Pergamon

Tetrahedron, Vol. 52, No. 15, pp. 5461-5468, 1996

0040-4020/96 $15.00 + 0.00

S0040-4020(96)00181-0

Synthesis of Cyclopentanone Derivatives with Polystyrene-Supported Cyclopentadienyl Rhodium Catalysts

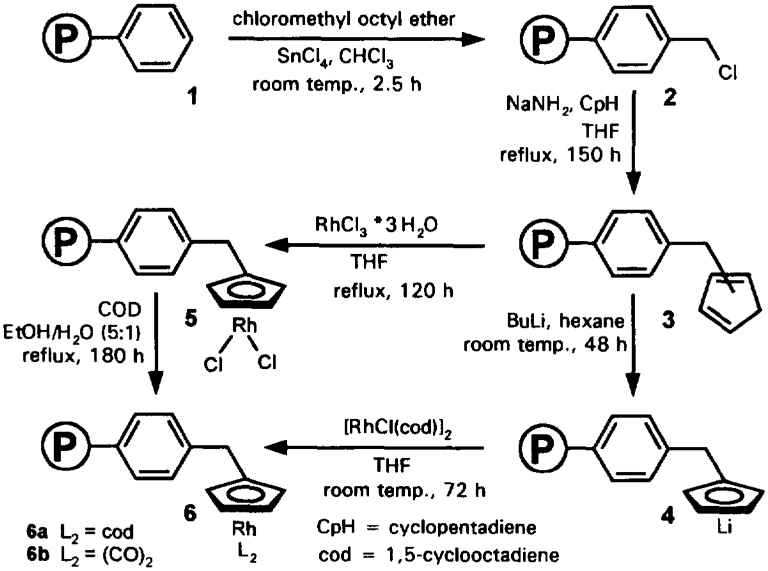
Dirk P. Dygutsch, Peter Eilbracht*

Lehrstuhl für Organische Chemie I, Fachbereich Chemie, Universität Dortmund, D-44221 Dortmund, Germany

Abstract: An efficient and reusable polystyrene-supported η^5-cyclopentadienyl rhodium catalyst is prepared and applied to the synthesis of substituted cyclopentanones either *via* hydrocarbonylative cyclization starting from 1,4-dienes or from allyl vinyl ethers *via* tandem Claisen rearrangement and intramolecular hydroacylation of the 4-pentenal intermediates. Copyright © 1996 Elsevier Science Ltd

Soluble rhodium complexes are known to catalyze various synthetically important organic reactions, such as hydrogenation, hydroformylation, cyclopropanation and many others.[1] Immobilizing of homogenous transition metal complexes onto solid supports offers advantages in catalyst separation and reuse and avoids loss of the precious metal during workup.[2] Although promising strong and inert binding to the solid support, only a few applications of polymer-attached cyclopentadienyl rhodium complexes are reported.[3] We here describe the preparation of an efficient polystyrene-supported cyclopentadienyl rhodium complex and its application to two different methods of cyclopentanone synthesis *via* intramolecular hydroacylation.

Scheme 1:



Preparation of the Polystyrene-Supported Catalyst

The polystyrene-supported cyclopentadienyl rhodium systems **5** and **6a** were prepared as outlined in scheme 1 by a modified and improved method introduced by Grubbs and co-workers.[3a,b]

Starting from a commercial 7% divinylbenzene-polystyrene copolymer, macroporous beads **1** the initial functionalization step is chloromethylation with chloromethyl octyl ether (CMOE) and tin(IV) chloride[4] followed by conversion of the chloromethylated resin using *in situ* generated cyclopentadienyl sodium from sodium amide and cyclopentadiene. After workup the beads were treated with butyl lithium in hexane to form the cyclopentadienyl anion **4**. Finally addition of $[RhCl(cod)]_2$ led to the dark brown catalyst precursors **6**.

Another introduction of the metal is achieved by treatment of the polystyrene-attached cyclopentadiene **3** with $RhCl_3 \cdot 3\,H_2O$ to obtain the Rh(III)-complex **5**, followed by reduction with ethanol/water (5:1) in the presence of 1,5-cyclooctadiene to form **6a**.

Hydrogenation and Hydroformylation of 1-Octene

To investigate the efficiency of the supported catalysts we carried out the hydrogenation and hydroformylation of 1-octene. In agreement with its monomeric analogue the supported catalyst showed only low activity in the hydrogenation of olefins. Furthermore, we observed decompostion during the reaction. This obviously results from the formation of rhodium metal due to the lack of stabilizing ligands.

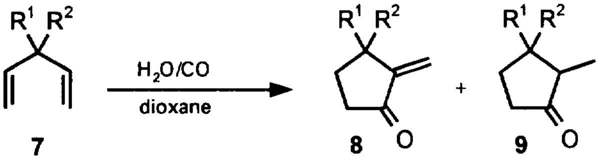
Transition metal complexes of cobalt and rhodium are well known as good catalysts for hydroformylation of olefins. Grubbs[3a] found that polymer-attached $CpRh(CO)_2$ is powerful in such reactions, too. We tested our system in the hydroformylation of octene. Reactions were carried out by stirring the catalyst beads (0.2 mol%) in the pesence of 1-octene in dioxane under 70 bar of carbon monoxide/hydrogen-atmosphere (1:1). The mixture was heated for 16 h at 120 °C. After workup the yields were detected by GC.

All conversions had been quantitative. Under the conditions described hydrogenation products are formed with ratios lower than 2 percent. This confirms the trend observed with hydrogenation. In addition to the expected linear and branched hydroformylation products (ratio 1:1, 75 %), two other branched aldehydes could be detected (20 %). Formation of these products results from isomerizations prior to the final hydroformylation step. The linear/branched selectivity in favour of the linear aldehyde can be controlled by the addition of triphenylphospine. In all cases the supported catalyst is recovered by filtration as its $CpRh(CO)_2$ complex **6b** showing two strong CO stretching bands at 1975 and 2040 cm^{-1}. This system was reused over three cycles without loss of activity and also used in the formation of cyclopentanone derivatives as described below. The results of the reactions confirm that the polymer-attached CpRh(cod) complex is a good and reusable hydroformylation catalyst.

Hydrocarbonylative Cyclization of Substituted 1,4-Dienes

Cyclopentanones can be formed with transition metal catalysts by the hydrocarbonylative cyclization of non-conjugated dienes. This procedure has been successfully applied to various 1,4-dienes especially those with a quarternary center at C-3.[5] Three different 1,4-dienes of type 7 have been used to test the polymeric catalyst in this type of reaction. The results in table 1 show high overall yields with product selectivities depending on the pressure and reaction time.

Scheme 2:



	R^1	R^2
a	Me	CH_2CO_2Et
b	Me	Ph
c	Me	$p\text{-}C_6H_4\text{-}CH_3$

Table 1: Hydrocarbonylative Cyclization of Substituted 1,4-Dienes in the Presence of **6**[i)]

Entry	Diene	Catalyst [mol%]	Pressure [bar]	Time [h]	Temperature [°C]	**7** [%]	**8**+**9** [%]	Ratio **8/9**
1	7a	1.00	200	24	150	----	97	0.5
2	7a	1.00	50	24	120	3	95	2.2
3	7a	0.75	50	22	120	----	80	3.9
4	7a	1.00	30	72	100	54	46	4.9
5	7b	1.00	50	24	120	7	84	0.3
6	7b	0.50	30	72	100	14	73	1.7
7	7c	1.00	50	36	100	37	41	1.8

i) Yields were determined by GC. Isolated yields were usually 5% lower.

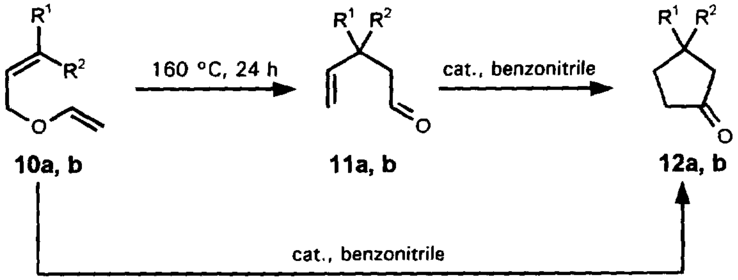
In contrast to monomeric rhodium catalysts like $[RhCl(cod)]_2$ the use of the polymer-attached rhodium catalyst leads to higher yields of the α,β-unsaturated cyclopentenones **8** which might serve as an interesting starting material for further conversions. The unsaturated **8** is favoured with up to 5:1 at low pressure, short reaction time and small amounts of catalyst, unfortunately at lower degrees of conversion. Reuse of the catalyst is possible without any problems.

Claisen Rearrangement/Hydroacylation of Allyl Vinyl Ethers

An other way to generate cyclopentanone derivatives is the Claisen rearrangement of allyl vinyl ethers followed by rhodium-catalyzed hydroacylation. Both steps can be carried out in a one-pot procedure.[6] This is achieved under argon atmosphere in benzonitrile at temperatures between 130 and 200 °C depending on the substrate. DMF as solvent is less effective, with decane the cyclization step fails. RhCl(dppe)(cod) is preferred over

Wilkinson's catalyst because of its stability at such temperatures. To demonstrate the ability of the polystyrene-supported catalyst precursor, we investigated two simple allyl vinyl ethers **10a, b**. To further stabilize the system and suppress decarbonylation we added bis-(diphenylphosphino)-ethane (dppe) to the reaction mixture. The result of the reactions are presented in table 2.

Scheme 3:



	R^1	R^2
a	Me	Ph
b	Ph	Ph

Table 2: Claisen Rearrangement/Hydroacylation of Allyl Vinyl Ethers in the Presence of **6**[i)][ii)]

Entry	Substrate	Catalyst [mol%]	dppe [mol%]	Time [h]	Temp. [°C]	**10** [%]	**11** [%]	**12** [%]	Remarks
1	11a	3.0	----	40	160	----	6	11	82 % decarbonylation
2	11a	1.5	2.0	80	160	----	8	49	44 % decarbonylation
3	10a	1.5	3.0	80	160	----	2	96	
4	10a	1.0	1.0	36	160	3	4	88	cat. out of entry 1
5	10a	2.0	2.0	30	160	----	31	61	monomeric CpRh(cod)
6	10a	1.5	1.5	30	150	<1	8	68	solvent: DMF
7	10a	1.0	1.0	36	150	----	97	<1	solvent: decane
8	10a	1.5	1.5	36	140	----	5	93	cat. out of hydroformyl.
9	10a	1.5	----	36	150	----	1	95	cat. out of entry 6
10	10b	1.5	1.5	36	150	29	38	17	isolated yield
11	10b	1.5	1.5	72	160	3	10	67	isolated yield

i) Yields were determined by GC. Isolated yields were usually 5% lower. ii) Benzonitrile as solvent if not noted otherwise.

As shown in table 2 the hydroacylation of pent-4-enals **11** with the supported catalyst in the absence of phosphine ligands lead to low yields of cyclopentanones and preferred decarbonylation of the aldehyde (entry 1). By addition of dppe this effect could be decreased (entry 2). Nevertheless, the one-pot procedure is more effective. No decarbonylation takes place and under optimized conditions the yields of cyclopentanone are nearly quantitative (entry 3, 8, 9).

The polymer-supported catalyst is more powerful in the Claisen rearrangement/hydroacylation of allyl vinyl ethers than its monomeric analogue CpRh(cod) (entry 5). The polymer-attached rhodium catalyst leads to similar results as observed by use of RhCl(dppe)(cod). As shown in entry 8 it is not difficult to use a polymer-supported $Cp(Rh)(CO)_2$ in the tandem reaction which was regained from a hydroformylation reaction. The multiple use of the catalyst in this type of reaction is possible without loss of activity.

Experimental

IR spectra were obtained by using a Nicolet Impact 400D FTIR spectrometer on KI pellets (beads) or NaCl (film). NMR spectra were recorded with TMS as internal standard at room temperature on Bruker DRX 400. Gas chromatography was carried out with 25 m CP sil-5 (CB) or 15 m DB-1701 (19) capillary, FID. Column chromatography with silicagel 60 (70-230 mesh) from Merck, Darmstadt. All solvents used in reactions were anhydrous and purified according to standard procedures. The divinylbenzene-polystyrene copolymer (*Lewapol R 985/90* : macroporous beads, 7 % DVB) were washed[7] to remove impurities before use.

Typical Procedures

Chloromethylation[4, 8]*:* 50 g (0.48 mol) of copolymer beads were taken into 1 l three-necked flask with a dropping funnel and an overhead stirrer. Under argon atmosphere 140 ml (0.72 mol) chloromethyl octyl ether and 150 ml dry chloroform were added. After swelling of the beads for 30 min, 14 ml (0.12 mol) of $SnCl_4$ was slowly introduced through the dropping funnel. The reaction mixture was stirred vigorously at room temperature for 2.5 h. Then the polymer was filtered and washed in a Soxhlet extractor by the following sequence of solvents: THF/water 4:1, methanol and diethyl ether. The polymer was dried under vacuum.

Chlorine contents were determined by oxidative decomposition with sodium peroxide and subsequent titration against 0.1 N $AgNO_3$ following the Wurzschmitt method.[9] The chlorine analysis of the chloromethylated beads yielded 0.49 mmol Cl/g beads (Degree of Functionalizing = 5.2 %). Chloromethylation results between 0.08 mmol Cl/g (DF = 0.8 %) and 3.07 mmol Cl/g beads (DF = 37.4 %) are possible depending on the concentration of $SnCl_4$.
IR (KI): ν_{CH_2Cl} = 685, 1265 cm^{-1}.

Cyclopentadiene attachment: In a 500 ml three-necked flask with dropping funnel, a reflux condenser and an overhead stirrer 4 g (0.1 mol) sodium amide and 20 g of chloromethylated beads obtained above were suspended in 100 ml dry THF. Under argon atmosphere 10 ml (0.15 mol) cyclopentadiene in 50 ml dry THF were added dropwise at room temperature. The mixture were heated under reflux for 4 days. The solution was removed by filtration. The polymer was washed in a Soxhlet extractor with THF/water 4:1, ethanol, benzene and THF and dried under vacuum.

The beads contained no more chlorine, so the cyclopentadiene contents were 0.41 mmol/g beads (DF = 5.2 %) determined by the difference between the chlorine contents before and after reaction. Alternatively the cyclopentadiene contents were determined via derivatization[8]: a 1 g sample was swollen in CCl_4/ethanol (10:1) at -5 °C for 20 min. 5 ml of a 2 *M* bromine solution in CCl_4 was added slowly and the mixture stirred at -5 °C for 30 min. The polymer was filtered off washed with CH_2Cl_2 and acetone and dried. After oxidative decomposition the bromo derivative was analyzed by argentometric titration. Cyclopentadiene contents between 2.41 mmol Cp/g beads (DF = 34.4 %) and 0.17 mmol Cp/g (DF = 2.1 %) are available depending on degree of functionalizing of the chloromethylated beads.

Introduction of the metal (method 1): All steps were carried out under argon atmosphere. 13 g (5.33 mmol) of cyclopentadiene-substituted beads were stirred with a four-fold excess of butyllithium in hexane for 3 days. The solution was removed by filtration and the beads were washed twice with dry hexane and dry THF. Then they were suspended in 100 ml dry THF and 1.3 g (2.6 mmol) of $[RhCl(cod)]_2$ was introduced. The mixture was stirred for 4 days at room temperature. The beads were filtered, washed with THF and ethanol and dried under vacuum. The color of the beads changed during the reaction from beige over violet to brown.

Rhodium contents were determined by oxidative decomposition of the polymeric material[10] with conc. sulfuric acid and hydrogen peroxide. 150 mg of beads were suspended in 10 ml conc. sulfuric acid and heated at 160 °C for 30 min. At this temperature 10 ml hydrogen peroxide (30 %) was added dropwise. After 30 min the solution was concentrated under vacuum. The dropwise addition of 10 ml hydrogen peroxide and concentration were repeated until no more beads could be recognized. The solution was filled up to 100 ml with water. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) yielded 0.11 mmol rhodium/g beads.

Introduction of the metal (method 2): 2.0 g (0.82 mol) of cyclopentadiene-substituted beads and 0.26 g (0.64 mmol) of $RhCl_3 \cdot 3\,H_2O$ were refluxed in 20 ml THF for 5 days. The beads were separated by filtration, washed with THF and dried under vacuum. The color of the beads are now dark brown. The contents of chlorine were 0.50 mmol/g and the contents of rhodium were 0.23 mmol/g. 1.0 g (0.23 mmol Rh) beads obtained above were suspended in 10 ml of an oxygen-free mixture of ethanol and water (5:1) and treated with 1 ml (6 mmol) 1.5-cyclooctadiene. The mixture were refluxed for 8 days under argon. The solvent was removed and the beads were washed with THF. After decomposition analyzing of the polymer as described above yielded 0.01 mmol Cl/g and 0.15 mmol Rh/g.

Hydrogenation of 1-octene: The hydrogenation were carried out in a 100 ml round-bottom flask with a side arm using a 100 ml gas buret to measure the rate of hydrogen uptake. 1.0 g (0.11 mmol Rh) was weight into the flask, placed under an atmosphere of hydrogen and suspended in 8 ml of hexane. 2 ml (13 mmol) 1-octene was then added. The conversion of the reactions were determined by gas chromatography.

Hydroformylation of 1-octene: 0.3 g (0.03 polymer-attached CpRh(cod), 3 ml (19 mmol) 1-octene and 10 ml dry dioxane were introduced into a 250 ml stainless steel autoclave. The autoclave were flushed with argon, pressurized to 70 bar with CO and H_2 (1:1) and heated to 120 °C. After 16 h the vessel was cooled to room temperature, vented and flushed with argon. The clear golden solution was transferred with a syringe and filtered through aluminium oxide. The products were determined by GC, GC-IR and GC-MS.

Hydrocarbonylative cyclization of ethyl 3-methyl-3-vinyl-pent-4-enoate (**7a**)[5d]*:* 0.2 g (0.02 mmol Rh) polymer-supported catalyst, 0.34 g (2 mmol) **7a**, 0.5 ml water and 10 ml dry dioxane were introduced into a 250 ml stainless steel autoclave. The vessel were flushed with argon, pressurized to 50 bar with carbon monoxide and heated to 120 °C. After 24 h the autoclave was cooled to room temperature, expanded and flushed with argon. The clear golden solution was drawn out with a syringe and filtered through aluminium oxide. After removing of the solvent the products were determined by GC, GC-IR and GC-MS. Column chromatography to purify the

the product (silicagel; petroleum ether/MTBE 5:1) afforded ethyl 2-(1-methyl-2-methylene-3-oxocyclopentyl)-acetate (**8a**) and ethyl 2-(1,2-dimethyl-3-oxocyclopentyl)-acetate (**9a**)[5d] as a mixture.

Ethyl 2-(1-Methyl-2-methylene-3-oxocyclopentyl)-acetate (**8a**): IR (NaCl, film): ν_{CO} = 1735 cm^{-1};
^{1}H NMR(400MHz, CDCl$_3$, mixture): δ[ppm] = 1.24 (t, J = 7.0 Hz, 3H, OCH$_2$C*H*$_3$), 1.26 (s, 3H, C*H*$_3$-Cq), 2.16 (m, 2H, C*H*$_2$CH$_2$CO), 2.27 (m, 2H, CH$_2$C*H*$_2$CO), 2.40 (d, J = 14 Hz, 1H, CqCH*H*CO), 2.49 (d, J = 14 Hz, 1H, CqCH*H*CO), 4.11 (q, J = 7 Hz, 2H, OC*H*$_2$CH$_3$), 5.28 (s, 1H, C=CH*H*), 6.03 (s, 1H, C=C*H*H). - ^{13}C NMR (100 MHz, CDCl$_3$, mixture): δ[ppm] = 13.9 (OCH$_2$*C*H$_3$), 26.7 (Cq*C*H$_3$), 32.2 (*C*H$_2$CH$_2$CO), 35.1 (CH$_2$*C*H$_2$CO), 41.2 (*C*qCH$_3$), 44.7 (Cq*C*H$_2$CO), 60.2 (O*C*H$_2$CH$_3$), 143.8 (C=*C*H$_2$), 152.3 (*C*=CH$_2$), 170.6 (CO$_{\text{Ester}}$), 206.1 (CO). - MS (70 eV, EI): m/z [%] = 197 (100, M$^+$+1), 151 (15), 140 (10), 123 (40), 109 (30), 81 (25).

Hydrocarbonylative cyclization of 3-methyl-3-phenyl-1,4-pentadiene (**7b**)[5b]*:* Conversion of **7b** like mentioned afforded 3-methyl-2-methylene-3-phenylcyclopentanone (**8b**) and 2,3-dimethyl-3-phenylcyclopentanone (**9b**)[5b] as a mixture.

3-Methyl-2-methylene-3-phenylcyclopentanone (**8b**): IR (NaCl, film): ν_{CO} = 1720 cm^{-1};
^{1}H NMR(400MHz, CDCl$_3$, mixture): δ[ppm] = 1.55 (s, 3H, CqC*H*$_3$), 1.94 - 2.43 (m, 4H, C*H*$_2$C*H*$_2$CO), 5.26 (s, 1H, C=C*H*H), 6.23 (s, 1H, C=CH*H*), 7.16 - 7.36 (m, 5H, H$_{\text{arom.}}$). - ^{13}C NMR(100 MHz, CDCl$_3$, mixture): δ[ppm] = 28.2 (Cq*C*H$_3$), 35.3 (*C*H$_2$CH$_2$CO), 36.0 (CH$_2$*C*H$_2$CO), 47.8 (*C*qCH$_3$), 145.8 (C=*C*H$_2$), 152.9 (*C*=CH$_2$), 125.9, 126.8, 129.0 (C$_{\text{arom.}}$), 206.2 (CO). - MS (70 eV, EI): m/z [%] = 187 (100, M$^+$+1), 171 (25), 144 (25), 129 (65), 115 (70), 102 (10), 91 (20).

Hydrocarbonylative cyclization of 3-methyl-3-p-tolyl-1,4-pentadiene (**7c**)[5c]*:* Conversion of **7c** as described above afforded 3-methyl-2-methylene-3-*p*-tolylcyclopentanone (**8c**)[5c] and 2,3-dimethyl-3-*p*-tolyl-cyclopentanone (**9c**)[5c] as a mixture.

Hydroacylation of 3-methyl-3-phenyl-pent-4-enal (**11a**)[6]*:* 0.6 g (3 mol% Rh) polymer-attached CpRh(cod), 0.34 g (2 mmol) **11a** and 1 ml dry benzonitrile were placed in a 5 ml round-bottom flask with a reflux condenser and heated at 160 °C for 36 h under argon. After cooling to room temperature the mixture was filtered through aluminium oxide. The conversion was determined by GC, GC-IR and GC-MS. The 3-methyl-3-phenyl-cyclopentanone (**12a**)[6] could be purified by column chromatography (silicagel; petroleum ether/MTBE 10:1).

Claisen rearrangement/hydroacylation of 3-phenyl-1-vinyloxybut-2-ene (**10a**)[11]*:* 0.3 g (1.5 mol% Rh) polymer-attached CpRh(cod), 0.34 g (2 mmol) **10a** and 1 ml dry benzonitrile were placed in a 5 ml round-bottom flask with a reflux condenser and heated at 160 °C for 36 h under argon. After cooling to room temperature the mixture was filtered through aluminium oxide. The conversion was determined by GC, GC-IR and GC-MS. 3-methyl-3-phenylcyclopentanone **12a**[6] could be purified by column chromatography (silicagel; petroleum ether/MTBE 10:1).

Claisen rearrangement/hydroacylation of 1,1-diphenyl-3-vinyloxybut-2-ene **(10b)**[6]: Conversion of **10b** as described above afforded 3,3-diphenylcyclopentanone **(12b)**.[11]

Acknowledgement

This work has been supported by the Volkswagen Stiftung and the Fonds der Chemischen Industrie. The polystyrene starting material Lewapol R 985/90 has been kindly supplied by the Bayer AG (Leverkusen) and rhodium compounds by the Degussa AG (Hanau). We are deeply indebted to Prof. Dr. J. Broekaert and Dipl. Chem. R. Nehm (Analytische Chemie, Universität Dortmund) for measurement of rhodium contents.

References

1. McQuillin, F. J. *Transition Metal Organometallics for Organic Synthesis*; University Press: Cambridge, 1991.
2. Hartley, F. R. *Supported Metal Complexes*; D. Reidel Publishing Company: Dordrecht, 1985.
3. a) Chang, B.-H.; Grubbs, R. H.; Brubaker jr., C. H. *J. Organomet. Chem.* **1979**, 172, 81-89.
   b) Tung, H. S.; Brubaker jr., C. H. *J. Organomet. Chem.* **1981**, 216, 129-137.
   c) Sekiya, A.; Stille, J. K. *J. Am. Chem. Soc.* **1981**, 103, 5096-6000.
4. Warshawsky, A.; Deshe, A.; Gutmanm, R. *Brit. Polym. J.* **1984**, 16, 234-238.
   Warshawsky, A.; Deshe, A.; Belfer, S.; Glozman, R. *J. Applied Polymer Sci.* **1980**, 25, 2241-2263.
5. a) Eilbracht, P.; Hüttmann, G.-E.; Deußen, R. *Chem. Ber.* **1990**, 123, 1063-1070.
   b) Eilbracht, P.; Balß, E.; Acker, M. *Chem. Ber.* **1985**, 118, 825-829.
   c) Eilbracht, P.; Acker, M.; Hädrich, I. *Chem. Ber.* **1988**, 121, 519-524.
   d) Eilbracht, P.; Hüttmann, G.-E. *Chem. Ber.* **1990**, 123, 1053-1061.
6. Eilbracht, P.; Gersmeier, A.; Lennartz, D.; Huber, T. *Synthesis* **1995**, 330-334.
7. Relles, H. M.; Schluenz, R. W. *J. Am. Chem. Soc.* **1974**, 96, 6469-6475.
8. Neumann, W. P.; Peterseim, M. *React. Polym.* **1993**, 20, 189-205.
9. a) Wurzschmitt, B.; Zimmermann, W. *Fortschr. Chem. Forsch.* **1950**, 1, 485-507.
   b) Roth H.; Zinnecke, F. *Quantitative organische Elementaranalyse,* Houben-Weyl-Methoden der organischen Chemie, Vol. 2, Thieme: Stuttgart 1963, p. 222.
   c) Ehrenberger, F.; Gorbach, S. *Methoden der organischen Elementar- und Spurenanalyse;* Verlag Chemie: Weinheim 1973; p. 274.
10. Gorsuch, T. T. *The Destruction of Organic Matter*; Pergamon Press: Oxford, 1970; p. 24.
11. Fairly, D. P.; Bosnich, B. *Organometallics* **1988**, 7, 946-954.

(*Received in Germany* 13 *December* 1995; *revised* 26 *January* 1996; *accepted* 7 *February* 1996)