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Purity testing of organometallic catalysts by packed capillary supercritical fluid chromatography

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Abstract

A packed capillary column supercritical fluid chromatography system with flame ionization detection has been used for purity testing of candidates for homogeneous catalysis such as methyl tricarbonyl pentamethylcyclopentadienyl tungsten [$Cp^*W(CO)_3Me$], methyl tricarbonyl cyclopentadienyl tungsten [$CpW(CO)_3Me$], tetramethyl pentamethylcyclopentadienyl iridium (Cp^*IrMe_4), trimethyl (1,4,7-trimethyl-1,4,7-triazocyclononane) rhodium ($CnRhMe_3$), trimethylphosphine hydride dicarbonyl cyclopentadienyl molybdenum [η^5-$CpMoH(CO)_2PMe_3$] and triphenylphosphine hydride dicarbonyl cyclopentadienyl molybdenum [η^5-$CpMoH(CO)_2PPh_3$]. A mass limit of detection of 240 pg was found for η^5-$CpMoH(CO)_2PMe_3$ when using a 60-nl injection volume and pure CO_2 as mobile phase on a 5 μm Kromasil C_{18} column. The stability of the catalysts in solution has been examined. After 24 h more than 70% of η^5-$CpMoH(CO)_2PMe_3$ and 50% of η^5-$CpMoH(CO)_2PPh_3$ had decomposed. Due to the instability of the compounds the purity testing had to take place rapidly after sample dissolution.

Keywords: Purity testing; Organometallic compounds; Catalysts

1. Introduction

The use of organometallic compounds as homogeneous catalysts in organic synthesis, metathesis and polymerization has gained increased attention during the last few years. Some of the reasons for this have been the high substrate selectivity, ease of spectroscopic monitoring and high tunability of the catalyst obtained by the use of this method [1]. In a synthetic catalyst impurities will always be present to some extent. The type and amount of impurities might alter the mechanism of a catalysed reaction, thus in product specification it is important to determine the relative amounts of impurities present.

Organometallic compounds of the d-block elements are often highly reactive and unstable; oxidatively, thermally, hydrolytically or photochemically, and may therefore be troublesome to purity test. This prevents the use of separation techniques which uses high temperatures, e.g., gas chromatography or high-temperature liquid chromatography. Previously, normal-phase [2–4] and reversed-phase [5] high-performance liquid chromatography (HPLC) at room temperature have been used to separate mixtures of organometallic compounds. However, supercritical fluid chromatography (SFC) can overcome many of the practical difficulties since the analysis can be performed at relatively low temperatures, in the

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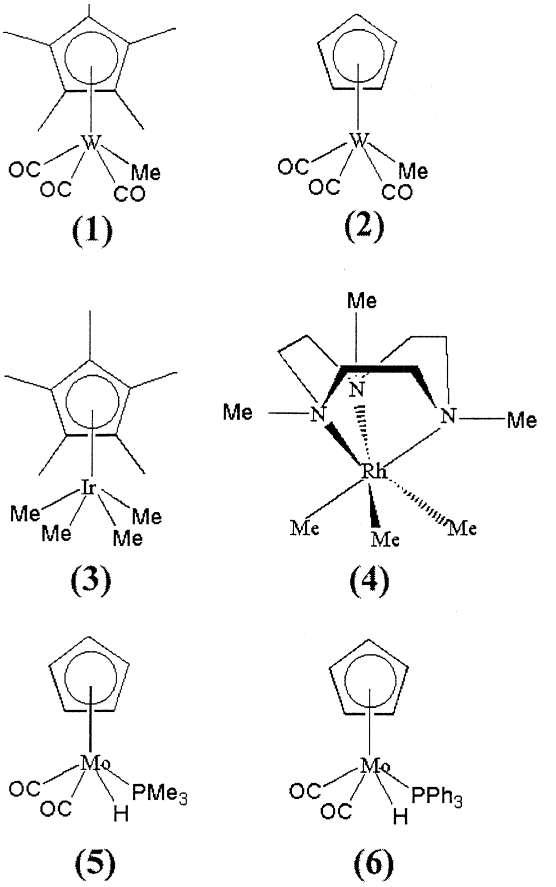
absence of light, and with a relatively inert mobile phase. Thus, SFC is in many ways an ideal separation technique for many organometallic compounds. Organometallic compounds of the transition elements have been successfully chromatographed by both open tubular [6–8] and packed capillary column [9,10] SFC. The low flow-rate from a packed capillary column of an internal diameter of 320 μm is compatible with a flame ionization detector without post-column splitting of the mobile phase. Flame ionization detection (FID) is an ideal detection method for use in purity testing due to its high linear range and low detection limits.

In this study we show the use of packed capillary column SFC for purity testing of potential catalysts such as: η^5-Cp*W(CO)$_3$Me (Cp*=pentamethylcyclopentadienyl), η^5-CpW(CO)$_3$Me (Cp=cyclopentadienyl), η^5-Cp*IrMe$_4$, CnRhMe$_3$ (Cn=1,4,7-trimethyl-1,4,7-triazocyclononane), η^5-CpMoH(CO)$_2$PMe$_3$ and η^5-CpMoH(CO)$_2$PPh$_3$ (Fig. 1). The aim was to detect impurities at, and if possible below, the 1% concentration level. The detectability of the compounds by FID has been evaluated. In addition, the stability in solution has been studied for the compounds Cp*W(CO)$_3$Me, CpW(CO)$_3$Me, [CpMo(CO)$_3$]$_2$, CpMoH(CO)$_2$PPh$_3$, CpMoH(CO)$_2$Me$_3$ and CnRhMe$_3$.



(1) (2) (3) (4) (5) (6)

Fig. 1. Structures of the organometallic compounds η^5-Cp*W(CO)$_3$Me (1), η^5-CpW(CO)$_3$Me (2), η^5-Cp*IrMe$_4$ (3), CnRhMe$_3$ (4), η^5-CpMoH(CO)$_2$PMe$_3$ (5) and η^5-CpMoH(CO)$_2$PPh$_3$ (6).

2. Experimental

2.1. Instrumentation

All experiments were performed on a Carlo Erba SFC 3000 (Carlo Erba, Milan, Italy). The injector, from Valco (Schenkon, Switzerland) was equipped with a 60-nl loop and actuated using helium and used with time split injection. The injector and the FID system were maintained at a temperature of 20°C and 330°C, respectively. The pressure program used for linearity and stability studies, at 75°C, was: 100 bar (hold 5 min), then 20 bar/min until 400 bar. The flow was controlled by a ceramic frit restrictor in fused-silica (50 μm I.D.×350 μm O.D.) from Dionex (Salt Lake City, UT, USA).

The samples were separated on a capillary column of 45 cm×320 μm I.D.×450 μm O.D., packed with 5 μm Kromasil-100 C$_{18}$ particles (Shandon Southern Products, Cheshire, UK). The column was packed according to a procedure described previously [11]. The fused-silica capillaries were purchased from (Polymicro Technologies, Phoenix, AZ, USA), unions and ferrules were from Valco. Carbon disulfide (puriss) was obtained from Fluka (Buchs, Switzerland). Carbon dioxide (SFC grade), air (99.1%), helium (helium 99.1%) and hydrogen (99.998%) were all obtained from AGA (Oslo, Norway). η^5-CpMn(CO)$_3$ and [CpMo(CO)$_3$]$_2$ were from Strem (Kehl, Germany). η^5-CpW(CO)$_3$Me [12], η^5-Cp*W(CO)$_3$Me [13], Cp*IrMe$_4$ [14], CnRhMe$_3$ [15], η^5-CpMoH(CO)$_2$PMe$_3$ [16] and η^5-CpMoH(CO)$_2$PPh$_3$ [16] were synthesized according to a procedure described by others. Heneicosane (n-C_{21}) and nonadecane (n-C_{19}) were obtained from Alltech (Deerfield, IL, USA). All compounds were dissolved in CS_2.

2.2. Determination of linearity, limit of detection, column efficiency and purity

Solutions of 10–3000 μg η^5-CpW(CO)$_3$Me/ml CS_2, 5–500 μg of η^5-Cp*W(CO)$_3$Me/ml CS_2, and 100–2500 μg CnRhMe$_3$/ml CS_2 were used for testing of linearity. The n-alkanes n-C_{21} and n-C_{19} were used as internal standards in the stability experiments. The limit of detection (LOD) was reported as the concentration of the analyte necessary to produce a signal-to-noise ratio of two. The efficiency was reported in reduced plate heights ($h = H/d_p$). The purity was determined by relating the total area of the impurities to area of the main peak.

3. Results and discussion

3.1. Chromatography

The use of a packed capillary column was found advantageous compared to an open tubular column due to the following reasons: higher sample capacity, higher number of plates produced per unit time and higher speed. To prevent permanent adsorption or tailing of the analytes the capillary column was packed with a well end-capped stationary phase, Kromasil-100 C_{18}. The Kromasil material had also low content of heavy metals, according to the manufacturer. Carbon dioxide, the eluent used, has been reported to bind in a η^1-OCO fashion even to 18e$^-$ organometallic complexes [17]. However, this was not observed during chromatography. After all, supercritical CO_2 will provide a more inert atmosphere compared to any mobile phase used in HPLC. Solvents like acetonitrile, methanol and water are all commonly used ligands in organometallic chemistry.

The flow-rate of a packed capillary column, 120 nl/s, was compatible with FID without post column splitting. FID is a suitable detection method for purity testing because it provides nearly universal response to organic compounds, a high sensitivity and an exceptional linear response range. A high linear response was also found for the following compounds: Cp*W(CO)$_3$Me, CnRhMe$_3$ and CpW(CO)$_3$Me (Table 1). The relative weight response factors [18] were calculated (Table 1). A value of 1 indicates the same response as the internal standard added (n-C_{19} or n-C_{21}). The FID relative response, compared to the hydrocarbon internal standard, was as expected lower for all the organometallic compounds investigated. Other detection methods such as evaporative light scattering detection (ELSD) and UV detection were not expected to be satisfactory for purity testing. The UV response factor is dependent on the size of the chromophore, i.e., molar absorptivity, while ELSD does not detect volatile compounds.

Non-polar and moderately polar compounds (e.g., esters, ethers, lactones, epoxides) are soluble in CO_2. In order to separate larger and more polar analytes, CO_2 is usually mixed with methanol. Unfortunately, FID is not compatible with the use of methanol as modifier. However, a modifier was not needed for the separation of η^5-CpMn(CO)$_3$, η^5-CpMoH(CO)$_2$PMe$_3$, η^5-CpW(CO)$_3$Me and η^5-CpMoH(CO)$_2$PPh$_3$ (Fig. 2). η^5-Cp*W(CO)$_3$Me, η^5-Cp*IrMe$_4$, CnRhMe$_3$ and [η^5-CpMo(CO)$_3$]$_2$ could also be eluted without modifier. All the compounds were dissolved in CS_2 because of its low FID response. A reduced plate height (h) of 7.1 and an asymmetry (A_s) of 1.3 were found for CnRhMe$_3$, separated at 210 bar. The Cn ligand, with a potential

Table 1
The response factor (RF) and the tested linearity range for flame ionization detection of organometallics.

Compound	RF	Range (μg/ml)	Correlations coefficient (r)
η^5-Cp*W(CO)$_3$Me	0.2	5–500	0.9995
CnRhMe$_3$	0.21	100–2500	0.9975
η^5-CpW(CO)$_3$Me	0.16	10–3000	0.9978
η^5-CpMoH(CO)$_2$PPh$_3$	0.45		
η^5-CpMoH(CO)$_2$PMe$_3$	0.32		

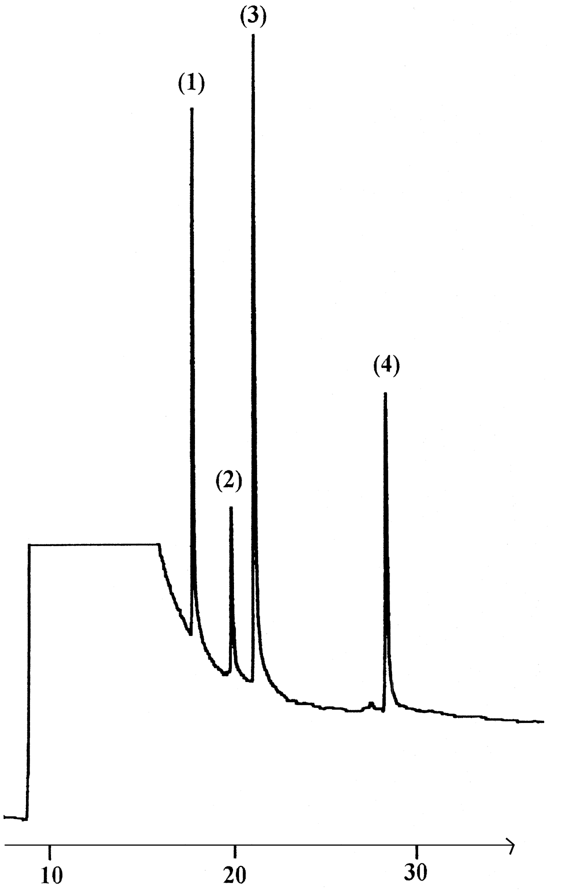


Fig. 2. Separation of (1) $CpMn(CO)_3$ (0.7 mg/ml), (2) η^5-$CpMoH(CO)_2PMe_3$ (0.2 mg/ml) (3) η^5-$CpW(CO)_3Me$ (0.8 mg/ml) and (4) η^5-$CpMoH(CO)_2PPh_3$ (0.5 mg/ml) by a capillary column packed with 5 μm Kromasil-100 C_{18} particles. The pressure program used was 100 bar (hold 10 min) then 10 bar/min until 180 bar (hold 1 min), then 10 bar/min until 300 bar (hold 1 min) then 10 bar/min until 400 bar (hold 10 min). Temperature was set at 60°C.

of interacting with silanol groups, was not found to increase the peak tailing because $h=5.3$ and $A_s=1.4$ were found for the *n*-alkane heneicosane under the same conditions. In order to be able to separate both volatile and non-volatile impurities from the main component in the same run, a pressure program had to be used. In addition, injecting 60 nl of the sample at low eluent strength was expected to result in phase focusing and sharper peaks. The η^5-$CpMn(CO)_3$ concentration limit of detection (cLOD) was 3.3 μg/ml, and the mass limit of detection (mLOD) was 200 pg. The mLOD and cLOD of $CnRhMe_3$ were 0.7 ng and 12.0 μg/ml, respectively. The mLODs for the other organometallic compounds are listed in Table 2.

The SFC oven was set to a temperature which resulted in low analysis time, high peak resolution and prevented thermal decomposition of the analyte. Purity testing of η^5-$CpMoH(CO)_2PMe_3$ and $CpMoH(CO)_2PPh_3$ was performed at different temperatures (60–90°C) and degradation of the analytes was observed at 75°C and 70°C, respectively (Fig. 3). When the peak height of η^5-$CpMoH(CO)_2PMe_3$ was reduced, an increase in peak height of a decomposition product was observed. The height of this decomposition product increased as a function of temperature and was 13% of the main component at 90°C.

To prevent decomposition of the analyte the purity testing was performed at 60°C.

3.2. Stability

In order to be able to catalyze, e.g., polymerization reactions, organometallic compounds have to generate vacant coordination sites by losing ligands. Thus, a catalyst with weakly bonded ligands is expected to do so easily, hence generating high turnover numbers. Elimination of a ligand is facilitated by the presence of light, heat or air, resulting in a complex with a vacant site. In order to regenerate a saturated species, the site is rapidly trapped by a the same ligand or a new ligand (e.g., the solvent or O_2). To determine how fast, and which physical parameters influenced the degradation of the catalyst in solution, the peak area relative to an internal standard was measured as a function of time. η^5-$Cp^*W(CO)_3Me$ and η^5-$CpW(CO)_3Me$, both dissolved in carbon disulfide, decomposed by 20% when stored in the dark at 3°C after 14 days. If the analytes were stored

Table 2
Mass limit of detection of different organometallic compounds

Compound	mLOD (pg)
η^5-$CpMoH(CO)_2PPh_3$	264
η^5-$CpMoH(CO)_2PMe_3$	240
η^5-$CpMn(CO)_3$	200
$(\eta^5$-$CpCOMe)Fe(\eta^5$-$Cp)$	333
$CnRhMe_3$	700

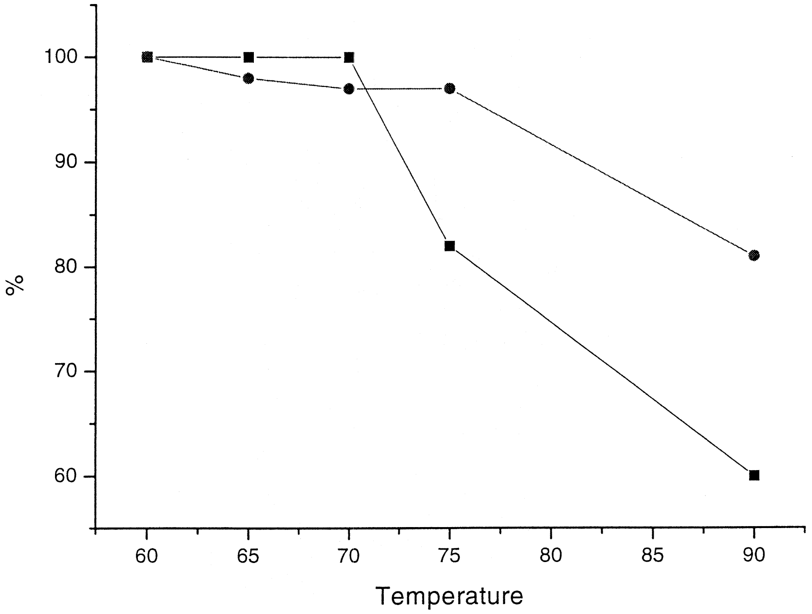


Fig. 3. % of original concentration of η^5-CpMoH(CO)$_2$PMe$_3$ (333 μg/ml) and η^5-CpMoH(CO)$_2$PMe$_3$ (370 μg/ml) as a function of column temperature. ■=η^5-CpMoH(CO)$_2$PMe$_3$ and ●=η^5-CpMoH(CO)$_2$PMe$_3$.

in the presence of light at 20°C, 90% were decomposed after the same time (results not shown). [η^5-CpMo(CO)$_3$]$_2$ and CnRhMe$_3$, both dissolved in carbon disulfide, decomposed by only 20% after 5 days, regardless of which way of storage used, except [η^5-CpMo(CO)$_3$]$_2$ which decomposed by 100% after 1 day of storage in the presence of light at 20°C (results not shown). Hence purity testing had to be performed quickly after the catalyst was dissolved. No new peaks were found in the chromatogram as the amount of the analyte decreased. The decomposition products were not detectable by FID or they co-eluted with the solvent or irreversibly adsorbed.

The stability of η^5-CpMoH(CO)$_2$PMe$_3$ and η^5-CpMoH(CO)$_2$PPh$_3$ dissolved in CS$_2$ was also examined (Figs. 4 and 5). In order to clarify which physical parameter is causing decomposition, the compounds were either stored in the dark at 3°C or 20°C, or at 20°C in the presence of daylight. The rate of decomposition of η^5-CpMoH(CO)$_2$PMe$_3$ seemed to be independent of light exposure (Fig. 4), while η^5-CpMoH(CO)$_2$PPh$_3$ degraded slower when kept in the dark at 20°C (Fig. 5). During the first 24 h the decomposition rate was high for both compounds, but η^5-CpMoH(CO)$_2$PMe$_3$ decomposed by 70%. If rate of degradation is linearly dependent of time, 0.5% of the analyte degrades during the first 10 min. Ligand substitution reactions in organometallic chemistry is either first-order kinetics (S$_N$1 like) or second-order (S$_N$2 like). If decomposition occurs by ligand substitution reactions, decay of the analyte will be exponential. Thus, catalysts which degrade even more rapidly than η^5-CpMoH(CO)$_2$PMe$_3$, the analysis must be performed under inert conditions without the use of solvent, e.g., on-line supercritical fluid extraction (SFE)–SFC. Future work will be devoted to solve this problem.

3.3. Purity testing

The aim of the purity testing was to detect impurities at and if possible below the 1% concentration level. Impurities are in this context defined to be both by-products from the synthesis and decomposition products not caused by the analysis.

The mLOD and cLOD of η^5-CpMoH(CO)$_2$PPh$_3$ were 264 pg and 4.4 μg/ml, respectively. Thus, solutions with concentration of at least 440 μg/ml of the analyte had to be injected. Non-polar and non-

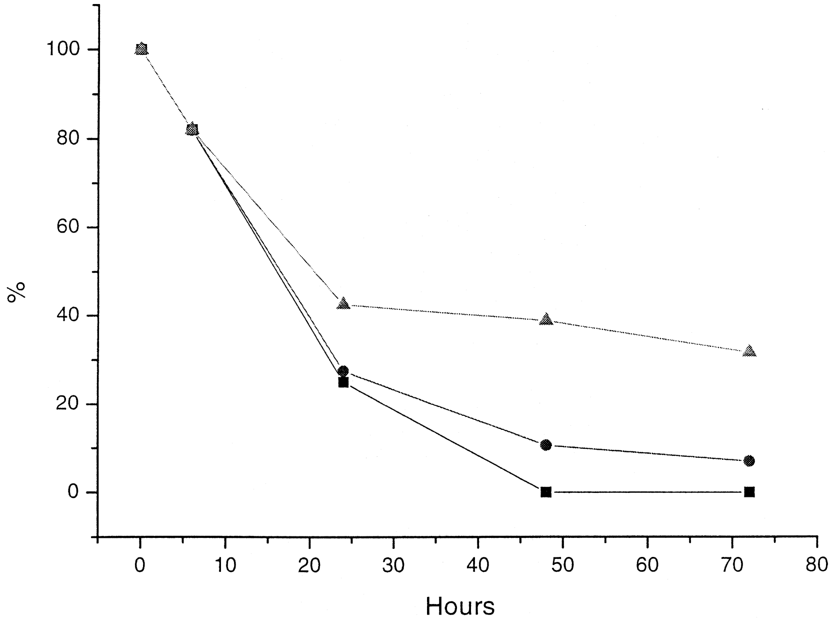


Fig. 4. % of original concentration of η^5-CpMoH(CO)$_2$PMe$_3$ dissolved in CS_2 as a function of days. ■=Sample exposed to daylight at 20°C. ●=Sample stored in dark at 20°C. ▲=Sample stored in dark at 3°C.

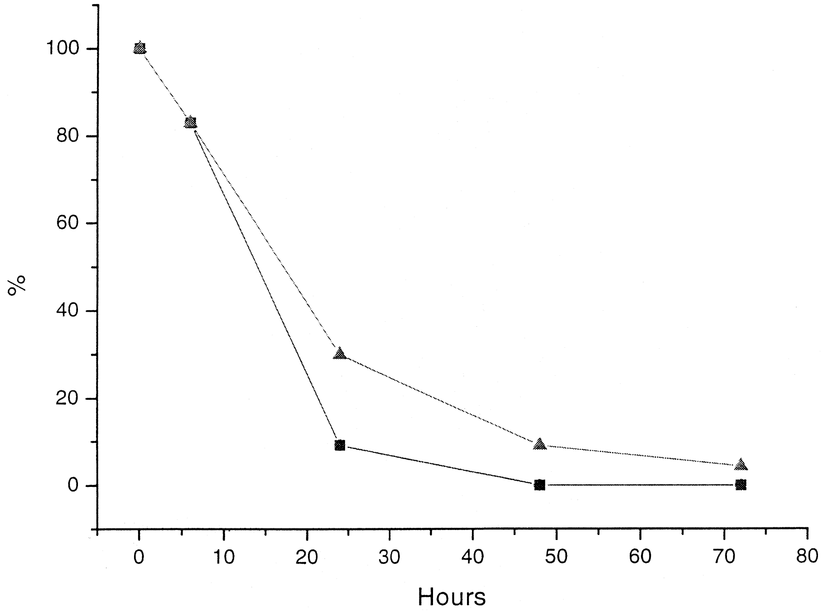


Fig. 5. % of original concentration of η^5-CpMoH(CO)$_2$PPh$_3$ dissolved in CS_2 as a function of days. ■=Sample exposed to daylight at 20°C. ●=Sample stored in dark at 20°C. ▲=Sample stored in dark at 3°C. ■ and ● show identical decomposition rate.

ionic compounds could easily be dissolved in carbon disulfide above this limit. However, if the mLOD and/or the solubility is low, then purity testing need to include higher injection volumes by solvent venting [19] or other methods. Fig. 6 shows η^5-CpMoH$(CO)_2PPh_3$ which had a purity 98.8%. The purity of the following potential catalysts was also determined: η^5-Cp*W$(CO)_3$Me (98%), η^5-CpW$(CO)_3$Me (97%), η^5-CpMn$(CO)_3$ (99%), [η^5-CpMo$(CO)_3]_2$ (99%), CnRhMe$_3$ (99%), and η^5-Cp*IrMe$_4$ (95%). All impurities were well resolved from the main peak.

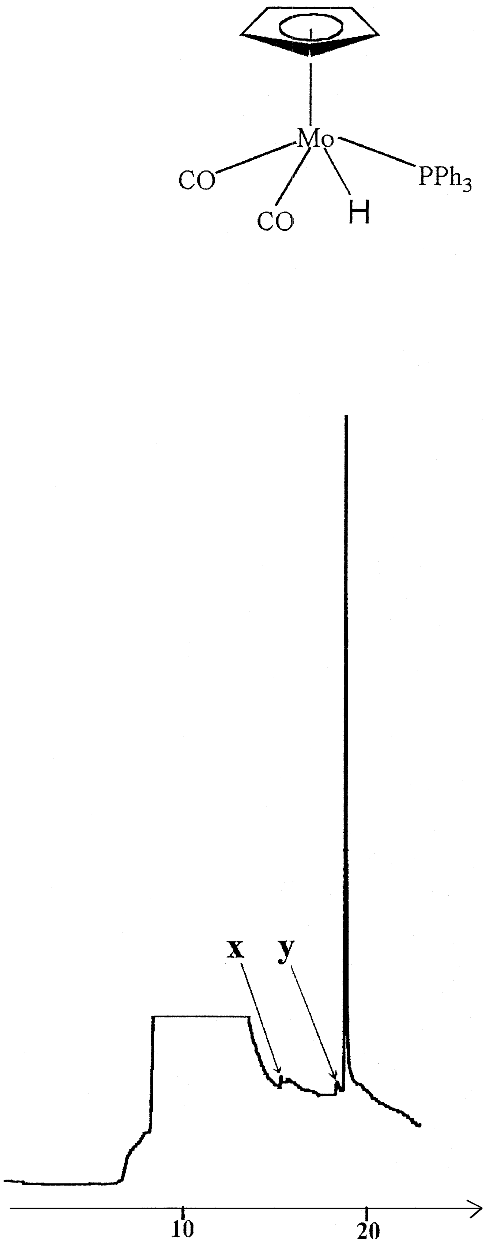


Fig. 6. Purity testing of CpMoH$(CO)_2PPh_3$ (370 μg/ml). The analysis was performed under the following conditions: 100 bar (hold 10 min) the 30 bar/min until 180 bar (hold 1 min) the 30 bar/min until 400 bar (hold 10 min). Temperature 60°C. The peaks labeled x and y are impurities.

4. Conclusion

Relatively unstable homogeneous catalyst could be purity tested by SFC and impurities down to 1% level could be found by using FID. SFC provided high resolution of the sample, and no interactions with supercritical carbon dioxide could be observed. In order to detect impurities at even lower level, future work might be devoted to the coupling of SFC with inductive coupled plasma mass spectrometry or by the injection of larger sample volumes.

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References

[1] P.G. Jessop, T. Ikariya, R. Noyori, Chem. Rev. 99 (1999) 475.
[2] M. Careri, A. Mangia, P. Manini, G. Predieri, E. Licandro, A. Papagni, Rapid Commun. Mass Spectrom. 11 (1997) 51.
[3] M. Careri, C. Graiff, A. Mangia, P. Manini, G. Predieri, Rapid Commun. Mass Spectrom. 12 (1998) 225.
[4] H. Veening, B.R. Villeford, Adv. Chromatogr. 22 (1983) 117.
[5] I. Bruheim, E.C. Fooladi, E. Lundanes, T. Greibrokk, Chromatographia 50 (1999) 479.
[6] R.D. Brauer, T.E. Bitterwolf, N.G. Smart, M.D. Burford, C.M. Wai, Anal. Chim. Acta 349 (1997) 239.
[7] E. Blake, M.W. Raynor, D. Cornell, J. High Resolut. Chromatogr. 18 (1995) 33.
[8] S.R. Almquist, L. Nyholm, K.E. Markides, J. Microcol. Sep. 6 (1994) 495.
[9] S.F. Dressmann, A.C. Michael, Anal. Chem. 67 (1995) 1339.

[10] A. Khorassani, L. Taylor, J. Hellgeth, Anal. Chem. 59 (1987) 2077.

[11] R. Trones, A. Iveland, T. Greibrokk, J. Microcol. Sep. 7 (1995) 505.

[12] G.W.T.S. Piper, J. Inorg. Nucl. Chem. 3 (1956) 304.

[13] V. Skagestad, personal communication, 1991.

[14] P.M. Maitlis, K. Isobe, A. Vázquez de Miguel, A. Nutton, J. Chem. Soc., Dalton Trans. (1984) 929.

[15] L. Wang, C.M. Wang, R. Bau, T.C. Flood, Organometallics 15 (1996) 491.

[16] A. Bainbridge, P.J. Craig, M. Green, J. Chem. Soc. A (1968) 2715.

[17] T. Herskovitz, J. Am. Chem. Soc. 99 (1977) 2391.

[18] J.T. Scanion, D.E. Willis, J. Chromatogr. Sci. 23 (1985) 333.

[19] B.E. Berg, T. Greibrokk, J. High Resolut. Chromatogr. 17 (1994) 49.