# CHAPTER III

OXIDATION OF HYDROCARBON CATALYZED BY CHROMIUM COMPLEXS

3.1 Introduction

The development of an efficient method for oxidation of unactivated C-H bonds of alkanes is of importance from view point of both industrial and synthetic chemists. The oxidation of cyclohexane under mild condition, is still a topic of great interest. Cyclohexanol and cyclohexanone are the main products from cyclohexane oxidation which also represents an important commercial reaction in the preparation of Nylon (Scheme 3.1) [70]. Many attempts have been made to avoid the classical processes by biomimetic systems that can catalyze the selective oxidation of alkanes at room temperature with different oxidants. H_2O_2 is the preferred oxidant as it only produced water as a by-product in an environmentally friendly reaction and has a high oxygen uptake [71]. Unfortunately, cyclohexane oxidation with H_2O_2 catalyzed by biomimetic systems still gives low conversions and turnover number, thus making its industrial use difficult.
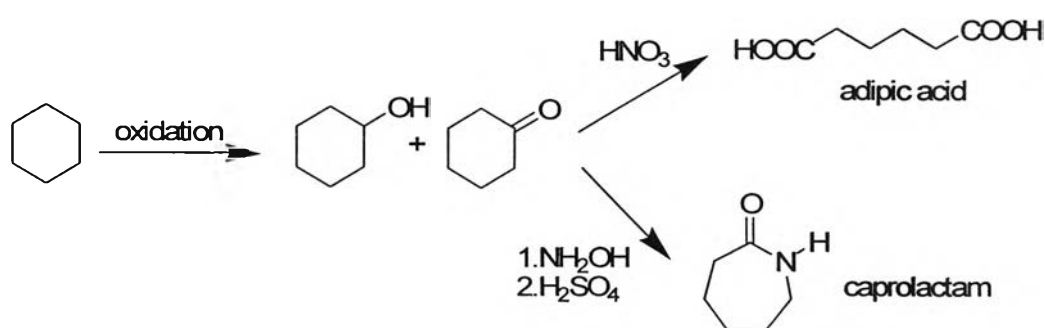

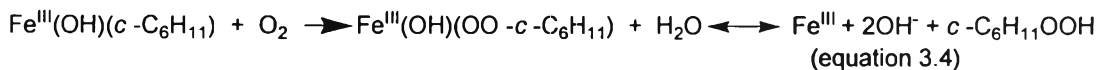**Scheme 3.1** Conversion of cyclohexane to adipic acid or caprolactam
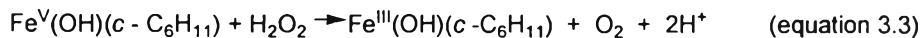
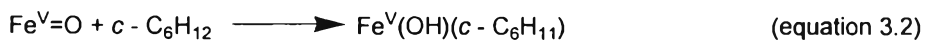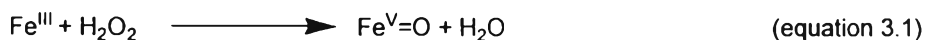The Gif catalytic systems, developed by Barton and co-workers over the past 15 years, have proved to be among the most active and moreover selective catalytic systems under ambient conditions for the monoxygenation of cycloalkanes to give ketone products [72]. Few systems can match the high turnover numbers (>1000 in less than 1 day) as well as the unusually high selectivity to the ketone, as shown by

both the early iron-based Gif^{IV}-type systems ($Fe_{cat}/Zn/O_2$) and the more recent H_2O_2-dependent analogues ("GoAgg" versions), the latter relying on combinations of simple iron salts such as $FeCl_3$ and H_2O_2 [73]. For maximum activity and efficiency, these systems work most effectively in pyridine/acetic acid, although addition of picolinic acid to solutions of $FeCl_3$ has been shown to increase the rate of the catalytic reaction by 50-fold.
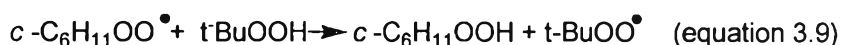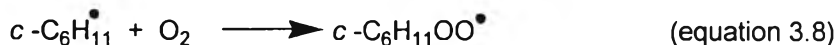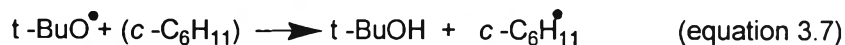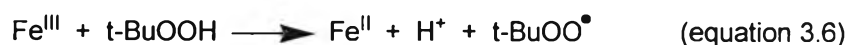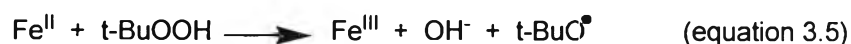
In Gif^{IV}-type oxygenation systems, the trinuclear complex $[Fe_3O(O_2CCH_3)_6(py)_3].py$ has been frequently used as the added iron reagent in conjunction with zinc powder (reductant) in aerated pyridine/acetic acid (10:1 v/v) [74]. This system remains of considerable interest owing to the desirable use of molecular dioxygen as the primary oxygen source and the potential biomimetic analogies.

M = Fe
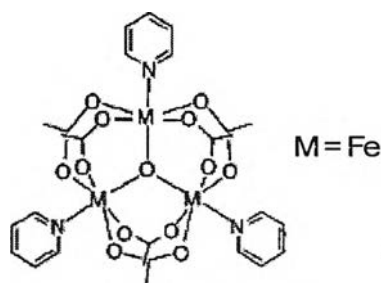
Despite significant advances in the elucidation of structural and mechanistic elements involved in these reactions, very little is specifically known about the nature of the metal species present during active turnover and whether the observed product profile (high ketone selectivity) can be traced to favorable generation of and subsequent reactions involving the secondary alkylhydroperoxide, which has been detected as an intermediate in $FeCl_3/H_2O_2$ mediated oxygenation of cyclohexane [75] In relation to cyclohexylhydroperoxide, two diametrically opposing hypotheses have been advanced to interpret the mode of its formation. The original Barton mechanism (equations 3.1-3.4), invokes a non-radical [2 + 2] C-H activation by high-valent $Fe^V=O$ units to generate metal-cyclohexyl intermediates, which eventually undergo dioxygen insertion to form metal-bound cyclohexylperoxyl species [76].

$$Fe^{III} + H_2O_2 \longrightarrow Fe^V=O + H_2O \qquad \text{(equation 3.1)}$$

$$Fe^V=O + c\text{-}C_6H_{12} \longrightarrow Fe^V(OH)(c\text{-}C_6H_{11}) \qquad \text{(equation 3.2)}$$

$$Fe^V(OH)(c\text{-}C_6H_{11}) + H_2O_2 \longrightarrow Fe^{III}(OH)(c\text{-}C_6H_{11}) + O_2 + 2H^+ \qquad \text{(equation 3.3)}$$

$$Fe^{III}(OH)(c\text{-}C_6H_{11}) + O_2 \longrightarrow Fe^{III}(OH)(OO\text{-}c\text{-}C_6H_{11}) + H_2O \longleftrightarrow Fe^{III} + 2OH^- + c\text{-}C_6H_{11}OOH$$
$$\text{(equation 3.4)}$$

In contrast, investigations by Minisci and Ingold on t-BuOOH-dependent Gif reagents, and the related "oxygenated Fenton" systems, have provided compelling evidence in support of a radical mechanism via the formation of a diffusively free substrate centered alkyl and alkylperoxyl radicals (equations 3.5-3.9) [77].

$$Fe^{II} + t\text{-}BuOOH \longrightarrow Fe^{III} + OH^- + t\text{-}BuO^\bullet \qquad \text{(equation 3.5)}$$

$$Fe^{III} + t\text{-}BuOOH \longrightarrow Fe^{II} + H^+ + t\text{-}BuOO^\bullet \qquad \text{(equation 3.6)}$$

$$t\text{-}BuO^\bullet + (c\text{-}C_6H_{11}) \longrightarrow t\text{-}BuOH + c\text{-}C_6H_{11}^\bullet \qquad \text{(equation 3.7)}$$

$$c\text{-}C_6H_{11}^\bullet + O_2 \longrightarrow c\text{-}C_6H_{11}OO^\bullet \qquad \text{(equation 3.8)}$$

$$c\text{-}C_6H_{11}OO^\bullet + t\text{-}BuOOH \longrightarrow c\text{-}C_6H_{11}OOH + t\text{-}BuOO^\bullet \qquad \text{(equation 3.9)}$$
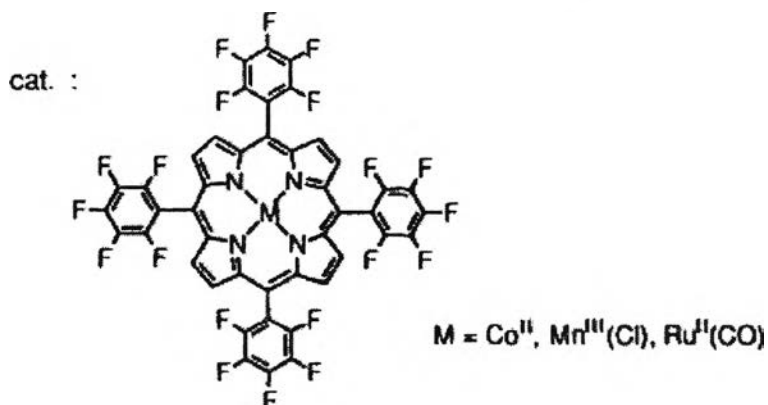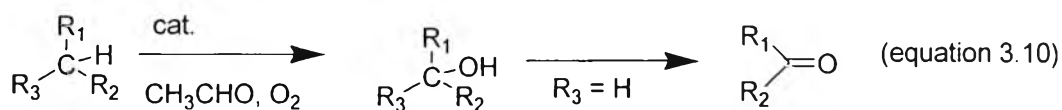
Moreover, in the presence of cyclohexane soluble iron and copper catalysts such as tris(trimethylacetate)iron(III), bis(trimethylacetate)copper(II), tris (1,1,1,2,2,3,3–heptafluoro–7,7–dimethyl–4,6–octanodionate)iron(III) and bis (ethylenediamine)copper(II)nitrate dihydrate with TBHP the oxidation of cyclohexane to cyclohexanol and cyclohexanone was selective [78]. After the reaction was carried out at reflux for 24 h without O_2 and using Cu complex as catalyst, the conversions are 4 to 5% and the selectivities above 90%. Under 25 bar of oxygen at 70^0C for 24 h, conversions with the iron catalysts are 9% but the selectivities are below 80%, as large amounts of adipic acid is also formed. The copper catalysts are more selective under these conditions. Using bis(trimethylacetate)copper(II) the conversion is 11% and the selectivity is 91%. The oxygenated products are formed by the well known free radical process which molecular oxygen add to the cyclohexyl radical[3]. In the presence of Cu (II)complex catalyst captured cyclohexyl radicals by proton elimination easier than the presence of Fe (III)complex.

In addition to other iron complexes such as polychlorophthalocyanine $(Cl_{16}PcFe^{II})$ and tetrasulfophthalocyanine $([Fe^{II}TSPc]^{4-})$, iron complexes are

employed as catalysts for the oxidation of cyclohexane using TBHP, *m*-CPBA and
H_2O_2 as oxidants [79]. The products are cyclohexanone, cyclohexanol and
cyclohexanediol. The relative yields of the products depended on oxidant and catalyst.
TBHP was found to be the best oxidant since minimal destruction of the catalyst and
higher selectivity in the products were observed when this oxidant was employed. The
mechanism of the oxidation of cyclohexane in the presence of the $C_{16}PcFe_{II}$ and
$[Fe^{II}TSPc]^{4-}$ involves the oxidation of these catalysts, forming an Fe(III)
phthalocyanine species as an intermediate. Higher yields were observed when
$[FeTSPc]^{4-}$ was employed as a catalyst, which is more soluble than the perchlorinated
iron phthalocyanine catalyst.

Na₄FeTSPc   FePc(Cl)₁₆
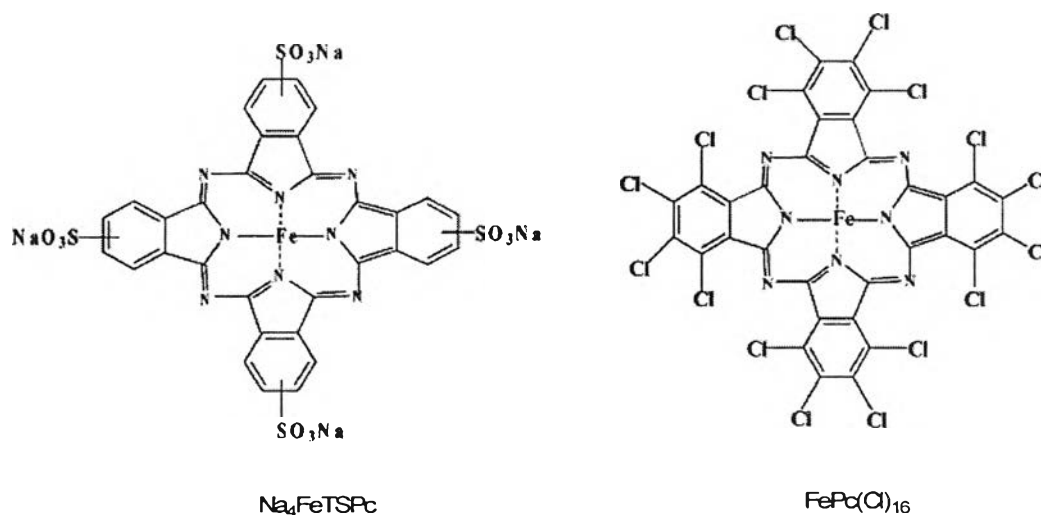
Furthermore, metalloporphyrins bearing meso-pentafluorophenyl groups are
highly efficient catalysts for aerobic oxidation of alkanes with acetaldehyde under
oxygen atmosphere (equation 3.10) [80]. Various alkanes and alkylated arenes can be
converted into the corresponding alcohols and ketones with a high turnover number.
High yields of alcohols and ketones based on acetaldehyde can be achieved by using
the present catalysts. The selectivity of this reaction is up to 95%.

$$R_3 - \underset{\underset{R_2}{|}}{\overset{\overset{R_1}{|}}{C}} - H \xrightarrow[\text{CH}_3\text{CHO, O}_2]{\text{cat.}} R_3 - \underset{\underset{R_2}{|}}{\overset{\overset{R_1}{|}}{C}} - OH \xrightarrow{R_3 = H} \underset{R_2}{\overset{R_1}{>}} = O \qquad \text{(equation 3.10)}$$

cat. :

$M = Co^{II}, Mn^{III}(Cl), Ru^{II}(CO)$

3.2 Scope of this study

From the literature reviews, both metal catalyst complexes and hydroperoxide are crucial parameters affecting the oxidation of hydrocarbons. The main features of this research focused on the methodology toward the oxidation of hydrocarbons such as saturated hydrocarbons or benzylic compounds to more valuable products catalyzed by a chromium complex.

3.3 Experimental

3.3.1 General procedure:

This section provides general information of general and/or specific reaction conditions and spectral data for compounds along with a representative ^{1}H NMR and ^{13}C NMR spectra. The reactions were monitored by analytical TLC on aluminium sheets precoated with silica gel (Merck's, Kieselgel 60 PF254). Visualization was observed by UV light (254 nm), followed by dipping the plate into the appropriate stain. All reactions were stirred with Teflon-coated magnetic bars in condenser fitted round bottom flask. Removal of solvents was normally accomplished using a *Buchi* rotary evaporator connected to a vacuum pump.

Chromatography: Gas chromatography analysis was carried out on Shimadzu Gas Chromatography 9A instrument equipped with flame ionization with N_2 as a carrier gas. The columns used for analysis were HP5 20M. Column chromatography was performed on silica gel (Merck 's, Kieselgel 60 G Art 7734 (70-230 mesh)).

^{1}H and ^{13}C-NMR spectra were recorded at 400 MHz on a Varian spectrometer. Chemical shifts are reported in ppm from tetramethylsilane with the solvent resonance of $CDCl_3$ (7.26 ppm).

Infrared spectra: Infrared spectra were recorded on a Shimadzu Fourier transform infrared spectrometer with 2 cm^{-1} resolution in a solution cell. Infrared frequencies are reported in reciprocal centimeters (cm^{-1}).

Melting points: Melting points were measured on a Fisher-Johns melting point apparatus and are uncorrected.

Elemental analysis (EA) was carried out on CHNS/O ANALYSER (Perkin Elmer PE2400 Series II) at Scientific and Technological Research Equipment Center Chulalongkorn University. Gaseous products freed by pyrolysis in high-purity oxygen 15 and were chromotographically separated by frontal analysis and quantitatively detected by thermal conductivity detector.

Chemicals: All solvents in this research were purified according to the procedures described in the standard methodology except for reagents and solvents that are reagent grade. The reagents for the preparation of Cr(str)$_3$ and for synthesizing some substrates as well as commercial available substrates, *e.g.* cyclohexanol, benzyl alcohol, cinnamyl alcohol, menthol *etc.*, were purchased from Fluka chemical company and were used without further purification.

3.3.2 Synthesis

3.3.2.1 Preparation of Cr(acac)$_3$

Chromium(III) chloride hexahydrate (2.66 g, 10 mmol) was dissolved in distilled water (3 mL) and the mixture was heated until homogeneity. After that concentrated ammonium hydroxide solution (4.5 mL) was dropped slowly. The solution was stirred for about 15-20 min on a water bath (80 ^{0}C) and brown solid was filtered off and washed with distilled water until no more chloride was detected. The precipitate was placed in Erlenmeyer flask, acetylacetone (6 mL; 10 mmol) was slowly dropped for 35 min on water bath and a precipitate of red solid was observed. The products were filtered and recrystallized by 95% ethanol. The blue gray solid of Cr(acac)$_3$ was obtained (75%), m.p. 209-215°C. IR (KBr, cm^{-1}): 1527-1578(s), 1381 (s), 1277 (s), 1018 (s) and 927 (m).

3.3.2.2 Preparation of Cr(bza)₃

$CrCl_3$ (0.16 g, 0.99 mmol) and benzoylacetone (0.46 g, 2.80 mmol) were dissolved into EtOH 50 mL. CH_3COONa solution (0.15 g in 10 mL) was added. The solution was stirred for 24 h, a red precipitate was obtained, then collected and dried in *vacuo* (26%), m.p. 223-225°C. IR (KBr, cm⁻¹): 3000-3450 (b), 1517-1588 (s), 1301-1447 (s), 557-1070 (m).

3.3.2.3 Preparation of Cr(cur)₃

Curcumin (6.26 g; 22 mmol) in MeOH 50 mL was dissolved into a solution of NaOH (0.88 g NaOH in 20 mL) at 80 °C. The solution was stirred until clear and homogeneity, $CrCl_3.6H_2O$ (7.3 mmol) dissolved in 10 mL of distillated water was added giving a yellow precipitate. The reaction mixture was allowed to stir at the same temperature until the complex occurred, then the precipitate was collected and dried in *vacuo* (60%), m.p. 248-252°C. IR (KBr, cm⁻¹): 3000-3450 (w), 1600 (m), 1501 (s), 1455 (s), 1266 (s), 900-1029 (m).

Metal(III) curcumin was prepared as described in the preparation of Cr(cur)₃ but different metal salts, Ni, VO, Co, Zn, Cu, Fe were used.

3.3.2.4 Preparation of Cr(str)₃

Stearic acid (6.26 g; 22 mmol) was dissolved into a solution of NaOH (0.88 g NaOH in 20 mL) at 80 °C to give a 2 M solution. The solution was stirred until clear and homogeneity, $CrCl_3.6H_2O$ (7.3 mmol) dissolved in 10 mL of distillated water was added giving a light purple precipitate. The reaction mixture was allowed to stir at the same temperature until the complex formed, then the precipitate was collected and dried in vacuo (75%), m.p. 100-103°C. IR (KBr, cm⁻¹): 1750 (s), 1607 (s), 1473 (m), 1327 (s), 1287 (s), 1051 (m), 864 (m), 767 (m), 475 (s). (EA), %C = 48.35, %H = 3.27 and %N = 9.44.

3.3.2.5 Preparation of Cr(pic)₃

The catalyst was prepared by dissolving 5.12 g of $CrCl_3.6H_2O$ and 7.50 g of picolinic acid in 40 mL of deionized water then crystals of Cr(pic)₃ formed after stirred the solution mixture 24 hours (70% yield). m.p. 100-103°C. IR (KBr, cm⁻¹): 1677 (s), 1607 (s), 1473 (m), 1327 (s), 1287 (s), 1159 (m), 1051 (m), 864 (m), 767 (m), 716 (m), 692 (m), 659 (w), 475 (s)

3.3.3 The general procedure for the oxidation of hydrocarbon compounds.

To a solution of hydrocarbon (5 mmol) in isooctane (5 mL) containing the catalyst (0.2 mmol) in a round bottom flask was added 18 mmol of TBHP. The reaction mixture was heated and kept constant at 70°C. After the specified time or completion of the reaction (followed by TLC), 1 mL of the reaction mixture was taken and extracted twice with Et_2O. The combined extracts were washed with 30% H_2SO_4 and saturated $NaHCO_3$, respectively. The organic layer was dried over anh Na_2SO_4 and analyzed by GC with the addition of an exact amount of an appropriate internal standard.

3.3.4 Oxidation of cyclohexane catalyzed by chromium (III) complexes

Oxidation of cyclohexane catalyzed by Cr(acac)₃

The oxidation of cyclohexane was conducted as described in general procedure catalyzed by Cr(acac)₃ but different times were used (1, 3, 5, 24 h).

Oxidation of cyclohexane catalyzed by Cr(bza)₃

The oxidation of cyclohexane was conducted as described in general procedure catalyzed by Cr(bza)₃ but different times were used (1, 3, 5, 24 h).

Oxidation of cyclohexane catalyzed by metal curcumin

The oxidation of cyclohexane was conducted as described in general procedure catalyzed by metal curcumin (metal = Ni, VO, Co, Zn, Cu, Fe).

Oxidation of cyclohexane catalyzed by Cr(cur)₃

The oxidation of cyclohexane was conducted as described in general procedure catalyzed by Cr(cur)₃ but the ratio between AcOH/py (10:1):CH₃CN (5:0, 4:1, 3:2, 1:1) were used as solvent.

3.3.5 Oxidation of adamantane catalyzed by chromium (III) complexes

The oxidation reaction was conducted as described in general procedure using Cr(str)₃ and Cr(pic)₃ as catalysts and adamantane as substrate.

3.3.6 Epoxidation of cyclohexene catalyzed by Cr(pic)₃

To a solution of cyclohexene (5 mmol) in various solvents (15 mL) (toluene : CH₃CN 13:2, toluene : CH₃CN 13:2, isooctane, acetonitrile, acetone, pyridine : acetic

acid 9:1) containing the catalyst (0.2 mmol) in a round bottom flask was added 2-ethylbutyladehyde to give a purple suspension. The reaction mixture was kept constant at ambient temperature. After the specified time or completion of the reaction (followed by TLC), 1 mL of the reaction mixture was taken and extracted twice with diethyl ether. The combined extracts were washed with 30% H_2SO_4 and saturated $NaHCO_3$, respectively. The organic layer was dried over anhydrous Na_2SO_4 and analyzed by GC with the addition of an exact amount of an appropriate internal standard.

3.3.7 Oxidation of benzylic methylene compounds catalyzed by Cr(pic)₃

3.3.7.1 Effect of amount of Cr(pic)₃

The oxidation reaction was carried out as described in general procedure employed Cr(pic)₃ as catalyst, but the different the amounts of catalysts were varied (0.2, 0.5, 1.0).

3.3.7.2 Oxidation of acenaphthene catalyzed by Cr(pic)₃

The oxidation reaction was carried out as described in general procedure employing Cr(pic)₃ as catalyst, but different amounts of catalyst (0.1, 0.2, 0.5 mmol), TBHP (9, 18 mmol) and times (3, 5, 24 h) were used.

3.3.7.3 Oxidation of different types of benzylic methylene compounds catalyzed by Cr(pic)₃

The oxidation reaction was carried out as described in general procedure employed Cr(pic)₃ as catalyst, but the substrates were varied (ethylbenzene, propylbenzene, o-nitroethylbenzene, o-bromoethylbenzene, cymene, tetralin, acenapthene, 1-acenaptanone, benzoin, xanthene, phenylethyl aceate, benzoyl acetate, ethyl benzoate, dibenzyl ether).

1-acenaphthenone: bright yellow crystalline solid, m.p. 256–260°C (70%); ^{1}H-NMR (CDCl₃, 400MHz, δ (ppm)): 3.84 (2H, s), 7.47 (1H, d, J = 6.8 Hz), 7.61 (1H, t, J = 15.2 Hz), 7.72 (1H, t, J = 14.8 Hz), 7.83 (1H, d, J = 8.4 Hz), 7.97 (1H, d, J = 6.8 Hz), 8.09 (1H, d, J = 8.4 Hz).

acenaphthenequinone: bright yellow crystalline solid, m.p. 256–260° C (70%); ^{1}H-NMR (CDCl₃, 400MHz, δ (ppm)): 7.26 (2H, t, J = 8.3 Hz), 7.44 (2H, t, J = 8.9 Hz), 7.58 (2H, d, J = 8.9 Hz). IR (KBr, cm^{-1}): 3033, 2918, 1710, 1225-1270 and 820.

benzil: yellow solid (24%), m.p. 93-95°C; ^{1}H-NMR (CDCl$_3$, 400MHz, δ (ppm)): 7.52 (2H, t, J = 15.6 Hz), 7.66 (1H, t, J = 14.8 Hz), 7.97 (2H, d, J = 7.2 Hz)

xanthone: yellow solid (97%), m.p. 171-174°C; ^{1}H-NMR (CDCl$_3$, 400MHz, δ (ppm)): 7.39 (2H, t, J = 7.8 Hz), 7.51 (2H, d, J = 8.6 Hz), 7.74 (2H, t, J = 8.7 Hz), 8.35 (2H, d, J = 7.9 Hz); IR (KBr, cm^{-1}): 3053, 1602-1658, 1263 and 930.

α-tetralone: yellow solid (90%), m.p. 125-127°C; ^{1}H-NMR (CDCl$_3$, 400MHz, δ (ppm)): 2.12 (2H, quint, J = 6.2 Hz), 2.64 (4H, t, J = 6.1 Hz), 7.24 (1H, t, J = 7.4 Hz), 7.32 (1H, d, J = 8.1), 7.45 (1H, t, J = 7.4), 8.01 (1H, d, J = 7.6)

benzoic acid: colorless solid (80%), m.p. 120-122°C; ^{1}H-NMR (CDCl$_3$, 400MHz, δ (ppm)): 7.48 (2H, t, J = 7.1 Hz), 7.62 (1H, t, J = 6.1 Hz), 8.12 (2H, d, J = 7.1 Hz); IR (KBr, cm^{-1}): 3000, 1715 and 925.

Synthesis of benzyl acetate

Pour 15 mL (15.68 g, 0.15 mole) of benzyl alcohol and 20 mL (21 g, 0.35 mole) of glacial acetic acid into a 100-mL round-bottomed flask. Carefully add 4 mL of conc. H$_2$SO$_4$ to the contents of the flask, with stirring. Heat the mixture under reflux for 1 hour. Remove the heating source and allow the mixture to cool to room temperature. The combined extracts were washed with water and saturated NaHCO$_3$, respectively. The organic layer was dried over anh Na$_2$SO$_4$. The mixture was distilled and collected the fraction boiling between 210 and 215 °C in a dry flask.

benzyl acetate: colourless liquid (85%), b.p. 212-214°C; ^{1}H-NMR (CDCl$_3$, 400MHz, δ (ppm)): 2.09 (3H, s), 5.09 (2H, s), 7.24-7.40 (5H, m).

Synthesis of ethyl benzoate

The oxidation reaction was carried out as described in general procedure to synthesis of benzyl acetate: ethanol 15 mL (11.84 g, 0.26 mole) and benzoic acid (42.7 g, 0.35 mole) as substrates. The mixture was distilled and collected the fraction boiling between 210 and 215 °C in a dry flask.

ethyl benzoate: colorless liquid, aromatic odor (80%), b.p. 212-214°C; ^{1}H-NMR (CDCl$_3$, 400MHz, δ (ppm)): 1.38 (3H, t, J = 7.1 Hz), 4.36 (2H, q, J = 7.1 Hz), 7.51 (2H, t, J = 3.2 Hz), 7.57 (1H, t, J = 1.5 Hz), 8.03 (2H, dd, J = 3.2, 1.6 Hz).

Synthesis of phenylethyl acetate

The oxidation reaction was carried out as described in general procedure to synthesis of benzyl acetate employed phenylethanol 16.0 g (0.13 mole) and acetic acid 10 mL (14.5 g, 0.18 mole) as substrates. The mixture was distilled and collected the fraction boiling between 230 and 233 °C in a dry flask.

phenylethyl acetate: colorless liquid, aromatic odor, (80% yield), b.p. 231-233°C; ^{1}H-NMR (CDCl$_3$, 400MHz, δ (ppm)): 2.01 (3H, s), 2.83 (2H, t, J = 7.1), 4.41 (2H, t, J = 3.2 Hz), 7.24-7.40 (5H, m).

3.4 Results and discussion

3.4.1 Oxidation of cyclohexane catalyzed by chromium(III) complexes

The oxidation of cyclohexane was found to be an efficient reaction. Cr(acac)$_3$ in addition was reported to use as a catalyst for alkene oxidation such 1-octene to its corresponding oxo-product in high conversion [81]. Thus, Cr(acac)$_3$ seemed to be a useful catalyst for hydrocarbon oxidation. This complex was therefore selected to apply as a catalyst in oxidation of cyclohexane under the same reaction conditions examined.

3.4.1.1 Synthesis and characterization of Cr(acac)$_3$

Cr(acac)$_3$ was prepared by the mixing acetylacetone in NH$_4$OH solution with CrCl$_3$.6H$_2$O at 80 °C. A blue gray solid precipitate was formed in 75% yield and the melting point was around 212-216°C. The identity of synthesized Cr(acac)$_3$ was confirmed by comparison of physical properties, EA, and IR spectroscopic data with those reported [82].

Elemental analysis (EA)

Percent composition of carbon and hydrogen in Cr(acac)$_3$ was analyzed by EA. The result is presented in Table 3.1.

Table 3.1 Elemental analysis of prepared Cr(acac)₃

Value	%C	%H
Theoretical	51.14	6.82
Experimental	51.47	6.07

Table 3.1 presents the composition of prepared Cr(acac)₃ and the theoretical values. The result indicated that the complex contains 51.47% and 6.07% of carbon and hydrogen, respectively *vs* the theoretical value of 51.14% carbon and 6.82% hydrogen. The theoretical and experimental values for both carbon and hydrogen were acceptable to claim that this synthesis of Cr(acac)₃ was fruitful.

Infrared spectroscopy (IR)

From IR spectrum, this chromium complex presents a significant absorption band of carbonyl C-O around 1000-1300 cm⁻¹. The C-H stretching vibration was detected around 2850-2900 cm⁻¹. Furthermore, the absorption peak around 1700 cm⁻¹ corresponded to the C=O stretching could not observed because C=O in fact should be in form of its enol form and coordinate with Cr. The IR spectrum of Cr(acac)₃ is presented in Figure 3.1.
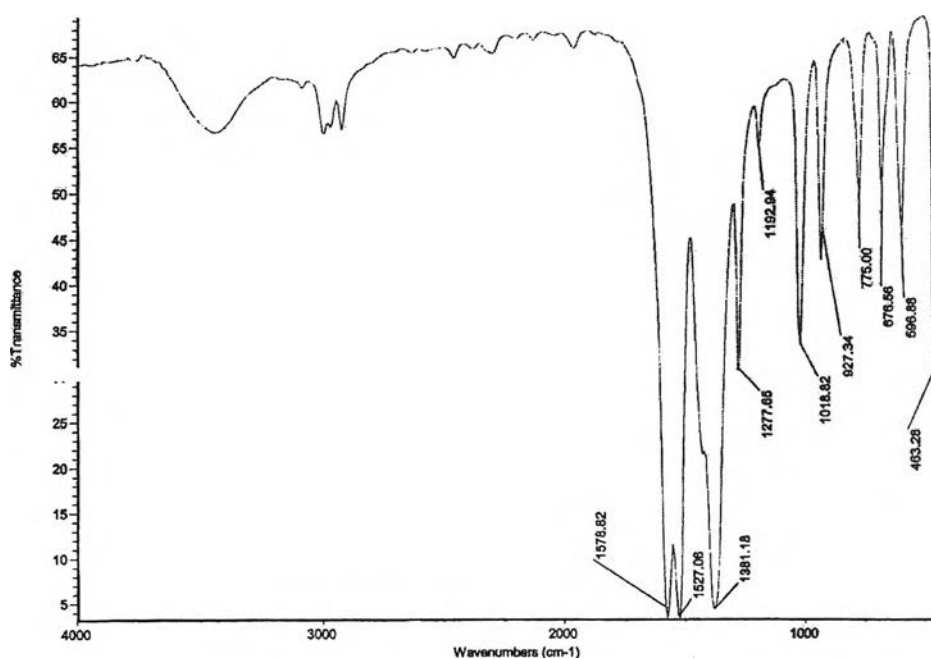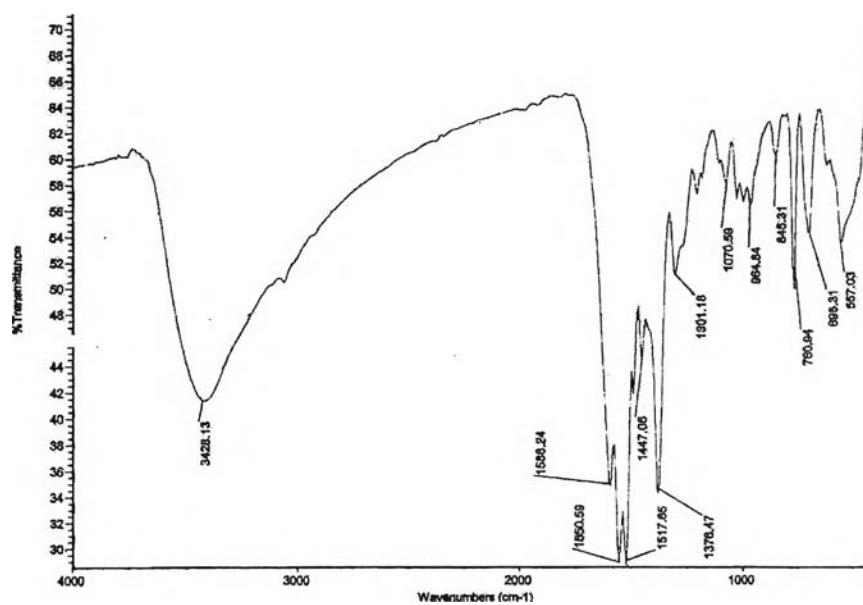

Figure 3.1 IR spectrum of Cr(acac)₃.

3.4.1.2 Oxidation of cyclohexane catalyzed by Cr(acac)₃

Cyclohexane was selected as a model substrate for optimization the reaction conditions. Cr(acac)₃ was previously reported to be an active catalyst for oxidation of alcohols to aldehydes and ketones using periodic acid as a co-oxidant [83]. The results of cyclohexane oxidation by TBHP with Cr(acac)₃ are presented in Table 3.2 and Figure 3.2.

Table 3.2 The oxidation of cyclohexane catalyzed by Cr(acac)₃

entry	time (h)	product (mmol)		Σ
		cyclohexanone	cyclohexanol	
1	0.5	0.23	0.16	0.39
2	1	0.32	0.32	0.64
3	3	0.49	0.46	0.95
4	5	0.75	0.48	1.23
5	17	1.00	0.45	1.45
6	24	1.23	0.78	2.01

Reaction conditions: cyclohexane (50 mmol), Cr(acac)₃ (0.2 mmol), TBHP (9 mmol), at $70^{0}C$
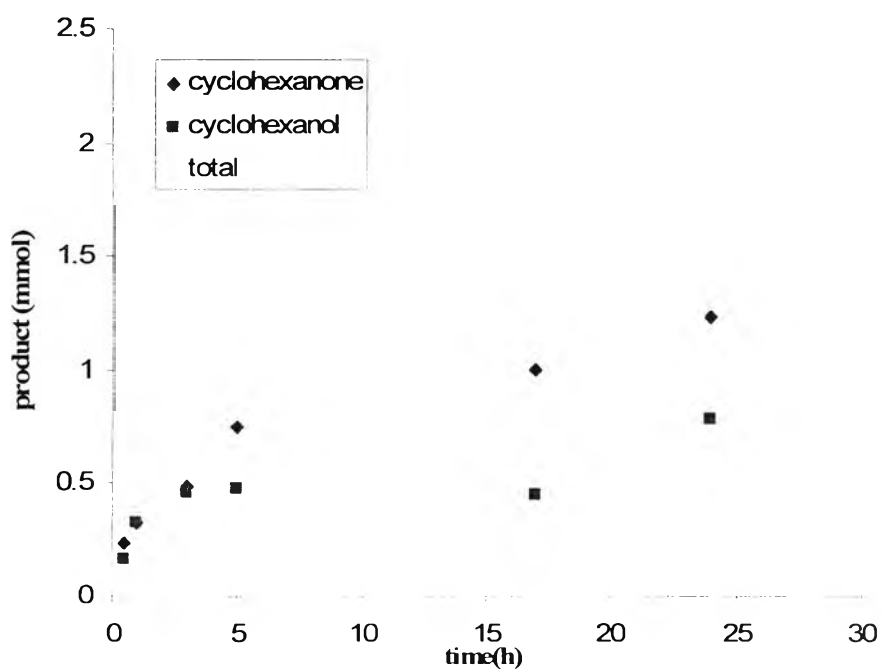
Figure 3.2 The oxidation of cyclohexane catalyzed by Cr(acac)₃

From Table 3.2 and Figure 3.2, it was observed that the longer reaction time, the more desired products were formed. It should be noted that after 17 h, the selectivity of cyclohexanone/cyclohexanol decreased. The half-life of cyclohexanone and cyclohexanol formation was around 3 h. Based on the efficiency of $Cr(acac)_3$ as a catalyst for alkane oxidation, it was conceivable to consider other 1,3-dicarbonyl ligands that may provide a proper complex with chromium (III). $Cr(bza)_3$ was another complex selected to proof this assumption.

3.4.1.3 Synthesis and characterization of $Cr(bza)_3$

$Cr(bza)_3$ was prepared by mixing of benzoylacetone in CH_3COONa solution with $CrCl_3.6H_2O$. A red solid precipitate was formed in 26% yield and the melting point was around 223-225°C. The identity of synthesized $Cr(bza)_3$ was confirmed by comparison of physical properties and IR spectroscopic data with those reported [82].

Infrared spectroscopy (IR)

From IR spectrum, this chromium complex presents a significant absorption band of carbonyl C-O around 1000-1300 cm^{-1}. The C=C stretching of aromatic ring presented at 1588 and 1447 cm^{-1}. The C-H stretching vibration was detected around 2850-2900 cm^{-1}. Furthermore, the absorption peak around 1700 cm^{-1} corresponded to the C=O stretching could not be observed because C=O infact should be in front of its enol from and coordinate with chromium. The IR spectrum of $Cr(bza)_3$ is presented in Figure 3.3.

Figure 3.3 IR spectrum of $Cr(bza)_3$.

3.4.1.4 Oxidation of cyclohexane catalyzed by Cr(bza)₃

The results of cyclohexane oxidation catalyzed by Cr(bza)₃ are exhibited in Table 3.3.

Table 3.3 The oxidation of cyclohexane catalyzed by Cr(bza)₃

entry	time (h)	product (mmol)		Σ
		cyclohexanone	cyclohexanol	(mmol)
1	0.5	0.07	0.03	0.10
2	1	0.37	0.23	0.60
3	3	0.69	0.23	0.92
4	5	0.84	0.29	1.13
5	17	1.80	0.53	1.33
6	24	1.45	0.45	1.90

Reaction conditions: cyclohexane (50 mmol), Cr(bza)₃(0.2 mmol), TBHP (9 mmol), at 70⁰C
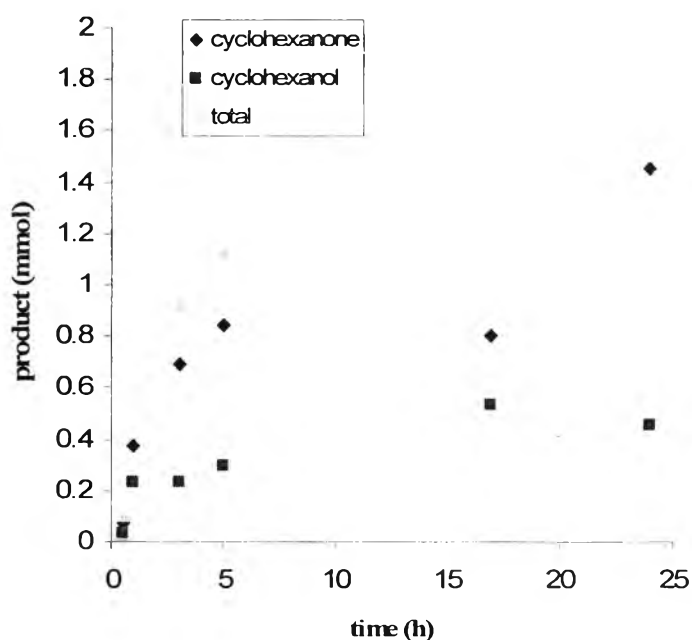
Figure 3.4 The oxidation of cyclohexane catalyzed by Cr(bza)₃

From Table 3.3 and Figure 3.4, the amount of products derived from cyclohexane oxidation catalyzed by Cr(bza)₃ is comparable that to obtained from that catalyzed by Cr(acac)₃. The half-life of cyclohexanone and cyclohexanol formation

was around 3 h. Nevertheless, the selectivity of the production of ketone to alcohol was prevailed. It can be noticed that chromium complex with aromatic ligand affected the production of cyclohexanone.

Based on previous results attained, a natural occurring compound such as curcumin was considered to use as a ligand for chromium complex and would employ as a catalyst.

3.4.1.5 Synthesis and characterization of Cr(cur)₃

Cr(cur)$_3$ was prepared by mixing curcumin in NaOH solution with CrCl$_3$.6H$_2$O at 80 °C. A yellow precipitate was formed in 60% yield and the melting point was around 248-252°C. The identity of synthesized Cr(cur)$_3$ was confirmed by compare with curcumin.

Infrared spectroscopy (IR)

From IR spectrum, this chromium complex presents a significant absorption band of carbonyl C-O around 1000-1300 cm^{-1}. The C=C stretching of aromatic ring presented at 1588 and 1447 cm^{-1} while the C=C stretching of alkene showed around 1600-1800 cm^{-1}. The C-H stretching vibration was detected around 2850-2900 cm^{-1}. The presence of O-H expressed broad band around 3400-3500 cm^{-1}. Furthermore, the absorption peak around 1700 cm^{-1} corresponded to the C=O stretching was not observed. The IR spectrum of Cr(cur)$_3$ is presented in Figure 3.5. The IR spectrum of curcumin also presents a signifiant fucntional group such as C=C stretching of alkene showed around 1423-1621 cm^{-1}[84]. When compare between curcumin and Cr(cur)$_3$ spectrum, it was found that the absorption band was shifted to 1600 cm^{-1} due to the complexation between metal and ligand.
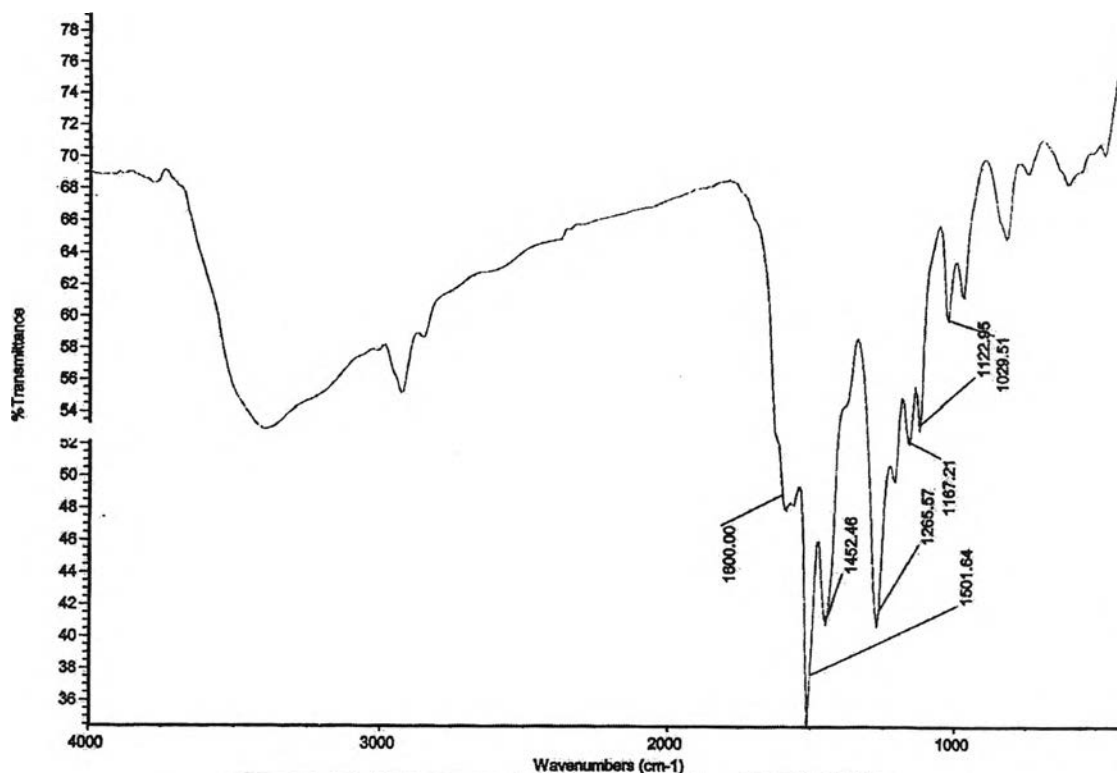
Figure 3.5 IR spectrum of Cr(cur)₃.

3.4.1.6 Oxidation of cyclohexane catalyzed by Cr(cur)₃

Curcumin is the main yellow pigment of a popular spice, turmeric and is widely used as a food colorant [84]. Curcumin has a unique conjugated structure including two methoxylated phenols and an enol form of β-diketone .
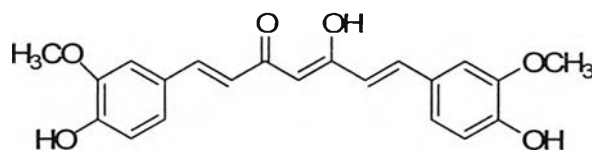
The carbonyl group in the structure of curcumin can bond with chromium and also the aromatic rings can increase the selectivity of oxidation reaction. Preliminary study using Cr(cur)₃ as a catalyst revealed that cyclohexane oxidation under the same condition as that performed using Cr(acac)₃ catalyst did not give good yield of cyclohexanol or cyclohexanone possibly due to the solubility of catalyst. To screen for suitable catalysts that could mediate the transformation of cyclohexane to the corresponding product in high yield, various metal curcumin complexes were synthesized to test for the catalytic oxidation. The synthesis of other metal curcumin complexes were conducted by the same method as that described for Cr(cur)₃. All prepared metal

curcumin complexes were tested for the solubility in various solvents and the results are expressed in Table 3.4.

Table 3.4 The solubility of metal curcumin complexes

metal complexes	EtOAc	CHCl$_3$	hexane	methanol	H$_2$O	pyridine:acetic acid 10:1	CH$_3$CN
Cr	x	x	x	x	x	+++	+++
Ni	x	x	x	++	+	+++	+++
V	x	x	x	++	+	+++	+++
Co	x	x	x	x	x	+++	+++
Zn	x	x	x	x	+	+++	+++
Cu	x	x	x	+	+	+++	+++
Fe	x	x	x	+	x	+++	+++

x = insoluble   + slightly soluble   ++ moderate soluble   +++ highly soluble

It was found that the use of acetic acid in pyridine and acetonitrile can completely dissolve all complexes. To study the effective oxidation by metal curcumin complexes, a variety of transition complex were considered. The results show in Table 3.5.

Table 3.5 The oxidation of cyclohexane catalyzed by metal curcumin complexes

entry	metal curcumin	product (mmol)		Σ
		cyclohexanol (mmol)	cyclohexanone (mmol)	
1	Co	0.22	0.47	0.69
2	Ni	0	0	0
3	Cr	0.24	1.23	1.47
4	Fe	0.18	0.36	0.54
5	Cu	0.16	0.46	0.62
6	Zn	0	0	0
7	V	0.06	0.10	0.16

Reaction conditions: cyclohexane (50 mmol), catalyst (0.2 mmol), TBHP (9 mmol), at 70^{0}C for 24 h, solvent: pyridine:acetic acid 10:1 5 mL.

Seven transition metal curcumin complexes were screened to observe their potential catalytic oxidation ability. It was disclosed that Ni and Zn curcumin complexes cannot catalyze cyclohexane oxidation. Furthermore, V-curcumin afforded a moderate yield for transformation of cyclohexane to cyclohexanone and cyclohexanol while Co, Fe and Cu-curcumin gave high yield of carbonyl compounds. Cr(cur)$_3$ provided the highest yield and selectivity without contamination with undesired products. However, the use of acetic acid and pyridine as a solvent in these systems made the adaptation to an industrially useful process impractical. Acetronitrile was chosen as a co-solvent to reduce the amount of pyridine and acetic acid required, and the result are demonstrated in Table 3.6.

Table 3.6 The oxidation of cyclohexane catalyzed by Cr(cur)$_3$

entry	AcOH/py (10:1) : CH$_3$CN (mL)	product (mmol)		Σ (mmol)
		cyclohexanone	cyclohexanol	
1	5:0	1.99	0.09	2.08
2	4:1	2.06	0.16	2.22
3	3:2	1.49	0.14	1.63
4	2.5:2.5	0.59	0.14	1.63

Reaction conditions: cyclohexane (50 mmol), catalyst (0.2 mmol), TBHP (9 mmol), at 70^{0}C for 24 h

From the above results concerning with the variation of solvent ratio, acetic acid/pyridine (10:1): acetonitrile 4:1 provided the highest yield of product. When the amount of acetonitrile increased, the amount of the corresponding product decreased. This may due to the fact that the solubility of catalyst decreased when the quantity of acetonitrile increased. In comparison with well-known Gif oxidation conditions, the catalytic oxidation with Cr(III) complexes in the presence of TBHP demonstrated poorer yields of the corresponding products. The oxidation of cyclohexane with FeCl$_3$.6H$_2$O and picolinic acid in pyridine afforded 1.29 mmol of cyclohexanone while the amount of cyclohexanol was approximately 0.05 mmol [85]. Moreover, Gif system can be applied to heterogeneous system by supporting the catalyst on an inorganic support which aids the efficiency of the process allowing easy separation of the reaction mixture [86]. Fe^{3+}-PA complex was prepared inside the zeolite

micropores which catalyze cyclohexane oxidation with H_2O_2. It was found that the conversion of cyclohexane to cyclohexanol and cyclohexanone was approximately 7%.

Examination of the reaction catalyzed by Cr(str)$_3$ under the aforementioned conditions [87] allowed the comparison of the activity of catalyst. It was determined that there was no significant different on the catalytic activity of Cr (III) complex when using different ligands. The radical pathway was believed to take place similar to that presented by Muzart. [3] It was proposed that a superoxide species from TBHP was transferred to Cr^{III} and the reaction was carried on Cr^{V} oxo species which could abstract a hydrogen from cyclohexane and produced alkyl radicals. The proposed mechanism for the oxidation of cyclohexane catalyzed by Cr(III) complexes using TBHP as oxidant is performed in Scheme 3.2.
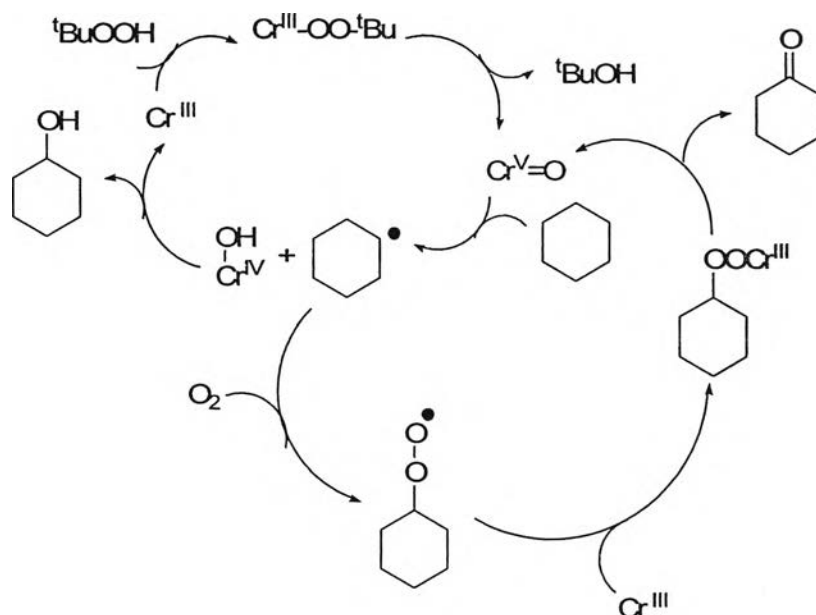
Scheme 3.2 The proposed mechanism on the oxidation cyclohexane catalyzed by Cr(III) complexes using TBHP as oxidant

3.4.2 Oxidation of adamantane catalyzed by chromium(III)complexes

Another selected saturated hydrocarbon to be studied is adamantine. This potential probe for regioselectivity study was due to the 12 equivalent secondary carbons and 4 equivalent tertiary carbons in its structure. The catalytic activity for adamantane oxidation between Cr(str)$_3$ and Cr(pic)$_3$ were compared in Table 3.7.

Table 3.7 The oxidation of adamentane catalyzed by Cr(III) complexes
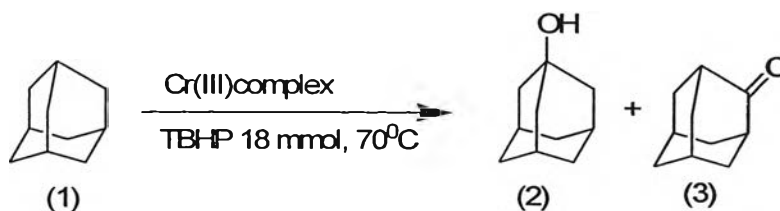
entry	catalyst	% recovery (1)	% yield (2)	% yield (3)	mass balance
1	Cr(str)$_3$	74	14	4	92
2	Cr(pic)$_3$	75	14	5	94

Reaction conditions: adamantane (5 mmol), catalyst (0.2 mmol), isooctane 5 mL, TBHP (18 mmol), at 70^{0}C for 24 h.

From Table 3.7, it is interesting to note that there is no significant differences in the catalytic activity between Cr(str)$_3$ and Cr(pic)$_3$. Adamantane was converted mainly to 1-adamentanol as a major product and 2-adamantanone as a minor one. The adamentane selectivity C^2/C^3 value derived from this system was found to be approximately 0.29. Defining C^2 as the total of the products oxidized at the secondary position and C^3 similarly for the tertiary position. The oxidation reaction might occur *via* a radical pathway, hence tertiary radicals should be more reactive. For alkoxide radical attack, a reliable C^2/C^3 of 0.15 has recently been established [88]. The same number has also been found for the oxidation of adamantane in acetone solution by ruthenium TBHP. This is also regarded as an alkoxide radical reaction [89]. Groves, using a porphyrin derivative as catalyst, found a number of less than 0.15 [90]. A number of reactions involving *tert*-butoxide radical attack on adamantane with subsequent carbon-carbon bond formation gave no significant attack on the secondary positions of the hydrocarbon or of its di-tert-methyl derivative. It is clear then that oxygen radical attack on the tertiary position of adamantane is a highly favored process.

It was observed that the oxidation of adamantane catalyzed by chromium(III) complexes with TBHP gave a high selectivity (C^2/C^3) although the conversion of adamantane was low (25% conversion).

3.4.3 Epoxidation of cyclohexene catalyzed by Cr(pic)₃

Development of oxidation processes using molecular oxygen as a safe, inexpensive, and readily available oxidant is of considerable interest. A number of metal catalysts have been used to achieve and improve the oxidation. The epoxidation of an olefin by molecular oxygen in the presence of aldehyde has been studied [91]. The pathways of the reaction proceed *via* formation of acyl radical as shown in Scheme 3.3.
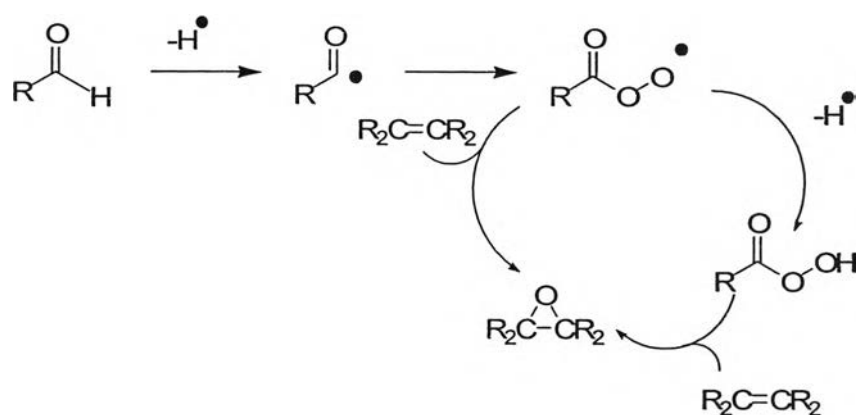
Scheme 3.3 The proposed mechanism on the epoxidation cyclohexene

These radicals react with oxygen to afford an acyl peroxy radical which lead to the corresponding peroxy acid. Moreover, the selective epoxidation of alkenes catalyzed by cobalt complexes in the presence of 2-ethylbutyraldehyde/O_2 was examined [92]. Cyclohexene can be produced to cyclohexene oxide as a major product with high yield and excellent selectivity (equation 3.12).
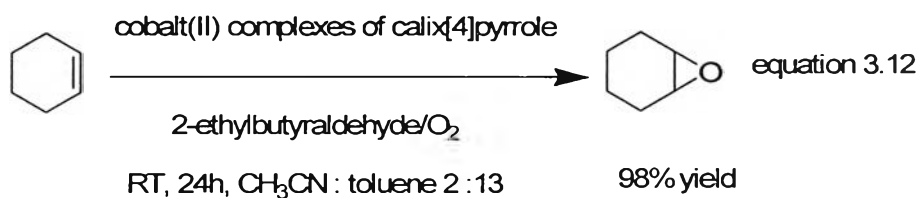
From the literature, metal complexes seem to catalyze epoxidation reaction with 2-ethylbutyraldehyde/O_2 in excellent yield. Cr(pic)₃ was selected to investigate the catalytic epoxidation with cyclohexene as a model substrate. The results are demonstrated in Table 3.8.

Table 3.8 The epoxidation of cyclohexene catalyzed by Cr(pic)$_3$

entry	catalyst	solvent	%recovery of cyclohexene	%yield of cyclohexene oxide	MB [a]
1	cobalt(II) calix[4]pyrrole	toluene:CH$_3$CN(13:2)	12	85	97
2	Cr(pic)$_3$	toluene:CH$_3$CN(13:2)	97	0	97
3	Cr(pic)$_3$	isooctane	93	0	93
4	Cr(pic)$_3$	acetonitrile	80	20	100
5	Cr(pic)$_3$	acetone	95	0	95
6	Cr(pic)$_3$	py:acetic acid(9:1)	53	41	94

Reaction conditions: cyclohexene (5 mmol), Cr(pic)$_3$ (0.2 mmol),

2-ethylbutyraldehyde (10 mmol) / O$_2$, at RT for 24 h

From Table 3.8, the use of acetonitrile-toluene, isooctane and acetonitrile failed to give the desired product due to insolubility of catalyst (entries 2-5). Cr(pic)$_3$ is moderately soluble in 2M aqueous HCl, DMF, and acetonitrile; slightly soluble in methanol; and insoluble in acetone, ethanol, DMSO and THF [56]. It should be noted that when a mixture of acetic acid and pyridine was employed, a higher yield of the desired product 41% (entry 6) was obtained. On the contrary, the epoxide product catalyzed by cobalt(II)calix[4]pyrrole under the same reaction condition was 85% (entry 1). These findings displayed that Cr(pic)$_3$ was not a good catalyst as cobalt(II) calix[4]pyrrole for cyclohexene epoxidation.

3.4.4 Oxidation of benzylic methylene compounds catalyzed by Cr(pic)$_3$

Benzylic oxidation is the foundation of many current important industrial and fine chemical processes, and it is utilized in such diverse fields as natural product chemistry to 'bucky ball' synthesis. Traditionally, a stoichiometric amount of oxidant such as manganese dioxide, chromic acid, potassium dichromate, or selenium dioxide was employed for these transformations [93]. In recent years, the use of small amounts of catalyst with cleaner oxidant such oxygen or hydroperoxides have received great attention for both economical and environmental benefits.

Simultaneously, many highly efficient systems have been developed for catalytic benzylic oxidation.

Recently, Mn(III)salen complexes, which are easily prepared and handled, have been utilized for the synthesis of carbonyl compounds from hydrocarbons. The oxidation proceeds in good yields under mild reaction conditions using iodozobenzene or sodium hypochlorite as stoichiometric oxidant (equation 3.13) [94].

77% conversion

94 : 6

(equation 3.13)
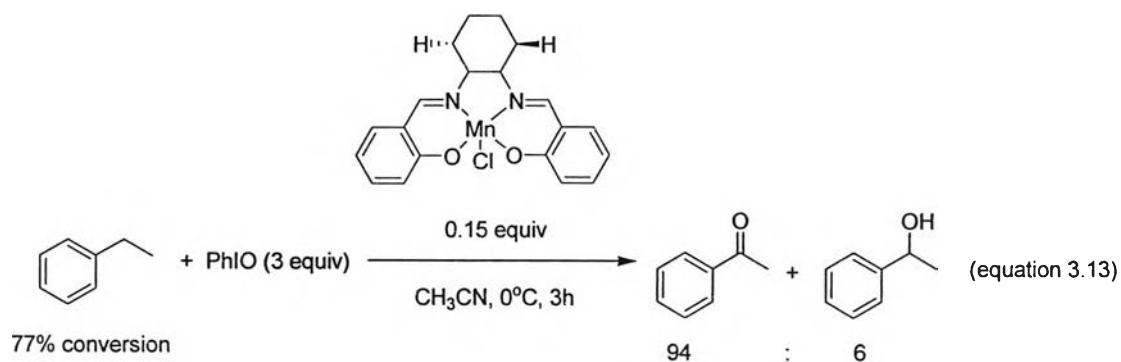
Iodosobenzene was found to be better than sodium hypochlorite. The reaction was dependant on the choice of solvent. The mechanism of the reaction proceeded through Mn=O intermediate. The likely reaction pathway for the oxidation of ethylbenzene is illustrated in Scheme 3.4. Based on the experimental results, it is considered that the second catalytic cycle where alcohol is converted to ketone is faster than the first step.
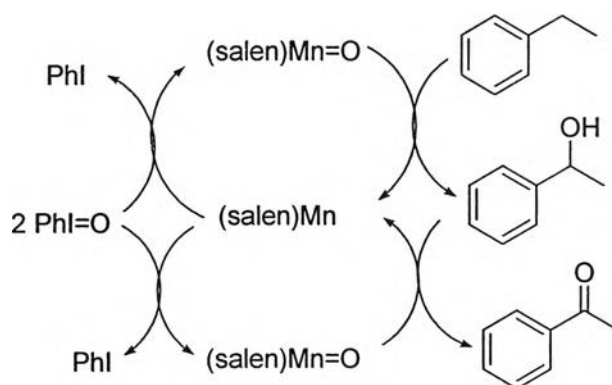
Scheme 3.4 The probably reaction pathway for the oxidation of ethylbenzene

Moreover, Mn(III) salen complexes can also be used to catalyze asymmetric benzylic oxidation with iodosobenzene to afford the corresponding benzylic alcohol with that solvents of high viscosity such as chlorobenzene or fluorobenzene. (equation 3.14) [95].

(equation 3.14)

57 %   10% ee 1 : 0.84 2% ee
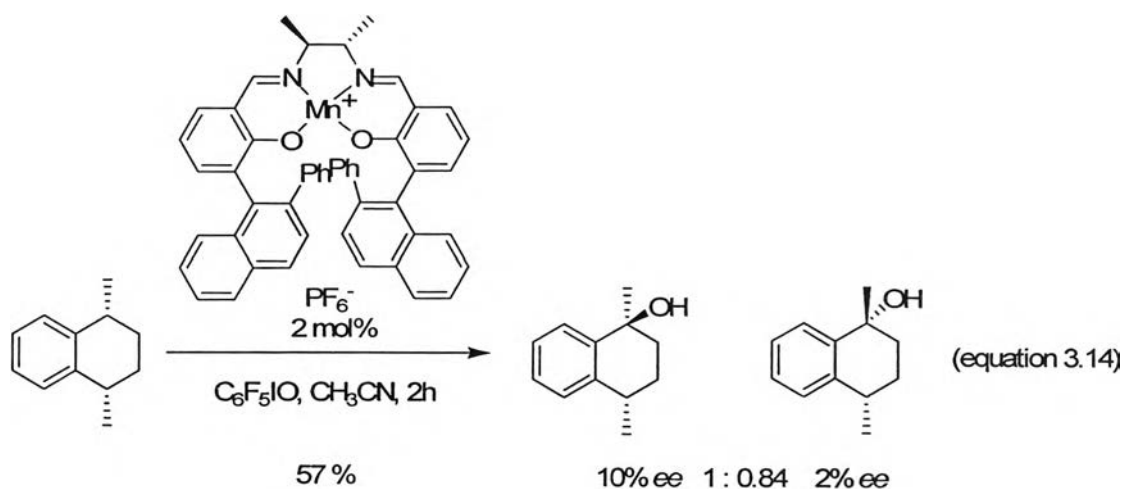
Furthermore, the use of H_2O_2 as an oxidant was applied with Mn(III) porphyrins [96]. The oxidation of ethylbenzene with H_2O_2 in the presence of catalyst afforded acetophenone as major product while 1-phenylethanol was the minor product. The reaction took only 6.5 h with 64 % conversion of ethylbenzene.

In addition, the use of TBHP as an oxidant was developed in the past few years. Benzylic oxidaiton catalyzed by bismuth and picolinic acid in pyridine and acetic acid was studied [97]. The oxidation of alkyl and cycloalkyl arenes gave the corresponding benzylic ketone (48-99%). Preliminary mechanistic studies were consistent with a radical mechanism. Indeed when 2,6-di-*tert*-butyl-4-methylphenol, a well known oxyl radical trap, was added during the oxidation of tetrahydronaphthalene, unreacted starting material was recovered unchanged. On the other hand, 2-methyl-1-phenylprop-2-yl hydroperoxide (MPPH) has been used as a mechanistic probe for *tert*-butoxyl radical formation. When MPPH was used as the oxidant only 4% of the α-tetralone was obtained and dibenzyl was isolated as the major by product (17%). Addition of chromium-catalyzed oxidation of benzylcyclopropane with TBHP led efficiently to cyclopropylphenylketone with a high selectivity (equation 3.15) [98].

62%   2%   4%   (equation 3.15)
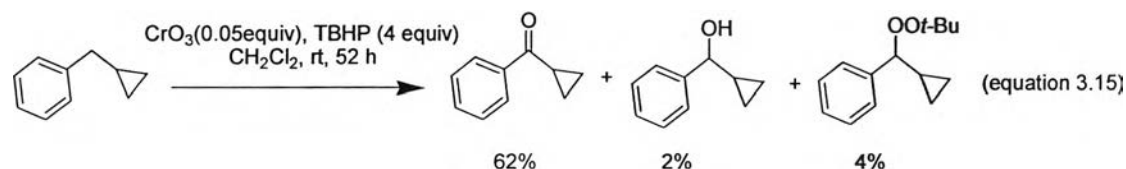
The result from the oxidation of benzylcyclopropane suggested the mechanism of the reaction involved the formation of α-benzylcyclopropane radical (A₁) which

would open to give radical B_1 (equation 3.16). However, under these condition rearrangement is quite unfavourably for the formation of cyclopropylphenylketone.
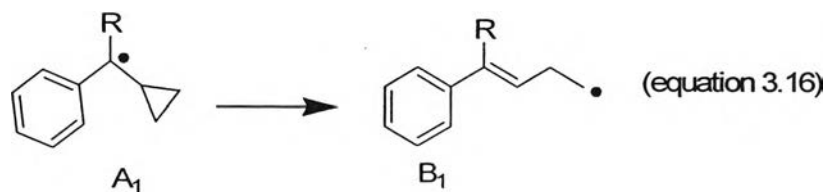
3.4.4.1 Effect of amount of catalyst

In order to investigate the most suitable condition of benzylic oxidation with $Cr(pic)_3$ in the presence of TBHP, ethylbenzene was used as the typical benzylic substrate. The amount of catalyst required was examined and the results were summarized in Table 3.9.

Table 3.9 The oxidation of ethylbenzene catalyzed by $Cr(pic)_3$

entry	catalyst amounts (mmol)	% recovery of ethylbenzene	%yield of acetophenone	mass balance
1	0.2	17	81	98
2	0.5	14	83	97
3	1.0	9	91	100

Reaction conditions: ethylbenzene (5 mmol), isooctane 5 mL, TBHP (18 mmol), at 70^0C for 24 h.

As seen from Table 3.9, it was observed that when the amounts of catalyst was increased, the amounts of acetophenone also increased. Nevertheless, using 0.2 mmol of $Cr(pic)_3$ did not differ from 0.5 mmol while 1.0 mmol gave the highest yield.

3.4.4.2 Oxidation of acenaphthene catalyzed by $Cr(pic)_3$

Another interesting area to study is the complete burning process of coal, oil, gas *etc.* which produces hazardous polycyclic aromatic hydrocarbon such as acenaphthene. From an environmental concern view point, fictionalization to other less toxic forms, such as oxidized compound, is of significant interest. Initial experiments focused on the oxidation of acenaphthene to acenaphthenequinone. The

parameters to study the oxidation of acenaphthene were catalyst amounts, times and oxidant amounts. The results are demonstrated on Table 3.10.

Table 3.10 The oxidation of acenaphthene catalyzed by Cr(pic)$_3$
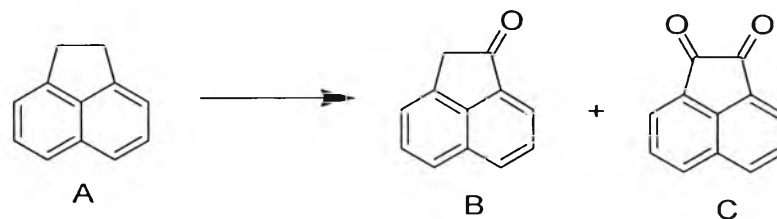
entry	time (h)	catalyst amount (mmol)	% isolated recovery of A	% isolated yield of B	% isolated yield of C	mass balance
1	5	0.1	60	41	0	91
2	5	0.2[a]	90	7	0	97
3	24	0.2[a]	59	5	36	100
4	3	0.2	92	7	0	99
5	5	0.2	41	51	0	92
6	24	0.2	0	69	25	94
7	24	0.5	0	45	48	93

Reaction conditions: acenaphthene (5 mmol), Cr(pic)$_3$ (0.2 mmol) isooctane 5 mL, TBHP (18 mmol), at 70^{0}C, [a] TBHP 9 mmol

Two corresponding products were separated by silica gel column chromatography and characterized by ^{1}H-NMR spectroscopy. The ^{1}H-NMR spectrum of **B** exhibited the 6H signals of aromatic protons at δ 7.47-8.09. The presence of methylene protons expressed as a siglet signal at δ 3.84 ppm. (Figure 3.6) On the other hand, ^{1}H-NMR spectrum of **C** revealed only the aromatic protons detected in the range of δ 7.52-8.02 ppm (Figure 3.7).

From Table 3.10, it was found that using a small amount of catalyst and time (entry 1) afforded only product B in moderate yield. On the other hand, when using 0.2 mmol or 0.5 mmol of Cr(pic)$_3$ and increasing the reaction time length (entries 5, 6) resulted in the formation of **C** in moderate yield as well. However, when the oxidant was decreased to 9 mmol, the percent yield of products **A** and **B** decreased. It can be concluded at this point that product **B** could be attained by the oxidation of product **A**. Recent report involved the oxidation of acenaphthene (**A**) with TBHP

catalyzed by bismuth and picolinic acid in pyridine and acetic acid gave only 1-acenaphthenone (B) 50% yield within 16h [97].
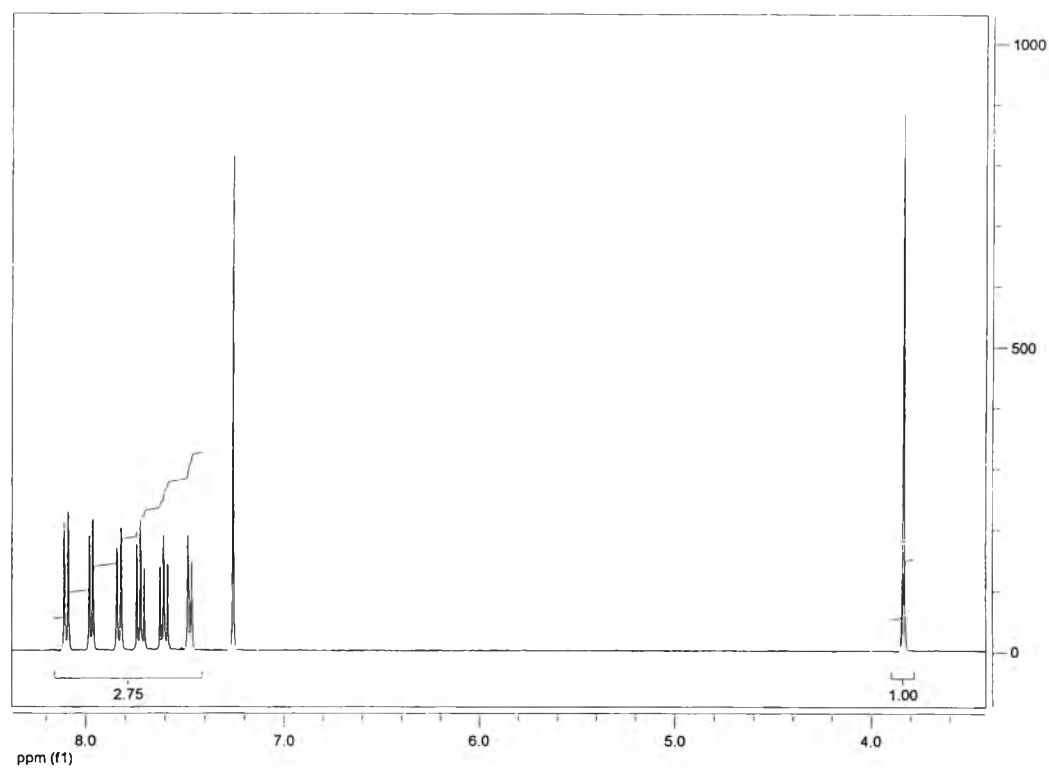
Figure 3.6 ^{1}H-NMR spectrum of isolated 1-acenaphthenone
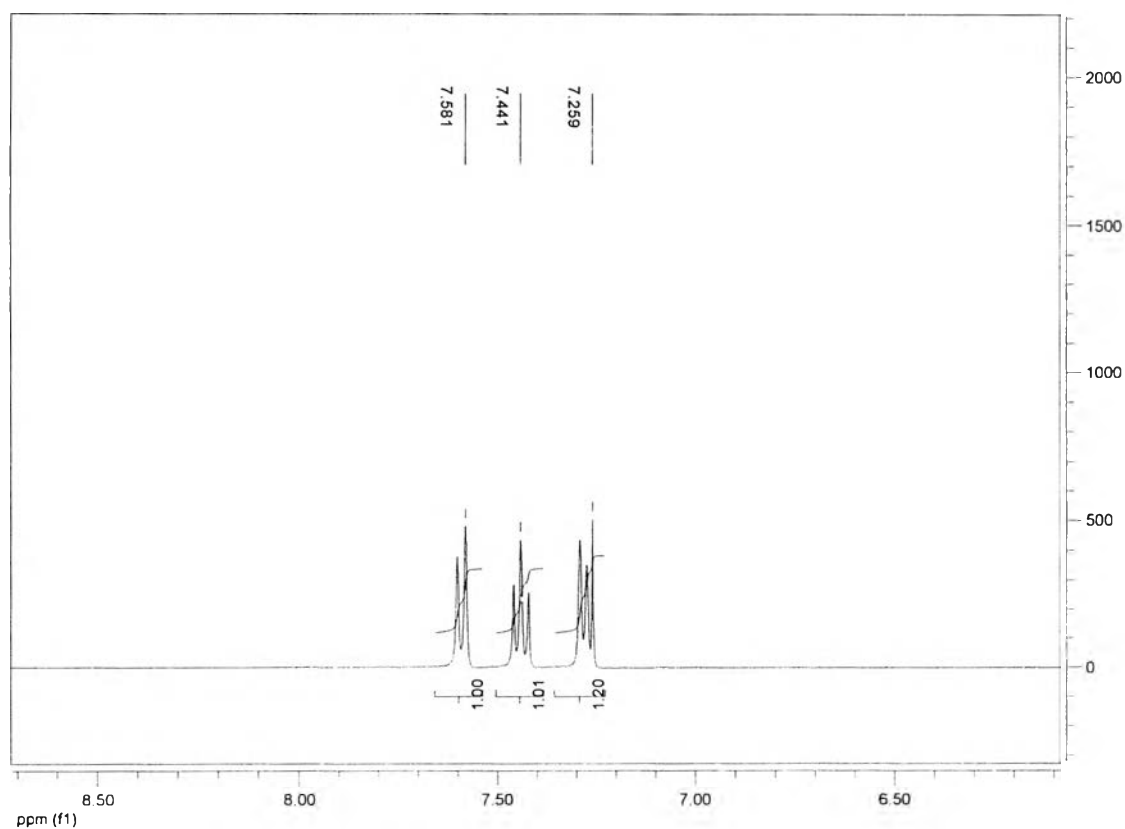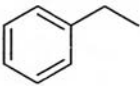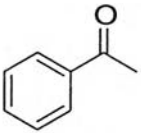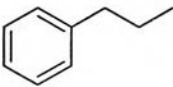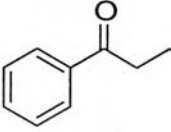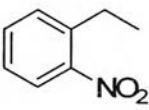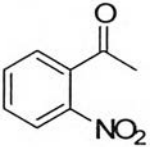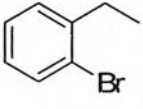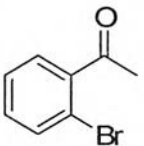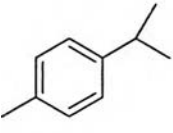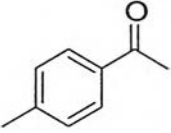
Figure 3.7 ^{1}H-NMR spectrum of isolated acenaphthenequinone

3.4.4.3 Oxidation of benzylic methylene compounds catalyzed by Cr(pic)₃

The benzylic methylene oxidation reaction was applied for a range of substrates. The results are demonstrated in Table 3.11.

Table 3.11 The oxidation of benzylic methylene compounds catalyzed by Cr(pic)₃

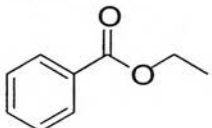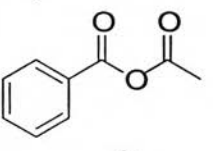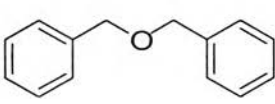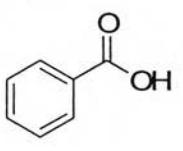| entry	substrates	products	%recovery substrates	% isolated yield	Mass balance
1			17	81	98
2			35	65	100
3			80	18	98
4			95	0	95
5			43	49	92
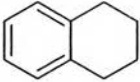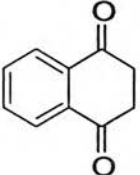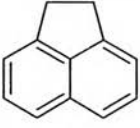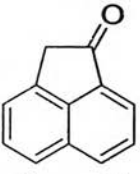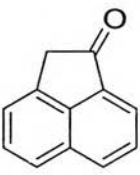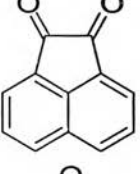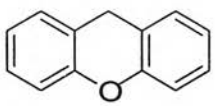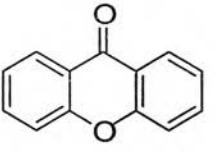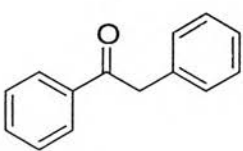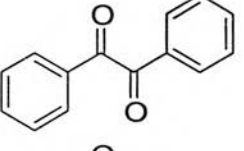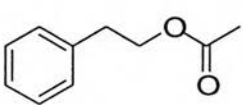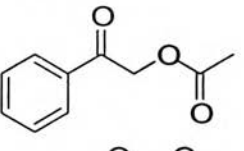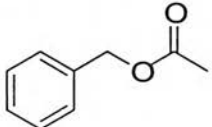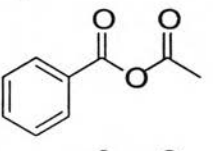
Reaction conditions: substrate (5 mmol), Cr(pic)₃ (0.2 mmol), isooctane 5 mL, TBHP 18 mmol, 70°C for 24 h,

Different types of benzylic methylene substrates were subjected to the reaction conditions examined above. As seen in Table 3.11, Cr(pic)₃ catalyzed oxidation was efficient to give the carbonyl compounds in good to moderate yields (entries 1-3, 5). For alkyl benzene derivatives, benzylic oxidation products were obtained with high selectivity employing TBHP as the oxidant (entries 1-2). A substrate bearing a strongly electron-withdrawing substituent underwent oxidation in poor yield (entries 3,4). It is interesting to note that the oxidation of o-bromoethylbenzene was suppressed by bromine.

3.4.4.4 Oxidation of cyclic alkyl benzylic compounds catalyzed by Cr(pic)₃

Cyclic benzylic compounds, esters and benzyl ethers were considered for the selectivity of the oxidation. The results are presented on Table 3.12.

Table 3.12 The oxidation of cyclic alkyl benzylic compounds catalyzed by Cr(pic)₃

entry	substrate	product	% isolated yield
1			90
2			69
3			70
4			97
5			25
6			17 (42[a])
7			8
8			13
9			97

Reaction conditions: substrate (5 mmol), isooctane 5 ml, TBHP 18 mmol, at 70°C for 24 h, [a] 48 h

Cyclic alkyl benzylic substrates such as acenaphthene and tetrahydronaphthalene were performed the oxidation reaction identified to give mono-oxidation product selectively under the reaction condition (entries 1, 2). For the oxidation of acenapthene, the reaction was considered to proceed *via* 1-acenaphthenone. Excellent yields were obtained with xanthene (entry 4) which contained the doubly activated benzylic position without appreciable oxidation of oxygen atom. The structure of attained product, xanthone was fully verified by ^{1}H-NMR spectrum. According to ^{1}H-NMR spectrum presented in Figure 3.8, an important peak of aromatic protons was clearly detected around δ 7.39-8.37 ppm.
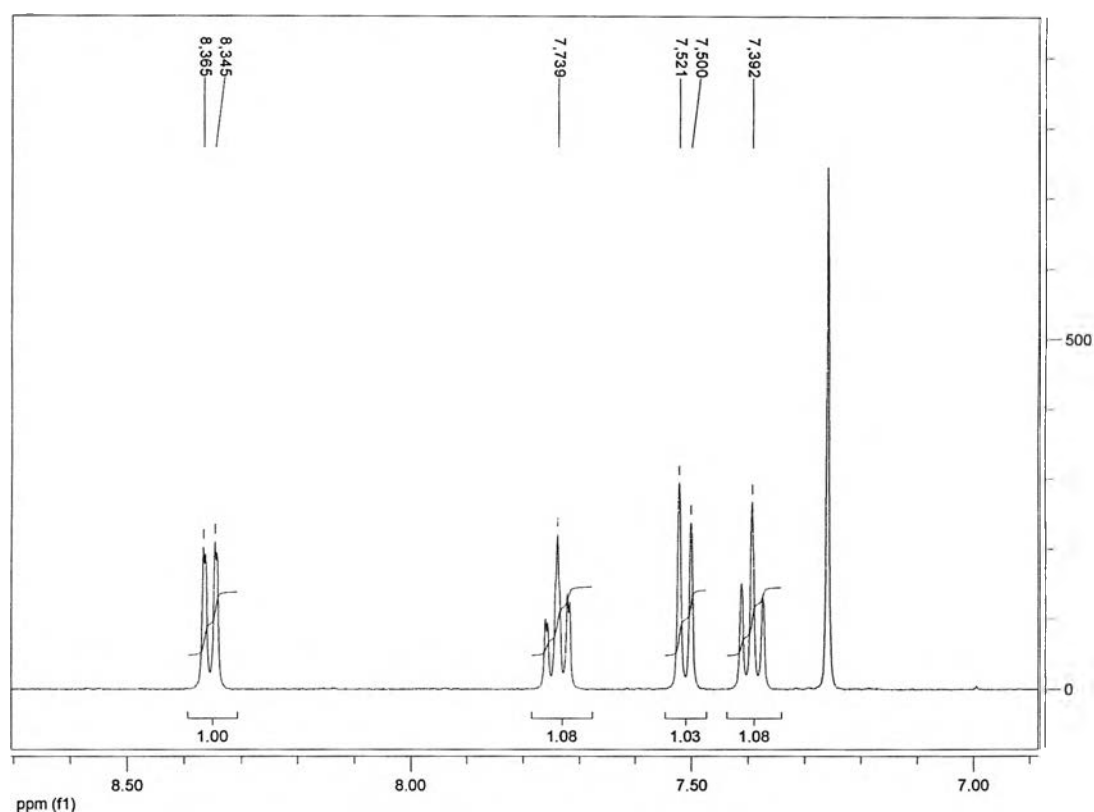

Figure 3.8 ^{1}H-NMR spectrum of isolated xanthone

Not only benzil was observed from the catalytic oxidation of benzoin but benzaldehyde and benzoic acid were also detected (entry 5). Sodium perborate in acetic acid at 95°C oxidized benzoin to benzoic acid in 70% yield [99]. Moreover, catalytic oxidation of benzoin with CrO_3 and sodium perborate, gave benzil (51%) and benzoic acid (38%) respectively [100].

In addition to studying the oxidation of arylacetic esters (entries 6-7), the model compound used for this regard were phenylethyl acetate, ethyl benzoate and

benzyl acetate. Arylacetic esters were accomplishly prepared from the esterification of corresponding alcohols and carboxylic acid [51]. The substrates were confirmed and characterized by ^{1}H-NMR spectroscopy. The ^{1}H-NMR spectrum of phenyl ethyl acetate (Figure 3.9) exhibited the signal of aromatic protons as a multiplet (5H) around δ 7.12-7.26 , -OCH$_2$CH$_2$ as a triplet (2H) at δ 3.57-3.54, -CH$_2$-Ph as a triplet (2H) at δ 2.83 and –CH$_3$-COO as a singlet (3H) at δ 2.01. ^{1}H-NMR spectrum of ethyl benzoate (Figure 3.10) exhibited the signal of aromatic protons as a multiplet (5H) around δ 7.51-8.03, -COO–CH$_2$- as a quartet (2H) at δ 4.36 and methyl protons as a triplet (3H) at δ 1.38 ppm. The ^{1}H-NMR spectrum of benzyl acetate (Figure 3.11) shows a characteristic singlet peak with integrations of 3H due to the methyl group, at δ 2.01 and the aromatic proton signals around δ 7.24-7.40 while the methylene protons exhibited the singlet signal at 5.09 ppm.
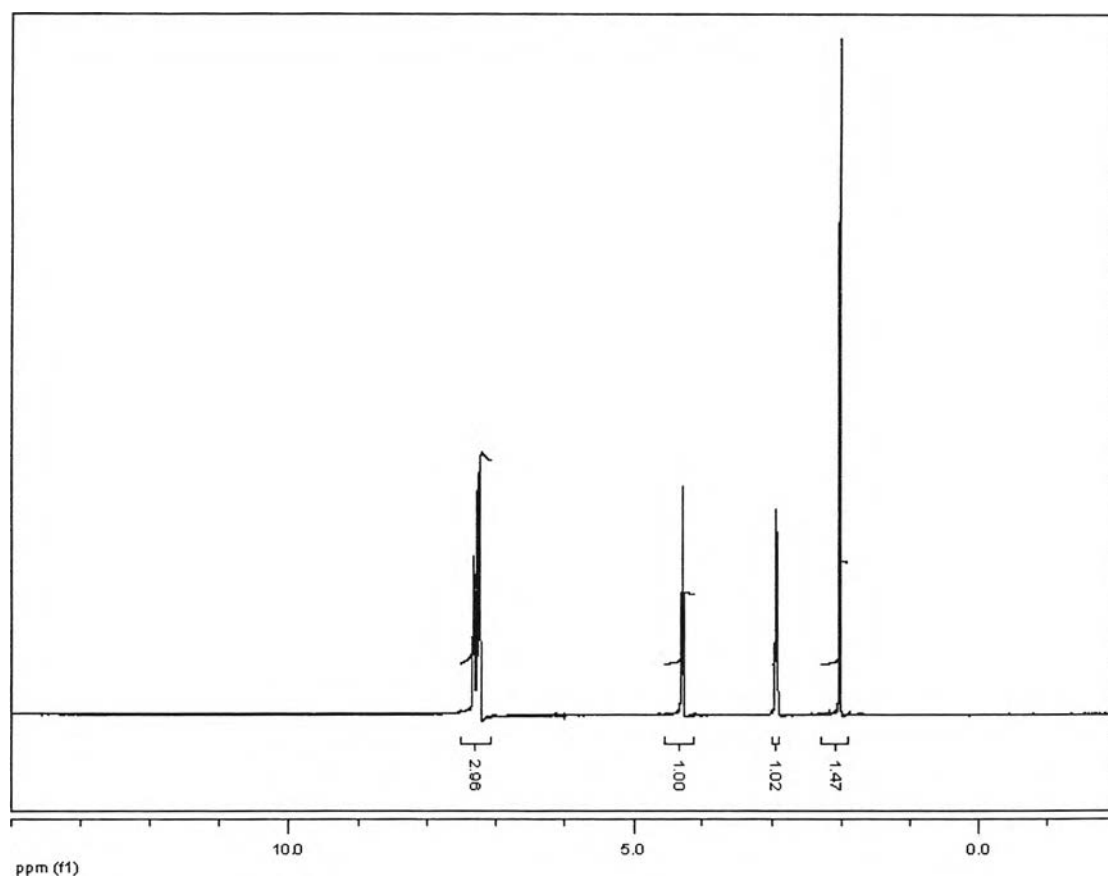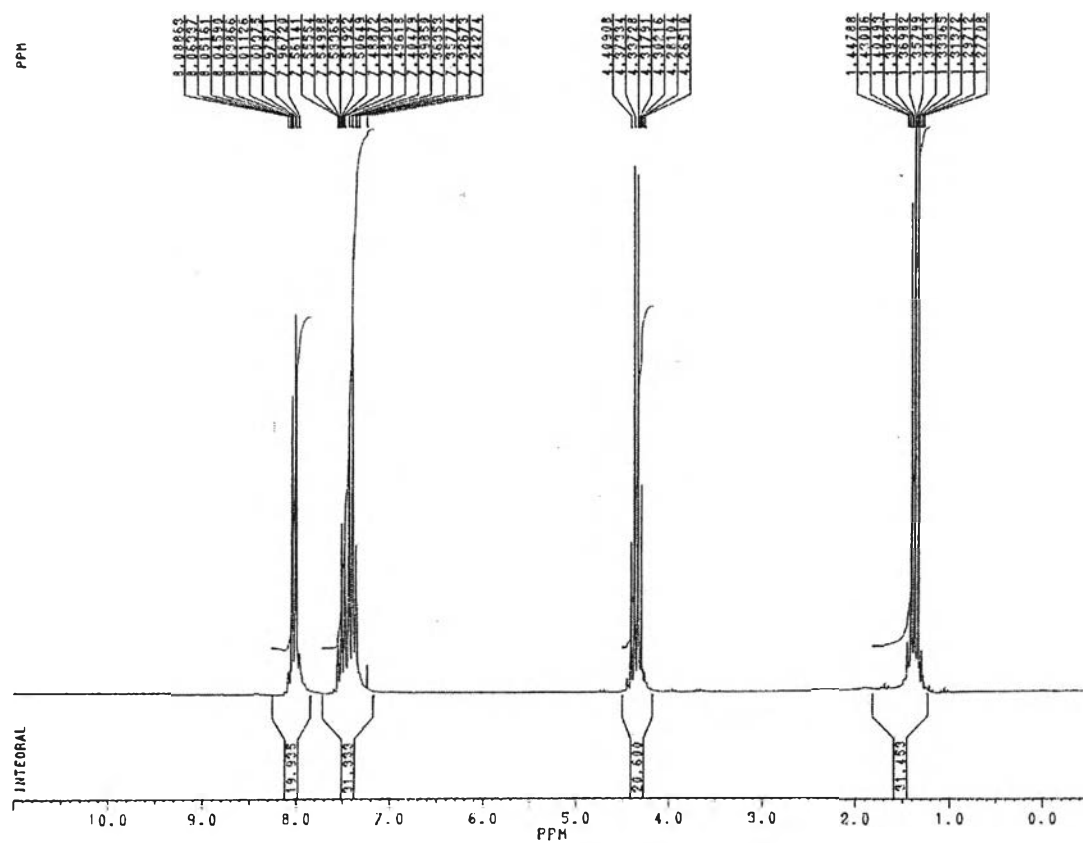

Figure 3.9 ^{1}H-NMR spectrum of phenyl ethyl acetate
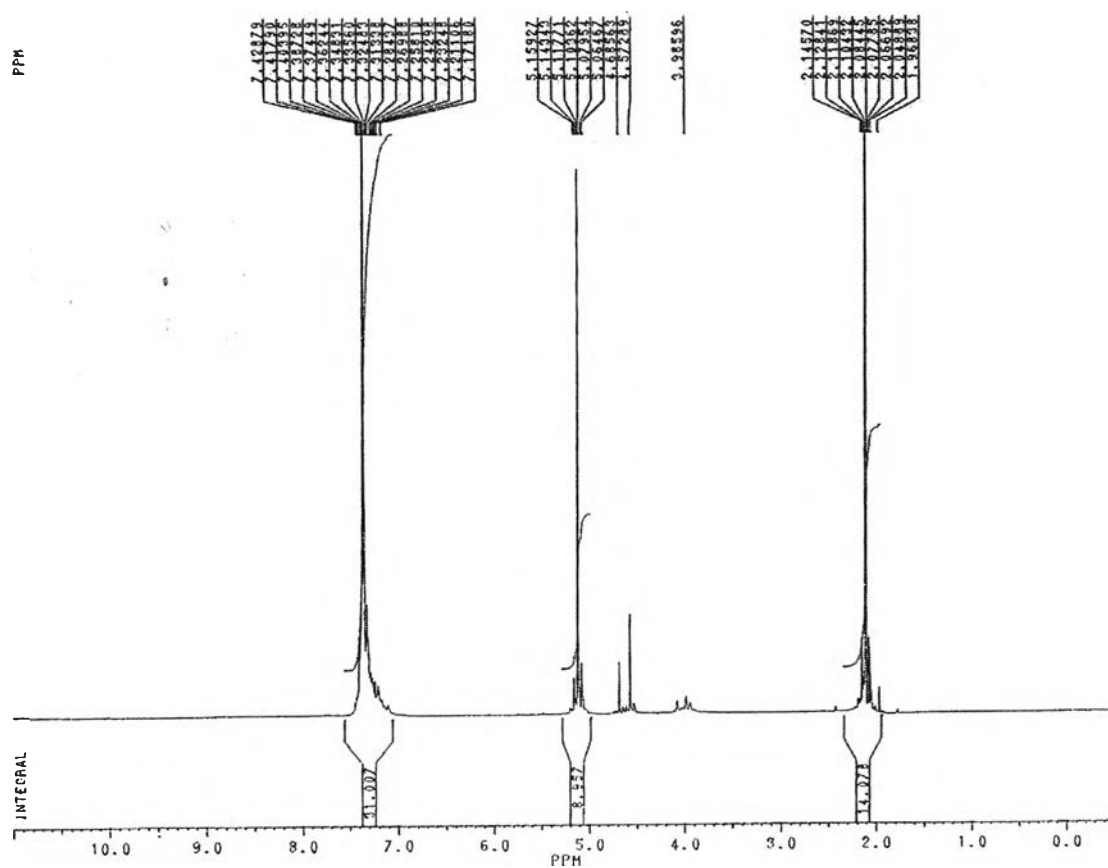
Figure 3.10 ^{1}H-NMR spectrum of ethyl benzoate

Figure 3.11 ^{1}H-NMR spectrum of benzyl acetate

From Table 3.12, the oxidation of esters gave poor yields of the corresponding carbonyl products (8-17 % yield) (entries 6-8). Although, the reaction times were increased to 48 h for the oxidation of phenylethyl acetate, the percent yield of the corresponding product was still moderate (42%). Recently, an efficient catalytic method for the low temperature oxygenation of organic substrates with O_2 was developed using N-hydroxyphthalimide (NHPI) as a catalyst and metal salt as co-oxidant (equation 3.17) [101].

$$\text{NHPI/Co}^{II}, O_2 \xrightarrow{\text{acetic acid, 40}^{0}\text{C}}$$

(equation 3.17)

73 % yield
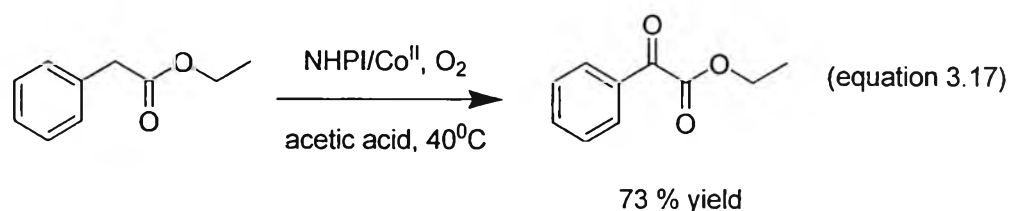
The oxidation with electron donating substituent (such as a methoxy group) at the *para* position to the substrate was shown to have a positive effect on the yield of glyoxylate (90% yield). An electron withdrawing substituent (*i.e.* Br) in the *para* position of the substrate suppressed the oxidation of the benzylic position (0% yield). Any substituent at *ortho* position with respect to the acetic ester functionality inhibits oxidation completely. Steric influences are probably the reason for this effect, since both electron withdrawing and donating substituents displayed the same effect. Oxidation of ethers with Cr(pic)$_3$ afforded only benzoic acid in high yields (entry 9) [101].

3.4.4.5 Oxidation of dibenzyl ether catalyzed by Cr(pic)$_3$

Further study was conducted on the oxidation of dibenzyl ether with various of time to find out the mechanism for the production of benzoic acid and the results are presented in Table 3.13.

Table 3.13 The oxidation of dibenzyl ether catalyzed by Cr(pic)₃

entry	time (h)	% recovery of substrate	% yield			mass balance
			alcohol	aldehyde	acid	
1	1	32	38	25	0	95
2	3	34	35	31	0	100
3	5	17	7	35	37	96
4	8	6	6	8	75	95
5	24	0	0	0	97	97

Reaction conditions: dibenzyl ether (5 mmol), Cr(pic)₃ (0.2 mmol), isooctane 5 mL, TBHP 18 mmol, at 70⁰ C

It was revealed that benzoic acid was produced *via* benzyl alcohol and benzaldehyde. After 5 hours the amounts of benzoic acid gradually increased from 37 to 97 % yield at 24 h while benzyl alcohol and benzaldehyde gradually decrease after 5 h. The C-O bond may be easy to break to give a radical. This radical can react with a TBHP radical to give benzyl alcohol and benzaldehyde which were further oxidized to benzoic acid.

The disclosure of Cr(pic)₃ as a catalyst coupled with TBHP as an oxidant to become an effective system was presented. The oxidation of benzylic compounds both alkyl and cyclic alkyl without strongly electron-withdrawing substituent gave high yield of the corresponding products. However, arylacetic esters afforded low yield while benzyl ethers produced benzoic acid instead of the corresponding carbonyl compounds.