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## Synthesis of novel branched polymers for enhanced oil recovery

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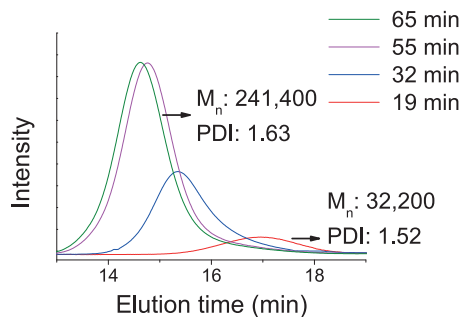
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# 3

## Industrially Relevant Reversible Addition Fragmentation chain Transfer Polymerisation of Acrylamide in Water

Adapted from: van Mastrigt, F., van Oosterhout, H.N., Roelfes, J.G. & Picchioni, F. (2017). *Industrially Relevant Reversible Addition Fragmentation chain Transfer Polymerisation of Acrylamide in Water*. Submitted to ACS Omega.

## Abstract



Chain extension of PDMA with AM

An industrially relevant Reversible Addition Fragmentation chain Transfer (RAFT) polymerisation was employed for the polymerisation of acrylamide (AM) and *N,N*-dimethylacrylamide (DMA) in aqueous media. Polymerisation was mediated by chain transfer agent (CTA) 3-(((benzylthio)carbonothioyl)thio)propanoic acid (BCPA) and initiated by 4,4'-Azobis(4-cyanovaleric acid) (ACVA, 70 – 80 °C) or 2,2'-Azobis(2-methylpropionamidine) dihydrochloride (AAPH, 60 °C). Experimental molecular weights up to 620,000 Da (polydispersity index (PDI) < 1.7) were obtained, in good agreement with theoretical values, with monomer conversion approaching 100%. Control over the reaction was confirmed by linear first order kinetic plots. Livingness of the reaction was displayed by a chain extension experiment of an AM macro CTA (molecular weight: 2,420, PDI: 1.51), which was polymerised with DMA to yield a block copolymer with a molecular weight of 241,400 Da (PDI: 1.63).

## 3.1 Introduction

Polyacrylamide (PAM) finds many applications, ranging from the oil industry (e.g. enhanced oil recovery, drilling, fracturing, and cementing), to flocculation, drug release, gene therapy, and bioseparation.<sup>1–4</sup> With respect to tailoring of the properties to the desired application, control over the polymerisation is necessary. In that respect, investigating the structure-property relationship has proven very useful, as rheological properties are related to the structure of the polymer.

In previous research, atom transfer radical polymerisation (ATRP) was employed in the aqueous polymerisation of linear polyacrylamides and block copolymers with *N*-isopropylacrylamide (NIPAM) at 25 °C with molecular weights ranging up to 108,800 Da.<sup>5,6</sup> Next, linear acrylamide (AM) polymers synthesised with ATRP were compared with star (4-arm) and comb (12-arm) equivalents with

number average molecular weights (gel permeation chromatography; GPC) up to 210,200, 216,500, and 271,600 Da respectively.<sup>7</sup> At comparable  $M_{n,SPAN}$ , comb polymers were found to display more pronounced elastic behaviour, compared to linear and star polymers. Enhanced elasticity was especially obtained at frequencies up to  $10 \text{ rad s}^{-1}$ . The effect of a hydrophobic block was studied by synthesising random and diblock branched copolymers with 4, 8, or 13 arms with ATRP.<sup>8</sup> Diblock polymers consisting of AM and NIPAM were polymerised up to number average molecular weights of 736,000 Da, with NIPAM blocks ranging from 1,700 up to 501,000 Da. Random copolymers were synthesised with molecular weights up to 3,519,000 Da, containing approximately 50 mol% NIPAM. Block copolymers were found to precipitate out of solution at temperatures above the lower critical solution temperature (LCST) ( $32 \text{ }^\circ\text{C}$ ). Contrarily, random copolymers were found to stay in solution and display thermothickening behaviour at low shear rates. The effect of the number of arms on the solution rheology of polymer samples has been clearly displayed.<sup>9,10</sup> Intrinsic viscosities of a linear, 4 and 8 arm PAM were found to be comparable, however, 13 and 17 arm PAM equivalents displayed a significantly higher viscosity.

In ATRP, however, a transition metal complex is employed as catalyst in the polymerisation. During the polymerisation, the catalyst loses its activity because of the presence of oxygen.<sup>11</sup> More sophisticated approaches as initiators for continuous activator regeneration (ICAR) or activator regenerated by electron transfer (ARGET) ATRP, can reduce the amount of catalyst required. However, a trade-off between reaction rate and control over the polymerisation is necessary.<sup>12,13</sup> A major challenge regarding its industrial applicability is the regeneration and recycling of the catalyst. Because of the high expenses related to the recycling, ATRP suffers from difficulties in its applicability on an industrial scale. An industrially relevant process, employing an affordable and effective catalyst and regeneration procedure, still needs to be developed,<sup>14</sup> and requires additional research on scaling up and application engineering.<sup>15</sup> From an industrial point of view, it is desirable to employ a different polymerisation technique for the preparation of polymers for application as thickeners in aqueous solutions. Reversible addition fragmentation chain transfer (RAFT) polymerisation is a promising alternative.

RAFT polymerisation, a controlled radical polymerisation (CRP) technique, is based on an equilibrium between active and dormant chains. It has been receiving a lot of attention, due to its versatile character and suitability to be used with a lot of different monomers.<sup>16–18</sup> Several results with different monomers are described in literature, ranging from acrylates and methacrylates, to styrenes, vinyl esters, and acrylamides.<sup>19–22</sup> While controlled radical polymerisations are of increasing interest in the scientific community, synthesising polymers of high molecular weight still appears to be challenging, especially when emphasising on water-based systems. A brief comparison between ATRP and RAFT is displayed in Table 1.

**Table 1:** Comparison between ATRP and RAFT polymerisation

	ATRP	RAFT
Reaction rate	High <sup>23,24</sup>	Higher <sup>23,24</sup>
Control over molecular weight	High <sup>25</sup>	High <sup>25</sup>
Versatility toward different monomers	High	Very high <sup>16</sup>
Sensitivity to O <sub>2</sub>	High <sup>11</sup>	Moderate <sup>26</sup>
Catalyst	Transition metal	N.A. <sup>a</sup>
Catalyst regeneration	Expensive procedure <sup>12,13</sup>	N.A. <sup>a</sup>

<sup>a</sup>Not Applicable

Next to aliphatic dithioester cumyl phenyldithioacetate (CPDA),<sup>27</sup> several RAFT agents are reported for the polymerisation of AM. Early reports are available on aromatic dithiocarbonate agents cumyl dithio-benzoate (CDB),<sup>27</sup> cyanopentanoic acid dithiobenzoate (CTP),<sup>27,28</sup> and sodium 2-(2-thiobenzoylsulfonyl propionylamino) ethanesulfonate (TSPE).<sup>27,29</sup> While it was possible to polymerise up to a molecular weight 100,000 Da with a polydispersity index (PDI) below 1.40, the best control was offered when a xanthate *O*-ethyl-*S*-1-(methyloxycarbonyl)ethylxanthate (MCEX)<sup>30,31</sup> or trithiocarbonate RAFT agent was applied.<sup>27</sup> Trithiocarbonate dibenzyl carbonotrithioate (DBTTC) has proven to be an efficient transfer agent in MeOH, effectively mediating the polymerisation under UV-irradiation up to a molecular weight of 50,000 Da with PDIs up to 1.20.<sup>32</sup> Slightly higher molecular weights, up to 72,000 Da were obtained with *S,S'*-bis ( $\alpha$ ,  $\alpha'$ -dimethylacetic acid) trithiocarbonate (BDAT) in water at 25 – 70 °C, while maintaining PDI values below 1.25.<sup>33</sup> Later work employed gamma radiation in the polymerisation of AM in water with BDAT and water/acetone with 3-(((benzylthio)carbonothioyl)thio)propanoic acid (BCPA).<sup>34</sup> Molecular weights of 17,000 and 37,000 Da were reported respectively, while maintaining low PDIs. Low temperature polymerisation was explored with redox initiation of AM at 25 – 45 °C in presence of trithiocarbonate BDAT. The polymers had molecular weights in good correspondence with their theoretical values, up to 13,400 Da with PDIs up to 1.31. Low temperature polymerisation was also reported up to higher molecular weights. Promising results were obtained with xanthate MCEX, however, the RAFT agent was subjected to an additional modification step. MCEX was modified with AM in a mixture of ethanol and water up to a molecular weight of 650 Da. After purification, the macro CTA

was applied in the polymerisation of additional AM in water, initiated by redox initiation at ambient temperature.<sup>31</sup> Molecular weights of almost 1,000,000 Da were reached with a claimed PDI of 1.12.

Branching in AM polymers was introduced by copolymerising with *N,N'*-methylenebis (acrylamide) (BisAM), a bi-functional AM monomer.<sup>30,32,35</sup> Xanthate MCEX was employed in a mixture of water and 2-propanol, yielding branched copolymers of AM and BisAM with a molecular weight up to 7,370 Da, and PDI values ranging from 2.68 to 11.9. Higher molecular weights, ranging from 560,000 to 1,280,000 Da were obtained when BCPA was used as RAFT agent in an aqueous buffer.<sup>35</sup> GPC traces displayed bimodal peaks, resulting in PDIs from 4.7 to 8.6. Next, the feeding policy of BisAM was explored.<sup>32</sup> By polymerising the arms before the addition of BisAM, star-shaped polymers were prepared. Molecular weights up to 715,000 Da were listed, with PDIs ranging from 1.1 to 2.2. In a second approach, the core was synthesised by reaction of BisAM with the RAFT agent, followed by the addition of AM in order to grow arms from the core. The latter approach yielded polymers with molecular weights up to 579,000 Da and PDIs between 1.6 and 2.4. In a batch approach, AM was directly copolymerised with BisAM. Molecular weights were limited to 204,000 Da (PDI: 1.9), at higher BisAM concentration gelation was observed. With a continuous feeding approach of BisAM, molecular weights up to 1,290,000 Da with PDIs from 1.4 to 9.4, were obtained.

In the present work a one-step RAFT polymerisation of acrylamide in aqueous buffer (pH = 5) is employed at 60 – 80 °C with an industrially relevant RAFT agent BCPA. BCPA is synthesised in a two step, one pot reaction under mild conditions.<sup>36</sup> Next to AM (*vide supra*), this RAFT agent has been employed in the polymerisation of several monomers. Literature is available on the polymerisation in a mixture of water and acetone with gamma radiation at ambient temperature. The latter research describes the polymerisation of several monomers, including 2-hydroxyethyl acrylate, acrylic acid (AA), NIPAM, 2-acrylamido-2-methylpropane sulfonic acid, and DMA.<sup>37</sup> A multifunctional RAFT agent (12 arms) with a polyester core was synthesised and applied in the polymerisation of butyl acrylate (BA) and styrene (St).<sup>36</sup> Moreover, BCPA was employed in the synthesis of a 7 arm multifunctional RAFT agent by coupling of BCPA to cyclodextrin (core as part of the Z-group). This core was polymerised with St in bulk at 60 – 120 °C initiated by azobisisobutyronitrile (AIBN) to yield star shaped polymers.<sup>38</sup> Finally, BCPA was employed in the polymerisation of poly(ethylene glycol) monomethyl ether methacrylate (PEGMA) in acetonitrile with AIBN at 70 °C.<sup>34</sup> The polymer was chain extended with cross-linker (*N,N'*-bis(acryloyl)cystamine (biodegradable) or BisAM) and vinyl benzyl amine with AIBN in toluene at 70 °C. Obtained polymers were envisioned for application as drug carriers. A reaction mechanism for the polymerisation of AM with BCPA is depicted in figure 1. The employed

RAFT agent was found to favour polymerisation on the R-group, due to the low stability of the primary alkyl radical Z-group.<sup>39</sup>

Regarding sustainability and scaling up of the procedures, polymerisation in aqueous media is preferred, even if this results in a polymerisation that is not perfectly living. The first step towards synthesising thickeners for aqueous fluids through RAFT polymerisation consists of the linear polymerisation of acrylamide(s). While some results of aqueous RAFT polymerisations of acrylamide are available from literature, only limited results present molecular weights >100,000 Da. Literature describing RAFT polymerisations of acrylamide up to higher molecular weights, on the other hand, has limited industrial applicability by requiring a circuitous synthetic approach. To the best of our knowledge, no synthetic procedure has been presented for an industrially relevant preparation of high molecular weight polyacrylamide by RAFT polymerisation in water with an easily synthesised RAFT agent. Therefore, the present work describes the polymerisation of acrylamide up to high molecular weight, by a synthetic approach that can be applied on an industrial scale.

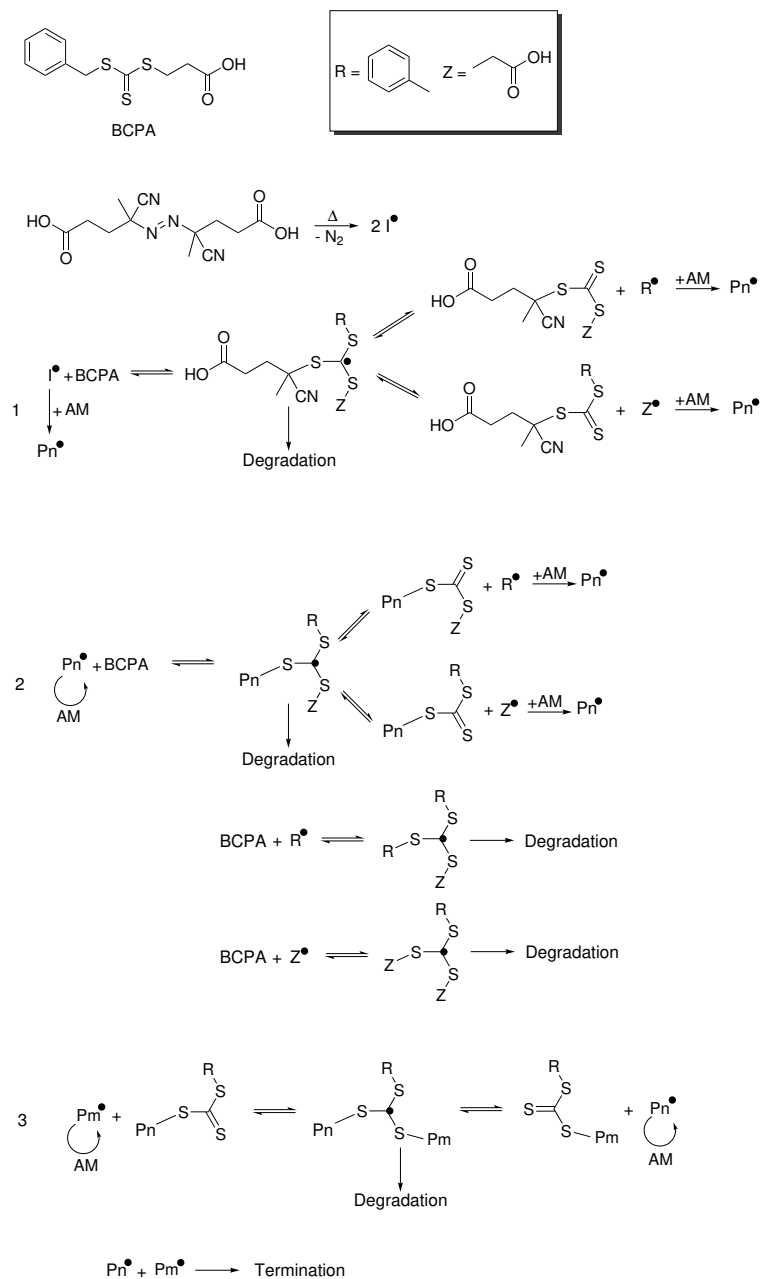
## 3.2 Experimental

### 3.2.1 Chemicals

Acrylamide (AM, electrophoresis grade,  $\geq 99\%$ ) and *N,N*-dimethylacrylamide (DMA, 99%) were purchased from Sigma-Aldrich and used as received. 4,4'-Azobis(4-cyanovaleric acid) (ACVA,  $\geq 98.0\%$ ), 2,2'-azobis(2-methylpropionamidine) dihydrochloride (AAPH, granular, 97%), and benzoyl peroxide (BPO, 75%) were obtained from Sigma-Aldrich and used without further purification. The RAFT agent 3-benzyltrithiocarbonyl propionic acid (BCPA) was synthesised according to the method outlined in literature,<sup>36</sup> however, the product was recrystallised twice from dichloromethane. The RAFT agent was obtained as a yellow solid with 66% yield (<sup>1</sup>H-NMR spectrum depicted in the supplementary information).

### 3.2.2 RAFT polymerisation of AM and DMA

AM or DMA was dissolved in a buffer (pH = 5) of acetic acid (0.27 M) and sodium acetate (0.73 M) and charged to a 250 ml three-neck flask, equipped with a stirring magnet. BCPA was added and the mixture was degassed by purging with N<sub>2</sub> under vigorous stirring for at least 30 min. The reaction mixture was subsequently heated to the designated temperature (60 – 80 °C) and initiated by addition of AAPH or ACVA. After the polymerisation time the reaction mixture was exposed to air and diluted with demineralised water in order to terminate the reaction. Polymers



**Figure 1:** Reaction scheme for RAFT polymerisation of AM with BCPA as CTA and ACVA as initiator



were precipitated in methanol or acetone, dried at 70 °C up to constant weight and subsequently characterised. An overview of the performed polymerisation is displayed in table 2.

**Table 2:** RAFT polymerisation of AM (and DMA) with BCPA and ACVA

Entry	[CTA]	[I]	[M]	M/solv. (wt:vol)	T (°C)	t (min)	Conv. (%)	[M] <sub>n,theor.</sub> (-)	[M] <sub>n,GPC</sub> (-)	PDI (-)
1	1	0.51	32	0.23 <sup>a</sup>	70	120	95	2,412	2,420	1.51
2 <sup>b</sup>	1	0.35	2,490	0.17	73	65	85	209,759	241,400	1.63
3	1	0.10	909	0.14	80	1440	97	63,299	65,970	1.66
4	1	0.37	3,681	0.24	80	330	92	241,551	209,500	1.82
5	1	0.94	10,591	0.20	80>70	95	95	715,653	623,300	1.66
6 <sup>c</sup>	1	1.89	21,371	0.14	78	30	72	1,095,123	-	-
7 <sup>c</sup>	1	3.46	43,598	0.11	78	66	84	2,617,510	-	-

<sup>a</sup> 50:50 vol% mixture of buffer and ethanol

<sup>b</sup> Chain extension of entry 1 with DMA

<sup>c</sup>  $M_{n,exp}$  and PDI not measured for this sample due to limitations of GPC calibration

### 3.2.3 Kinetic experiments

The general polymerisation procedure was followed, however, at certain time intervals aliquots of 0.3 ml were taken from the reaction mixture and immediately precipitated in acetone. The conversion of samples was determined, followed by drying of the samples and characterisation by GPC. An overview of the kinetic experiments is shown in table 3, whereby the name of the entry denotes the reaction conditions, e.g. K3 T80/0.06/Half I corresponds with kinetic experiment 3, polymerised at 80 °C with 0.06 g of RAFT agent and half of the initiator concentration relative to the other experiments. Entries K1 - K5 are polymerised with AM, whereas entry 6 and 7 are polymerised with DMA.

### 3.2.4 Chain extension experiment

A two-step chain extension was conducted by following the general polymerisation procedure, however, the polymerisation was performed at 70 °C in a mixture of ethanol and demineralised water (50:50 vol%). The macro CTA was subsequently charged to a 100 ml three-neck flask, equipped with a stirring magnet. DMA was dissolved in a buffer of acetic acid and sodium acetate (pH = 5) and added to the flask. The mixture was purged with N<sub>2</sub> under vigorous stirring for 30 minutes. The flask was heated to 73 °C and the reaction was initiated by addition of ACVA. Aliquots were taken from the reaction mixture at certain time intervals, precipitated

**Table 3:** Kinetic experiments: RAFT polymerisation of AM and DMA with BCPA and ACVA/AAPH

Entry	[CTA]	[I]	[M]	T (°C)	t (min)	Conv. (%)	$[M]_{n,theor.}$ (-)	$[M]_{n,GPC}$ (-)	PDI (-)
K1 T80/0.03 <sup>b</sup>	1	0.19	1,810	80	112	96	123,943	107,500	1.75
K4 T80/0.06 <sup>b</sup>	1	0.19	905	80	30	86	55,775	53,160	1.46
K3 T80/0.06/Half I <sup>b</sup>	1	0.10	908	80	62	90	58,347	56,850	1.45
K2 T70/0.03 <sup>b</sup>	1	0.19	1,810	70	420	85	109,683	84,820	1.85
K5 <sup>a</sup> T60/0.03/AAPH <sup>b</sup>	1	0.19	1,822	60	129	98	126,587	123,300	1.60
K6 T80/0.03/DMA <sup>c</sup>	1	0.19	1,804	80	62	90	161,910	119,420	1.66
K7 T80/0.06/DMA <sup>c</sup>	1	0.20	908	80	63	93	83,599	76,180	1.51

<sup>a</sup>Experiment performed with initiator AAPH

<sup>b</sup>M:buffer (w:v) = 0.14

<sup>c</sup>M:buffer (w:v) = 0.20

in acetone, subjected to gas chromatography (GC) analysis in order to determine the conversion. Hereafter, samples were dried and subsequently characterised by GPC.

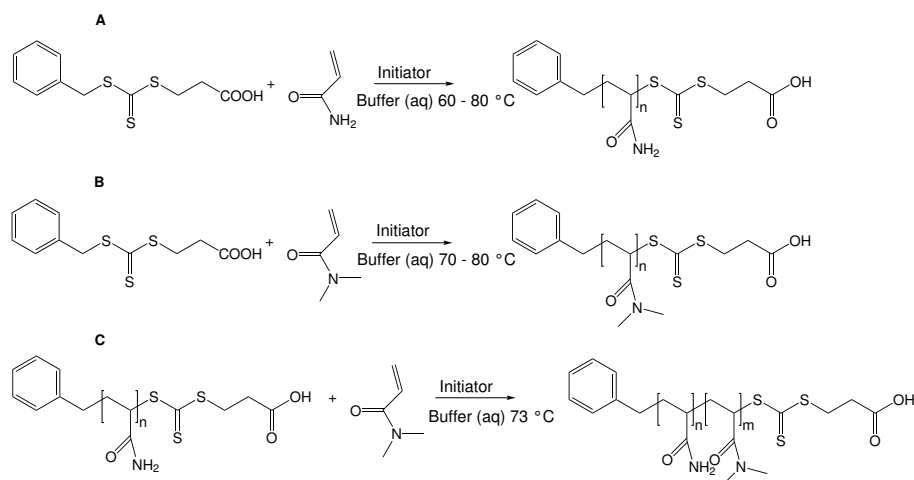
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### 3.2.5 Characterisation

Conversion of AM was measured using GC. Samples of reaction mixtures were dissolved in acetone containing 1,000 ppm pentadecane (reference) and injected on a Hewlett-Packard 5890 GC equipped with an Elite-Wax ETR column. Polymer samples were dissolved in milli-Q water containing 0.05M sodium nitrate and subjected to GPC. An Agilent 1200 system was equipped with Polymer Standard Service (PSS) columns (100 Å and 3,000 Å, 8 x 300 mm) and an aqueous 0.05M sodium nitrate solution was used as the eluent. Column temperature was maintained at 40 °C and detection of polymers was conducted with a refractive index (RI) detector, operated at 40 °C. AM-based calibration and WinGPC software (GPC) were used to calculate the apparent molecular weight and PDI of the samples. Proton nuclear magnetic resonance (<sup>1</sup>H-NMR) spectra were recorded using a Varian Mercury Plus spectrometer operating at 400 MHz. D<sub>2</sub>O and CDCl<sub>3</sub> were used as solvents. For evaluation of the kinetic experiments, OriginLab Origin software was used, whereby kinetic data were plotted and a linear fit was rendered.

### 3.3 Results and discussion

#### 3.3.1 RAFT polymerisation of AM and DMA



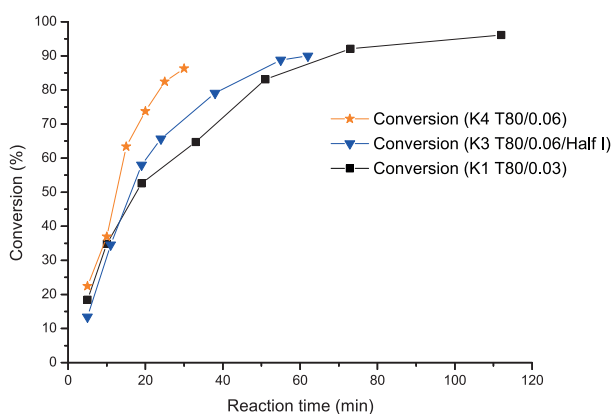
**Figure 2:** RAFT polymerisation of AM (A), DMA (B), and block polymerisation of AM and DMA (C)

RAFT polymerisations of AM and DMA were performed according to the reaction scheme displayed in figure 2. Reaction conditions were varied as outlined in table 2 and 3. Theoretical molecular weights were calculated by multiplying the ratio between monomer and RAFT agent with the conversion and molar mass of the monomer, and adding the molar mass of the RAFT agent (Eq. 3.1).

$$M_{n, \text{theo}} = \frac{[M]_0 \times \text{Conversion} \times M_M}{[CTA]_0} + M_{CTA} \quad (3.1)$$

As shown, polymers with number average molecular weights up to 2,600,000 Da and reasonable PDIs can be obtained with the aligned method. No retardation was found for the RAFT polymerisation of AM in aqueous media (figure 3 and supplementary information), while a retardation period of 13 minutes was found when DMA was polymerised (not shown for brevity). For the latter monomer, the retardation period was found to increase to 28 minutes upon doubling the concentration of RAFT agent. Similar to the presented results with AM, no influence of the RAFT agent concentration on the induction period was reported for polymerisation of *N,N*-diethylacrylamide.<sup>40</sup> Applying different dithiobenzoate RAFT agents and varying solvents (dioxane, toluene, and in bulk) influenced the induction period. In general, however, an increase in induction period is found with increas-

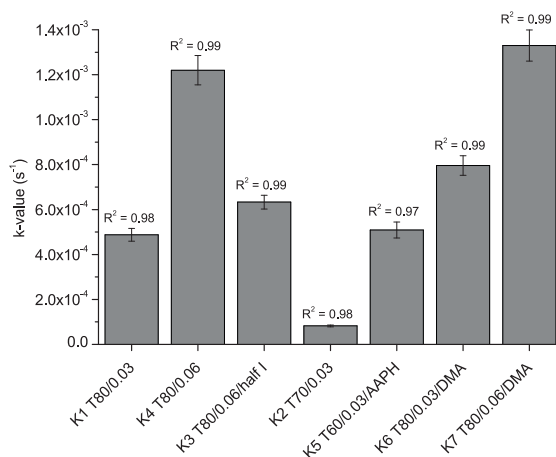
ing the amount of RAFT agent.<sup>41,42</sup> Moreover, no noticeable induction period was found for polymerisation of both AM and DMA with a trithiocarbonate RAFT agent at 25 °C.<sup>20</sup> Sun et al, on the other hand, obtained significant induction periods in RAFT polymerisation of DMA and NIPAM with trithiocarbonate structures.<sup>43</sup> However, after modification of the RAFT agent with polyethylene glycol (PEG), the order of inhibition time was reversed. The latter effect was left open to further investigation. Based on an extensive study with several RAFT agents, inhibition was ascribed to the stability of intermediate radical 2 (figure 1).<sup>44</sup> The longer induction period obtained with DMA might be related to inferior hydrophilicity of the monomer, resulting in a prolonged phase to reach the RAFT pre-equilibrium (figure 1, reaction 1). At higher RAFT agent concentration, a longer induction period is observed for DMA, which is in line with a longer expected period to reach the pre-equilibrium. In order to fully explain this phenomenon, further research is required.



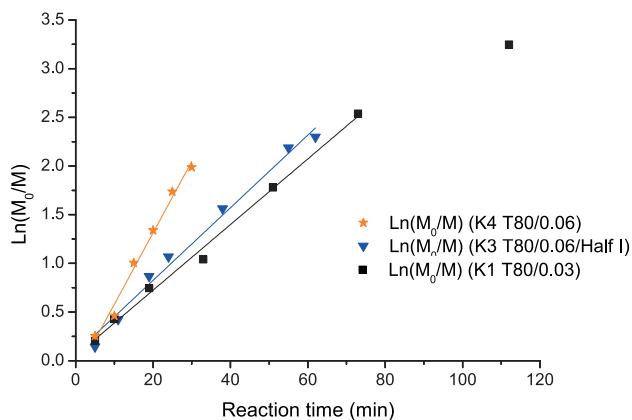
**Figure 3:** Effect of RAFT agent concentration and RAFT agent and initiator ratio on conversion

For batch reactions, first order kinetics are calculated according to Eq. 3.2.<sup>45</sup>  $M_0$  denotes the monomer concentration at the start of the reaction,  $M$  the monomer concentration,  $k$  the kinetic constant, and  $t$  the reaction time in seconds. Values of the kinetic constants derived from these fits, as well as the coefficients of determination are displayed in figure 4. Linear fits were found to be in good agreement with the experimental data, judged from the  $R^2$  values of 0.97 and higher.

$$\ln \frac{M_0}{M} = kt \quad (3.2)$$



**Figure 4:** Kinetic constants and statistical data for linear fit of RAFT polymerisation of AM and DMA. The name of the polymers corresponds with the entries in table 3



**Figure 5:** Kinetic plot: effect of RAFT agent concentration and RAFT agent to initiator ratio on reaction rate

The kinetic plots of conversion of AM and DMA display linear first order behaviour up to monomer conversions of at least 85% (figure 5 and supplementary

information). This linearity illustrates the absence of termination reactions, which would reduce the reaction rate gradually over the course of the polymerisation. The latter demonstrates the suitability of using RAFT agent BCPA in combination with ACVA or AAPH in the polymerisation of AM. In the final stage of the polymerisation, deviations from the first order reaction rate become apparent. More specifically, the experiments targeting higher molecular weights display a high apparent viscosity and thus a lower diffusion rate in the final stage of the polymerisation.<sup>46</sup> The latter leads to a less efficient transfer of propagating radical chains to generate dormant chains.<sup>47</sup> Consequently, the concentration of propagating radical chains increases under influence of the constant generation of radicals, leading to an increase in reaction rate. The latter effect, combined with a relatively low concentration of dormant chains enhances termination reactions and thus increases PDIs.

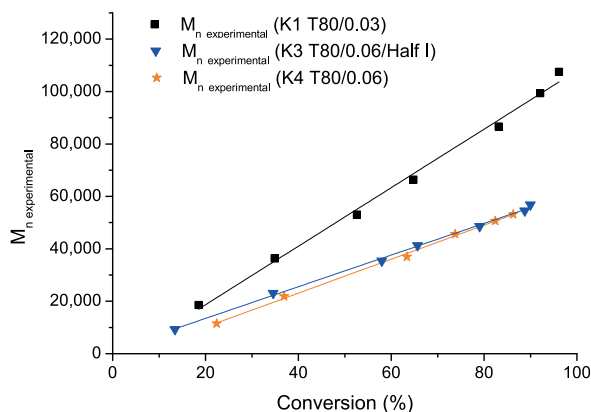
Specifically of interest is entry K5, initiated by AAPH at 60 °C. GPC traces of the latter polymer can be found in the supplementary information and show the chain growth during the final stage of the polymerisation. Under the applied conditions, PDI values <1.60 are sustained up to conversions of 97.5%, while the number average molecular weight surpassed 100,000. The latter stresses the importance of applying optimal reaction conditions in order to maintain the highest degree of control over the reaction.

Increasing the RAFT agent concentration leads to a higher k-value for both AM and DMA polymerisation, while in literature the reverse effect was obtained when polymerising NIPAM in dioxane.<sup>41</sup> However, in the present work the concentration of both RAFT agent and initiator were doubled. Performing the polymerisation at constant initiator concentration yields similar k-values (i.e. reaction rates) at two different RAFT agent concentrations. The latter effect is in contrast to a polymerisation study of *N*-tert-butylacrylamide with a dithiobenzoate RAFT agent.<sup>48</sup> In the latter study, kinetics were not affected at constant initiator to RAFT agent ratio. Since doubling of the RAFT agent does not pronouncedly influence reaction rate in the present work, while increasing radical initiator concentration does, the reaction appears to be limited by the generation of free radicals in the system. At constant RAFT agent to initiator ratio, higher k-values at higher RAFT agent concentration are attributed to a correspondingly higher initiator concentration in the mixture, leading to a higher concentration of propagating chains during polymerisation.

For RAFT polymerisation of AM, the importance of the ratio between RAFT agent and initiator became apparent in the work of Thomas et al., in which the kinetics of RAFT polymerisation with 4-cyanopentanoic acid dithiobenzoate were studied. Similar to the presented results, the exact amount of initiator was found to have a pronounced effect on the polymerisation rate. Increasing the initiator concentration with a factor 4 led to more than doubling of the polymerisation

rate.<sup>27</sup>

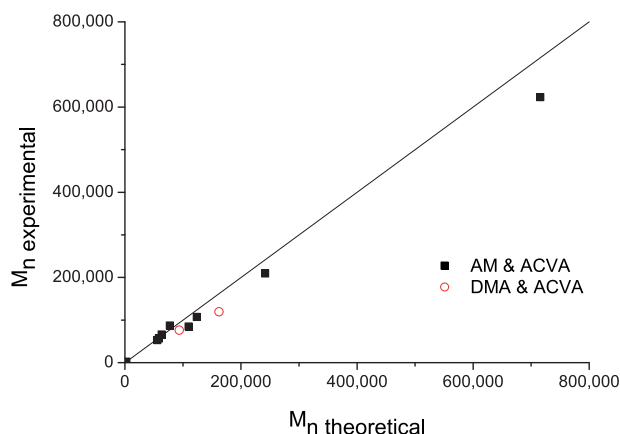
Another criterion for a controlled polymerisation is a linearly developing molecular weight with conversion. In figure 6 and in the supplementary information, the experimental molecular weight versus the conversion are plotted. As shown, samples display a linear increase in molecular weight up to very high conversion (>90%). Moreover, a clear dependence of the (final) molecular weight of the polymer on the concentration of RAFT agent is displayed, demonstrating the degree of control that is offered by the RAFT agent. The latter is enforced by data in table 2 and figure 7. A clear relation between the experimental and theoretical molecular weight (Eq. 3.1) is shown.



**Figure 6:** Experimental molecular weight as a function of conversion at different RAFT agent and initiator concentrations

Some deviation from the theoretical molecular weight was observed, however, especially at higher molecular weight and outside the range of the GPC calibration. As expected, increasing the concentration of RAFT agent results in a narrower PDI, as the degree to which recombination prevails decreases. PDIs were found to remain relatively constant up to approximately 50% conversion, after which a pronounced increase is found. The latter is ascribed to an increase in the statistical probability of termination reactions and an increase in the viscosity of the reaction mixture, limiting diffusion. A similar trend regarding the PDIs was found by Favier et al., for RAFT polymerisation of *N*-acryloyl morpholine in dioxane.<sup>49</sup> In the present work, reasonably low PDIs are obtained even though the applied PAM calibration standards have average PDIs, whereas in literature poly(sodium acrylate)<sup>50</sup> and PEG<sup>32,35,51,52</sup> standards with low PDIs are generally applied.

Finally, treating the polymers with an excess of benzoyl peroxide (BPO), a



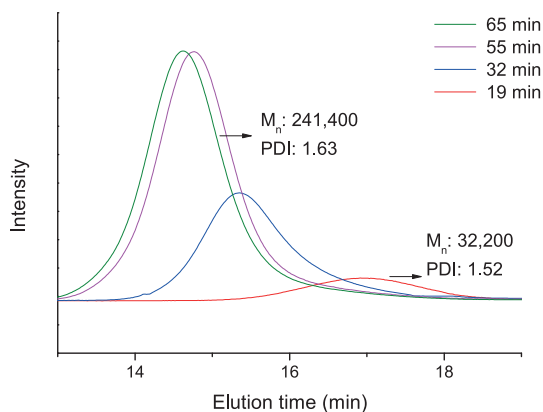
**Figure 7:** Experimental molecular weight versus theoretical molecular weight based on conversion. Open symbols correspond with DMA experiments

well-known method to remove RAFT functional groups,<sup>53</sup> led to discolouration of the polymer from yellowish to white, while no change in GPC traces was observed. The latter suggests successful removal of the RAFT group and confirms that polymerisation takes place on the R-group. Low molecular weight traces were absent, indicating no (slight) growth of polymer on the Z-group. The absence of polymerisation on the Z-group of the RAFT agent was confirmed by Wang et al., and ascribed to the low stability of the propionic acid radical.<sup>39</sup> Therefore, the R-group (figure 1, reaction 1) or the propagating chain attached to the RAFT agent (figure 1, reaction 2) are the preferred leaving groups.

### 3.3.2 Chain extension

The living character of a controlled polymerisation is generally evaluated based on chain extension experiments. Hereby, a homo-polymer is subjected to a subsequent polymerisation step, in order to yield a block copolymer. In the present work, an AM macro CTA ( $M_n = 2,420$  Da, PDI = 1.51) is polymerised with additional DMA under similar conditions as described for a homo-polymerisation. The GPC traces of the chain extension are displayed in figure 8. The molecular weight of the polymer was found to increase with reaction time (19 min:  $M_n = 32,200$  Da, PDI = 1.52; 65 min:  $M_n = 241,400$  Da, PDI = 1.63). Based on a linear fit of the kinetic data, the  $k$ -value was found to be of the same order of magnitude as for homo-polymerisation of DMA, namely  $4.6 \times 10^{-4} \text{ s}^{-1}$  ( $R^2 = 0.95$ ). The  $^1\text{H-NMR}$  spectrum of the copolymer after thorough dialysis (cutoff 12 - 14 kDa) and development of the molecular weight as function of conversion are available in the





**Figure 8:** Elugram of chain extension experiment

supplementary information. Benzylic protons from the R-group are still present after the second polymerisation step with DMA. Furthermore, the molecular weight develops linearly with conversion. The latter, combined with the absence of low-molecular weight tailing in the GPC traces after chain extension, indicates that the macro CTA retained its functional RAFT groups and supports the RAFT nature of the chain extension.

### 3.4 Conclusions

In an industrially relevant process, linear polyacrylamide (PAM) was synthesised using 3-(((benzylthio)carbonothioyl)thio)propanoic acid (BCPA) as RAFT agent and 4,4'-Azobis(4-cyanovaleric acid) (ACVA) or 2,2'-Azobis(2-methylpropionamidine) dihydrochloride (AAPH) as initiator in an aqueous buffer solution. Polymers with experimental molecular weights of >600,000 Da were synthesised with reasonable polydispersity indices (PDIs) (<1.7), and molecular weights were found to display good correspondence with theoretical values. Initial experiments suggest that a reaction temperature of 60 °C, in combination with AAPH offers the highest degree of control over the polymerisation. The degree of control was confirmed by linear first order kinetic plots and a successful chain extension experiment in which an acrylamide (AM) macro CTA was extended with *N,N*-dimethylacrylamide (DMA) in order to yield a block copolymer. The polymerisation procedure was found to be versatile with respect to monomers, i.e. suitable for polymerisation of AM and DMA, as well as different temperatures and radical initiators. The ease of the synthetic procedure and high degree of

control over the molecular weight, combined with a high reaction rate, offers an industrially relevant process in the synthesis of well-defined hydrophilic polymers.

## 3.5 Acknowledgement

This research forms part of the research program of the Dutch Polymer Institute, Project 778.

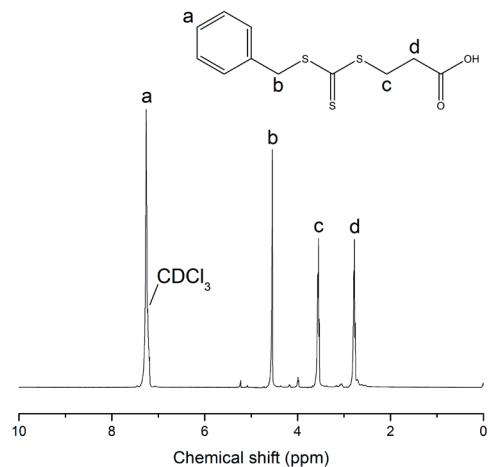
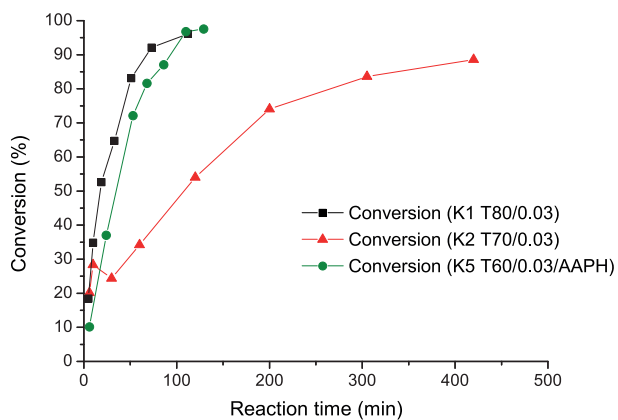
## References

- [1] Witham, M. I.; Grabsch, A. F.; Owen, A. T.; Fawell, P. D. *International Journal of Mineral Processing* **2012**, *114-117*, 51-62.
- [2] Liu, R.; Fraylich, M.; Saunders, B. R. *Colloid and Polymer Science* **2009**, *287*, 627-643.
- [3] Fitch, S.; Horton, R. L.; Mueller, B. L. Thermo-responsive hydrogels and thermo-responsive polymer solutions. 2012.
- [4] Dimitrov, I.; Trzebicka, B.; Müller, A. H. E.; Dworak, A.; Tsvetanov, C. B. *Progress in Polymer Science* **2007**, *32*, 1275-1343.
- [5] Wever, D. A. Z.; Raffa, P.; Picchioni, F.; Broekhuis, A. A. *Macromolecules* **2012**, *45*, 4040-4045.
- [6] Wever, D. A. Z.; Ramalho, G.; Picchioni, F.; Broekhuis, A. A. *Journal of Applied Polymer Science* **2014**, *131*, 1-9.
- [7] Wever, D. A. Z.; Picchioni, F.; Broekhuis, A. A. *European Polymer Journal* **2013**, *49*, 3289-3301.
- [8] Wever, D. A. Z.; Riemsma, E.; Picchioni, F.; Broekhuis, A. A. *Polymer* **2013**, *54*, 5456-5466.
- [9] Wever, D. A. Z.; Polgar, L. M.; Stuart, M. C. A.; Picchioni, F.; Broekhuis, A. A. *Industrial & Engineering Chemistry Research* **2013**, *52*, 16993-17005.
- [10] Wever, D. A. Z.; Picchioni, F.; Broekhuis, A. A. *Industrial & Engineering Chemistry Research* **2013**, *52*, 16352-16363.
- [11] Mandal, B. M. *Fundamentals of Polymerization*; World Scientific, 2013.
- [12] Sun, J.; Zhang, Y.; Li, J.; Ren, Q.; Wang, C.; Xu, Z. *Journal of Macromolecular Science, Part A* **2015**, *52*, 609-616.
- [13] K. A. Payne.; M. F. Cunningham.; R. A. Hutchinson, *Progress in Controlled Radical Polymerization: Mechanisms and Techniques*; ACS Symposium Series 1100; American Chemical Society, 2012; Vol. 1100; pp 183-202.
- [14] Mishra, M.; Tunca, U.; Yagci, Y.; Atilla Tasdelen, M.; Acar, M.; Hizal, G. *Handbook of Vinyl Polymers*; Plastics Engineering; CRC Press, 2008; pp 231-306.
- [15] Lou, Q.; Shipp, D. A. *ChemPhysChem* **2012**, *13*, 3257-3261.
- [16] Chiefari, J.; Chong, Y. K. B.; Ercole, F.; Krstina, J.; Jeffery, J.; Le, T. P. T.; Mayadunne, R. T. A.; Meijs, G. F.; Moad, C. L.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **1998**, *31*, 5559-5562.
- [17] Moad, G. *Polymer Chemistry* **2017**, *8*, 177-219.
- [18] Moad, G.; Rizzardo, E.; Thang, S. H. *Chemistry - An Asian Journal* **2013**, *8*, 1634-1644.
- [19] Drache, M.; Schmidt-Naake, G.; Buback, M.; Vana, P. *Polymer* **2005**, *46*, 8483-8493.
- [20] Lima, V.; Jiang, X.; Brokken-Zijp, J.; Schoenmakers, P. J.; Klumperman, B.; Van Der Linde, R. *Journal of Polymer Science Part A: Polymer Chemistry* **2005**, *43*, 959-973.

- [21] Barner-Kowollik, C.; Quinn, J. F.; Morsley, D. R.; Davis, T. P. *Journal of Polymer Science Part A: Polymer Chemistry* **2001**, *39*, 1353–1365.
- [22] Harrison, S.; Liu, X.; Ollagnier, J.-N.; Coutelier, O.; Marty, J.-D.; Destarac, M. *Polymers* **2014**, *6*, 1437–1488.
- [23] Hutchinson, R. A.; Penlidis, A. In *Polymer Reaction Engineering*; Asua, J. M., Ed.; Blackwell Publishing Ltd, 2007; pp 118–178.
- [24] Yu, Q.; Xu, S.; Zhang, H.; Ding, Y.; Zhu, S. *Polymer* **2009**, *50*, 3488–3494.
- [25] Matyjaszewski, K.; Spanswick, J. *Materials Today* **2005**, *8*, 26–33.
- [26] Zhang, Z.; Zhu, J.; Cheng, Z.; Zhu, X. *Polymer* **2007**, *48*, 4393–4400.
- [27] Thomas, D. B.; Convertine, A. J.; Myrick, L. J.; Scales, C. W.; Smith, A. E.; Lowe, A. B.; Vasilieva, Y. A.; Ayres, N.; McCormick, C. L. *Macromolecules* **2004**, *37*, 8941–8950.
- [28] Vasilieva, Y. A.; Scales, C. W.; Thomas, D. B.; Ezell, R. G.; Lowe, A. B.; Ayres, N.; McCormick, C. L. *Journal of Polymer Science Part A: Polymer Chemistry* **2005**, *43*, 3141–3152.
- [29] Thomas, D. B.; Sumerlin, B. S.; Lowe, A. B.; McCormick, C. L. *Macromolecules* **2003**, *36*, 1436–1439.
- [30] Taton, D.; Baussard, J.-F.; Dupayage, L.; Poly, J.; Gnanou, Y.; Ponsinet, V.; Destarac, M.; Mignaud, C.; Pitois, C. *Chemical Communications* **2006**, 1953–1955.
- [31] Read, E.; Guinaudeau, A.; Wilson, D. J.; Cadix, A.; Violleau, F.; Destarac, M. *Polymer Chemistry* **2014**, *5*, 2202–2207.
- [32] Wang, D.; Wang, W.-J.; Li, B.-G.; Zhu, S. *AIChE Journal* **2013**, *59*, 1322–1333.
- [33] Convertine, A. J.; Lokitz, B. S.; Lowe, A. B.; Scales, C. W.; Myrick, L. J.; McCormick, C. L. *Macromolecular Rapid Communications* **2005**, *26*, 791–795.
- [34] Liu, J.; Duong, H.; Whittaker, M. R.; Davis, T. P.; Boyer, C. *Macromolecular Rapid Communications* **2012**, *33*, 760–766.
- [35] Wang, W.-J.; Wang, D.; Li, B.-G.; Zhu, S. *Macromolecules* **2010**, *43*, 4062–4069.
- [36] Jesberger, M.; Barner, L.; Stenzel, M. H.; Malmström, E.; Davis, T. P.; Barner-Kowollik, C. *Journal of Polymer Science Part A: Polymer Chemistry* **2003**, *41*, 3847–3861.
- [37] Millard, P.-E.; Barner, L.; Reinhardt, J.; al, e. *Polymer* **2010**, *51*, 4319–4328.
- [38] Stenzel, M. H.; Davis, T. P. *Journal of Polymer Science Part A: Polymer Chemistry* **2002**, *40*, 4498–4512.
- [39] Wang, R.; McCormick, C. L.; Lowe, A. B. *Macromolecules* **2005**, *38*, 9518–9525.
- [40] Zhang, X.; Giani, O.; Monge, S.; Robin, J.-J. *Polymer* **2010**, *51*, 2947–2953.
- [41] Schilli, C.; Lanzendörfer, M. G.; Müller, A. H. E. *Macromolecules* **2002**, *35*, 6819–6827.
- [42] Bathfield, M.; D’Agosto, F.; Spitz, R.; Ladavière, C.; Charreyre, M.-T.; Delair, T. *Macromolecular Rapid Communications* **2007**, *28*, 856–862.
- [43] Sun, X.-L.; He, W.-D.; Li, J.; Li, L.-Y.; Zhang, B.-Y.; Pan, T.-T. *Journal of Polymer Science Part A: Polymer Chemistry* **2009**, *47*, 6863–6872.
- [44] Perrier, S.; Barner-Kowollik, C.; Quinn, J. F.; Vana, P.; Davis, T. P. *Macromolecules* **2002**, *35*, 8300–8306.
- [45] Fogler, H. S. *Essentials of Chemical Reaction Engineering*; Pearson Education, 2010.
- [46] Wang, A. R.; Zhu, S. *Macromolecular Theory and Simulations* **2003**, *12*, 196–208.
- [47] Bian, Q.; Xiao, Y.; Lang, M. *Journal of Polymer Science Part A: Polymer Chemistry* **2012**, *50*, 571–580.
- [48] de Lambert, B.; Charreyre, M.-T.; Chaix, C.; Pichot, C. *Polymer* **2005**, *46*, 623–637.

- [49] Favier, A.; Charreyre, M.-T.; Pichot, C. *Polymer* **2004**, *45*, 8661–8674.
- [50] Bai, W.; Zhang, L.; Bai, R.; Zhang, G. *Macromolecular Rapid Communications* **2008**, *29*, 562–566.
- [51] Taton, D.; Wilczewska, A.-Z.; Destarac, M. *Macromolecular Rapid Communications* **2001**, *22*, 1497–1503.
- [52] Su, X.; Zhao, Z.; Li, H.; Li, X.; Wu, P.; Han, Z. *European Polymer Journal* **2008**, *44*, 1849–1856.
- [53] Willcock, H.; O'Reilly, R. K. *Polymer Chemistry* **2010**, *1*, 149–157.

## Supplementary Information Chapter 3

**Figure S1:** <sup>1</sup>H-NMR spectrum of BCPA (recorded in CDCl<sub>3</sub>)**Figure S2:** Conversion as function of reaction time for three different conditions

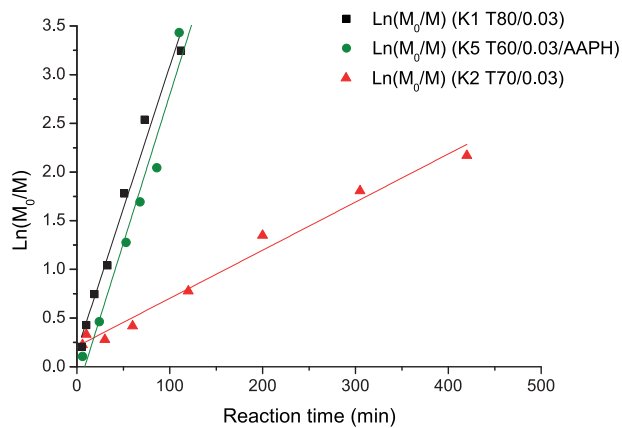


Figure S3: Kinetic plot for three different conditions of AM polymerisation

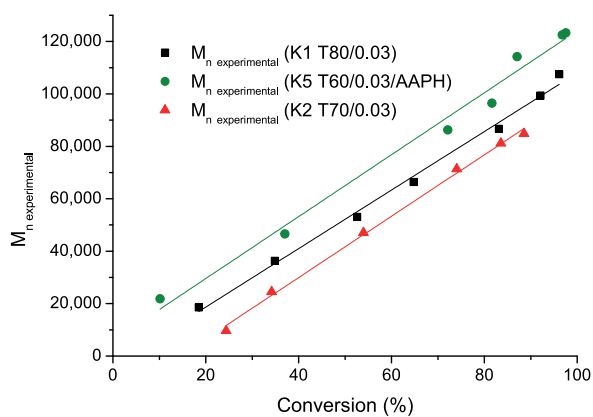
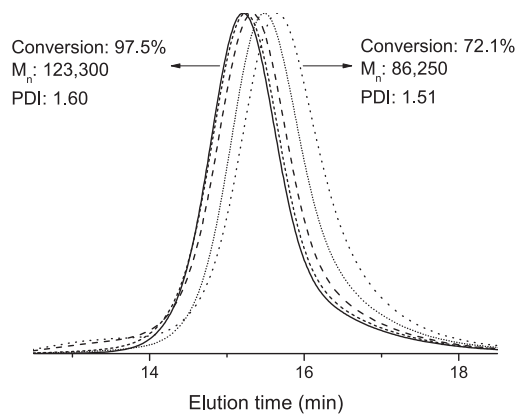
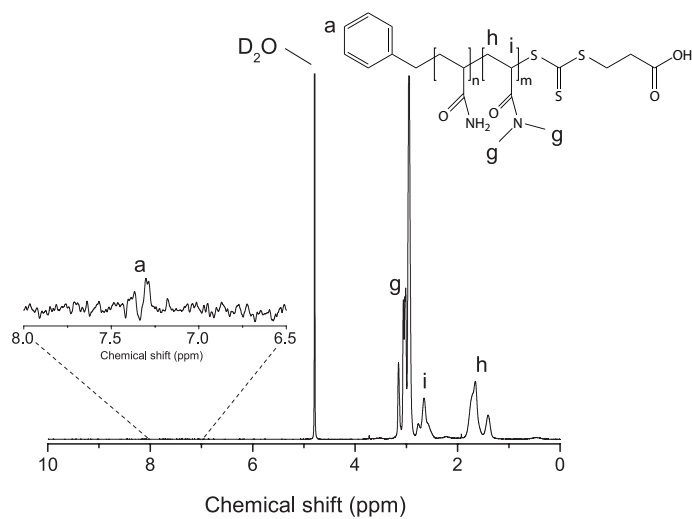


Figure S4: Experimental molecular weight as a function of conversion at different temperatures

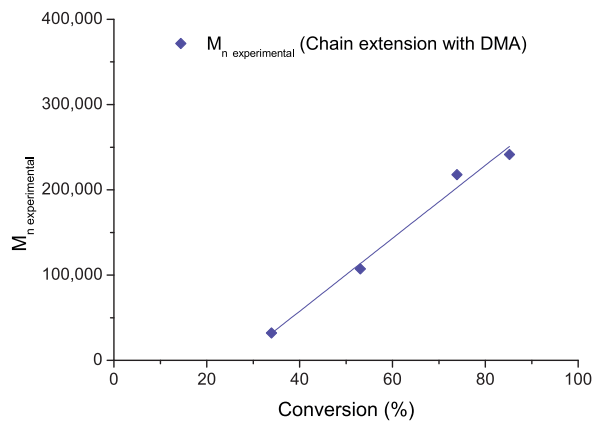
3



**Figure S5:** Development of molecular weight as a function of conversion for polymerisation of AM with BCPA and AAPH at 60 °C (Entry K5)



**Figure S6:**  $^1\text{H-NMR}$  spectrum of chain-extension of an AM macro CTA with DMA (recorded in  $\text{D}_2\text{O}$ )



**Figure S7:** Experimental molecular weight of a chain extended AM macro CTA with DMA as a function of conversion

**3**



