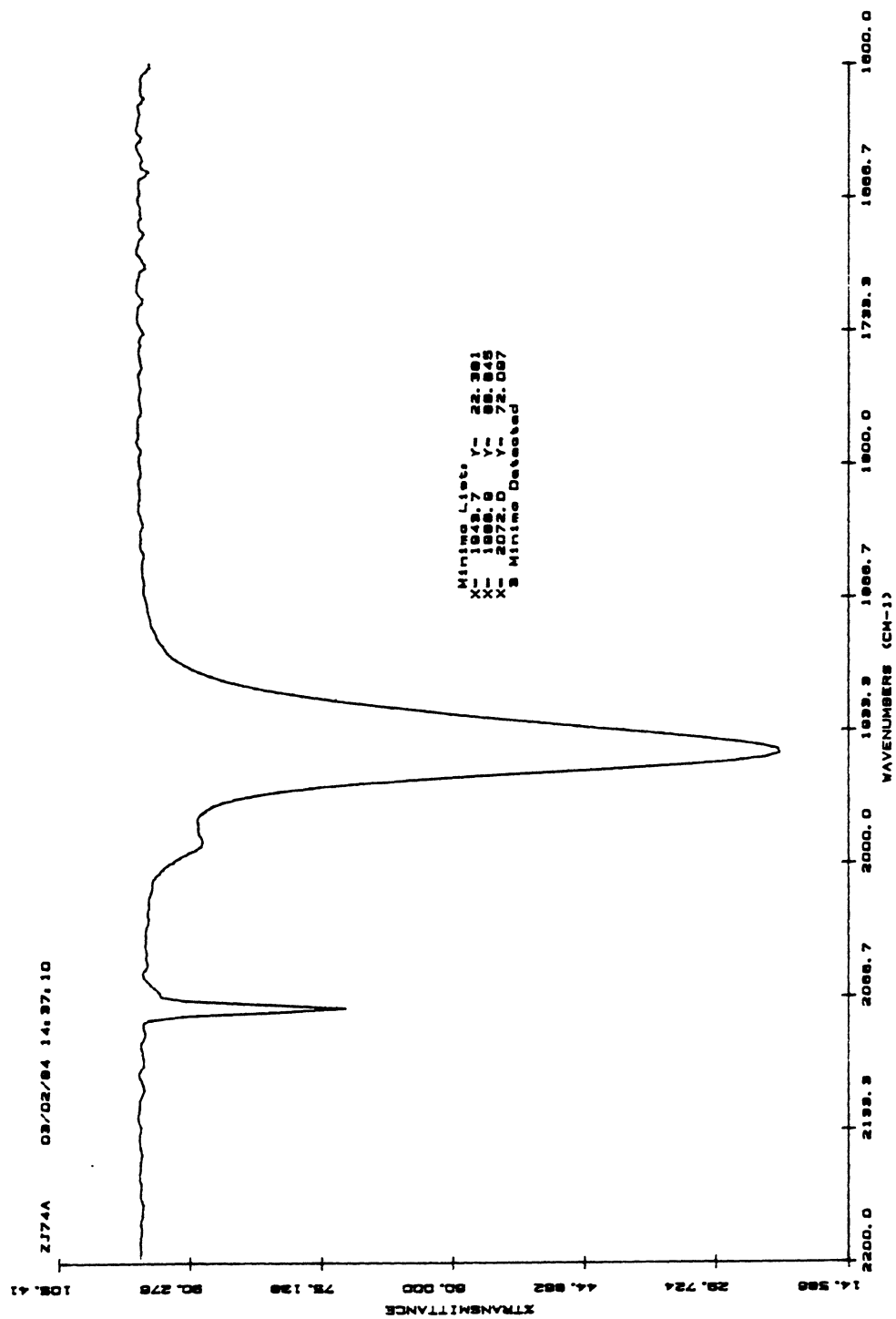


Figure 29.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{WPPPh}_2\text{CH}_2\text{CH}_2\text{PPh}_2$

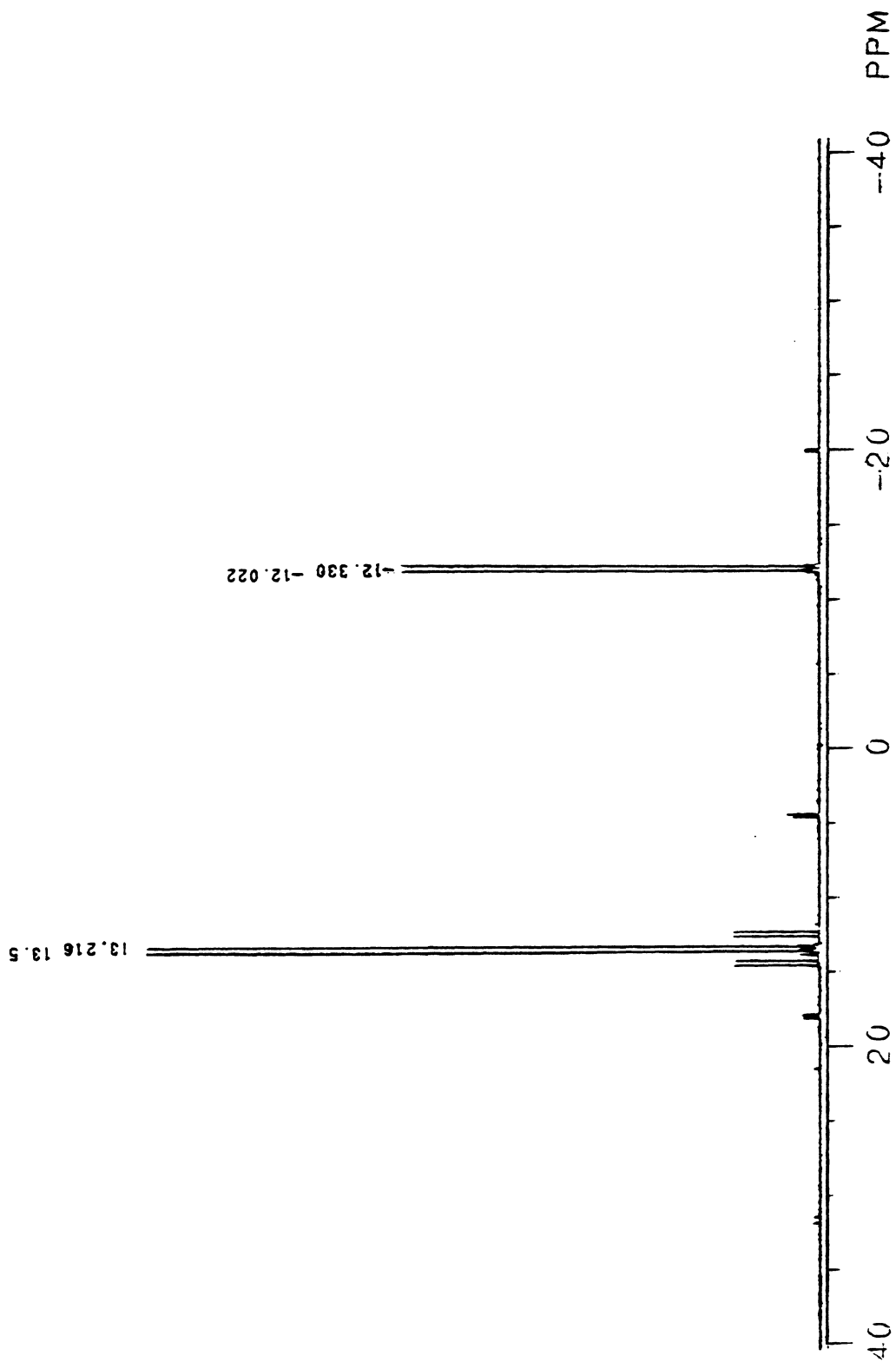


Figure 30. IR Spectrum of  $(OC)_5WPPh_3CH_2CH_2PPh_3$

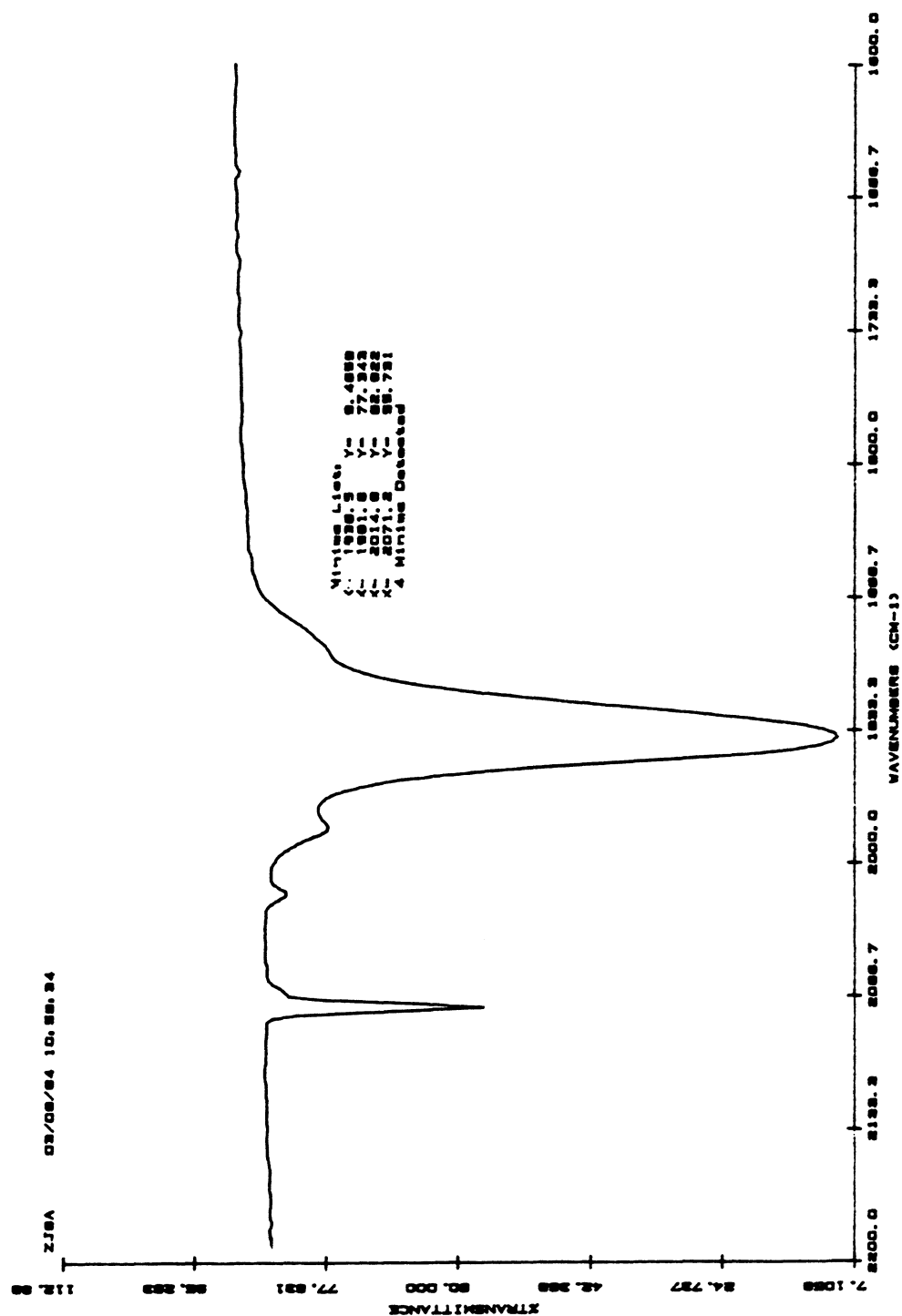


Figure 31.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_4\text{MoPPh}_2\text{CH}_2\text{CH}_2\text{P}(\text{p-tol})_2$

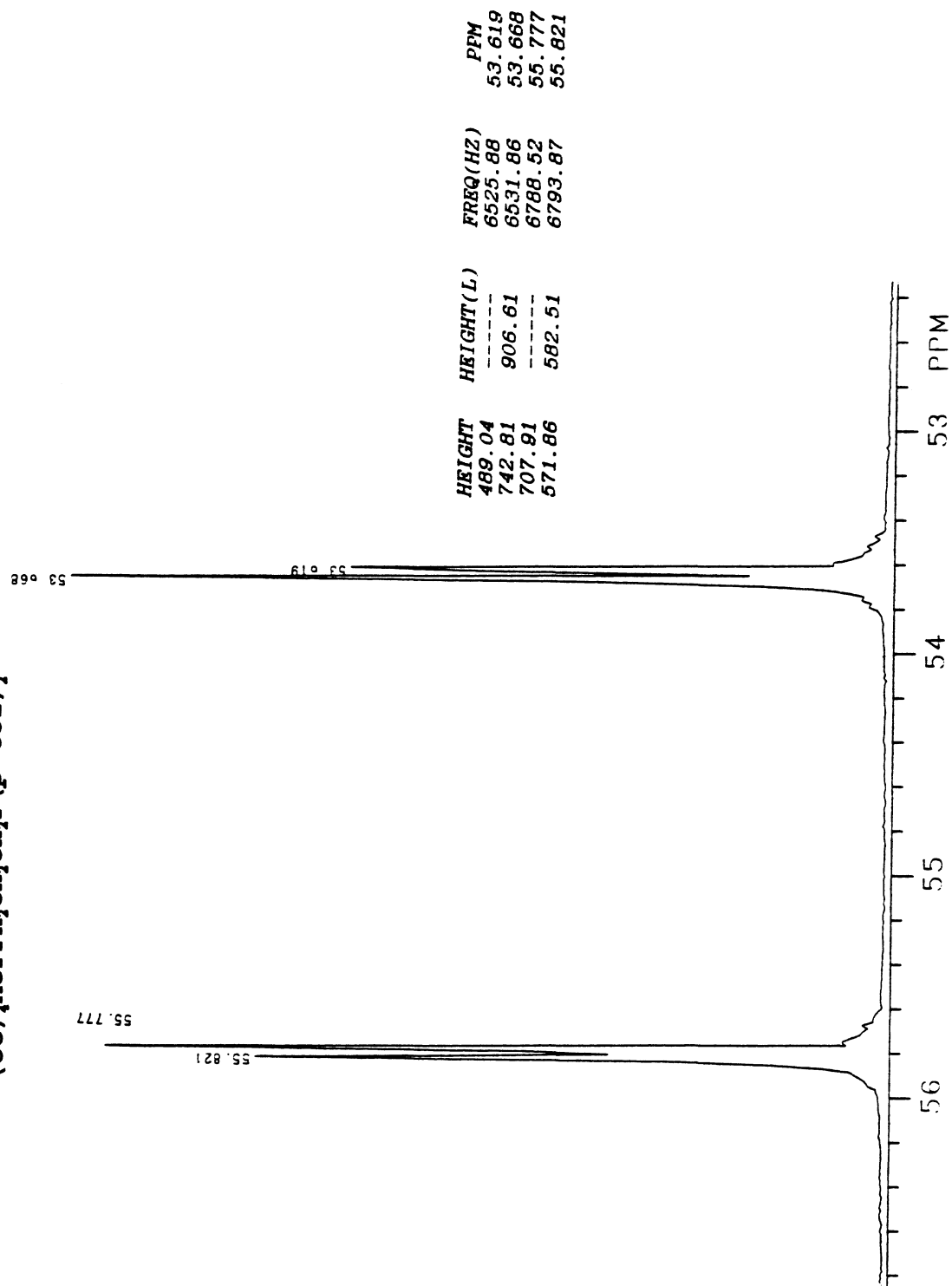


Figure 32. IR Spectrum of  $(OC)_4MoPh_4CH_2CH_2P(p-tol)_2$

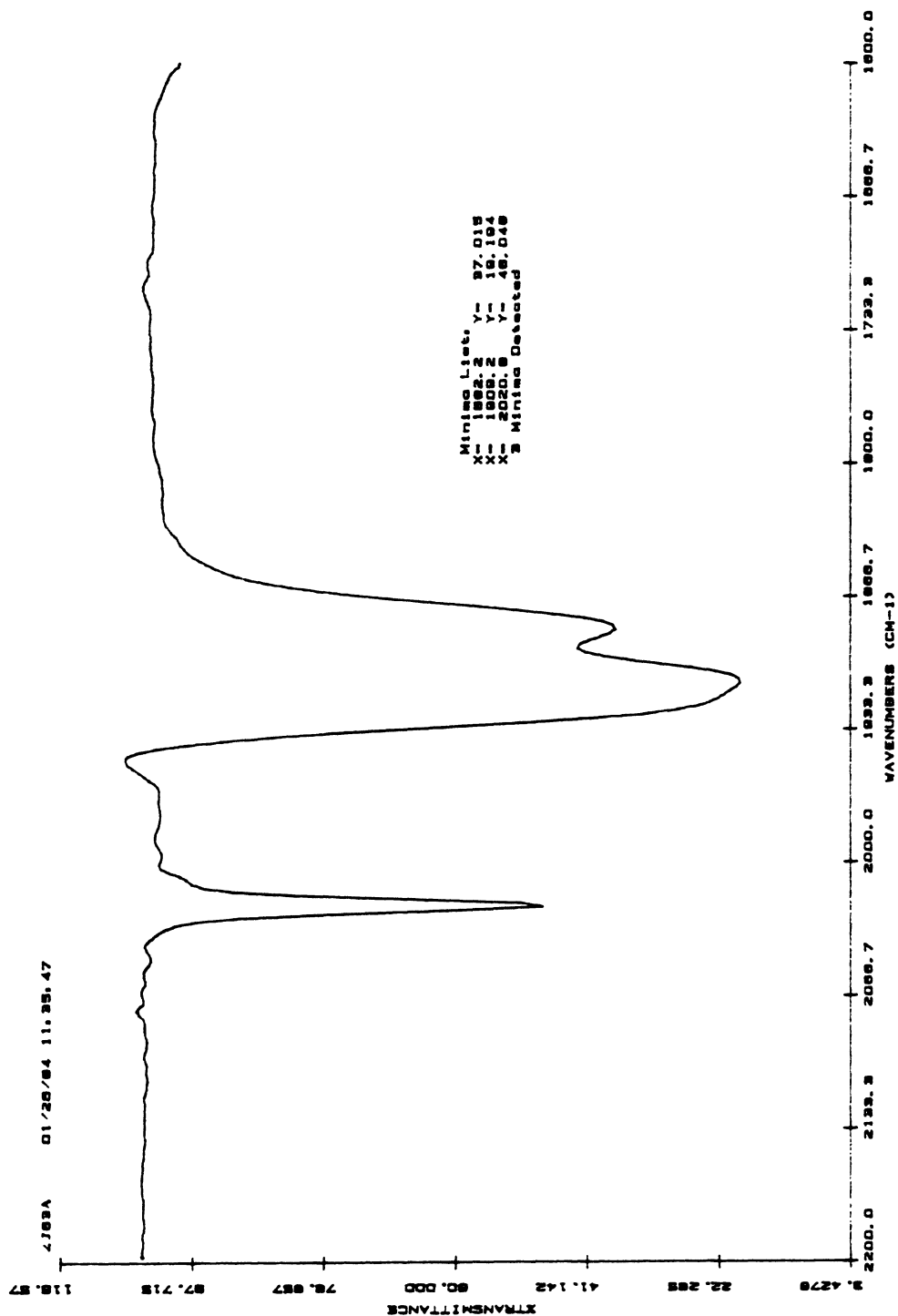


Figure 33.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum (upfield) of  
 $(\text{OC})_5\text{WPPh}_2\text{CH}_2\text{CH}_2\text{PPh}_2$  at 30 °C

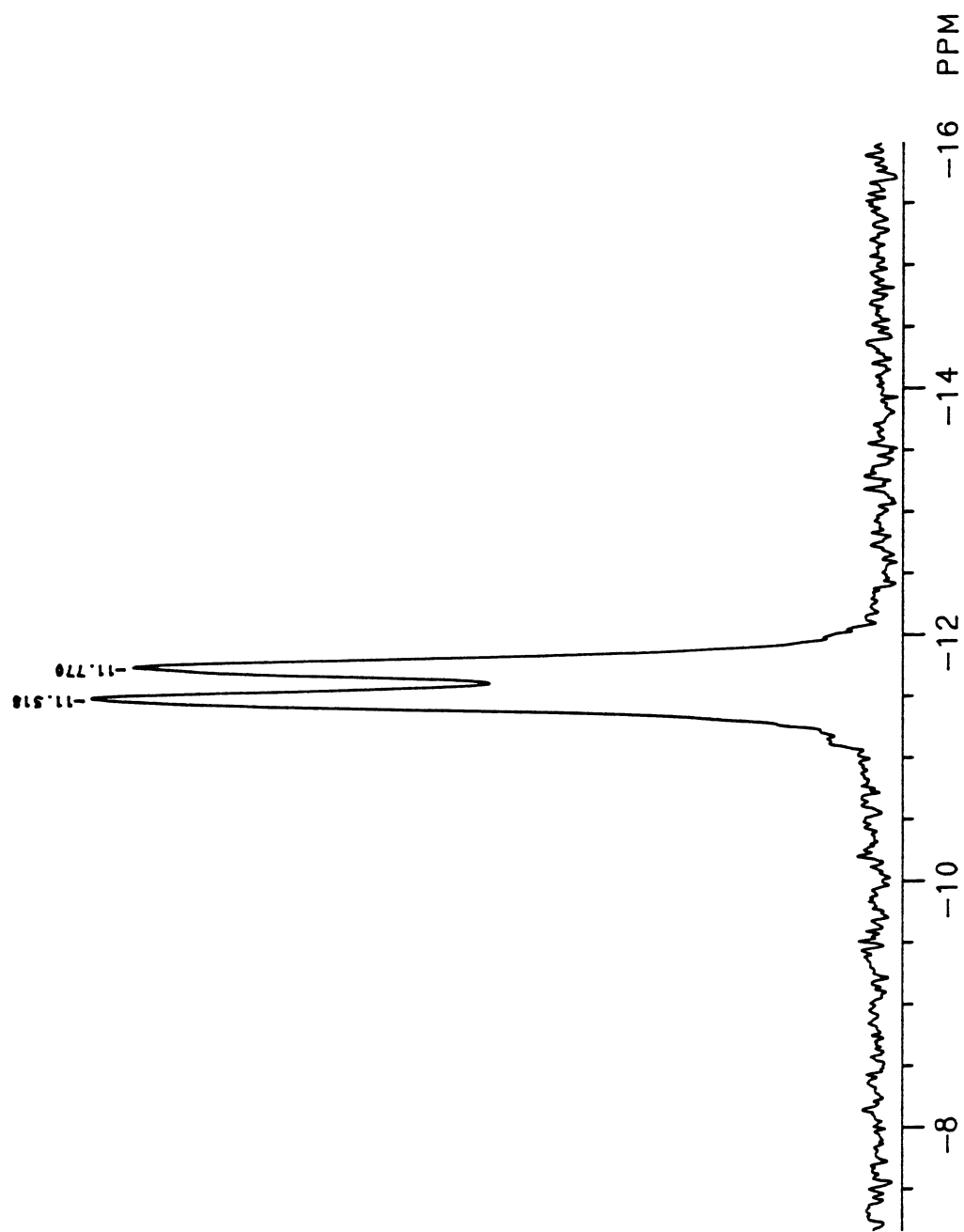




Figure 34.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum (upfield) of  
 $(\text{OC})_5\text{WPPPh}_2\text{CH}_2\text{CH}_2\text{PPh}_2$  at  $80^\circ\text{C}$

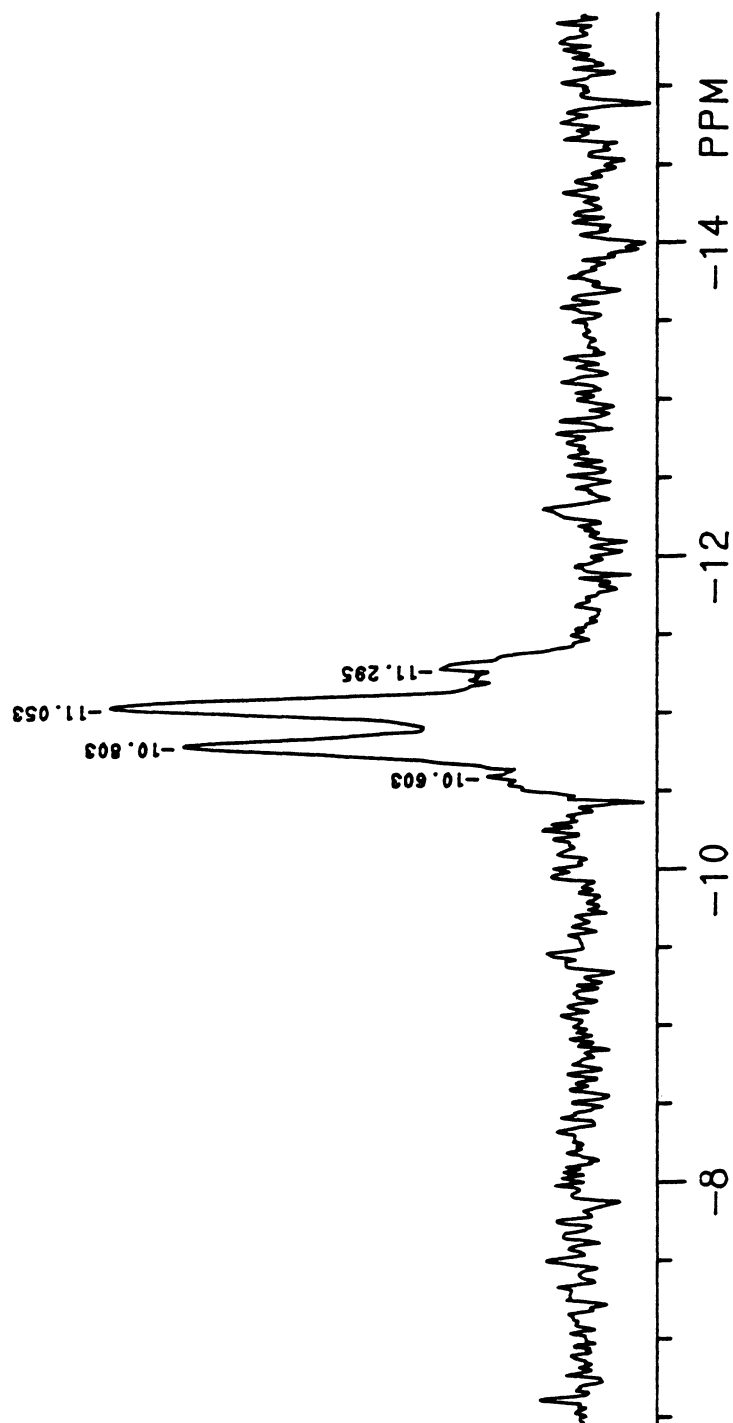


Figure 35.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum (upfield) of  
 $(\text{OC})_3\text{WPPh}_2\text{CH}_2\text{CH}_2\text{P}(\text{O})\text{Ph}_2$  at  $80^\circ\text{C}$

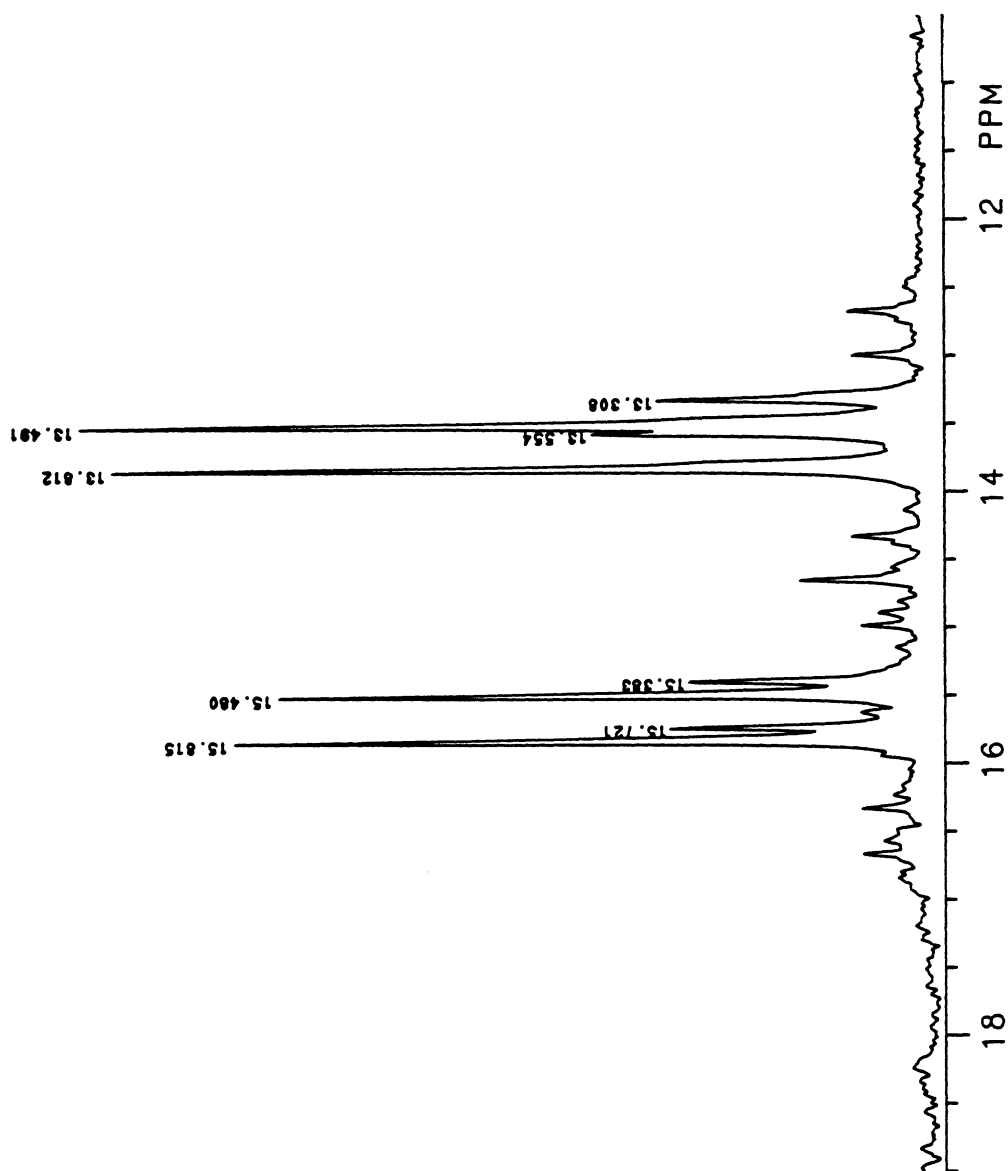


Figure 36.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{WPPPh}_2\text{CH}_2\text{PPh}_2$  at  $-50^\circ\text{C}$

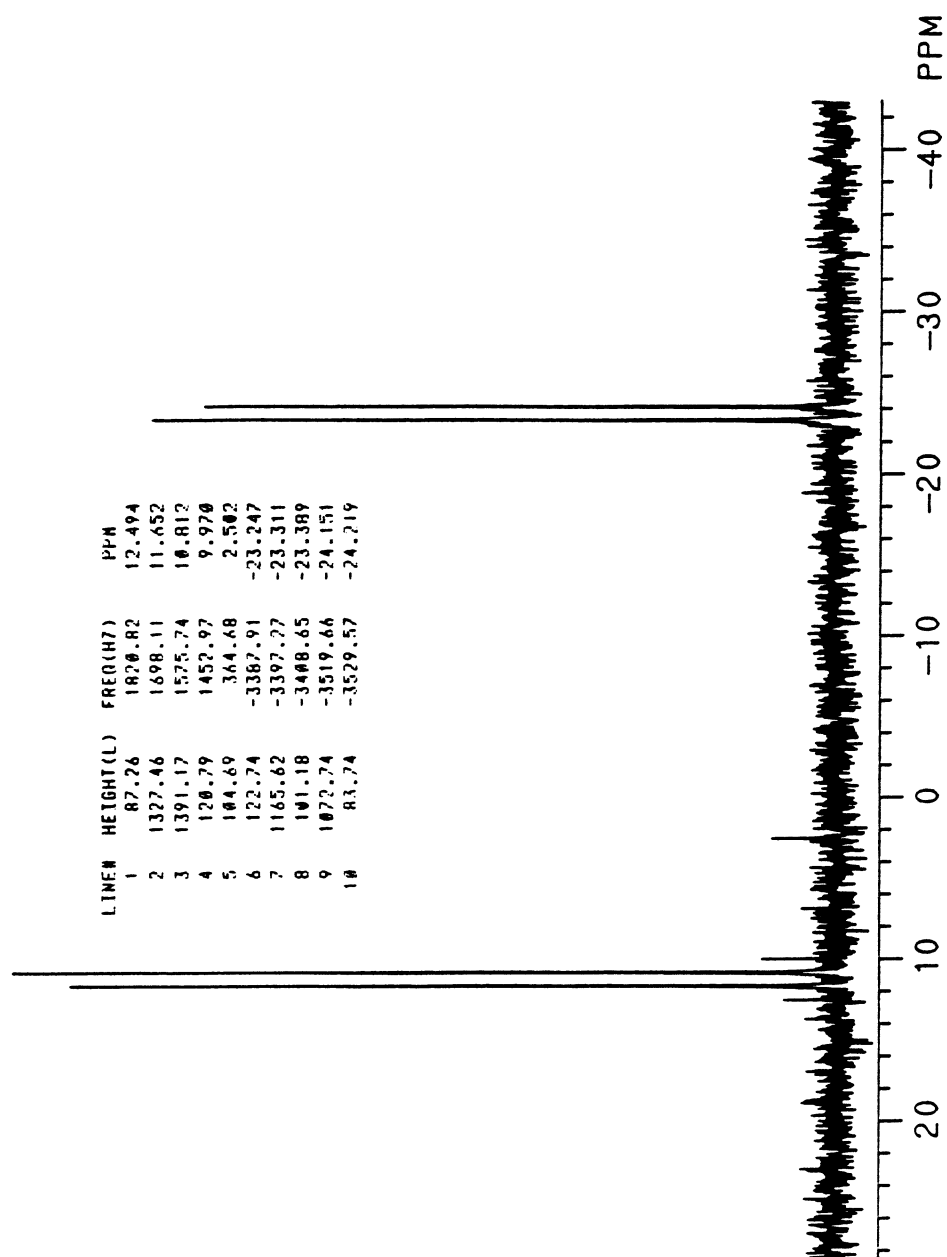


Figure 37.  $^{31}\text{P}\{^1\text{H}\}$  NMR Spectrum of  
 $(\text{OC})_5\text{WPPh}_2\text{CH}_2\text{PPh}_3$  at 70 °C

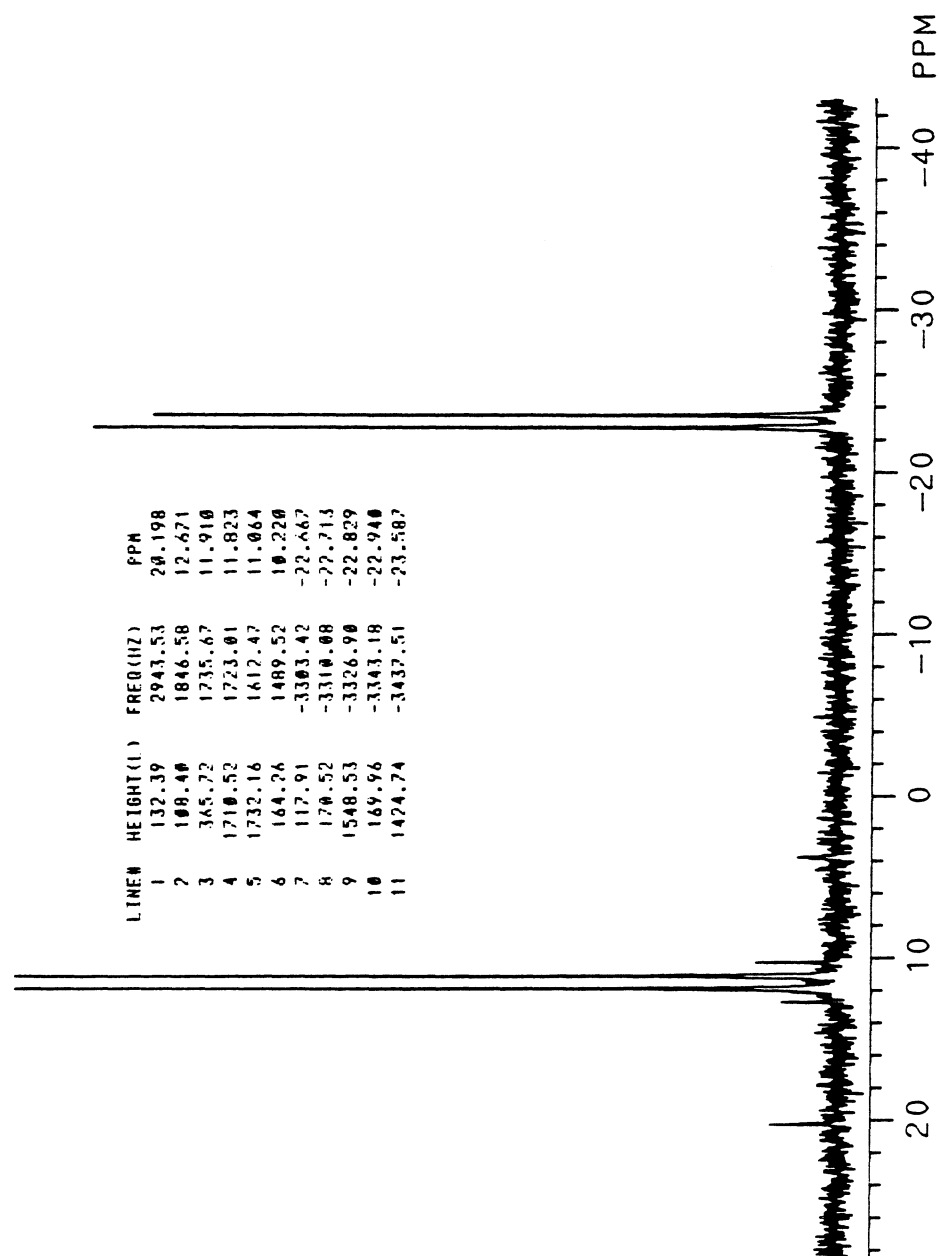


Figure 38.  $^{31}\text{P}\{\text{H}\}$  NMR for the isomerization of  
 $(\text{OC})_2\text{MoPPh}_2\text{CH}_2\text{CH}_2\text{P}(p\text{-tol})_2$ , at various  
times at 55 °C in perdeuterated toluene.

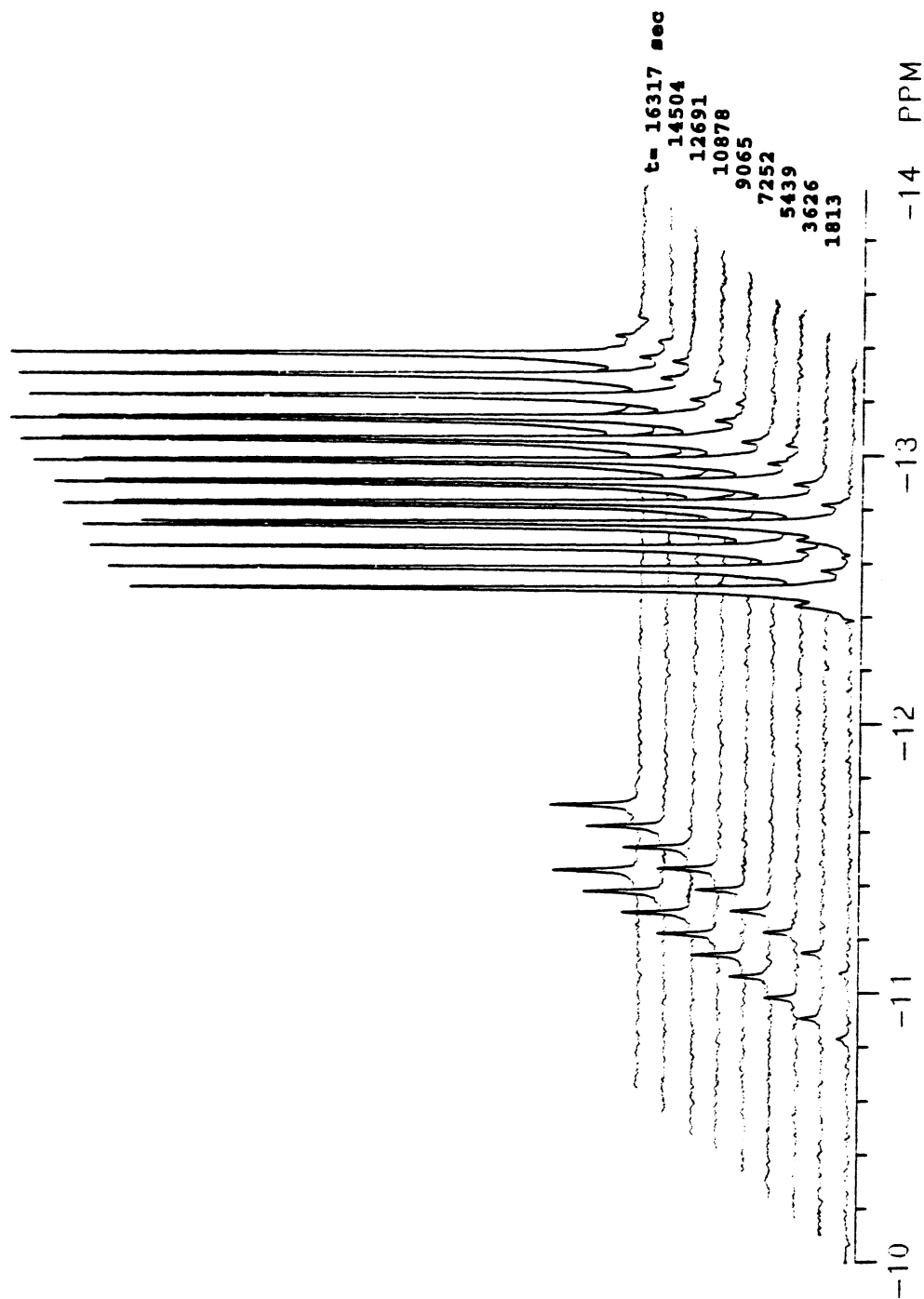


Figure 39. Plot of  $\ln([A]/[A]_0 - [A]_{eq}/[A]_0)$  vs  $t$

$[A = (OC)_2MoPPh_2CH_2CH_2P(p-tol)_2]$

at 55 °C in perdeuterated toluene.

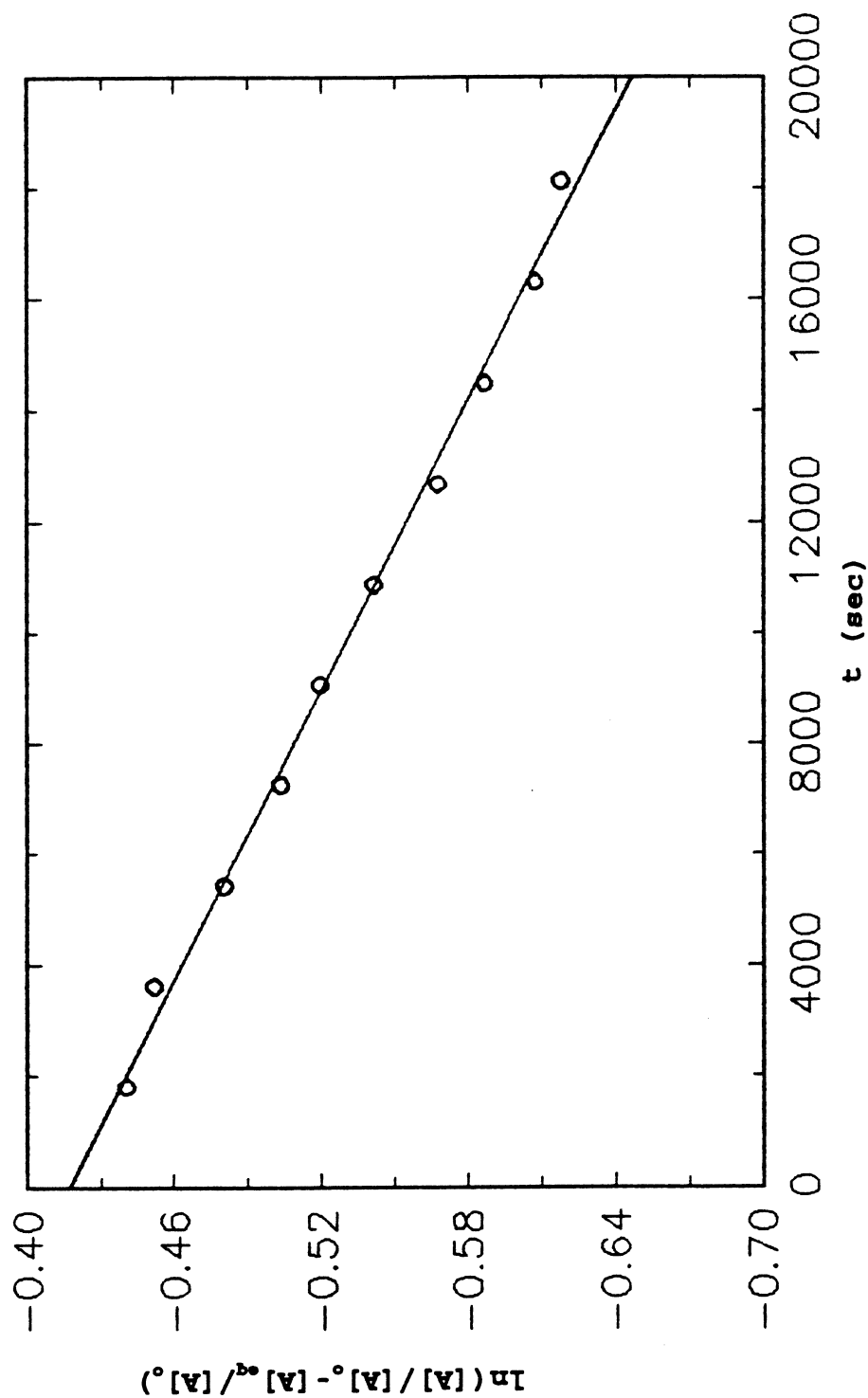


Figure 40. Plot of  $[A]/[A]_0$  vs  $t$   $[A=(OC)_5CrPPPh_2CH_2CH_2P(p-tol)_2]$   
at 55 °C in perdeuterated toluene.

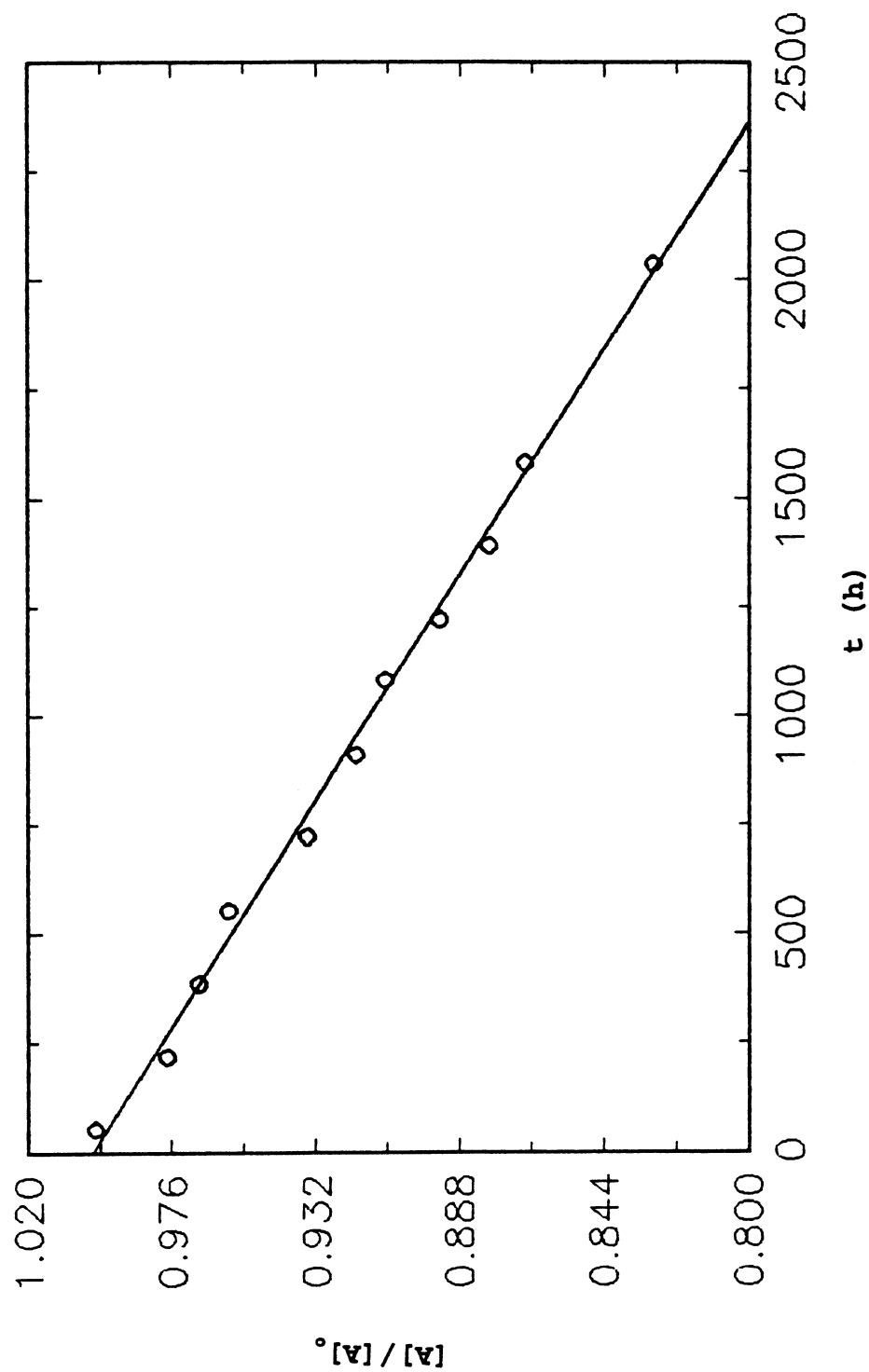


Figure 41. Plots of  $[B]/[A]_0$  or  $[C]/[A]_0$  vs  $t$   
 $[B = (OC)_5CrP(p-tol)_2CH_2CH_2PPh_3; C = (OC)_4Cr(dpdt)]$   
 at 55 °C in perdeuterated toluene.

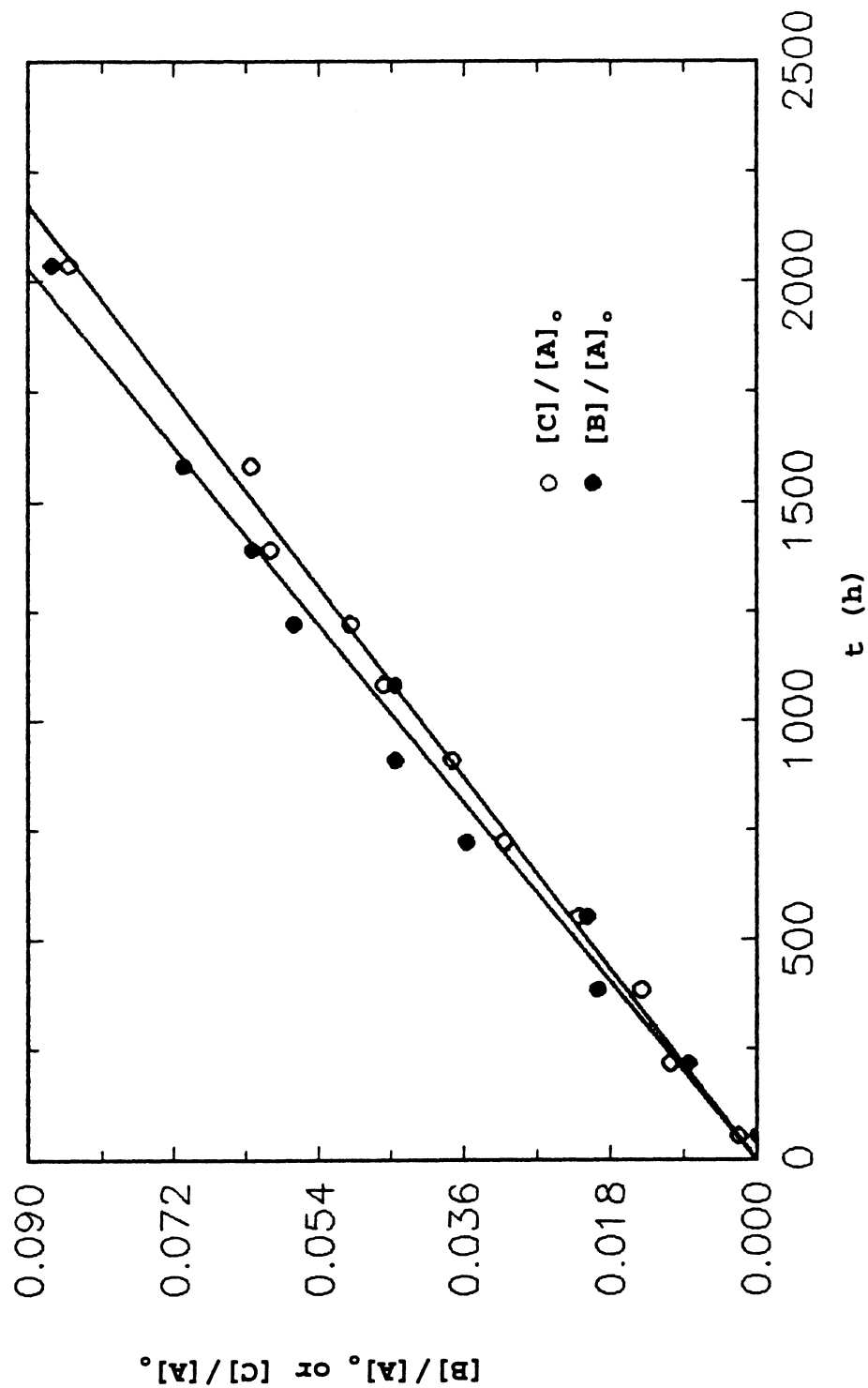




Figure 42. Plot of  $[B]/[B]_0$  vs  $t$   $[B=(OC)_5CrP(p-tol)_2CH_2CH_2PPh_2]$   
at 55 °C in perdeuterated toluene.

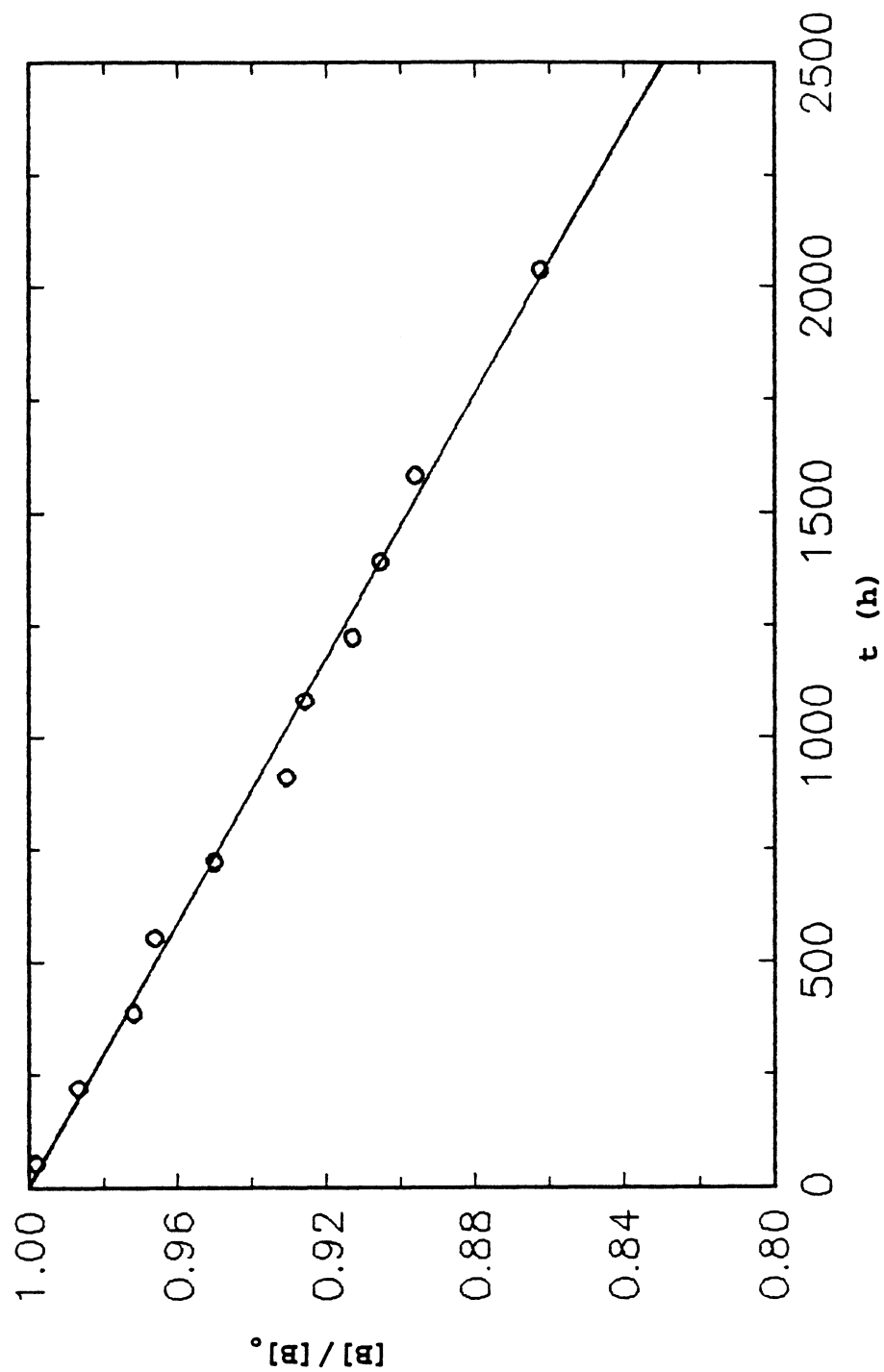


Figure 43. Plots of  $[A]/[B]_0$  or  $[C]/[B]_0$  vs  $t$   
 $[A = (OC)_5CrPPPh_2CH_2CH_3(p-tol)_2; C = (OC)_4Cr(dpdt)]$   
 at 55 °C in perdeuterated toluene.

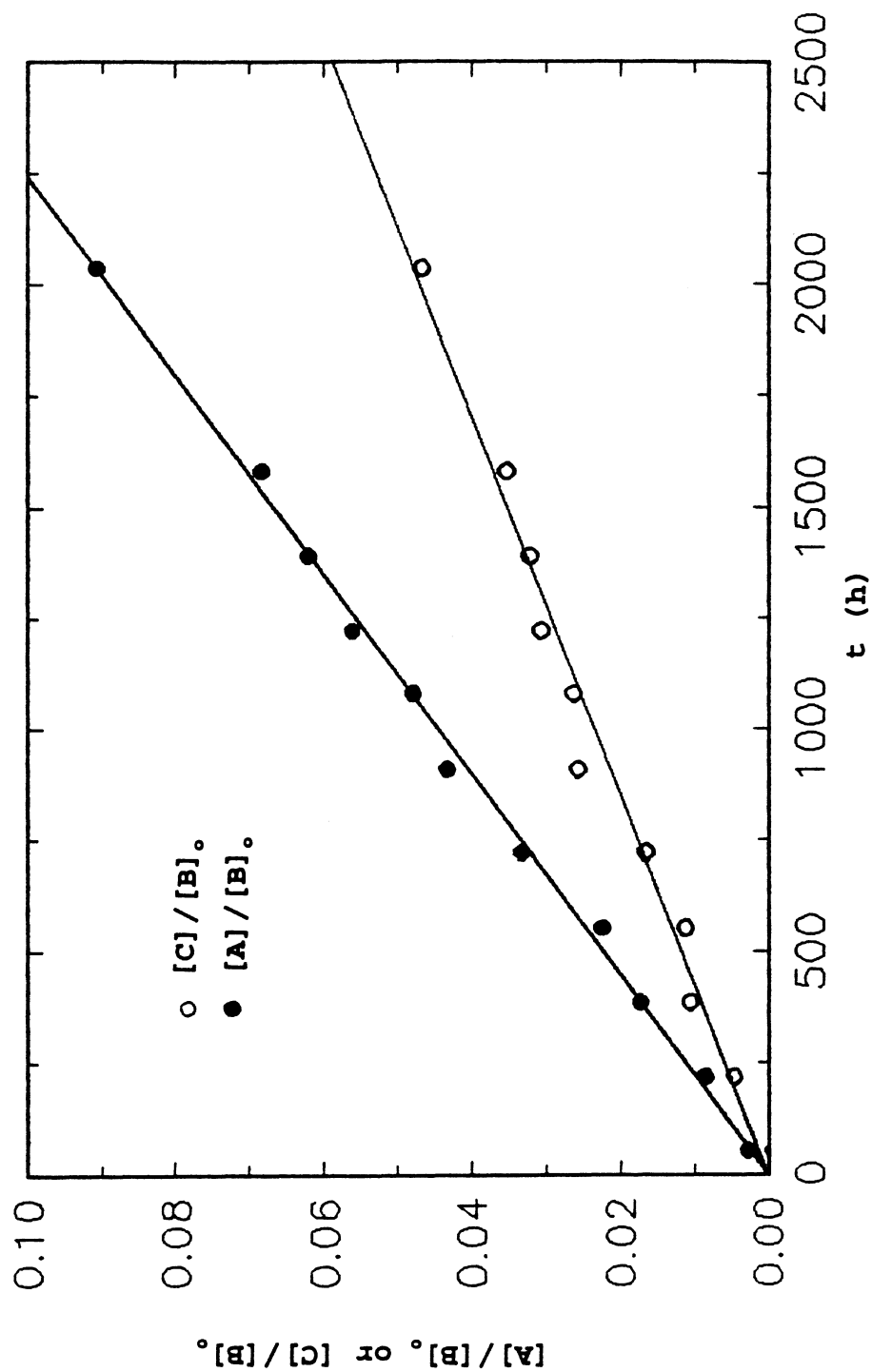


Figure 44. Plot of  $[C]/[A]_0$  vs  $t$   $[C=(OC)_4Mo(dpdt)]$   
at 55 °C in predeuterated toluene.

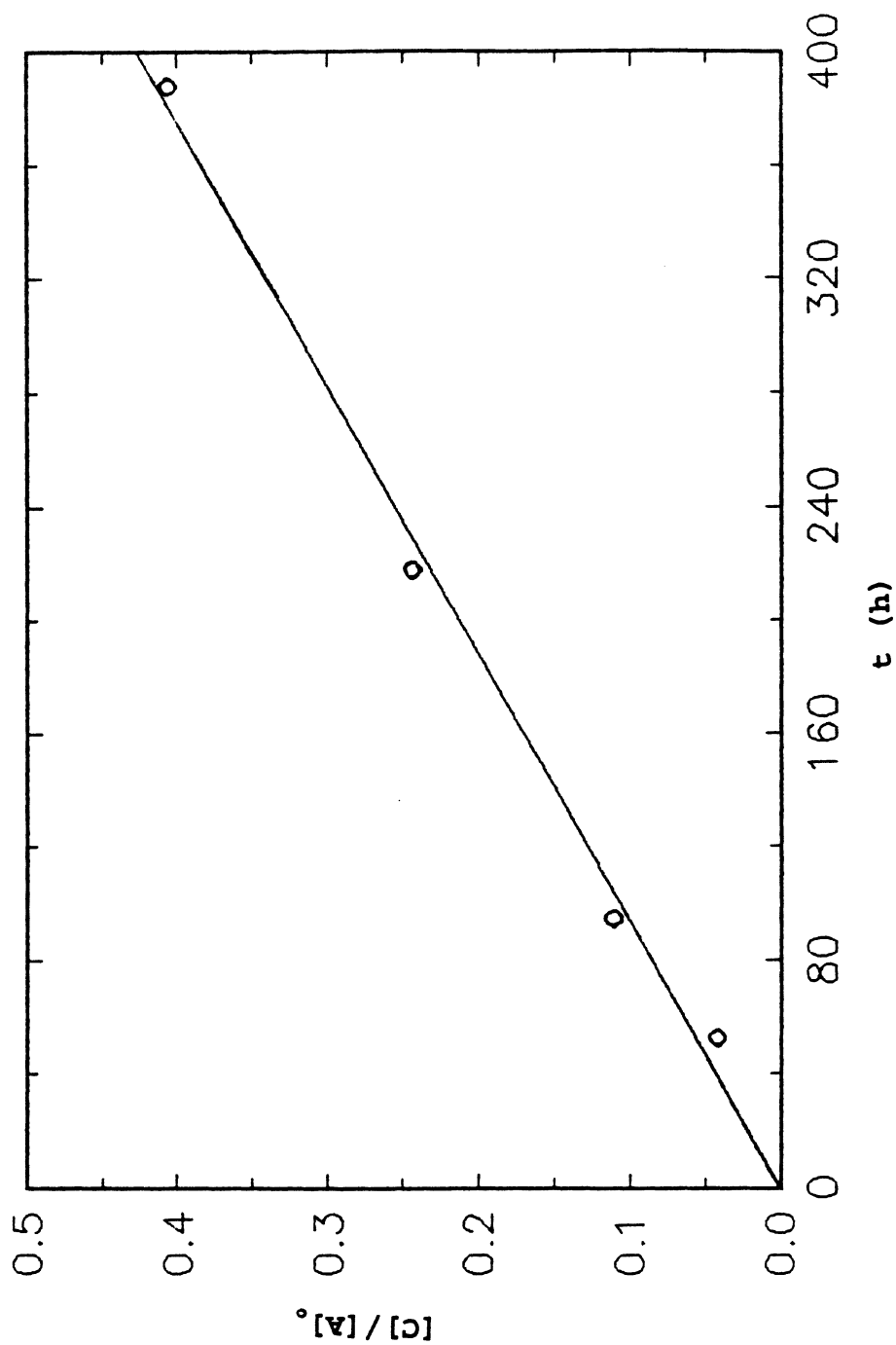


Figure 45. Plot of  $[C]/[B]_0$  vs  $t$   $[C=(OC)_4Mo(dpdt)]$   
at 55 °C in predeuterated toluene.

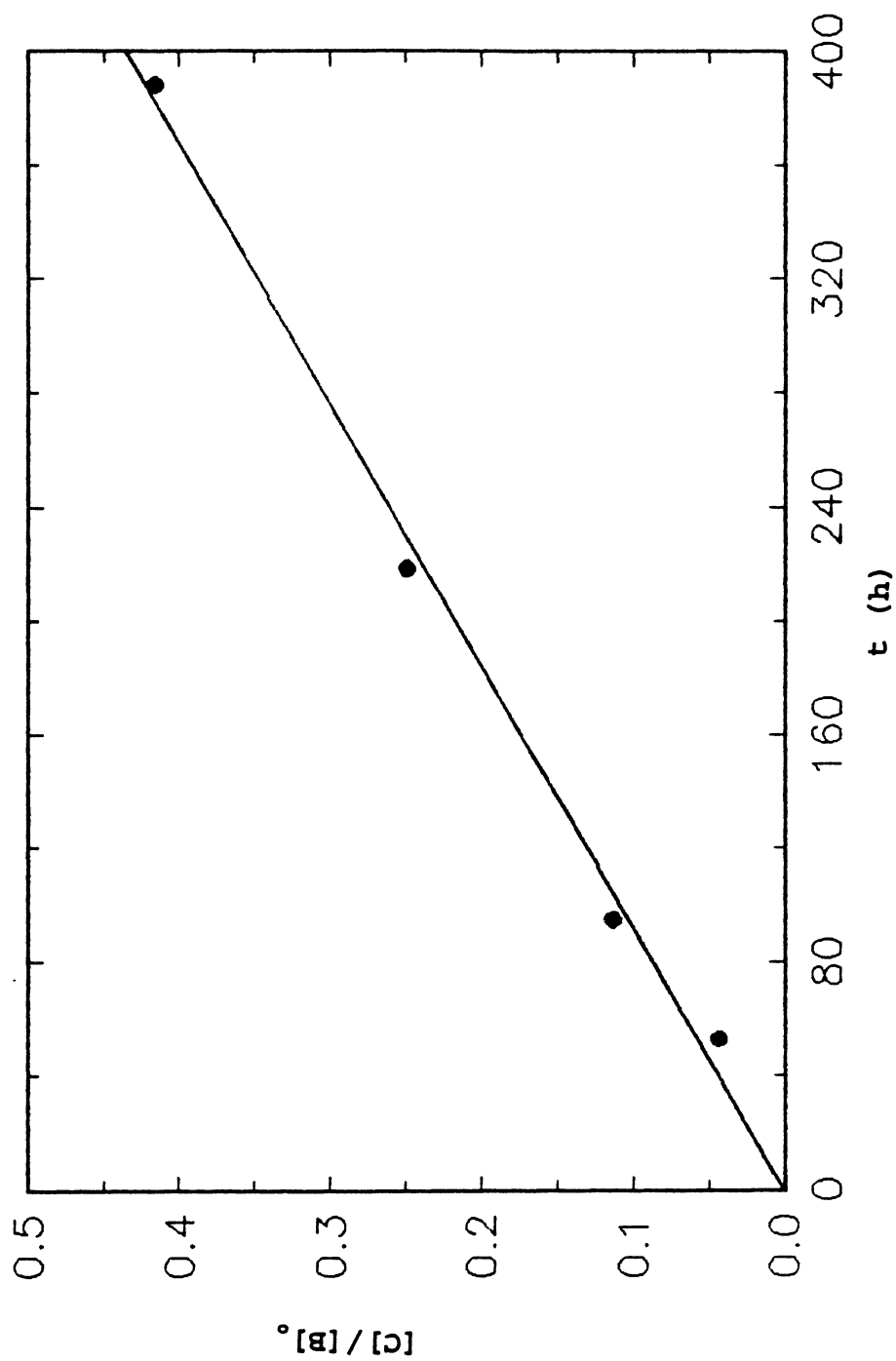


Figure 46. Plot of  $[A]/[A]_0$  vs  $t$   $[A=(OC)_5WPPh_2CH_2CH_2P(p-tol)_2]$   
at 55 °C in perdeuterated toluene.

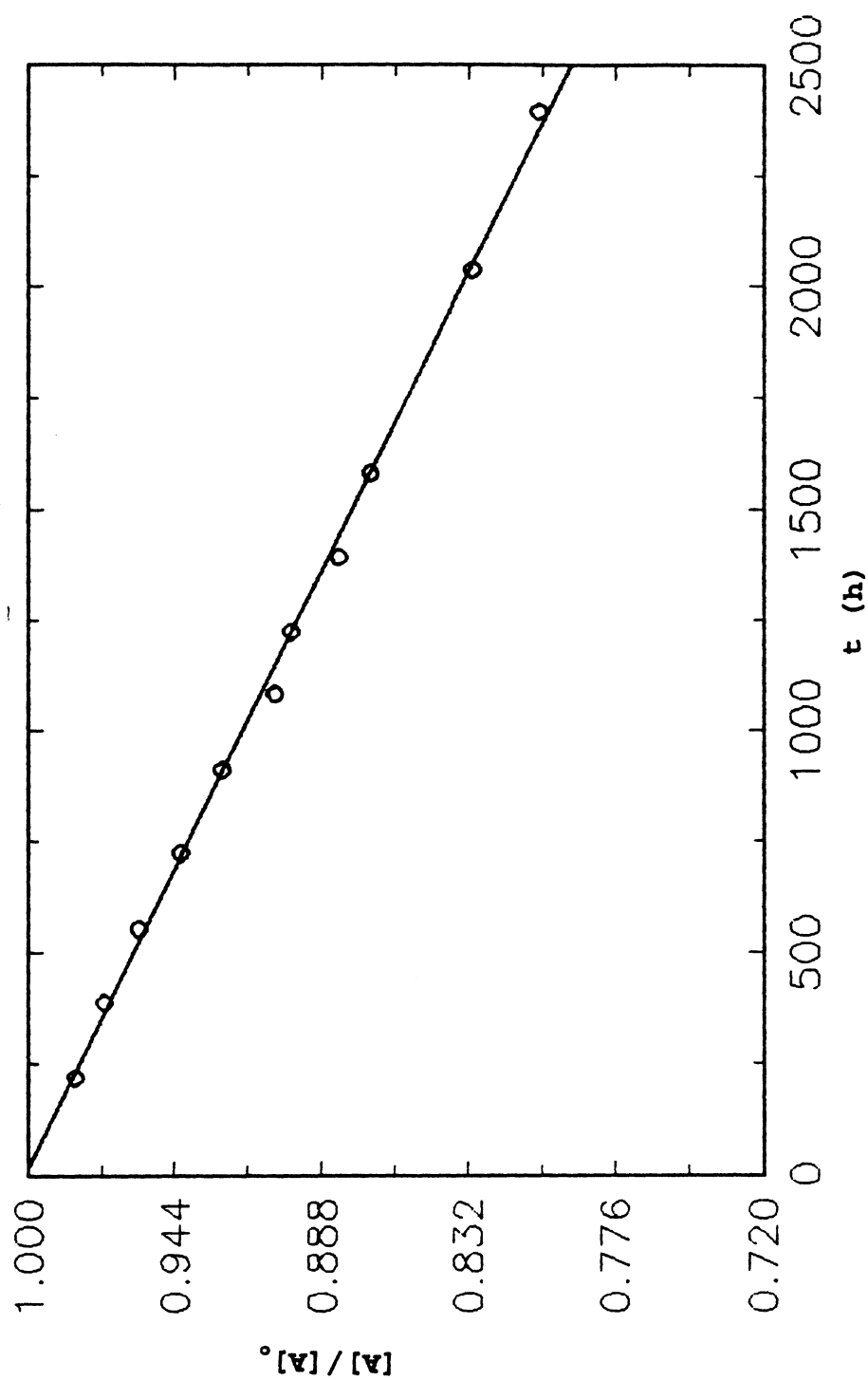


Figure 47. Plot of  $\ln([A]/[A]_0)$  vs  $t$  at 55 °C in perdeuterated  
toluene  $[A=(OC)_3WPPPh_2CH_2CH_2P(p-tol)_2]$ .

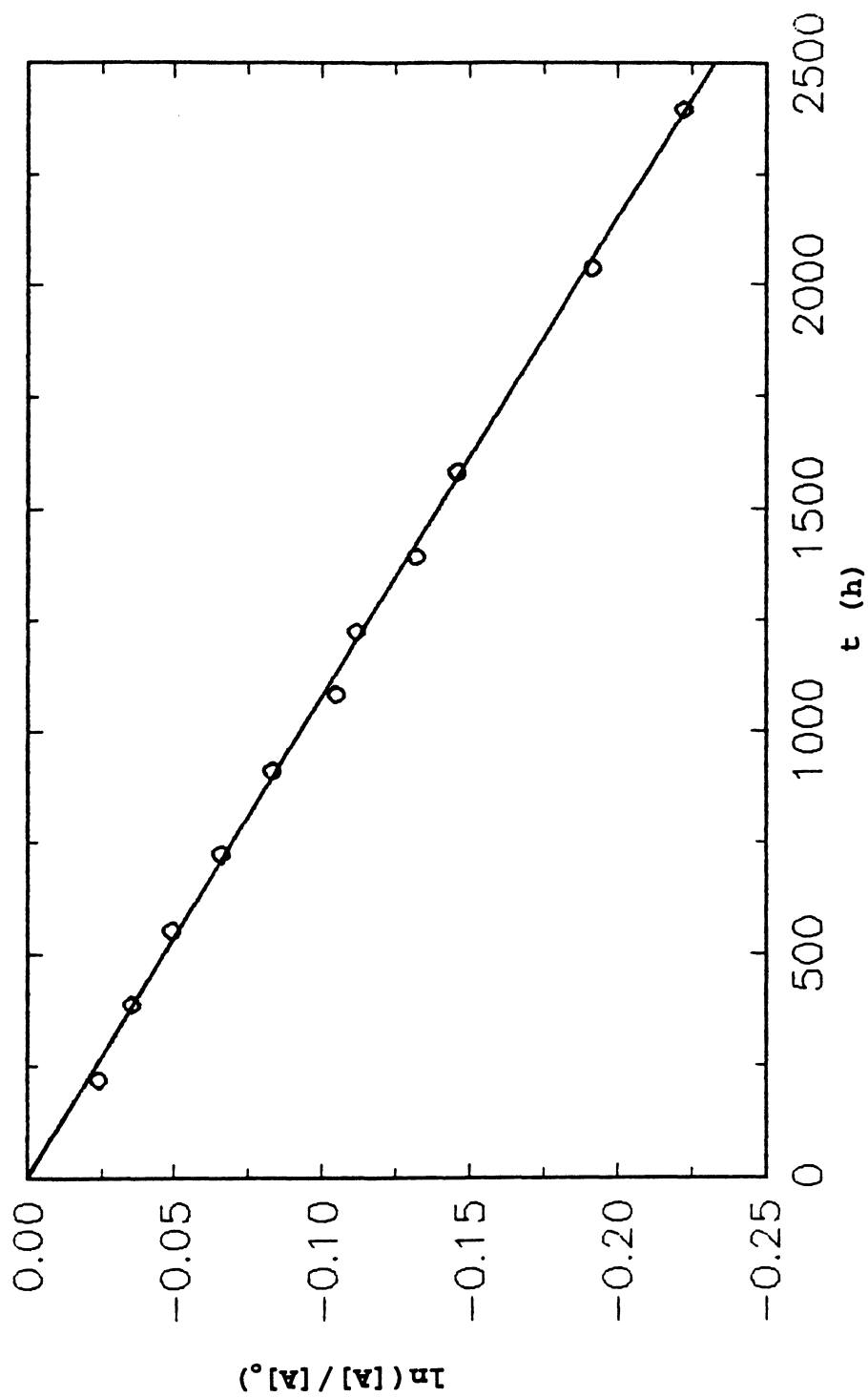


Figure 48. Plot of  $[B]/[A]_0$  vs  $t$   $[B=(OC)_5WP(p\text{-tol}), CH_2CH_2PPh_2]$   
at 55 °C in perdeuterated toluene.

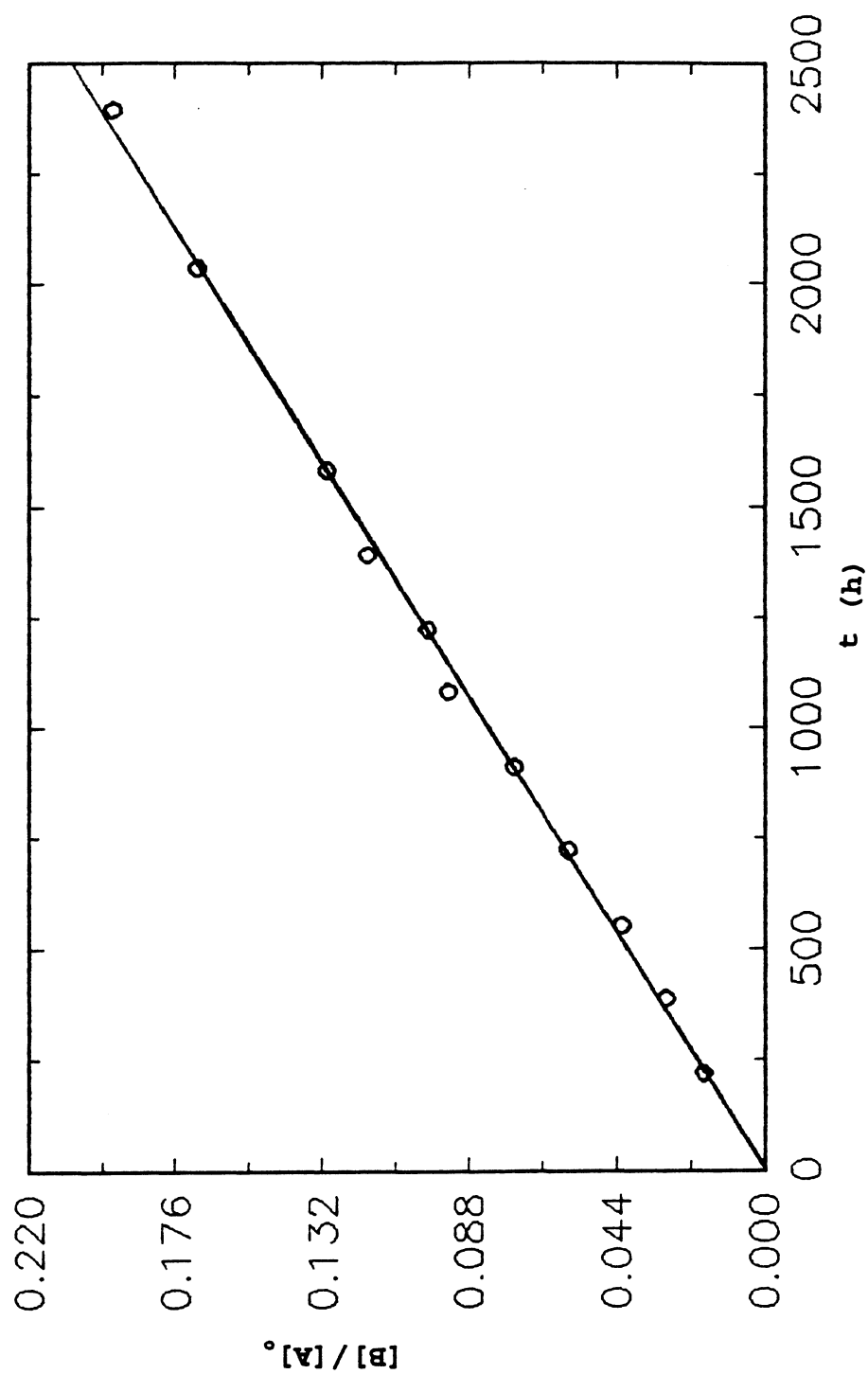


Figure 49. Plot of  $\ln([B]/[A]_0)$  vs  $t$  at 55 °C in perdeuterated  
toluene  $[B = (OC)_2WP(p\text{-tol),CH}_2\text{CH}_2\text{PPh}_2]$ .

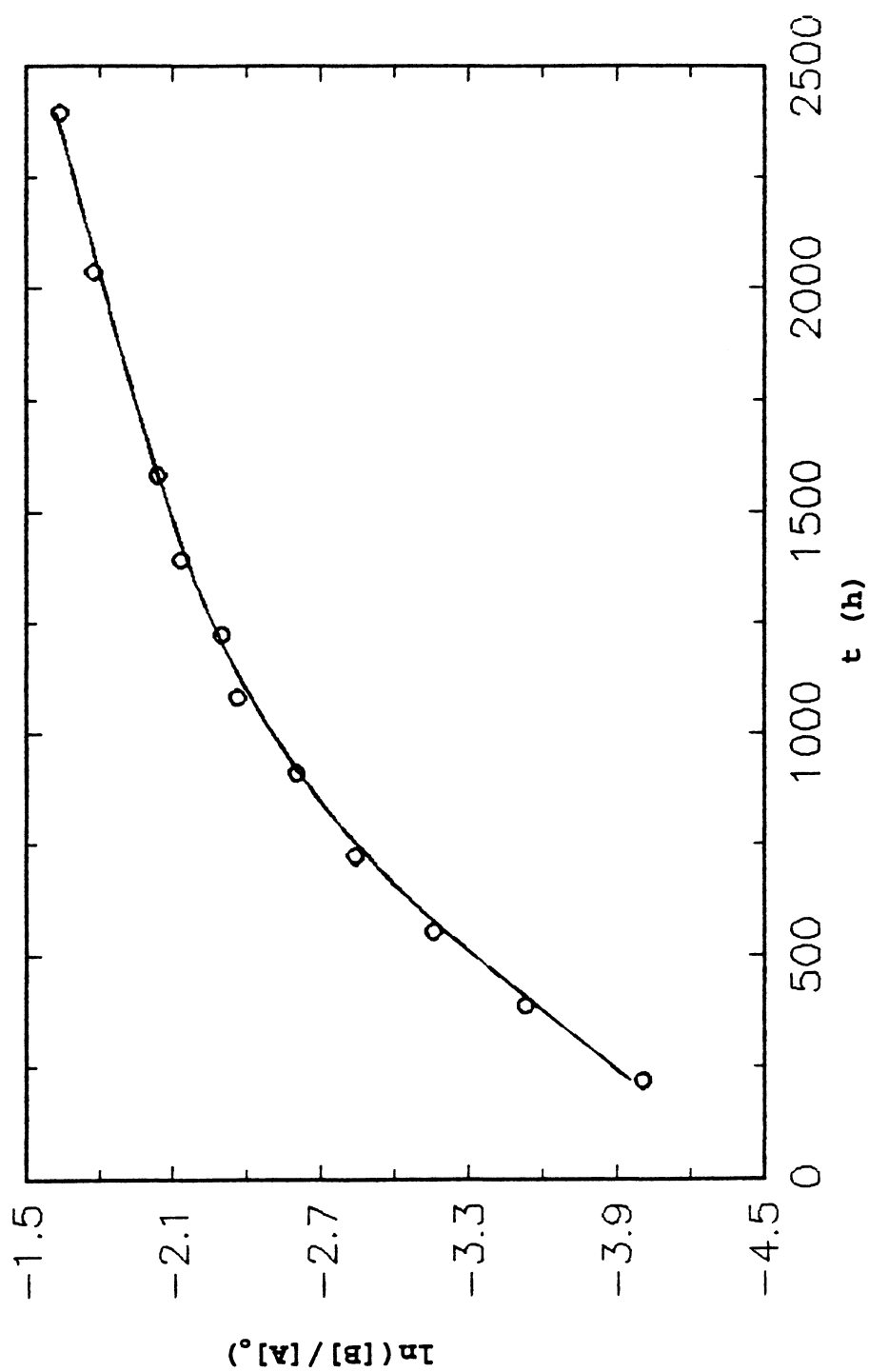




Figure 50. Plot of  $[B]/[B]_0$  vs  $t$   $[B = (OC)_5WP(p\text{-tol}), CH_3CH_2PPh_2]$   
at 55 °C in perdeuterated toluene.

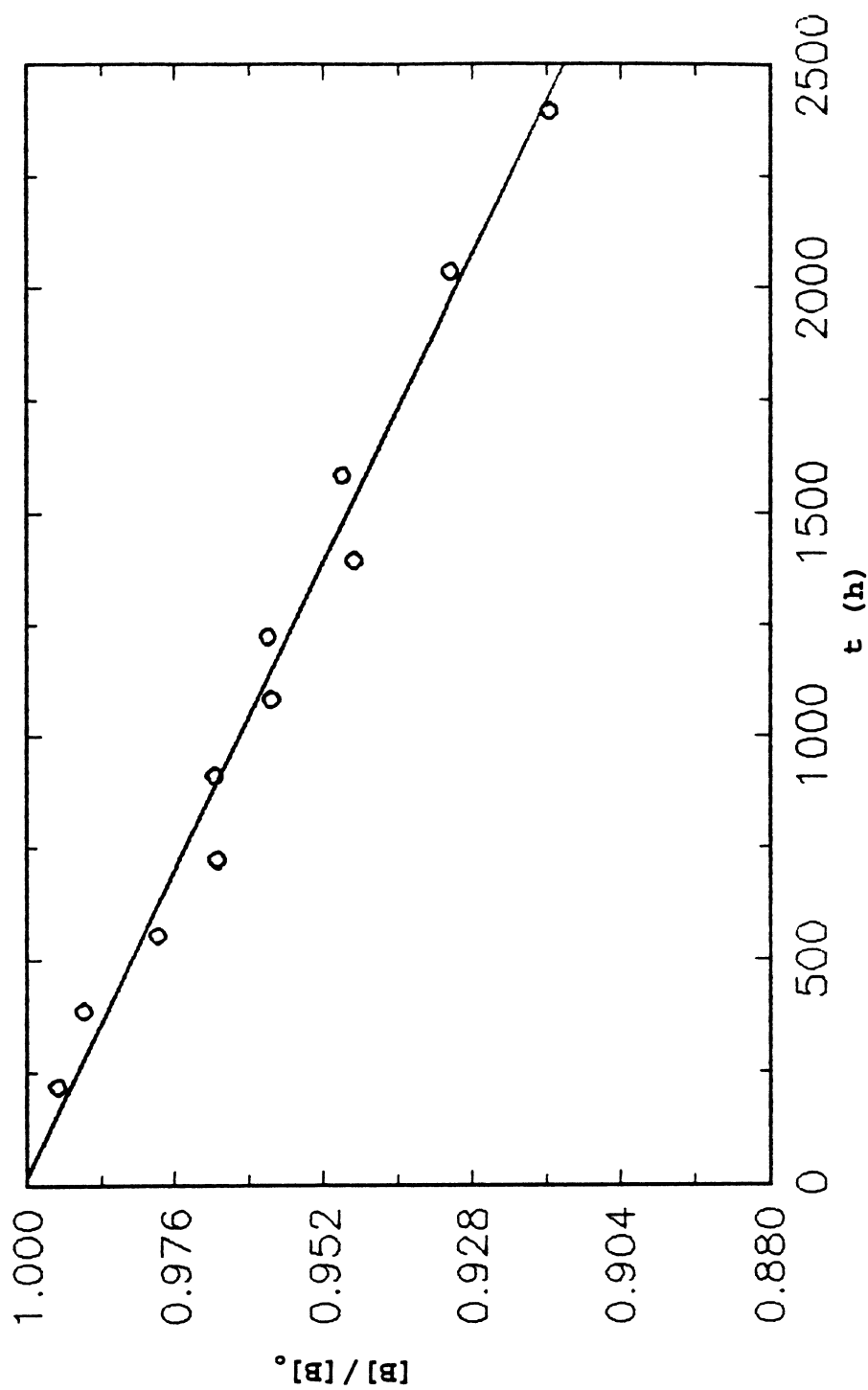


Figure 51. Plot of  $[A]/[B]_0$  vs  $t$  [ $A=(OC)_5WPPPh_2CH_2CH_2P(p-tol)_2$ ]  
at 55 °C in perdeuterated toluene.

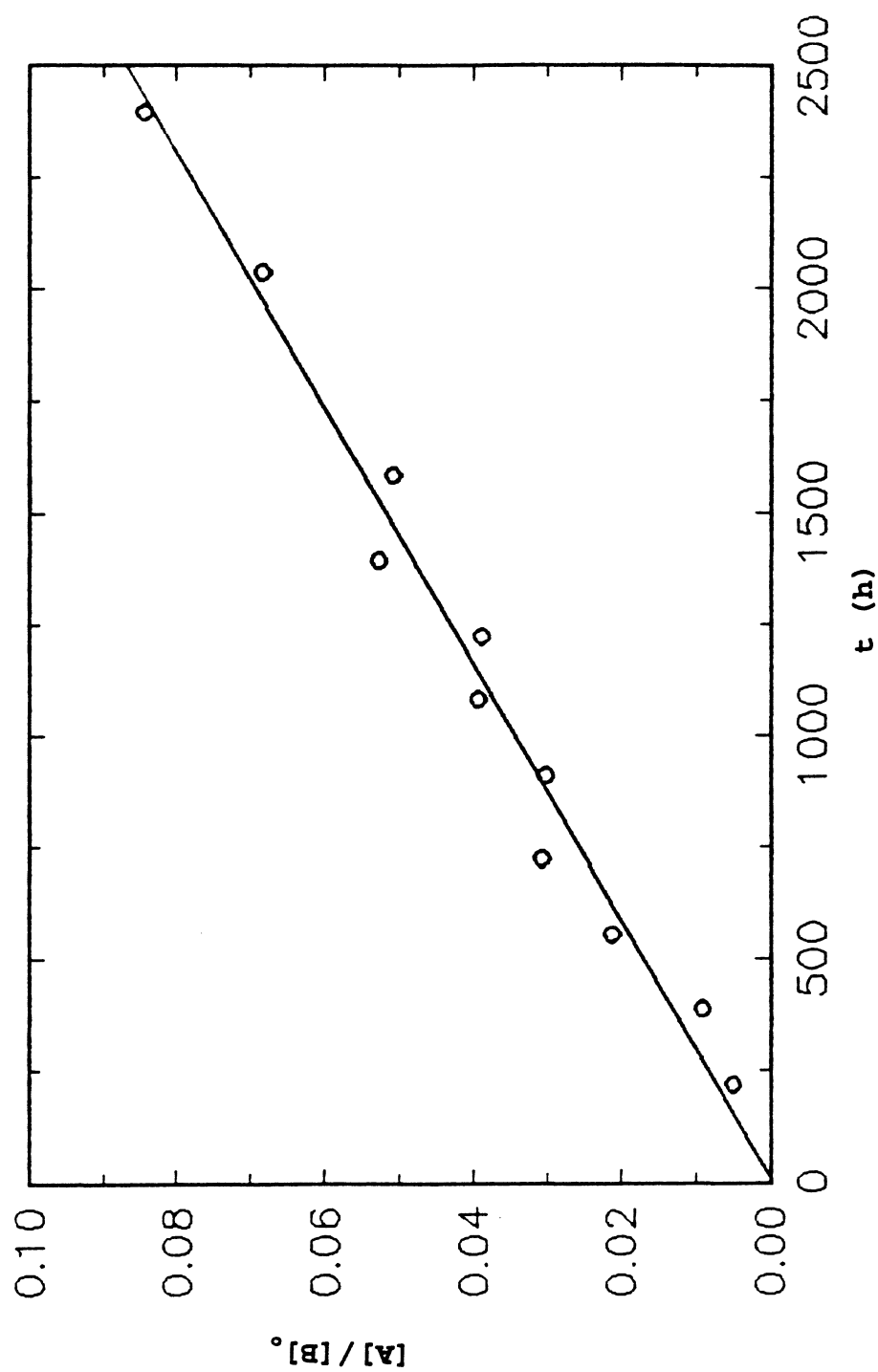


Figure 52. Plot of  $[A]/[A]_0$  vs  $t$  [ $A=(OC)_3WPPh_3CH_2CH_2P(p-tol)_3$ ]  
at 55 °C in perdeuterated chloroform.

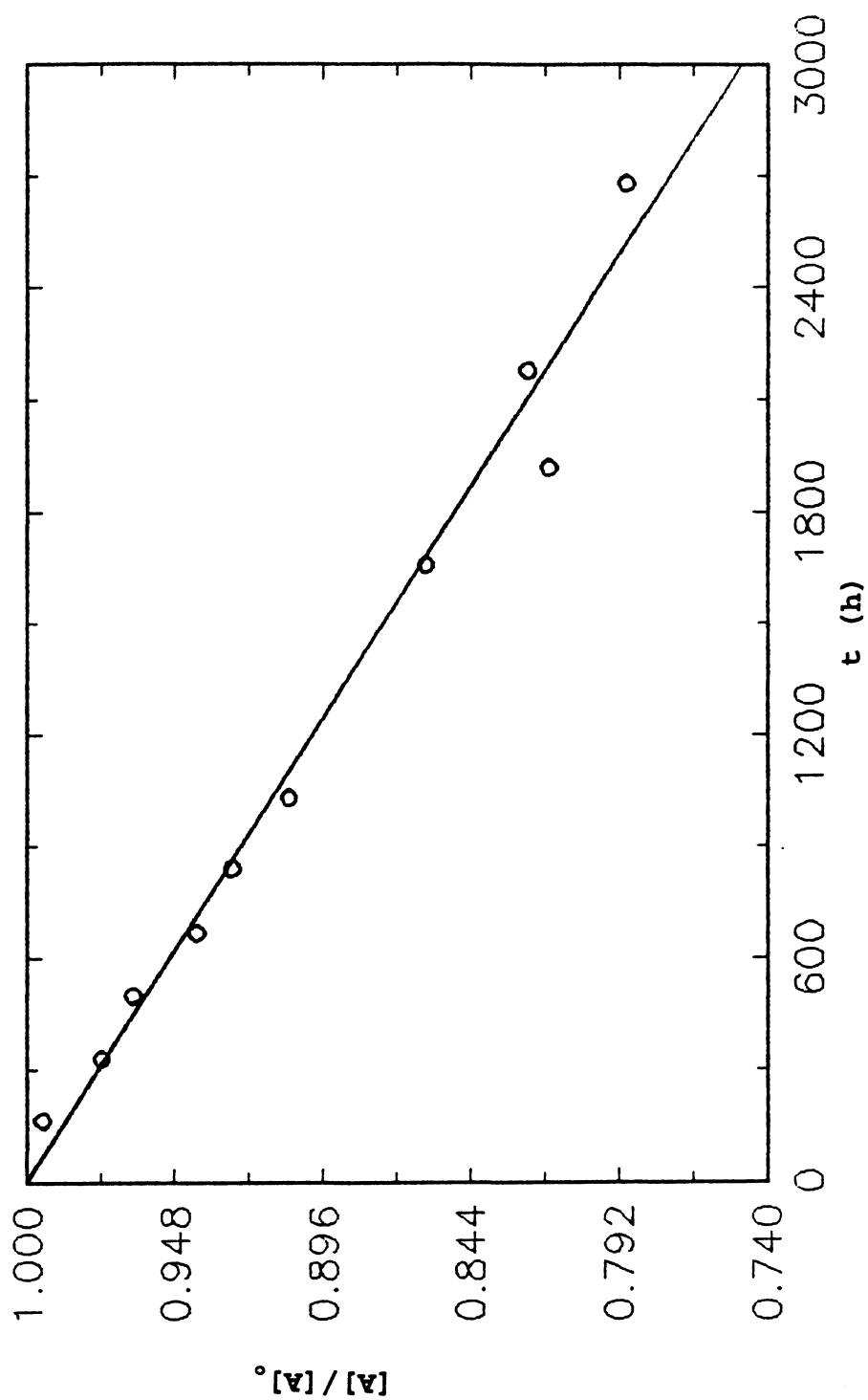


Figure 53. Plots of  $[B]/[A]_0$  or  $[C]/[A]_0$  vs  $t$   
 $[B = (OC)_5WP(p\text{-tol}), CH_2CH_2PPh_2; C = (OC)_4W(dpdt)]$   
 at 55 °C in perdeuterated chloroform.

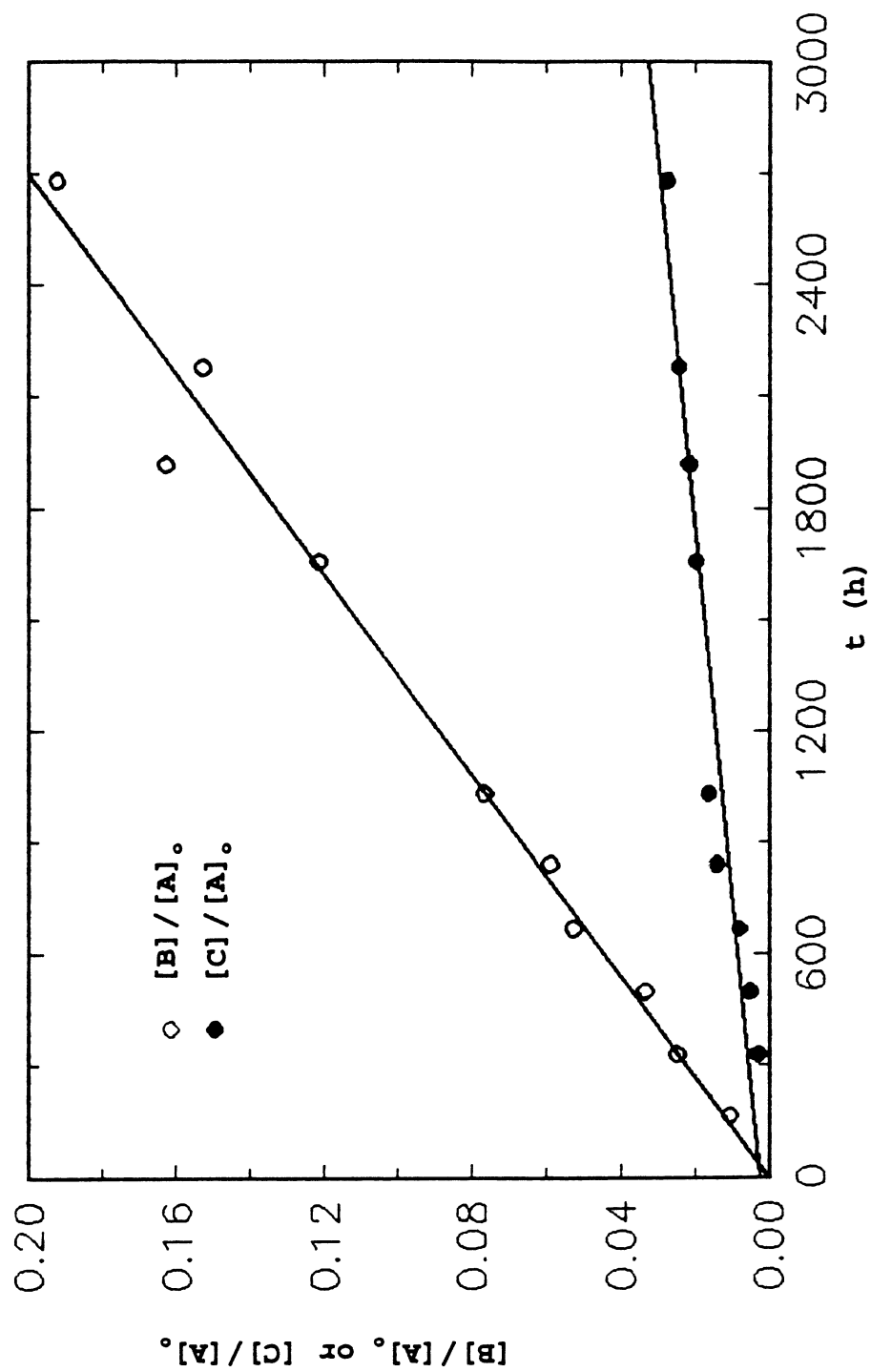


Figure 54. Plot of  $[B]/[B]_0$  vs  $t$   $[B = (OC)_3WP(p\text{-tol})_2CH_2CH_2PPh_2]$   
at 55 °C in perdeuterated chloroform.

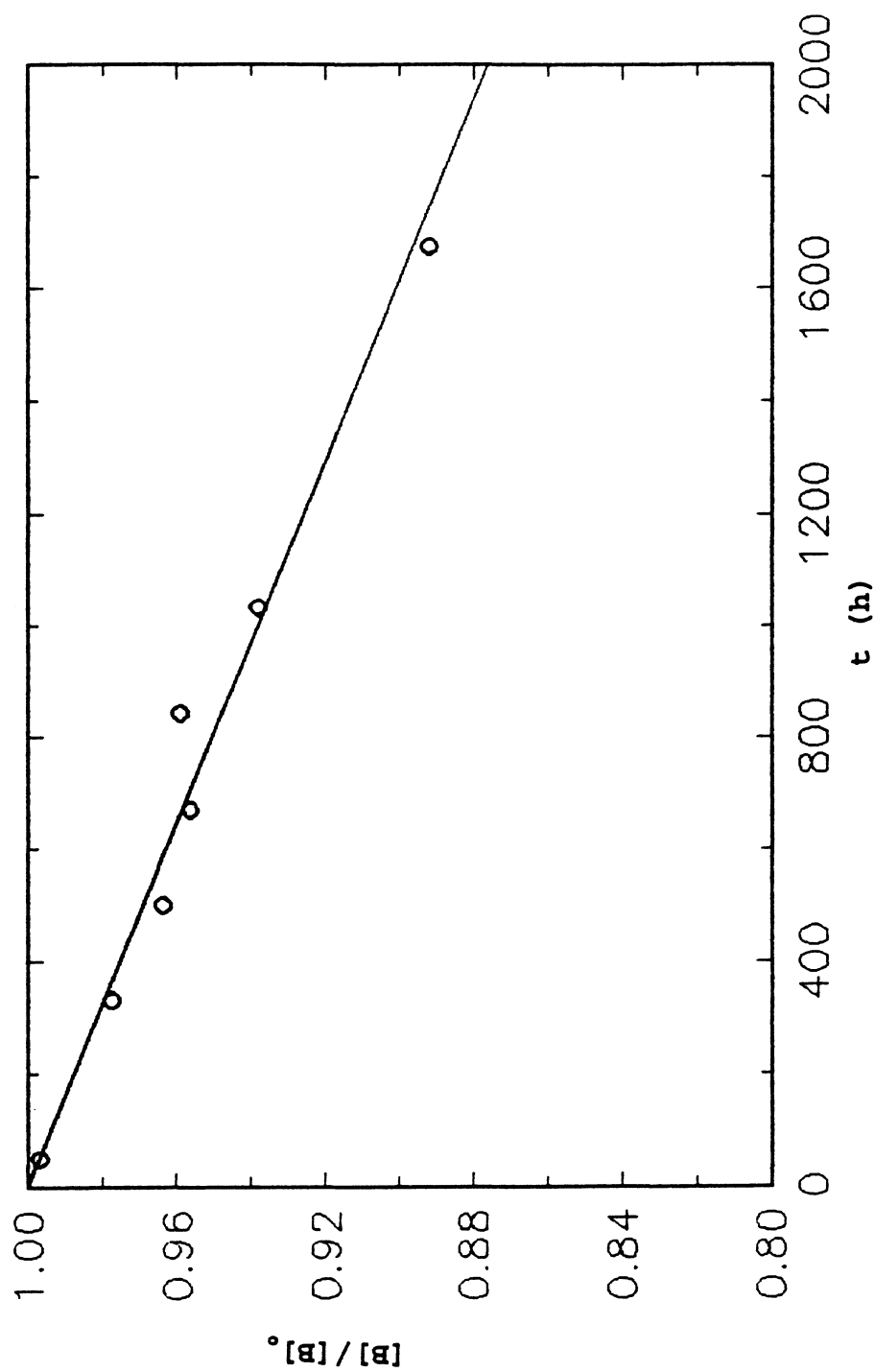
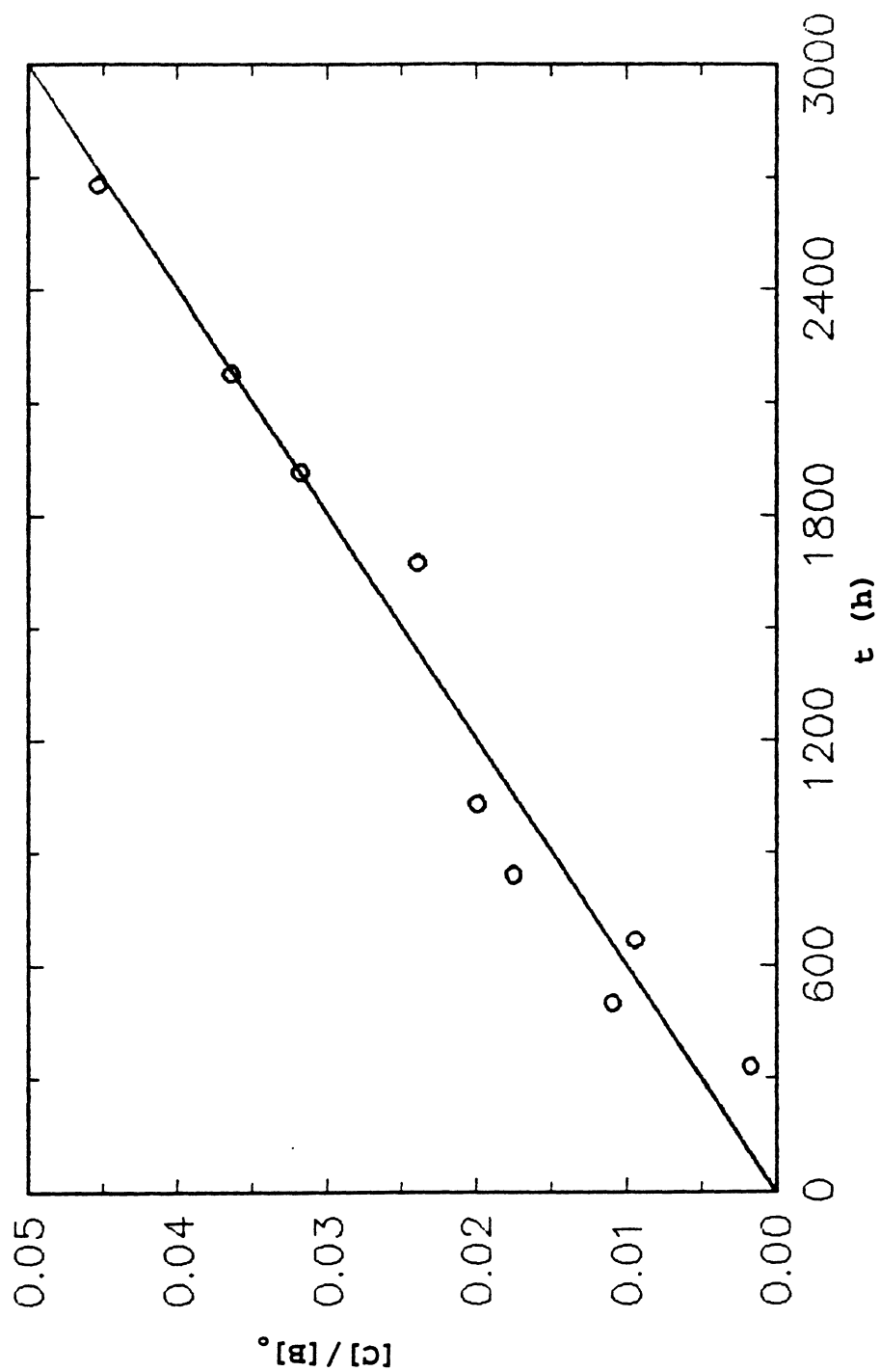


Figure 55. Plot of  $[C]/[B]_0$  vs  $t$  [ $C=(OC)_4W(dpdt)$ ] at 55 °C in perdeuterated chloroform.



### III. Experimental Section

#### 1. Materials

Tetrahydrofuran (THF) was predried over calcium hydride and was freshly distilled from sodium and benzophenone as needed. All other solvents were used without further purification. Metal hexacarbonyls and phosphines were purchased from Strem Chemicals Inc. and Aldrich Chemical Co., respectively, and used without further purification.

#### 2. Physical Measurements

$^{31}\text{P}\{^1\text{H}\}$  NMR spectra of all synthesized compounds were recorded with a General Electric QE-300 spectrometer. Deuteriochloroform,  $\text{CDCl}_3$ , and phosphoric acid,  $\text{H}_3\text{PO}_4$  (85%), were used as solvent and reference, respectively. The IR spectra were obtained with a Nicolet 20 DXB spectrometer with dichloromethane as a solvent. All melting points were taken with an Arthur H. Thomas Unimelt apparatus without correction.

Microanalyses were performed by the Microanalytical Laboratory, University of Illinois at Urbana. The variable temperature NMR experiments on  $(\text{OC})_5\text{WPPh}_2\text{CH}_2\text{CH}_2\text{PPh}_2$  and  $(\text{OC})_5\text{WPPh}_2\text{CH}_2\text{PPh}_2$  were performed at 30, 50, 65, and 80 °C in  $(\text{CDCl}_2)_2$  and at -50, -30, -10, 10, 30, 50, 70 °C in  $\text{C}_6\text{D}_6$ , respectively, with a Nicolet NT-360 instrument by Spectral Data Services, Inc., Champaign, IL. The sample was in solution for 15-20 min at each temperature.

### 3. Isomerization Studies

An NMR tube containing 20-40 mg of one of the isomers  $(OC)_5M(dpdt)$  ( $M = Cr, Mo, W$ ), dissolved in 0.25-0.50 ml of  $CDCl_3$  or  $C_6D_5(CD_3)$ , was sealed under  $N_2$  and put into a 55 °C water bath. The  $^{31}P\{^1H\}$  NMR spectra were taken of the samples periodically. The amounts of the isomers in the NMR tubes were determined by the integration of the signals from the uncoordinated phosphorus. A delay time of 15 sec provide internal consistency. Appendix I contains the kinetic data obtained from these studies.

### 4. Synthesis

#### (1). Preparation of Tri(*p*-tolyl)phosphine, $(p-MeC_6H_4)_3P$

A solution of *p*-bromotoluene (100 ml; 0.813 mol) dissolved into 200 ml of anhydrous ethyl ether, together with a granule of iodine, was added in drops in the course of 3 hours to a stirred mixture of 25.00 g (1.030 mol) of magnesium turnings and 300 ml of anhydrous ethyl ether contained in a 2000 ml 3-neck flask equipped with a condenser, a  $N_2$  inlet, and a dropping funnel. A piece of freshly cut Mg turning was needed to initiate the Grignard reaction. The exothermic reaction was controlled within 35-36 °C by a cold water bath to allow gentle reflux.

A solution of  $PCl_3$  (20.0 ml; 0.229 mol) in anhydrous  $Et_2O$  (180 ml) was added in drops in the course of 6 h to the Grignard solution prepared as above and cooled to -6 °C by a



mixture of ice and NaCl. After the completion of addition, the solution was heated to reflux for 1 h.

The resulting solution was cooled with ice, hydrolyzed by drops with 50 ml of highly concentrated  $\text{NH}_4\text{Cl}$  solution, and filtered to remove the solid. The filtrate was dried over anhydrous  $\text{MgSO}_4$  overnight, and then filtered. After some of the solvent was removed with a rotary evaporator, to the filtrate was added an equal volume of ethyl alcohol and the solution was cooled to  $-5\text{ }^\circ\text{C}$ . Recrystallization gave 47.6 g (yield 57.7%) of white solid: mp  $145\text{--}146\text{ }^\circ\text{C}$ ;  $^{31}\text{P}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}}$   $-7.5\text{ ppm}$  (see reference 24).

(2). Preparation of Di(*p*-tolyl)phosphine,  $(p\text{-MeC}_6\text{H}_4)_2\text{PH}$

To a rapidly stirred solution of 10.14 g (33.31 mmol) of  $(p\text{-tol})_3\text{P}$  dissolved in 300 ml of dried THF was added 0.943 g (0.136 mol) of finely cut Lithium under  $\text{N}_2$ . The solution became deep dark within a few minutes. After stirring for 33 h at ambient temperature, the solution was cooled to  $0\text{ }^\circ\text{C}$  and hydrolyzed with 20-30 ml of highly concentrated aqueous  $\text{NH}_4\text{Cl}$  which was purged with  $\text{N}_2$  for 30 min in drops. The dark color of the solution changed to colorless. Distillation of the resulted solution under vacuum gave 5.4 g (yield 74%) of colorless liquid: bp  $\sim 110\text{ }^\circ\text{C}$  (0.1 mmHg);  $^{31}\text{P}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}}$   $-42.0\text{ ppm}$ ,  $^1\text{J}_{\text{PH}}$  218.4 Hz (see references 38 and 79).

(3). Preparation of 1,2-bis(di-*p*-tolylphosphino)ethane,  
 $(p\text{-tol})_2\text{PCH}_2\text{CH}_2\text{P}(p\text{-tol})_2$  (dtpe)

To a rapidly stirred solution containing dried THF (30 ml) and  $\text{P}(p\text{-tol})_2\text{H}$  (1.0 ml; 4.7 mmol) was added finely cut lithium (0.14 g; 20.2 mmol) under  $\text{N}_2$ . The solution was cooled to 0 °C. Then 0.2 ml (2.5 mmol) of  $\text{ClCH}_2\text{CH}_2\text{Cl}$  dissolved in 2 ml of dried THF was added to the solution as above. The resulting solution was hydrolyzed with 2.5 ml of  $\text{H}_2\text{O}$  and filtered to remove the inorganic salt. After removing the solvent from the filtrate, the residue was recrystallized from methanol at -5 °C to give 0.25 g (yield 11.8%) of white solid: mp 148-149 °C;  $^{31}\text{P}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}}$  -14.0 ppm. Anal. Calcd. for  $\text{C}_{30}\text{H}_{32}\text{P}_2$ : C, 79.28; H, 7.10. Found: C, 77.18; H, 6.93.

(4). Preparation of 1-(diphenylphosphino)-2-(di-*p*-tolylphosphino)ethane,  $\text{Ph}_2\text{PCH}_2\text{CH}_2\text{P}(p\text{-tol})_2$  (dpdt)

A mixture of  $\text{Ph}_2\text{PCH}=\text{CH}_2$  (2.5 ml; 12.6 mmol),  $\text{P}(p\text{-tol})_2\text{H}$  (2.5 ml; 12.5 mmol), and AIBN (0.33 g) was heated to 76 °C and stirred for 17 h under  $\text{N}_2$ . The solution solidified after a few hours. The solid was crystallized from 3:1  $\text{CH}_3\text{OH}/\text{CH}_2\text{Cl}_2$  to give 5.01 g (yield 94.4%) of white solid: mp 108-109 °C;  $^{31}\text{P}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{PPh}_2}$  -12.1 ppm,  $\delta_{\text{P}(p\text{-tol})_2}$  -14.2 ppm,  $^3\text{J}_{\text{PP}}$  34.6 Hz; Anal. Calcd for  $\text{C}_{28}\text{H}_{28}\text{P}_2$ : C, 78.86; H, 6.62; Found: C, 79.46; H, 6.69 (see references 38 and 60).

(5). Preparation of Pentacarbonyldi(*p*-tolyl)phosphine-tungsten(0),  $(OC)_5WP(p\text{-tol})_2H$

To a solution containing 1.839 g (5.228 mmol) of  $W(CO)_6$ , 0.581 g (5.228 mmol) of  $Me_3NO \cdot 2H_2O$ , and 50 ml of  $CH_2Cl_2$  purged with  $N_2$  for 20 min was added 1.12 g (5.23 mmol) of  $P(p\text{-tol})_2H$  and stirred under  $N_2$ . The initial yellow color of the solution gradually turned to a deep brown color and then changed back to yellow after a few hours. After 72 h, the solvent of the solution was evaporated to dryness under vacuum. To the residue was added 80 ml of 1:3  $CH_2Cl_2/CH_3OH$  and filtered to remove the unreacted  $W(CO)_6$ .

Recrystallization from the filtrate at  $-5^\circ C$  gave 1.21 g of grey solid which showed three triplet signals in the  $^{31}P\{^1H\}$  NMR spectrum. The solid was separated by  $Al_2O_3$  column chromatography with gradient elution from 5:1 to 1:1 (v/v) *n*-hexane/ $CH_2Cl_2$ . The first yellow band was collected and evaporated to remove the solvent under vacuum.

Recrystallization of the residue from methanol at  $-5^\circ C$  gave 0.367 g (yield 13.0%) of white solid which was  $(OC)_5WP(p\text{-tol})_2H$ : mp  $89-90^\circ C$ ; IR [ $\nu(C\equiv O)$  ( $CH_2Cl_2$ ,  $cm^{-1}$ )] 2074 (m), 1940 (vs);  $^{31}P$  NMR ( $CDCl_3$ )  $\delta_P$  -15.5 ppm,  $^1J_{WP}$  227.5 Hz,  $^1J_{PH}$  332.3 Hz. Anal. Calcd for  $C_{19}H_{15}O_5PW$ : C, 42.41; H, 2.81. Found: C, 42.57; H, 2.88.

The second colorless band was collected and recrystallized as above to give 0.048 g (yield 2.5%) of white solid which was showed to be *cis*- $(OC)_4W[P(p\text{-tol})_2H]_2$ :

mp 138-139 °C; IR [ $\nu(\text{C}\equiv\text{O})$  ( $\text{CH}_2\text{Cl}_2$ ,  $\text{cm}^{-1}$ )] 2021(m), 1906(vs, br);  $^{31}\text{P}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}}$  -4.4 ppm,  $^1\text{J}_{\text{PW}}$  223.8Hz,  $^1\text{J}_{\text{PH}}$  336.6 Hz. Anal. Calcd for  $\text{C}_{32}\text{H}_{30}\text{O}_4\text{P}_2\text{W}$ : C, 53.06; H, 4.17. Found: C, 52.90; H, 4.17.

The third compound which showed a triplet in its  $^{31}\text{P}\{^1\text{H}\}$  NMR spectrum ( $\delta_{\text{P}}$  = 4.6 ppm,  $^1\text{J}_{\text{WP}}$  = 215.9Hz) was lost.

#### (6). Preparation of $(\text{OC})_5\text{WPPH}_2\text{H}$

The procedure was the same as that for preparing  $(\text{OC})_5\text{WP}(p\text{-tol})_2\text{H}$  except that 6.10 g (17.3 mmol) of  $\text{W}(\text{CO})_6$ , 3.0 ml (17.3 mmol) of  $\text{PPh}_2\text{H}$ , and 2.01 g (18.1 mmol) of  $\text{Me}_3\text{NO}\cdot 2\text{H}_2\text{O}$  were used. Recrystallization gave 5.01 g (yield 55.3%) of white solid: mp 90-91 °C; IR [ $\nu(\text{C}\equiv\text{O})$  ( $\text{CH}_2\text{Cl}_2$ ,  $\text{cm}^{-1}$ )] 2075 (m), 1942 (vs);  $^{31}\text{P}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}}$  -13.2 ppm,  $^1\text{J}_{\text{PH}}$  345.3Hz,  $^1\text{J}_{\text{WP}}$  229.3Hz (see reference 65).

#### (7). Preparation of $(\text{OC})_5\text{CrP}(p\text{-tol})_2\text{H}$

In a quartz reaction vessel equipped with a 400w uv lamp was added  $\text{Cr}(\text{CO})_6$  (4.02 g; 18.3 mmol) and THF (250 ml). After irradiating for 6 h, 4.0 ml (18.6 mmol) of  $\text{P}(p\text{-tol})_2\text{H}$  was injected into the solution. The solution changed from bright orange to light yellow within 10 min, and then to green. After stirring for 1.5 h, the solvent was removed from the solution. By dissolving the residue into 1:1  $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{OH}$ , the unreacted  $\text{Cr}(\text{CO})_6$  was removed by precipitation. Some other unwanted solids were removed by

further precipitation with  $\text{CH}_3\text{OH}$  in several steps.

Recrystallization from the solution at  $-5\text{ }^\circ\text{C}$  for several days gave 1.2 g (yield 31.7%) of light yellow crystal: mp  $91\text{--}92\text{ }^\circ\text{C}$ ; IR [ $\nu(\text{C}\equiv\text{O})$  ( $\text{CH}_2\text{Cl}_2$ ,  $\text{cm}^{-1}$ )] 2066(m), 1984(w), 1943(vs);  $^{31}\text{P}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}}$  30.9 ppm,  $^1\text{J}_{\text{PH}}$  338.2 Hz. Anal. Calcd for  $\text{C}_{19}\text{H}_{15}\text{O}_5\text{PCr}$ : C, 56.17; H, 3.72. Found: C, 55.54; H, 3.60.

(8). Preparation of  $(\text{OC})_5\text{MoP}(p\text{-tol})_2\text{H}$

A solution of  $\text{Mo}(\text{CO})_6$  (3.56 g; 0.036 mol) and 1,2-dimethoxyethane (60 ml) was heated to reflux for 1 h. To the resulting solution was added 2.9 ml (0.036 mol) of  $\text{P}(p\text{-tol})_2\text{H}$  and the solution was allowed to reflux for 2.5 h. The solvent was removed by the rotary evaporator. The residue was dissolved into a mixture of  $\text{CH}_3\text{OH}/\text{CH}_2\text{Cl}_2$  (1:1). Recrystallization from the solution at  $-5\text{ }^\circ\text{C}$  gave 3.6 g (yield 58.3%) of white solid: mp  $81\text{--}82\text{ }^\circ\text{C}$ ; IR [ $\nu(\text{C}\equiv\text{O})$  ( $\text{CH}_2\text{Cl}_2$ ,  $\text{cm}^{-1}$ )] 2075(m), 1948(vs);  $^{31}\text{P}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}}$  4.5 ppm,  $^1\text{J}_{\text{PH}}$  332.3 Hz. Anal. Calcd for  $\text{C}_{19}\text{H}_{15}\text{O}_5\text{PMo}$ : C, 50.69; H, 3.36. Found: C, 50.59; H, 3.25.

(9). Preparation of  $(\text{OC})_5\text{WPPH}_2\text{CH}=\text{CH}_2$

The procedure is the same as that for  $(\text{OC})_5\text{WP}(p\text{-tol})_2\text{H}$  except that 6.00 g (0.0170 mol) of  $\text{W}(\text{CO})_6$ , 3.4 ml (0.017 mol) of  $\text{PPh}_2\text{CH}=\text{CH}_2$ , and 1.89 g (0.0170 mol) of  $\text{Me}_3\text{NO}\cdot 2\text{H}_2\text{O}$  were used. Recrystallization gave 3.99 g (yield 43.8%) of white solid: mp  $59\text{--}60\text{ }^\circ\text{C}$ ; IR [ $\nu(\text{C}\equiv\text{O})$  ( $\text{CH}_2\text{Cl}_2$ ,  $\text{cm}^{-1}$ )] 2072(m),

1979(w), 1939(vs);  $^{31}\text{P}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}}$  11.9 ppm,  $^1\text{J}_{\text{WP}}$  239.3 Hz (see reference 65).

(10). Preparation of  $(\text{OC})_5\text{CrPPh}_2\text{CH}=\text{CH}_2$

Method A:

The procedure is the same as that for  $(\text{OC})_5\text{WP}(p\text{-tol})_2\text{H}$  except that  $\text{PPh}_2\text{CH}=\text{CH}_2$  (0.95 ml; 4.8 mmol),  $\text{Cr}(\text{CO})_6$  (1.0 g; 4.8 mmol), and  $\text{Me}_3\text{NO}\cdot 2\text{H}_2\text{O}$  (0.53 g; 4.8 mmol) were used. Recrystallization at  $-5\text{ }^\circ\text{C}$  for 7 days gave 1.16 g (yield 60.2%) of light yellow crystal  $(\text{OC})_5\text{CrPPh}_2\text{CH}=\text{CH}_2$  : mp  $54\text{--}55\text{ }^\circ\text{C}$ ;  $^{31}\text{P}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}}$  47.9 ppm; IR [ $\nu(\text{C}\equiv\text{O})$  ( $\text{CH}_2\text{Cl}_2$ ,  $\text{cm}^{-1}$ )] 2064(m), 1983(w), 1941(vs) (see reference 66).

Method B:

The procedure is the same as that for  $(\text{OC})_5\text{CrP}(p\text{-tol})_2\text{H}$  except that a mixture of  $\text{Cr}(\text{CO})_6$  (5.07 g; 23.0 mmol) and THF (250 ml) was irradiated for 2 h followed by the injection of 4.6 ml (23.1 mmol) of  $\text{PPh}_2\text{CH}=\text{CH}_2$ . Recrystallization gave 1.67 g (yield 17.9%) of light yellow crystals: mp  $54\text{--}55\text{ }^\circ\text{C}$ .

(11). Preparation of *cis*- $(\text{OC})_4\text{Mo}(\text{PPh}_2\text{CH}=\text{CH}_2)_2$

The procedure is the same as that for  $(\text{OC})_5\text{WP}(p\text{-tol})_2\text{H}$  except that  $\text{Mo}(\text{CO})_6$  (7.14 g; 0.0269 mol),  $\text{PPh}_2\text{CH}=\text{CH}_2$  (5.4 ml; 0.027 mol), and  $\text{Me}_3\text{NO}\cdot 2\text{H}_2\text{O}$  (2.99 g; 0.0269 mol) were used. Recrystallization gave 2.2 g (yield 25.9%) of white crystal: mp  $93\text{--}94\text{ }^\circ\text{C}$ ;  $^{31}\text{P}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}}$  29.3 ppm; IR [ $\nu(\text{C}\equiv\text{O})$  ( $\text{CH}_2\text{Cl}_2$ ,  $\text{cm}^{-1}$ )] 2022(m), 1907(vs), 1883(vs). Anal. Calcd for

$C_{32}H_{26}O_4P_2Mo$ : C, 60.77; H, 4.14. Found: C, 60.78; H, 4.02.

(12). Preparation of  $(OC)_5WPPh_2CH_2CH_2PPh_2$

A mixture of  $(OC)_5WPPh_2CH=CH_2$  (3.01 g; 5.61 mmol),  $PPh_2H$  (0.98 ml; 5.6 mmol), and AIBN (0.11 g) was heated to 80 °C and stirred for 24 h under  $N_2$ . Then the resulting solution was evaporated under vacuum at 80 °C for 1 h. The unreacted materials were removed by precipitation from 3:1  $CH_3OH/CH_2Cl_2$  and the solution was recrystallized at -5 °C to give 0.85 g (yield 42.9%) of white solid: mp 112-115 °C;  $^{31}P\{^1H\}$  NMR ( $CDCl_3$ )  $\delta_{P-W}$  13.4 ppm,  $\delta_P$  -12.2 ppm,  $^3J_{PP}$  37.5 Hz,  $^1J_{WP}$  239.4 Hz; IR [ $\nu(C\equiv O)$  ( $CH_2Cl_2$ ,  $cm^{-1}$ )] 2071(m), 1982(w), 1937(vs) (see references 67 and 86).

(13). Preparation of  $(OC)_5WPPh_2CH_2CH_2P(p-tol)_2$

The procedure is the same as that for  $(OC)_5WPPh_2CH_2CH_2PPh_2$  except that 3.0 g (5.6 mmol) of  $(OC)_5WPPh_2CH=CH_2$ , 1.1 g (5.1 mmol) of  $(p-tol)_2PH$ , and 0.13 g of AIBN were used. Recrystallization gave 1.71 g (yield 44.3%) of white solid: mp 143-144 °C; IR [ $\nu(C\equiv O)$  ( $CH_2Cl_2$ ,  $cm^{-1}$ )] 2071(m), 1981(w,br), 1937(vs);  $^{31}P\{^1H\}$  NMR ( $CDCl_3$ )  $\delta_{PPh_2}$  13.6 ppm,  $\delta_{P(p-tol)_2}$  -13.7 ppm,  $^3J_{PP}$  37.6 Hz,  $^1J_{WP}$  239.3 Hz. Anal. Calcd for  $C_{33}H_{28}O_5P_2W$ : C, 52.82; H, 3.76. Found: C, 52.64; H, 3.75.

(14). Preparation of  $(OC)_5WP(p-tol)_2CH_2CH_2PPh_2$

The procedure is the same as that for  $(OC)_5WPPh_2CH_2CH_2PPh_2$

except that  $(OC)_5WP(p\text{-tol})_2H$  (0.31 g;  $5.69 \times 10^{-4}$  mol),  $PPh_2CH=CH_2$  (0.15 ml;  $6.6 \times 10^{-4}$ ), and AIBN (0.12 g) were used. Recrystallization gave 0.33 g (yield 77%) of yellow solid which was a mixture. Further purification by  $Al_2O_3$  column chromatography with gradient elution of 3:1 to 1:1 *n*-hexane/ $CH_2Cl_2$  gave 0.190 g (yield 44.5%) of white solid: mp 111-112 °C; IR [ $\nu(C\equiv O)$  ( $CH_2Cl_2$ ,  $cm^{-1}$ )] 2071 (m), 1981 (w), 1936 (vs);  $^{31}P\{^1H\}$  NMR ( $CDCl_3$ )  $\delta_{P(p\text{-tol})_2}$  11.5 ppm,  $\delta_{PPh_2}$  -12.0 ppm,  $^3J_{PP}$  38.0 Hz,  $^1J_{WP}$  238.4 Hz. Anal. Calcd for  $C_{33}H_{28}O_5P_2W$ : C, 52.82; H, 3.76. Found: C, 51.75; H, 3.82.

(15). Preparation of  $(OC)_5CrPPh_2CH_2CH_2P(p\text{-tol})_2$

The procedure is the same as that for  $(OC)_5WPPH_2CH_2CH_2PPh_2$  except that  $(OC)_5CrPPh_2CH=CH_2$  (1.10 g; 2.72 mmol),  $P(p\text{-tol})_2H$  (0.55 ml; 2.57 mmol), and AIBN (0.12 g) were used. Recrystallization gave 0.41 g (yield 25.9%) of white crystal: mp 133-134 °C;  $^{31}P\{^1H\}$  NMR ( $CDCl_3$ )  $\delta_{PPh_2}$  50.5 ppm,  $\delta_{P(p\text{-tol})_2}$  -13.6 ppm,  $^3J_{PP}$  35.1 Hz; IR [ $\nu(C\equiv O)$  ( $CH_2Cl_2$ ,  $cm^{-1}$ )] 2063(m), 1983(w), 1939(vs). Anal. Calcd for  $C_{33}H_{28}O_5P_2Cr$ : C, 64.08; H, 4.56. Found: C, 63.82; H, 4.22.

(16). Preparation of  $(OC)_5CrP(p\text{-tol})_2CH_2CH_2PPh_2$

The procedure is the same as that for  $(OC)_5WPPH_2CH_2CH_2PPh_2$  except that  $(OC)_5CrP(p\text{-tol})_2H$  (1.09 g; 2.68 mmol),  $PPh_2CH=CH_2$  (0.55 ml; 2.60 mmol), and AIBN (0.15 g) were used. Recrystallization gave 0.98 g (yield 58.9%)



of light yellow crystal: mp 103-104 °C;  $^{31}\text{P}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}(\text{p-tol})_2}$  48.4 ppm,  $\delta_{\text{PPh}_2}$  -11.8 ppm,  $^3\text{J}_{\text{PP}}$  35.0 Hz; IR [ $\nu(\text{C}\equiv\text{O})$  ( $\text{CH}_2\text{Cl}_2$ ,  $\text{cm}^{-1}$ )] 2062 (m), 1982 (w), 1937 (vs). Anal. Calcd for  $\text{C}_{33}\text{H}_{28}\text{O}_5\text{P}_2\text{Cr}$ : C, 64.08; H, 4.56. Found: C, 63.71; H, 4.58.

(17). Preparation of  $(\text{OC})_5\text{MoPPh}_2\text{CH}_2\text{CH}_2\text{P}(\text{p-tol})_2$

The procedure is the same as that for  $(\text{OC})_5\text{WPPH}_2\text{CH}_2\text{CH}_2\text{PPh}_2$  except that  $(\text{OC})_5\text{MoPPh}_2\text{CH}=\text{CH}_2$  (1.52 g;  $3.38 \times 10^{-3}$  mol),  $\text{P}(\text{p-tol})_2\text{H}$  (0.8 ml;  $3.7 \times 10^{-3}$ ), and AIBN (0.21 g) were heated at about 43 °C. Recrystallization gave 0.82 g (yield 36.6%) of white solid: mp 130 °C; IR [ $\nu(\text{C}\equiv\text{O})$  ( $\text{CH}_2\text{Cl}_2$ ,  $\text{cm}^{-1}$ )] 2073 (m), 1989 (w), 1945 (vs);  $^{31}\text{P}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{PPh}_2}$  31.7 ppm,  $\delta_{\text{P}(\text{p-tol})_2}$  -13.6 ppm,  $^3\text{J}_{\text{PP}}$  37.0 Hz. Anal. Calcd for  $\text{C}_{33}\text{H}_{28}\text{O}_5\text{P}_2\text{Mo}$ : C, 59.83; H, 4.26. Found: C, 59.84; H, 4.18.

(18). Preparation of  $(\text{OC})_5\text{MoP}(\text{p-tol})_2\text{CH}_2\text{CH}_2\text{PPh}_2$

The procedure is the same as that for  $(\text{OC})_5\text{WPPH}_2\text{CH}_2\text{CH}_2\text{PPh}_2$  except that  $(\text{OC})_5\text{MoP}(\text{p-tol})_2\text{H}$  (2.00 g;  $4.42 \times 10^{-3}$  mol),  $\text{PPh}_2\text{CH}=\text{CH}_2$  (0.94 ml;  $4.42 \times 10^{-3}$ ), and AIBN (0.12 g) were heated at about 40 °C. Recrystallization gave 2.18 g (yield 74.5%) of white solid: mp 90-91 °C; IR [ $\nu(\text{C}\equiv\text{O})$  ( $\text{CH}_2\text{Cl}_2$ ,  $\text{cm}^{-1}$ )] 2072 (m), 1989 (w), 1943 (vs);  $^{31}\text{P}\{^1\text{H}\}$  NMR ( $\text{CDCl}_3$ )  $\delta_{\text{P}(\text{p-tol})_2}$  29.7 ppm,  $\delta_{\text{PPh}_2}$  -11.8 ppm,  $^3\text{J}_{\text{PP}}$  35.9 Hz. Anal. Calcd for  $\text{C}_{33}\text{H}_{28}\text{O}_5\text{P}_2\text{Mo}$ : C, 59.83; H, 4.26. Found: C, 59.68; H, 4.16.

(19). Preparation of  $(OC)_4MoPPh_2CH_2CH_2P(p-tol)_2$

The procedure is the same as that for  $(OC)_5WPPh_2CH_2CH_2PPh_2$  except that  $(OC)_5WPPh_2CH=CH_2$  (2.50 g;  $5.59 \times 10^{-3}$  mol),  $P(p-tol)_2H$  (1.2 ml;  $5.6 \times 10^{-3}$ ), and AIBN (0.16 g) were heated at about 80 °C. Recrystallization gave 1.5 g (yield 42.3%) of white solid which was chelated compound: mp 147-148 °C; IR [ $\nu(C\equiv O)$  ( $CH_2Cl_2$ ,  $cm^{-1}$ )] 2021 (m), 1909 (vs), 1882 (s);  $^{31}P\{^1H\}$  NMR ( $CDCl_3$ )  $\delta_{PPh_2}$  55.8 ppm,  $\delta_{P(p-tol)_2}$  53.6 ppm,  $J_{PP}$  5.7 Hz. Anal. Calcd for  $C_{32}H_{28}O_4P_2Mo$ : C, 60.58; H, 4.45. Found: C, 60.74; H, 4.33.

(20). Preparation of *cis*- $(OC)_4W(PPh_2Et)(PPh_2H)$

A solution containing dried THF (50 ml),  $(OC)_5WPPh_2H$  (1.22 g; 2.33 mmol),  $PPh_2Et$  (0.50 ml; 2.5 mmol), and KOBut (0.21 g; 1.9 mmol) was refluxed for 2 h. Then 1 ml of  $H_2O$  was added to the solution to quench the reaction. The solution became red. The resulting solution was extracted with 1:1  $H_2O/CH_2Cl_2$ . After removing the solvent from the organic layer, the residue was recrystallized from 4:1  $CH_3OH/CH_2Cl_2$  to give 0.62 g (yield 38.2%) of white solid: mp 130-130.5 °C;  $^{31}P\{^1H\}$  NMR ( $CDCl_3$ )  $\delta_{PPh_2H}$  2.4 ppm ( $^1J_{WP}$  230.1 Hz),  $\delta_{PPh_2Et}$  14.8 ppm ( $^1J_{WP}$  225.7 Hz),  $^2J_{PP}$  16.7 Hz; IR [ $\nu(C\equiv O)$  ( $CH_2Cl_2$ ,  $cm^{-1}$ )] 2019 (m), 1901 (vs), 1877 (m) (see reference 83).

A small triplet also appeared on the spectra at -2.1 ppm ( $^1J_{WP}$  224.0 Hz) which was believed to be *cis*- $(OC)_4W(PPh_2H)_2$ .

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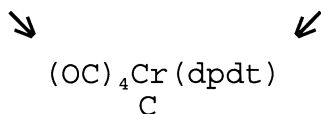
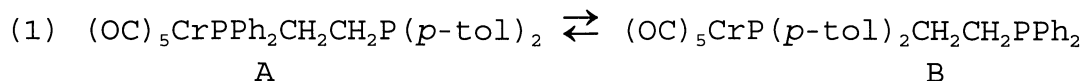
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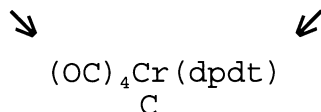
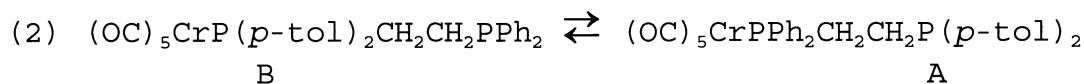
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## Appendix I



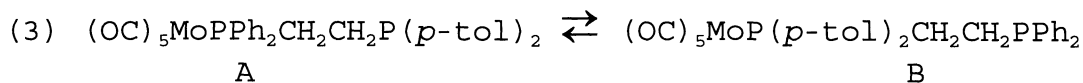
at 55 °C in perdeuterated toluene

Time (h)	$[\text{A}] / [\text{A}]_0$	$[\text{B}] / [\text{A}]_0$	$[\text{C}] / [\text{A}]_0$
52.0	0.9841	0.007996	0.007861
218.8	0.9621	0.01652	0.01635
386.9	0.9524	0.02777	0.01987
554.4	0.9434	0.02904	0.02753
723.0	0.9194	0.04388	0.03673
910.1	0.9042	0.05268	0.04318
1082.4	0.8955	0.05283	0.05166
1221.8	0.8789	0.06532	0.05581
1391.0	0.8638	0.07046	0.06576
1581.6	0.8528	0.07902	0.06817
2036.3	0.8140	0.09531	0.09071



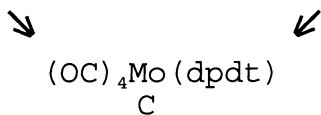
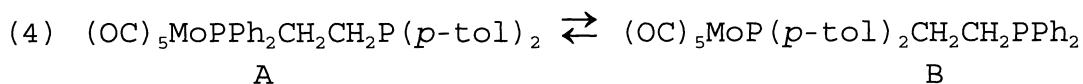
at 55 °C in perdeuterated toluene

Time (h)	$[\text{B}] / [\text{B}]_0$	$[\text{A}] / [\text{B}]_0$	$[\text{C}] / [\text{B}]_0$
52.3	0.9786	0.01394	0.007478
220.2	0.9673	0.01936	0.01330
387.3	0.9525	0.02538	0.02209
554.7	0.9468	0.02603	0.02717
723.3	0.9307	0.03130	0.03799
910.4	0.9114	0.04053	0.04806
1081.7	0.9063	0.04108	0.05265
1222.2	0.8936	0.04553	0.06092
1391.4	0.8861	0.04702	0.06684
1581.8	0.8768	0.05010	0.07310
2037.7	0.8430	0.06152	0.09551



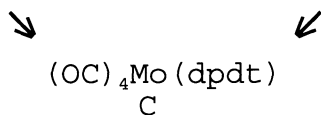
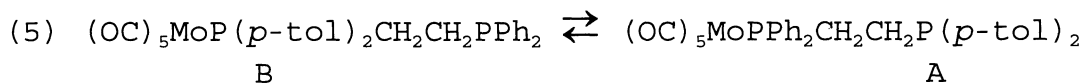
at 55 °C in perdeuterated toluene (K=1.96)

Time (sec)	$[A] / [A]_0$	$\ln([A] / [A]_0 - [A]_{\text{eq}} / [A]_0)$
1813	0.9815	-0.4406
3626	0.9742	-0.4520
5439	0.9563	-0.4805
7252	0.9424	-0.5033
9065	0.9327	-0.5194
10878	0.9198	-0.5414
12691	0.9047	-0.5676
14504	0.8940	-0.5867
16317	0.8826	-0.6074
18130	0.8769	-0.6179



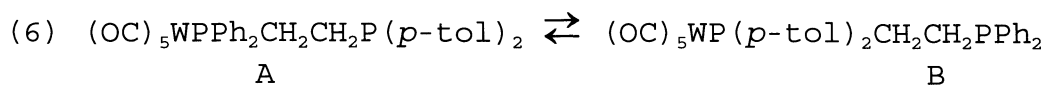
at 55 °C in perdeuterated toluene

Time (h)	$[C] / [A]_0$
52.8	0.0948
95.0	0.1637
218.0	0.2967
388.0	0.4594



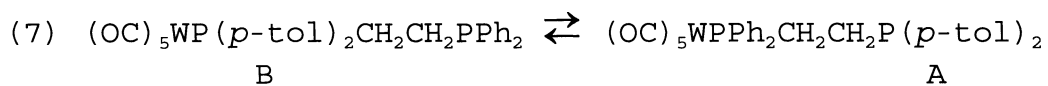
at 55 °C in perdeuterated toluene

Time (h)	$[C] / [B]_0$
53.1	0.0884
95.1	0.1585
218.4	0.2944
388.3	0.4612



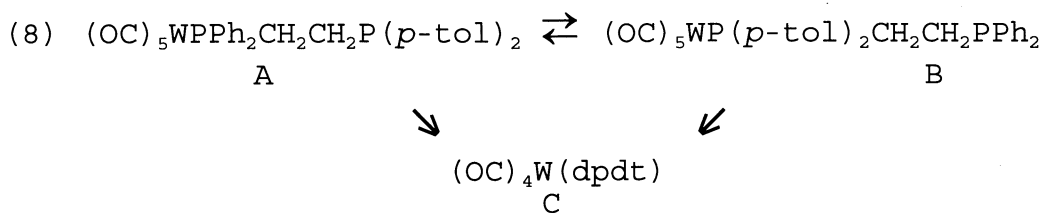
at 55 °C in perdeuterated toluene

Time (h)	[A] / [A] <sub>0</sub>	[B] / [A] <sub>0</sub>
219.4	0.9691	0.0309
387.9	0.9580	0.0420
555.4	0.9447	0.0553
724.0	0.9289	0.0711
911.0	0.9128	0.0872
1082.4	0.8929	0.1071
1223.0	0.8867	0.1133
1392.2	0.8687	0.1313
1582.4	0.8566	0.1434
2037.3	0.8178	0.1822
2396.1	0.7925	0.2075



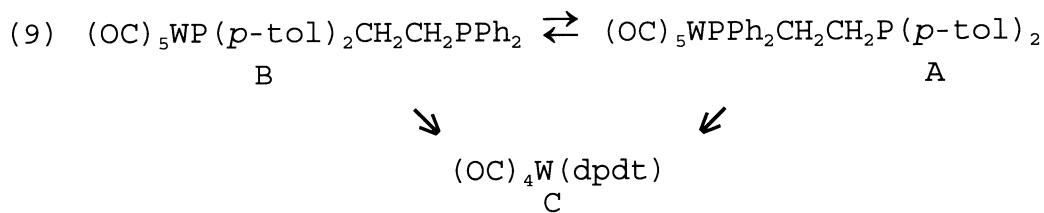
at 55 °C in perdeuterated toluene

Time (h)	[B] / [B] <sub>0</sub>	[A] / [B] <sub>0</sub>
219.8	0.9480	0.0520
388.3	0.9438	0.0562
555.7	0.9318	0.0682
724.3	0.9222	0.0778
911.4	0.9227	0.0773
1082.7	0.9136	0.0864
1223.5	0.9141	0.0859
1392.5	0.9002	0.0998
1583.0	0.9021	0.0979
2037.8	0.8846	0.1154
2396.4	0.8686	0.1314



at 55 °C in perdeuterated chloroform

Time (h)	$[\text{A}] / [\text{A}]_0$	$[\text{B}] / [\text{A}]_0$	$[\text{C}] / [\text{A}]_0$
166	0.9679	0.0214	0.0107
331	0.9471	0.0355	0.0174
500	0.9361	0.0443	0.0196
669	0.9138	0.0636	0.0226
842	0.9014	0.0697	0.0289
1031	0.8815	0.0874	0.0311
1657	0.8332	0.1324	0.0344
1918	0.7902	0.1737	0.0361
2180	0.7974	0.1636	0.0390
2680	0.7630	0.2031	0.0339



at 55 °C in perdeuterated chloroform

Time (h)	$[\text{B}] / [\text{B}]_0$	$[\text{A}] / [\text{B}]_0$	$[\text{C}] / [\text{B}]_0$
164	0.9876		
332	0.9527	0.0265	0.0208
502	0.9391	0.0308	0.0301
670	0.9317	0.0397	0.0286
843	0.9343	0.0290	0.0367
1032	0.9136	0.0473	0.0391
1675	0.8673	0.0896	0.0431
1915	0.8902	0.0588	0.0510
2179	0.9444		0.0556
2680	0.9355		0.0645