Electronic Supplementary Material (ESI) for Green Chemistry.

A highly sustainable route to pyrrolidone derivatives – direct access to biosourced solvents

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Outlines

1. Equipment and methods

Levulinic acid (99%), formic acid (98%) and amines were purchased from Acros. The reactions were carried out in a Zook autoclave reactor type FPB-001. Amount of reagents were calculated on the basis of levulinic acid. Solvents for extractions such as ethyl acetate or ether were used without any further purification. Reagents were used as provided by the supplier unless otherwise stated. Reactions were performed in the absence of special care (e.g. no inert gas) unless otherwise stated. GCMS analyses were performed on a Shimazu GCMS type QP2010SE auto injector AOC-20i. The injected volume is around 1µL. The temperature of oven was heated from 180°C to 300°C depending on the method. The column employed is type ZB-5HT. NMR spectra ^{1}H were recorded on a Bruker AM 300 (300 MHz). NMR ^{13}C were recorded on a Bruker AM 300 (75.5 MHz). The chemical shifts (δ) are reported in parts per million (ppm) and calibrated to the residual solvent peak $CDCl_3$ (δ = 7.26 (^{1}H) and 77.16 ppm (^{13}C)). The following abbreviations are used for spin multiplicity: s (singlet), bs (large singlet), d (doublet), t (triplet), q (quartet) and m (multiplet).

2. Typical procedures for the Ruthenium-catalyzed synthesis of *N*-alkyl-5-methylpyrrolidones developed for air and moisture tolerance.

2.1. Procedure A1 : Formic acid as hydrogen source

At room temperature in a tube equipped with a Teflon septum and a stir bar was charged the $[Ru(p\text{-cymene})Cl_2]_2$ complex (1,2 mmol, 734 mg, 1 mol%) and $(o\text{-tolyl})_3P$ (3.6 mmol, 1.044g, 3 mol%,). Then levulinic acid (120 mmol, 13.93 g, 1 eq.) is added followed by the propylamine (120 mmol, 7.09 g, 1 eq.). Formation of a solid can be observed due to the acid-base reaction. Formic acid (120 mmol, 5.52 g, 1 eq.) is added dropwised (exothermic), yielding a brown to orange mixture. The reaction is allowed to proceed for 12 h at 120°C to 140°C. When the reaction is completed, the solution is diluted with aqueous Na_2CO_3 solution (100 mL). The resulting mixture is extracted with ethyl acetate (3 x 40 mL). The separated organic layers are washed with saturated aqueous NaCl solution (50 mL). Organic phases are dried over anhydrous

$MgSO_4$, filtered and concentrated under reduced pressure. The crude product is purified by silica gel column chromatography yielding a colorless liquid.

2.2 Procedure A2 : With gaseous dihydrogen

At room temperature the pyrex reactor equipped with a Teflon septum and a stir bar is charged with [Ru(*p*-cymene)Cl_2]$_2$ complex (1,2 mmol, 734 mg, 1 mol%,) and (*o*-tolyl)$_3$P (3.6 mmol, 1.044g, 3 mol%,) ligand. Then levulinic acid (120 mmol, 13.93 g, 1 eq.) is added followed by the dropwise addition of propylamine (120 mmol, 7.09 g, 1 eq. Formation of a solid can be observed due to the acid-base reaction. 1mL of water can be advantageously added. A brown to orange mixture is obtained. After removing the septum, the reactor is placed and sealed in the autoclave. The autoclave was filled up with H_2 until reaching a pressure of 3 bar. The autoclave was heated to 140°C and the reaction is allowed to proceed for 12 h. When the reaction is completed, the system is depressurized after being cooled to room temperature. Autoclave is opened and the crude orange to brown solution is diluted with aqueous Na_2CO_3 solution (100 mL). The resulting mixture is extracted with ethyl acetate (3 x 40 mL). The separated organic layers are washed with a saturated aqueous NaCl solution (50 mL). Organic phases are dried over anhydrous $MgSO_4$, filtered and concentrated under reduced pressure. The crude product is purified by silica gel column chromatography yielding a colorless liquid.

3. Procedure B : Typical procedure for the synthesis of *N*-alkyl-5-methylpyrrolidones in autoclave, without any catalyst or additive

Before the experiment, parameters of the reaction are calculated from the ideal-gas law in order to determine the maximum pressure (see part. 4, S4)

The reaction is performed into an Autoclave equipped with a manometer and a thermocouple. At room temperature the 100 mL pyrex-reactor equipped with a Teflon septum and a stir bar is charged with levulinic acid (60 mmol, 6.97 g) and propylamine (60 mmol, 3.55 g, 1 eq.) which is added dropwise. Formation of a solid can be observed due to the acid-base reaction. Formic acid (60 mmol, 3.60 g, 1 eq.) is then added dropwise (exothermic). After removal of the septum, the reactor is placed and sealed into the autoclave system. The autoclave is heated to 160°C and the reaction is allowed to proceed until the calculated maximum pressure value is reached. When the

reaction is complete (after 4.2 hours, P = 25 bars) the system is depressurized after being cooled to room temperature. The autoclave is opened and the crude yellow to orange solution is recovered as almost pure (see ^{1}H NMR spectrum of the crude part. 8, S22). The product is purified by simple distillation under reduced pressure to yield a colorless liquid.

In case of high boiling point products (bp > 250°C), extraction with ethyl acetate can be realized (3 x 20 mL). Organic layers are combined and washed with brine and dried over anhydrous $MgSO_4$, filtered and concentrated under reduced pressure to obtain colorless oil.

4. Calculation of parameters for the typical procedure B using the ideal gas law

Ideal gas law : PV = nRT

For our system the law become : $\boxed{P^{max}V^{free} = n(CO_2)_{final}RT}$

Set parameters :

Set temperature: T = 160°C = 433K

Reagent amount : $n(\text{formic acid})_{initial}$= 60 mmol

Total volume of the reactor: V^{tot} = 100 mL = 1.0*10^{-4} m^3

Determination of the free volume V^{free} :

Available volume after introduction of reagents

$V^{tot} = V^{free} + V^{reagent} \Leftrightarrow V^{free} = V^{tot} - V^{reagent}$

$d^{formic\ acid}$ = 1.22	$M^{formic\ acid}$ = 46.02 g/mol
$d^{levulinic\ acid}$ = 1.14	$M^{levulinic\ acid}$ = 116.11 g/mol
$d^{propylamine}$ = 0.719	$M^{propylamine}$ = 59.11 g/mol

$V^{reagent} = V^{formic\ acid} + V^{levulinic\ acid} + V^{propylamine}$

$n^{formic\ acid} = n^{levulinic\ acid} = n^{propylamine} = 60$ mmol

$V^{formic\ acid} = m^{formic\ acid} / d^{formic\ acid} = n^{formic\ acid} * M^{formic\ acid} / d^{formic\ acid}$

$V^{formic\ acid} = 0.060*46.02 / 1.22 = 2.263$ cm^3 = 2.263*10^{-6} m^3

Using the same calculation:

$V^{levulinic\ acid} = 6.111*10^{-6}$ m^3 and $V^{propylamine} = 4.933*10^{-6}$ m^3

So : $V^{reagent} = (2.263 + 6.111 + 4.933) *10^{-6}$ m^3

$V^{reagent} = 13.3*10^{-6}\ m^3$

$V^{free} = (100-13.3)*10^{-6}\ m^3$

$V^{free} = 86.7*10^{-6}\ m^3$

Determination of the maximum pressure P^{max} :

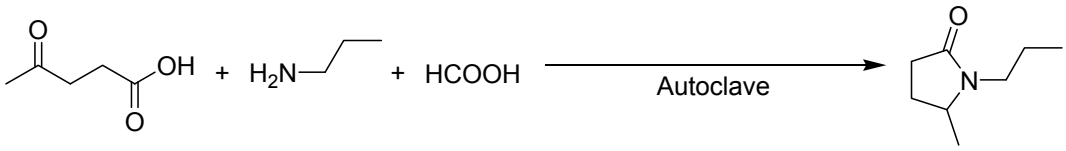
At maximum conversion: $n(\text{formic acid})_{initial} = n\ (CO_2\ )_{final} = 60$ mmol

$P^{max} = n(CO_2)_{final}\ RT/V^{free}$

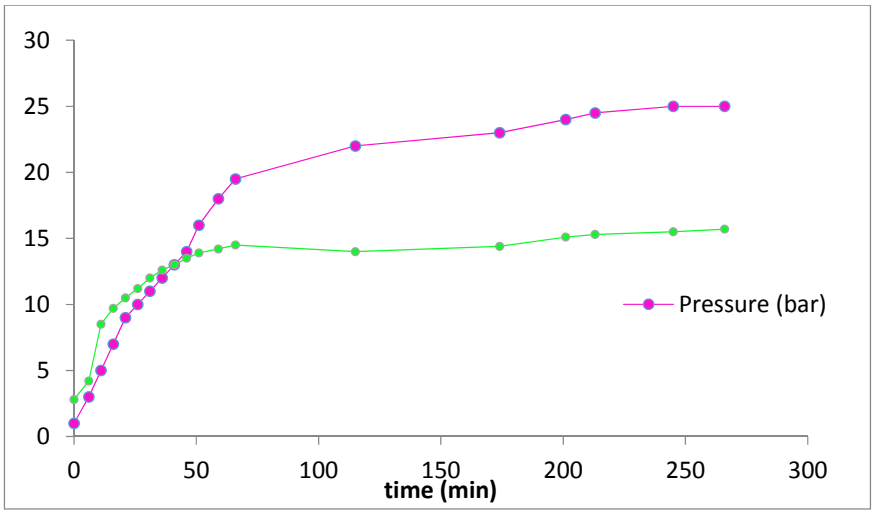
N.A. : $P^{max} = 0.06*8.314*433/\ 86.7*10^{-6} = 2.49\ 10^6$ Pa

$P^{max} = 25$ bars

5. Typical Pressure and Temperature profiles

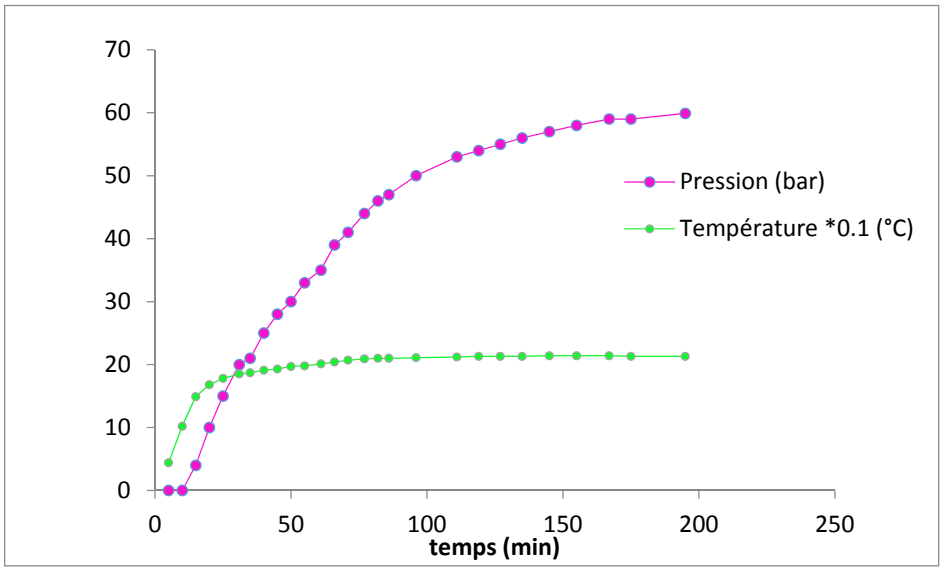


5.1. For a maximum Pressure set at 25 bars



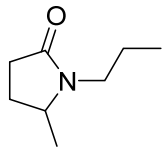
Conditions: LA (60 mmol), propylamine (60 mmol), HCOOH (60 mmol), in 100mL autoclave. Set temperature 160°C, maximum pressure set 25 bars, measured 25 bars.

5.2. For a maximum Pressure set at 60 bars



Conditions : Conditions: LA (120 mmol), propylamine (120 mmol), HCOOH (120 mmol), in 100mL autoclave. Set temperature 200°C, maximum pressure set 64 bars, measured 62 bars.

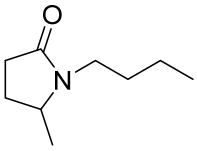
6. Analytical data



2a

5-methyl-*N*-propylpyrrolidone (5MeNPP) **2a** was synthesized following the procedure A1 and isolated as colorless liquid with 64% yield. **2a** was synthesized following the procedure B on 60 mmol scale. Volume of reactor 100mL, temperature 160°C, maximum pressure set 25 bars, measured 25 bar after 4.2 h. Conversion > 99 %. Isolated by distillation as a colorless oil. Yield 84 %. See the Temperature and Pressure chart above.

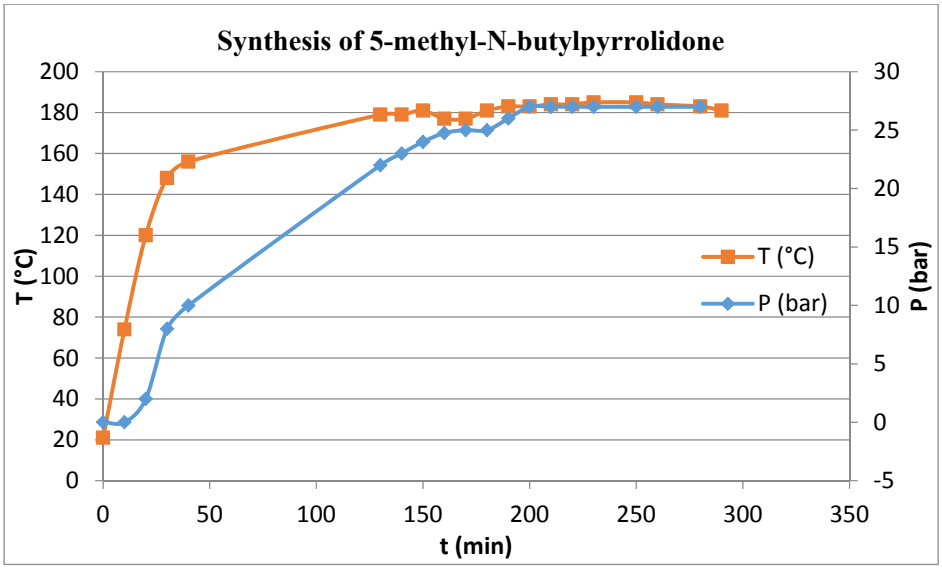
^{1}H NMR (300MHz, $CDCl_3$): δ(ppm) = 3.72-3.61 (m, 1H), 3.52 (ddd, *J* = 13.8; 9.0; 7.2 Hz, 1H); 2.88 (ddd, *J* = 13.8; 8.7; 5.1 Hz, 1H); 2.40-2.31 (m, 2H); 2.22-2.11 (m, 1H), 1.60-1.50 (m, 1H), 1.50-1.40 (m, 2H); 1.18 (d, *J* =6.3 Hz, 3H), 0.87 (t, *J* =7.4 Hz, 3H). ^{13}C NMR (75MHz, $CDCl_3$): δ(ppm) = 175.2, 53.6, 41.9, 30.6, 27.1, 21.0, 20.1, 11.7. Spectroscopic data in accordance with the literature.[1]

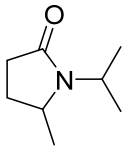


2b

5-methyl-*N*-butylpyrrolidone (5MeNBP) **2b** was synthesized following the procedure A1 and isolated as colorless liquid with 49% yield. **2b** was synthesized following the procedure B on 120 mmol scale. Volume of reactor 200 mL, temperature 200°C. Maximum pressure set 26 bar, measured 26 bar. Conversion > 99 %. Isolated by distillation as a colorless oil. Yield 82 %.

^{1}H NMR (300MHz, $CDCl_3$): δ (ppm) = 3.75-3.54 (m, 2H), 2.90 (ddd, *J* = 13.8, 8.7, 5.3 Hz, 1H); 2.50-2.12 (m, 3H); 1.62-1.25 (m, 5H); 1.21 (d, J = 6.3 Hz, 3H); 0.93 (t, J = 7.2 Hz, 3H). ^{13}C NMR (300MHz, $CDCl_3$): δ (ppm) = 174.9, 53.5, 40.0, 30.6, 29.8, 27.1, 20.4, 20.1, 14.1. Spectroscopic data in agreement with the literature.[2]

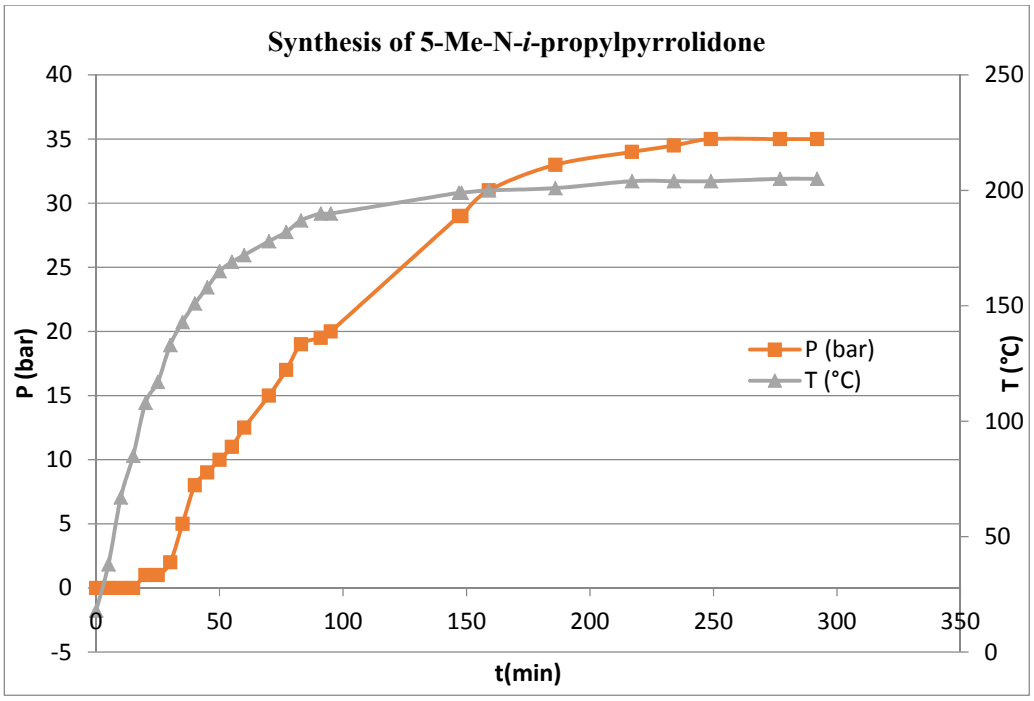


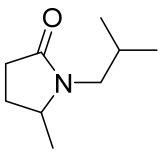


2c

5-methyl-*N*-isopropylpyrrolidone (5MeNiPP) **2c** was synthesized following the procedure A1 and isolated as colorless liquid with 38% yield. **2c** was synthesized following the procedure B on 150 mmol scale. Volume of reactor 200mL. Temperature 205°C. Maximum pressure set 35 bar, measured 35 bar after 4.9h min. Conversion >99 %. Isolated by distillation as a colorless oil. Yield 80 %.

^{1}H NMR (300MHz, $CDCl_3$): δ(ppm) = 4.15-4.00 (m, 1H), 3.77-3.67 (m, 1H), 2.55-2.30 (m, 2H), 2.27-2.07 (m, 2H), 1.57-1.45 (m, 1H), 1.20 (d, J = 6.2 Hz, 3H); 1.19 (d, J = 7.0 Hz, 3H); 1.17 (d, J = 6.7 Hz, 3H). ^{13}C NMR (75MHz, $CDCl_3$): δ(ppm) = 174.8, 52.9, 44.2, 30.7, 27.6, 22.6, 22.0; 19.8; GCMS calculated for $C_8H_{15}NO$, m/z =141; Found m/z = 141

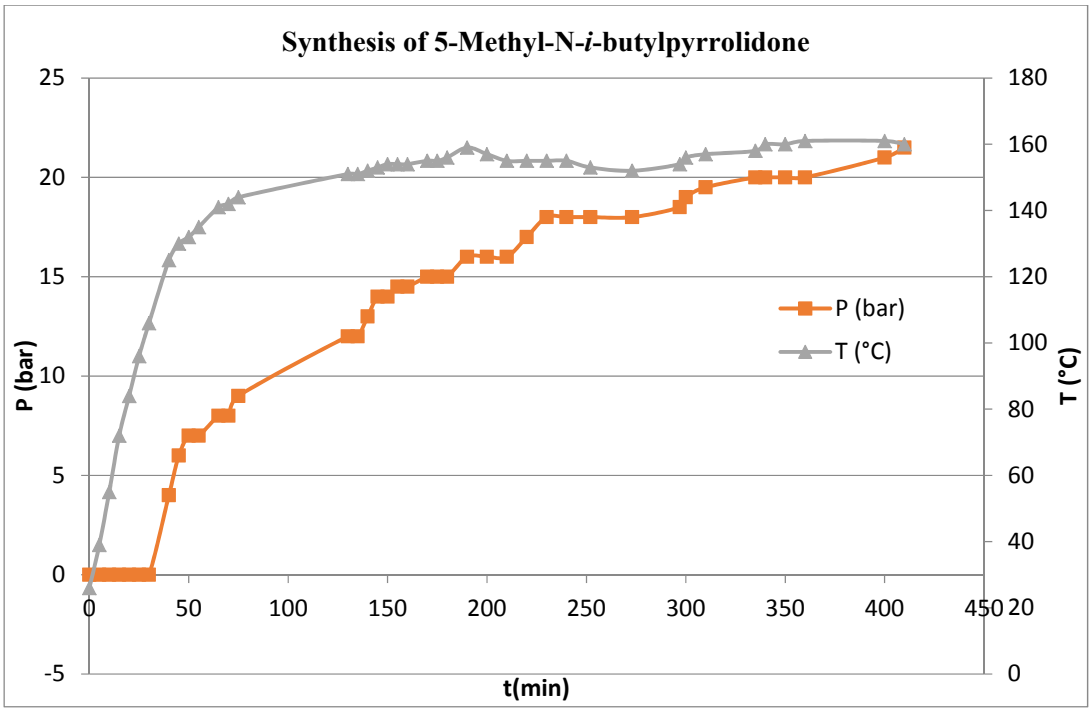


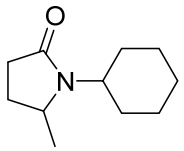


2d

5-methyl-*N*-isobutylpyrrolidone (5MeNiBP) **2d** was synthesized following the procedure A1 and isolated as colorless liquid with 87% yield. **2d** was synthesized following the procedure B on 110 mmol scale. Volume of reactor 200mL, temperature 160°C, maximum pressure set 22 bar, measured 22 bar after 6.8h. Conversion > 99 %. Isolated by distillation as a colorless oil. Yield 86%.

^{1}H NMR (300MHz, $CDCl_3$): δ(ppm) = 3,70-3.55 (m, 1H), 3.36 (dd, J = 13.7, 9.5 Hz, 1H); 2.69 (dd, J = 13.7, 5.7 Hz, 1H); 2.50-2.05 (m, 3H); 1.92-1.72 (m, 1H); 1.60-1.40 (m, 1H); 1.14 (d, J = 6.3 Hz, 3H); 0.87 (d, J = 6.7, 3H); 0.78 (d, J = 6.6 Hz, 3H). ^{13}C NMR (75MHz, $CDCl_3$): δ(ppm) = 175.0, 53.5, 47.2, 30.3, 26.8, 26.5, 20.4, 19.8, 19.6. GCMS calculated for $C_9H_{17}NO$, m/z =155; Found m/z = 155.

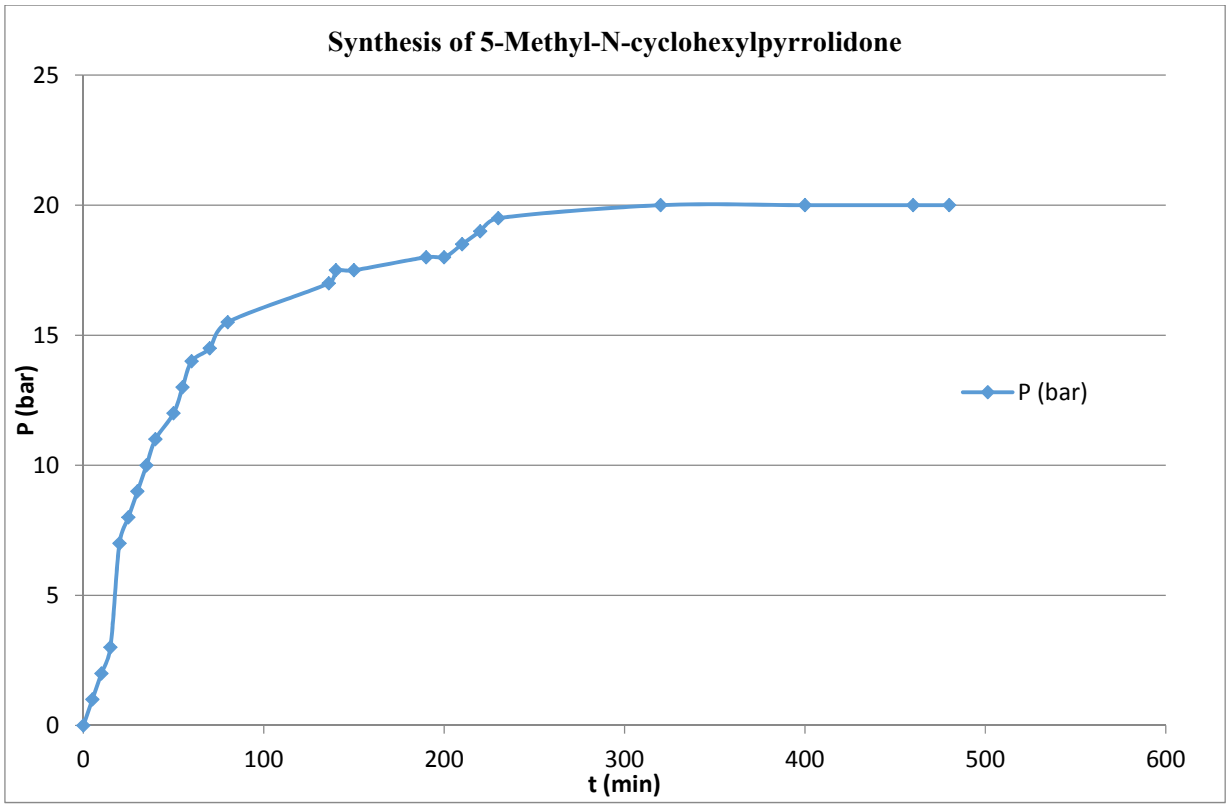


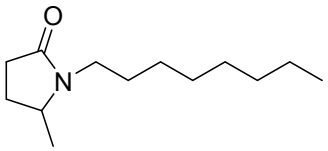


2f

5-methyl-*N*-cyclohexylpyrrolidone (5MeNcHP) **2f** was synthesized following the procedure B on 60 mmol scale. Volume of reactor 200mL, temperature 140°C. Maximum pressure set to 23 bar, measured 20 bar after 8h. Conversion 89 %. Isolated by distillation as a yellowish colorless oil. Yield 88 %.

^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) = 3.86-3.60 (m, 2H), 2.45-2.35 (m, 1H), 2.30-2.00 (m, 2H), 1.90-1.05 (m, 12H), 1.21 (d, J = 6.3 Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm) = 174.8, 53.2, 52.8, 32.3, 30.7, 30.5, 27.9, 26.2, 25.9, 22.8. Spectroscopic data in agreement with the literature data.[2]

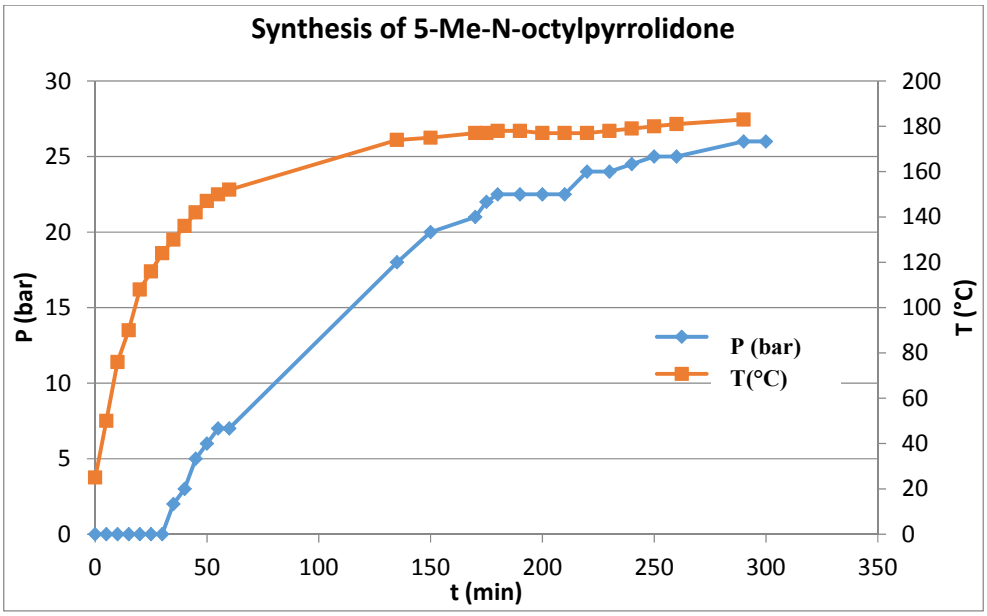


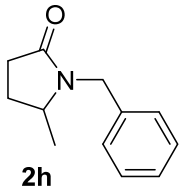


2g

5-methyl-*N*-*n*-octylpyrrolidone (MeNOP) **2g** was synthesized following the procedures A1 and A2 and isolated as an orange oil with 80% yield. **2g** was also synthesized following the procedure B on 120 mmol scale. Volume of reactor 200mL, temperature 180°C, maximum pressure set 28 bar, measured 24 bar. Conversion 86 %. Isolated by extraction as yellow oil. Yield 80%.

^{1}H NMR (300MHz, $CDCl_3$): δ (ppm) = 3.73-3.62 (m, 1H), 2.89 (ddd, *J* = 13.8, 6.7, 4.7 Hz, 1H); 2.45-2.31 (m, 3H); 2.20-2.13 (m, 1H); 1.60-1.35 (m, 2H); 1.35-1.20 (m, 12H); 1.19 (d, *J* = 6.3 Hz, 3H); 0.87 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR (300MHz, $CDCl_3$): δ (ppm) = 174.4, 53.2, 39.9, 31.8, 30.3, 29.3, 29.2, 27.2, 27.0, 26.9, 22.7, 19.8, 14.1. Spectroscopic data are in agreement with the literature data.[2]

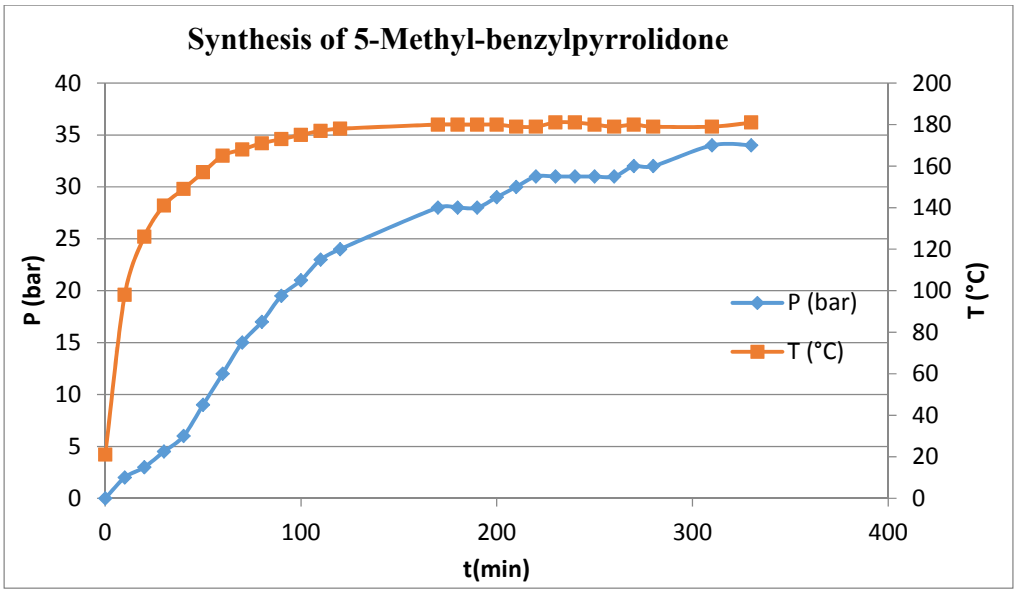




2h

5-methyl-*N*-benzyl-2-pyrrolidone (5MeNBzP) **2h** was synthesized according to the procedure A1 and isolated as colorless liquid with 49% yield. **2h** was synthesized also according to the procedure B on 150 mmol scale. Volume of the reactor 200mL, temperature 185°C. Maximum pressure set to 34 bar, measured 34 bar. Conversion > 99 %. Isolated by extraction as a colorless oil. Yield 49 %.

^{1}H NMR (400MHz, $CDCl_3$): δ(ppm) = 7.43-7.14 (m, 5H), 4.94 (d, *J*=15.0 Hz, 1H), 3.98 (d, *J* = 15.0 Hz, 1H), 3.57-3.41 (m, 1H), 2.60-2.29 (m, 2H), 2.24-2.02 (m, 1H), 1.68-1.47 (m, 1H), 1.15 (d, *J* = 6.3 Hz, 3H). ^{13}C NMR (100 MHz, CDCl3) δ (ppm): 175.0, 136.8, 128.6, 128.0, 127.4, 52.9, 44.0, 30.3, 26.7, 19.6. Spectroscopic data are in agreement with the literature.[1,2]



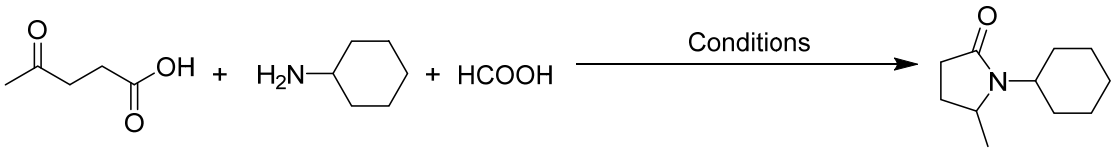
7. Determinations of E-factors[4]

"E-factor = Kg **waste** / Kg product"

Will be calculated as E-factor = mass wastes / mass product, normalized to 1 mmol of product formed from 1mmol LA substrate, regardless of the experimental yield. The only compound not considered as a waste is water.[4]

E-factors of 5-methyl-N-cyclohexylpyrrolidone have been estimated for different procedures reported in the literature[13] and compared with our approach. E-factors were calculated approximatively but using the same approach in order to have an element of comparison.

Calculation of E-factor for the synthesis of 5-methyl-N-cyclohexylpyrrolidone using the following procedures:



1. **Huang *et al*. conditions (***ChemSusChem*, 2011, **4**, 1578)[1]

Conditions: LA (1 mmol), FA (1 mmol), cyclohexylamine (1 mmol), [Ru(*p*-cymene)Cl_2]$_2$ (0.5 mol%), *t*-Bu_3PHBF_4(1.5 mol%), 80°C, 12 h.

Purification: dilution in aqueous Na_2CO_3 (5mL), extraction with ether (10mL), purification by column chromatography (SiO_2 : 5g, ether/hexane : 10mL)

Density of solvents is estimated at d = 0.7

Wastes: 15 mL solvents + 5g SiO_2 + [Ru(*p*-cymene)Cl_2]$_2$ (0.5 mol%), t-Bu_3PHBF4(1.5 mol%)+ 1mmol CO_2

Mass of wastes: 0.7*15 + 5 + 612*0.0005 + 290*0.0015 + 0.044 = 10.5+5+0.3+0.4 +0.044= 16.24g

Mass of product: 0.18 g (MW = 181.28 g/mol)

E-factor = 16.24/0.18 **E-factor = 90**

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2. **Wei *et al*. conditions (***Green Chemistry*, 2014, **16**, 1093)[2]

Conditions: LA (1 mmol), cyclohexylamine (2 mmol), HCOOH (5 mmol), Et_3N (1 mmol), DMSO (3 mL), 100 °C.

Purification: Extraction with DCM 5*3mL, flash chromatography (SiO_2 5g) with petroleum ether/ethylacetate (10 mL). Density of solvents is estimated at d = 0.7

Wastes: 1 mmol cyclohexylamine + 4 mmol HCOOH + 1 mmol CO_2 + 1 mmol Et_3N +3mL DMSO (d = 1.1) + 15mL DCM (d = 1.33)+ 5g SiO_2 + 10mL solvents

Mass of wastes: 0.18 + 0.046*4 + 0.044 + 0.101+ 3*1.1 + 15*1.33 + 5 + 10*0.7

= 0.18 + 0.184 + 0.044 + 0.101 + 3.3 + 20 + 5 + 7

Mass of wastes: 35.81g

Mass of product: 0.18 g (MW = 181.28 g/mol)

E-factor = 35.81/0.18 **E-factor = 199**

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3. **Touchy *et al.* conditions** (*ACS Catal.* 2014, **4**, 3045)[3]

Conditions: LA (1 mmol), cyclohexylamine (1 mmol), H_2 (3 bar, 3.4 equiv.), 0.001 mmol Pt catalyst.

Purification: Filtration and flash chromatography (SiO_2 5g) with hexane/ethylacetate (10 mL). Density of solvents estimated at d = 0.7

Catalyst: Pt-MoO_X/TiO_2 is previously prepared from a Mo-precursor and a Pt-precursor in water and HNO_3 aqueous solution. Moreover Pt-MoO_X/TiO_2 catalyst is recyclable 4 times without significant modification of its activity.

Calculation of the total amount of reagents to prepare the catalyst and convert 1 mmol of LA substrate:

Pt-MoO_X/TiO_2 catalyst (5 w% Pt, 7 w% Mo) has been prepared from 5g TiO_2, 0.88 mmol of $(NH_4)_6Mo_7O_{24}.4H_2O$, 0.88 mmol of citric acid ($C_6H_8O_7$) and HNO_3 solution of $Pt(NH_3)_2(NO_3)_2$ (unspecified amount).

To simplify the calculations we will consider that the preparation of Pt-MoO_X/TiO_2 is quantitative. That is to say: for 1 equivalent of Pt-MoO_X/TiO_2 material, only 1 equivalent of **Pt**$(NH_3)_2(NO_3)_2$ Pt-precursor has been used with 1/7 equivalent of $(NH_4)_6$**Mo$_7$**$O_{24}.4H_2O$ Mo-precursor. HNO_3 aqueous solution will not be considered (lack of information)

Mass of the catalyst required for 1 mmol substrate:

0.001 mmol Pt (MW = 195g/mol, 0.2 mg, 5 *w*%, 1/20 total weight) ⇔ **0.0014 mmol Mo** (MW = 96g/mol, 0.13 mg, 7 *w*%, 1/14 total weight) ⇔ **3.2 mg TiO_2** (0.2*16, around 8/10 total weight)

Mass of the catalyst for 1 mmol substrate (0.001 mmol Pt) = 3.53 mg

Total mass of metals and TiO_2 required considering their preparation as catalysts (for 0.001 mmol Pt):

0.001 mmol Pt ⇔ 0.001 mmol $Pt(NH_3)_2(NO_3)_2$ (MW= 353g/mol) ⇔ **0.35 mg**

0.0014 mmol Mo ⇔ 0.0014/7 mmol $(NH_4)_6Mo_7O_{24}.4H_2O$ ⇔ 0.0002 mmol $(NH_4)_6Mo_7O_{24}.4H_2O$ (MW= 1236 g/mol) ⇔ **0.25 mg**

TiO_2⇔ 3.2 mg

Total mass of metals and TiO_2 required to convert 1 mmol of substrate (0.001 mmol Pt) : 4.13 mg

Knowing that the catalyst is recyclable 4 times by simple filtration we will consider that only ¼ of the previously calculated amount is necessary: 4.13/4 = **1.03 mg**

Total mass of metals and TiO_2 required to prepare the **catalyst** and to convert **1 mmol of substrate** (0.001 mmol Pt) considering the recyclability of Pt-MoO_X/TiO_2**: 1.03 mg**

Wastes: 2.4 mmol H_2 (MW=2g/mol) + 1.03 mg catalyst + 5g SiO_2 + 10mL solvents
Mass of wastes: 0.0024*2 + 0.00103 + 5 + 10*0.7
= 0.0048 + 0.00103 + 5 + 7
= 12.006 g

Mass of product: 0.1813 g (MW = 181.28 g/mol)
E-factor = 12.006/0.1813

E-factor = 66

---

4. This work

Conditions: LA (1 mmol), cyclohexylamine (1 mmol), HCOOH (1 mmol), 140°C in autoclave.
Purification: Simple distillation under reduced pressure

Wastes: 1 mmol CO_2 (MW=44g/mol)
Mass of wastes: 0.044g

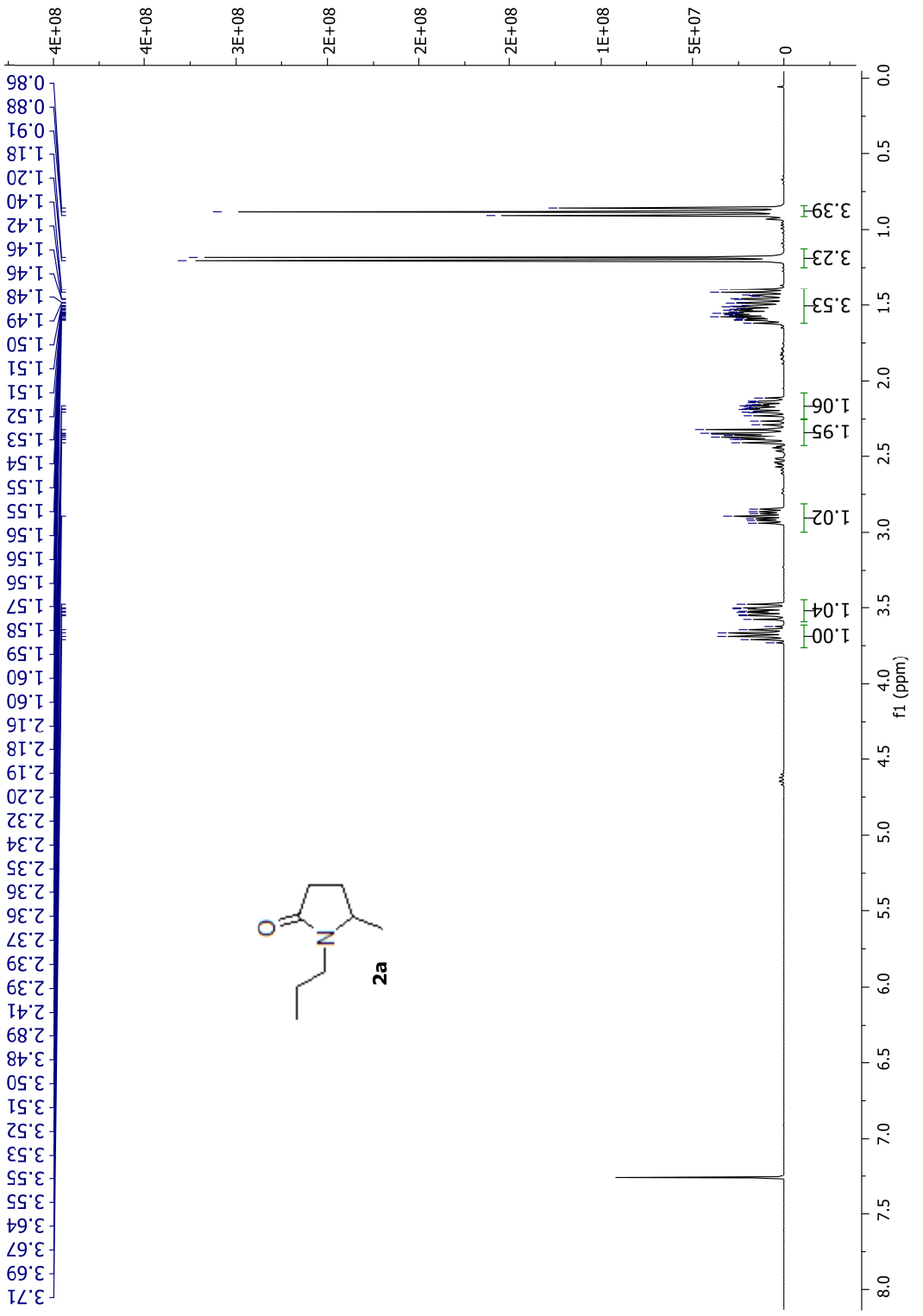
Mass of product: 0.181 g (MW = 181.28 g/mol)
E-factor = 0.044/0.181

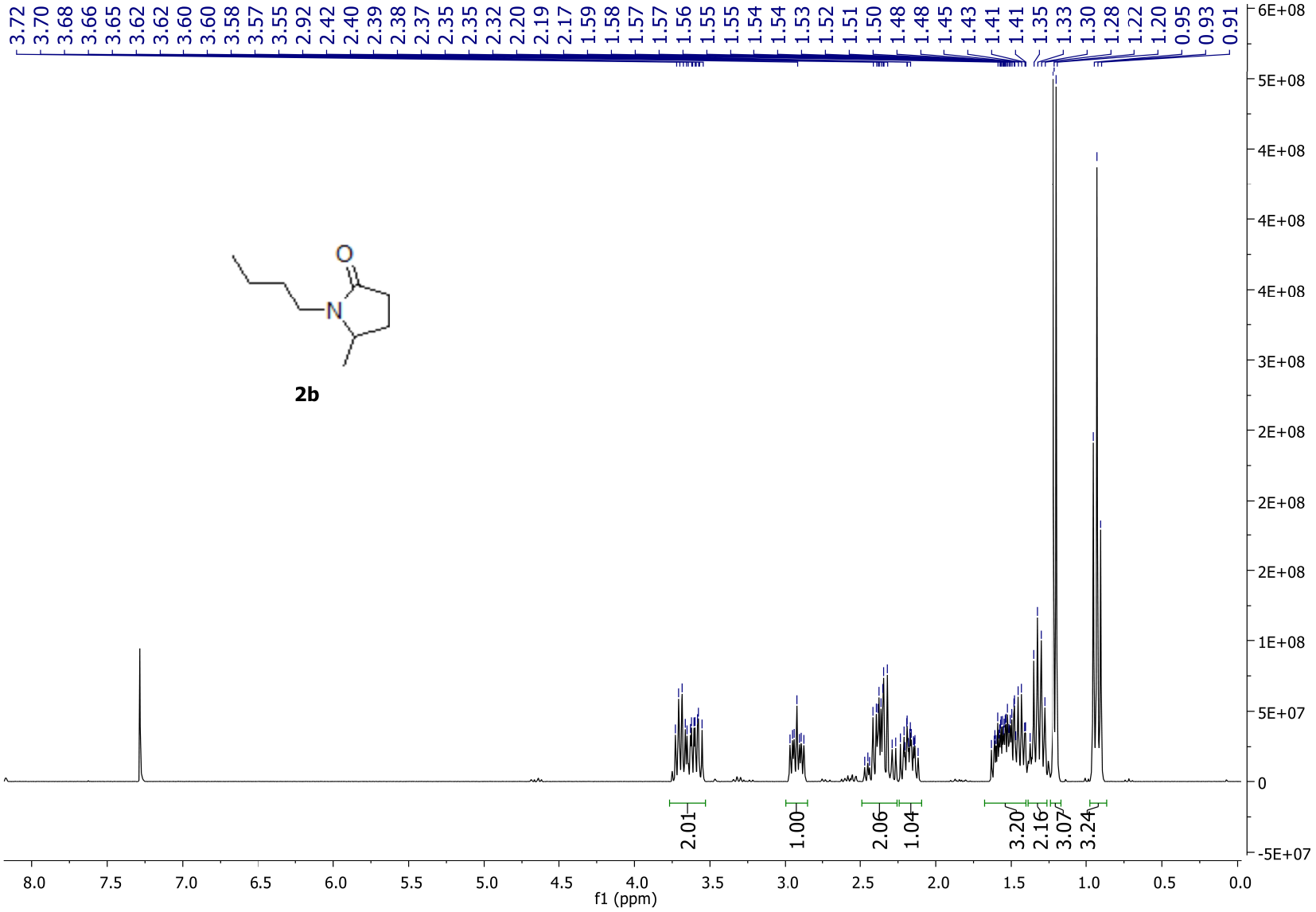
E-factor = 0.2

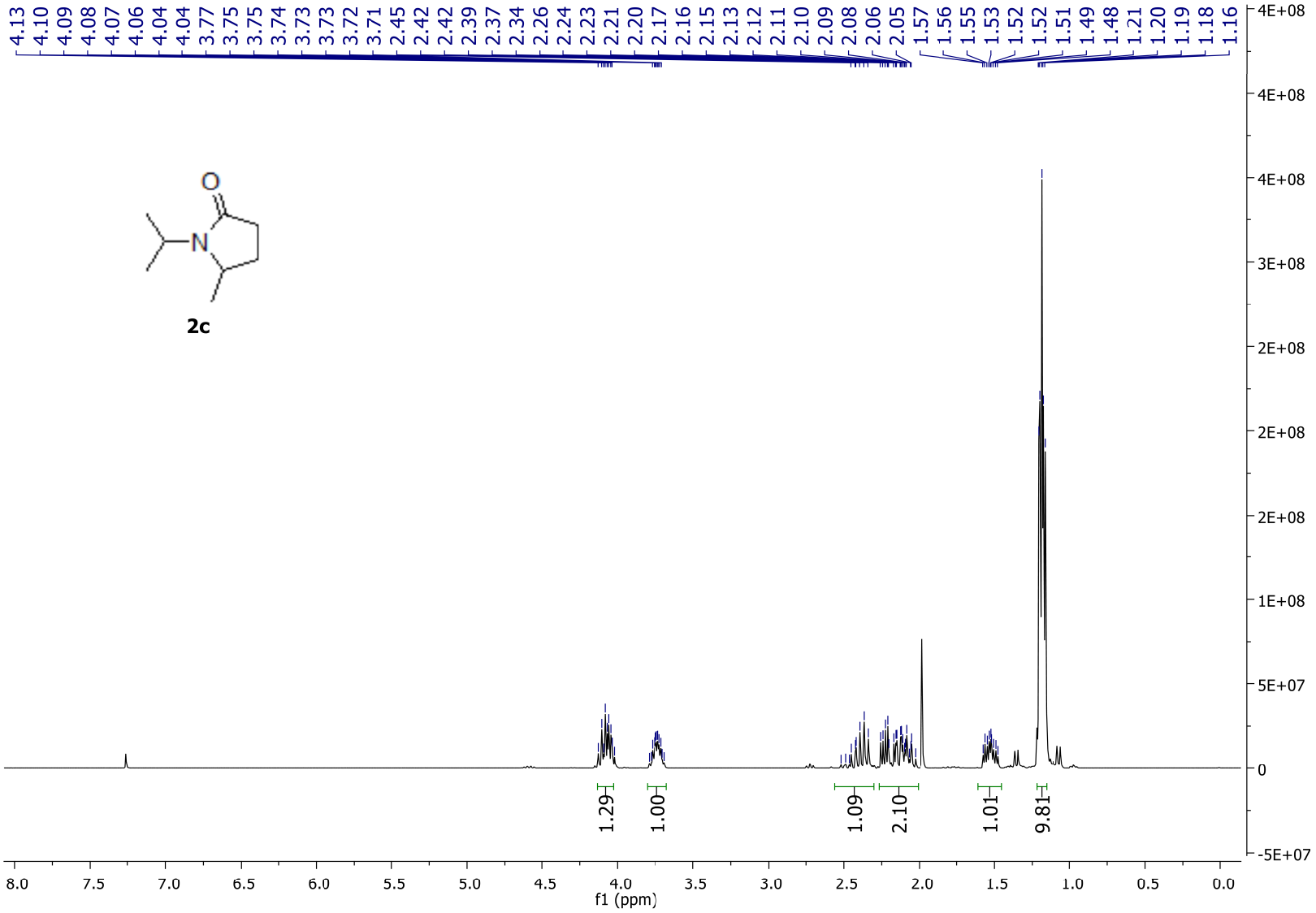
Comparison of E-factors for the synthesis of 5-Methyl-N-cyclohexylpyrrolidone:

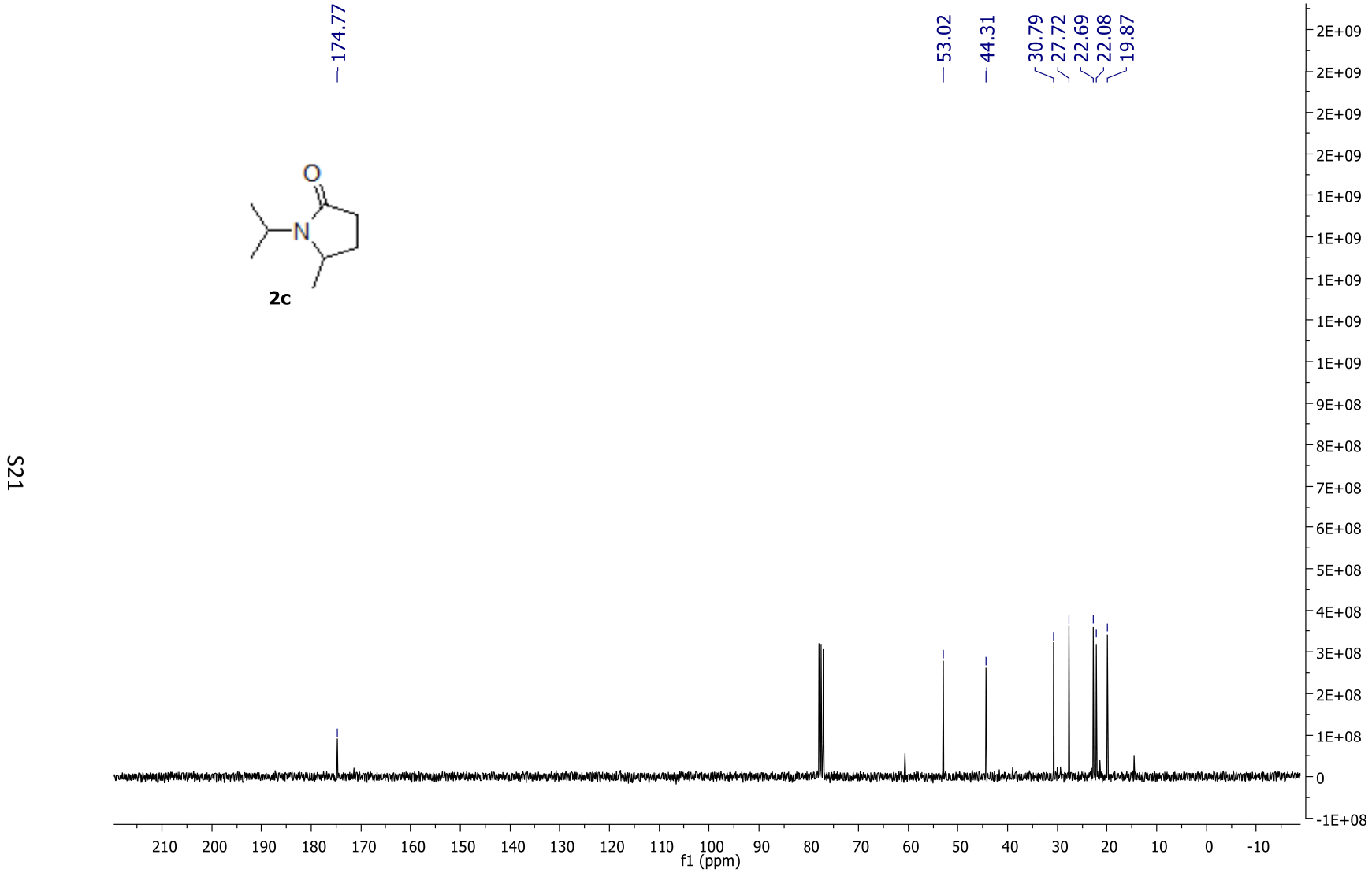
Reference	Promoter	E-factor
1	Homogeneous Ruthenium catalyst	**90**
2	Activating agents	**199**
3	Heterogeneous Platinium/Molybdenium catalysts	**66**
This work	**none**	**0.2**

8. NMR spectra




3.72 3.70 3.68 3.66 3.65 3.62 3.62 3.60 3.60 3.58 3.57 3.55 2.92 2.42 2.40 2.39 2.38 2.37 2.35 2.35 2.32 2.20 2.19 2.17 1.59 1.58 1.57 1.57 1.56 1.55 1.55 1.54 1.54 1.53 1.52 1.51 1.50 1.48 1.48 1.45 1.43 1.41 1.41 1.35 1.33 1.30 1.28 1.22 1.20 0.95 0.93 0.91
O
N
2b
6E+08
5E+08
4E+08
4E+08
4E+08
3E+08
2E+08
2E+08
2E+08
1E+08
5E+07
0
-5E+07
2.01
1.00
2.06
1.04
3.20
2.16
3.07
3.24
8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
f1 (ppm)


4.13 4.10 4.09 4.08 4.07 4.06 4.04 4.04 3.77 3.75 3.75 3.74 3.73 3.73 3.72 3.71 2.45 2.42 2.42 2.39 2.37 2.34 2.26 2.24 2.23 2.21 2.20 2.17 2.16 2.15 2.13 2.12 2.11 2.10 2.09 2.08 2.06 2.05 1.57 1.56 1.55 1.53 1.52 1.52 1.51 1.49 1.48 1.21 1.20 1.19 1.18 1.16
O
N
2c
4E+08
4E+08
4E+08
3E+08
2E+08
2E+08
2E+08
1E+08
5E+07
0
-5E+07
1.29
1.00
1.09
2.10
1.01
9.81
8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
f1 (ppm)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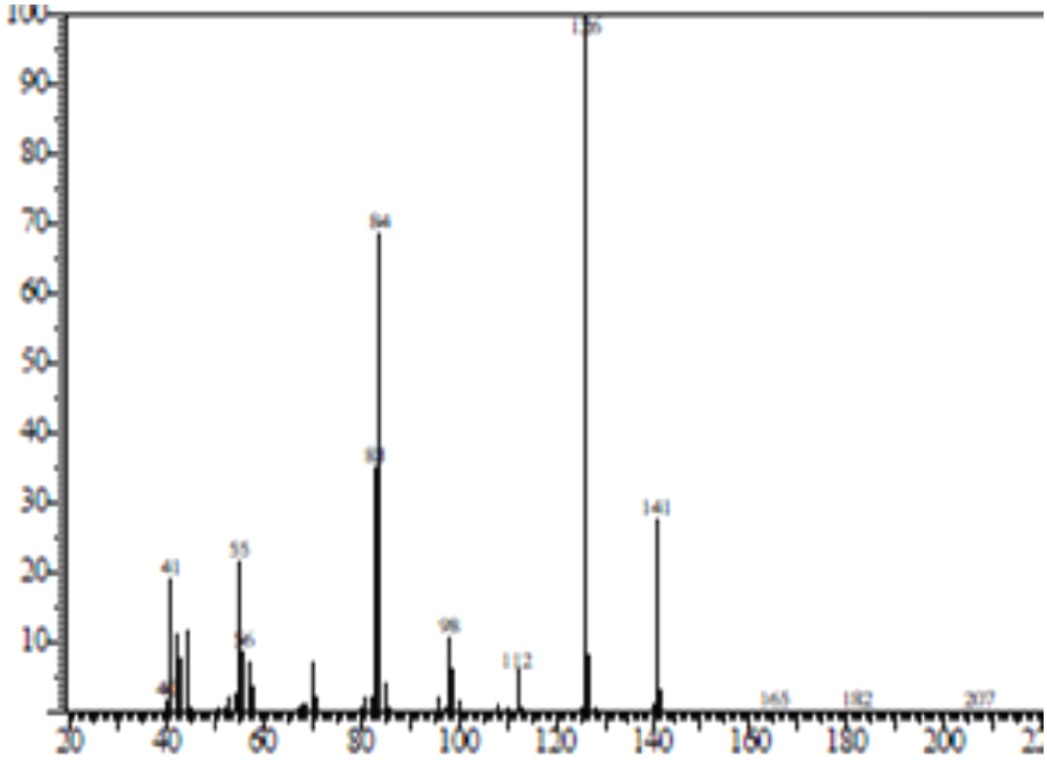
53.02
44.31
30.79
27.72
22.69
22.08
19.87
O
N
2c
f1 (ppm)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90
80
70
60
50
40
30
20
10
41
55
84
98
112
126
141
165
182
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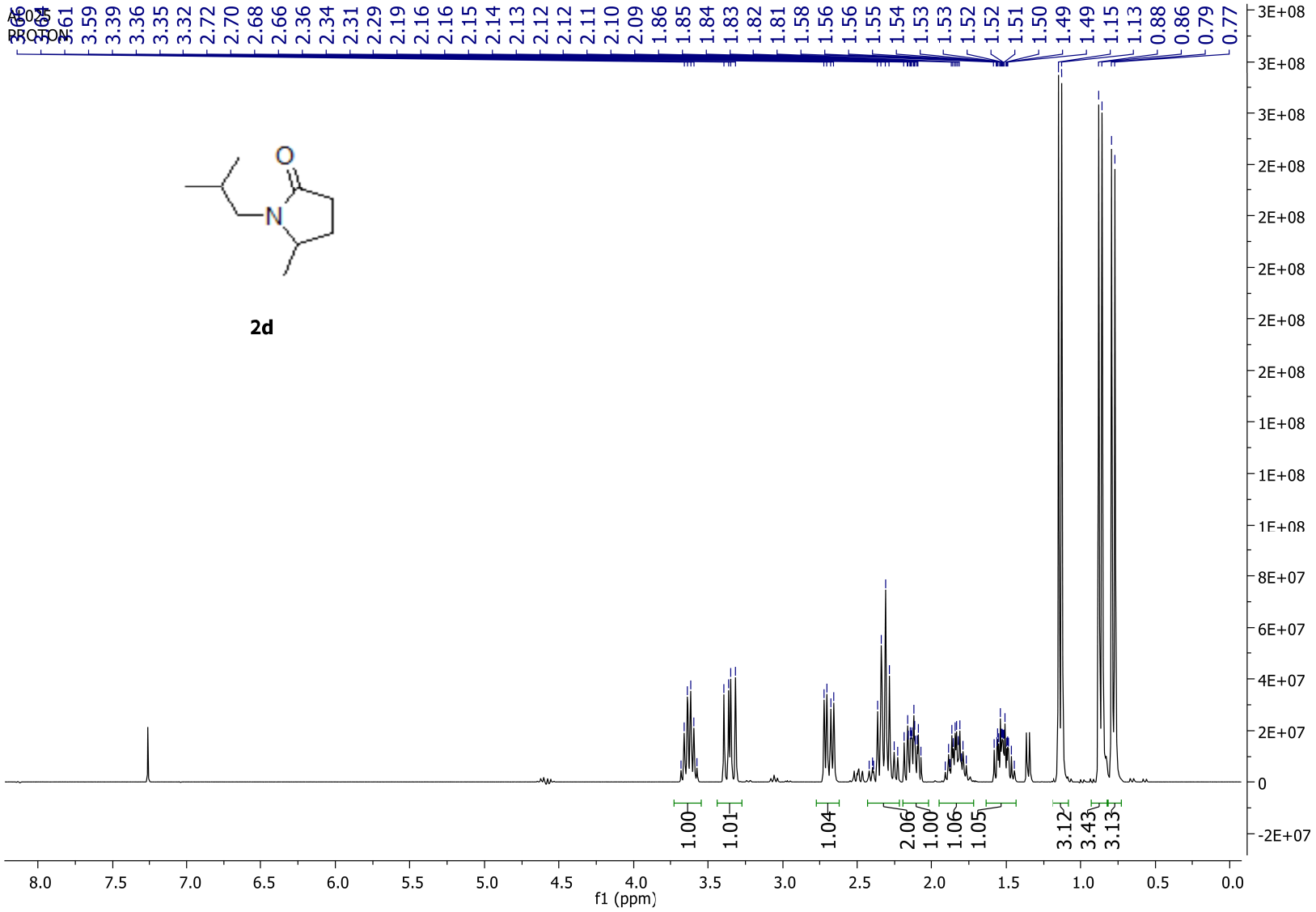
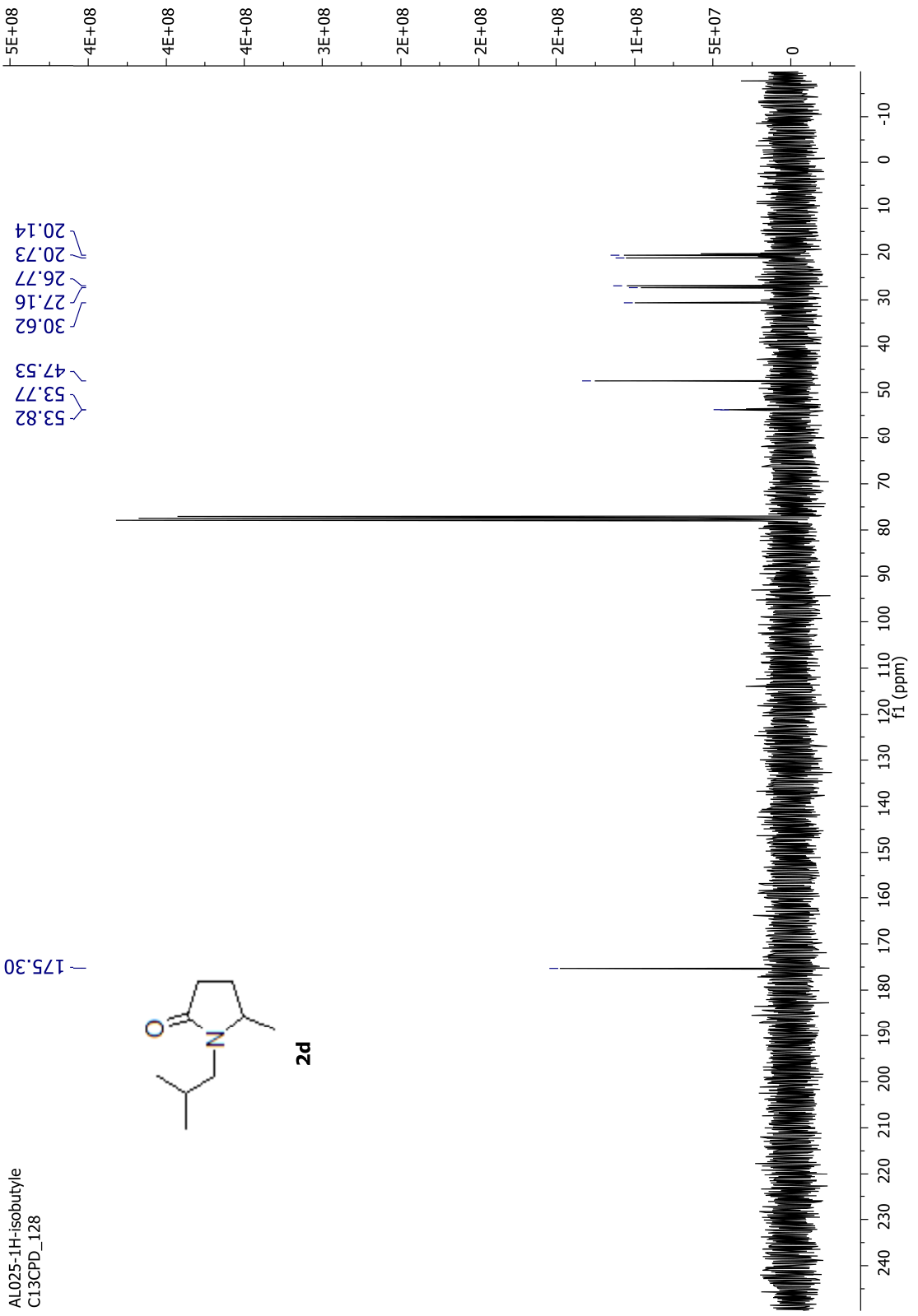
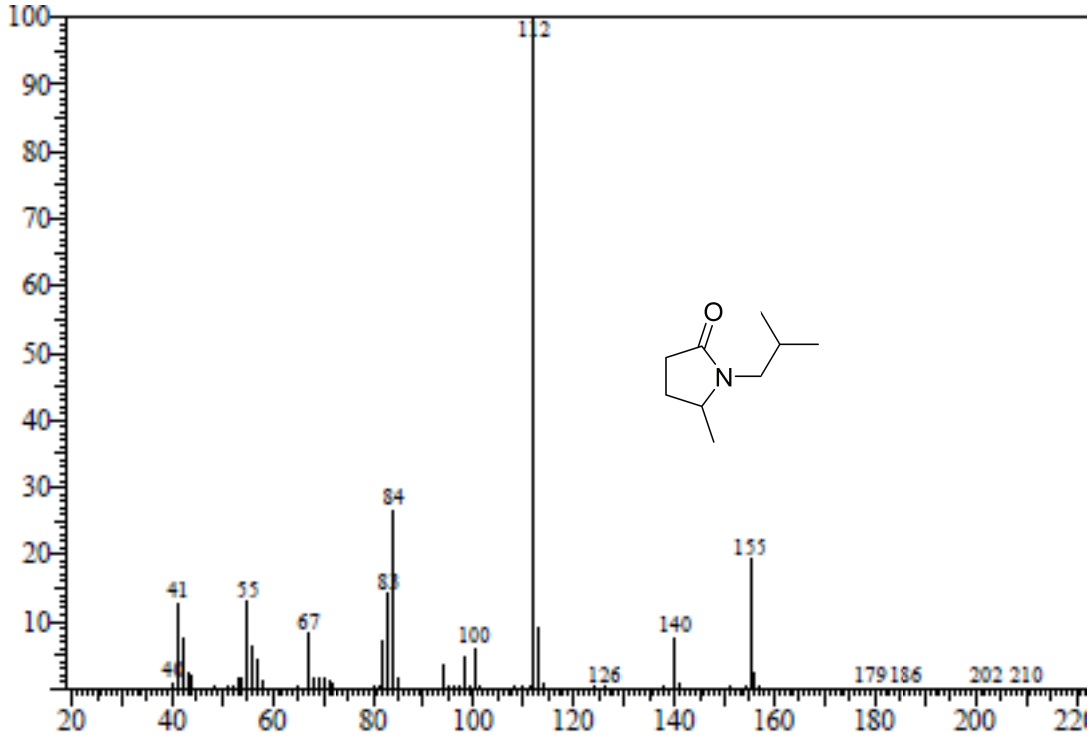
20
40
60
80
100
120
140
160
180
200


AS-024
PROTON
3.61 3.59 3.39 3.36 3.35 3.32 2.72 2.70 2.68 2.66 2.36 2.34 2.31 2.29 2.19 2.16 2.16 2.15 2.14 2.13 2.12 2.12 2.11 2.10 2.09 1.86 1.85 1.84 1.83 1.82 1.81 1.58 1.56 1.56 1.55 1.54 1.53 1.53 1.52 1.52 1.51 1.50 1.49 1.49 1.15 1.13 0.88 0.86 0.79 0.77
O
N
2d
1.00 1.01 1.04 2.06 1.00 1.06 1.05 3.12 3.43 3.13
f1 (ppm)


AL025-1H-isobutyle
C13CPD_128
175.30
53.82
53.77
47.53
30.62
27.16
26.77
20.73
20.14
2d
f1 (ppm)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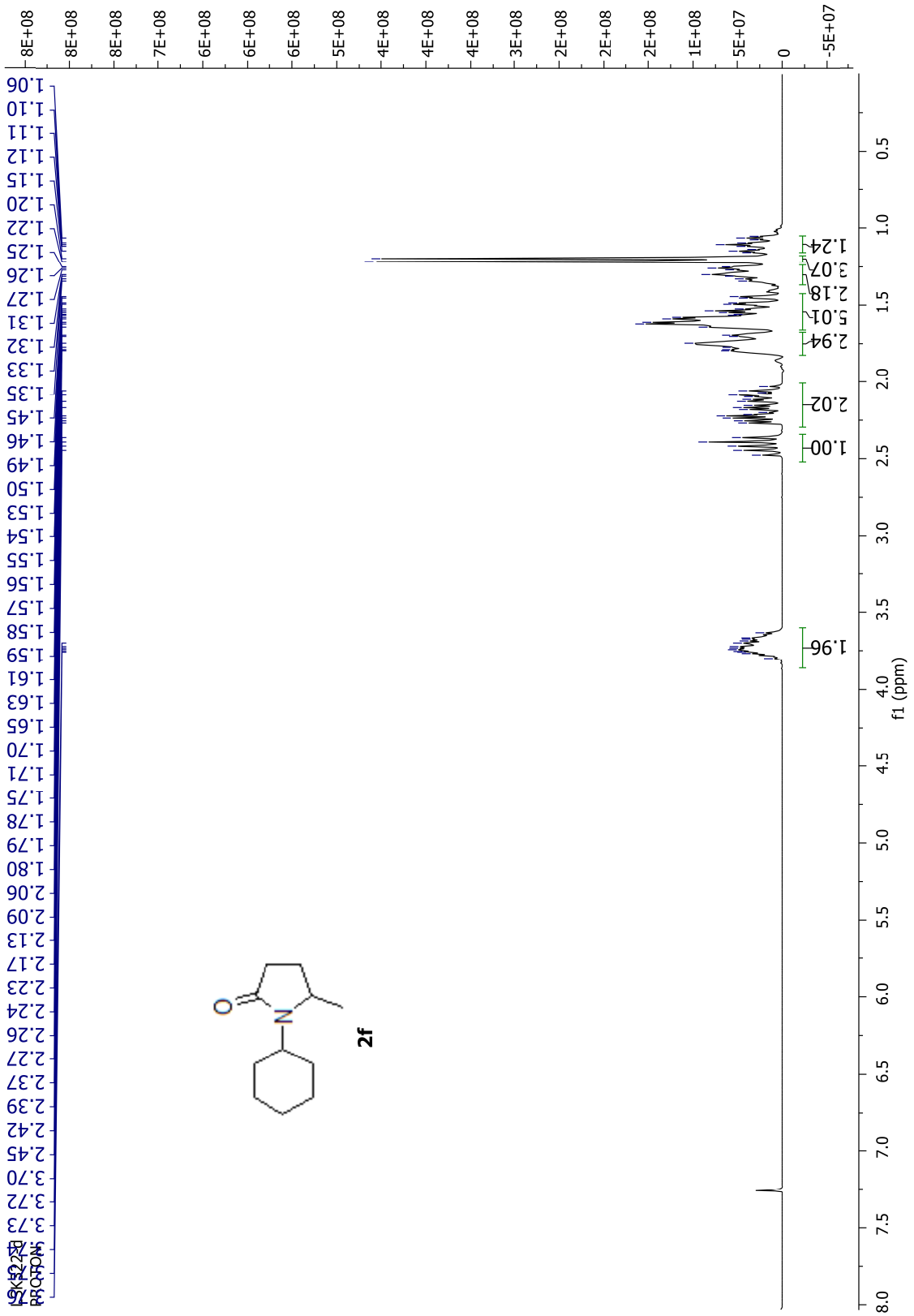
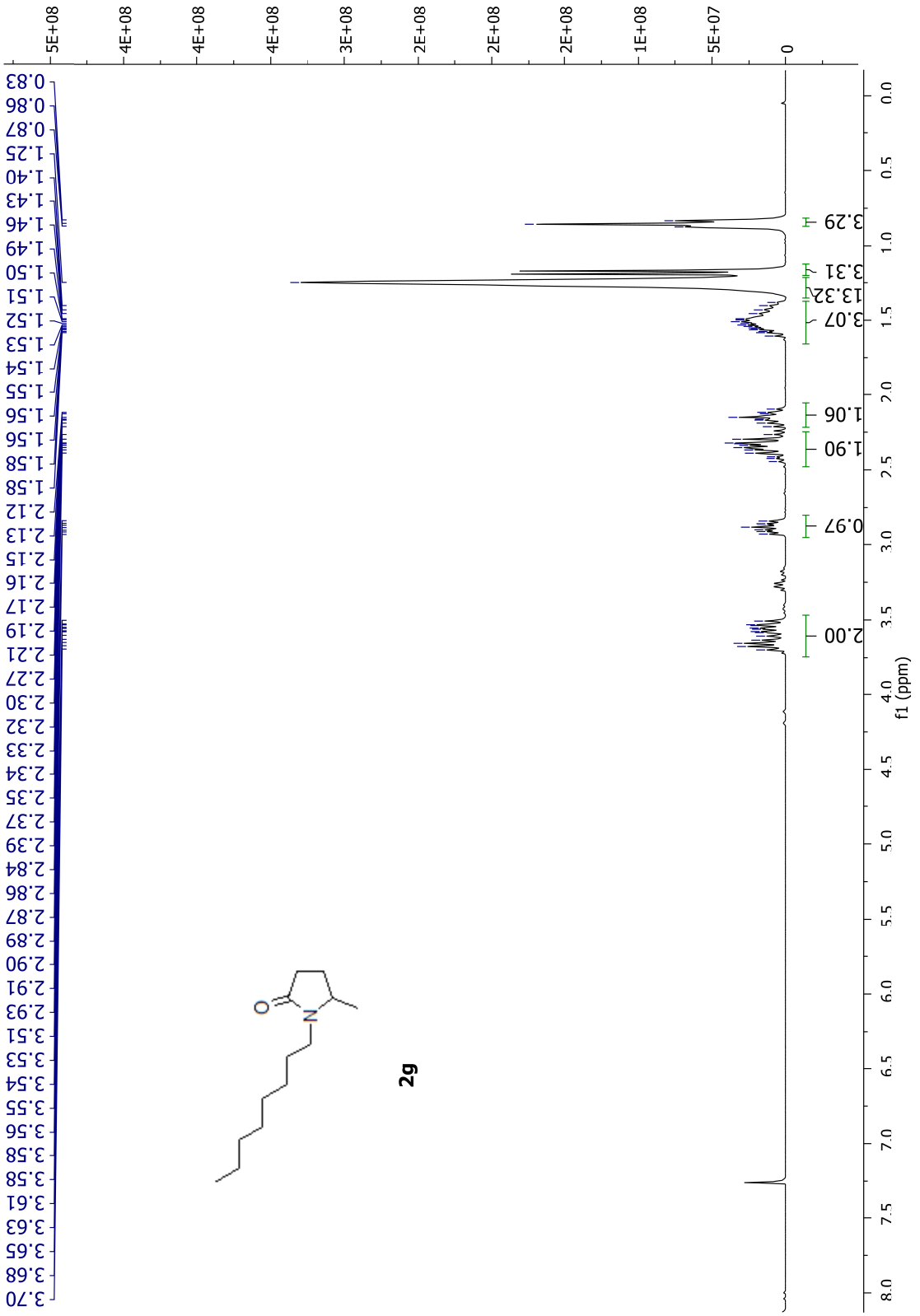
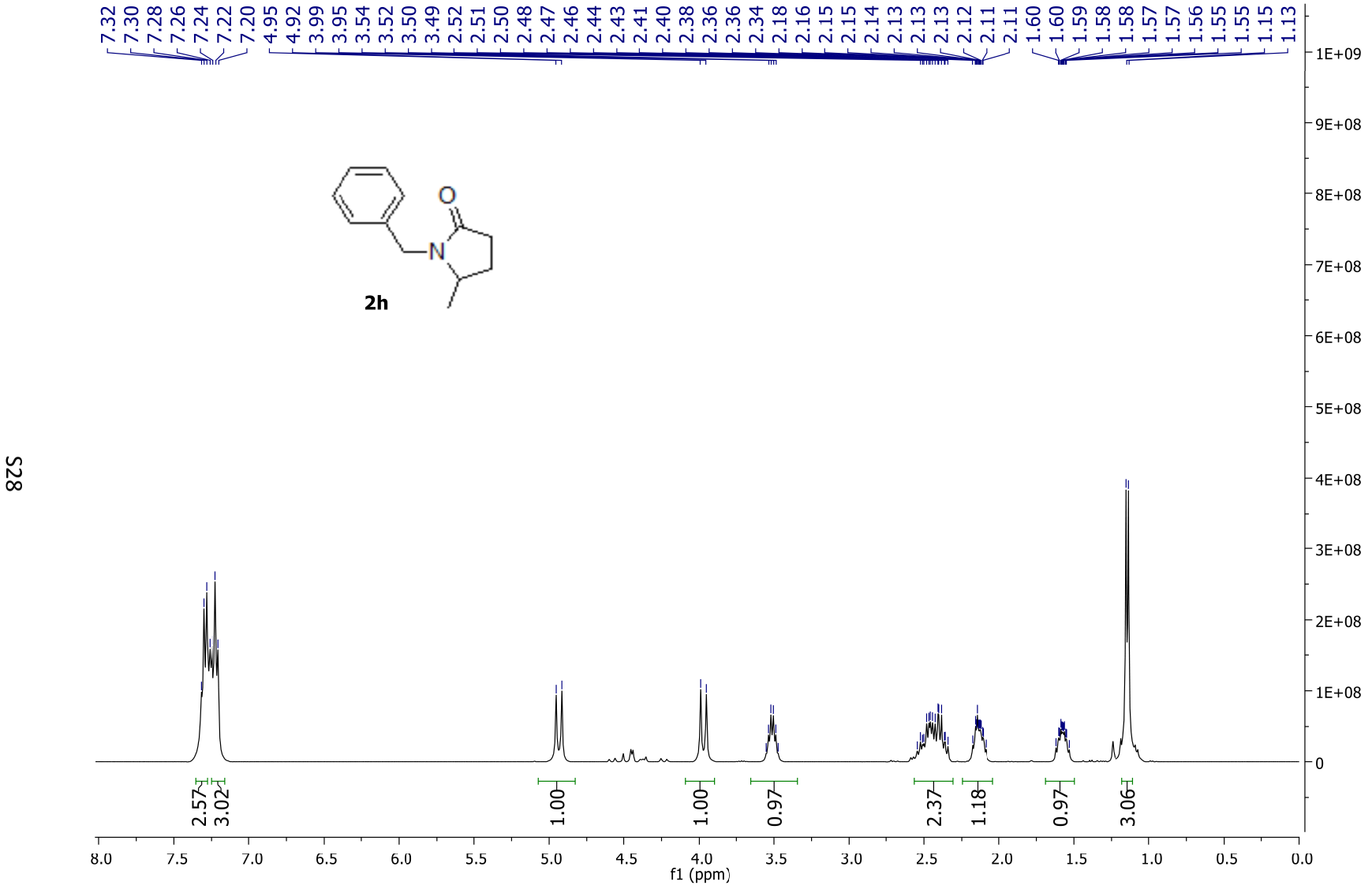
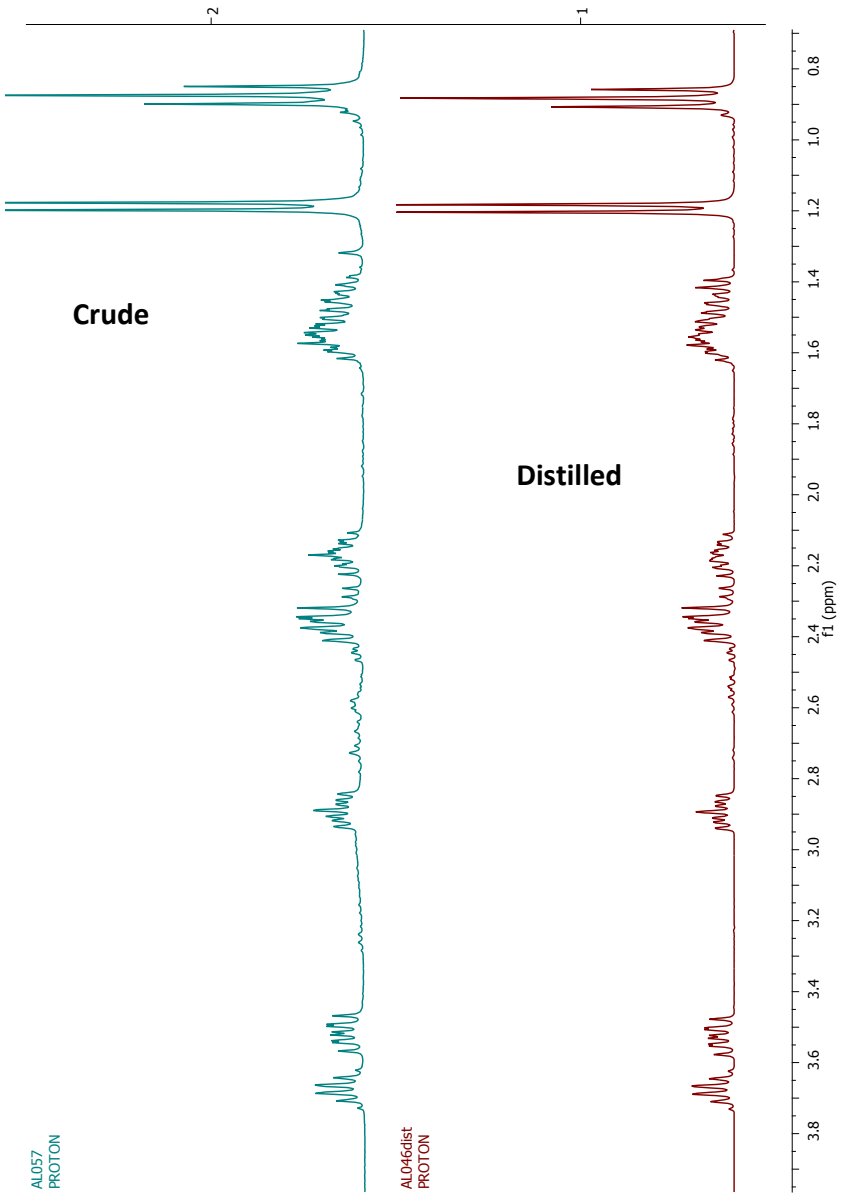
90
80
70
60
50
40
30
20
10
112
84
155
41
55
83
67
100
140
126
179 186
202 210
20
40
60
80
100
120
140
160
180
200
O
N


2f
1.96
1.00
2.02
2.94
5.01
2.18
3.07
1.24
f1 (ppm)


2g
f1 (ppm)
2.00
0.97
1.90
1.06
3.07
13.32
3.31
3.29


7.32 7.30 7.28 7.26 7.24 7.22 7.20 4.95 4.92 3.99 3.95 3.54 3.52 3.50 3.49 2.52 2.51 2.50 2.48 2.47 2.46 2.44 2.43 2.41 2.40 2.38 2.36 2.36 2.34 2.18 2.16 2.15 2.15 2.14 2.13 2.13 2.13 2.12 2.11 2.11 1.60 1.60 1.59 1.58 1.58 1.57 1.57 1.56 1.55 1.55 1.15 1.13
O
N
2h
1E+09
9E+08
8E+08
7E+08
6E+08
5E+08
4E+08
3E+08
2E+08
1E+08
0
2.57
3.02
1.00
1.00
0.97
2.37
1.18
0.97
3.06
8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
f1 (ppm)


Crude
Distilled
AL057
PROTON
AL046dist
PROTON
f1 (ppm)

References

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[2] Y. Wei, C. Wang, X. Jiang, D. Xue, Z.-T. Liu and J. Xiao, *Green Chemistry*, 2014, **16**, 1093.
[3] A. S. Touchy, S. M. A. Hakim Siddiki, K. Kon, K. Shimizu, *ACS Catal*. 2014, 4, 3045-3050.
[4] R. A. Sheldon, *Chemical Communications*, 2008, 3352.