

# RING EXPANSION METHODS FOR THE SYNTHESIS OF CYCLIC POLYMERS

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## INTRODUCTION

Of all polymer topologies, cyclic polymers are some of the most fascinating yet elusive to synthetic chemists, despite their seemingly simple structure. In recent decades, cyclic biopolymers in nature have been shown to exhibit increased thermal and metabolic stability when compared to their linear analogs.<sup>1</sup> These properties are desirable in a myriad of applications ranging from drug delivery to nanolithography, so methods of synthesizing these compounds are of great interest. Early syntheses utilized the ring-closure of linear polymers; however, these methods require highly dilute conditions to reduce the production of linear and oligomeric impurities, limiting scalability.<sup>2</sup> Conversely, ring expansion approaches maintain the cyclic architecture during the polymerization, thus achieving high yields without requiring extensive purification methods or large amounts of solvent.

## RUTHENIUM-CATALYZED METATHESIS

Inspired by their previous work on ring-opening metathesis polymerization (ROMP), Grubbs and coworkers developed a novel method of synthesizing cyclic polymers in 2002.<sup>3a</sup> Unlike conventional

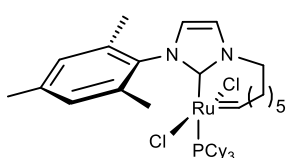


Figure 1. REMP catalyst.

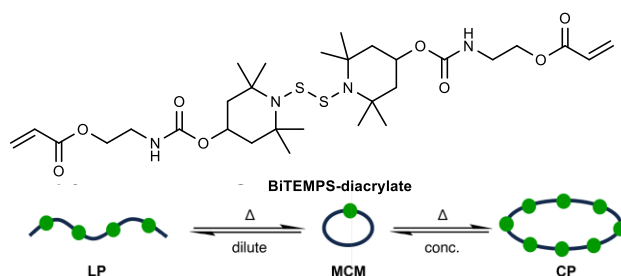
ROMP catalysts, ring-expansion metathesis polymerization (REMP) catalysts contain a methylene chain between the alkylidene bond and an N-heterocyclic carbene ligand (Fig. 1). This allows the growing polymer chain to be tethered to

the catalyst through two ligands, maintaining the cyclic architecture throughout the polymerization and avoiding linear intermediates. This method was used to synthesize cyclic polyethylene (PE), unattainable by conventional approaches; however, the structural simplicity resulted in insignificant differences between linear and cyclic PE. More recently, Grubbs and coworkers used these REMP catalysts in the polymerizations of more complex olefins, demonstrating this method's utility in generating cyclic polymers with high molecular weights and low dispersities.<sup>3b</sup>

## ENTROPY-DRIVEN DISULFIDE EXCHANGE

Aoki, Otsuka, and coworkers took advantage of the dynamic covalent chemistry of disulfides to generate cyclic polymers without requiring catalysts or an inert atmosphere.<sup>4</sup> At high temperatures, these disulfides undergo homolytic cleavage, producing sulfur radicals that are unreactive towards most functional groups. A thiol-ene click reaction between BiTEMPS-diacrylate and a dithiol yielded a linear polymer, which was then heated in moderately dilute conditions to produce macrocyclic monomers in a

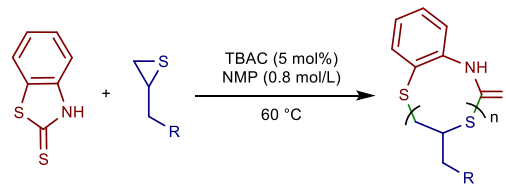
translational entropy-driven process (Fig. 2). Conformational entropy drove the subsequent equilibrium towards the formation of cyclic polymers in a concentrated solution. Minimal side reactions were observed, but the target polymer was synthesized with a relatively broad molecular weight distribution (PDI = 2.4). Optimization of the polymerization itself and further confirmation of the cyclic architecture are imperative, but this relatively simple, scalable synthesis has the potential to be applied to a broad range of polymer frameworks in the future.



**Figure 2.** Entropy-driven cyclic polymer preparation.

## THIOACYL TRANSFER

Aiming to increase the controllability of these polymerizations, the Nishikubo and Kameyama groups have investigated thiirane ring-expansion methods utilizing cyclic dithiocarbamate and thiourethane initiators.<sup>5,6</sup> In the presence of a green catalyst, these initiators undergo an acyl-transfer reaction with a substituted thiirane repeatedly until the thiirane is completely consumed, producing a cyclic polysulfide (Fig. 3). Polymers initiated with the dithiocarbamate had remarkably narrow molecular weight distributions (PDI = 1.1), even in the presence of competing side reactions. These cyclic polysulfides were also able to act as initiators themselves in the generation of block copolymers, confirming the “living” nature of this polymerization. This method is currently limited to polysulfides, but utilizing more complex thiiranes could allow for the synthesis of cyclic brush polymers as well. The thermal properties of these polymers have not yet been investigated, but demonstrating high thermal stability would increase the scope of potential applications.



**Figure 3.** Thio-acyl transfer polymerization.

## CONCLUSIONS AND OUTLOOK

Ring expansion methods offer distinct advantages over the more traditional ring closure methods. Because most of the methodologies discussed were developed very recently, much more research needs to be done before these can be implemented commercially. The primary focus in this field is optimizing the current polymerization methods. However, discovering key applications in materials chemistry and chemical biology wherein cyclic polymers are significantly superior to linear polymers is vital to demonstrating the importance and value of these methods.

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