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Metal salen catalysts for reactions of epoxides and heterocumulenes

A thesis submitted for the degree of Doctor of Philosophy

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Abstract

This thesis details the research carried out into the reaction of epoxides with various heterocumulenes, forming five-membered heterocyclic products. The catalyst systems used are numerous forms of metal salen compounds. It begins with the **introduction**, which summarises the body of literature outlining the reactions of epoxides with heterocumulenes. Previously developed catalytic systems are discussed along with any mechanistic studies that have taken place. A conclusion regarding the most active systems for each reaction is given, which will provide an understanding of the requirements needed to be a successful catalyst.

The **results and discussion** section is divided into four main chapters. It begins with a study into forming novel one-component catalysts for the synthesis of cyclic carbonates from epoxides and carbon dioxide. Four new catalysts are conceived and tested on this reaction, but with very limited success due to the level of steric hindrance present in the backbone of the salen ligands. The catalysts that are successfully synthesised are then examined for other reactions for which they may be suited, namely the synthesis of thiocarbonates from epoxides and carbon disulphide and asymmetric cyanohydrin synthesis. Both reactions gave mixed results. The activity exhibited for thiocarbonate synthesis ranged from 0-100 % conversion, while the asymmetric induction of the cyanohydrin products was disappointing (18-79 % *ee*). Both proving to be less active than previously devised salen-based systems.

The next chapter describes a mechanistic exploration of previously developed monometallic and bimetallic catalyst systems for the reaction of epoxides with isocyanates. The experiments result in a proposed mechanism for this reaction which is

distinct from those proposed for similar reactions of other heterocumulenes. This work is followed by variable temperature kinetic studies which aimed to give a comparison of the activation parameters of the reactions of epoxides with carbon dioxide, carbon disulphide and isocyanates catalysed by aluminium salen complexes to explain the relative reactivity of each heterocumulene. The results found that the reactions of isocyanates and carbon disulphide had relatively high enthalpies of activation and therefore the catalyst systems could potentially be improved by using metals with more Lewis acidic character.

The last two chapters of the results and discussion cover the development of new metal salen catalyst systems for both the synthesis of oxazolidinones and thiocarbonates from epoxides by reaction with isocyanates and carbon disulphide respectively. The development of these systems was based on the results obtained from the variable temperature kinetics studies carried out in the previous chapter. The results show that new, highly active catalysts for these transformations were developed by varying the metal at the centre of the salen ligand. Use of these systems allowed catalyst loading to be decreased, in some cases by up to a factor of ten (from 5 mol% to 0.5 mol%). Kinetic studies are also included which provided the information required to propose mechanisms for the reactions.

The thesis is completed with the **experimental** section, which provides details of all procedures (both synthetic and kinetic), along with all physical and spectral data from isolated compounds. This is then followed by an appendix of all kinetic data collected.

Declaration

With the exception of areas that are specifically indicated, the work outlined in this thesis is the work of the author exclusively. None of the research carried out has been previously submitted for any other degree or qualification, either at Newcastle University or elsewhere.

Christopher Beattie

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Acknowledgements

Firstly, I would like to thank Professor Mike North for extending me the opportunity to undertake my PhD at Newcastle University. Without the expert guidance which I have received throughout my time, both at an undergraduate and postgraduate level, it would have been impossible to produce this thesis. I have found the experience of studying for my PhD to be extremely rewarding, both in terms of furthering my practical and theoretical chemistry knowledge as well as improving more general skills such as writing and presentation techniques.

I would also like to show my gratitude to my many colleagues I have known during my time working in Newcastle. Dr Pedro Villuendas gave me excellent guidance through my masters in the group, then continued to help in the early stages of my PhD, before returning to his native Spain. I am also very grateful to Dr Carl Young who assisted me for the remainder of my research and on into the writing stage. Acknowledgements are also due to all the past members of the North group; the various Erasmus, masters and PhD students as well as postdoctoral researchers who all contributed to making an excellent working environment in the lab.

Outside of the North group I would like to thank the EPSRC for my funding and Newcastle University for accepting me as a PhD student, and for providing a first class learning environment in the form of the chemistry department. The provision of professional laboratory workspace coupled with excellent staff, both technical and academic, made undertaking a PhD a highly rewarding task. In particular, I would like to thank Dr Corinne Wills of the NMR suite, whose contributions led to the smooth running of that service.

Outside of the chemical field, there are many people I would wish to acknowledge. Firstly, the group of friends that I have accumulated in my time living in Newcastle. These people proved to be an excellent distraction from working life. My various sets of housemates helped make my homes the most inhospitable environment for studying (in the best possible way!) which kept me sane over the years. Also, my thanks go to Irene whose invaluable contribution to this thesis involved providing either the gentle encouragement to work or the necessary diversion from it, depending on what was required at the time.

Finally, I would like to show my gratitude to my family, in particular, my parents Jack and Marie. Without their love and support in every possible form - from the early days of my school education, all the way through to the end of my postgraduate studies - this thesis would not exist. Therefore, it is to them that it is dedicated.

Selected Abbreviations

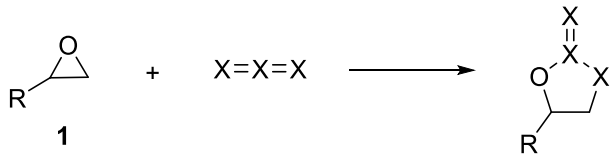
Bn	Benzyl group
Br	Broad
^{t}Bu	Tertiary butyl group
DCM	Dichloromethane
d	doublet
δ	NMR chemical shift
ee	Enantiomeric excess (%)
Eq.	Equivalents
GC	Gas chromatography
Hz	Hertz
IR	Infra-red
m	multiplet
mp	Melting point
MS	Mass spectrometry
NMR	Nuclear magnetic resonance
Ph	Phenyl group
ppm	Parts per million

^{i}Pr	Isopropyl group
^{n}Pr	Linear propyl group
q	Quartet
RT	Room temperature
Salen	Structures based around *N,N'*-bis(salicylidene)diaminoethane or *N,N'*-bis(salicylidene)diaminocyclohexane
s	singlet
TBAB	Tetrabutylammonium bromide
THF	Tetrahydrofuran
TMSCN	Trimethylsilyl cyanide - Me_3SiCN
t	triplet

Chapter 1. Introduction

The reactive nature of highly-strained, three-membered cyclic ethers known as epoxides (**1**) has rendered them extremely useful in chemical synthesis.[1] As well as often being desirable targets for organic synthesis, their reactivity also makes them valuable intermediates for further reactions. The best known chemistry in which epoxides are utilised is in polymerisation, forming epoxy resin products, which are used globally as powerful adhesives.[2]

A heterocumulene is defined as a molecule in which there are two or more consecutive double bonds including at least one heteroatom.[3] Numerous examples exist, including by far the best known, carbon dioxide (**2**), along with carbon disulphide (**3**), sulphur dioxide (**4**), isocyanates (**5**), isothiocyanates (**6**) and carbodiimides (**7**).



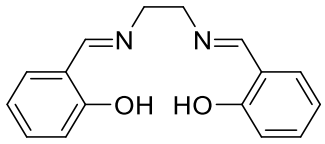
Scheme 1 - Coupling reaction of epoxides and heterocumulenes

O=C=O	S=C=S	O=S=O	RN=C=O	RN=C=S	RN=C=NR
2	**3**	**4**	**5**	**6**	**7**

The focus of this thesis is on the coupling reactions of epoxides with heterocumulenes (Scheme 1).[4] These reactions are attractive as the products are highly functionalised five-membered heterocyclic rings, which are produced in a way which is 100% atom economical. The product functionality can be highly varied, and by

changing the epoxide and the heterocumulene used it is possible to tailor the reaction to produce a multitude of different molecules each with different properties.

The catalysts being examined for these transformations will be from the metal salen family. The term salen refers to the class of ligands developed from the condensation of salicylaldehyde derivatives and diamines. The simplest salen structure is *N,N'*-bis(salicylidene)diaminoethane, **8**, the synthesis of which was first reported in 1933.[5] Salen ligands have proven very popular among chemists due to both the wide variety of metals that they are known to chelate to and the ease with which they can be altered to fit different synthetic needs. This has resulted in them being extensively studied in homogeneous catalysis.[6]



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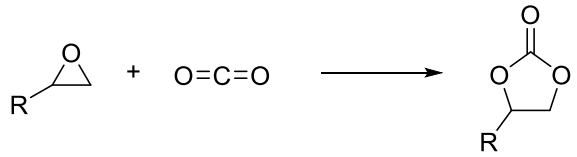
1.1 Epoxides and carbon dioxide



1 **2** **9**

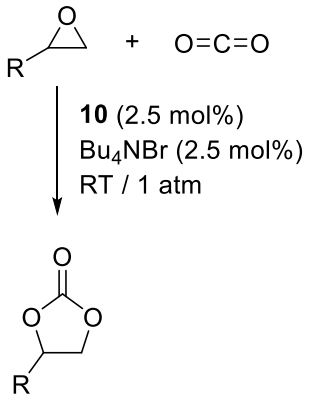
Scheme 2 - Formation of cyclic carbonates from epoxides and CO_2

The ability to form cyclic carbonates (**9**) by insertion of carbon dioxide into epoxides (Scheme 2) could provide help in the combatting of two major problems faced by the global community; climate change caused by the amount of carbon dioxide released into the atmosphere,[7] and finding new, sustainable raw materials for the

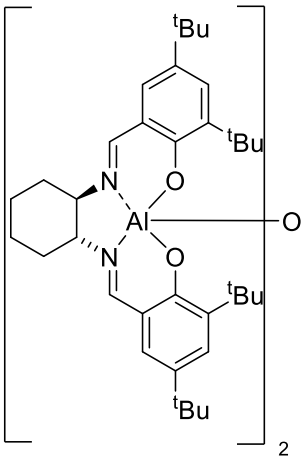
chemical industry to replace the diminishing supplies of crude oil.[8] In order for this process to be a realistic solution to reducing emissions, it needs to be carried out under ambient conditions, otherwise the result may be a net release of carbon dioxide. There is a precedent for other processes using carbon dioxide as a starting material - notably in the commercial production of salicylic acid[8,9] and urea,[10] along with a number of other reactions.[9]

The synthesis of cyclic carbonates is a commercial process[11] (for the production of ethylene and propylene carbonate) and has been extensively studied for a number of years. As a result, many catalyst systems have been developed and reported to be active. Unsurprisingly, as the process is so widely studied, it has also been extensively reviewed,[12] and will therefore not be comprehensively discussed in this introduction.

1.1.1 *North Group work*



Scheme 3 - Synthesis of cyclic carbonates using complex **10** as catalyst



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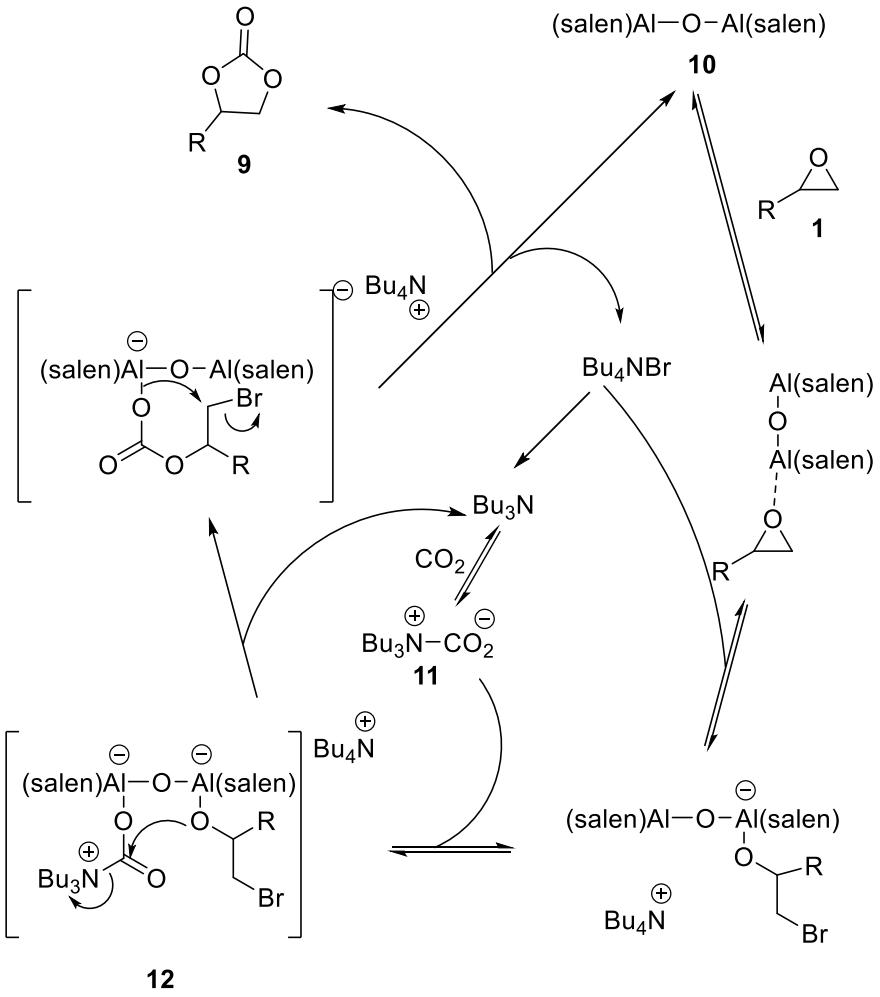
A feature of cyclic carbonate synthesis had been that it required high temperatures and/or high pressures in order to obtain product formation in any

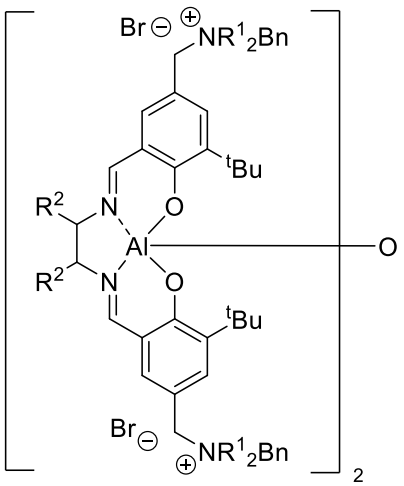
meaningful amount.[12] However, in 2007, a breakthrough was made in the North group when it was discovered that a combination of bimetallic aluminium complex **10** and tetrabutylammonium bromide gave excellent conversions at room temperature and atmospheric pressure, with loadings of just 2.5 mol% of both catalyst and cocatalyst (Scheme 3).[13] In order for these reactions to produce a net decrease in atmospheric carbon dioxide, it is necessary to seek out a system which requires as little energy to be put into the system as possible. Given the ambient conditions required for the catalysts, the North group results meant that, for the first time, a significant step towards a net decrease of carbon dioxide could be achieved from the synthesis of cyclic carbonates.



Scheme 4 - Proposed catalytic cylce for cyclic carbonate synthesis catalysed by complex **10** and Bu_4NBr

After mechanistic studies were carried out on this system it was found that the rate equation took the form shown in Equation 1.[14] A mechanism (shown in Scheme 4) which accounts for the second order dependence on the concentration of tetrabutylammonium bromide was proposed. In this mechanism tetrabutylammonium bromide performed two roles; to ring-open the epoxide by attack of a bromide anion and to act as a source of tributylamine which would form carbamate structure **11** by coordinating to the carbon dioxide. This would activate the carbon dioxide for nucleophilic attack. The bimetallic nature of complex **10** was essential as one metal centre coordinates to the epoxide and the other to carbamate **11**, bringing the two reacting species together, such as in adduct **12**.

Equation 1: Rate = k [epoxide] [CO_2] [**10**] [Bu_4NBr]^2



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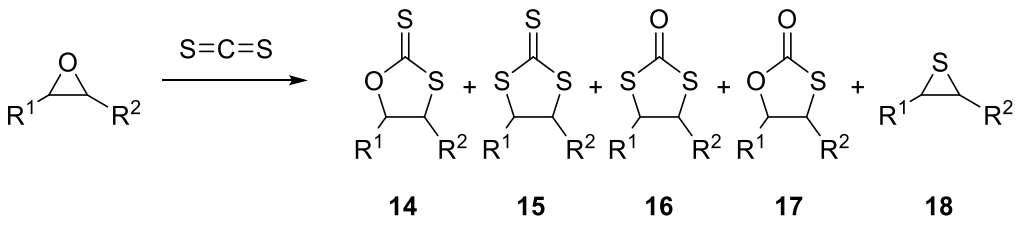
Work was then focussed on producing one-component catalysts which combined the catalyst and cocatalyst by incorporating the tetrabutylammonium bromide into the salen ligand.[15] These take the general form of complex **13** and could then be mounted

onto a solid support with a view to using them in the exhaust streams of industrial plants which produce large amounts of carbon dioxide, in order to make cyclic carbonates from the waste. To test this, the catalytic activity of the catalysts mounted on a silica support was examined under continuous flow conditions,[16] with results again showing excellent conversions, and therefore a significant amount of carbon dioxide could be removed from the gas which was being passed over the system. The breakthrough using complex **10** for this reaction led the group to study the catalytic activity of this system on other reactions involving other heterocumulenes.

1.2 Epoxides and carbon disulphide

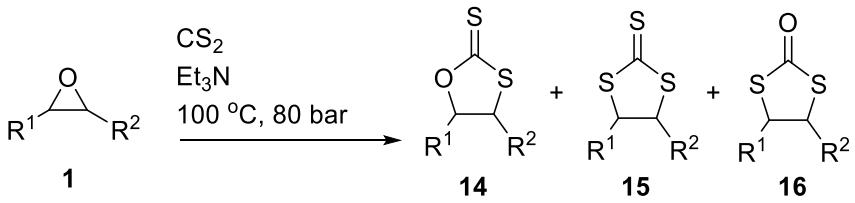
Despite the obvious similarities, the reaction between epoxides **1** and carbon disulphide **3** is known to be much more complicated than the synthesis of cyclic carbonates. This is mainly due to the potential number of products that can be formed.[17] As shown in Scheme 5, there is a possibility of forming five different products from these two reagents, and the products formed depend on the catalyst system used and the conditions of the reaction. The potential products include 1,3-oxathiolane-2-thiones **14**,[18,19] 1,3-dithiolane-2-thiones **15**,[20] 1,3-dithiolane-2-ones **16**,[21,22] 1,3-oxathiolane-2-ones **17**[17b] and thiiranes **18**.[18a]



Scheme 5 - Products from reaction of epoxides and carbon disulphide

The interest of this thesis is mainly in the production of 1,3-oxathiolane-2-thiones (dithiocarbonates) **14** and 1,3-diothiolane-2-thiones (trithiocarbonates) **15**. These products have a number of commercial applications, for example, both dithiocarbonates and trithiocarbonates are known to possess radioprotective activity.[23] Also, dithiocarbonates are used as reagents in polymer synthesis,[18c, 24 , 25] and trithiocarbonates are known to possess insecticidal activity.[26]

Previously, Taguchi reported that, at temperatures of 100 ^{o}C and pressures up to 80 bar, triethylamine showed catalytic activity for the synthesis of a mixture of thiocarbonate products **14**, **15** and **16** in the presence of carbon disulphide (Scheme 6).[17] The reactions gave good yields across a number of different epoxide substrates, but despite a reasonably high catalyst loading of 10 mol%, significant amounts of product could not be obtained without very harsh conditions, namely reaction pressures of up to 80 bar.



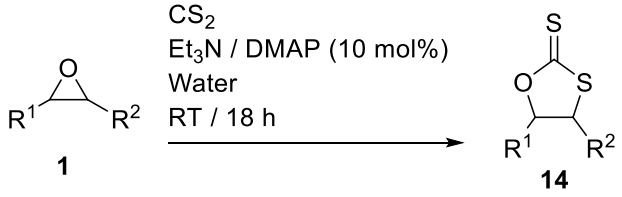
Scheme 6 - Use of triethylamine as a catalyst for thiocarbonate synthesis

1.2.1 *Dithiocarbonate formation*

Numerous catalyst systems have been reported for the selective synthesis of 1,3-oxathiolane-2-thiones **14**. In 1995, Endo investigated the use of alkali metal salts as catalysts.[18a] Salts containing various metals and counterions were tested and it was found that lithium bromide offered the best combination of catalytic activity and product selectivity. Having also investigated varying the solvent used, it was reported

that 5 mol% of catalyst in THF, at room temperature were the optimum conditions for producing the highest yields, while maintaining the best product ratio.

In 2008, Yavari reported that a catalyst system of a mixture of sodium hydride and methanol, forming sodium methoxide *in situ*, gave excellent yields of thiocarbonate product **14** from epoxides and carbon disulphide.[18f] Despite the fact that a clean reaction occurred at room temperature, the system required a reasonably high catalyst loading of 10 mol%. The need for this amount of catalyst is thought to be due to the poor leaving group ability of the methoxide anion.



Scheme 7 - Use of Lewis bases in water as a catalyst system for thiocarbonate synthesis

Although literature precedent[17] reported that high temperatures and very high pressures were required in order for triethylamine to be an effective catalyst for this reaction, Saidi showed that by using water as a solvent, reasonable yields could be obtained under ambient conditions. Other Lewis bases were tested including DABCO and DBU, but it was found that the only truly effective systems were with triethylamine and DMAP (Scheme 7).[18g] Unlike Yavari's work with high pressure and in organic solvents, this reaction was very selective in only forming dithiocarbonate product **14**. The proposed mechanism involves the DMAP or triethylamine attacking the carbon disulphide forming a thiocarbamate species, while the epoxide is activated by hydrogen

bonding by a water molecule. The thiocarbamate then ring-opens the epoxide and then both water and the Lewis base are released in a ring-closure step forming the five-membered dithiocarbonate ring.

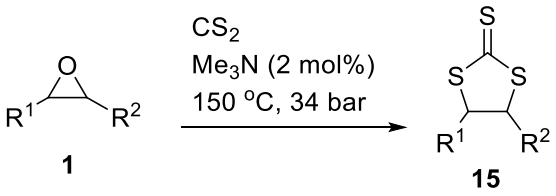
In 2009, a novel heterogeneous system was proposed by Maggi,[18e] in which the basic solid hydrotalcite was investigated as a catalyst for the selective production of dithiocarbonate product **14**. It was found that the reaction occurred on the surface of the solid-state catalyst, and it produced good yields using various substrates with excellent product selectivity. The conditions were optimised and consisted of a temperature of 50 ^{o}C with a time of 5 hours. The reactions did require a relatively high catalyst loading; however it was possible to recover the catalyst from the reaction mixture via a simple filtration step. Following this, the catalyst could be reused effectively and repeatedly with no significant drop in activity.

Other systems have been reported to be active for the selective synthesis of 1,3-oxathiolane-2-thiones **14** including tributylphosphine and lithium perchlorate by Endo in 2005[18c] and Huo in 2008[18d], which gave good results. Also, using the Lewis base DMAP this time with 4-methoxyphenol as cocatalyst, gave good yields and selectivity, but required reaction temperatures of 120 ^{o}C in order to achieve them.

1.2.2 *Trithiocarbonate formation*

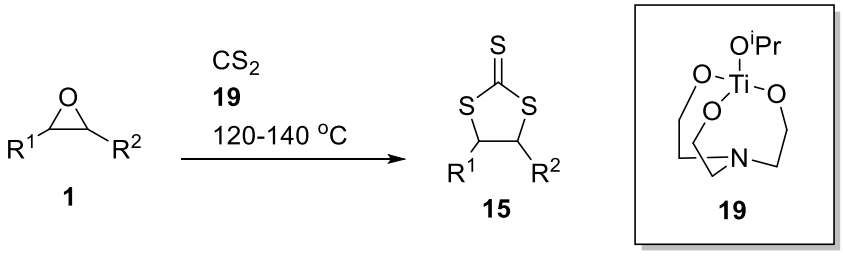
A number of catalytic systems have been proposed that selectively produce 1,3-thiolane-2-thiones, or trithiocarbonates **15**, from epoxides and carbon disulphide. The first example was in 1960,[20a] when Durden attempted to use tertiary amines to catalyse this transformation. Of the amines tested, trimethylamine gave the best results – a moderate yield and 100% product selectivity. The conditions required were relatively

harsh, with a reaction temperature of 150 °C, 34 bar pressure and 2 mol% catalyst (Scheme 8), but this result did pave the way for future work in this area.



Scheme 8 - Use of trimethylamine as a catalyst for selective trithiocarbonate synthesis

For the next two decades research focussed on the selective formation of trithiocarbonates **15**, and was mainly performed using potassium hydroxide or alkoxides.[20b,c,d] In 1974, both McCasland[20e] and Owen[20f] used potassium hydroxide in order to make trithiocarbonates from epoxidised sugar derivatives. These were intermediates in the production of various sugar derived thiocarbonates and thioethers.

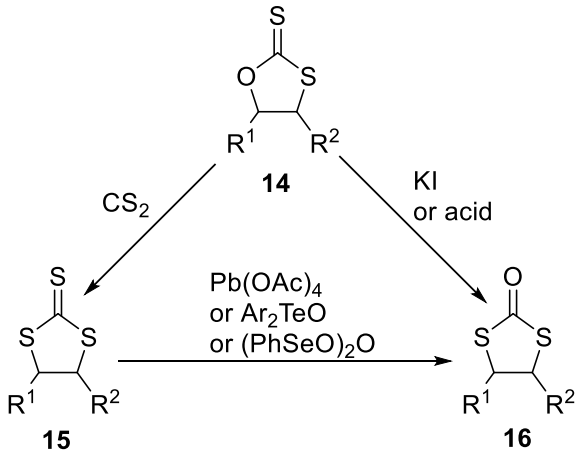


Scheme 9 - Use of **19** as a catalyst for thiocarbonate synthesis

The first example of a titanium complex being used for this type of transformation was in 2001, when Endo reported the use of (2-propanolato)titanitrane **19** as an effective catalyst.[20g] Both five- (from epoxides) and six-membered (from

oxetanes) cyclic trithiocarbonates were synthesised in excellent yields, with good substrate diversity (Scheme 9). A mechanism was proposed in which the titanium centre of **19** activates the carbon disulphide forming a thiocarbamate like species. It then acts as a Lewis acid and simultaneously activates the epoxide for attack by the carbamate and brings the two species together. A ring-closure step then occurs and a dithiocarbonate species is formed, which then rapidly re-enters the cycle and O=C=S is eliminated and another molecule of carbon disulphide is inserted, forming the trithiocarbonate. A disadvantage of the system was that it required temperatures up to 140 ^{o}C and a reaction time of 48 hours in order to gain good results.

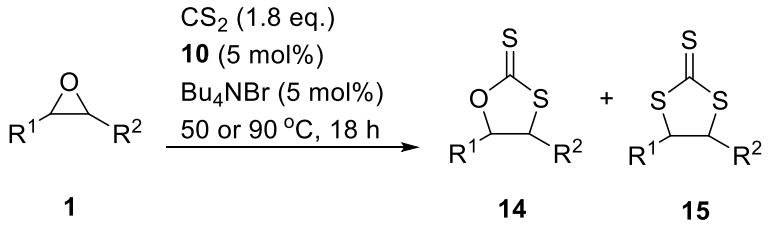
In addition to the formation of thiocarbonate products directly from epoxides and carbon disulphide, it is also possible to perform reactions on the products themselves in order to manipulate which product is formed. As shown in Scheme 10, it is possible to produce trithiocarbonate **15** by reacting dithiocarbonate **14** with excess carbon disulphide. Previous work has also shown that **14**, in the presence of potassium iodide[19] or an acid[24] will isomerise to form 1,3-diothiolane-2-ones **16**. These products can also be formed by reaction of trithiocarbonate **15** with any of; lead tetraacetate,[22b] various diaryl tellurium complexes[22c] or benzeneseleninic anhydride.[22d]



Scheme 10 - Rearrangement of thiocarbonate products **14**, **15** and **16**

1.2.3 *North group work*

In 2010, the first catalytic system involving a salen complex was developed for this reaction.[27] Having proved so successful with the synthesis of cyclic carbonates, the North group investigated the use of complex **10** for the insertion of carbon disulphide into epoxides. It was found that, as with cyclic carbonate synthesis, the catalyst required a cocatalyst (tetrabutylammonium bromide) in order for any products to form, with both the catalyst and cocatalyst showing no activity individually. However, unlike the insertion of carbon dioxide into epoxides, increased temperatures were required for this reaction to initiate, even with higher catalyst loadings. It was found during the optimisation steps that by controlling the temperature, it was possible to control which product formed; and it was observed that if the reaction was run at 50 ^{o}C, dithiocarbonate product **14** would form predominantly, while at a temperature of 90 ^{o}C, trithiocarbonate **15** was the major product. After optimisation, the ideal conditions were found to be using 5 mol% of catalyst and cocatalyst, 1.8 equivalents of carbon disulphide in solvent free conditions, at 50 or 90 ^{o}C (Scheme 11).



Scheme 11 - Optimum conditions for the synthesis of thiocarbonates

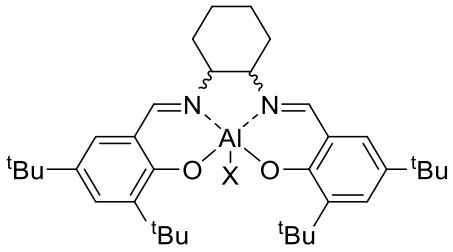
The system exhibited excellent substrate tolerance when tested with various epoxides, and in each case, with the exception of styrene oxide (which only ever formed

15), dithiocarbonate **14** was formed at 50 ^{o}C and trithiocarbonate **15** was formed at 90 ^{o}C. It was found by X-ray crystallography that the products which bore a vicinally substituted cyclohexyl ring were *trans*-fused to the 5-membered thiocarbonate ring. Since the substrate cyclohexene oxide has to be *cis* to begin with, this proves that an inversion of stereochemistry occurs at the reacting carbon, which gives a clue as to the mechanism. This was different to the results for cyclic carbonate synthesis in which the products formed with retention of stereochemistry, and therefore implies a different mechanism. Another way in which this reaction differs from cyclic carbonate synthesis is that tributylamine can be just as effective a cocatalyst as tetrabutylammonium bromide, implying that the function of the cocatalyst is merely to act as a source of tributylamine for the reaction rather than a source of bromide ion.

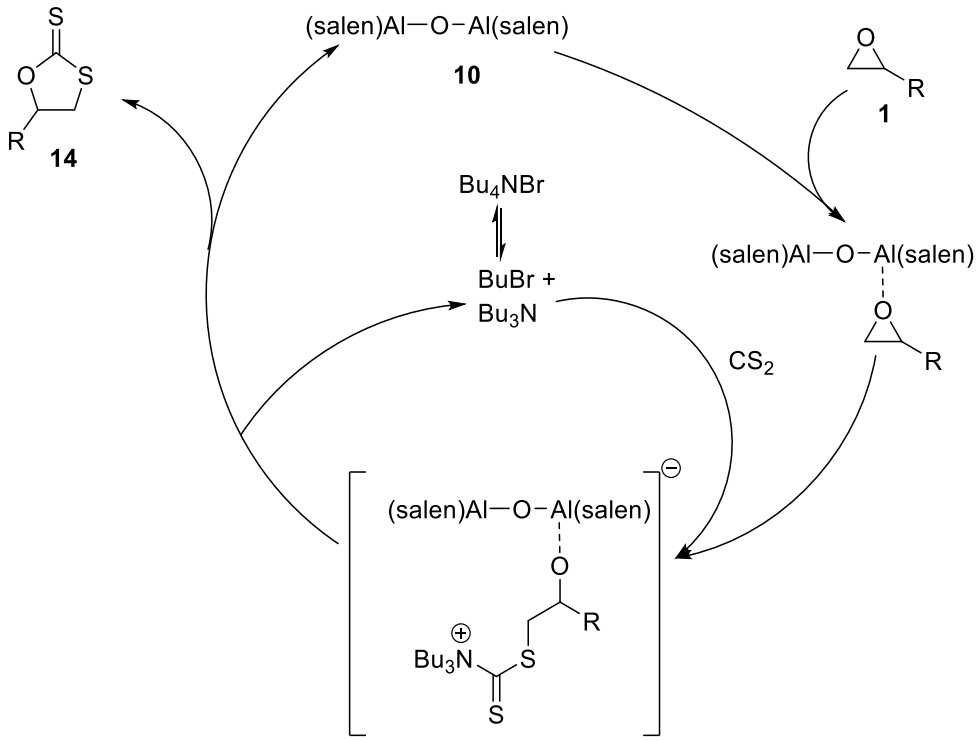
Equation 2: Rate = k [**10**] [epoxide].

Kinetic studies were carried out on this system and the rate equation was determined (Equation 2). This took a significantly different form to the one determined for cyclic carbonate synthesis, which further implies that this transformation occurs via a different mechanism. A catalytic cycle which accounts for the differences between the carbon dioxide and carbon disulphide reactions was proposed and is shown in Scheme 12. Firstly, complex **10** coordinates to the epoxide, activating it for attack. A tributylamine molecule then reacts with carbon disulphide forming a thiocarbamate species, which then ring-opens the activated epoxide. A ring-closure then occurs, eliminating the dithiocarbonate, and reforming the tributylamine and complex **10**. This mechanism implies that the sole purpose of the aluminium centre is to act as a Lewis

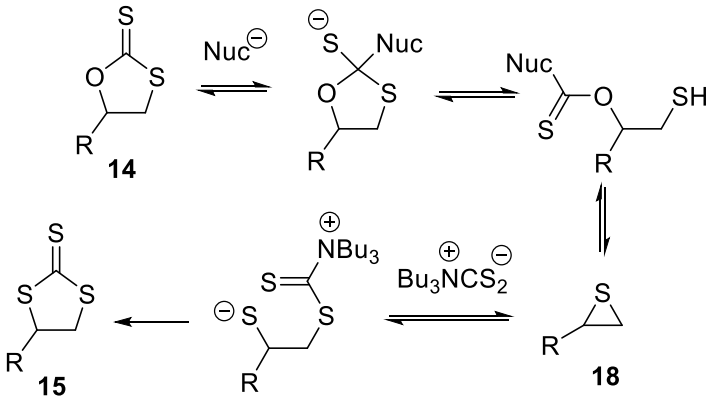
acid, and that the bimetallic nature of complex **10** is not necessary for this reaction. This was further backed up by test reactions carried out using monosubstituted complexes **20**, **21** and **22**. It was found that the monometallic catalysts were just as effective as bimetallic complex **10**, producing products in approximately the same yield and ratio of di- to trithiocarbonate.



20: X = Et
21: X = OEt
22: X = Cl



Scheme 12 - Catalytic cycle for production of thiocarbonates catalysed by **10**



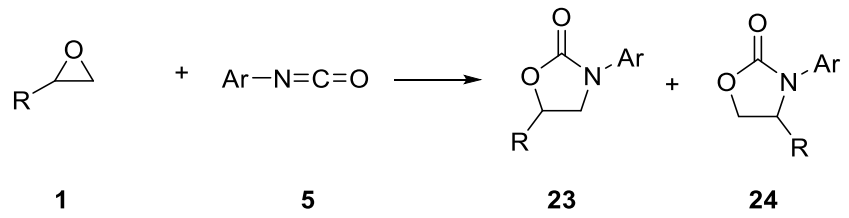
Scheme 13 - Mechanism for formation of trithiocarbonates **15**

This cycle (Scheme 12) accounts for the formation of dithiocarbonates **14**. The mechanism by which trithiocarbonates **15** form from these products has previously been proposed and accepted (Scheme 13).[17,20a,b,d] It involves the attack on the carbon-sulphur double bond by a nucleophile, which then ring opens the thiocarbonate. The sulphur anion then eliminates O=C=S to form a thiirane **18**, which in turn reacts irreversibly with another triethylamine-activated carbon disulphide molecule, to form trithiocarbonate **15**.

1.3 Epoxides and Isocyanates

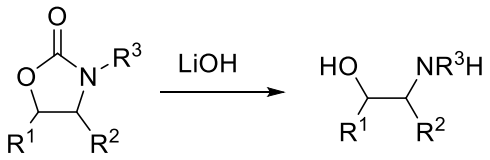
Another type of heterocumulene that epoxides have been known to react with is isocyanates, **5**. This reaction has been the focus of a substantial amount of research[4b,28] as the products, shown in Scheme 14, known as oxazolidinones (**23** and **24**), can be highly varied by altering the substituents on both the epoxide and isocyanate, and also due to the fact that two regioisomers tend to form. Oxazolidinones are desirable products in themselves, as they are known to possess various medicinal properties, and

are therefore in use as antibacterial and antimicrobial agents.[29] They are also useful intermediates in other chemical syntheses; most notably in the production of ß-amino alcohols, **25**, as shown in Scheme 15.[30]



1 **5** **23** **24**

Scheme 14 - Formation of oxazolidinones from epoxides and isocyanates



25

Scheme 15 - Formation of β–aminoalcohols from oxazolidinones

1.3.1 *Quaternary ammonium halide salts*

Previous work in this area has mostly involved arylisocyanates reacting with monosubstituted epoxides. It has been found that these react much more readily with each other than when using isocyanates with alkyl substituents or epoxides with multiple substituents. An early example of the synthesis of oxazolidinones from epoxides and isocyanates is from 1958,[31] when Peppel developed a catalyst system involving quaternary ammonium halides. It was reported that ethylene oxide and phenylisocyanate were good substrates for this reaction, giving high yields when using tetraethylammonium bromide as the catalyst. While this reaction did require harsh

conditions, high pressures and temperatures of up to 200 ^{o}C were reportedly necessary, this work did pave the way for this route of oxazolidinone synthesis and was the first time that the reactions did not merely result in the polymerisation of the isocyanate.

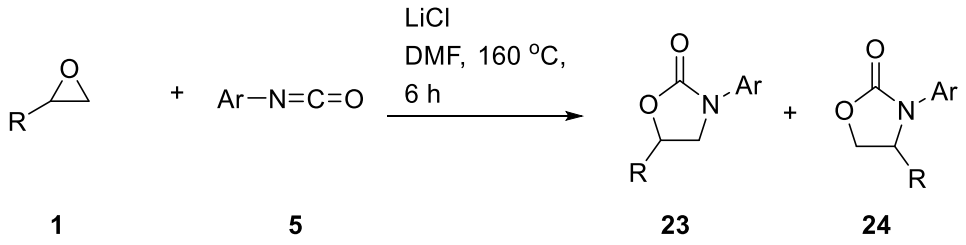
Similar results on the use of quaternary ammonium salts as catalysts were reported by Gambaryan in 1971.[32] Again it was found that tetraethylammonium bromide could act as an effective catalyst for the synthesis of the corresponding oxazolidinone, this time from the reaction of perfluoro-*tert*-butyl isocyanate with ethylene oxide. Despite the fairly harsh conditions applied to the system, the yields were not exceptional, at around only 50%.

The next use of quaternary ammonium salts as catalysts for this reaction was not until 2008. Sucheck reported that tetrabutylammonium bromide catalysed the reaction between epibromohydrin and a series of *para*-substituted aryl isocyanates, which gave moderate yields of oxazolidinones.[33] The chemistry was then expanded to test a number of different epoxides, each time giving yields between 39 and 61%, despite reactions running in toluene under reflux. Therefore, quaternary ammonium salts have some advantages as catalysts; they are simple, inexpensive and can easily be removed from reaction mixtures via an aqueous wash. However, the results obtained tend to be moderate in terms of yields of products, and the conditions required can be quite harsh.

1.3.2 *Lithium halide salts*

A different type of catalyst system which has received much attention throughout the last few decades has been lithium halide species. In 1968, Herweh presented results showing that lithium chloride was catalytically active for this transformation.[34] Mixtures of the 3,4- (**23**) and 3,5- (**24**) substituted oxazolidinones

were obtained in good yields of up to 76%. However the conditions, as shown in Scheme 16, were harsh; involving dimethylformamide under reflux and high catalyst loadings.

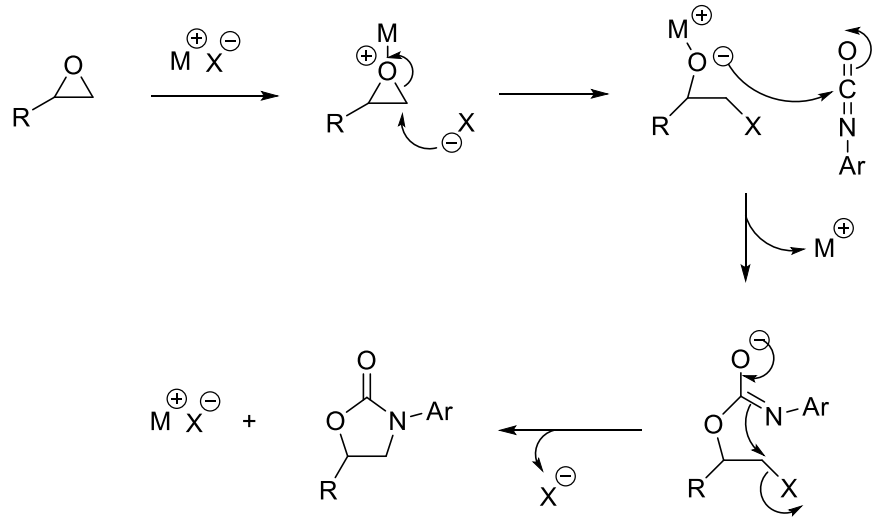


Scheme 16 - Formation of oxazolidinones catalysed by lithium chloride

The same group reported improvements to the reaction conditions required by using lithium bromide as a catalyst,[35] and this time including a cocatalyst of tributylphosphine oxide. It is thought that the role of the cocatalyst was to interact with the salt and increase its solubility. It was for this reason that the reaction temperature was able to be reduced and the need for the highly polar solvent was negated. The substrate versatility was then tested by using various arylisocyanates and a selection of epoxides, with similar results being obtained across the range.[36] The use of lithium bromide in this system for production of compounds **23** and **24** was adopted as the chosen route for Wang,[37] Britelli[38,39] and Barbachyn,[40] who wanted to synthesise a series of oxazolidinone products for an investigation into the antibacterial activities of these compounds.

Some mechanistic studies were carried out by Javni in 2003.[41] It was proposed that when a metal halide salt is acting as a catalyst for this transformation the halide anion ring-opens the epoxide, possibly while the metal atom is acting as a Lewis acid by

coordinating to the oxygen atom. This action promotes the nucleophilic attack. The anionic species then attacks the carbon of the isocyanate group, which in turn ring-closes the molecule and therefore forms the oxazolidinone which in turn eliminates both the halide ion and the metal cation, reforming the catalyst. This mechanism is outlined in Scheme 17. Despite being developed as early as 1971, this catalyst system is still in use today.[42,43] The simplicity and ready availability of the catalytic species, along with the relatively mild conditions, good substrate range and product control has made this system popular amongst researchers.



Scheme 17 - Mechanism of oxazolidinone formation catalysed by metal halide salts

1.3.3 *Organotin and organoantimony halide salts*

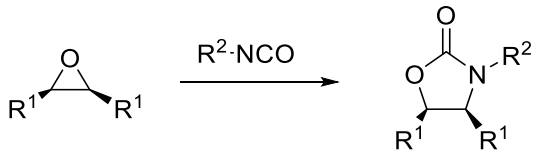
Another class of catalyst system which has received attention for its activity in this transformation involves either tetraphenylantimony iodide or organotin halide complexes, or in some cases a mixture of both. The first research reported was carried out by Baba in 1986.[44] In this work, he showed that using tetraphenylantimony iodide

on its own as a catalyst could force the selective production of the 3,5- substituted oxazolidinone product **23**, rather than the 3,4- substituted variant. This was significant as it was the first time that a catalyst was reported to promote the reaction which favourably formed this particular regioisomer.

The initial work involved showing that the system could work on a wide range of terminal epoxides, and then to demonstrate the substrate versatility across a range of arylisocyanates. A study to see whether altering the metal and counterion used could positively affect the results obtained was carried out. It was found that of the ones tested only an antimony metal centre and iodide counterion showed any activity. Later the same year, the system was expanded and it was shown that by using a mixture of the antimony compound and tributyltin iodide the substrate versatility could be improved further and included disubstituted epoxides.[45] Control experiments were carried out showing that individually, the two metal compounds showed no catalytic activity for this reaction.

Again in 1986, Shibata began work using tin complexes for the same reaction.[46] He found that by introducing a Lewis basic component into the catalyst system involving an organotin compound, a highly active mixture formed and produced excellent results. A cocatalyst screening of Lewis bases found that triphenylphosphine oxide showed the highest activity. It was found that under mild reaction conditions of atmospheric pressure, a temperature of 40 ^{o}C and a reaction time of only two hours, yields of up to 100 % could be obtained. This system was proven to work on a range of epoxides and aryl isocyanates. In 1990, the first research was done in order to investigate the mechanistic pathway that these reactions follow, when a tin based catalyst was in use.[47] Work was carried out on chiral epoxides to observe any pieces of stereochemical information that could provide clues to the reaction mechanism. It was

found that the initial stereochemistry of the epoxide used was retained in the products, as shown in Scheme 18.

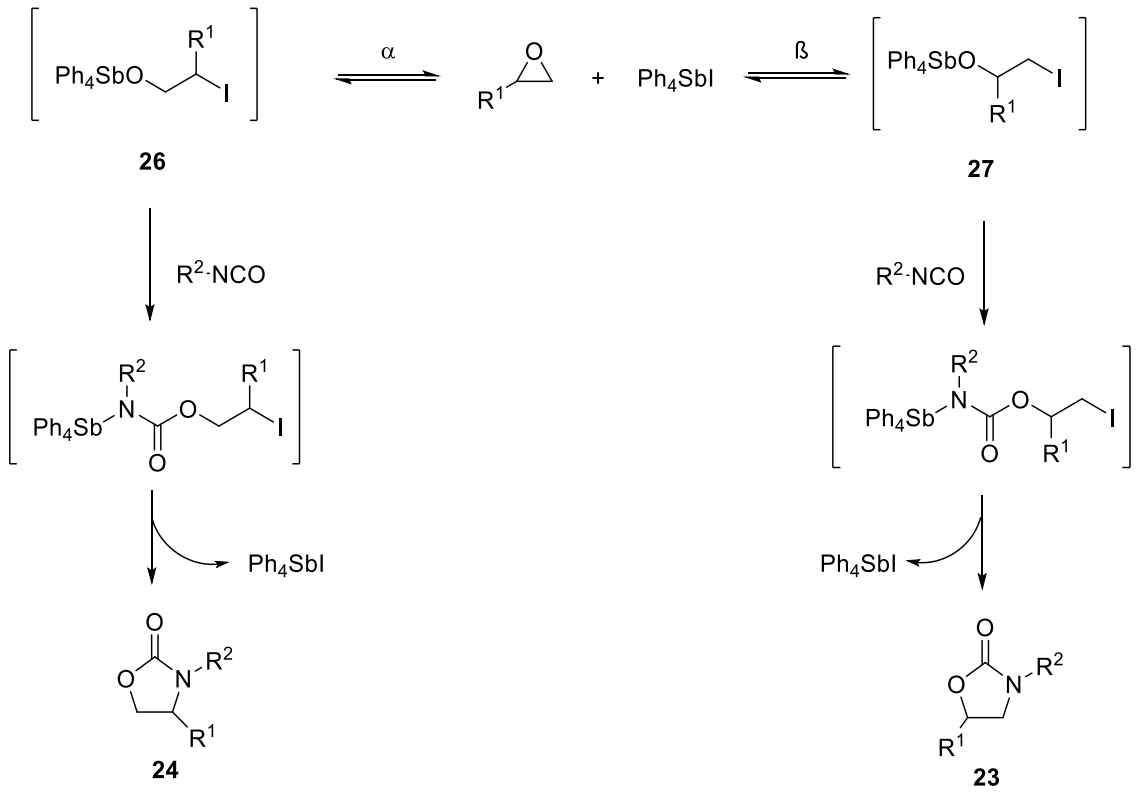


Scheme 18 - Stereochemical retention of oxazolidinone products

In 1990, Baba released a paper detailing mechanistic studies that were carried out using tetraphenylantimony iodide.[48] The proposed mechanism is shown in Scheme 19. The general structure of the mechanism is the same as that of the metal halide salt catalysed reaction, shown in Scheme 17, in that it involves three steps; cleavage of epoxide, insertion of isocyanate and finally, ring-closure to form the cycloadduct products. The reason that this catalyst system stands out is the fact that the opposite regioisomer is formed. The regioisomer selectivity depends upon the position upon which the epoxide is ring-opened in the first step. An α-cleavage, as is the case in this reaction, will result in the 3,4-isomer (**24**) while a ß-cleavage results in 3,5- isomer (**23**).[49] The pathways to both regioisomers are shown in Scheme 19.

As has been shown, trialkyltin and trialkylantimony complexes have proven to be good systems for the production of oxazolidinones from epoxides and isocyanates. The systems can be optimised to produce excellent results and can be tailored to be regioselective to form the desired products. The main drawbacks with the system stem from the fact that the catalysts are based on expensive metals, and also the high toxicity

of both organotin and organoantimony compounds make them undesirable to use on a large scale.

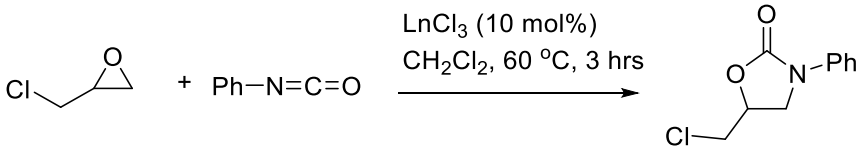


Scheme 19 - Proposed mechanisms of formation of regioisomers of oxazolidinones

1.3.4 *Rare Earth metal salts*

Lanthanide catalysts have also been investigated as potentially important for this chemical transformation. In 1994, in what appeared to be the first of its kind, a lanthanide based system was reported by Qian.[50] The reactions used lanthanide chloride catalysts and a narrow screening of three rare earth metals (yttrium, ytterbium and erbium) was conducted on the reaction between epichlorohydrin and phenylisocyanate which exclusively formed the 3,5- regioisomer. These catalysts were presumably

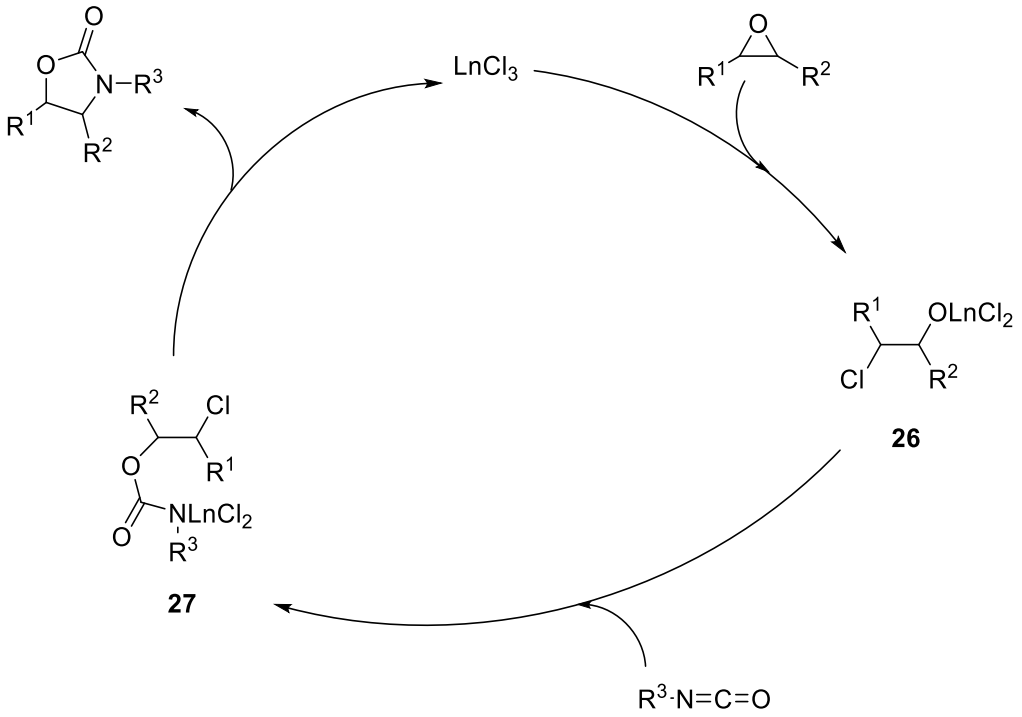
selected for testing as they have the advantages of being relatively inexpensive and commercially available. Firstly, the three metals were tested under the conditions shown in Scheme 20; a sealed tube at 60 ^{o}C, with 10 mol% of catalyst, in dichloromethane for 3 hours. It was found that while all three catalysts gave excellent yields, yttrium was the most active, giving a 99% yield, while the result using erbium was the lowest giving an 89 % yield.



Scheme 20 - Lanthanide catalysed synthesis of oxazolidinones

As this system proved to be so successful, it was tested across a range of common epoxides which showed that it could successfully catalyse reactions involving alkyl, aryl and disubstituted substrates. Interestingly it was then proven to be active in transformations involving two examples of isocyanate substrates which contained alkyl substituents, which is a rare trait for catalysts of this reaction. Other notable observations made were that yttrium trichloride hexahydrate showed no activity and triphenylphosphine oxide had to be added to the reaction mixture involving the aryl example, in order to get a quantitative yield. A catalytic cycle was proposed and is outlined in Scheme 21. It shows the metal activating the epoxide to nucleophilic attack by the chloride anion, which ring-opens the epoxide forming adduct **26**. The isocyanate molecule then inserts itself into the metal-oxygen bond forming adduct **27**, which is

followed by the ring-closing step in which the catalyst is eliminated and the oxazolidinone is produced.



Scheme 21 - Proposed mechanism of lanthanide-catalysed oxazolidinone synthesis

This remained the only publication of a catalytic system based on a lanthanide compound until 2003 when Wu reported research done on this transformation.[51] It was suggested that the previous results obtained by Qian[50] could be improved upon by switching to a samarium-based catalyst. While Qian found that heating the mixture was necessary for obtaining favourable results using the yttrium-based system, reactions were found to go to completion under mild conditions when using samarium triiodide as a catalyst. It was found that using 10 mol% of catalyst, at room temperature for three hours yielded excellent results across a range of substrates. A reaction mechanism identical to that of the yttrium system was proposed, again with the lanthanide

activating the epoxide for opening via attack by the halogen anion. Since the two mechanisms are identical it is thought that the improvement in the required reaction conditions was due to the better leaving group ability of the iodide ion when compared to its chloride counterpart.

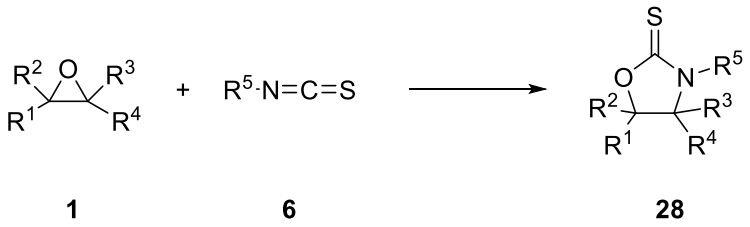
The disadvantages of this system are that it still requires a reasonably high 10 mol% of catalyst. However, due to the improved conditions under which the system can operate, along with its simplicity and the short reaction time coupled with high yields, this class of catalyst has been selected for further study, both in a multi-step synthesis of medically active compounds,[29b] as well as the asymmetric synthesis of oxazolidinones using chiral versions of lanthanide compounds.[52]

1.3.5 *Magnesium halides*

The final class of catalyst which has been researched for the formation of oxazolidinones from epoxides and isocyanates is magnesium halides. While not very widely studied, these compounds have the advantage of being non-toxic, abundant and inexpensive. This was first reported in one of the steps in the synthesis of the antibiotic linezolid in 2009.[53] It was reported that a chemical yield of 96% was obtained when using either magnesium iodide or magnesium bromide as the catalyst. Following this, in 2010, Zhang showed that the reported system could give high yields under ambient conditions producing a variety of oxazolidinones, but as for the previous report in the Linezolid synthesis,[53] a very high catalyst loading of 50 mol% was required.[54] Despite the ready availability of the compounds used, this was a major disadvantage in using this chemistry.

1.4 Epoxides and Isothiocyanates

As has already been shown, epoxides, **1**, react readily with oxygen, sulphur and nitrogen based heterocumulene nucleophiles, therefore, it is reasonable that they will also react to some extent with isothiocyanates, **6**, as well. As with the other heterocumulenes discussed, the products of these reactions are 5-membered heterocyclic compounds, however this time containing a carbon-sulphur double bond. The reaction is outlined in Scheme 22 and the products, **28**, are known as oxazolidine thiones. For the last few decades oxazolidinone thiones have drawn some attention due to the interesting biological activity that some sulphur containing heterocycles have exhibited.[55,56,57,58,59]



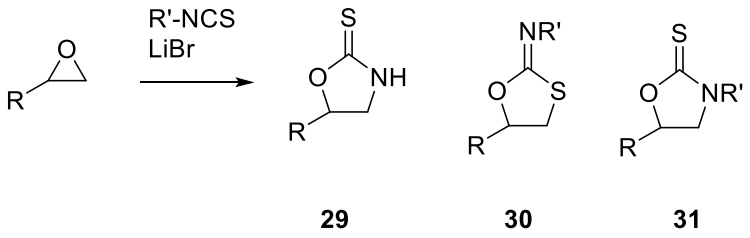
1 **6** **28**

Scheme 22 - Reaction of epoxides with isothiocyanates

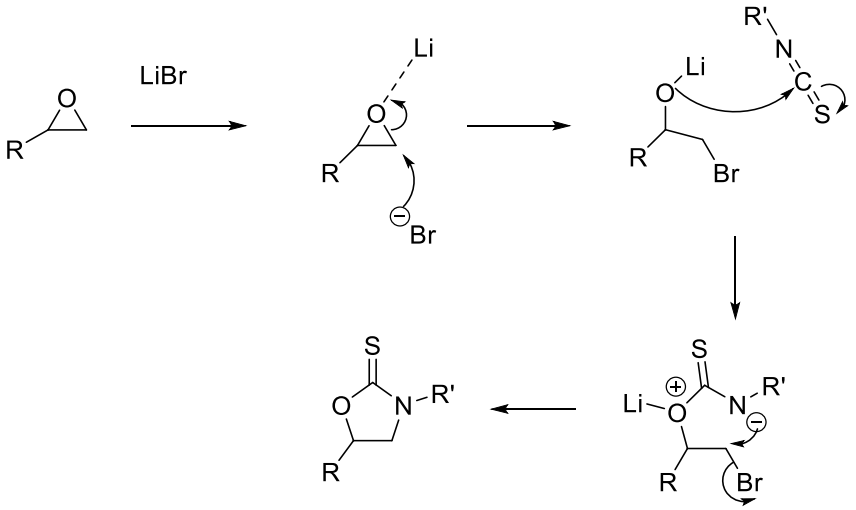
1.4.1 *Lithium halide complexes*

The first reports of any oxazolidine thione-forming reaction from epoxides and isothiocyanates were presented as early as 1965 when a Russian and a German group independently isolated the products amongst various other reported compounds that formed during the reaction.[60,61] In 1982, Wittman reported the formation of oxazolidine thiones from these reactions upon carrying out a screening of coupling reactions involving epoxides and various other reagents including numerous heterocumulenes.[62] The class of catalyst chosen to investigate was lithium halides and it was found that a reasonable amount of activity was exhibited by using catalytic amounts of lithium

chloride. It was later theorised that oxazolidine thiones may possess properties with positive biological implications, which resulted in some work being focussed on developing and optimising catalyst systems for their synthesis.[55-59]



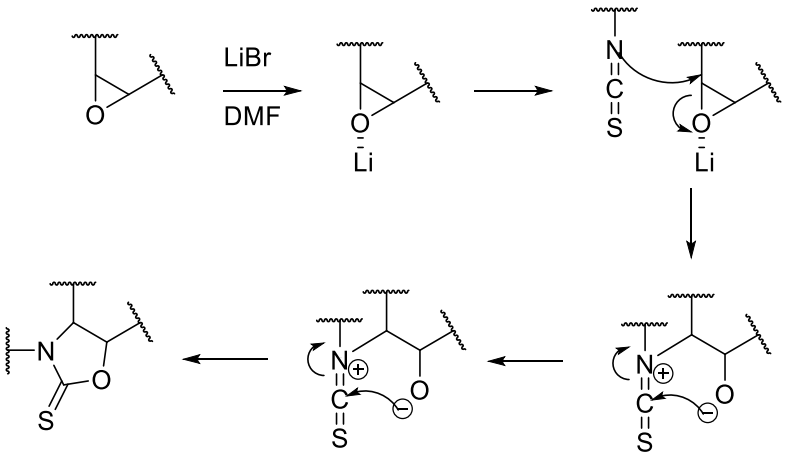
Scheme 23 - Outline of products formed



Scheme 24 - Proposed mechanism for formation of oxazolidine thiones

In 1990, Ahmad built on the previous results using lithium halide catalyst systems, trying to optimise one for this transformation in particular.[63] It was found that equimolar amounts of epoxide and isothiocyanate would react in the presence of a catalytic amount of lithium bromide in refluxing dimethylformamide. It was believed

that the result of this reaction was the formation of three products (**29**, **30**, **31**), the details of which are outlined in Scheme 23. A reaction mechanism was proposed which accounted for the formation of the oxazolidine thione product **31** which is shown in Scheme 24. The lithium acts as a Lewis acid, activating the epoxide for the ring-opening attack by the bromide anion. The epoxide then attacks the imide bond of the isothiocyanate group, creating a zwitterionic species, which intramolecularly ring-closes, forming the five-membered ring product.

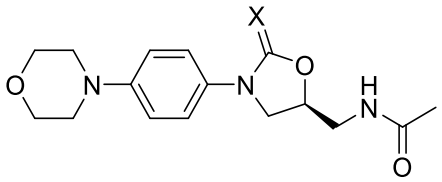


Scheme 25 - Mechanism of steroidal oxazoline thione formation

Two further examples of lithium bromide being selected as a catalyst for this transformation exist in the literature, both from 2004. Mushfiq tested steroidal epoxides as substrates in order to gain steroidal oxazolidine thiones with a view to test their biological effects.[64] The system that was used again involved lithium bromide in DMF under reflux. The synthesis was successful as Mushfiq was able to fully characterise these steroidal products as well as using them as intermediates in making further derivatives. A mechanism was proposed which was different to the one reported by

Ahmad in 1990.[63] This mechanism, shown in Scheme 25, involves the lone pair of the nitrogen atom in the isothiocyanate group ring-opening the lithium-activated epoxide, rather than the bromide ion. The resultant oxygen anion then attacks the carbon-sulphur double bond resulting in the heterocyclic product.

This chemistry was also adopted by Lohray,[65] who aimed to develop thio-analogues, **32**, of the antibiotic drug linezolid, **33**, which is used to treat infections caused by bacteria which are resistant to some standard antibiotics. Lithium bromide was selected as the catalyst system of choice and it proved successful for this synthesis. Given the interest in 5-membered sulphur containing heterocycles for their biological activity[55-59] and the well-established antibacterial nature of linezolid, it was thought that these products may have very beneficial biological properties. Disappointingly, however, the thio-analogues of linezolid displayed negligible antibacterial character. This discovery was followed by an investigation into the reasons for this lack of activity via molecular modelling.



32: X = S
33: X = O = Linezolid

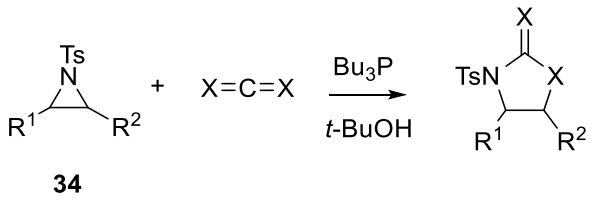
1.4.2 *Organotin and Lewis base systems*

Although lithium halide systems are the most commonly adopted catalysts for this reaction, other systems have been reported. Along with the work carried out by

Shibata on epoxides and isocyanates,[46] the same group tested that catalyst combination – an organotin compound coupled with the Lewis basic triphenylphosphine oxide – on the reaction involving isothiocyanates.[46] It was found that the reaction time needed to be increased by a factor of 12 in order to achieve quantitative yields. These disappointing results were due to the lower reactivity of the isothiocyanates when compared to the isocyanate substrates. However, when the Lewis basic component of the catalyst was swapped to hexamethylphosphoramide (HMPA) it was found that excellent yields could be obtained under equivalent conditions to that of the isocyanate system. This study was not comprehensive, and as a result the substrate tolerance of this system was not tested. Interestingly, the products formed from these reactions were not the usual oxazolidine thiones. Instead 2-oxathiolamimines (**30**, Scheme 23) were the major products detected. This implies that this catalyst system favours attack by the sulphur nucleophile in the ring-closing substitution step of the mechanism.

1.4.3 *Tributylphosphine*

As previously discussed on page 13 of the introduction, Huo touched on the use of tributylphosphine as a catalyst for the formation of oxathiolane-2-thiones from epoxides and carbon disulphide as a side project while focussing on the coupling of aziridines, **34**, with heterocumulenes (Scheme 26). In a similar way, a brief experiment was carried out using the same catalyst system on epoxides and isothiocyanates. It was found that using 10 mol% of tributylphosphine with 10 mol% of lithium perchlorate cocatalyst, in refluxing acetonitrile for 24 hours resulted in an 88% yield. While the conditions were harsh and a reasonably high catalyst loading was necessary, it was still a novel catalyst system for a transformation which has not been widely studied.

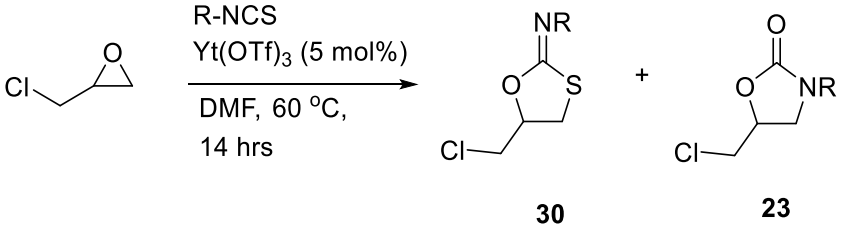


Scheme 26 - Reaction of aziridines with heterocumulenes

1.4.4 *Rare Earth metals*

In 2009, Su chose to investigate the use of rare earth metal catalysts for the reaction of epoxides with isothiocyanates.[66] The level of water tolerance they displayed and the recyclability were the reasons cited for working with this class of catalyst. Just as for Shibata's use of organotin catalysts,[46] it was found that 2-oxathiolimines (**30**) were the major products detected, however unlike Shibata, the equivalent oxazolidinone products (**23**) were also produced in a side-reaction. The aim of this work by Su was to optimise the system to selectively form 2-oxathiolimines. Having investigated many catalysts (mostly rare earth based, but some transition metal along with group three catalysts were tested), it was found that ytterbium triflate gave the most promising results. Much optimisation was carried out and it was decided that the best reaction conditions were; 60 ^{o}C, with 5 mol% catalyst loading, and a reaction time of 14 hours, in DMF (many solvents were tested but the only one in which any products were detected was DMF). It was observed that good yields and excellent regioselectivity was possible for the reactions of epichlorohydrin with a range of different electron-rich isothiocyanates, while little or no reaction occurred with any other epoxide or electron deficient isothiocyanate. These conditions are outlined in Scheme 27. Therefore, while this novel system was very regioselective and the catalysts reasonably active for a

specific set of reagents, the poor substrate versatility meant that the overall results were disappointing.



30 **23**

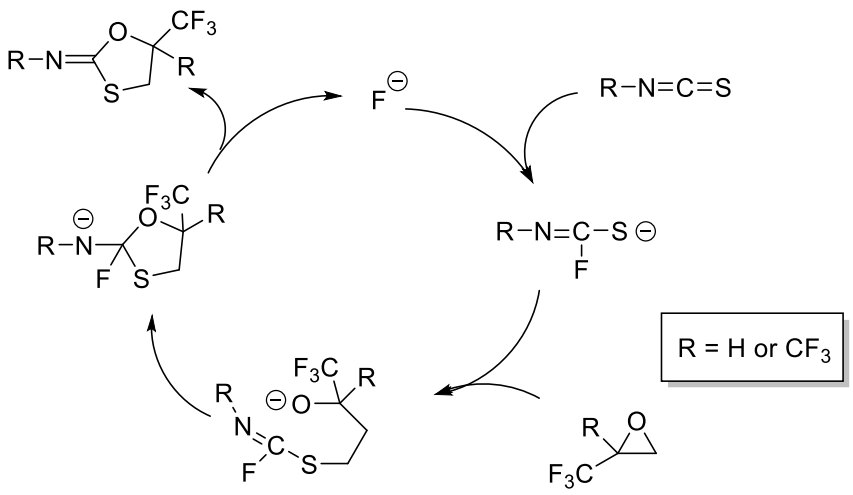
Scheme 27 - Optimal conditions for ytterbium triflate catalyst system

1.4.4 *Fluoride*

A final class of catalyst which has been developed and tailored to the formation of 2-oxathioimines (**31**) from epoxides and isothiocyanates involve the utilization of fluoride anions. In 2011, Petrov detailed the work being carried out using either the quaternary ammonium salt tetrabutylammonium fluoride (TBAF) or caesium fluoride.[67] The research was mainly focussed on the transformations involving epoxides containing trifluoromethyl groups. The results showed that high chemical yields could be obtained using these catalysts across a range of different isothiocyanate substrates. The nature of the isothiocyanate tended to dictate the outcome of the reaction with only aryl substrates showing any reactivity. A trend was also observed in that TBAF showed more catalytic activity when electron rich aromatic isothiocyanates were being used, while caesium fluoride was the more active catalyst when using electron poor substrates.

A catalytic cycle explaining the mechanism was reported in which the fluoride nucleophile first reacted with the isothiocyanate group, making it much more reactive towards the epoxide, which it in turn attacks, initiating the cycloaddition step. Following this, the cyclic imine group forms, which eliminates the fluoride anion. This

mechanism is outlined in Scheme 28. From these results, it can be concluded that fluoride salt based catalysts can be highly active for this reaction, and have the advantage of being simple and readily available. However, the inability to catalyse reactions on a wide range of substrates is the main disadvantage of this system.

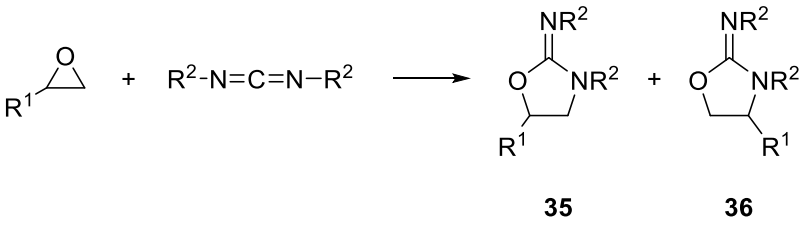


Scheme 28 - Mechanism for the reaction of epoxides with isothiocyanates, catalysed by fluoride salts

1.5 *Epoxides and Carbodiimides*

Carbodiimides are a class of heterocumulene consisting of two consecutive double bonds in a chain of nitrogen-carbon-nitrogen atoms. They react with epoxides to form imino-oxazolidines which take two forms (**35** and **36**) depending on the regioselectivity of the reaction. The general form of this reaction is shown in Scheme 29. Carbodiimides tend to be difficult to study due to their propensity to hydrolyse forming urea-based products in the presence of adventitious water. As a result of this,

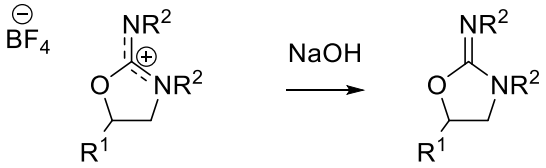
the reaction between epoxides and carbodiimides has not been comprehensively researched when compared to some other heterocumulenes. However, since the imino-oxazolidine products contain some uses – they have proven to be building blocks of polymers with some useful characteristics, such as high thermal stability and desirable physicomechanical parameters – some thought has been focussed on catalytic routes for their synthesis.[68,69]



35 **36**

Scheme 29 - Reaction of epoxides and carbodiimides

1.5.1 *Initial work*



37 **35**

Scheme 30 - Formation of imino-oxazolidine from tetrafluroboric salt

The first report of a route for the synthesis of imino-oxazolidines involving the additions of carbodiimides to epoxides was in 1972.[70] Radau detailed his work using tetrafluoroboric acid as a catalyst on terminal epoxide substrates. It was proposed that this reaction first formed the tetrafluoroboric salt of the product, **37**, which then requires

treatment with a base - in this case sodium hydroxide - in order to form the desired product. This process is shown in Scheme 30. This work was the first of its kind and showed promise as a system as, while the chosen catalyst was very simple, it produced good yields working with both aliphatic and aromatic carbodiimides and numerous examples of epoxides. It was also very regioselective, giving product **35** exclusively.

Other early work on this reaction involved testing catalyst free transformations.[71] Equimolar amounts of reagents were mixed in both solvent-free conditions and in a dichlorobenzene medium. It was found that some reactions did occur, but very harsh conditions were required (175-200 ^{o}C). Even under these conditions the chemical yields of product were only fair and the products that were obtained were not particularly pure. Solvent-free conditions in particular resulted in very messy product spectral data. However, while the results gained from these experiments were fairly poor, they do prove the point that the development of catalytic systems is necessary for the formation of quantitative yields of pure product.

1.5.2 *Organotin and organoantimony catalysts*

As covered in section 1.3.3 of this introduction, some research has been focussed on the use of tin and antimony based system for the reaction of isocyanates with epoxides.[44-49] It was shown that these compounds were successful in catalysing the production of oxazolidinones. Throughout this work, which was carried out by various academics, the compounds ability to catalyse reactions involving other heterocumulenes, namely carbodiimides, was also mentioned.

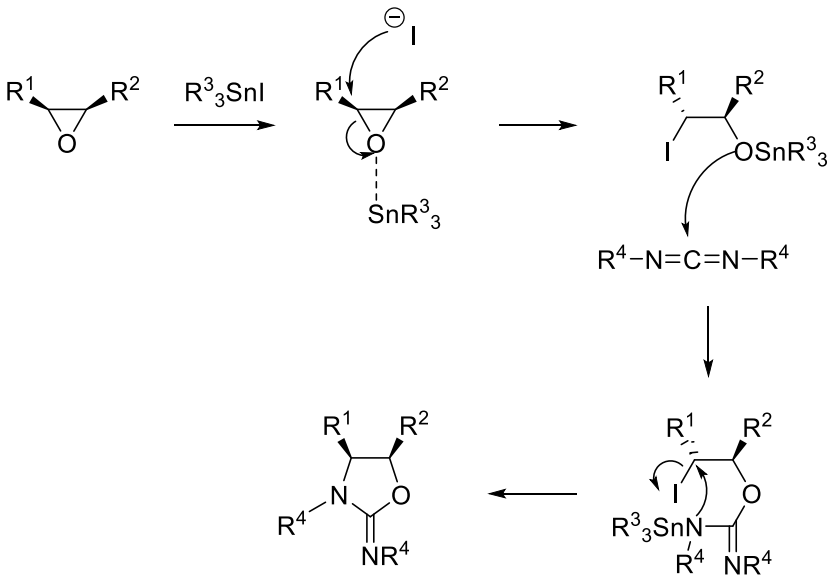
In 1986, having optimised a system involving an organotin halide species and triphenylphosphine oxide, which produced excellent results, Shibata decided to test its

activity on the formation of imino-oxazolidines.[46] It was found that high yields could be obtained when using dibutyltin diiodide and triphenylphosphine. This system was shown to be effective on a narrow range of both aromatic and aliphatic carbodiimides, but the latter were far less reactive. As expected, carbodiimides were found to be less reactive towards epoxides than isocyanates. Although it was only a brief investigation into the possibility of using these compounds as catalysts, this work showed that catalytic activity was present and the system could be optimised for future work on this transformation alongside other heterocumulenes.

This work was built upon by Baba, who decided to look into antimony based catalysts.[72] Tetraphenylantimony iodide proved to be an effective catalyst for both oxazolidinone formation from isocyanates and imino-oxazolidine synthesis from carbodiimides. The catalyst promoted the α-cleavage of epoxides selectively. It was again observed that carbodiimides were less reactive than isocyanates, needing a longer reaction time in order to achieve similar yields. However, one advantage they had over the other heterocumulene is that they did not trimerize in the reaction mixture, resulting in loss of product, which meant that unlike isocyanates they did not need to be added dropwise to the reaction mixture.

To further the understanding of mechanisms of reactions catalysed by trialkyltin halides, Baba (as for the reactions between isocyanates and epoxides[47]) carried out experiments using enantiomerically pure epoxides in order to determine the stereospecificity of the reactions. It was found that, without exception, the imino-oxazolidine products contained identical stereochemistry to that of the epoxides. From these results it was therefore reasoned that the reaction mechanism followed a pathway containing two inversion steps. This mechanism is outlined in Scheme 31. The first inversion occurs when the iodide ring-opens the Lewis acid-activated epoxide. This is

followed by the insertion of the carbodiimide into the oxygen-tin bond. The second inversion occurs when the lone pair on the nitrogen attacks the carbon atom, eliminating the iodide and forming the five-membered ring and, therefore, retaining the stereochemistry.



Scheme 31 - Stereospecific mechanism of imino-oxazidine formation

As discussed in section 1.3.3 of this introduction, Baba carried out work on the formation of oxazolidinones from epoxides and isocyanates using tetraphenylantimony iodide as the catalyst.[48] Concomitant work undertaken using carbodiimides drew the same conclusions – that this catalytic system could be used in order to selectively form the opposite regioisomer that usually formed. Most systems favour the formation of the 3,5- substituted ring, while this system exclusively forms the 3,4- substituted version. The reason for this is identical to that of the reaction of isocyanates and is based on which atom upon which the epoxide is ring-opened. This is explained in the mechanism

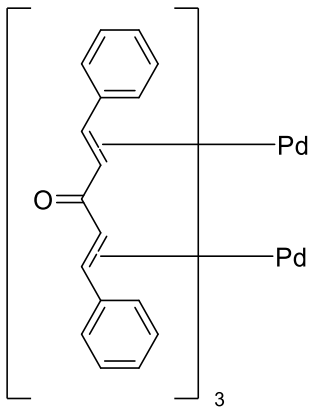
shown in Scheme 19. A detailed mechanistic study was carried out to support these results and the proposed mechanism.[49]

1.5.3 *Asymmetric palladium catalysts*

Palladium-based catalyst systems have been known to contain some activity for the formation of imino-oxazolidines from epoxides and carbodiimides.[73] In 1997, Alper decided to investigate the use of chiral palladium catalysts to form asymmetric five-membered vinyl-substituted heterocyclic products from the reaction of vinyl epoxides and carbodiimides.[74] Firstly, in order to prove the catalytic activity of the catalyst systems, tests were carried out using achiral compounds as catalysts. It was found that palladium catalysts were highly active. At room temperature, with a reaction time of 15 hours, tetrakis (3 mol%) and triphenylphosphine (6 mol%) gave yields of up to 98%. It was found that using the metal compound alone, with no additional ligand resulted in significantly decreased yields.

With these results, the same conditions were tested employing chiral catalyst systems and with optimisation it was found that a system of 3 mol% of $Pd_2(dba)_3$ (**38**) and 6 mol% of (*S*)-TolBinap (**39**) gave a yield of 94 % and an *ee* of 95% (determined by chiral HPLC). It was also shown that these excellent results were consistent across a range of different substrates. It is thought that the mechanism follows a pathway in which the palladium coordinates to the alkene bond in the epoxide, which activated the epoxide for nucleophilic attack by the heterocumulene. The asymmetric induction is thought to stem from the ring closing step of the now chiral palladium-vinyl intermediate. This chemistry was then expanded to test the catalyst system on asymmetric carbodiimides.[75] This meant that there would always be two diastereomers

formed and one would be isolated as the major product. This resulted in similarly excellent results, and has inspired others to investigate the fine tuning of these palladium bisphosphine catalyst systems in order to optimise the results gained for this reaction.[76]



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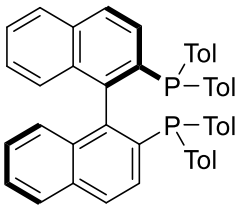

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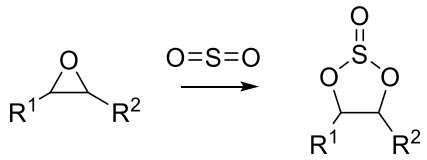
1.6 Epoxides and Sulphur dioxide

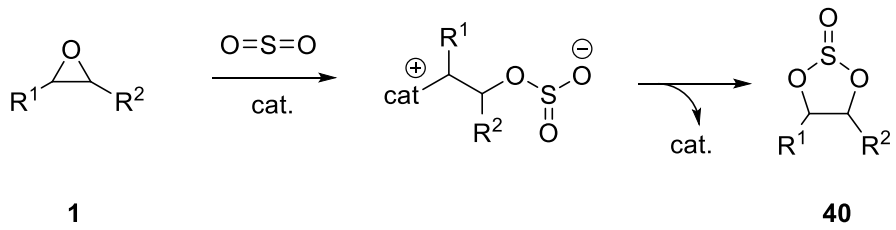


1 **40**

Scheme 32 - Reaction of epoxides and sulphur dioxide

The final reaction of epoxides with a heterocumulene to be discussed is that of sulphur dioxide (Scheme 32). This is by far the least studied reaction of the heterocumulenes but despite this, it has the characteristics to be desirable to chemical researchers. It is 100 % atom economical, meaning no waste products can be expected from it and the use of sulphur dioxide as a reactant is attractive as it is cheap, readily

available and is often a waste product from industrial processes. The products, known as cyclic sulphites (**40**), are useful as electrolytes in lithium-ion batteries.[77] Their purpose is to deter the decomposition of other solvents present and to offer protection to the internal graphite anodes of the battery. This is achieved by forming a film-coating around the graphite anodes to prevent intercalation of the cyclic carbonates into the graphite structure. The normal route to their synthesis is by reacting diols with thionyl chloride in the presence of an organic base catalyst.[78,79] While this may be a cheaper alternative, it produces copious amounts of waste in the form of ammonium or pyridinium salts.



1 **40**

Scheme 33 - Mechanism of heterogeneous catalytic cyclic sulphite formation

Although some work has been focussed on the polymerisation of the two reactants,[80,81] there have been a few examples of the selective synthesis of five-membered heterocyclic products. Early work involved the use of quaternary ammonium salts as catalysts with a reasonable amount of success.[82,83] This was selected as the route for the heterogeneous synthesis of these products by Takaneka in 2012.[84] It was shown that these quaternary ammonium based catalysts could be immobilised on a solid silica medium and these catalysts could produce the cyclic sulphites in excellent yields (up to 96%). The reactions could be run at 100 ^{o}C in solvent-free conditions and, since the

catalysts were mounted on the solid support, the products could be very simply separated from the catalysts via a filtration step. This also allowed for the catalysts to be recovered and reused on different batches of the reaction. It is thought that the reaction follows the mechanism shown in Scheme 33. The catalyst ring-opens the epoxide, which in turn attacks the sulphur-oxygen double bond. The ring-closing step then eliminates the catalyst from the five-membered heterocyclic product.

1.7 Summary

Despite the clear similarities in the reactions between epoxides and various heterocumulenes, it is obvious from the literature that the reactions are all highly individual and require specifically optimised catalytic systems in order to produce quantitative results. The best system for the production of one heterocyclic product may not be suited to the products of another. For example, in the production of cyclic carbonates many catalysts have been proposed over decades of research and although some are very simple and readily available, the best system appears to be the aluminium salen complex, along with TBAB first developed by North in 2007.[13] This marked the first time that this process could be carried out under ambient conditions and therefore could take in more carbon dioxide than it produced.

Next, in the synthesis of di- and trithiocarbonates, another highly studied reaction, there are a wider range of products formed, and therefore a wider range of catalysts to choose from depending on the selectivity desired. For the exclusive production of dithiocarbonates, the best system appeared to be triethylamine in water.[18g] On the other hand, potassium hydroxide or alkoxides appeared to be the best catalysts for production of trithiocarbonates.[20b,c,d] As with cyclic carbonate formation, the more complicated

catalyst and cocatalyst combination developed by North proved to be more sophisticated, in that its selectivity could be tailored to produce either product by altering the reaction temperature, so this system could effectively produce either regioisomer.[27]

For reactions involving isocyanates and isothiocyanates, much work was carried out using organotin and organoantimony complexes, which gave excellent results for both sets of reactions.[44-49] However, although first developed in 1971,[35,36] lithium bromide prevailed as the system of choice for researchers, due to it being both relatively inexpensive and much less toxic than the tin and antimony alternatives. This has resulted in it being used in multi-step processes for the production of large biomolecules.[64,65]

The bulk of the work done on the reaction of carbodiimides with epoxides was carried out at the same time as the work carried out using isocyanates and isothiocyanates, and was mainly focussed on the organotin and organoantimony systems.[44-49] These have proved to be the most effect catalysts for this reaction, with excellent yields obtained across a wide variety of substrates. Finally, while not much research has been carried out on the reaction between sulphur dioxide and epoxides, the system which has showed the most promise has been based on quaternary ammonium salt catalysts.[82-84]

1.8 Project Aims

The general aim of this project was to further both the use and mechanistic knowledge of metal salen complexes as catalysts for the coupling reactions of

heterocumulenes and epoxides. It involved optimising and studying systems that were already established as well as the development of novel catalyst systems for well-known transformations. The project was split into four main sections.

The first section concerned the formation of cyclic carbonates from epoxides and carbon dioxide. The main aim was to improve the lifetime of the one-component catalysts developed in the North group in 2009,[15,16] by optimising the quaternary-ammonium side-groups to try and alleviate the problems caused by dequaternisation. Once the catalyst system had been optimised, the secondary aim of this section was to increase the range of reactions that these complexes have been known to catalyse.

The aim of the second section was to develop an understanding of the mechanism of the reaction between isocyanates and epoxides, forming oxazolidinones. A catalytic cycle was proposed which was to incorporate the data collected from kinetic studies carried out on the system which is catalysed by aluminium salen complexes. In addition to this, variable temperature studies were to be carried out on systems involving three different heterocumulenes catalysed by both monometallic and bimetallic aluminium complexes. This data was brought together to form a comprehensive conclusion of the differences between the reactions of various heterocumulenes with epoxides.

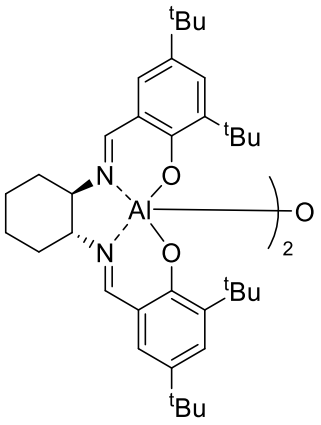
The third and fourth sections aimed to describe new catalyst systems for reactions of heterocumulenes with epoxides, by testing new metal salen compounds as catalysts. Section three exhibits the attempts to develop a more active catalyst system for the synthesis of oxazolidinones from epoxide and isocyanates by testing more Lewis acidic metal centres. Section four outlines the attempted improvements on previous systems for the formation of thiocarbonates from epoxides and carbon disulphide, again, by altering the metal centres in the catalyst.

Chapter 2. Results and Discussion

2.1 One-component catalysts

2.1.1 *Cyclic carbonate synthesis*

In 2007, North reported that a combined system of aluminium salen complex **10** and TBAB showed an unprecedented level of catalytic activity for the formation of cyclic carbonates from terminal epoxides and CO_2.[13] Mechanistic studies showed that the TBAB cocatalyst played two very important roles in the catalytic cycle.[14] Firstly, to provide a bromide ion to ring-open the epoxide and then to generate tributylamine which reacts with the CO_2 forming a carbamate species. Complex **10** then brings the two intermediate species together, to facilitate their reaction to form the product.



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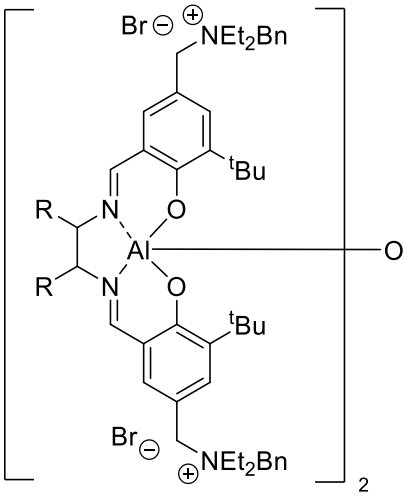


13

Despite the high activity shown by complex **10**, the obvious disadvantage was the need for both a catalyst and cocatalyst to be present, since the goal of this system was to immobilise the catalyst and carry out reactions under continuous flow conditions.

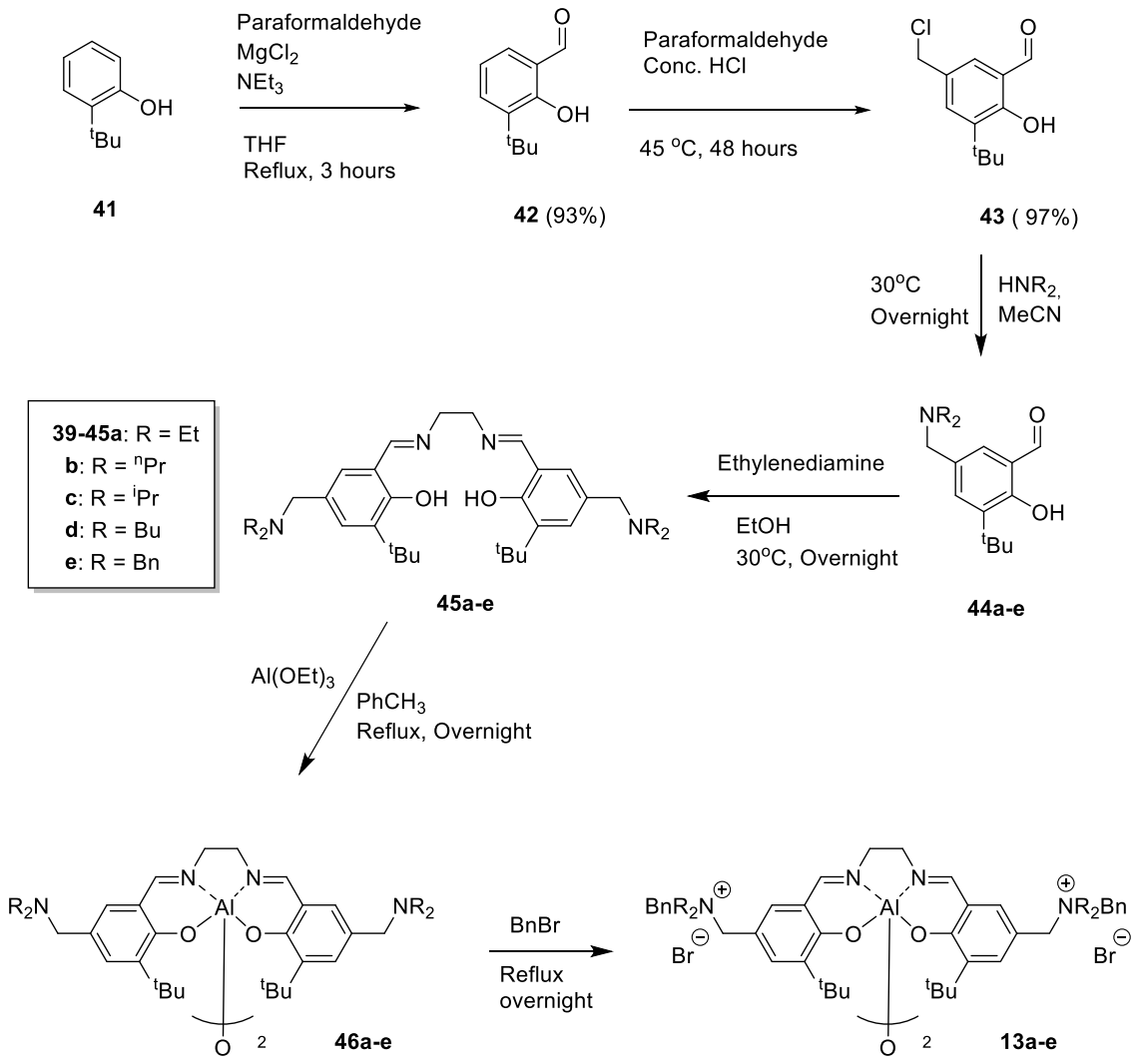
Therefore, in 2009, one-component catalysts were developed in which quaternary ammonium salts were built into the salen ligand.[15] This therefore eliminated the need for TBAB and allowed the catalyst to be mounted onto an inorganic support, but still retained the exceptional activity of the two-component system.

A silica-immobilised version of catalyst **13** was then tested in a gas-phase flow reactor for the production of ethylene and propylene carbonate.[16] This was to examine how it would perform in an environment more related to that of a commercial application using waste CO_2, such as in the exhaust fumes from a power plant, as the source. It was shown that when the catalyst was mounted on a silica-based support, it could remove up to 98% of the CO_2 that passed through the reactor under certain conditions. However, a catalyst reusability study showed that the activity of the system dropped upon repeated recycling. This was likely due to the dequaternisation of the ammonium salts in the salen ligand and not catalyst decomposition. This could therefore be reversed by requaternising the amines by reaction with excess benzyl bromide, after which the activity of the catalyst returned to the initial levels observed.

The aim of this part of the project was to synthesise a series of new one-component catalysts for this reaction. Each catalyst would have a different quaternary ammonium salt attached onto the salen ligand and the catalysts would be tested to explore whether these were more or less stable to dequaternisation. The goal was therefore to examine whether the lifetime of the immobilised catalyst could be improved by reducing the need for the requaternisation.

The basic procedure for the synthesis of these catalysts was taken from the literature for the previous work done on the one-component catalyst, which incorporated a diethylamino group onto the salen ligand.[15,16] This was then quaternised to form the

ammonium salt. Different amines would be used in the synthesis to afford the different quaternary ammonium salts present in the final catalysts.

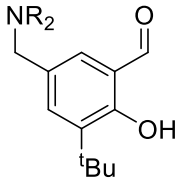


Scheme 34 - Synthesis of one-component catalysts

The multistep synthesis, shown in Scheme 34, for each of these catalysts begins with the same two steps. The first of these is the formylation of 2-*tert*-butylphenol **41** to give salicylaldehyde derivative **42** in excellent yield. This was followed by

chloromethylation of **42** to give product **43**. It was found that unlike in the literature, the reaction needed to be run at 45°C rather than 70°C to avoid polyalkylation of the product, and when the reaction time was extended to two days an excellent yield could be obtained.

Table 1 – Synthesis of tertiary amine salicylaldehyde derivatives (44a-e)[a]



44a-e

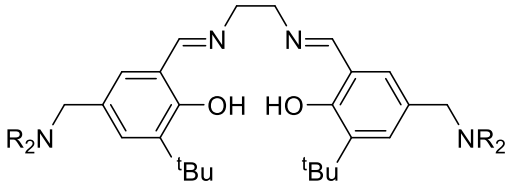
Entry	Compound	R	Yield[b] (%)
1	**44a**	Et	98
2	**44b**	^{n}Pr	95
3	**44c**	^{i}Pr	89
4	**44d**	Bu	94
5	**44e**	Bn	83

[a] Reaction carried out at 30°C overnight; [b] Yields obtained after volatiles evaporated under reduced pressure

It was decided to experiment with catalysts with varied amine substituents incorporated into the ligand. Catalysts derived from intermediates **44b-e** would be compared alongside the original example (**44a**), made with diethylamine, which would also be re-synthesised for the study. As shown in Table 1, excellent yields were obtained across the range of compounds (**44a-e**). One problem occurred in that a large amount of ammonium chloride salt seemed to form from the excess of amine used in the

reaction. However, this was easily removed by addition of diethyl ether to the products, after which the salt precipitated out of solution and could be isolated via suction filtration. This yielded a product which was pure enough to be used in the next step. The amines with straight-chain aliphatic R groups gave the best yields (94-98%), as they are the least sterically hindered. A slight drop in the chemical yield was observed for the more hindered amines with isopropyl (**44c**) and benzyl (**44e**) amines giving 89% and 83% yield respectively.

Table 2 – Synthesis of salen ligands (45a-e) from salicyladehydes (44a-e) and ethylenediamine[a]



45a-e

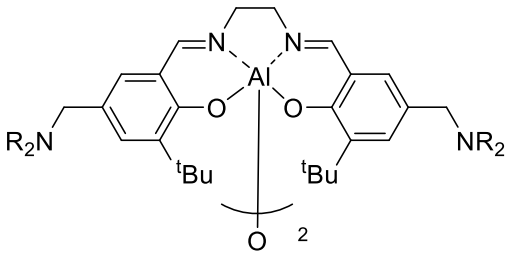
Entry	Ligand	R	% Yield[b]
1	**45a**	Et	90
2	**45b**	^{n}Pr	88
3	**45c**	^{i}Pr	79
4	**45d**	Bu	86
5	**45e**	Bn	76

[a] Reactions carried out at 30^{o}C overnight in ethanol; [b] Yields obtained after volatiles were removed under vacuum

The next step was to make the five salen ligands (**45a-e**) by combining two molecules of the modified salicylaldehyde with ethylenediamine. It was found that using just two equivalents of salicylaldehyde gave a product with some peaks duplicated in the ^{1}H NMR, which was attributed to monosubstituted ethylene diamine. By adding 2.2 equivalents of salicylaldehyde derivative the problem was solved and the

result was salen ligands which needed no further purification. Table 2 shows the high yields obtained for all five salen ligands. A similar trend to the salicylaldehyde products was observed in that the less hindered substituents on the aromatic ring afforded the highest yield, while the more hindered ones showed a slight decrease in yield.

Table 3 – Synthesis of bimetallic aluminium salen complexes 46a-e[a]



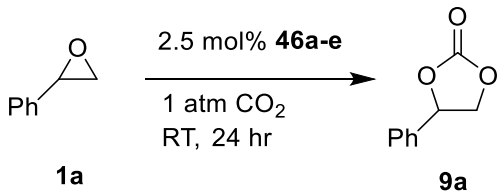
46a-e

Entry	Compound	R	% Yield[b]
1	**46a**	Et	64
2	**46b**	^{n}Pr	58
3	**46c**	^{i}Pr	51
4	**46d**	Bu	53
5	**46e**	Bn	57

[a] Products formed by refluxing **45a-e** with $Al(OEt)_3$ in toluene overnight; [b]Yields obtained after washing with diethyl ether and evaporating volatiles under reduced pressure.

Compounds **45a-e** could then be coordinated to aluminium to form bimetallic structures, with a bridging oxygen atom (**46a-e**). This was achieved by heating the salen ligands under reflux in toluene with aluminium triethoxide, which was either commercially available or could be formed *in situ* by reacting shredded aluminium foil with ethanol under reflux in the presence of a catalytic amount of iodine. This was

followed by an aqueous work-up, during which the dimer was formed around the bridging oxygen atom. The yields obtained for each of the complexes were moderate (Table 3), but very consistent (51-64%). They were also consistent with the reported yields for the synthesis of other similar complexes, which were made using the same procedure.[15]



Scheme 35 - Styrene carbonate formation

Table 4 – Investigation of complexes 46a-e as catalysts for the formation of styrene carbonate (9a) from styrene oxide (1a) with and without 2.5 mol% TBAB cocatalyst[a]

Entry	Catalyst	TBAB (mol%)	% Conversion[b]
1	**46a**	0	0
2	**46b**	0	0
3	**46c**	0	0
4	**46d**	0	0
5	**46e**	0	0
6	**46a**	2.5	93
7	**46b**	2.5	93
8	**46c**	2.5	96
9	**46d**	2.5	94
10	**46e**	2.5	90

[a] All reactions were run for 24 hr, at room temperature, under 1 atm pressure of CO_2 obtained from dry ice pellets, using 2.5 mol% catalyst and cocatalyst; [b] conversions obtained by ^{1}H NMR analysis

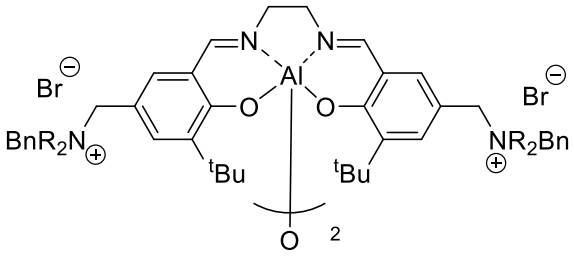
In order to investigate the activity of these complexes, control reactions were carried out with complexes **46a-e** (Table 4), where the catalytic activity was tested for the formation of styrene carbonate (**9a**) from styrene oxide (1**a**) (Scheme 35). As expected, when no cocatalyst was used, no catalytic activity was observed, but when the catalysts were used in the presence of an equimolar amount of TBAB, they exhibited very high activity. As complexes **46a-e** had been proven to be active in the presence of a bromide ion source, the last step in the formation of this series of one-component catalysts was to quaternise the tertiary amine substituents of these complexes. This would be carried out using an excess of benzyl bromide and would ensure that there is a source of bromide in the catalyst, which is essential for the ring opening of the epoxides according to the mechanism of cyclic carbonate synthesis.

The first attempt at quaternisation was carried out with six equivalents of benzyl bromide in acetonitrile under reflux for 16 hours. All catalysts appeared to undergo the expected colour change, from a bright yellow to a reddish-orange. When analysed by ^{1}H and ^{13}C NMR however, the spectra proved to be unclear and there were numerous extra peaks across the spectrum. This was most noticeable in the ^{13}C NMR spectra where it seemed that almost every peak had a duplicate present. The reason for this was taken to be that the products were not quaternised on every nitrogen atom. This, therefore, meant that since each molecule has four amines, and only some are being quaternised, the molecule then loses its symmetry and extra peaks appear in the NMR spectra. The one exception to this was the previously reported[15] diethylamine derived catalyst **7a** for which the NMR spectra proved that the quaternised complex had been successfully formed.

It was apparent that at least some of the complexes **46b-e** were not fully soluble in acetonitrile, which may have been the reason for the failure to form pure quaternary

ammonium salt containing complexes **13b-e**. In order to find a way around this problem, the quaternisation step was repeated, but this time using a solvent mixture of acetonitrile and chloroform (1:1). The solution appeared to be fully homogeneous and the reaction mixture was heated under reflux overnight this time with ten equivalents of benzyl bromide. Once again, upon viewing the ^{1}H and ^{13}C NMR spectra, extra signals were visible in all regions, and it was difficult to tell by how much the degree of quaternisation had improved from the previous attempt. Again the formation of styrene carbonate was used as a test reaction in order to observe the catalytic activity of these one-component systems. The results are shown in Table 5.

Table 5 – Test reactions of catalysts 13a-e which had been quaternised using MeCN : $CHCl_3$ (1:1) on the formation of styrene carbonate (9a) from styrene oxide (1a)[a]



13a-e

Entry	Catalyst	R	Conversion (%)[b]
1	**13a**	Et	97
2	**13b**	^{n}Pr	92
3	**13c**	^{i}Pr	31
4	**13d**	Bu	91
5	**13e**	Bn	11

[a] All reactions run for 24 hr, room temperature, under 1 atm of CO_2 from dry ice pellets, using 2.5 mol% catalyst; [b] conversions obtained by ^{1}H NMR

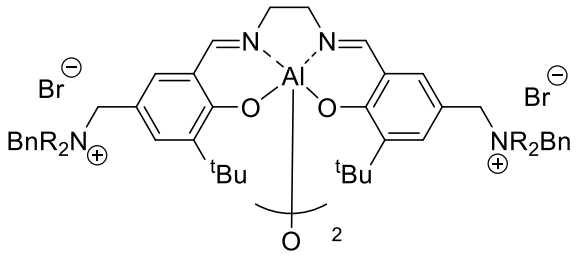
Table 5, entry 1 shows the result for catalyst **13a**, which was made using diethylamine and was shown to be fully quaternised. This shows that 97% of the styrene oxide was converted to styrene carbonate, and therefore complex **13a** exhibits excellent activity for this transformation. By using this as a guideline result, it is possible to estimate the level of quaternisation of the other catalysts (**13b-e**) and obtain an idea of the trend across the range of catalysts. A problem, however, is that this estimation would have to be made from the assumption that the complexes would have roughly equal activity for this transformation.

As can be seen from entries 2-5 in Table 5, the amines with the less bulky substituents give the highest conversions while the more bulky groups were shown to be less active. Complexes **13b** and **13d** both contain straight chain aliphatic R groups which are not much bulkier than the ethyl groups present in **13a**. While the conversion is not quite as high as for **13a** which is fully quaternised, the catalysts still show excellent activity giving conversions of 92 and 91 % respectively. The activity dropped dramatically when using catalysts with bulkier side-chains. Catalyst **13c**, which contained two isopropyl groups on the nitrogen atom, gave a conversion indicating that the catalyst was less than a third as active as **13a**. Similarly, complex **13e** gave a conversion of just 11% to styrene carbonate, implying very little quaternisation. The benzylic R groups present were obviously sterically hindering the attempts to quaternise to form the ammonium salts.

As the results showed that **13b-e** had been synthesised without complete quaternisation, another attempt using benzyl bromide was carried out, this time with the very polar propylene carbonate as the solvent. Complexes **46b-e** were heated for three days with ten equivalents of benzyl bromide in order to try to force the reaction to go to completion. However, signals in the ^{1}H and ^{13}C NMR spectra still indicated numerous

species present and, as seen in Table 6, there was no significant improvement to any of the results in the test reaction.

Table 6 – Test reactions of catalysts 13b-e (quaternised using propylene carbonate as solvent and refluxing for 3 days) on the formation of styrene carbonate from styrene oxide[a]



13a-e

Entry	Catalyst	R	Conversion (%)[b]
1	**13b**	^{n}Pr	89
2	**13c**	^{i}Pr	37
3	**13d**	Bu	94
4	**13e**	Bn	8

[a] All reactions run for 24 hr, room temperature, under 1 atm of CO_2 from dry ice pellets, using 2.5 mol% catalyst; [b] conversions obtained by ^{1}H NMR

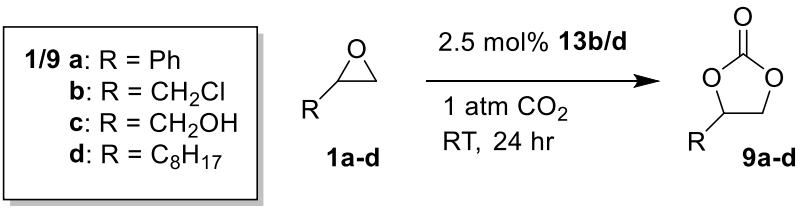
As a different approach to prepare the pure catalysts, attempts were made to make quaternary ammonium salts of the salen ligands before complexation to the aluminium centre. Ligands **45a-e** only contain two amine groups each, compared to four for complexes **46a-e**, which should make the reaction easier to analyse. However, once again pure samples proved impossible to synthesise, judging by the ^{1}H and ^{13}C NMR spectra obtained.

In a final attempt to obtain some form of quaternary ammonium salt substituted catalysts, allyl bromide was used instead of benzyl bromide. Since this is much less

bulky than the benzyl bromide, it should produce a less sterically hindered ammonium salt and larger R groups on the amine could possibly have been used. However, the NMR spectra obtained still looked complex, showing that there were numerous species present.

Despite the fact that it had proven very difficult to characterise pure, quaternised complexes for any of the catalysts (**13a-e**) with R groups on the amines larger than an ethyl group, the activity was tested across a range of epoxides (**1a-d**) (Scheme 36). The two catalysts chosen were **13b** and **13d** since these exhibited equivalent activity to the fully quaternised **13a** in the test reaction with styrene oxide **9a** (Scheme 35, Table 6).

As Table 7 shows, both catalysts were highly active for this transformation. For comparison, results previously published using catalyst **13a** are included (Table 7, entries 1-3), which were obtained after six hours. Conversions ranging between 79-96% were obtained for both catalysts **13b** and **13d** across the range of epoxides. As expected the dibutylamine variation, **13d**, was slightly less active for each reaction, which is in agreement with the theory that the more sterically hindered amines had a lower degree of quaternisation.



Scheme 36 - Cyclic carbonate formation

Table 7 – Various epoxides (1a-d) to cyclic carbonates (9a-d) catalysed by 13b and 13d [a]

Entry	Catalyst	Epoxide	Conversion (%)[b]
1	**13a**	**1b**	100[c]
2	**13a**	**1c**	79[c]
3	**13a**	**1d**	81[c]
4	**13b**	**1a**	84
5	**13b**	**1b**	96
6	**13b**	**1c**	93
7	**13b**	**1d**	88
8	**13d**	**1a**	79
9	**13d**	**1b**	94
7	**13d**	**1c**	90
8	**13d**	**1d**	86

[a] All reactions run for 24 hr, room temperature, under 1 atm of CO_2 from dry ice pellets, using 2.5 mol% catalyst; [b] conversions obtained by ^{1}H NMR; [c] Literature result catalysed by complex **45a** after 6 hours.[15,16]

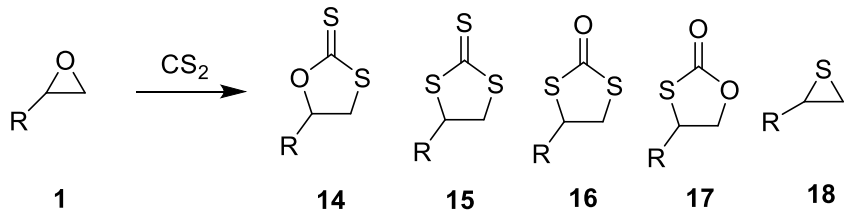
The aim of this part of the project was to synthesise a series of new one-component catalysts which incorporated different ammonium salts into the salen ligands. Once these had been fully characterised and tested they were to be immobilised on a support and analysed to see if the lifetime of the existing catalyst system could be improved by altering the R groups in a way which would discourage dequaternisation of the ammonium salts.

Some of the new catalysts (**13b** and **13d**) showed good activity compared to the existing system **13a** (Table 7). Disappointingly, however, the new catalysts proved impossible to obtain in a pure form and therefore were impossible to characterise

properly. It appeared that if the R groups on the amine were any larger than the original ethyl groups used,[10] the nitrogen became too sterically hindered to be able to undergo quaternisation. This meant that the ammonium bromide salt could not be formed. Therefore the stage of immobilisation was never achieved and testing on the gas-phase flow reactor system was not possible. The only one-component catalyst to be successfully synthesised was **7a**, made with diethylamine. Since this had previously been tested extensively and successfully for the synthesis of cyclic carbonates, it made sense that an investigation could be carried out into its use in other catalytic transformations for which the two-component system had already been applied.

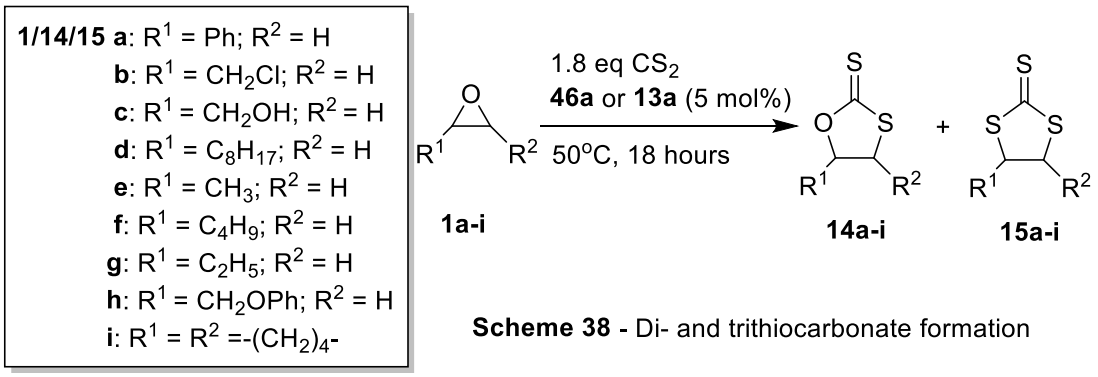
2.1.2 *One-component catalyst for di- and trithiocarbonate synthesis*

In 2010, North showed that complex **10** combined with either TBAB or tributylamine was an effective catalyst system for the formation of 1,3-oxathiolane-2-thiones (**14**) and 2,3-dithiolane-2-thiones (**15**) from epoxides (**1**) and CS_2.[27] This reaction is clearly related to the formation of cyclic carbonates as it is the insertion of a heterocumulene into an epoxide. However, it is more complicated in that it can form multiple products. Other compounds which have been shown to form in the same reaction with other catalysts are 1,3-dithiolane-2-ones (**16**), 1,3-oxathiolane-2-ones (**17**) and thiiranes (**18**) as shown in Scheme 37.



Scheme 37 - Insertion of CS_2 into epoxides

It was decided to test the catalytic activity of complexes **46a** and **13a** on this reaction. They may offer improved activity since for every one molecule of aluminium salen complex, there are four molecules of cocatalyst built in. The previous work showed that excellent yields could be obtained using 5 mol% of both catalyst and cocatalyst whilst running the reaction for 18 hours at 50°C. These were therefore the selected conditions for testing the one-component system (Scheme 38).



Scheme 38 - Di- and trithiocarbonate formation

Firstly, catalyst **46a** was tested on a range of epoxides **1a-i**, which included aliphatic, aromatic, functionalised aliphatic and disubstituted substrates. The results are shown in Table 8. When compared to the results obtained using complex **10** with a cocatalyst,[27] the yields are almost all lower across the whole range. The catalyst was particularly bad for aliphatic substrates, where the best conversion obtained was for **1g** which gave 14% conversion to products. The more functionalised epoxides gave conversions high enough to obtain isolated yields, however, they still did not come close to the results obtained for the two-component system, with the exception of phenyl glycidyl ether, **1h**. As seen with the previous system the product ratio tended to favour the formation of dithiocarbonate **14** rather than trithiocarbonate **15** at 50°C.

Table 8 - Synthesis of cyclic di- and trithiocarbonates catalysed by 13a[a]

Entry	Epoxide	Yield (%)[b]	Ratio (14 : 15)[c]
1	**1a**	60	0 : 100
2	**1b**	75	85 : 15
3	**1d**	0	-
4	**1e**	0	-
5	**1f**	2 [d]	100 : 0
6	**1g**	14 [d]	54 : 46
7	**1h**	99	91 : 9
8	**1i**	11 [d]	100 : 0

[a] Reactions run for 18 hours with no solvent in a sealed Young's flask; [b] Yields obtained after purification by column chromatography; [c] Ratio determined by ^{1}H NMR spectroscopy; [d] Yield not obtained so conversion reported which was obtained by ^{1}H NMR spectroscopy

It is reported that the role of the TBAB in the two-component system is to act as a source of tributylamine. Therefore, it should not make a difference whether one uses complex **46a** or **13a**. Table 9 shows the results when catalyst **13a** is used on the same range of epoxides and the trend shows a very slight improvement across the range using the catalyst with the quaternary ammonium salt on the ligand. While most of the differences are so small they could be assumed to be within the experimental error range, substrates **1d** and **1i** show a significant enough improvement to assume that having a bromide ion source present may encourage the reactions slightly.

Table 9 - Synthesis of cyclic di- and trithiocarbonates catalysed by 45a[a]

Entry	Epoxide	Yield (%)[b]	Ratio (14 : 15)[c]
1	**1a**	60	0 : 100
2	**1b**	80	83 : 17
3	**1d**	17 [d]	51 : 49
4	**1e**	0	-
5	**1f**	6 [d]	100 : 0
6	**1g**	18 [d]	42 : 58
7	**1h**	98	89 : 11
8	**1i**	34	54 : 46

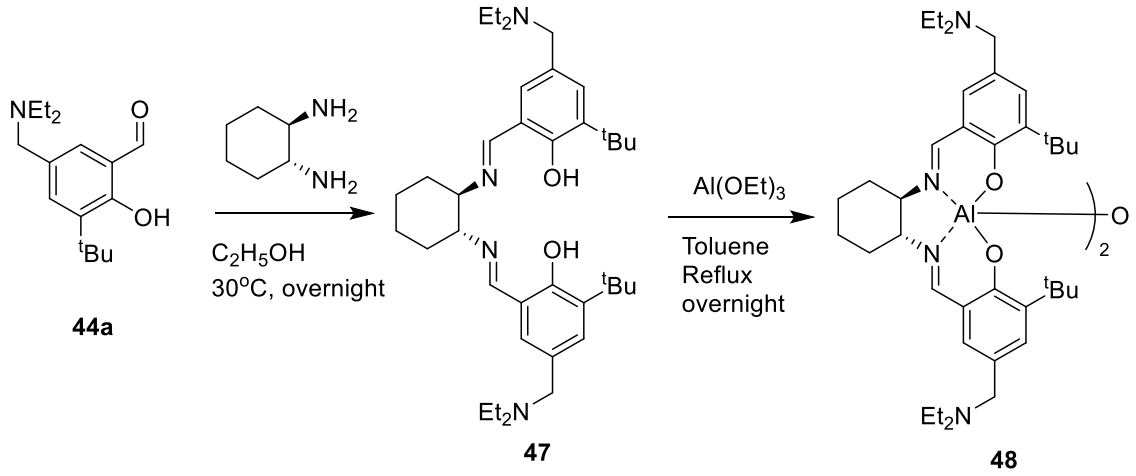
[a] Reactions run for 18 hours with no solvent in a sealed Young's flask; [b] Yields obtained after purification by column chromatography; [c] Ratio determined by ^{1}H NMR spectroscopy; [d] Yield not obtained so conversion obtained by ^{1}H NMR spectroscopy reported

The aim of this part of the project was to investigate whether using a one-component catalyst system for the production of di- and trithiocarbonates could improve on the results obtained when a catalyst and cocatalyst were used. It was found that, despite the larger number of either tertiary amine (4**6a**) or quaternary ammonium salt (**13a**) present in the one-component systems, the activity of the catalysts were significantly lower than those reported in previous work.

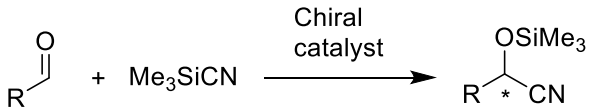
2.1.3 *One-component catalyst for asymmetric cyanohydrin synthesis*

A chiral version of complex **46a** can be easily synthesised. Instead of using ethylenediamine when forming the salen ligand, using resolved cyclohexanediamine

means that the salen ligand (**47**) will have a chiral backbone and this can then be coordinated to the aluminium centre as before, producing aluminium complex **48**. This process is shown in Scheme 39.



Scheme 39 - Synthesis of chiral aluminium salen one-component catalyst

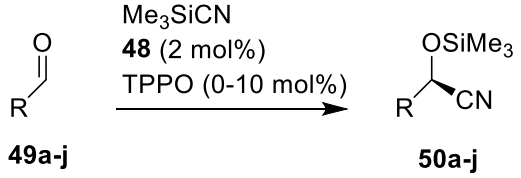


Scheme 40 - Asymmetric cyanohydrin synthesis

Experiments were carried out to investigate the catalytic activity of complex **48** for the synthesis of non-racemic cyanohydrins by addition of trimethylsilyl cyanide (TMSCN) to aldehydes (Scheme 40). Both Lewis acid[85] and Lewis base[86] catalysts have been extensively researched for this highly studied transformation. In theory, complex **48** should be a highly active catalyst, since it incorporates a Lewis acid component, in the form of the aluminium centres, and a basic component, in the form of the amines

built into the salen ligand. Since it is made from resolved cyclohexane diamine, this means that it possesses a chiral environment which may lead to asymmetric induction.

49, 50 a: R = Ph
b: R = *m*-MeO Ph
c: R = *p*-F Ph
d: R = *p*-Me Ph
e: R = *p*-Br Ph
f: R = *m*-Cl Ph
g: R = *p*-Cl Ph
h: R = *m*-Me Ph
i: R = C_8H_{17}
j: R = Cy



49a-j **50a-j**

Scheme 41 - Asymmetric cyanohydrin synthesis

Table 10 – Addition of Me_3SiCN to benzaldehyde (49a) in CH_2Cl_2 catalysed by 48 (2mol%)[a]

Entry	TPPO (mol%)	Temperature (°C)	Conversion (%)[b]	*ee* (%)[c]
1	0	RT	100	7
2	0	0	100	7
3	10	RT	100	38
4	10	0	100	37
5	10	-30	100	35
6	10	-60	100	33

[a] Reactions run for 2 hours at RT, or for 24 hours at lower temperature in 3 mL CH_2Cl_2; [b] Conversion determined by ^{1}H NMR spectroscopy; [c] Reactions carried out in duplicate and average *ee* determined by G.C.

The first experiments carried out were to investigate the effect of catalyst **48** on the addition of TMSCN to benzaldehyde (Scheme 41). The results are outlined in Table 10. Entry 1 shows that when the reaction was performed with 2 mol% of **48**, in 3 mL of

dichloromethane, the catalyst was highly active, giving a 100% conversion after just two hours, but it was found that the product obtained was effectively racemic, with an *ee* of just 7%. No improvement in the enantioselectivity of the reaction was observed when the temperature was lowered (Entry 2).

It was found that adding 10 mol% of the Lewis base triphenylphosphine oxide (TPPO) to the reaction mixture had a positive effect on the enantioselectivity. At room temperature, the *ee* obtained increased to 38% (Entry 3). This was an effect which had previously been observed when using other aluminium salen catalysts for this reaction.[87] This result, however, could not be improved further by lowering the temperature. Entries 4, 5 and 6 show that no positive change in enantioselectivity was observed, even for temperatures as low as -60^{o}C.

Table 11 - Addition of TMSCN to benzaldehyde (49a) in toluene catalysed by 48 (2mol%)[a]

Entry	Temperature (°C)	Reaction Time (hours)	Yield (%)[b]	*ee* (%)[c]
1	-30	6	100	43
2	-60	24	100	64
3	-80	48	99	78

[a] Reactions performed in 3 mL of toluene, with cocatalyst TPPO (10 mol%); [b] Yields determined by ^{1}H NMR spectroscopy; [c] *ee* determined by G.C.

Upon switching solvent to the much less polar toluene, improvements were immediately seen. Table 11, entry 1 shows that when the reaction was run for six hours at -30^{o}C, the conversion remained at 100% and the *ee* had risen slightly to 43%. In this solvent, the temperature did have an effect on the enantioselectivity. When it was

reduced to -60°C, the *ee* increased to 64% (entry 2) and at -80°C it was as high as 78% (entry 3). Since the temperature was so low, in order to make the reaction run until completion, the reaction time was increased to 48 hours.

Table 12 – Cyanohydrin synthesis from various aldehydes (49a-j) catalysed by 48[a]

Entry	Aldehyde	R	Conversion (%)[b]	*ee* (%)[c]
1	**49a**	Ph	100	78
2	**49c**	*p*-F Ph	89	79
3	**49e**	*p*-Br Ph	58	18
4	**49f**	*m*-Cl Ph	100	34
5	**49g**	*p*-Cl Ph	100	66
6	**49h**	*m*-Me Ph	47	5
7	**49i**	C_8H_{17}	100	61
8	**49j**	Cy	100	49

[a] Reactions performed in 3 mL of toluene, with cocatalyst TPPO (10 mol%), 48 hours at -80 °C; [b] Yields determined by ^{1}H NMR spectroscopy; [c] *ee* determined by G.C.

As the melting point of toluene is -95°C, decreasing the temperature further was not possible. The optimum reaction conditions were taken as 2mol% of **48**, 10 mol% of TPPO, in 3 mL of toluene, at -80°C for 48 hours. These conditions were tested on a range of aliphatic and aromatic aldehydes, and the results are shown in Table 12. In general, electron-rich aromatic groups tended to give poor results both in terms of yields and *ee*. This can be seen for substrates **49e** and **h** which gave yields of 47 and 58% and poor *ee*'s of 5 and 18%. Electron-deficient aromatic substrates gave better results. Yields were generally higher and *ee*'s ranged from 34-79%, however they were still

only moderate and similar results were obtained for the two aliphatic aldehydes tested (**49i** and **j**). Compounds **49b** and **d** gave yields of 53 and 54 respectively, however no peaks could be found in the G.C. trace for *ee* determination.

In conclusion, complex **48** did not prove to be an effective catalyst for the synthesis of asymmetric cyanohydrin trimethylsilyl ethers. Since the catalyst incorporated both Lewis acid and basic characteristics, it was shown to be very active in the formation of the products, but required very low temperatures and long reaction times to achieve relatively poor enantioselectivity when compared to previous catalyst systems.[85a,c,87] This was probably due to the fact that the catalytically active components are too distant from the chiral component of the structure to promote any significant effects.

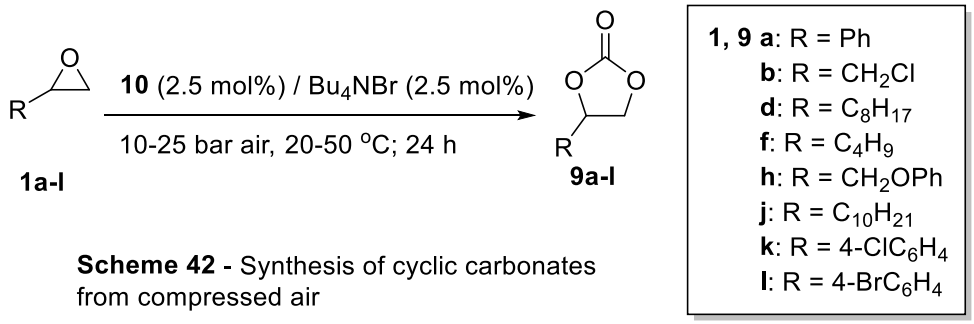
2.2 High pressure and mechanistic work using catalyst 10

2.2.1 *Cyclic carbonate synthesis from compressed air*

Past work by the North group in the area of cyclic carbonate synthesis catalysed by complex **10** has been focussed on mixing **10**, TBAB and epoxide in the presence of pure CO_2,[13] or a mixture of 5% CO_2 in helium gas.[88] These reactions tended to be performed at atmospheric pressure and room temperature, giving excellent results. However, when attempts were made to use air as the source of CO_2 under these conditions, no catalytic activity was observed, even after extended reaction times. The explanation for this became clear once mechanistic studies had been carried out,[14] as the reactions were proven to be first order with respect to CO_2 concentration and, since CO_2 is present at only 385 ppm in air, no reaction was observed.

Recently, however, investigations have been carried out to observe whether using catalyst **10** and TBAB at higher temperatures and pressures of CO_2 could improve the catalytic activity of the system.[89] The results showed that under slightly harsher conditions, the catalytic activity increased by an order of magnitude. It was therefore decided that the use of compressed air would be reinvestigated as a CO_2 source for cyclic carbonate synthesis, this time observing whether elevated temperatures and pressures would have a positive influence on the reaction outcome.

The model reaction for this investigation was chosen to be the synthesis of styrene carbonate (**9a**) from styrene oxide (**1a**). The reaction conditions are outlined in Scheme 42 and the results are shown in Table 13, and can be compared to the equivalent results obtained when using the same catalyst system under atmospheric pressure and pure carbon dioxide (entry 7). The initial conditions tested (entry 1) were 10 bar pressure at 50 ^{o}C and this resulted in a conversion to the product of 61% after 24 hours. By increasing the reaction time to 72 hours (entry 2) a slight improvement was evident, with the conversion up to 78%. However, an equal improvement could be achieved by increasing the pressure of compressed air in the vessel to 25 bar (entry 3), with the conversion up to 78%. To observe whether this same result could be achieved without the elevated temperature used in entries 1-3, the reaction temperature was reduced to 20 ^{o}C (entry 4). However, this resulted in a sharp drop in conversion to 19%. The final two entries in Table 13 (5 and 6) illustrate the effect of depressurising and repressurising the reaction vessel. These reactions were carried out to reveal whether reactions at lower pressures were exhibiting poorer conversions as a result of less CO_2 being present in the autoclave as the reactions proceeded. However, by comparing entry 4 with entry 5 and entry 1 with entry 6, it is clear that no significant improvement is seen after recharging the vessel with fresh compressed air.



Scheme 42 - Synthesis of cyclic carbonates from compressed air

Table 13 – Synthesis of styrene carbonate from compressed air and styrene oxide (1a)[a]

Entry	Epoxide	Air (bar)	Temp. (°C)	Time (h)	Conversion[b] (%)
1	**8g**	10	50	24	61
2	**8g**	10	50	72	78
3	**8g**	25	50	24	79
4	**8g**	25	20	24	19
5	**8g**	25	20	8+16	25
6	**8g**	10	50	8+16	54
7	**8g**	1[c]	20	3	98

[a] Reaction carried out in a 300 mL autoclave heated by a thermostatically controlled oil bath for 24 hours at 50°C in air (25 bar); [b] Conversions obtained by ^{1}H NMR analysis of the crude reaction mixture; [c] Result shown using bimetallic complex **10** in pure carbon dioxide at atmospheric pressure.[13]

Since the conditions shown in Table 13, entry 3 combined the best conversion with the shortest reaction time, they were taken as being optimal. These conditions were then applied to various epoxides (**1b**-**l**) in order to see how effective the catalyst system was across a range of substrates. The results are outlined in Table 14. The conversions to cyclic carbonates **9b**-**l** were reasonable (28-79%), with the highest being for epoxydecane (**1d**) and styrene oxide (**1g**). One of the limitations of this chemistry was

in the equipment used. The autoclave reactor which was available was only 300 mL in volume. Thus even when charged with 25 bar pressure of air, the vessel only contained approximately 0.13 mmol of CO_2 (assuming that CO_2 makes up 385 ppm of air and that 1 mol of air occupies 24,000 mL at room temperature and pressure). This meant that the amount of material that was being handled was very small (0.1 mmol) to ensure that a slight excess of CO_2 was present in the autoclave. For this reason obtaining isolated yields of purified products via column chromatography was difficult for each product.

Table 14 – Synthesis of cyclic carbonates from compressed air and various epoxides[a]

Entry	Epoxide	R	Conversion[b] (%)
1	**1b**	CH_2Cl	31
2	**1d**	C_8H_{17}	73
3	**1f**	C_4H_9	57
4	**1h**	CH_2OPh	53
5	**1j**	$C_{10}H_{21}$	39
6	**1k**	4-ClC_6H_4	54
7	**1l**	4-BrC_6H_4	28

[a] Reaction carried out in a 300 mL autoclave heated by a thermostatically controlled oil bath for 24 hours at 50°C in air (25 bar); [b] conversions obtained by ^{1}H NMR analysis of the crude reaction mixture

In order to prove that the reported conversions were accurate, and were not being influenced by, for example, some of the unreacted epoxide evaporating due to the

increased temperatures, it was decided to repeat one of the reactions a number of times in order that the combined crude mixtures gave enough material to purify by chromatography. Since decene oxide (**1d**) occupied the largest volume and gave a relatively good conversion, it was selected and the reaction repeated eight times. These individual crude products were combined, and after purification by column chromatography, an isolated yield of 67% was obtained, which compared favourably with the 73% conversion (Table 14, entry 2).

Table 15 – Synthesis of cyclic carbonates from compressed air and various epoxides[a]

Entry	Epoxide	R	External Temp (^oC)	Internal Temp (^oC)	Conversion[b] (yield) (%)
1	**1j**	$C_{10}H_{21}$	50	36	15
2	**1j**	$C_{10}H_{21}$	60	45	19
3	**1j**	$C_{10}H_{21}$	60[c]	53	25 (18)
4	**1b**	CH_2Cl	60[c]	53	19 (15)
5	**1k**	4-ClC_6H4	60[c]	53	29 (24)
6	**1l**	4-BrC_6H4	60[c]	53	16 (14)

[a]Reactions carried out in a 2000 mL autoclave heated by a thermostatically controlled oil bath for 24 hours in air (25 bar); [b] Yields obtained after column chromatography; [c] Outside of reactor lagged with cotton wool and aluminium foil for heat insulation

After the work using the 300 mL autoclave was finished, a larger autoclave with a volume of 2,000 mL was acquired. This meant that experiments could be scaled up by a factor of six, with approximately the same ratio of reactant to CO_2 as in the smaller autoclave. This meant that the study could potentially be completed in a reasonable time with isolated yields reported for each epoxide.

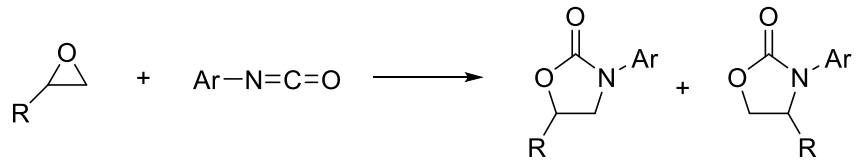
Dodecene oxide (**1j**) was chosen as the first epoxide to work with and the results are shown in Table 15. The conditions which had been optimised for the 300 mL vessel were used: an oil bath (external) temperature of 50 ^{o}C, and reaction pressurized to 25 bar. However under these conditions only a 15% conversion was observed (entry 1). When the internal temperature of the autoclave was measured, it read only 36 ^{o}C, and this was therefore assumed to be the reason for the decrease in catalytic activity between the two systems. The reaction was run again, this time with the external temperature raised to 60 ^{o}C (internal temperature measured at 45 ^{o}C) however an insignificant increase in conversion of only 4% was observed. Since the 2,000 mL autoclave is significantly larger than the 330 mL version, the depth of the oil bath covers a much smaller surface area. This means that there is a greater amount of heat lost to the atmosphere through the unheated metal portion of the vessel. This meant that although the heat applied to the bottom of the autoclave was the same for both the small and the large versions, it was not distributed evenly in the larger one and therefore was not affecting the reaction as much.

The reaction was run again under the same conditions, this time lagging the outside of the autoclave with cotton wool and aluminium foil in order to contain the heat more effectively and to distribute it evenly throughout the entirety of the cylinder (entry 3). This time, the internal temperature rose to 53 ^{o}C, and therefore the result should be equivalent to the reactions carried out in the smaller autoclave, however the conversion observed was only just over a third of the one reported with the 300 mL reactor. As any higher external temperatures applied resulted in the evaporation of the epoxide from the reaction vial within the autoclave into the autoclave itself, these conditions were used to test other epoxides (**1b**, **k** and **l**), and it was found that each of these was also significantly lower than before. However, it was possible to purify these

products by column chromatography, so isolated yields were recorded for all four products (14-24%).

In summary, due to the substantial increase in catalytic activity of complex **10** in the formation of cyclic carbonates by applying higher temperature and pressure to the reaction, compressed air could be used as a source of carbon dioxide for the first time. It has been shown that reasonable conversions can be obtained across a range of epoxide substrates. The results were limited by the equipment used which allowed only very small scale work to be carried out, which meant that isolated yields could not be obtained for all the products. Unfortunately, the same system could not be applied to be used on a larger scale as the uneven heating and heat loss due to conduction through the large unheated surface of the metal autoclave resulted in large reductions in conversions.

2.2.2 *Investigation of the catalytic cycle for reaction of isocyanates with epoxides*

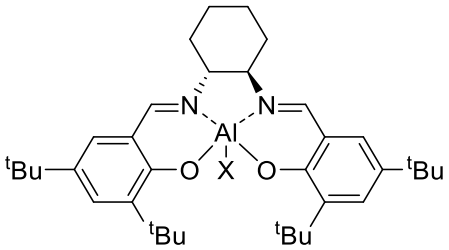


5 **23** **24**

Scheme 43 - Synthesis of oxazolidinones from epoxides and isocyanates

The reaction between epoxides and isocyanates, catalysed by **10** has been a focus of some research within the North group. Recently it was found that bimetallic

aluminium salen complex **10** can catalyse the addition of isocyanates to epoxides, forming oxazolidinone products in excellent yields (Scheme 43).[90] Unlike the reactions of other heterocumulenes with epoxides catalysed by **10** it was found that good yields could be achieved without the use of a cocatalyst, with the use of TBAB found to retard the reaction.



20: X = Et
21: X = OEt
22: X = Cl

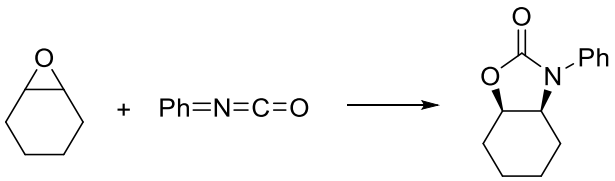
Table 15 – Monometallic aluminium salen catalysed synthesis of oxazolidinones[a]

Entry	R	Catalyst[b]			
		20	**21**	**22**	**10**
1	**Ph**	0	0	53 (1:2.4, **23**:**24**)	100 (1:1.9, **23**:**24**)
2	**^{n}Oct**	6 (1:0, **23**:**24**)	7 (1:0, **23**:**24**)	35 (5.4:1, **23**:**24**)	91 (1.6:1, **23**:**24**)
3	**CH_2Cl**	57 (1:0, **23**:**24**)	49 (1:0, **23**:**24**)	56 (1:0, **23**:**24**)	100 (1:0, **23**:**24**)

[a] Reactions carried out at 80 ^{o}C in toluene for 24 h, using 5 mol% catalyst [b] Conversion of epoxide into 23 and 24 with the ratio (determined by ^{1}H NMR spectroscopy of the crude mixture) shown in brackets.

It was decided to investigate the relative activity of monometallic aluminium salen complexes for this transformation. Three catalysts (**20**, **21** and **22**) with different groups coordinated to the aluminium centre were selected and tested on reactions with three different epoxides and phenyl isocyanate. The results are shown in Table 15, which also includes the equivalent results reported for complex **10,** the bimetallic version of these catalysts.[90]

As can be seen from Table 15, entry 1, compounds **20** and **21** showed no catalytic activity for the synthesis of oxazolidinones **23a** and **24a** from styrene oxide and phenyl isocyanate. However, compound **22**, containing the chloride counterion, gave 53% conversion, which was around half of the activity of complex **10**. The ratio of the regioisomeric products for the two catalysts was approximately equal. Similar results were observed for reactions with decene oxide (entry 2) in which catalysts **20** and **21** gave very little conversion, while **22** offered a significant improvement, again with a similar ratio of products when compared to catalyst **10**. A different trend was however observed for the substrate 3-chloropropylene oxide (entry 3) in which all three monometallic catalysts exhibited virtually identical activity, which was again approximately half of that of catalyst **10**.

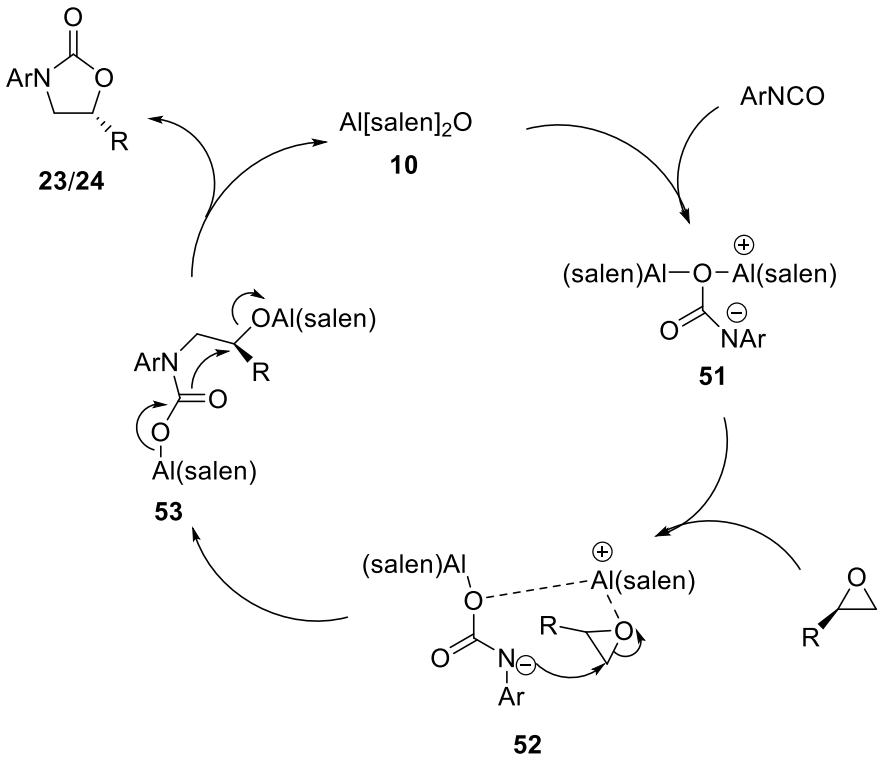


24i

Scheme 44 - Cyclohexene oxide and phenyl isocyanate

It was found (by obtaining a crystal of **24i** for X-ray analysis) that the reaction between cyclohexene oxide and phenyl isocyanate (Scheme 44) produced the *cis*-product.[90] This stereochemical outcome clearly implies that the mechanism involves a double inversion. This means that the mechanism is similar to the one proposed for the formation of cyclic carbonates catalysed by **10**.[14] This was a surprising outcome, as the double inversion in the cyclic carbonate mechanism is presumed to be due to the ring opening of the epoxide by the bromide ion which is present from the TBAB cocatalyst. Since there is no cocatalyst in this system, it was thought that this mechanism would be more similar to the formation of thiocarbonates by **10** and tributylamine.[27]

Taking the stereochemistry of the products into account, and also the observed regiochemistry (in which product **23** is formed preferentially) a catalytic cycle can be proposed, which can also help explain the results with the monometallic catalysts in Table 15. This cycle is shown in Scheme 45. Firstly, the Lewis basicity of the bridging oxygen atoms allows the formation of adduct **51**. This, in turn, enhances the Lewis acidity of the aluminium centres, one of which will coordinate to the epoxide, activating it for attack and subsequent ring-opening by the nitrogen anion (adduct **52**). The system tends to favour the formation of product **23**, which means the epoxide is opened at the terminal carbon, by an S_N2 mechanism, with potential inversion of configuration. The only exception is the case of styrene oxide in which the benzylic position offers an electronic stabilisation by the aromatic ring which outweighs the steric hindrance. This, therefore, explains this substrate favouring the formation of the opposite regioisomer. Adduct **52** is then formed (with the aluminium-oxygen-aluminium bridge broken) and this is followed by ring-closure via an intramolecular substitution, resulting in a second inversion after which the product (**23** or **24**) is formed and catalyst **10** is reformed.



Scheme 45 - Proposed catalytic cycle

The mechanism shown in Scheme 45 requires a catalyst with an aluminium-X-aluminium bridge, which can be broken and reformed when required. The fact that monometallic catalyst **22** is about half as active as the bimetallic **10** can be explained by the fact that it is known that chlorine can be a bridging atom between two aluminium centres,[91] which would result in oligomeric species assuming the same general structure as **10**, resulting in a bimetallic catalyst active for this process. However, since 5 mol% of each catalyst was used and complex **10** is bimetallic, this results in twice as many aluminium centres, which could account for the increase in catalytic activity. This aggregation is not possible with complex **20** and is disfavoured due to steric hindrance in the case of complex **21**. For the reaction between epichlorohydrin and phenylisocyanate, Table 15 shows that all three monometallic catalysts are active in the formation of the oxazolidinones. It would appear that the chlorine atom in the epoxide

can be transferred to the catalysts in order to form a bimetallic structure, and therefore all three become active in these transformations, once again with around half of the activity exhibited by complex **10.**

2.2.3 *Kinetic investigation of the reaction of isocyanates with epoxides*

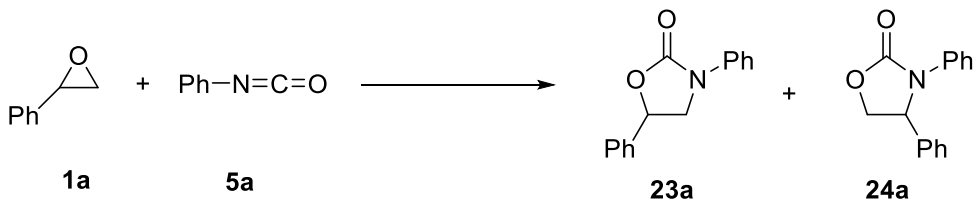
As discussed in the introduction to this thesis, despite the similarities between the complex **10** catalysed reactions of epoxides with carbon dioxide, carbon disulphide and isocyanates, there are enough discrepancies in the results to suggest significant differences in the respective reaction mechanisms. For the reaction between epoxides and carbon dioxide; TBAB was necessary as a cocatalyst, the reaction required a bimetallic aluminium complex in order to proceed and the products were shown to form with retention of epoxide stereochemistry.[9] A kinetic study revealed the rate equation to be that of Equation **1** (Introduction, page 9).

For the reaction of epoxides with carbon disulphide; both TBAB and tributylamine were found to be effective as cocatalysts,[22] the formation of products was seen to proceed with inversion of epoxide stereochemistry, and monometallic complexes were also observed to be catalytically active. After another kinetic study the rate equation for the reaction was proposed to be Equation 2 (introduction, page 17).

Finally, for the reaction of epoxides with isocyanates; no cocatalyst was required, the product stereochemistry was retained from that of the epoxide and monometallic complexes were revealed to be effective catalysts. Since a detailed kinetic study has never been undertaken for this reaction, and therefore no rate equation exists, it was decided to carry out an investigation. This would be followed by varied

temperature experiments on all three systems in order to provide an understanding of the fundamental differences in the mechanisms of these three reactions.

The starting point of this study was to observe the reaction kinetics of the reaction between epoxides and isocyanates catalysed by **10**. This would allow the rate equation to be determined and a comparison to be drawn with the rate equations for the reaction between epoxides and carbon dioxide or carbon disulphide. The conditions for analysing reaction kinetics were chosen to match the synthetic results as closely as possible. This meant that the reactions were carried out at 80 ^{o}C in toluene, with the chosen reaction substrates, styrene oxide **1a** and phenyl isocyanate **5a** in equimolar amounts, along with 5 mol% of catalyst **10** (Scheme 46). These reactions were monitored by removing samples at set intervals, and analysing them by ^{1}H NMR spectroscopy. This allowed the rate of product formation to be measured, as well as the ratio of the two products (**23a**:**24a**, found to be 1:1.9) to be calculated.



Scheme 46 - Reaction of stryene oxide and phenylisocyanate

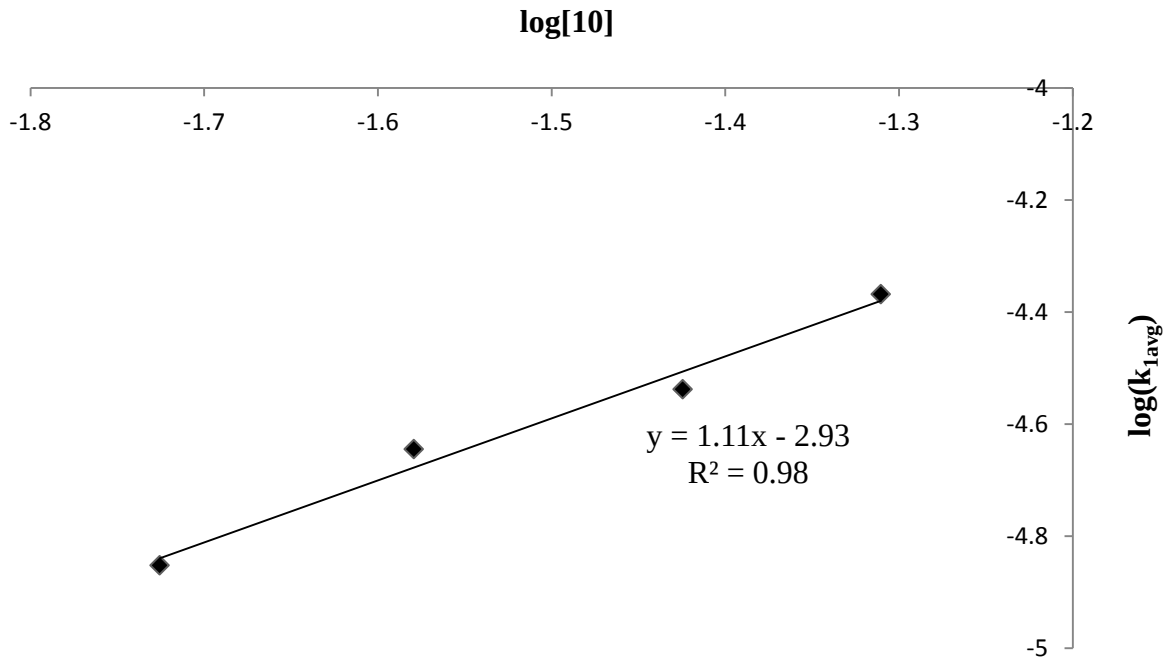


Figure 1 – Plot of log[**10**] against log(k_{1avg}) for the synthesis of oxazolidinones (**23a**/**24a**). Reactions carried out at 80 °C, in toluene with [**1a**]$_0$ = 0.4 M and [**5a**]$_0$ = 0.42 M.

Reactions carried out under these conditions were observed to show a good fit to first order kinetics. When results were compared using three separate initial concentrations of styrene oxide **1a**, no change in the initial reaction rate was seen (see Appendix, page 188). On the other hand, the reaction rate was observed to vary directly with a change in initial phenylisocyanate (**5a**) concentration (see appendix, page 189).

The order with respect to the catalyst **10** was also to be determined. This was achieved by carrying out reactions at various concentrations of the catalyst (catalyst concentrations of 5-13 mol% were chosen). All reactions were carried out in duplicate (see appendix, pages 190–193), and the resulting plot of log[**10**] against log(k_{1avg}) is shown in Figure 1. A straight line with a slope of 1.1 was fitted to the data collected, which would suggest that the reaction was first order in complex **10** concentration. This analysis was confirmed by plotting [**10**] against k_{1avg} (Figure 2) which also gave a

straight line. A conclusion can therefore be drawn that the rate equation for this reaction (Scheme 46) could be written in the form of Equation 3.

Equation 3: Rate = k[**10**][isocyanate]

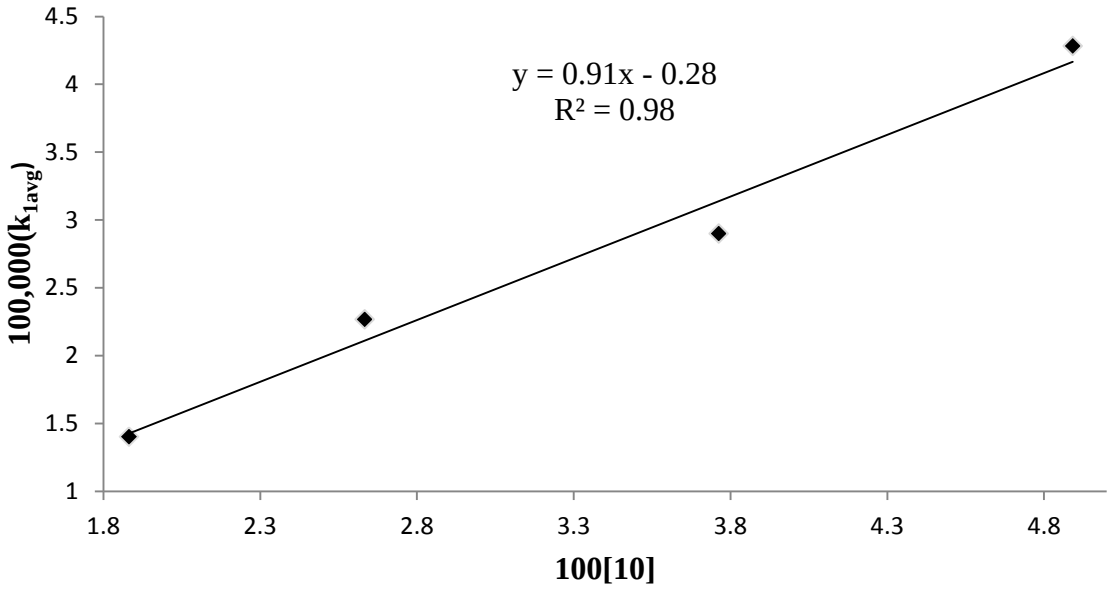


Figure 2 – Plot of [**10**] against k_{1avg} for the synthesis of oxazolidinones (**23a**/**24a**) from styrene oxide **1a** and phenylisocyanate **5a**.

This rate equation is clearly very different to the equations for the reactions of epoxides with carbon dioxide (Equation **1**) and carbon disulphide (Equation **2**). This is evidence for an entirely different catalytic cycle in which the initial interaction is between complex **10** and the isocyanate, rather than the epoxide. In order to investigate this further, NMR spectroscopic studies were carried out to see if any interaction between the two species could be observed. A ^{13}C NMR experiment was run in which complex **10** was mixed with isocyanate **5a** in $CDCl_3$, this was compared to the ^{13}C NMR spectrum of **10** on its own. It was observed that the chemical shifts of complex **10**

appeared to change upon addition of the isocyanate, and the total number of peaks increased, which were consistent with the formation of a new species with less symmetry than complex **10**. These spectra are shown in Figure 3. It should be noted that when a similar study was carried out with styrene oxide (**1a**) in place of isocyanate **5a**, no changes in the spectrum were seen.

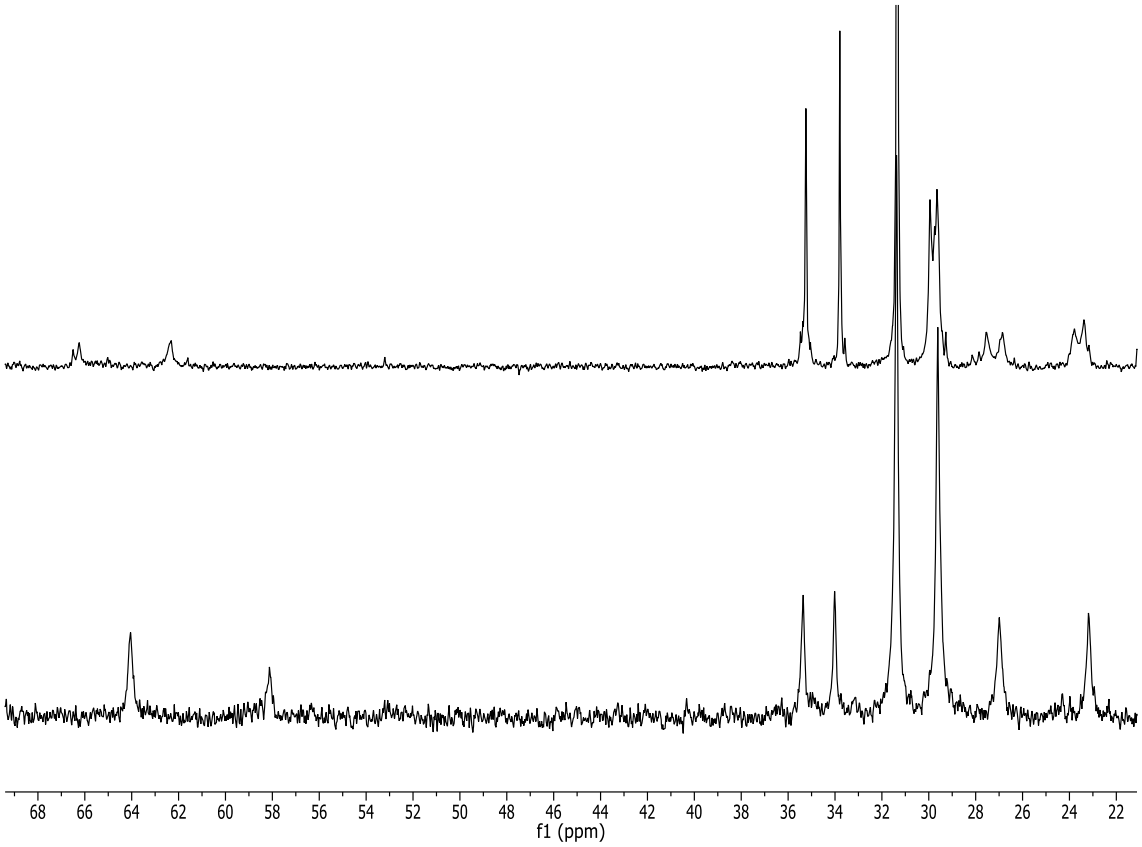
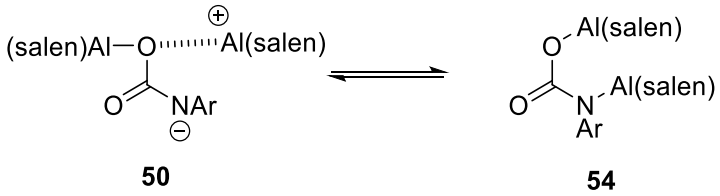


Figure 3 – Aliphatic region of the ^{13}C NMR spectra of complex **10** mixed with isocyanate **5a** in $CDCl_3$ (top), and complex **10** only in $CDCl_3$ (bottom).

As can be seen in Figure 3, the aliphatic region of the ^{13}C NMR spectrum of complex **10** changes significantly upon the addition of isocyanate **5a**. The signals observed in the region between 22 and 36 ppm correspond to the cyclohexyl ring and the methyl carbons on the tertiary butyl groups, whilst the two signals that come at approximately 58 and 64 ppm in complex **10** correspond to the CH-N carbons of

complex **10**. Upon addition of the isocyanate the CH-N signals shift to over 62 and 67 ppm respectively, with the peak at 67 ppm being resolved into two separate signals.

A similar change is seen in the other peaks in the spectrum. One of the two largest signals in complex **10**, corresponding to the tertiary butyl methyl groups, which come at approximately 30 ppm, is split into two separate peaks. Two out of the four remaining peaks (corresponding to the cyclohexyl ring group), are also resolved into two separate peaks upon interaction with the isocyanate.

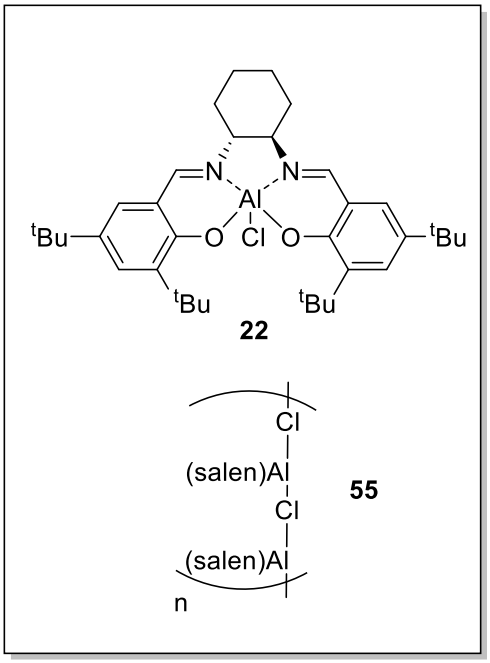


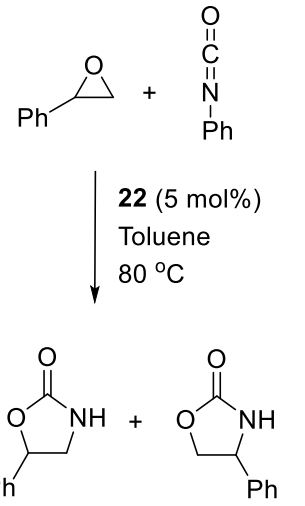
50 **54**

Scheme 47 - Interaction between complex **10** and phenyl isocyanate **5a**

In the proposed mechanistic cycle for this reaction (Scheme 45), intermediate **51**, which shows an interaction between complex **10** and the isocyanate, is drawn with both aluminium ions of the catalyst interacting with the bridging oxygen atom, which emphasises the increased Lewis acidity of the metal centres. In the way this is drawn, both aluminium ions, and hence the salen ligands which are coordinating to them, would be identical, as the positive charge would be expected to be delocalised between them. If, however, this zwitterionic species was drawn as the neutral molecule **54** (Scheme 47), it would create an unsymmetrical molecule, the salen ligands would therefore be different, and this may explain the changes in the spectra between the two complexes shown in Figure 3.

2.2.4 *Kinetic investigation of reaction of isocyanates with epoxides catalysed by complex 15*





Scheme 48 - Reactions of styrene oxide with phenyl oxazolidinone catalysed by complex **22**

As shown in Table 15, monometallic complex **22** is also an active catalyst for the synthesis of oxazolidinones from epoxides and isocyanates, showing about half of the activity of complex **10**. Previously it was found that complex **22** is active for the synthesis of thiocarbonates,[27] exhibiting similar activity to that shown by complex **10**, but is completely inactive for cyclic carbonate synthesis. Scheme 12 (introduction page 18) shows that the mechanism for thiocarbonate synthesis only requires a monometallic species, while Scheme 4 (introduction, page 8) explains the need for a bimetallic complex as the catalyst for cyclic carbonate synthesis. However, the catalytic cycle proposed for the synthesis of oxazolidinones by complex **10** involves the catalytic species interconverting between a monometallic and bimetallic species when required

(Scheme 45). In order to clarify this a detailed kinetic study was undertaken, with the same reagents and conditions used for the kinetic study of the reaction catalysed by complex **10** (Scheme 48).

As with the study involving complex **10**, reactions were carried out with various initial concentrations of epoxide **1a** and isocyanate **5a** (appendix, pages 194–195). Again, it was shown that the reaction rate varied directly with the initial isocyanate concentration, and did not vary with the initial concentration of styrene oxide. It was therefore assumed to be first order in isocyanate and zero order in epoxide. Again, products **23a** and **24a** were shown to form in a ratio of 1.9:1.

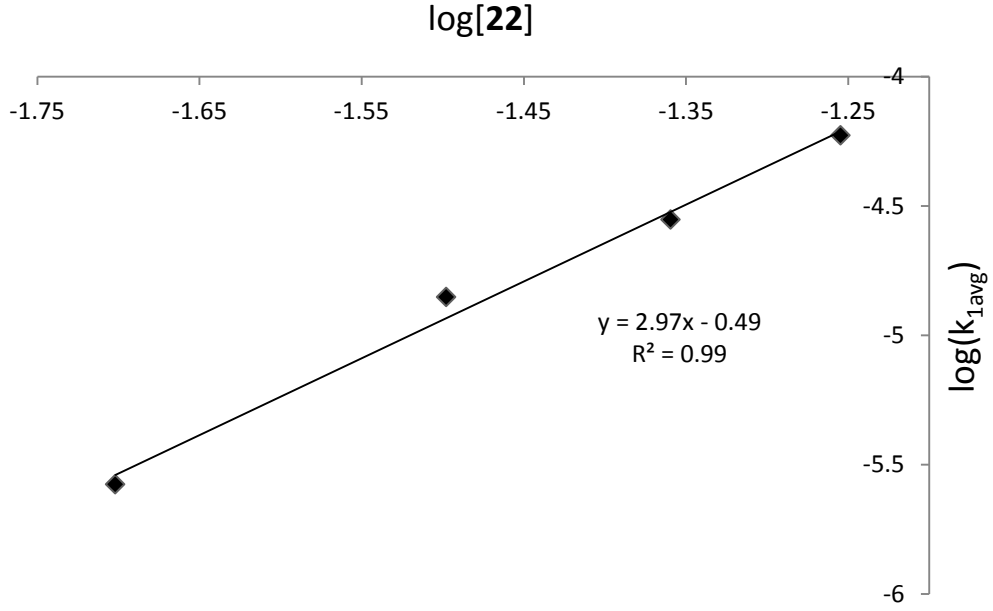


Figure 4 – Plot of log[**22**] against log(k_{1avg}) for the synthesis of oxazolidinones (**23a**/**24a**). Reactions carried out at 80°C, in toluene with $[\mathbf{1a}]_0$ = 0.40 M and $[\mathbf{5a}]_0$ = 0.42 M

Reactions were then carried out (in duplicate) at four different concentrations of catalyst **22**, and the resulting plot of log([**22**]) against log(k_1), shown in Figure 4, indicated that the reaction was third order in catalyst concentration. This was further

confirmed by a plot of [**22**] against (k_1/[**22**]^2), which was found to be a straight line, which passed through the origin (Figure 5). It was therefore concluded that the rate equation for this reaction is given by Equation 4.

Equation 4 – Rate = k[**22**]^3[isocyanate]

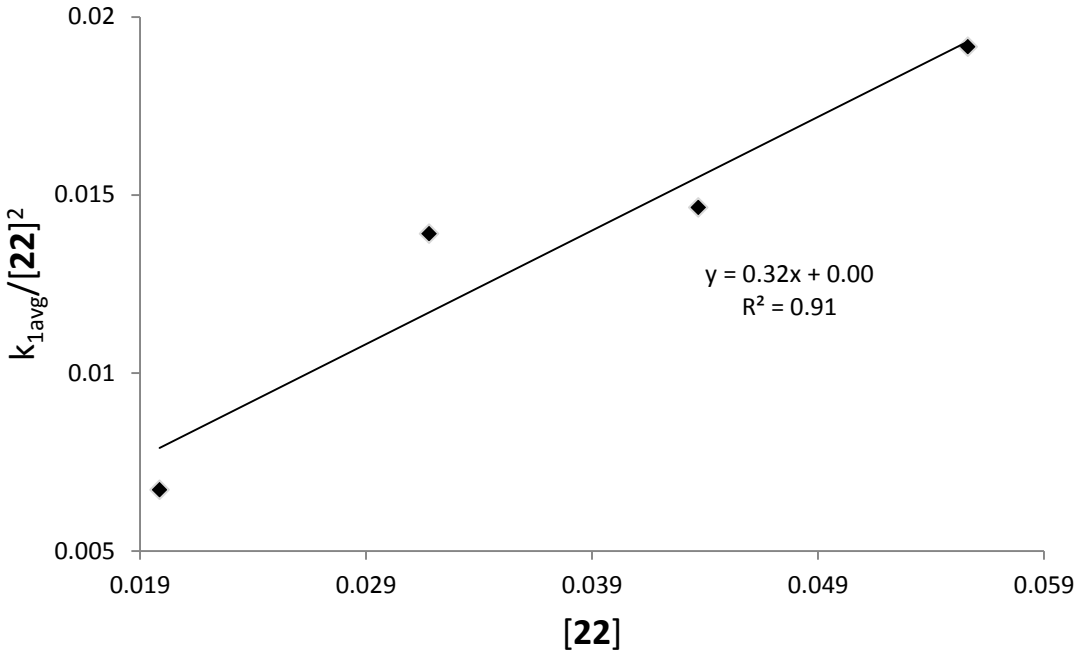


Figure 5 – Plot of [**22**] against k_{1avg} for the synthesis of oxazolidinones (**23a**/**24a**) from styrene oxide **1a** and phenylisocyanate **5a**.

An explanation for both the third order kinetics, and the fact that this reaction can be catalysed by a monometallic species despite the mechanism implying that two metal centres are required is that catalyst **22** exists as chloride bridged oligomers or molecular clusters in the form of the one shown as complex **55**. There has been much

literature precedent for aluminium-chloride-aluminium bridges, and for these bridges to bind molecules together resulting in the formation of clusters.[92,93]

2.2.5 *Varied temperature kinetic studies on reactions of epoxides with heterocumulenes*

Once kinetic studies had been carried out to determine the rate equations of **10** catalysed reactions of epoxides with all three heterocumulenes, a varied temperature kinetic study was carried out to allow the activation parameters of each reaction to be determined. The Eyring equation (Equation 5) shows how the rate constant of a reaction is related to the enthalpy and entropy of activation. The actual rate constant (in Equation 5) can be replaced with k_{obs} (where $k_{obs} = k[\mathbf{10}]^x[Bu_4NBr]^y$), and after rearranging can form Equation 6. If logarithms are taken of both sides, this gives Equation 7.

Equation 5: $k = (k_B \cdot T/h) \cdot \exp(-\Delta H^{\ddagger}/RT) \cdot \exp(\Delta S^{\ddagger}/R)$

Equation 6: $k_{obs}/T = (k_B/h) \cdot [\mathbf{10}]^x \cdot [Bu_4NBr]^y \cdot \exp(-\Delta H^{\ddagger}/RT) \cdot \exp(\Delta S^{\ddagger}/R)$

Equation 7: $\ln(k_{obs}/T) = (-\Delta H^{\ddagger}/RT) + (\Delta S^{\ddagger}/R) + \ln(k_B/h) + x \cdot \ln[\mathbf{10}] + y \cdot \ln[Bu_4NBr]$

(k_B = Boltzmann's constant, h = Planck's constant, R = gas constant)

By plotting a graph of $\ln(k_{obs})/T$ against 1/T, the activation parameters can be determined. The slope of the best fit line will give the enthalpy of activation ($\Delta H^{\ddagger}$) and the intercept on the y-axis can provide the entropy of activation ($\Delta S^{\ddagger}$) once the

fundamental constants and x·ln[**10**] and y·ln[Bu_4NBr] (where x and y are the reaction orders with respect to **10** and TBAB, respectively) have been subtracted. In the system for oxazolidinone synthesis, styrene oxide **1a** and phenylisocyanate **5a** were again used (Scheme 48). Duplicate reactions were run at five different temperatures between 70 and 110 °C using 5 mol% catalyst **10** in toluene (see appendix page 200–204). The resulting Eyring plot is shown in Figure 6.

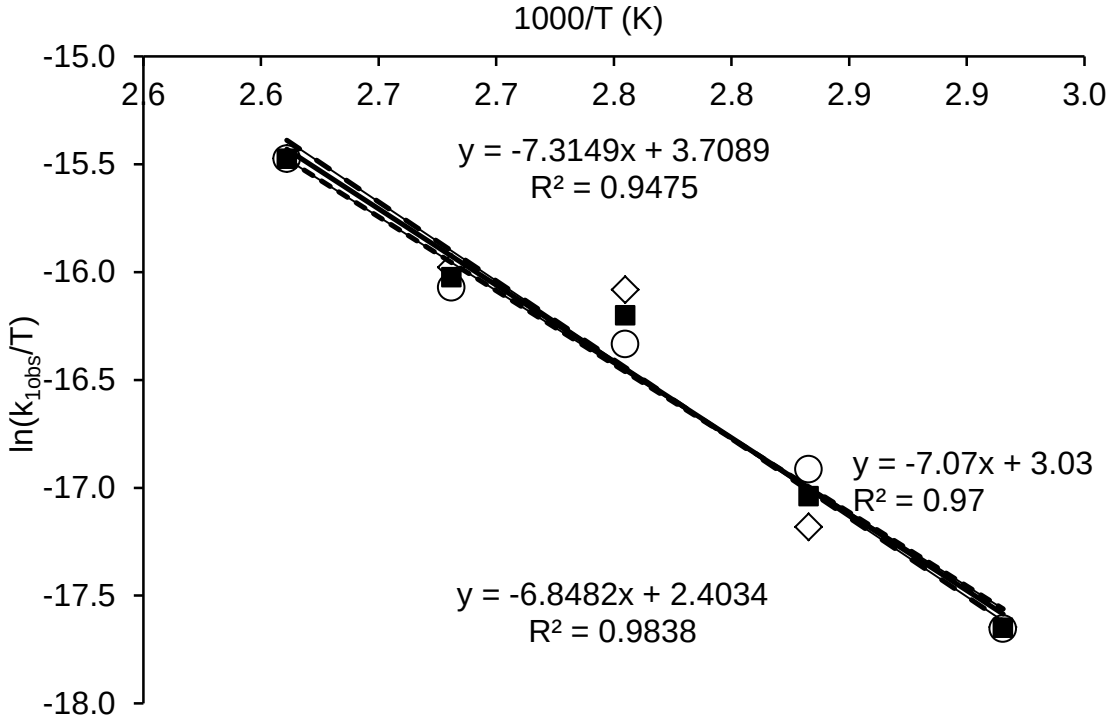
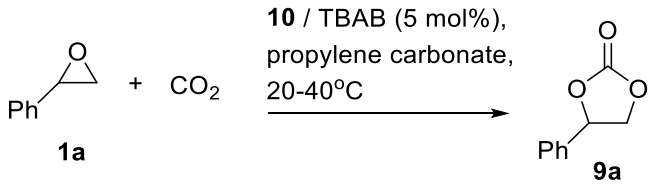


Figure 6 – Eyring plot for the synthesis of oxazolidinones **23a**/**24a** catalysed by complex **10**. Reactions performed in toluene at 70-110 °C with $[\mathbf{1a}]_0$ = 0.4 M, $[\mathbf{5a}]_0$ = 0.4 M and [**10**] = 0.2 mM. The dashed trend lines, empty symbols and equations with four decimal places represent the two individual runs and the solid line, filled squares and equation to two decimal places represent the average of the two runs.

A variable temperature kinetic study for the reaction between epoxides and CO_2 was also carried out. The substrate chosen was again styrene oxide **1a**, forming the product styrene carbonate **9a**, catalysed by a combination of 5 mol% of **10** and 5 mol% of TBAB. The reactions were performed in duplicate (see appendix, page 205–208) in propylene carbonate at temperatures ranging between 20-40 °C (Scheme 49). The

reactions were again monitored by periodically removing and quenching reaction mixture samples, and analysing them by ^{1}H NMR spectroscopy, to obtain the ratio of carbonate product to epoxide starting material. The Eyring plot obtained is shown in Figure 7.



Scheme 49 - Varied temperature study of synthesis of styrene carbonate

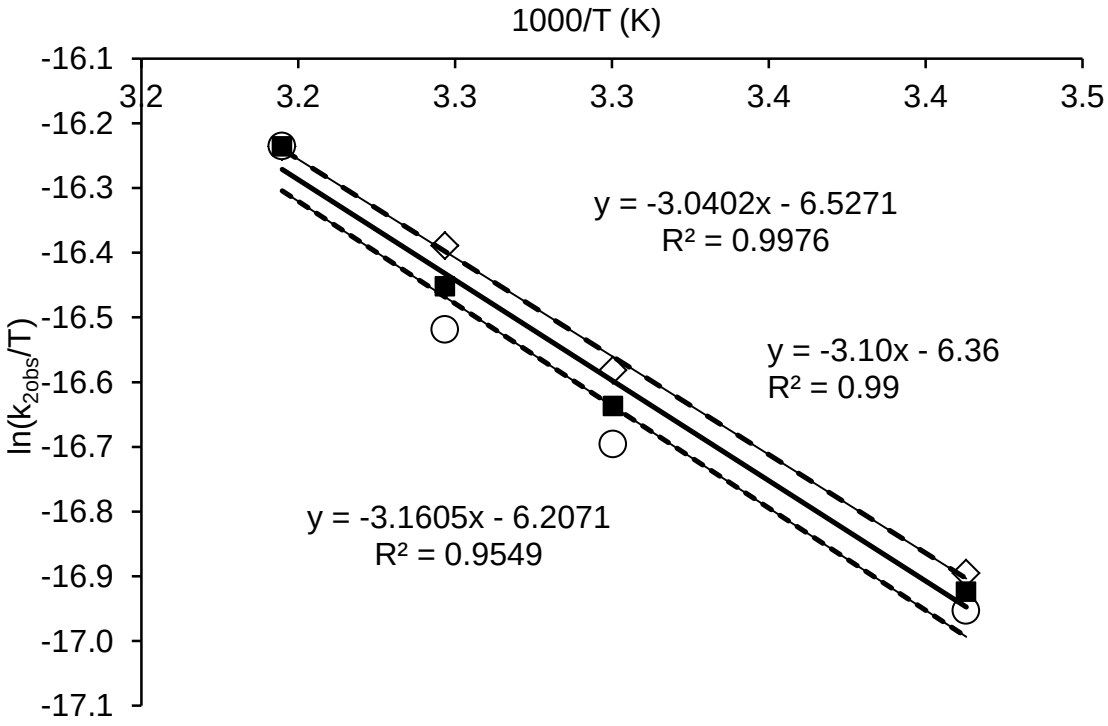


Figure 7 – Eyring plot for the synthesis of styrene carbonate **9a** catalysed by complex **10** and TBAB. Reactions performed in propylene carbonate at 20-40 °C with [**1a**]$_0$ = 1.46 M, [**10**] = 0.2 mM and [TBAB] 73 mM. The dashed trend lines, empty symbols and equations with four decimal places represent the two individual runs and the solid line, filled squares and equation to two decimal places represent the average of the two runs.

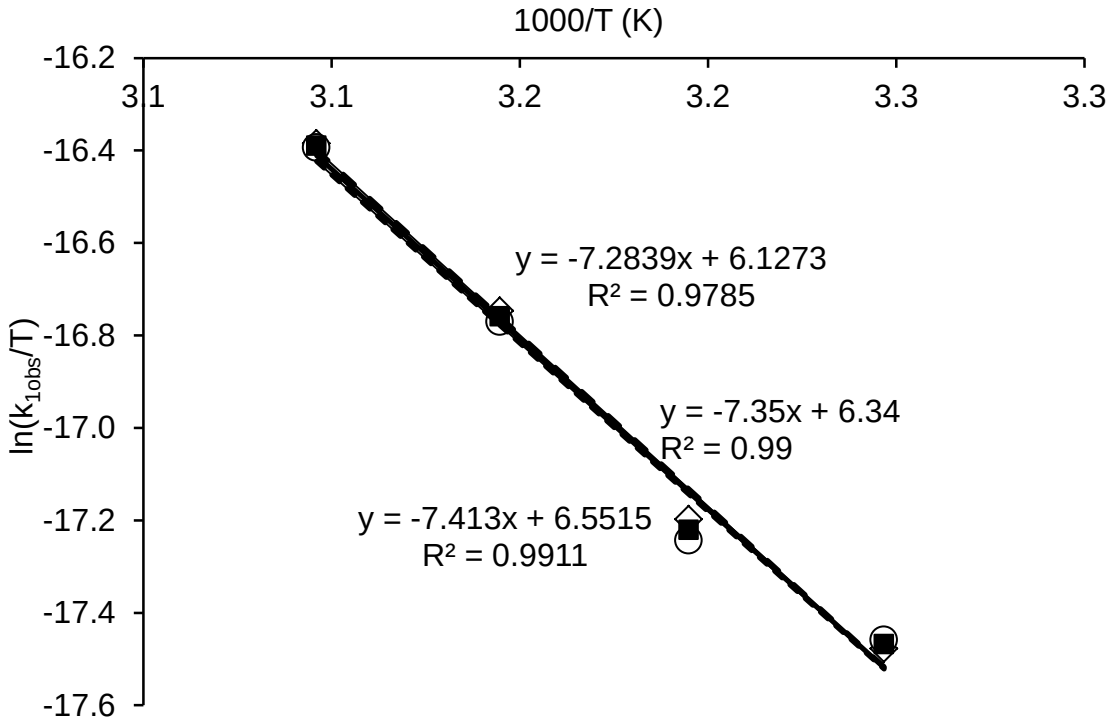
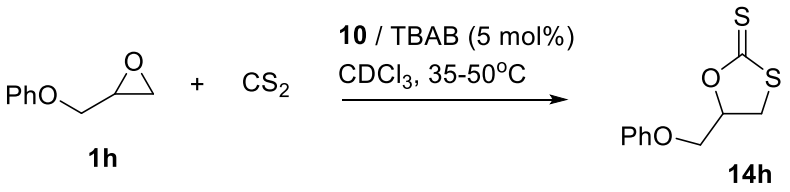


Figure 8 - Eyring plot for the synthesis of dithiocarbonate **14h** catalysed by complex **10** and TBAB. Reactions performed in $CDCl_3$ at 35-50 ^oC with $[\mathbf{1h}]_0$ = 1.43 M, $[CS_2]_0$ = 2.58 M, [**10**] = 72 mM and [TBAB] 72 mM. The dashed trend lines, empty symbols and equations with four decimal places represent the two individual runs and the solid line, filled squares and equation to two decimal places represent the average of the two runs.

In order to undertake a variable temperature experiment involving the reaction of epoxides with CS_2, epoxide **1h** was selected as the standard substrate, since its tendency to form the dithiocarbonate product almost exclusively meant that the reaction would be easier to follow kinetically. Therefore, reactions were carried out at temperatures ranging from 35-50 ^oC in $CDCl_3$, with 5 mol% of catalyst **10** and 5 mol% of TBAB (Scheme 50). These reactions were monitored over the course of 12 hours by ^1H NMR spectroscopy. The resulting Eyring plot is shown in Figure 8.

A final variable temperature experiment was carried out. Again, it was on the reaction of phenyl isocyanate **5a** reacting with styrene oxide **1a**, this time catalysed by monometallic complex **22**. This was to obtain a direct comparison between using a

bimetallic aluminium salen catalyst (**10**) and a monometallic catalyst (**22**). The resulting Eyring plot is shown in Figure 9.



Scheme 50 - Reaction of epoxide **1h** with CS_2 forming diothiocarbonate product **14h**

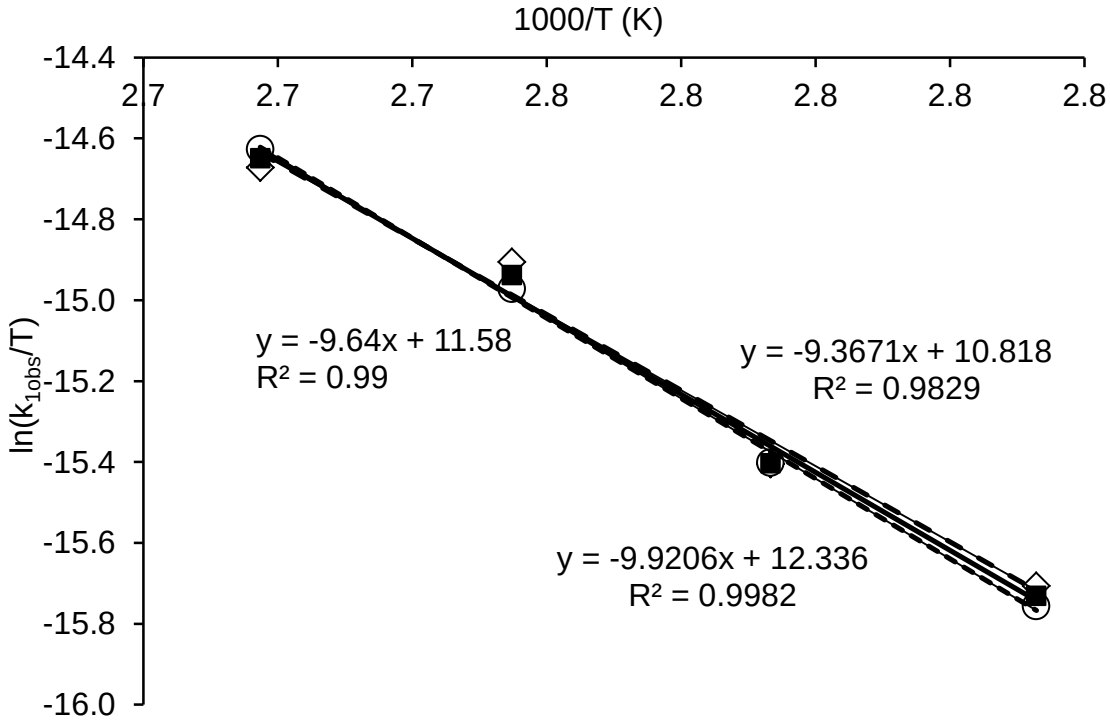


Figure 9 – Eyring plot for the synthesis of oxazolidinones **23a**/**24a** catalysed by complex **22**. Reactions performed in toluene at 80-95 °C with $[\mathbf{1a}]_0$ = 1.25 M, $[\mathbf{5a}]_0$ = 1.31 M and [**22**] = 125 mM. The dashed trend lines, empty symbols and equations with four decimal places represent the two individual runs and the solid line, filled squares and equation to two decimal places represent the average of the two runs.

Table 16 shows the activation energies calculated from the Eyring plots for the reactions of epoxides with various heterocumulenes. As can be seen by comparing entry

2 with entries 1 and 3, the Gibbs free energy of activation is significantly lower (approximately 20 kJ mol^{-1}) than that of the other two reactions. This is in agreement with the fact that the catalyst system being used was optimised for this process, and that it can be carried out at room temperature, whilst the other two transformations require temperatures of up to 90 ^{o}C to occur.

Table 16 – Activation parameters for reactions of epoxides with heterocumulenes, catalysed by complex 10[a,b]

Entry	Catalyst	Hetero-cumulene	$\Delta H^{\ddagger}$ (kJ mol^{-1})	$\Delta S^{\ddagger}$ ($Jmol^{-1}K^{-1}$)	$\Delta G^{\ddagger}$ ($kJmol^{-1}$)
1	**10**	**PhNCO**	58.9 ± 2.0	-140 ± 6	97.0 ± 3.6
2	**10**	**CO_2**	25.8 ± 0.5	-185 ± 2	76.3 ± 1.1
3	**10**	**CS_2**	61.1 ± 0.6	-123 ± 2	94.7 ± 1.2
4	**22**	**PhNCO**	80.2 ± 2.3	-49 ± 7	93.7 ± 4.2

[a] Data based on average of two data sets, with the error limits calculated from the two individual sets. [b] $\Delta G^{\ddagger}$ at 273 K.

When looking at the enthalpy and entropy of activation of both thiocarbonate and oxazolidinone synthesis, the two sets of data appear to be very similar. This can be explained by looking at the rate equations for both reactions (Equations 3 and 2, page 83 and 17, respectively). These imply that the rate determining steps of the catalytic cycles (Schemes 12 and 45, pages 18 and 79) are the first steps. Both involve complex **10** coordinating with one reacting species to form a single activated complex, all occurring

in a homogenous liquid phase. Therefore, negative entropies of activation would be expected of both reactions and the values would be expected to be reasonably similar.

A significant difference between the entropies and enthalpies of activation of cyclic carbonate synthesis compared to thiocarbonate and oxazolidinone synthesis can be seen in Table 16. Rate Equation 1 (introduction, page 9) implies that the rate determining step for this process is later in the catalytic cycle, since all reaction components appear in the equation. This fact, combined with the knowledge that CO_2 is a gas, offers an explanation as to the much more negative entropy of activations for this process. This increase in the magnitude of the entropy of activation is far outweighed by the much lower enthalpy of activation. This enthalpy value also suggests that the rate determining step is later in the cycle, since it would happen after the ring opening step, and therefore the strain energy of the epoxide would already have been released.

In the comparison between the formation of oxazolidinones from isocyanates and epoxides catalysed by either bimetallic complex **10** or monometallic complex **22**, the most striking feature is the differences in entropy of activation. In the reaction catalysed by complex **22** (entry 4), the entropy of activation is calculated as approximately one third that of the reaction by complex **10** (entry 1). Since all the conditions are the same (substrates, solvents and temperature), it is reasonable to assume that the difference in entropy of activations arises from the dissociation of oligomeric catalyst species **55**. This would result in an increase in entropy during the transition state which would cancel out the decrease in entropy from the aluminium salen complex and the isocyanate coordinating to one another.

The enthalpy of activation of the reaction catalysed by bimetallic complex **22** is significantly higher than that of complex **10**. Since the difference in the catalysts is the

type of atom which is bridging the two aluminium salen units together. The difference in the enthalpy of activation presumably arises from the fact that a chloride atom is not as effective as oxygen when used to coordinate to the isocyanate when forming the transition state. Since the Gibbs free energy of activation for the two catalysts (**10** and **22**) are effectively identical, within the experimental errors, it can be ascertained that the differences between the respective entropy and enthalpies of activation cancel each other out.

To summarise the mechanistic studies carried out on the **10** catalysed reactions of epoxides and heterocumulenes, it has been found that different five-membered heterocyclic products can be formed from the reactions of epoxides with carbon dioxide, carbon disulphide and isocyanates. Three rate equations have been derived as Equations 1 and 2 (introduction, page 9 and 17) and Equation 3 (results and discussion, page 79).

Rate equations for the reactions involving carbon disulphide and isocyanate (Equations 2 and 3) both have the same general form (rate = k[substrate]), but they differ in the substrate upon which the rate relies. The carbon disulphide reaction rate depends upon the epoxide, and it can be assumed that the initial interaction is between complex **10** and the epoxide. In contrast, the isocyanate reaction rate depends upon the heterocumulene, and the initial interaction appears to be between complex **10** and the isocyanate (this interaction can be observed via analysis of ^{13}C NMR spectra). The initial interactions of these two reactions seem to be the respective rate determining steps. In a very different mechanism, the **10** catalysed formation of cyclic carbonates from epoxides and carbon dioxide, the rate equation takes on a much more complicated form in which it contains all the reaction species (Equation 1). This suggests that the rate determining step of this reaction comes much later in the catalytic cycle.

The varying rate equations for the three reactions can potentially be explained by the differing levels of susceptibility to nucleophilic attack of the heterocumulenes. Isocyanates are known to be particularly susceptible to attack by oxygen-based nucleophiles,[94] whilst carbon disulphide and carbon dioxide are less vulnerable to this sort of attack, although there is precedent for reaction with oxygen and nitrogen based nucleophiles.[95,96] The bridging oxygen of complex **10** is potentially a good, hard nucleophile and therefore, as shown in the proposed mechanism outlined in Scheme 45, may be involved in the first step in the cycle.

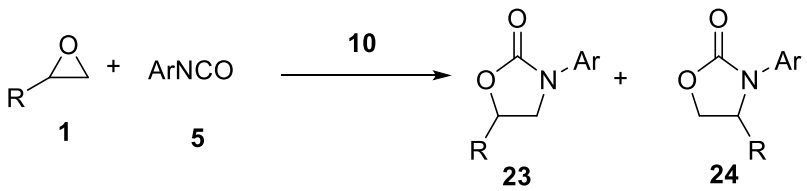
On the other hand, for the reactions involving heterocumulenes that are less vulnerable to attack by nucleophiles, it is more likely to be the Lewis acidic aluminium centres coordinating to the epoxide that would initiate the catalytic cycles. This coordination step appears to be the rate determining step of the reaction involving carbon disulphide and epoxides. However, for the reaction between epoxides and carbon dioxide, it appears that the rate determining step comes much later in the mechanistic cycle, hence the complexity of the rate equation.

The respective entropies of activation determined from the variable temperature kinetic experiments carried out support the preceding hypothesis. As can be seen in Table 16, the reactions of epoxides with carbon disulphide and isocyanates have very similar negative entropies of activations, which is consistent with the rate equations taking the same general form (i.e. catalyst **10** and one substrate coming together in the rate determining step). In contrast the reaction involving carbon dioxide has a much more negative entropy of activation which can be explained by the fact that the rate determining step comes much later in the catalytic cycle, and hence the rate equation involves many species coming together to form the rate determining transition state. However, the overall analysis suggests that catalyst **10** is more optimal for the reaction

with carbon dioxide to form cyclic carbonates, since the enthalpy and Gibbs free energy of activation calculated for this reaction are both approximately 20-30 kJ mol^{-1} lower than for the other two reactions. This would explain why this reaction can be carried out at ambient temperature, while the other two need to be heated to up to 90 ^{o}C.

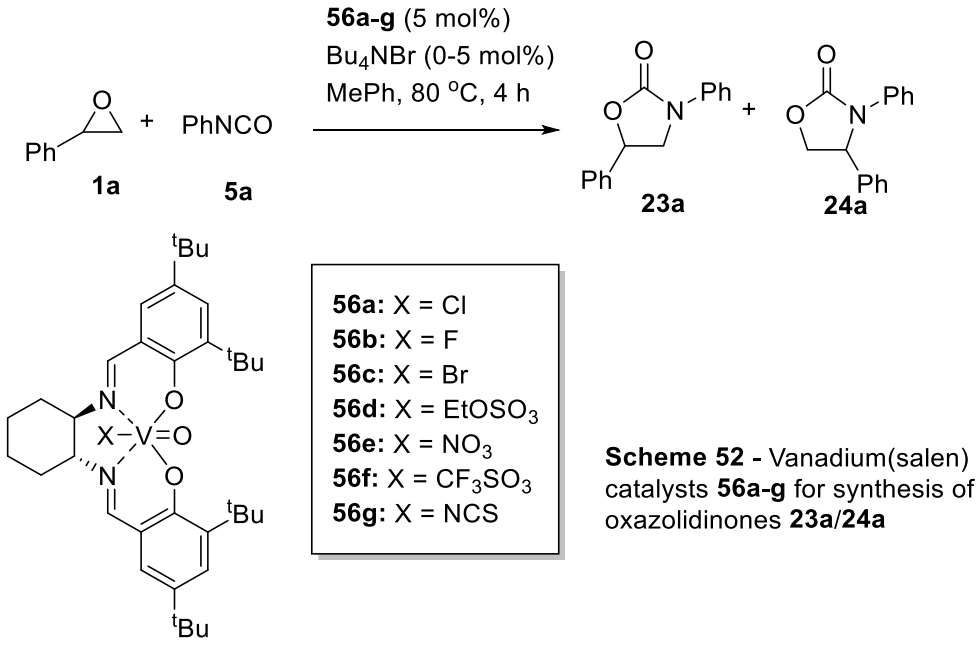
2.3 Vanadium^{V}(salen) catalysed synthesis of oxazolidinones

When compared to cyclic carbonate synthesis, the synthesis of oxazolidinones from epoxides and isocyanates catalysed by aluminium(salen) complex **10** (Scheme 51) requires much harsher conditions. Both the temperature and the catalyst loading have to be increased in order to gain good yields of the product. As the previous mechanistic study has revealed, when using aluminium(salen) catalyst **10** the enthalpy of activation is much higher, and the entropy of activation is less negative than cyclic carbonate synthesis (Table 16). It was therefore decided to investigate more active catalyst systems for the formation of oxazolidinones based on using more Lewis acidic metals in order to lower the enthalpy of activation.



Scheme 51 - Synthesis of oxazolidinones from epoxides and isocyanates

Previous work in the North group has found that vanadium^{V}(salen) complexes **56a-g** are highly enantioselective catalysts for asymmetric cyanohydrin synthesis,[97] asymmetric Strecker synthesis,[98] and asymmetric Michael additions of cyanide to nitroalkenes.[99] It was found that the activity of these complexes varied depending on which counterion was present, in that the complexes with the highest Lewis acidity (**56d**, **f**) were found to be the most active, whilst the least Lewis acidic (**56g**) was the least active. It was therefore decided to screen all complexes **56a-g** for the synthesis of oxazolidinones **23a**/**24a** from styrene oxide **1a** and phenyl isocyanate **5a** (Scheme 52). Since some reactions have benefited from the presence of Bu_4NBr, it was decided to also screen reactions with an equimolar amount of this cocatalyst. The results are shown in Table 17.



Scheme 52 - Vanadium(salen) catalysts **56a-g** for synthesis of oxazolidinones **23a**/**24a**

All of the complexes **56a-g** showed some catalytic activity. In the absence of TBAB the activities displayed were modest, with complexes **56e** and **56g** being the best,

giving conversions of 56% and 47% respectively (Table 17, entries 5 and 7). However, it was observed that upon addition of an equimolar amount of TBAB, the activities of the catalyst systems increased significantly (in all cases except **56g**, entry 7). The two best systems were complexes **56d** and **56f** (entries 4 and 6), which both gave conversions of 90%.

Table 17 – Use of complexes 56a-g as catalysts for synthesis of oxazolidinones 23a/24a[a]

Entry	Catalyst	Conversion (%)[b]	Conversion (%)[b,c]
1	**56a**	26 (1:1.7)	42 (1:2.7)
2	**56b**	14 (1:1.3)	55 (1:2.7)
3	**56c**	18 (1:1.4)	61 (1:2.4)
4	**56d**	12 (1:1.3)	90 (1:2.8)
5	**56e**	56 (1:1.5)	77 (1:2.9)
6	**56f**	10 (1:1.3)	90 (1:3.5)
7	**56g**	47 (1:1.4)	44 (1:1.7)

[a] Reactions carried out at 80 ^{o}C, for four hours, in Toluene with 5 mol% catalyst. Conversions calculated by ^{1}H NMR analysis of reaction mixture; [b] Ratio of products (**23a**:**24a**) shown in brackets; [c] With use of 5 mol% Bu_4NBr as cocatalyst.

The role of the TBAB in the reaction may be one of two things: it could be reacting with the vanadium^{V}(salen) complexes to form complex **56c** in situ, however, given that this is not the most active complex, and that the catalytic activity of **56c** increases upon addition of TBAB, it is unlikely that this is the sole function. The other role it could occupy is to provide a good nucleophile (and in turn a good leaving group) to ring-open the epoxide.

The two complexes which gave the best conversions of styrene oxide **1a** into oxazolidinones **23a**/**24a**, were **56d** and **56f**. A feature that these two complexes have in common is that the respective counterions are completely dissociated from the vanadium ions,[100] meaning that these are the two most Lewis acidic catalysts. This implies that the role of the vanadium complex is to coordinate to the epoxide (or the newly ring-opened bromo-alkoxide) to activate it for attack during the rate determining step of the mechanism.

Table 18 – Influence of cocatalyst counterion for synthesis of oxazolidinones 23a/24a[a]

Entry	Cocatalyst	Conversion (%)[b]
1	Bu_4NF	0
2	Bu_4NCl	41 (1:1.6)
3	Bu_4NI	87 (1:1.8)

[a] Reactions carried out at 80 °C, for four hours, in toluene with 5 mol% **56d** and cocatalyst. Conversions calculated by ^{1}H NMR analysis of reaction mixture; [b] Ratio of products shown in brackets.

In order to observe the importance of the counterion on the tetrabutylammonium cocatalyst, three reactions were carried out under the same conditions as in Table 17, using tetrabutylammonium fluoride (TBAF), tetrabutylammonium chloride (TBACl) and tetrabutylammonium iodide (TBAI) as the cocatalyst along with complex **56d**. As can be seen in Table 18 entry 1, the use of TBAF resulted in no conversion, TBAC gave a 41% conversion and TBAI, gave a conversion of 87% to oxazolidinones **23a** and **24a**. This shows the amount of influence the cocatalyst counterion has on the catalyst system activity, and therefore highlights the importance of the presence of a good nucleophile

or leaving group in the reaction mechanism. The results using TBAF cocatalyst is very interesting, as the presence of this cocatalyst seems to completely hinder any catalytic activity exhibited by **56d** shown in Table 17, in the absence of any cocatalyst. Since its use as a cocatalyst resulted in the highest conversion, Bu_4NBr is the optimal cocatalyst for this reaction.

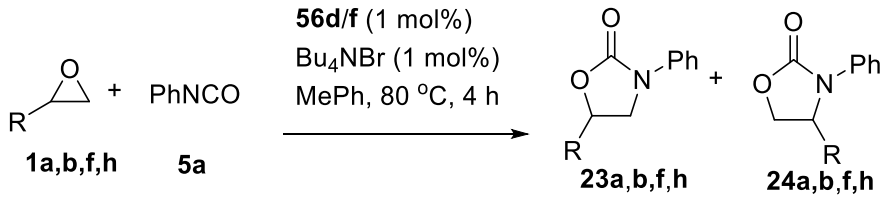
Table 19 – Use of complexes 56d/56f as catalysts for synthesis of oxazolidinones 23a,b,f,h/24a,b,f,h[a]

Entry	Catalyst	Epoxide	Conversion (%)[b]
1	**56d**	**1a**	90 (1:2.8)
2	**56d**	**1b**	52 (1:0)
3	**56d**	**1f**	41 (2.3:1)
4	**56d**	**1h**	58 (1:0)
5	**56f**	**1a**	90 (1:3.5)
6	**56f**	**1b**	42 (1:0)
7	**56f**	**1f**	24 (2.3:1)
8	**56f**	**1h**	49 (1:0)

[a] Reactions carried out at 80 ^oC, for four hours, in Toluene with 1 mol% catalyst, 1 mol% Bu_4NBr. Conversions calculated by ^1H NMR analysis of reaction mixture; [b] Ratio of products shown in brackets.

Aryl epoxides, such as styrene oxide **1a** are known to be atypical for epoxide ring-opening reactions in general, in that the position of the phenyl ring means that the epoxide favours opening at the secondary carbon, and product formation occurs in favour of **24a** rather than **23a**. In order to investigate the trend in oxazolidinone synthesis, the two most active catalysts screened in Table 17, **56d** and **56f** were tested on epoxides **1a**, **b**, **f** and **h** (Scheme 53). These reactions would give a good idea of the generality of oxazolidinone synthesis, since they contain one unfunctionalised aliphatic

epoxide and two functionalised examples. Catalyst loading was reduced to just 1 mol% of the vanadium^{V}(salen) complex and TBAB, and the results are shown in Table 19.



Scheme 53 - Vanadium complexes **56d/f** for oxazolidinone synthesis

The results show that, for both catalysts, the reaction involving styrene oxide gave excellent and equal conversions. For substrates **1b**,**f**,**h** the conversions were substantially lower, but in every case **56d** was more active for this transformation compared to **56f**. It was decided that this catalyst was optimal and it was therefore selected for further experiments to optimise reaction conditions such as catalyst and cocatalyst loading, reaction time and substrate concentration using epoxides **1b**,**f**,**h**. The results of the optimisation study are shown in Table 20.

Firstly, the effect of varying the concentration of catalyst **56d** and Bu_4NBr were investigated. This was found to be substrate dependant. For epoxide **1b** only a 4% increase in the final conversion was observed when increasing catalyst loading from 0.5 mol% to 4 mol%, from 51-55% (Table 20, entries 1, 7, 10 and 13). For the other two substrates, epoxides **1f** and **h**, the change was much more pronounced: the conversion increased from 16 % up to 53% when using epoxide **1f** (entries 2, 8, 11 and 14), and an increase from 46% to 81% was seen for epoxide **1h** (entries 3, 9, 12 and 15).

Table 20 – Effect of catalyst loading and substrate concentrations in the synthesis of oxazolidinones 23a,b,d,f and 24a,b,f,h catalysed by complex 56d[a]

Entry	Epoxide (conc, M)	56d (mol%)	Time (h)	Conversion (%)[b]
1	**1b**	0.5	24	51 (1:0)
2	**1b**	0.5	48	51 (1:0)
3	**1f**	0.5	24	16 (4.0:1)
4	**1f**	0.5	48	16 (4.0:1)
5	**1h**	0.5	24	46 (1:0)
6	**1h**	0.5	48	46 (1:0)
7	**1b**	1.0	24	52 (1:0)
8	**1f**	1.0	24	41 (2.33:1)
9	**1h**	1.0	24	58 (1:0)
10	**1b**	2.0	24	54 (1:0)
11	**1f**	2.0	24	45 (2:1)
12	**1h**	2.0	24	70 (1:0)
13	**1b**	4.0	24	56 (1:0)
14	**1f**	4.0	24	53 (1.9:1)
15	**1h**	4.0	24	81 (1:0)
16	**1b**	2.0	24	70 (1:0)
17	**1f**	2.0	24	45 (2.4:1)
18	**1h**	2.0	24	93 (1:0)
19	**1b**	2.0	24	58 (1:0)
20	**1f**	2.0	24	41 (2.4:1)
21	**1h**	2.0	24	74 (1:0)
22[c]	**1b**	1.0	24	48 (1:0)
23[c]	**1f**	1.0	24	31 (3.1:1)
24[c]	**1h**	1.0	24	47 (1:0)

[a] Reactions carried out at 80 ^{o}C in toluene with same concentration of Bu_4NBr as **56d**, unless stated. Conversions calculated by ^{1}H NMR analysis of reaction mixture; [b] Ratio of products shown in brackets; [c] 1.2 equivalents of **56d**.

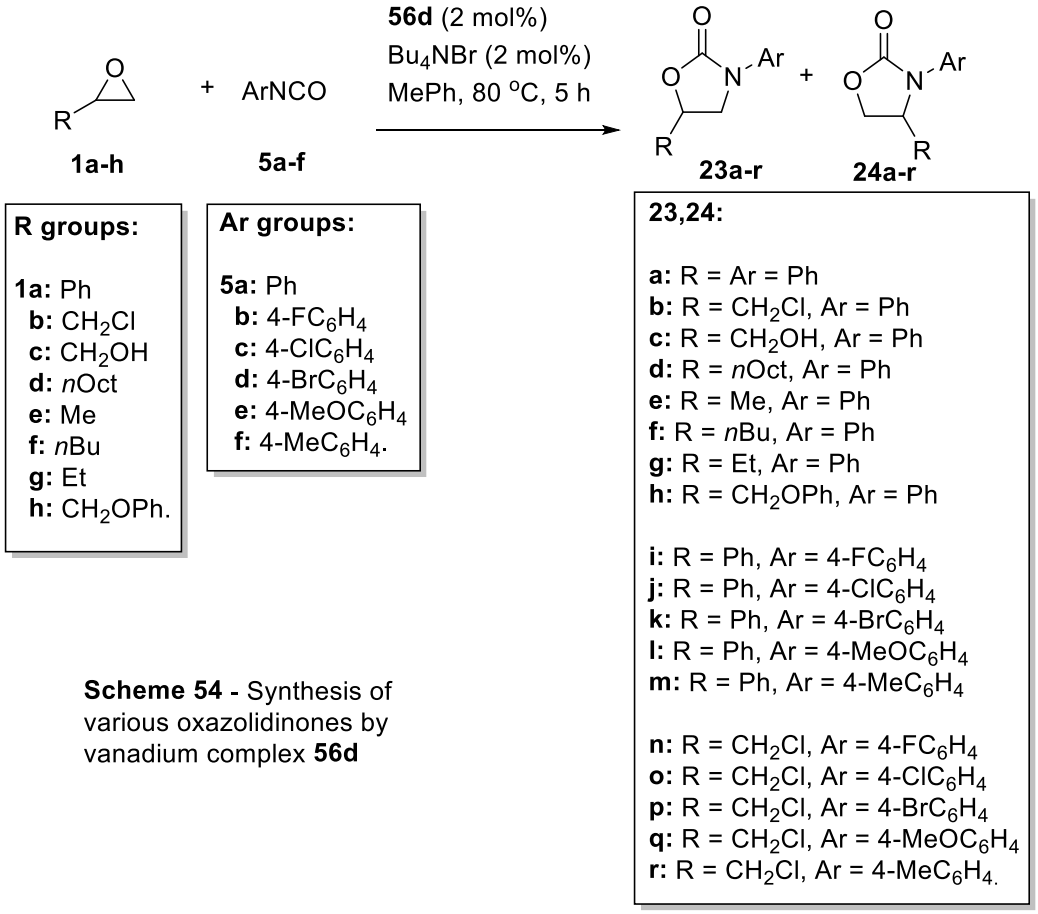
Experiments were carried out to test the influence a longer reaction time had on the conversions to products. Reactions were run with 0.5 mol% of **56d** and TBAB, and left for 24 and 48 hours for comparison. It was found that a longer reaction time did not result in any improvement for any of the substrates (Table 20, entries 1-6).

Finally, reactions were carried out to test the effect of varying substrate concentration. Epoxide **1c**, did not show any dependence on substrate concentration, with all three reactions giving approximately 45% conversion. On the other hand, epoxides **1b** and **h** were found to be much more sensitive to substrate concentration changes (entries 10, 16, 19 and 12, 18, 21). For both epoxides, a concentration of 0.84 M was found to be optimal (entries 16, 17, 18).

It was observed that it was the formation of a by-product, rather than catalyst degradation which inhibited any increase in conversion upon an increase of reaction time. The presence of diphenyl urea in the reaction mixture was detected, which was presumed to have arisen from the reaction of phenyl isocyanate **5a** with contaminating water. In an effort to counteract this, reactions were carried out with an increased concentration of isocyanate (1.2 equivalents), however for all three epoxides a lower conversion was achieved than when using equimolar amounts of isocyanate.

The optimal conditions for the synthesis of oxazolidinones by vanadium^{V}(salen) catalyst **55d** were chosen to be; 2 mol% of catalyst and cocatalyst, 80 ^{o}C and a substrate concentration of 0.84 M for both epoxide and isocyanate in toluene. By running some extra control experiments it was found that even though the previous reactions had been run for 24 hours, the reactions had reached their final conversions and did not continue after just five hours; therefore this was decided to be the standard reaction time. These conditions were applied to a greater range of epoxides, **1a**-**h**, and six different

isocyanates, **5a-f**. The reactions are outlined in Scheme 54, and the major regioisomer of the oxazolidinone products **23**/**24a-r** were isolated via column chromatography. The results are shown in Table 21.



Scheme 54 - Synthesis of various oxazolidinones by vanadium complex **56d**

Table 21 –Synthesis of oxazolidinones 23a-r/24a-r catalysed by complex 56d[a]

Entry	Epoxide	Isocyanate	Conversion[b]	Product(%)[c]
1	**1a**	**5a**	98 (1:2.5)	**24a** (64)
2	**1b**	**5a**	70 (1:0)	**23b** (68)
3	**1c**	**5a**	72 (1:3.2)	**24c** (49)
4	**1d**	**5a**	46 (3.0:1)	**23d** (31)
5	**1e**	**5a**	83 (4.0:1)	**23e** (60)
6	**1f**	**5a**	46 (2.4:1)	**23f** (36)
7	**1g**	**5a**	52 (3.0:1)	**23g** (36)
8	**1h**	**5a**	93 (1:0)	**23h** (89)
9	**1a**	**5b**	68 (1:2.2)	**24i** (41)
10	**1a**	**5c**	40 (1:1.9)	**24j** (25)
11	**1a**	**5d**	40 (1:1.2)	**24k** (23)
12	**1a**	**5e**	65 (1:2.6)	**24l** (41)
13	**1a**	**5f**	76 (1:2.1)	**24m** (47)
14	**1b**	**5b**	52 (1:0)	**23n** (44)
15	**1b**	**5c**	34 (1:0)	**23o** (30)
16	**1b**	**5d**	41 (1:0)	**23p** (40)
17	**1b**	**5e**	63 (1:0)	**23q** (58)
18	**1b**	**5f**	71 (1:0)	**23r** (69)

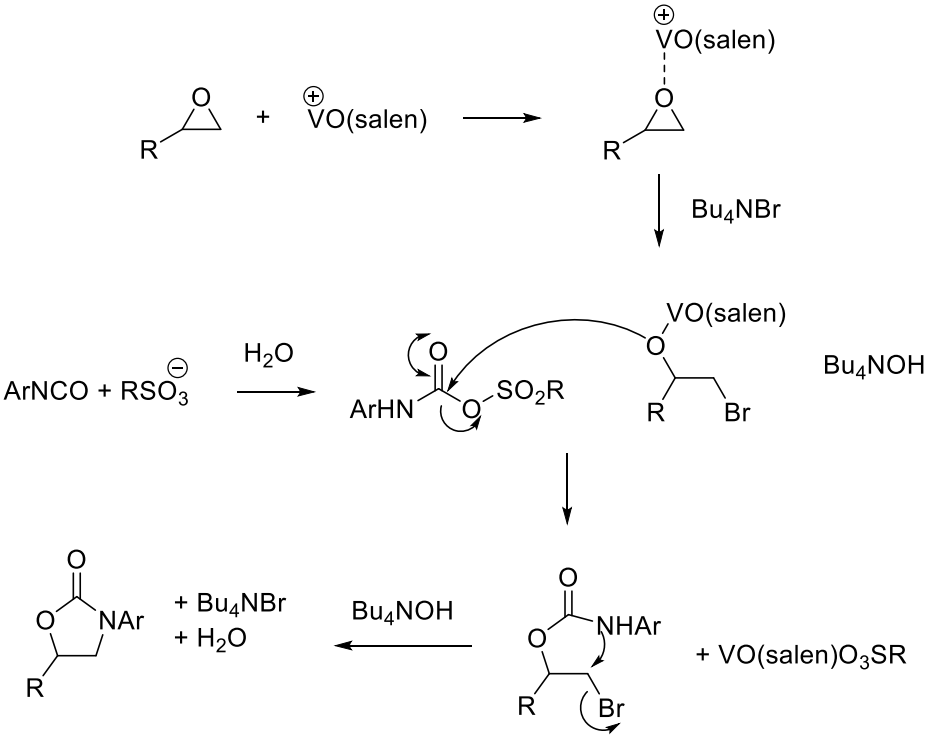
[a] Reactions carried out at 80 ^{o}C for 5 hours in toluene, 2 mol% of **56d** and Bu_4NBr, [**1**] = [**5**] = 0.84 M. Conversions calculated by ^{1}H NMR analysis of reaction mixture; [b] Ratio of products shown in brackets; [c] Figure in brackets is isolated chemical yield of major regioisomer

Aliphatic epoxides turned out to be the worst substrates for these reactions. Epoxides **1d**, **f** and **g** gave the lowest conversions to their respective oxazolidinone

products **23d**, **f**, and **g** (Table 21, entries 4, 6 and 7). Functionalised or aromatic epoxides gave higher conversions, and in turn higher isolated yields (entries 1, 2, 8). Glycidol, **1c**, and styrene oxide, **1a**, were both good substrates, giving high yields and were notable as the only substrates to favourably form the 3,4-isomer of the oxazolidinone products **24a** and **c** (entry 1 and 3). All the other epoxides gave the 3,5-isomer as their major product, which is formed when the epoxide is opened at the terminal carbon. Since styrene oxide contains an electron rich phenyl ring this directs the ring-opening to the benzylic position. Glycidol follows an entirely different mechanism in which a urethane intermediate is formed by the alcohol reacting with the isocyanate, after which an intramolecular ring-opening occurs leading to the product.[101] Epichlorohydrin **1b** and 3-phenoxypropylene oxide **1h** stood out as the only products to be completely regioselective, in that they exclusively formed the 3,5-oxazolinone products **23b** and **23d**.

To further test the catalysts, experiments were carried out reacting styrene oxide **1a** and epichlorohydrin **1b** with a range of aromatic isocyanates **5b-f** (Table 21, entries 9-18). These epoxides were selected as they tended to form the opposite regioisomers to one another. For both epoxides the regiochemistry of all the products remained the same as it was when using phenyl isocyanate as a substrate, and also the reactions involving epichlorohydrin were entirely regioselective (entries 14-18). Electronically neutral (entries 9 and 7) or electron-rich (entries 12, 13, 17, 18) aromatic rings on the isocyanates gave better yields than their electron deficient counterparts (entries 10, 11, 15, 16). This may indicate that the rate determining step of the reaction is the final ring closure in forming the oxazolidinone as this would be more favoured with an electron-rich substrate.

Attempts were also made to react epoxides with aliphatic isocyanates, but these all resulted in no product formation. Failed attempts were also made to use disubstituted epoxides as substrates. A mechanistic study was initiated, however the kinetics obtained from the reactions revealed that catalyst decomposition was occurring which prevented any worthwhile data from being retrieved. This was possibly the reduction of the vanadium species from vanadium^{V} to vanadium^{IV}. However, based on all the previous work carried out by the North group on this, and related systems, as well as using these catalysts on other systems,[13,27,90] combined with recent work carried out by Park,[102] a possible mechanistic explanation has been proposed in Scheme 55.



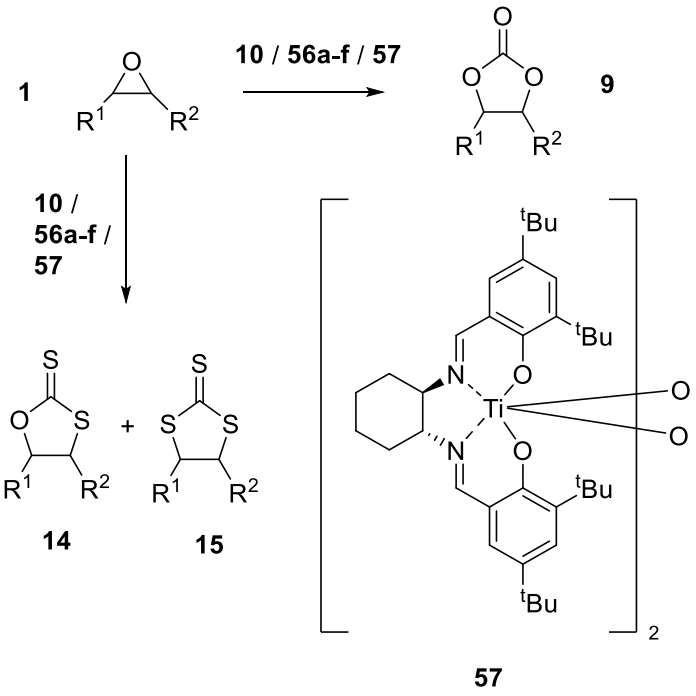
Scheme 55 - Proposed **56d** and TBAB catalysed mechanism of oxazolidinone synthesis

As is common for metal(salen) catalysed mechanisms of coupling reactions between epoxides and heterocumulenes, the first step involves the metal coordinating to

the epoxide, which activates the carbon-oxygen bond for nucleophilic attack. The bromide ion from the TBAB then ring-opens the epoxide. At the same time, the sulphonate counterion reacts with the isocyanate group, along with a water molecule forming a mixed anhydride species. This mixed anhydride is then attacked by the lone pair on the oxygen of the alkoxide intermediate, which releases both the sulphonate anion and the vanadium cation, reforming the original catalyst. The acyclic bromocarbamate species then cyclises by attack from the lone pair on the nitrogen to eliminate the bromide anion. This results in the formation of the oxazolidinone product, along with the reformation of the TBAB and water molecules. Since other catalysts which do not contain a sulphonate counterion still show some activity, it can be assumed that the reaction can still occur with a non-activated isocyanate molecule. However, since the conversions are not as high it can be assumed that the activated the isocyanates are much more susceptible to nucleophilic attack.

In conclusion, vanadium^{V}(salen) complex **56d**, combined with Bu_4NBr proved to be a highly active catalytic system for the formation of oxazolidinone synthesis from epoxides and isocyanates. Compared to the system reported using complex **10**,[90] the catalyst loading could be reduced from 5 mol% (since a bimetallic catalyst was used, this was 10 mol% of metal ions) to 2 mol%, and the reaction times were reduced to just 5 hours from 24 hours. Unfortunately the detrimental side reaction forming diphenyl urea meant that the yields reported tended to be lower than those for the aluminium catalyst.

2.4 Titanium(salen) catalysed synthesis of di- and tri-thiocarbonates



1/9/14/15a: R^1 = Ph; R^2 = H
b: R^1 = CH_2Cl; R^2 = H
d: R^1 = ^{n}Oct; R^2 = H
e: R^1 = Me; R^2 = H
f: R^1 = ^{n}Bu; R^2 = H
g: R^1 = Et; R^2 = H
h: R^1 = CH_2OPh; R^2 = H
j: R^1 = ^{n}Dec; R^2 = H

Scheme 56 - Catalyst screening for cyclic carbonate and thiocarbonate synthesis

As with the synthesis of oxazolidinones catalysed by complex **10**, when compared to the formation of cyclic carbonates, **9**, harsher conditions (temperatures up to 90 ^oC) and higher catalyst and cocatalyst loadings (5 mol%) were required for the synthesis of thiocarbonates (**14** and **15**). Therefore, it was decided to seek a more active catalyst system for this transformation, by screening different metal salen complexes (**56a-f** and **57**) which have more Lewis acidic character than aluminium complex **10**. This is outlined in Scheme 56. The same range of complexes was also tested on cyclic

carbonate synthesis to observe whether they showed any improvement on the existing system.

Table 22 – Complexes 10 / 56a-g / 57 as catalysts for the synthesis of thiocarbonates and cyclic carbonates from 1a

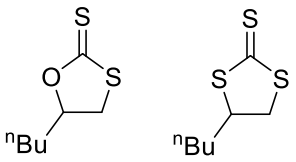
Entry	Complex	Conversion (%)[a]	Conversion (%)[b]
1	**10**	98[13]	91[27]
2	**56a**	12	0
3	**56b**	9	0
4	**56c**	3	19
5	**56d**	2	16
6	**56e**	2	23
7	**56f**	3	16
8	**56g**	2	44
9	**57**	13	100

[a] Reactions carried out at 1 atm CO_2, RT, 24 h, neat with 2.5 mol% catalyst, 2.5 mol% Bu_4NBr. Conversions calculated by ^1H NMR analysis of the reaction mixture; [b] Reactions carried out with 1.8 eq. CS_2, 90 ^oC, 24 h, neat, 5 mol% catalyst, 5 mol% Bu_4NBr.

The first investigation was into the use of the vanadium^V catalysts **56a-g**, which had shown excellent activity for the synthesis of oxazolidinones (Section 2.3). They were initially tested on the conversion of styrene oxide **1a** to styrene carbonate **9a**, via addition of CO_2, under the conditions previously optimised for aluminium complex **10** and comparing them to those results (Table 22, entry 1).[13] All catalysts showed very poor conversions when compared to the results using **10** (entries 2-8). The same vanadium^V(salen) catalysts were tested for the conversion of styrene oxide **1a** to styrene trithiocarbonate **15a**, again under the conditions optimised when using complex **10**.[27] Again, it was found that when comparing these results (entries 2-8) with the ones

previously obtained (entry 1), the results were disappointing, although they were more active for this transformation than for cyclic carbonate synthesis, with the catalyst containing the isothiocyanate counterion (**56g**, Entry 8) giving by far the best result, a conversion of 44%. This was still less than half of the activity exhibited by complex **10**, therefore vanadium^{V} complexes offered no improvement on the existing system.

Table 23 – Complex 57 as catalyst for reaction of 1,2-epoxyhexane 1f and CS_2 to form products 14f and 15f [a]



14f **15f**

Entry	[57] (mol%)	TBAB (mol%)	Time (h)	Conversion (%)	14f:15f
1	5	0	3	20	45:55
2	5	0	24	62	100:0
3	5	5	3	62	100:0
4	5	5	24	100	64:36
5	0	5	24	67	60:40
6	1	1	24	100	75:25
7	0.5	0.5	24	97	75:25
8	1	1	16	87	43:57

[a] Reactions carried out with 1.8 eq. CS_2 at 90 ^{o}C. Conversions and product ratio calculated by ^{1}H NMR analysis of reaction mixture.

It was decided to also test titanium(salen) complex **57** as a catalyst for both reactions (entry 9). Although a slight improvement on complexes **56a-g**, the result for

cyclic carbonate synthesis was still far worse than the aluminium complex **10**. However, when it was used as a catalyst for the synthesis of styrene trithiocarbonate **15a** under the same conditions as previously reported, complex **57** gave a conversion of 100%. Since the reaction of styrene oxide is known to be exceptional in only producing one product (trithiocarbonate **15a**),[27] the reaction conditions for the use of complex **57** were optimised on the reaction of 1,2-epoxyhexane **1f**. The results of this optimisation study are shown in Table 23.

As shown in entries 1 and 2, complex **6** showed a reasonable amount of activity for this reaction even in the absence of TBAB cocatalyst. However, as is clear from comparing entries 1 with 3, or 2 with 4, addition of an equimolar amount of Bu_4NBr relative to complex **57** is shown to help form a much more active catalytic system, similar to the results obtained with complex **10**.[2] Entry 5 shows that, even in the absence of complex **57**, a reasonable amount of catalytic activity was observed with 5 mol% of TBAB. It was clear that the optimal catalytic system was to use a combination of **57** and TBAB, as a higher conversion was obtained when using 1 mol% (entry 6) or 0.5 mol% (entry 7) of both than when using 5 mol% of either (entries 2 and 5). It should also be noted that the results for 0.5 mol% of complex **57** and TBAB showed a higher conversion than that previously obtained using 5 mol% of complex **10** and TBAB, which gave 87% conversion.[27]

Another difference to the result obtained using complex **10** is in the ratio of the products formed. When using complex **10** a ratio of 43:57 was observed in favour of the trithiocarbonate **15f** at 90 ^{o}C, while for complex **57** the dithiocarbonate **14f** was the major product with the ratio depending on the catalyst and cocatalyst loading. In the proposed mechanism, the dithiocarbonate is the initial product of the reaction[27] and these results suggest the catalyst system is also responsible for the conversion from **14**

to **15**. Since trithiocarbonates are the major products when using complex **10**, it must therefore be the more effective catalyst for the secondary transformation.

Table 24 – Complex 6 and Bu_4NBr as a catalyst for synthesis of thiocarbonates[a]

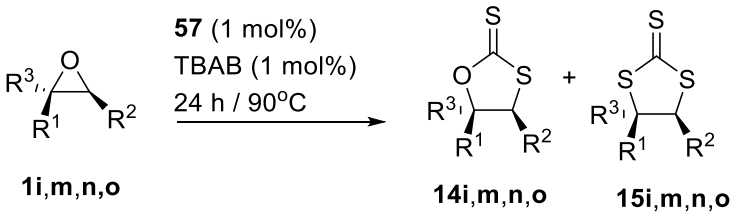
Entry	Epoxide	57 / TBAB (mol%)	Yield (%)	14:15
1	**1b**	0.5 / 0.5	36[b]	44:56
2	**1d**	0.5 / 0.5	83[b]	80:20
3	**1e**	0.5 / 0.5	79[b]	66:34
4	**1b**	1 / 1	58	34:66
5	**1d**	1 / 1	99	64:36
6	**1e**	1 / 1	94	60:40
7	**1a**	1 / 1	86	0:100
8	**1f**	1 / 1	96	75:25
9	**1g**	1 / 1	76	75:25
10	**1h**	1 / 1	98	81:19
11	**1j**	1 / 1	98	81:19

[a] Reactions carried out with 1.8 eq. CS_2, 90 ^oC, 24 h, neat. Conversions and product ratio calculated by ^1H NMR analysis of reaction mixture. [b] Conversion reported, not yield.

The conditions shown in Table 23, entry 7 were taken as standard and to ensure that this system could be applied to various substrates, a range of terminal epoxides were selected and tested. The results are shown in Table 24, entries 1-3. The results show that for the unsubstituted aliphatic epoxides, 1,2-decene oxide **1d** and 1,2-propylene oxide **1e** (entries 2 and 3), 0.5 mol% of catalyst and cocatalyst was enough to give good conversions to the thiocarbonate products in a ratio which favoured the

dithiocarbonates, **14d** and **14e**. However for substrate **2b**, epichlorohydrin, the conversion dropped under these conditions (Table 24, entry 1). Therefore it was decided that the optimal conditions for this reaction involved 1 mol% of complex **57** and TBAB. These were then applied to the reactions of eight terminal epoxides with carbon disulphide (Table 24, entries 4-11).

These reactions were all worked up and isolated yields of mixtures of thiocarbonates (**14**/**15a-j**) were obtained via purification by column chromatography, as previously reported.[27] Unsubstituted aliphatic epoxides **1d-g**,**h** were excellent substrates giving high yields and predominantly forming dithiocarbonates **14d-g**,**h**. 3-Phenoxypropylene oxide **2h** also gave an excellent yield with the major product being **14h**. The result for epichlorohydrin improved compared to the use of 0.5 mol% catalyst, giving a reasonable yield, but interestingly formed the trithiocarbonate **15e** predominantly. As reported when using aluminium complex **10**, styrene oxide **1a** gave exclusively trithiocarbonate **15a** in a high yield.



1/14/15i: R^1-R^2 = -$(CH_2)_4$-; R^3 = H
m: R^1-R^2 = -$(CH_2)_3$-; R^3 = H
n: R^1-R^2 = -$(CH_2)_8$-; R^3 = H
o: R^1 = Me; R^2 = H; R^3 = Me

Scheme 57 - Thiocarbonate synthesis from disubsituted epoxides

Since the combination of complex **57** and TBAB proved to be such an effective catalyst system for this transformation, it was decided to extend the scope of it by attempting to use disubstituted epoxides **1i**, **m**, **n**, **o** as substrates (Scheme 57). As these are much less reactive, it is much more difficult to obtain meaningful yields from these reactions and only cyclohexene oxide **1i** proved to be an effective substrate when using complex **10**.[27] This reaction resulted in formation of *trans*-di and trithiocarbonates **14i** and **15i** (Scheme 57). Reactions were carried out using 1 mol% of each of **57** and TBAB and the results are shown in Table 25.

Table 25 – Complex 6 as a catalyst for synthesis of thiocarbonates from disubstituted epoxides[a]

Entry	Epoxide	Conversion (%)	Yield (%)	8:9
1	**1i**	52	50	63:37
2	**1m**	0	-	-
3	**1n**	0	-	-
4	**1o**	12	-	83:17
5[b]	**1o**	42	33	83:17

[a] Reactions carried out with 1.8 eq. CS_2, 90 ^oC, 24 h, neat. Conversions and product ratio calculated by ^1H NMR analysis of reaction mixture. [b] Reaction time 72 h.

Cyclohexene oxide **1i**, proved to be a good substrate for this reaction, giving an isolated yield of 50% (Table 25, entry 1). Upon inspection of the ^{13}C and ^1H NMR spectra obtained from the products, and comparison with the previous work done with complex **10** and TBAB, where the stereochemistry of trithiocarbonate was determined by crystallographic analysis,[27] the rings were shown to be *trans*-fused. Unfortunately,

any attempts to expand this chemistry into other cyclic products proved unsuccessful, as the reactions with cyclopentene and cyclooctene oxide (**1m** and **1n**) yielded no product (entries 2 and 3). Another disubstituted epoxide which did react was the 1,1-disubstituted substrate **1o**, which gave a low conversion of 12% under these conditions (entry 4). It was found that by leaving this reaction for 72 hours instead of 24, the conversion increased to 42%, and an isolated yield of predominantly dithiocarbonate product **14o** could be obtained in a 33 % yield (entry 5).

It was decided to carry out a kinetics study in order to investigate the reaction mechanism, which would provide a direct comparison to that of the aluminium system using complex **10**. Since this required the use of a solvent, it was found that the reaction between 3-phenoxypropylene oxide **1h** and carbon disulphide, using a catalyst and cocatalyst loading of 5 mol% at 50 ^{o}C, proceeded to over 85% conversion in $CDCl_3$ after 12 hours. This meant that the kinetics of the reaction could be reliably monitored using ^{1}H NMR spectroscopy. Figure 10 shows a typical data set, and as can be seen from the conversion versus time graph, a significant induction period occurs for the first 2.5 hours. However, after this induction period is eliminated, the reaction shows a very good fit to first order kinetics, just as was seen with complex **10**.

Experiments were carried out varying the initial concentrations of both epoxide **1h** and carbon disulphide (see appendix, pages 217 and 218), and these confirmed that the reaction was first order with respect to the epoxide and zero order with respect to carbon disulphide, once the induction period had been eliminated from the data. Therefore, the rate equation could be written in the form shown in Equation 8. No change in rate was observed after 50% epoxide concentration, which indicates that even though a chiral catalyst species was being used, no asymmetric induction was being imposed upon the products.

Equation 8: Rate = k[epoxide]

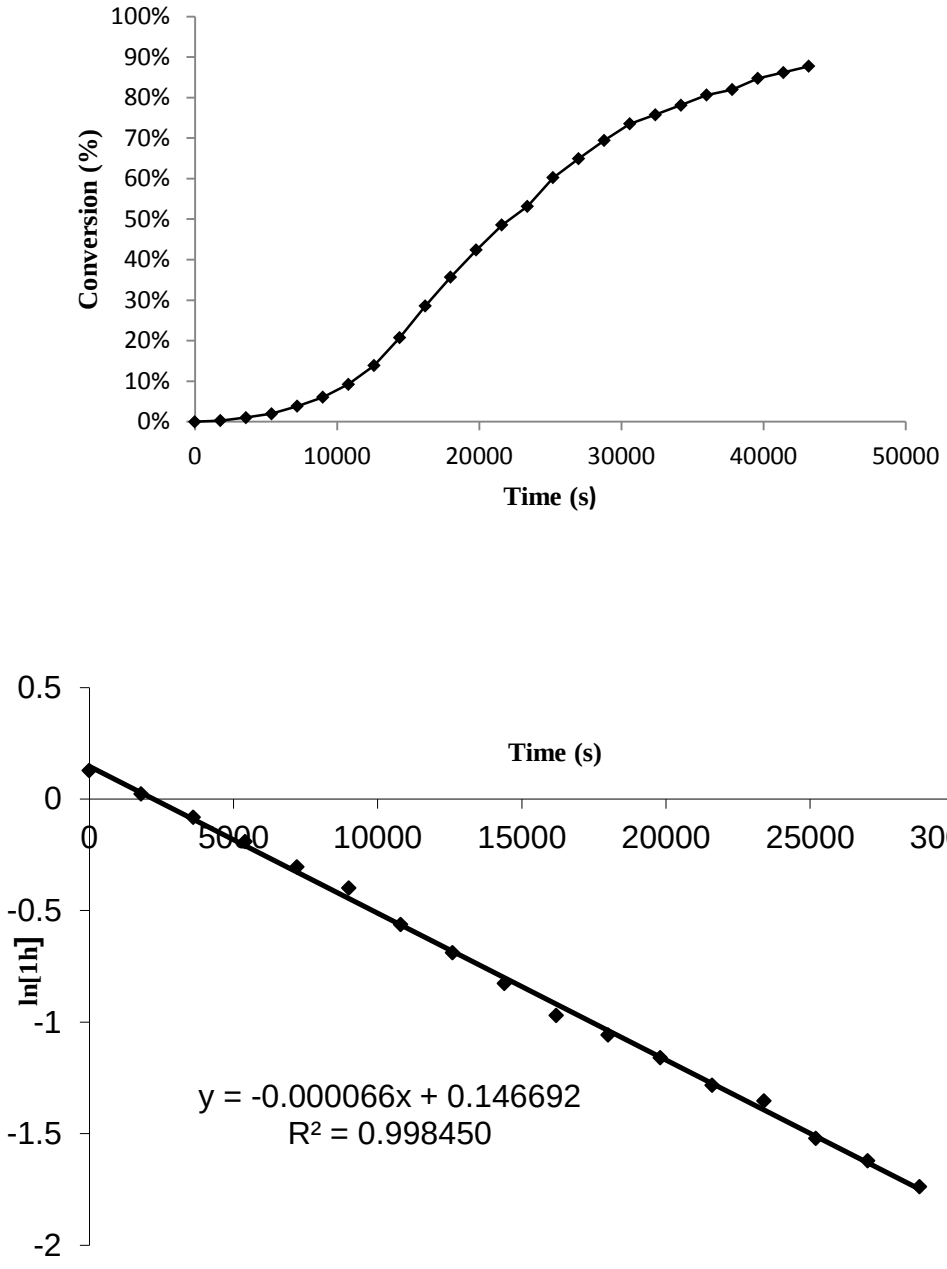
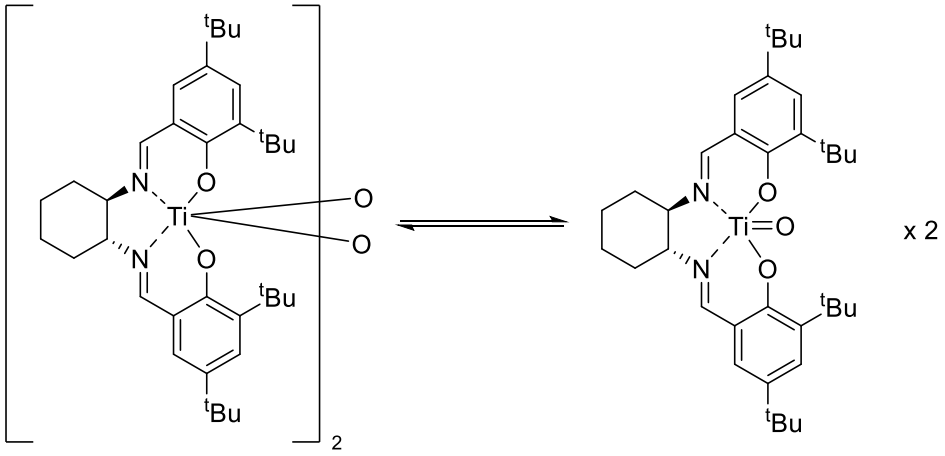


Figure 10 – Kinetic plots for reaction of 3-phenoxypropylene oxide **1h** with CS_2. Reaction conditions: 50°C, $CDCl_3$, with $[\mathbf{1h}]_0$ = 1.4 M, $[CS_2]_0$ = 2.6 M, [**57**] = 71 mM, [TBAB] = 71 mM. Top: conversion vs. time plot. Bottom: First order kinetics plot, with first 12,600 seconds eliminated to ignore induction period.



57 **58**

Scheme 58 - Equilibrium between bimetallic species **57** and monometallic species **58**

In $CDCl_3$, an equilibrium is known to exist between complex **57** and monometallic species **58** (Scheme 58), and the position of the equilibrium is dependent on the concentration of the solution.[103] The reactions carried out in this work were with catalyst concentrations between 20 and 70 mM, and at this concentration the major species present in the equilibrium is bimetallic complex **57**. However, the catalytically active species could be either complex **57** or **58**. To investigate this, kinetics experiments were performed at four different catalyst concentrations to determine the order with respect to catalyst. These were carried out in duplicate (appendix pages 219-222) and the resulting plots of log[**57**] versus log[k_{1avg}] and [**57**] versus k_{1avg} are shown in Figure 11.

Both plots indicate that the reaction is first order with respect to catalyst concentration. It has previously been shown[103] that in the case of a first order dependence on catalyst **57** concentration, at least one species in the catalytic cycle must contain the same amount of metal ions as the major species in the solution. In this case the major species is **57**, a bimetallic species.

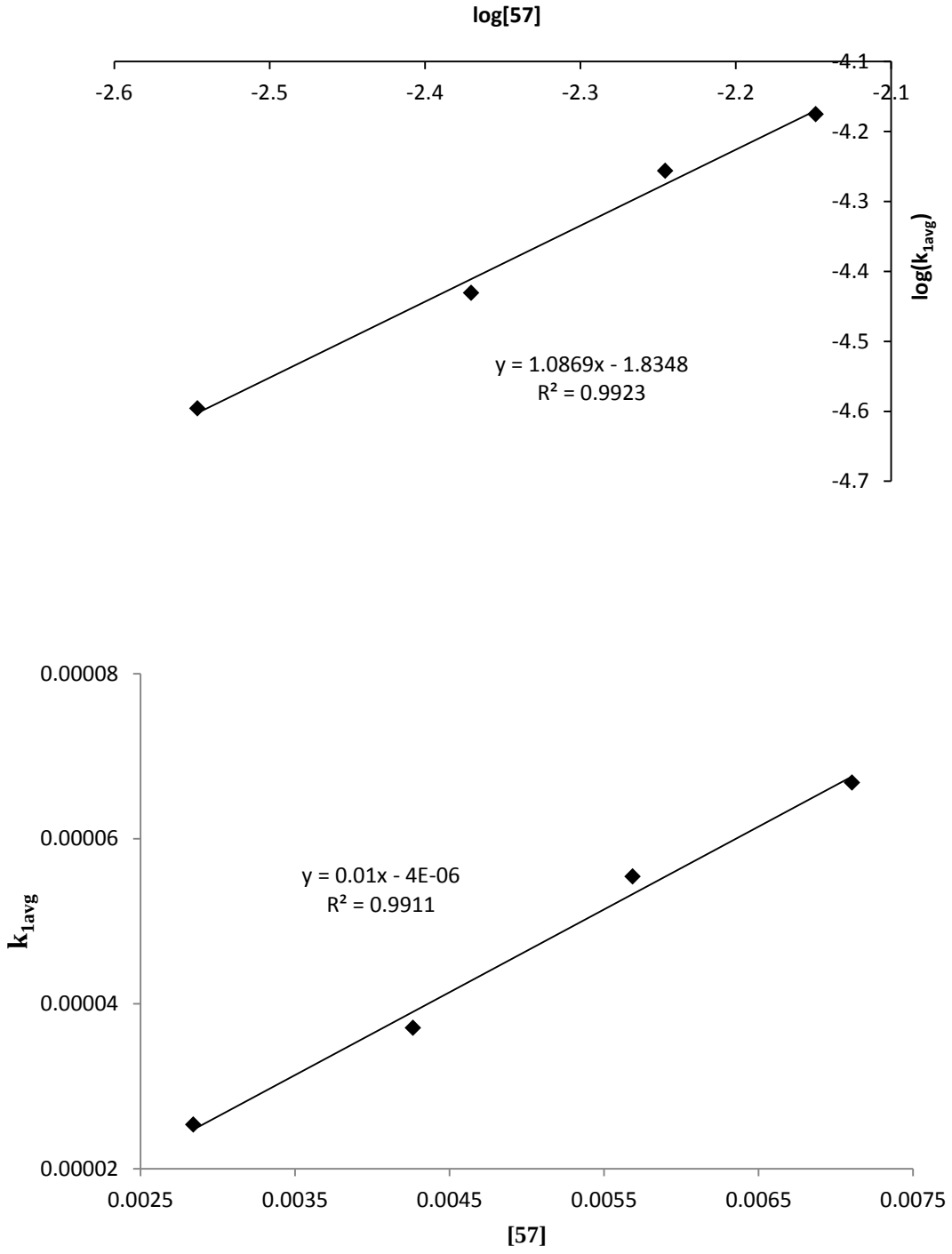


Figure 11 – Top: Plot of log[**57**] vs. log(k_{1avg}). Bottom: Plot of [**57**] vs. k_{1avg}. Reaction conditions: 50 ^{o}C, $CDCl_3$, [**1h**]$_0$ = 1.4 M, [CS_2] = 2.6 M, [**57**] = 28-71 mM, [TBAB] = 71 mM.

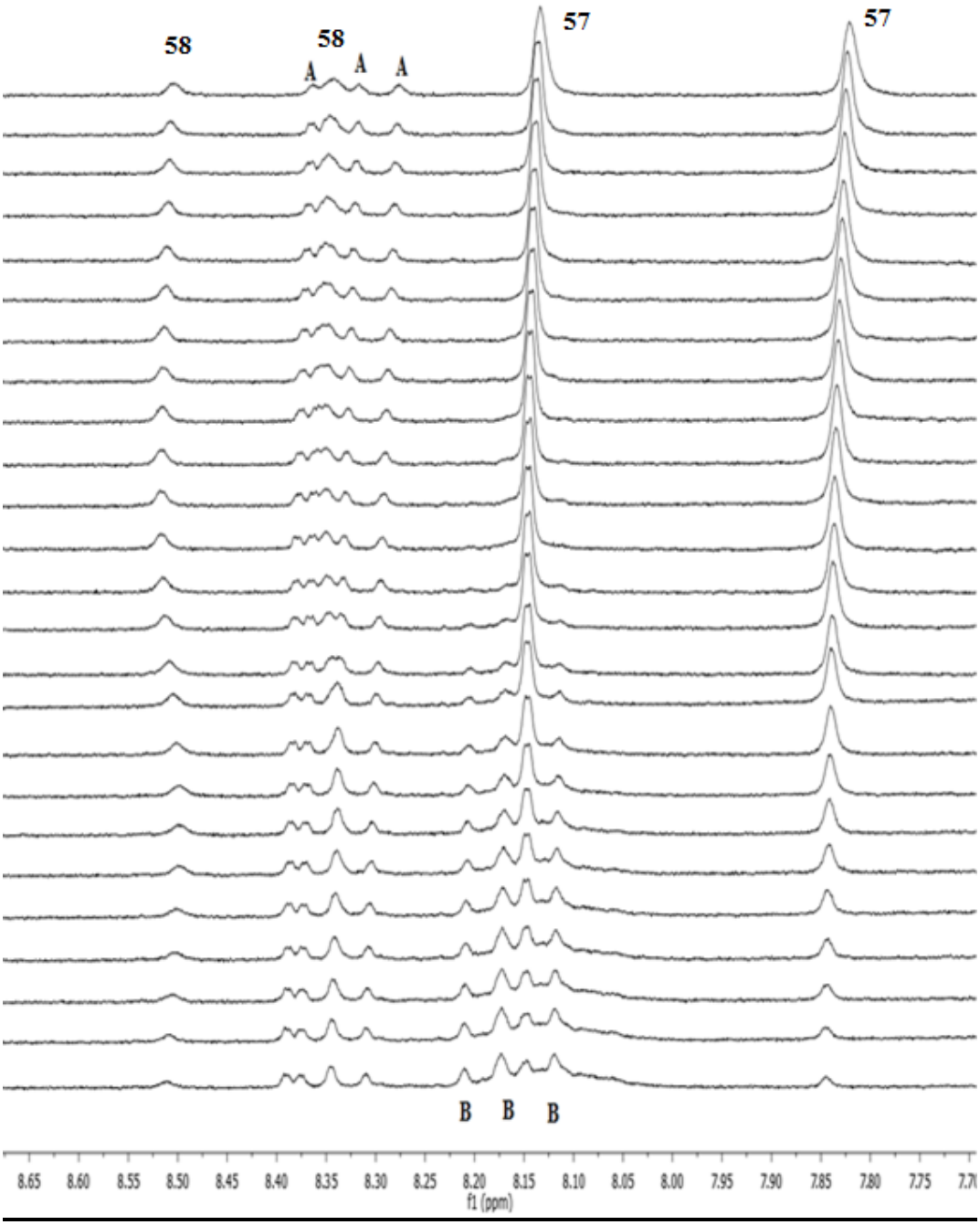


Figure 12 – ^{1}H NMR spectra recorded every 30 minutes (top to bottom) during the reaction between 3-phenoxypropylene oxide **1h** and CS_2 at 50 ^{o}C in $CDCl_3$. The spectra have been expanded to show the imine region of catalyst **57**.

By analysing the catalyst peaks in the ^{1}H NMR spectra obtained during the kinetics experiments, important insight was obtained into the species present during the reaction. Figure 12 shows a stacked plot from a typical experiment, expanded to show

the imine region of the catalyst. The peaks corresponding to complexes **57** and **58** are labelled, and as expected, it is clear that complex **57** is the dominant species present in the solution. The initial spectra also show three additional peaks present in the solution (labelled A), which cannot be attributed to either **57** or **58**. These appear in the region between 8.25-8.55 ppm, around the same position as the peaks corresponding to complex **58** appear. Figure 11 shows control experiments in which these peaks were not present in the pure catalyst spectrum, nor in the mixture of catalyst with carbon disulphide (40 equivalents) or TBAB (1 equivalent). However, in the spectrum of a mixture of complex **57** and 40 equivalents of 3-phenoxypropylene oxide **1h**, three new peaks did arise in this region. These peaks can be explained by the formation of complex **59** (Scheme 59), which involves the coordination of epoxide **1h** to monometallic species **58**, which has a free coordination site.

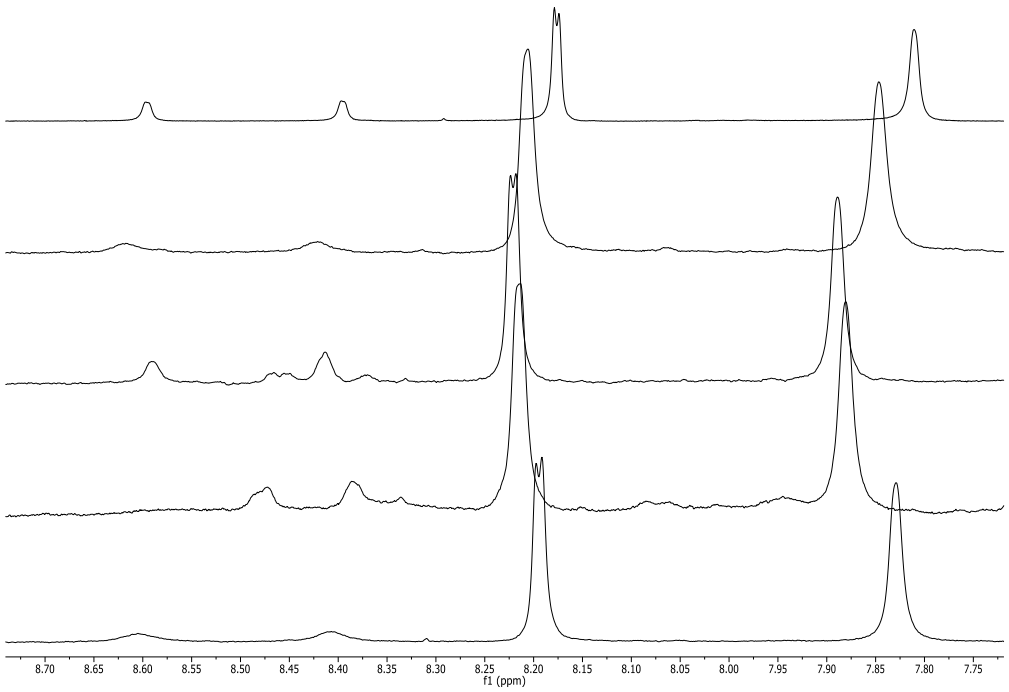
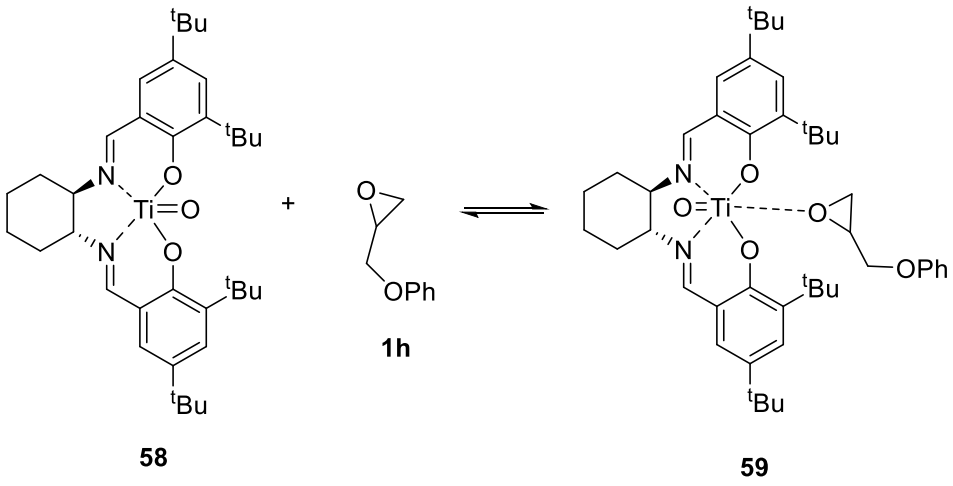


Figure 13 – ^{1}H NMR spectra of imine region of complex **57** in $CDCl_3$ (top), complex **57** in $CDCl_3$ stirred with 40 eq. of CS_2 (next to top), complex **57** in $CDCl_3$ stirred with 40 eq. of **1h** (middle), complex **57** in $CDCl_3$ stirred with 40 eq. of **14h**/**15h** (next to bottom) and complex **57** in $CDCl_3$ stirred with 1 eq. of TBAB (bottom).

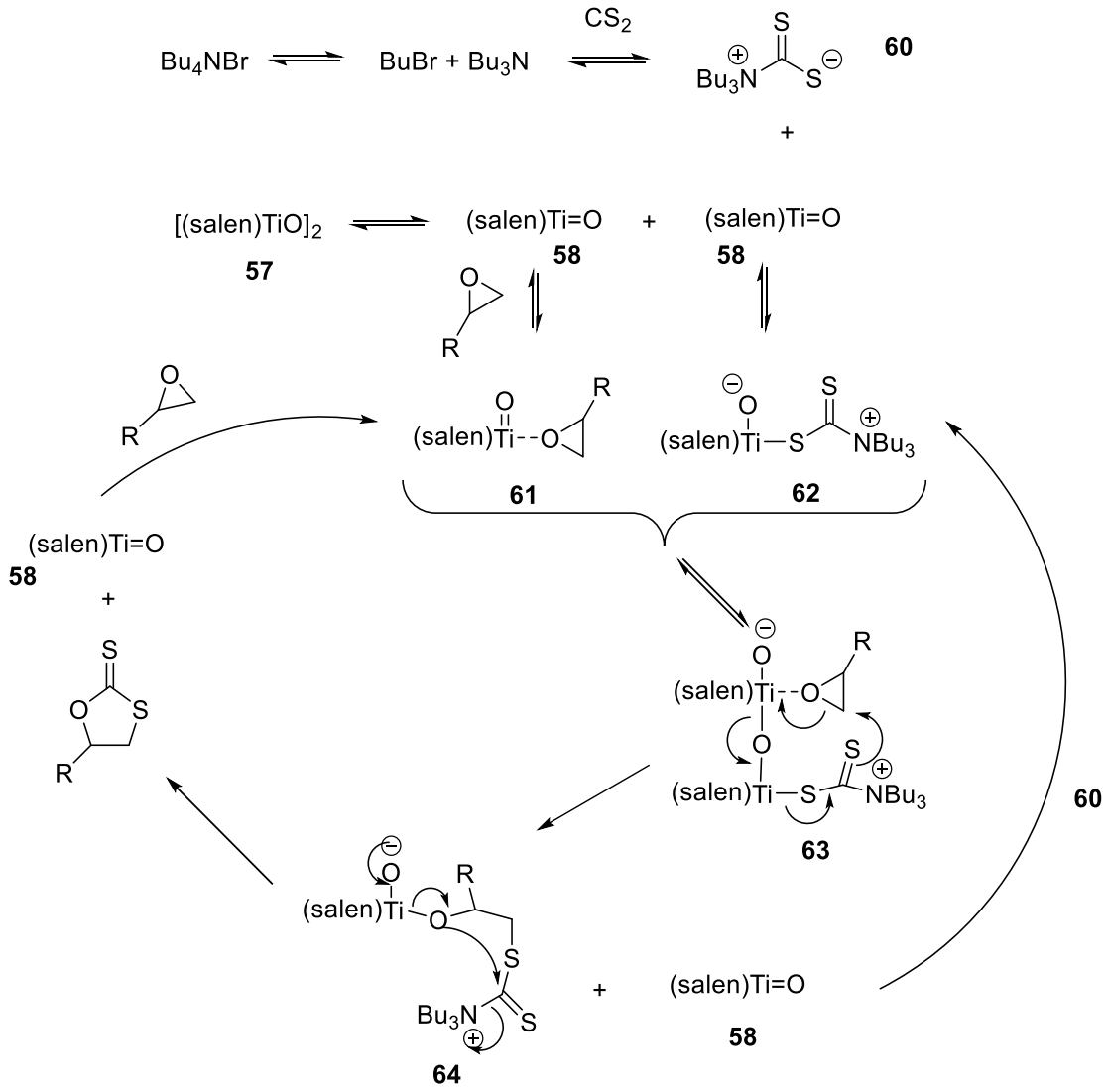


Scheme 59 - 1h coordinating to complex **58**, forming complex **59**

Another feature of interest in Figure 12 is the gradual formation of new peaks as the reaction nears completion (labelled B). These occur in the region containing the imine peaks of bimetallic complex **57**. Figure 13 shows a mixture of complex **57** stirred with 40 equivalents of the product mixture **14h**/**15h**, which has peaks forming in the same region. These peaks could potentially be assigned to a complex involving the catalyst and product. The final thing to note about the peaks in Figure 12, is that the imine peaks of the catalyst species change position over time. This illustrates the equilibrium present between complex **57** and **58**. The equilibrium is seen to change depending on the concentration of epoxide and product throughout the reaction.

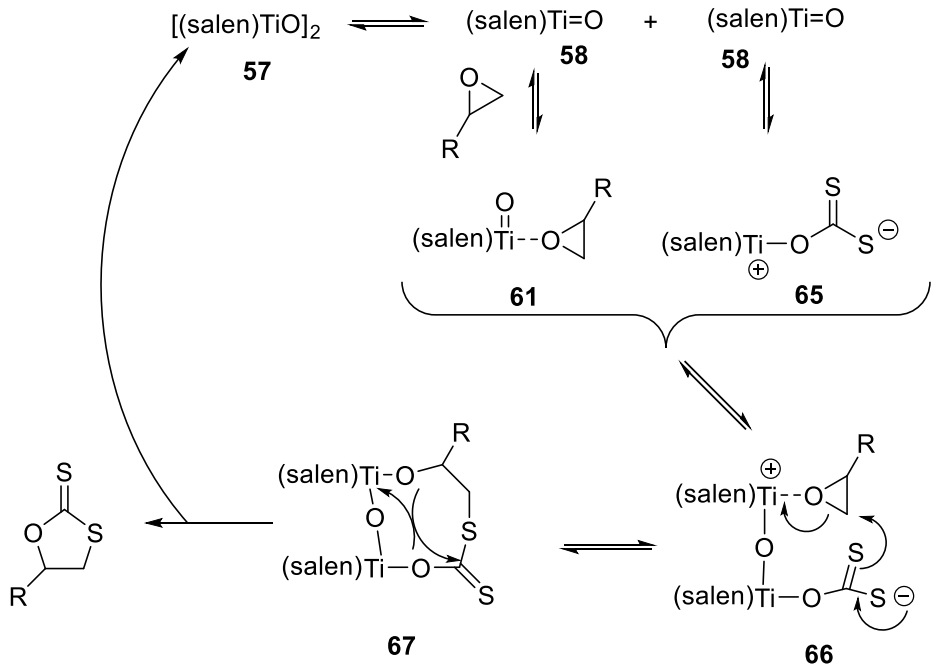
A reaction mechanism, which accounts for all the data accumulated from the various NMR spectra, is outlined in Scheme 60. It begins with the TBAB acting as an *in situ* source of tributylamine. This is known as a reverse Menschutkin reaction, and there is literature precedent for this process.[13,27,104] The tributylamine then reacts with carbon disulphide forming a dithiocarbamate **60**.[17,20a,96b,] Then one molecule of complex **58**, which is always in equilibrium with complex **57**, acts as a Lewis acid by coordinating to the epoxide and forms adduct **61**. While complex **62** forms from the other molecule of

complex **58** reacting with the dithiocarbamate **60**. Adducts **61** and **62** then reassemble to bring both reacting species together, in the form of an activated epoxide and a nucleophilic dithiocarbamate species, to form the key intermediate **63**. This then undergoes an intramolecular rearrangement to form adduct **64**, via an epoxide ring-opening. At this point one molecule of complex **58** is reformed. The other molecule of complex **58** is reformed by the collapse of adduct **64** which, in turn, reforms tributylamine and forms the dithiocarbonate product.



Scheme 60 - Proposed catalytic cycle for reaction containing TBAB

This mechanism involves a single nucleophilic substitution at the epoxide, and therefore agrees with the observed stereochemistry of the product from cyclohexene oxide **1i**. It is also consistent with the observed first order kinetics with respect to complex **57**, since the catalytic cycle involves adduct **63**, which contains two metal ion centres. The improved catalytic activity of this system over the aluminium complex **10** can be explained by the known higher Lewis acidity of the titanium metal catalysts.[100c]



Scheme 61 - Proposed catalytic cycle for reaction without TBAB

According to Table 23, entries 1 and 2, complex **57** shows catalytic activity, even in the absence of TBAB, this indicates that there must be a different reaction mechanism, which does not utilize the *in situ* formation of tributylamine. A proposed mechanism is outlined in Scheme 61. As in the previous mechanism (Scheme 60), one molecule of complex **58** coordinates to the epoxide acting as a Lewis acid, forming adduct **61**. In this mechanism, however, it is the other molecule of complex **58** which

reacts with the carbon disulphide forming dithiocarbamate species **65**. Again, adducts **61** and **65** react to form key intermediate **66** with the activated epoxide and sulphur-based nucleophile. This then intramolecularly ring-opens the epoxide forming nine-membered ring species **67**, which then collapses to form dithiocarbonate product and reforms complex **57**. The faster reactions observed while using the cocatalyst TBAB could possibly be explained by the fact that tributylamine is a better suited nucleophile to react with carbon disulphide and by the relatively stable neutral intermediate **67** being slower to collapse than intermediate **64**.

Table 26 – Complex 57 and Bu_3N as a catalyst system for the synthesis of thiocarbonates[a]

Entry	Epoxide	Conversion (%)	Yield (%)	14:15
1	**1a**	95	83	0:100
2	**1d**	100	97	83:17
3	**1e**	100	94	63:37
4	**1f**	94	89	75:25
5[b]	**1g**	87	82	72:28
6	**1h**	100	96	74:26
7	**1j**	100	94	80:20

[a] Reactions carried out with 1.8 eq. CS_2, 90 ^oC, 24 h, neat, 1 mol% of catalyst **57**, and 1 mol% of tributylamine. Conversions and product ratio calculated by ^1H NMR analysis of reaction mixture.

It is implied by Scheme 60 that the role of TBAB is solely to act as *in situ* source of tributylamine, therefore it made sense to investigate whether tributylamine instead of TBAB, was as effective a cocatalyst in this reaction. This was previously demonstrated on the reactions involving complex **10**,[27] and the results for this

investigation carried out under the same conditions are shown in Table 26. By comparing Tables 24 and 26 it can be seen that almost identical yields and product ratios are obtained with both cocatalysts, which backs up the claim that TBAB generates tributylamine.

The reaction between 3-phenoxypropylene oxide **1h** and carbon disulphide catalysed by complex **57** and tributylamine cocatalyst at 50°C in $CDCl_3$ was monitored by ^1H NMR spectroscopy. The resulting conversion versus time plot is shown in Figure 14. As is obvious from the plot, the induction period which is present in all of these reactions has not disappeared when using tributylamine as cocatalyst, which suggests that it is not due to the need to build up a concentration of tributylamine from TBAB. The most likely explanation is that it is due to the need to build up a concentration of another intermediate in the reaction cycle, most probably complex **63**, which requires two monometallic species coming together and reacting which are both present in low concentrations.

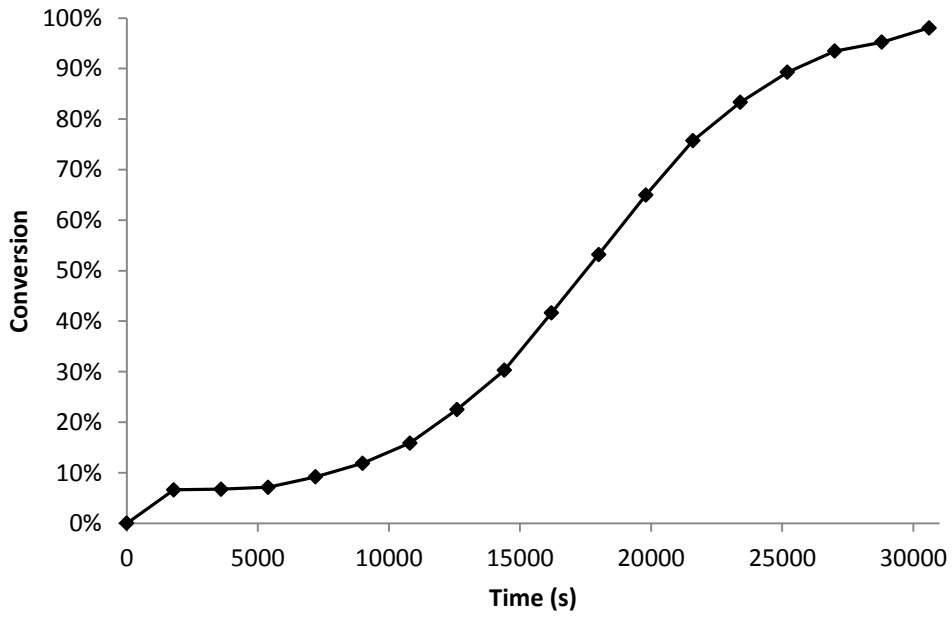


Figure 14 – Plot of conversion vs. time for reaction of 3-phenoxypropylene oxide **1h** with CS_2. Reaction conditions: 50 °C, $CDCl_3$, $[\mathbf{1h}]_0$ = 1.4 M, $[CS_2]_0$ = 2.6 M, $[\mathbf{7}]_0$ = 71 mM, $[Bu_3N]_0$ = 71 mM.

To summarise these results, it has been found that bimetallic complex **57** offers a much improved catalyst system to form di- and trithiocarbonates (**14** and **15**) from the reaction of epoxides with carbon disulphide. This has allowed the catalyst loading to be lowered by five- or even up to tenfold, when compared to the previous system using complex **10**, which can be explained by increased Lewis acidity of the metal centres. By using a combination of kinetic studies and ^{1}H NMR spectroscopic analysis, catalytic cycles have been proposed for these reactions.

2.5 Conclusion

This project began with an investigation into improving one-component metal salen catalysts for the synthesis of cyclic carbonates from epoxides and carbon dioxide. The catalysts being investigated did not get into the testing phase, as it proved impossible to quaternise the amines that were incorporated in the salen ligand. Since the already existing diethyl amine derived catalyst had been synthesised and characterised, it can be assumed that the problem was due to steric hindrance of anything bigger than an ethyl group around the nitrogen atom. As an alternative side project, the one-component catalysts which were successfully synthesised were tested on the synthesis of thiocarbonates and cyanohydrins. However, in both cases they did not offer any improvement on pre-existing systems.

Following the work on one-component systems, research was focussed on the original system comprising an aluminium salen catalyst and TBAB cocatalyst for the reaction of epoxides and heterocumulenes. Firstly, it was shown that by increasing the temperature and pressure of the reaction, compressed air could be used successfully as the source of carbon dioxide for cyclic carbonate synthesis. Detailed mechanistic studies

were then carried out in order to draw a comparison of the kinetics of the reactions between epoxides and heterocumulenes (carbon dioxide, carbon disulphide and isocyanates) using this catalytic system. The results of this include proposed catalytic cycles and activation parameters for the various reactions.

The final two chapters of the thesis involved the process of developing new catalyst systems for reactions of epoxides and two heterocumulenes. The aim was to investigate changing the metals at the core of the salen ligands to observe whether the results of the aluminium catalyst could be improved upon. It was notable that, as the reacting heterocumulene was changed, a different metal proved to be the most catalytically active.

In the reaction between epoxides and isocyanates, vanadium catalysts proved to be the most active. It was seen that both the catalyst loading and the reaction times required were much less than with the original aluminium salen system. The reaction appeared to occur through a completely different mechanism when using vanadium as it appeared that the presence of TBAB greatly increased the activity, unlike the aluminium catalysed reaction. One drawback of this system was that the overall yields decreased due to the formation of an unwanted by product, possibly by trimerisation of the isocyanate or its reaction with water to form diphenyl urea.

Titanium salen appeared to be the most active catalyst for the formation of thiocarbonates from epoxides and carbon disulphide. When compared to the aluminium salen catalyst system, it was found that the catalyst loading could be decreased by up to a factor of ten while still maintaining excellent yields. Unlike the previous system, even at increased temperatures the dithiocarbonate was the major product for almost all the

epoxide substrates. A mechanistic study was carried out on this system which resulted in a catalytic cycle being proposed.

2.6 Future Work

Future research on the one-component catalysts for cyclic carbonate synthesis should follow the route of incorporating cyclic diamines such as pyrrole or pyrrolidine into the salen ligand backbone. This may result in a catalyst that is less likely to dequaternise over time, and could also decrease the negative effect of dequaternisation because the group would still be tethered to the nitrogen due to the cyclic nature of the compound.

In terms of improving the systems presented in this thesis, methods should be sought to disfavour the formation of the unwanted by-products of the reactions of isocyanates. This could be attempted in numerous ways, such as using scrupulously dry conditions to disfavour reactions involving adventitious water. Another method may be to add the isocyanate reagent dropwise over a long period of time, thus keeping it in a relatively small concentration in the reaction mixture, and therefore encouraging the reaction of the isocyanate and epoxide while discouraging trimerisation.

Metal salen catalyst systems have now been optimised for the reactions of epoxides with three different heterocumulenes, with the best results for each reaction coming from a catalyst system based around a different metal centre. The chemistry in this field should be expanded in order to look into reactions of epoxides with other heterocumulenes. Metal salen compounds have never been tested as catalysts for reaction involving isothiocyanates, carbodiimides and sulphur dioxide. It can be

presumed, based on the similarities in the structures of these compounds, that metal salen catalysts will have at least some catalytic activity for these transformations.

Chapter 3. Experimental

3.1 General

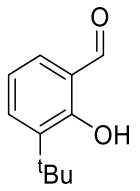
Commercially available chemicals were purchased from *Aldrich*, *Fluka*, *Acros* and *Alfa Aesar* and were used as received. Solvents were dried prior to use, when required. Commercial grade solvents were used for general lab practice such as work-ups and any chromatographic purification of products, and these were carried out using silica gel 60 (230-400 mesh) as standard.

Infrared spectra were recorded on a *Varian* 800 FT-IR Scimitar series spectrometer at room temperature. Signals are denoted as: strong (s), medium (m), weak (w) or broad (br). ^{1}H and $^{13}C\{^{1}H\}$ spectra were recorded on either a *Bruker* Avance 300 MHz, *JEOL* Oxford 400 MHz or a *JEOL* Lambda 500 MHz spectrometer. Unless stated, spectra were recorded at room temperature, and the deuterated solvent used for each spectrum is given in parentheses. All chemical shifts are reported in ppm, coupling constants in Hz and the signals are reported relative to TMS. The multiplicity of reported signals are denoted as singlet (s), doublet (d), triplet (t), quartet (q), multiplet (m), broad (br) or in combinations of any of these.

High and low resolution mass-spectra were recorded on a *Waters* LCT Premier LCMS spectrometer, using electrospray (ES) ionisation. Melting points were determined using a *Stuart* SMP3 system with an operating limit of 250 °C. Optical roations were determined using a Polaar 2001 *Optical Activity* automatic polarimeter at the sodium D-line using 0.5 dm thermostated cuvettes, with the solvent being reported along with the concentration which is in g/100 mL. Gas chromatography was performed on a *Varian* CP-3800 instrument with a TCD detector using a Factor-Four (VF-1 ms) capillary column (15m x 0.25 mm), using hydrogen as the carrier gas.

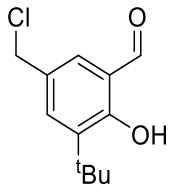
3.2 One-Component Catalysts

*Synthesis of 3-tert-butylsalicylaldehyde **42**[15]:*



To a stirred suspension of 2-*tert*-butylphenol (4.55g, 30mmol), magnesium chloride (5.71g, 60mmol) and paraformaldehyde (2.08 g, 66 mmol) in THF (120 ml) at room temperature, triethylamine (8.35 ml, 60 mmol) was added dropwise. The reaction was heated to reflux for 3 hours to give an orange suspension. This was extracted using EtOAc (3 x 50 ml). A small amount of diluted HCl was added if a permanent emulsion was formed. The organic layer was dried over $MgSO_4$ and the volatiles evaporated under low pressure to yield compound **42** as a pale yellow oil which needed no further purification. Yield: 4.96 g, 93%. $\delta_H(CDCl_3)$ 1.41 (9H, s, ^{t}Bu), 6.94 (1H, t, *J* 7.4 Hz, ArH), 7.39 (1H, dd, *J* 1.6 Hz, 7.4 Hz, ArH), 7.54 (1H, dd *J* 1.6 Hz, 7.4 Hz, ArH), 9.87 (1H, s, CHO), 11.77 (1H, s, OH).

Synthesis of 3-tert-butyl-5-chloromethylsalicylaldehyde ***43***[15]*:*

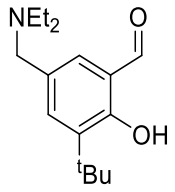


A mixture of 3-*tert*-butylsalicylaldehyde (**42**) (3.56 g, 20 mmol) and paraformaldehyde (1.20 g, 40 mmol) was stirred with conc. HCl (15 ml) at 50°C for 48 hours. A red emulsion formed immediately upon adding the HCl. The mixture was then extracted with EtOAc (3 x 30 ml), washed with H_2O, and dried with $MgSO_4$. The volatiles were then evaporated under reduced pressure to give product **45** as a red oil. Yield: 4.35 g, 96%. $\delta_H(CDCl_3)$ 1.41 (9H, s, ^tBu), 4.57 (2H, s, CH_2), 7.42 (1H, d, *J* 2.1 Hz, ArH), 7.50 (1H, d, *J* 2.1 Hz, ArH), 9.85 (1H, s, CHO), 11.84 (1H, s, OH).

General procedure for formation of 3-tert-butyl-5-dialkylaminomethylsalicylaldehyde ***44a-e*** [15]*:*

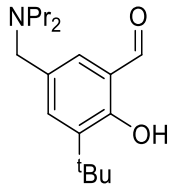
To a solution of 3-*tert*-butyl-5-chloromethylsalicylaldehyde (**42**) (0.453 g, 2 mmol) in acetonitrile (15 ml), the required secondary amine (2 mmol) was added dropwise (green solution formed). This reaction mixture was stirred at 30°C overnight. The volatiles were evaporated under reduced pressure to give the product.

3-Tert-butyl-5-diethylaminomethylsalicylaldehyde ***44a***[15]*:*



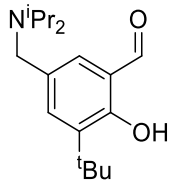
Using diethylamine (0.147 g, 2 mmol). Obtained as a brown oil. Yield 0.49 g, 98 %. $\delta_H(CDCl_3)$ $\delta_H(CDCl_3)$ 1.3-1.44 (15H, m, 2 x CH_3, ^tBu), 2.85-3.20 (4H, m, CH_2), 4.06 (2H, s, CH_2N), 7.65 (1H, d, *J* 2.2 Hz, ArH), 7.91 (1H, d, *J* 2.2 Hz, ArH), 9.87 (1H, s, CHO), 11.91 (1H, s, OH); $\delta_C(CDCl_3)$ 11.4, 28.9, 34.8, 46.9, 58.4, 121.1, 132.0, 131.9, 134.8, 149.7, 158.9, 197.0; ν_{max}(ATR) 3300 (br), 2899 (m), 1720 (s) cm^{-1}..

3-Tert-butyl-5-dipropylaminomethylsalicylaldehyde ***44b****:*



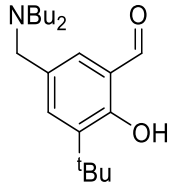
Using dipropylamine (0.2 g, 2 mmol). Obtained as a brown oil. Yield 0.553 g, 95 %). $\delta_H(CDCl_3)$ 0.98 (6H, t, *J* 7.1 Hz, 2 x CH_3), 1.4-1.7 (13H, m, 2 x CH_2, ^tBu), 2.41 (4H, t, *J* 7.1 Hz, 2 x CH_2), 3.61 (2H, s, CH_2), 7.34 (1H, d, *J* 2.2 Hz, ArH), 7.56 (1H, d, *J* 2.2 Hz, ArH), 9.91 (1H, s, CHO), 11.84 (1H, s, OH); $\delta_C(CDCl_3)$ 11.7, 20.3, 29.3, 34.8, 55.5, 58.6, 120.4, 130.8, 131.3, 134.9, 138.0, 160.1, 196.8; ν_{max}(ATR) 2959 (m), 2872 (m), 2802 (m), 1636 (s) and 1434 cm^{-1} (s).

3-Tert-butyl-5-diisopropylaminomethylsalicylaldehyde ***44c****:*



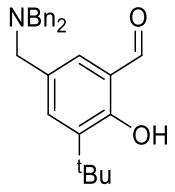
Using diisopropylamine (0.202 g, 2 mmol). Obtained as a brown oil. Yield (0.518, 89%). $\delta_H(CDCl_3)$ 1.04 (12H, d, *J* 9.0 Hz, CH_3), 1.43 (9H, s, ^{t}Bu), 3.03 (2H, m, CH), 3.61 (2H, s, CH_2), 7.40 (1H, s, ArH), 7.59 (1H, s, ArH), 9.88 (1H, s, CHO), 11.68 (1H, s, OH); $\delta_C(CDCl_3)$ 19.7, 20.8, 29.3, 34.8, 48.0, 120.4, 130.4, 133.6, 134.0, 137.8, 159.9, 196.9; ν_{max}(ATR) 2962 (m), 2871 (m), 1620 (s) and 1435 cm^{-1} (s).

3-Tert-butyl-5-dibutylaminomethylsalicylaldehyde ***44d****:*



Using dibutylamine (0.258 g, 2mmol). Obtained as a brown oil. Yield 0.57 g, 94 %. $\delta_H(CDCl_3)$ 0.90 (6H, t, *J* 9.0 Hz, CH_3), 1.2-1.6 (17H, m, CH_2, ^{t}Bu), 2.41 (4H, t, *J* 5.9 Hz, CH_2), 3.51 (2H, s, CH_2), 7.34 (1H, s, ArH), 7.52 (1H, s, ArH), 9.87 (1H, s, CHO), 11.87 (1H, s, OH); $\delta_C(CDCl_3)$ 13.6, 20.3, 27.4, 29.2, 34.9, 52.6, 57.4, 120.5, 131.1, 133.0, 135.5, 138.7, 160.9, 196.9; ν_{max}(ATR) 2957 (m), 2872 (m), 2805 (w), 2361 (m), 1682 (s) and 1435 cm^{-1} (s).

3-Tert-butyl-5-dibenzylaminomethylsalicylaldehyde ***44d:***

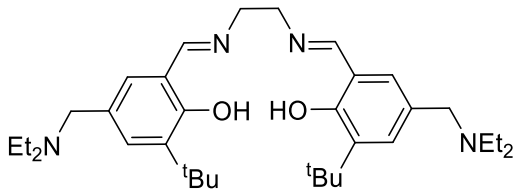


Using dibenzylamine (0.395 g, 2 mmol). Obtained as a brown oil. Yield 0.643 g, 83 %. $\delta_H(CDCl_3)$ 1.43 (9H, s, ^tBu), 3.59 (4H, s, 2 x CH_2), 3.84 (2H, s, CH_2), 7.1-7.4 (11H, m, ArH), 7.58 (1H, s, ArH), 9.88 (1H, s, CHO), 11.73 (1H, s, OH); $\delta_C(CDCl_3)$ 29.3, 34.9, 53.1, , 58.2, 127.0, 128.2, 128.3, 128.4, 128.5, 128.8, 129.6, 130.3, 131.4, 135.0, 138.2, 139.5, 160.3, 196.8; ν_{max}(ATR) 2958 (m), 2793 (m), 1648 (s) and 1434 cm^{-1} (s).

General procedure for synthesis of one-component salen ligands ***45a-e***[15]***:***

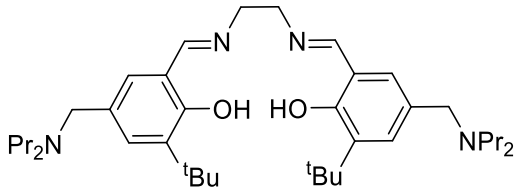
To a solution of ethylenediamine (0.5 mmol, 1 eq) in ethanol (10 ml), a solution of 3-*tert*-butyl-5-aminomethylsalicylaldehyde (**44a-e**) (1.1 mmol, 2.2 eq) in ethanol (5ml) was added. The mixture rapidly became yellow, and was stirred at 30°C overnight. Evaporation of solvent was followed by the addition of a saturated solution of Na_2CO_3 (20ml), and the organic compounds were extracted using dichloromethane (3 x 15 ml). The organic layers were dried with $MgSO_4$, and volatiles removed under reduced pressure to yield the products.

*Salen ligand **45a**[15]:*



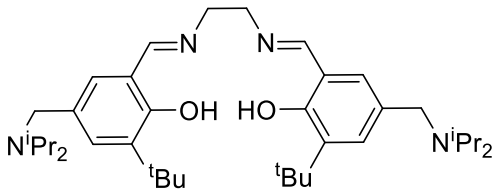
Obtained as a yellow solid. Yield 0.227g, 90 %. Mp >250°C. $\delta_H(CDCl_3)$ 1.01 (12H, t, *J* 7.1 Hz, 4 x CH_3CH_2), 1.44 (18H, s, 2 x ^{t}Bu), 2.53 (8H, q, *J* 7.1 Hz, 4 x CH_2CH_3), 3.50 (4H, s, 2 x CH_2), 3.94 (4H, s, 2 x CH_2N), 7.01(2H, d, *J* 2.0 Hz, 2 x ArH), 7.25 (2H, d, *J* 2.0 Hz, 2 x ArH), 8.40 (2H, s, 2 x CHN); $\delta_C(CDCl_3)$ 10.4, 28.0, 33.3, 45.2, 55.7, 58.1, 116.8, 128.2, 128.8, 135.6, 157.7, 165.3, 165.8; ν_{max}(ATR) 2965 (br), 2524 (m), 1629 (m).

*Salen ligand **45b**:*



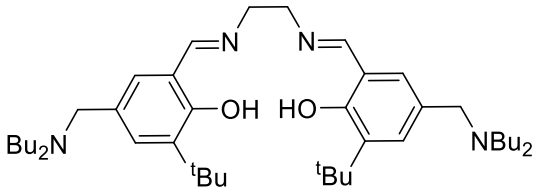
Obtained as a yellow solid. Yield 0.235 g, 88%. Mp >250°C. $\delta_H(CDCl_3)$ 0.88 (12H, t *J* 7.4 Hz, 4 x CH_3), 1.3-1.5 (26H, m, 4 x CH_2, 2 x ^{t}Bu), 2.36 (8H, t, *J* 5.9 Hz, 4 x CH_2), 3.48 (4H, s, 2 x CH_2), 3.94 (4H, s, 2 x CH_2), 7.06 (2H, s, 2 x ArH), 7.31 (2H, s, 2 x ArH), 8.40 (2H, s, 2 x CHN); $\delta_C(CDCl_3)$ 11.8, 19.6, 20.3, 29.4, 34.8, 55.8, 58.3, 59.6, 118.2, 129.3, 129.6, 130.3, 137.0, 159.1, 167.3; ν_{max}(ATR) 2957 (m), 2871 (m), 2798 (m), 1630 (s) and 1439 cm^{-1} (s).

*Salen ligand **45c**:*



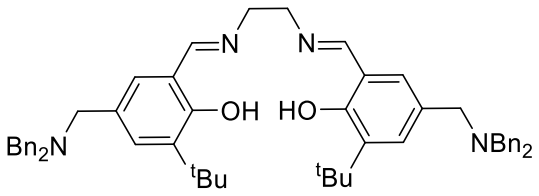
Obtained as a yellow solid. Yield 0.211 g, 79 %. Mp >250^{o}C. δ_H($CDCl_3$) 1.02 (12H, d *J* 9.0 Hz, 4 x CH_3), 1.45 (18H, s, 2 x ^{t}Bu), 3.01 (4H, m, 4 x CH), 3.56 (4H, s, 2 x CH_2), 3.94 (4H, s, 2 x CH_2), 7.11 (2H, s, 2 x ArH), 7.35 (2H, s, 2 x ArH), 8.40 (2H, s, 2 x CHN); δ_C($CDCl_3$) 19.7, 20.8, 29.5, 34.8, 47.8, 48.3, 59.7, 118.2, 128.6, 129.4, 131.8, 136.9, 158.8, 167.4; ν_{max}(ATR) 2961 (m), 2870 (m), 2800 (m), 1630 (s) and 1439 cm^{-1} (s).

*Salen ligand **45d**:*



Obtained as a yellow solid. Yield 0.241 g, 86 %. Mp >250^{o}C. δ_H($CDCl_3$) 0.88 (12H, t *J* 6.1 Hz, 4 x CH_3), 1.2-1.6 (34H, m, 8 x CH_2, 2 x ^{t}Bu), 2.39 (8H, t, *J* 5.7 Hz, 4 x CH_2), 3.51 (4H, s, 2 x CH_2), 3.95 (4H, s, 2 x CH_2), 7.05 (2H, s, 2 x ArH), 7.30 (2H, s, 2 x ArH), 8.41 (2H, s, 2 x CHN); δ_C($CDCl_3$) 13.9, 20.5, 29.4, 29.7, 34.7, 53.5, 58.3, 58.6, 118.2, 129.3, 129.6, 130.4, 137.0, 159.2, 167.3; ν_{max}(ATR) 2956 (m), 2931 (m), 2870 (m), 2796 (m), 1624 (s) and 1457 cm^{-1} (s).

*Salen ligand **45e**:*



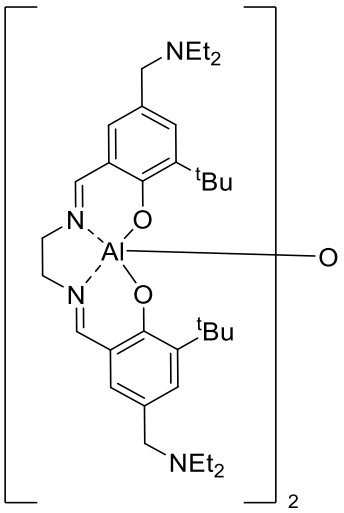
Obtained as a yellow solid. Yield 0.239 g, 76 %. Mp >250°C. $\delta_H(CDCl_3)$ 1.36 (18H, s, 2 x ^tBu), 3.41 (8H, s, 4 x CH_2), 3.64 (4H, s, 2 x CH_2), 3.84 (4H, s, 2 x CH_2), 6.99 (1H, s, ArH), 7.1-7.4 (11H, m, 11 x ArH), 8.31 (4H, s, 4 x CHN); $\delta_C(CDCl_3)$ 29.5, 34.8, 53.3, , 57.5, 57.9, 59.6, 118.2, 126.8, 128.1, 128.3, 128.5, 128.8, 137.3, 139.8, 159.4, 167.2; ν_{max}(ATR) 2955 (m), 2793 (m), 1630 (s) and 1440 cm^{-1} (s).

*General procedure for synthesis of one-component aluminium salen catalysts **46a-e**[15]:*

Procedure A: To a suspension of shredded aluminium foil (ca. 0.5cm by 1mm) (0.22 g, 8 mmol, 2 eq.) in EtOH (10 ml) and toluene (25 ml), a crystal of iodine was added (ca. 40 mg). The solution was then stirred and heated to reflux until a grey slurry formed. The reaction was cooled to room temperature and salen ligand (**45a-e**) (4 mmol, 1 eq.) in toluene (15 ml) was then added. The reaction was stirred overnight at 30°C. The mixture was filtered through a pad of celite and washed with dichloromethane. Volatiles were then evaporated, water (20 ml) was added and the product was extracted with dichloromethane and dried with $MgSO_4$. Solvent was then evaporated under reduced pressure to give the product, which was then washed with ether.

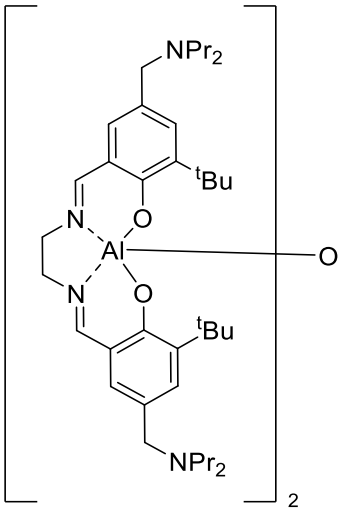
Procedure B: Salen ligand (**45a-e**) (4 mmol, 1 eq.) was dissolved in toluene (50 mL) and heated to reflux. Triethylaluminium (8 mmol, 2 eq.) was then added, dissolved in additional toluene (40 mL). The mixture was stirred vigorously under reflux for four hours, after which it was filtered through a pad of celite and washed with dichloromethane. The volatiles were then evaporated *in vacuo*, giving a yellow powder, which was washed with ether to give the product.

*Aluminium salen complex **46a**[15]:*



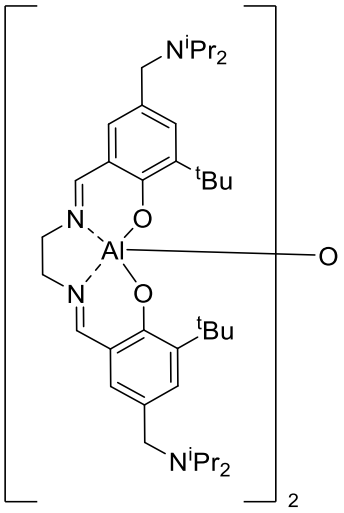
Prepared by procedure A using salen ligand **45a** (2.02 g, 4 mmol). Purified by washing with ether. Obtained as a yellow solid. Yield 1.36 g, 64 %. Mp > 250 °C. $\delta_H(CDCl_3)$ 1.07 (24H, t, *J* 6.9 Hz, 8 x CH_3), 1.50 (36H, s, 4 x ^tBu), 2.53 (16H, q, *J* 6.9 Hz, 8 x CH_2), 3.50 (8H, s, CH_2N), 3.7-4.1 (8H, m, 2 x $(CH_2)_2$), 7.06 (4H, s, 4 x ArH), 7.37 (4H, s, 4 x ArH), 8.32 (4H, s, 4 x HC=N); $\delta_C(CDCl_3)$ 11.4, 29.6, 46.4, 54.6, 57.0, 59.6, 118.8, 126.1, 132.0, 134.4, 141.1, 163.6, 169.6; ν_{max}(ATR) 2939 (m), 2798 (m), 1627 (m), 15 49 (s) cm^{-1}.

*Aluminium salen complex **46b**:*



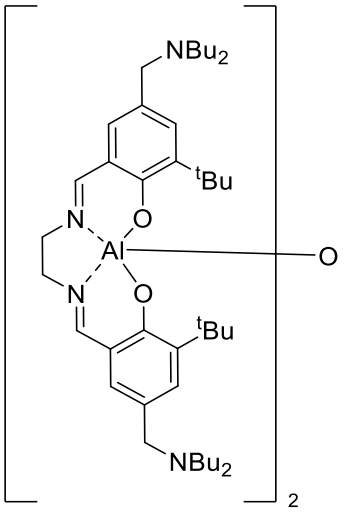
Prepared by procedure A using salen ligand **45b** (2.136 g, 4 mmol). Purified by washing with ether. Obtained as a yellow solid. Yield 1.29 g, 58 %. Mp > 250 °C. $\delta_H(CDCl_3)$ 0.89 (24H, t *J* 7.3 Hz, 8 x CH_3), 1.4-1.6 (52H, m, 8 x CH_2, 4 x ^tBu), 2.37 (16H, t, *J* 7.6 Hz, 8 x CH_2), 3.48 (8H, s, 4 x CH_2), 3.78 (4H, br s, 2 x CH_2), 4.14 (4H, br s, 2 x CH_2) 7.04 (4H, s, 4 x ArH), 7.43 (4H, s, 4 x ArH), 8.37 (4H, s, 4 x CHN); $\delta_C(CDCl_3)$ 11.8, 20.4, 29.7, 35.3, 55.3, 55.9, 58.3, 118.7, 127.5, 130.8, 133.8, 141.3, 164.5, 169.5; ν_{max}(ATR) 2956 (m), 2933 (m), 2870 (m), 2798 (m), 1608 (s) and 1549 cm^{-1} (s).

*Aluminium salen complex **46c**:*



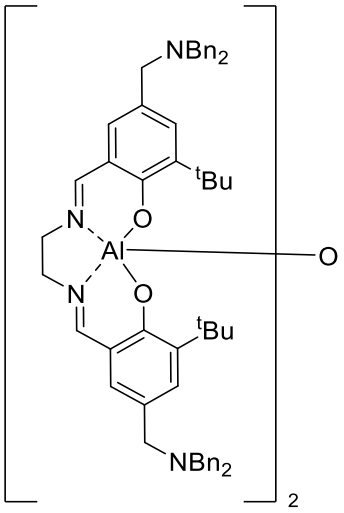
Prepared using procedure A using salen ligand **45c** (2.136 g, 4 mmol). Purified by washing with ether. Obtained as a yellow solid. Yield 1.14 g, 51 %. Mp > 250 °C. $\delta_H(CDCl_3)$ 1.04 (24H, d *J* 6.0 Hz, 8 x CH_3), 1.51 (36H, s, CH_2, 4 x ^{t}Bu), 3.03 (8H, m, 8 x CH), 3.56 (8H, s, 4 x CH_2), 3.88 (4H, br s, 2 x CH_2), 4.14 (4H, br s, 2 x CH_2) 7.09 (4H, s, 4 x ArH), 7.46 (4H, s, 4 x ArH), 8.33 (4H, s, 4 x CHN); $\delta_C(CDCl_3)$ 20.8, 29.7, 30.4 35.3, 47.7, 48.2, 55.3, 118.7, 129.9, 132.9, 141.1, 164.2, 169.6; ν_{max}(ATR) 2956 (m), 2960 (m), 2870 (m), 1624 (s) and 1550 cm^{-1} (s).

*Aluminium salen complex **46d**:*



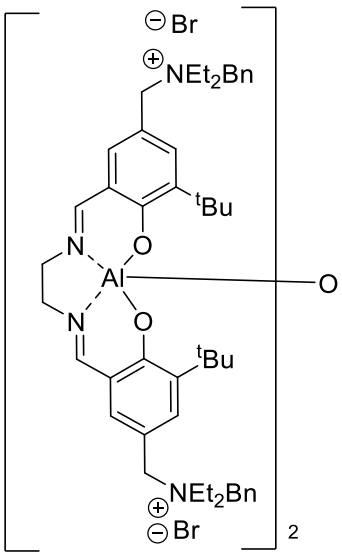
Prepared by procedure A using salen ligand **45d** (2.248 g, 4 mmol). Purified by washing with ether. Obtained as a yellow solid. Yield 1.24 g, 53 %. Mp > 250 °C. $\delta_H(CDCl_3)$ 0.90 (24H, t *J* 6.4 Hz, 8 x CH_3), 1.2-1.7 (68H, m, 16 x CH_2, 4 x ^tBu), 2.40 (16H, t, *J* 6.9 Hz, 8 x CH_2), 3.47 (8H, s, 4 x CH_2), 3.72 (4H, br s, 2 x CH_2), 4.12 (4H, br s, 2 x CH_2) 7.03 (4H, s, 4 x ArH), 7.42 (4H, s, 4 x ArH), 8.36 (4H, s, 4 x CHN); $\delta_C(CDCl_3)$ 14.0, 20.6, 28.6, 29.4, 35.3, 53.5, 55.4, 58.2, 118.7, 127.4, 131.0, 133.9, 141.2, 164.4, 169.6; ν_{max}(ATR) 2953 (m), 2926 (m), 2870 (m), 2791 (m), 1625 (s) and 1549 cm^{-1} (s).

*Aluminium salen complex **46e**:*



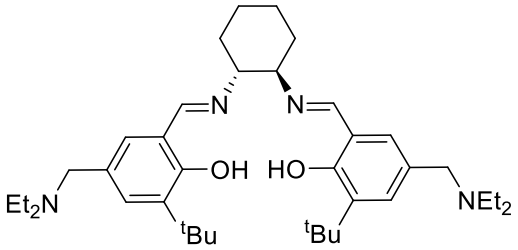
Prepared by procedure A using salen ligand **45e** (2.52 g, 4 mmol). Purified by washing with ether. Obtained as a yellow solid. Yield 1.50 g, 53 %. Mp > 250 °C. $\delta_H(CDCl_3)$ 1.55 (36H, s, 4 x ^tBu), 3.58 (16H, s, 8 x CH_2), 3.84 (8H, s, 4 x CH_2), 4.08 (4H, br s, 2 x CH_2), 7.09 (4H, s, 4 x ArH), 7.1-7.4 (10H, m, 10 x ArH), 7.50 (4H, s, 4 x ArH), 8.36 (4H, s, 4 x CHN); $\delta_C(CDCl_3)$ 29.7, 35.4, 55.3, 57.3, 57.8, 118.7, 126.8, 128.1, 128.3, 128.8, 131.1, 133.9, 139.8, 141.5, 159.4, 164.6. 169.5; ν_{max}(ATR) 3025 (w) 2953 (m), 2926 (m), 2789 (m), 1627 (s) and 1549 cm^{-1} (s).

Preparation of aluminium salen complex with quaternary ammonium salt backbone ***13a[15]:***



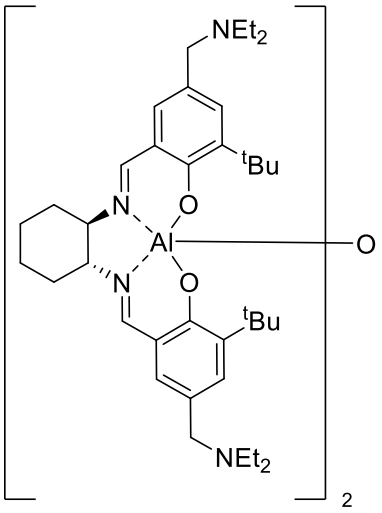
To a solution of aluminium salen complex **46a** (2.33 g, 2 mmol, 1 eq.) in acetonitrile (15 ml), benzyl bromide (1.4 ml, 12 mmol, 6 eq.) was added. The reaction mixture was refluxed overnight. The volatiles were then evaporated to give a brown oil, to which diethyl ether was added, causing product **7** to precipitate, after which it was filtered and air dried then purified by washing with ether. Product obtained as a yellow solid. Mp > 250 °C; $\delta_H(CDCl_3)$ 1.04 (24H, t *J* 7.4 Hz, 8 x CH_3), 1.49 (36H, s, 4 x ^tBu), 2.8-3.1 (16H, m, 8 x CH_2), 3.2-3.8 (8H, m, 4 x CH_2), 4.0-4.5 (16H, m, 8 x CH_2), 7.1-7.5 (28H, m, 28 x ArH), 8.02 (2H, s, 2 x CHN), 8.24 (2H, s, 2 x CHN); ν_{max}(ATR) 1549 (m), 1626 (m), 2585 (m) and 2936 (m) cm^{-1}.

*Salen ligand **47**[15]:*



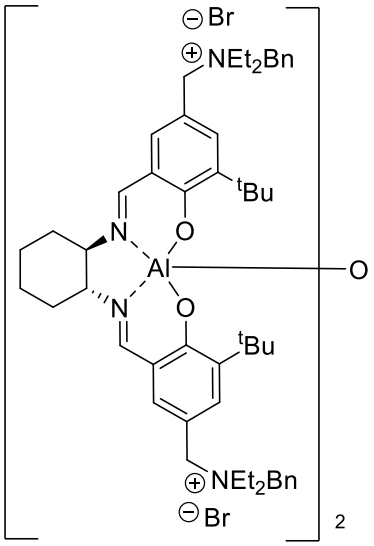
(1*R*,2*R*)-Cyclohexane-1,2-diammonium chloride (93.5 mg, 0.5 mmol, 1 eq.) and NaOMe were stirred in MeOH (10 ml) for 30 minutes. Following this, a solution of 3-*tert*-butyl-5-diethylaminomethylsalicyladehyde (**44a**) (359.8 mg, 1.2 mmol, 2.4 eq.) in MeOH (10 ml) was added. At this point the solution became yellow, and was stirred overnight at 30 °C. Evaporation of the solvent was followed by addition of a saturated solution of Na_2CO_3 (20 ml). Organic compounds were then extracted with dichloromethane (3 x 15 ml). The solution was then dried with $MgSO_4$ and volatiles removed under vacuum to give product **55** as a yellow brown oil. Yield 80%. $[\alpha]^{20}_D$ -184.5 (*c* 1.0, $CHCl_3$); $\delta_H(CDCl_3)$ 0.92 (12H, t, *J* 7.1 Hz, 4 x CH_3), 1.33 (18H, s, 2 x ^{t}Bu), 1.40-1.96 (8H, m, -$(CH_2)_4$-), 2.37 (8H, q, *J* 7.1 Hz, 4 x CH_2N), 3.20-3.36 (6H, m, 2 x NCH, 2 x $ArCH_2N$), 6.88 (2H, d, *J* 2.0 Hz, 2 x ArH), 7.09 (2H, d, *J* 2.0 Hz, 2 x ArH), 8.20 (2H, s, 2 x HC=N), 13.7 (2H, s, 2 x OH); $\delta_C(CDCl_3)$ 12.2, 24.7, 29.6, 33.5, 34.9, 46.8, 57.5, 72.8, 116.7, 129.1, 129.8, 130.1, 137.2, 159.5, 165.7

*Aluminium salen compound **48**[15]:*



To a solution of aluminium foil (0.22 g, 8 mmol, 2 eq.) in ethanol (10 ml) and toluene (25 ml), a crystal of iodine was added. The solution was then stirred and heated to reflux to give a grey slurry. The reaction was cooled to room temperature and salen ligand **47** (2.42 g, 4 mmol, 1 eq.) in toluene (15 ml) was then added. The reaction was stirred overnight at 30°C. The mixture was filtered through a pad of celite and washed with dichloromethane. Volatiles were then evaporated, water (20 ml) was added and the product was extracted with dichloromethane and dried with $MgSO_4$. Solvent was then evaporated under reduced pressure to give the product as a light brown powder. Yield 56 %. Mp > 250 °C. $[\alpha]^{20}_D$ -522 (*c* 1.0, $CHCl_3$); $\delta_H(CDCl_3)$ 0.98 (24H, t, *J* 7.1 Hz, 8 x CH_3), 1.45 (36H, s, 4 x ^{t}Bu), 1.5-2.1 (16H, m, 2 x -$(CH_2)_4$-), 2.45 (16H, q, *J* 7.1 Hz, 8 x CH_2N), 3.0-3.2 (2H, m, 2 x CHN), 3.3-3.5 (8H, m, 4 x CH_2N), 3.7-3.9 (2H, m, 2 x CHN), 7.03 (4H, d, *J* 8.4 Hz, 4 x ArH), 7.28 (4H, d, *J* 8.4 Hz, 4 x ArH), 8.26 (2H, s, 2 x HC=N), 8.30 (2H, s, 2 x HC=N). $\delta_C(CDCl_3)$ 11.1, 23.7, 27.3, 29.5, 33.7, 35.3, 46.2, 56.8, 118.7, 124.5, 133.1, 133.9, 137.4, 141.0, 163.7. ν_{max}(ATR) 2935 (m), 2858 (m), 1622 (s) and 1550 (s) cm^{-1}.

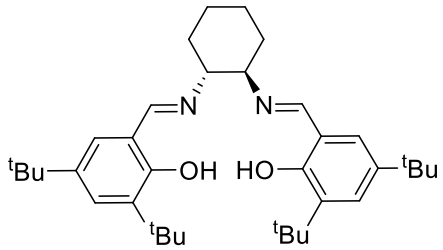
*Aluminium salen complex **13b**[15]:*



To a solution of salen complex **48** (2 mmol, 1 eq.) in acetonitrile (15 ml), benzyl bromide (1.4 ml, 12 mmol, 6 eq.) was added. The reaction mixture was refluxed overnight. The volatiles were then evaporated to give a brown oil, to which diethyl ether was added, causing product **13b** to precipitate, after which it was filtered and air dried then purified by washing with ether. Product obtained as a yellow solid. Mp > 250 °C; $[\alpha]^{20}_{D}$ -281 (*c* 1.0, $CHCl_3$); δ_H(DMSO-d_6) 1-1.8 (24H, m, 8 x CH_3), 1.5-2.0 (16H, m, 2 x -$(CH_2)_4$-), 2.5-2.6 (16H, m, 8 x CH_2), 3.1-3.8 (12H, m, 4 x CH & 4 x CH_2), 4.50 (8H, s, 4 x CH_2), 6.75 (4H, d *J* 7.6 Hz, 4 x ArH), 6.85 (4H, d *J* 7.6 Hz, 4 x ArH) 7.1-7.5 (20H, m, ArH), 8.34 (4H, s, CHN).

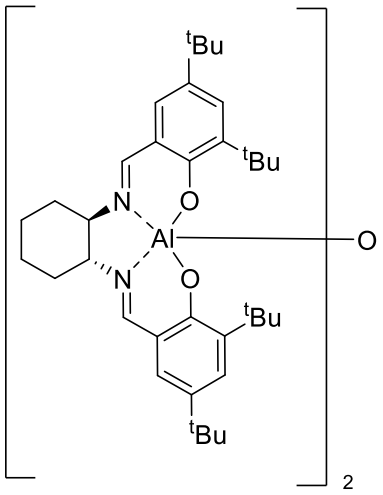
3.3 Two-component salen catalysts

*Preparation of salen ligand **8b**[105]:*



3,5-Di-*tert*-butyl-2-hydroxybenzaldehyde (2 eq., 74.8 mmol, 17.53 g) in methanol (300 mL) and ethanol (300 mL) was added to (*R*,*R*)-1,2-diaminocyclohexane dihydrochloride (1 eq., 7 g, 37.4 mmol) and sodium methoxide (1 eq., 4.46 g, 37.4 mmol). This mixture was then refluxed for three hours, after which the solvents were removed under vacuum. The resulting yellow residue was dissolved in dichloromethane (200 mL) and washed with water (2 x 250 mL) and brine (250 mL). It was then dried using magnesium sulphate and the solvents removed. Product obtained as a bright yellow powder. $[\alpha]^{20}_{D}$ -312 (*c* 1.0, CH_2Cl_2) (*lit.*[105] $[\alpha]^{20}_{D}$ -315 (*c* 1.0, CH_2Cl_2)); $\delta_H(CDCl_3)$; 1.18 (18H, s, 2 x ^{t}Bu), 1.39 (18H, s, 2 x ^{t}Bu) 1.6-1.8 (16H, m, 2 x -$(CH_2)_4$-), 3.1-3.2 (2H, m, 2 x CH), 6.94 (2H, s, 2 x ArH), 7.25 (2H, s, 2 x ArH), 8.25 (2H, s, 2 x CHN).

*Preparation of bimetallic catalyst **10**[106,107]:*

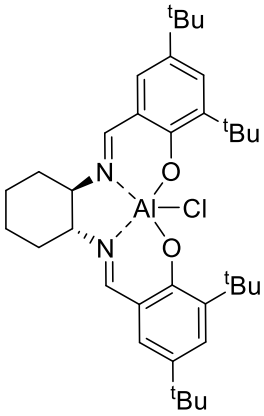


Method A: $Al(OEt)_3$ (0.28 g, 1.72 mmol) was stirred under reflux in toluene (50 mL) for 1 hour. A solution of salen ligand (**8b**) (0.918 g, 1.68 mmol) in toluene (20 mL) was added and the mixture was stirred under reflux for 3 hours and then was allowed to cool to room temperature. The solution was dried ($MgSO_4$) and solvents removed *in vacuo* to give a solid which was purified by washing with cold Et_2O. Obtained as a yellow powder in a 58% yield.

Method B: To a solution of aluminium foil (0.22 g, 8 mmol, 2 eq.) in ethanol (10 ml) and toluene (25 ml), a crystal of iodine was added. The solution was then stirred and heated to reflux to give a grey slurry. The reaction was cooled to room temperature and **8b** (4 mmol, 1 eq.) in toluene (15 ml) was then added. The reaction was stirred overnight at 30°C. The mixture was filtered through a pad of celite and washed with dichloromethane. Volatiles were then evaporated, water (20 ml) was added and the product was extracted with dichloromethane and dried with $MgSO_4$. Solvent was then evaporated under reduced pressure. The product was obtained as a light yellow powder. Mp > 250 °C. $\delta_H(CDCl_3)$ 1.31 (36H, s, 4 x ^{t}Bu), 1.52 (36H, s, 4 x ^{t}Bu), 1.6-2.7 (16H, m,

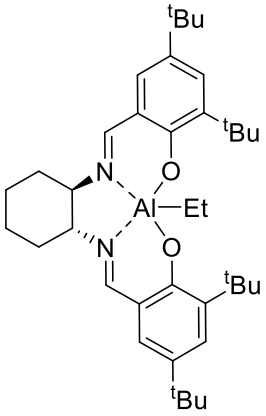
2 x -$(CH_2)_4$-), 3.0-3.1 (2H, m, 2 x CH), 3.6-3.8 (2H, m, 2 x CH), 7.07 (4H, d *J* 2.3 Hz, 4 x ArH) 7.52 (4H, d, *J* 2.3 Hz, 4 x ArH), 8.16 (2H, s, 2 x CHN), 8.33 (2H, s, 2 x CHN).

Preparation of monometallic catalyst ***22***[106,107,108]*:*



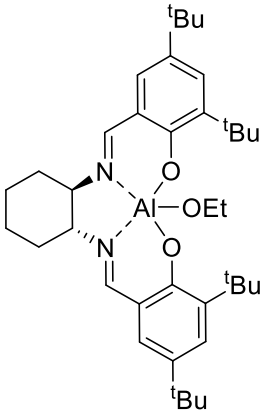
A solution of **8b** (0.45 g, 0.8 mmol) in dry toluene (40 mL) was cooled to 0 ^oC. To this, $AlEt_2Cl$ (0.5 mL of 1.8 M solution in toluene, 0.83 mmol) was added dropwise and the solution was stirred under nitrogen for 2 days. Solvents were then removed *in vacuo*, giving an orange solid, which was extracted with CH_2Cl_2 (40 mL), washed with H_2O (2 x 30 mL) and brine (30 mL). The organic layer was then dried ($MgSO_4$) and solvents evaporated *in vacuo*. Product obtained as an orange solid. Yield 0.40 g, 79 %); $[\alpha]^{20}_D$ -503 (*c* 1.0, CH_2Cl_2); $\delta_H(CDCl_3)$ 0.39 (36H, s, 4 x ^{t}Bu), 2-2.5 (8H, m, -$(CH_2)_4$-), 3.8-3.1 (2H, m, 2 x CH), 7.50 (2H, s, 2 x ArH), 7.96 (2H, s, 2 x ArH), 8.61 (2H, s, 2 x CHN).

*Preparation of monometallic catalyst **20**[108,109]:*



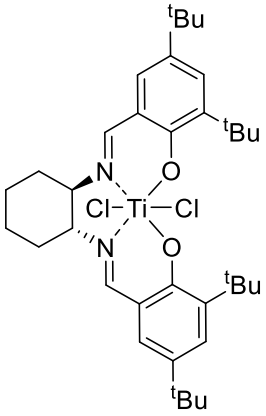
8b (1.94 g, 3.55 mmol) was dissolved in dry toluene (100 mL). $AlEt_3$ (1.98 mL of 1.9 M solution in toluene, 3.6 mmol) was then added to the solution dropwise. The reaction was then refluxed for 1 hour, allowed to cool to room temperature, dried ($MgSO_4$), and solvents removed *in vacuo*. This resulted in a yellow powder which was purified by washing with cold diethyl ether. Product was obtained as a yellow powder. Yield 0.60 g, 28 %. $[\alpha]^{20}_D$ -612 (*c* 0.08 g/100mL, CH_2Cl_2); $\delta_H(CDCl_3)$ -0.41 (2H, q, *J* 8.4 Hz, $AlCH_2$), 0.74 (3H, t, *J* 8.4 Hz, CH_3), 1.30 (18H, s, 2 x ^{t}Bu), 1.56 (18H, s, 2 x ^{t}Bu), 2-2.6 (8H, m, -$(CH_2)_4$-), 3.0-3.1 (1H, m, CH), 3.4-3.6 (1H, m, CH), 6.95 (1H, d *J* 2.2 Hz, ArH), 7.01 (1H, d *J* 2.2 Hz, ArH), 7.45 (2H, d *J* 2.8 Hz, 2 x ArH), 8.14 (1H, d *J* 1.4 Hz, CHN), 8.31 (1H, d *J* 1.4 Hz, CHN).

*Preparation of monometallic catalyst **21**[108,109]:*



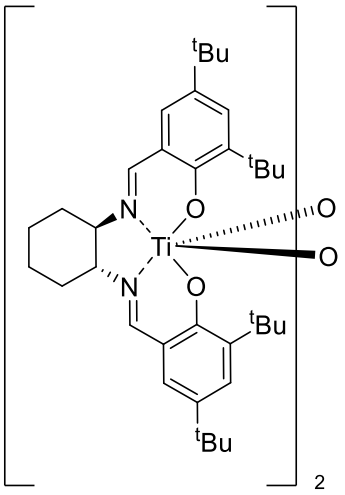
A mixture of salen ligand **8b** (1.0 g, 1.8 mmol) and aluminium ethoxide (0.29 g, 1.8 mmol) dissolved in toluene (80 mL) heated to reflux. This was then stirred for 16 hours, after which it was allowed to cool to room temperature. The solvent was then removed *in vacuo* to yield the crude product as a yellow solid. Impurities were removed by washing with hexane to give a bright yellow solid. Yield 37 %. $\delta_H(CDCl_3)$ 0.85 (3H, t, *J* 8.3 Hz, CH_3), 3.45 (2H, m, CH_2), 1.29 (9H, d, *J* 7.1 Hz, ^{t}Bu), 1.53 (9H, d, *J* 7.1 Hz, ^{t}Bu), 1.5-3.8 (8H, m, -(-CH_2)$_4$-), 6.99 (1H, s, ArH), 7.04 (1H, s, ArH), 7.47 (1H, s, ArH), 7.50 (1H, s, ArH), 8.15 (1H, d *J* 1.6 Hz, CHN), 8.35 (1H, d *J* 1.3 Hz, CHN).

*Preparation of monometallic titanium salen complex **59**[110]:*



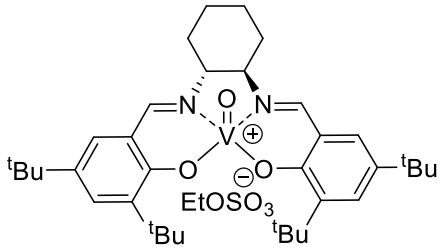
A solution of titanium tetrachloride (1.0 M in CH_2Cl_2, 2 mL) was added dropwise to a solution of **8b** (1 g) in CH_2Cl_2 (20 mL). The mixture turned dark red immediately, was stirred for 1 hour and the solvent evaporated *in vacuo*. Ether (60 mL) was added to the resulting red/brown residue, stirred and decanted. This process was repeated once more with ether then with 1/1 ether / hexane (40 mL). The residue was then dried *in vacuo*. Product was obtained as a rusty red powder. $\delta_H(CDCl_3)$ 1.35 (18H, s, 2 x ^{t}Bu), 1.4-1.7 (4H, m, 2 x CH_2), 1.55 (18H, m, 2 x ^{t}Bu), 2.0-2.1 (2H, m, CH_2), 2.5-2.7 (2H, m, CH_2), 4.0-4.1 (2H, m, CH_2), 7.35 (2H, d *J* 2.3 Hz, 2 x ArH), 7.61 (2H, d *J* 2.3 Hz, 2 x ArH), 8.32 (2H, s, 2 x CHN).

*Preparation of monometallic titanium salen complex **57**[97c]:*



Sodium phosphate buffer (1.2 g of $NaH_2PO_4.2H_2O$, 1.75 g of Na_2HPO_4 per 200mL H_2O, 100 mL) was added to a solution of **59** (1 g, 1.51 mmol) in CH_2Cl_2 (75 mL). This biphasic mixture was stirred vigorously for 1 hour. The buffer was decanted and replaced by a fresh portion (100 mL) with further stirring for 1 hour. The dark red / brown solution turned yellow. The buffer was decanted again, and the organic phase washed with H_2O (2 x 100 mL), dried ($MgSO_4$) and evaporated. Product was obtained as a yellow / orange solid. $\delta_H(CDCl_3)$ 1.04 (9H, s, ^tBu), 1.21 (9H, s, ^tBu), 1.31 (9H, s, ^tBu), 1.40 (9H, s, ^tBu), 1.4-1.9 (16H, m, 2 x $-(CH_2)_4-$), 2.3-2.4 (2H, m, 2 x CH), 2.6-2.7 (2H, m, 2 x CH), 6.99 (2H, s, 2 x ArH), 7.08 (2H, s, 2 x ArH), 7.25 (2H, s, 2 x ArH), 7.44 (2H, s, 2 x ArH), 7.52 (2H, s, 2 x CHN), 8.06 (2H, s, 2 x CHN).

*Preparation of vanadium salen complex **56d**[97c]:*



Vanadyl sulphate hydrate (327 mg, 201 mmol) was added to ethanol (30 mL) and heated to aid dissolution. This solution was then added to a solution of **8b** (1 g, 1.83 mmol) in ethanol (20 mL). This mixture was then stirred for 3 hours, under reflux, at which point a dark green solution formed. The ethanol was then evaporated *in vacuo* and the residue was dissolved in CH_2Cl_2 (20 mL). The product was purified by flash column chromatography by eluting with CH_2Cl_2 (150 mL), followed by 2 : 1 ethyl acetate / methanol (200 mL). The dark green fractions were combined and evaporated to give the product as a dark green solid. $\delta_H(CDCl_3)$ 1.29 (9H, s, ^{t}Bu), 1.54 (9H, s, ^{t}Bu), 1.7-2.2 (8H, m, -$(CH_2)_4$-) 3.9-4.0 (1H, m, CH), 4.3-4.4 (1H, m, CH), 7.42 (1H, s, ArH), 7.47 (1H, s, ArH), 7.65 (1H, s, ArH), 7.69 (1H, s, ArH), 8.54 (1H, s, CHN), 8.66 (1H, s, CHN).

3.4 Cyanohydrins

General procedure for synthesis of cyanohydrins

An aldehyde (0.98 mmol) was added to solution of catalyst (0.0192 mmol) in dry toluene (3 mL) at room temperature, and this was then cooled to the desired reaction temperate using a cryostat and Dewar vessel. Once cooled, trimethylsilyl cyanide (0.15 mL, 1.12 mmol) was added and the reaction left (1-48 hours). The solution was passed through a short silica plug, eluting with CH_2Cl_2. The solvent was evaporated and the

residue analysed by ^{1}H NMR to determine the conversion. The residue was then dissolved in MeCN (1 mL) and $Sc(OTf)_3$ (5 mg, 0.01mmol) and acetic anhydride (0.2 mL, 2.1 mmol) were added. After 20 minutes, the reaction mixture was passed through a short silica plug eluting with MeCN. The resulting solution was used for analysis by GC, for determination of the enantioselectivity.

Chiral Gas Chromatographic Enantiomeric Analysis

Method 1: Initial temperature 95°C, hold for 2 minutes, then ramp at a rate of 3°C per minute to 180°C, then hold for a further 5 minutes. Flow rate: 2 mL/min.

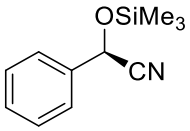
Method 2: Initial temperature 95°C, hold for 2 minutes, then ramp at a rate of 5°C per minute to 180°C, then hold for a further 5 minutes. Flow rate: 1 mL/min.

Method 3: Initial temperature 95°C, hold for 2 minutes, then ramp at a rate of 2°C per minute to 180°C, then hold for a further 5 minutes. Flow rate: 2 mL/min.

Method 4: Initial temperature 95°C, hold for 2 minutes, then ramp at a rate of 0.5°C per minute to 180°C, then hold for a further 5 minutes. Flow rate: 2 mL/min.

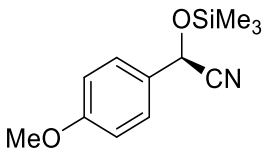
Method 5: Initial temperature 100°C, hold for 5 minutes, then ramp at a rate of 1°C per minute to 180°C, then hold for a further 5 minutes. Flow rate: 2 mL/min.

Preparation of cyanohydrin compound ***50a***[100b,111]*:*



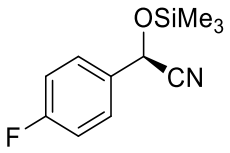
$\delta_H(CDCl_3)$ 0.25 (9H, s, $SiMe_3$), 5.51 (1H, s, CHCN), 7.36-7.52 (5H, m, ArH); enantiomeric determination of corresponding acetate by GC method 1: R_t(R) 19.3 min, R_t(S) 16.6 min.

Preparation of cyanohydrin compound ***50b***[100b,111]*:*



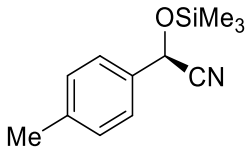
$\delta_H(CDCl_3)$ 0.22 (9H, s, $SiMe_3$), 3.83 (3H, s, OCH_3), 5.45 (1H, s, CHCN), 6.93 (2H, d *J* 8.6 Hz, ArH), 7.40 (2H, d *J* 8.6 Hz, ArH);

Preparation of cyanohydrin compound ***50c***[100b]*:*



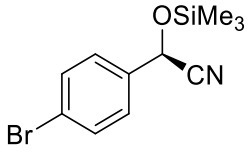
$\delta_H(CDCl_3)$ 0.26 (9H, s, $SiMe_3$), 5.50 (1H, s, CHCN), 7.06-7.18 (2H, m, ArH), 7.42-7.54 (2H, m, ArH); enantiomeric determination of corresponding acetate by GC method 3: R_t(R) 16.9 min, R_t(S) 17.2 min.

Preparation of cyanohydrin compound ***50d***[100b,111]*:*



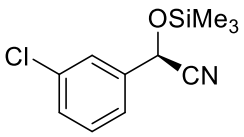
$\delta_H(CDCl_3)$ 0.24 (9H, s, $SiMe_3$), 2.38 (3H, s, CH_3), 5.47 (1H, s, CHCN), 7.23 (2H, d *J* 8.1 Hz, ArH), 7.37 (2H, d *J* 8.1 Hz, ArH); enantiomeric determination of corresponding acetate by GC method 2: R_t(R) 29.0 min, R_t(S) 29.5 min.

Preparation of cyanohydrin compound ***50e***[112]*:*



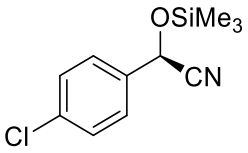
$\delta_H(CDCl_3)$ 0.24 (9H, s, $SiMe_3$), 5.45 (1H, s, CHCN), 7.35 (2H, d *J* 8.3 Hz, ArH), 7.55 (2H, d *J* 8.3 Hz, ArH); enantiomeric determination of corresponding acetate by GC method 3: R_t(R) 34 min, R_t(S) 34.6 min.

Preparation of cyanohydrin compound ***50f***[100b]*:*



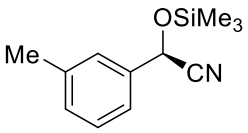
$\delta_H(CDCl_3)$ 0.26 (9H, s, $SiMe_3$), 5.48 (1H, s, CHCN), 7.32-7.40 (4H, m, ArH); 7.45-7.54 (1H, m, ArH); enantiomeric determination of corresponding acetate by GC method 4: R_t(R) 76.7 min, R_t(S) 78.4 min.

Preparation of cyanohydrin compound ***50g***[100b]*:*



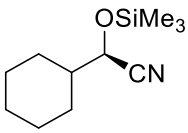
$\delta_H(CDCl_3)$ 0.25 (9H, s, $SiMe_3$), 5.48 (1H, s, CHCN), 7.32-7.48 (4H, m, ArH); enantiomeric determination of corresponding acetate by GC method 3: R_t(R) 34 min, R_t(S) 34.6 min.

Preparation of cyanohydrin compound ***50h***[100b,111]*:*



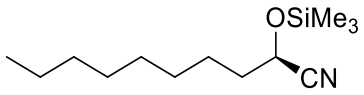
$\delta_H(CDCl_3)$ 0.26 (9H, s, $SiMe_3$), 2.41 (3H, s, CH_3), 5.49 (1H, s, CHCN), 7.18-7.25 (1H, m, ArH); 7.25-7.37 (3H, m, ArH); enantiomeric determination of corresponding acetate by GC method 4: R_t(R) 60.7 min, R_t(S) 62.2 min.

Preparation of cyanohydrin compound ***50i***[113]*:*



$\delta_H(CDCl_3)$ 0.20 (9H, s, $SiMe_3$), 0.95-1.35 (5H, m, 2 x CH_2, CH), 1.6-1.7 (2H, m, CH_2), 1.7-1.9 (4H, m, CH_2), 4.15 (1H, d *J* 6.4 Hz, CHCN); enantiomeric determination of corresponding acetate by GC method 5: R_t(R) 13.3 min, R_t(S) 13.5 min.

*Preparation of cyanohydrin compound **50j**[113]:*



$\delta_H(CDCl_3)$ 0.21 (9H, s, $SiMe_3$), 0.88 (3H, t *J* 6.9 Hz, CH_3), 1.2-1.7 (12H, m, CH_2) 1.78 (2H, q *J* 6.6 Hz, CH_2), 5.38 (1H, t *J* 6.6 Hz, CHCN); enantiomeric determination of corresponding acetate by GC method 5: R_t(R) 15.4 min, R_t(S) 15.6 min.

3.5 Cyclic Carbonates

General procedure for synthesis of cyclic carbonates from carbon dioxide:

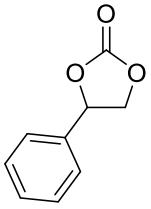
The reaction vessel was charged with a metal salen catalyst (2.5 mol%), TBAB (0-2.5 mol%) and an epoxide and stirred until the contents were a homogeneous mixture. The vessel was then placed in a conical flask, along with dry-ice pellets and this was placed in a thermostatically controlled bath. A rubber stopper was fitted on the top of the conical flask, and was pierced with a balloon and the pressure was allowed to equalise. This mixture was then stirred for a specified period of time, after which an aliquot was removed to determine the conversion and/or the mixture was purified by column chromatography to determine the isolated yield.

General procedure for the synthesis of cyclic carbonates using compressed air:

Epoxide **1a–h** (0.1 mmol), catalyst **10** (2.8 mg, 2.5 x 10^{-3} mmol) and Bu_4NBr (0.75 mg, 2.5 x 10^{-3} mmol) were added to a glass vial fitted with a stirrer bar. The vial was placed in an autoclave, pressurized to 25 bar with compressed air and heated to 50 ^oC. The

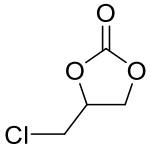
reaction was stirred under these conditions for 24 h, then the reactor was cooled using an acetone/dry ice bath and the pressure released. The reaction mixture was analysed by ^{1}H NMR spectroscopy to determine the conversion of epoxide **1a–h** into cyclic carbonate **9a–h**. In the case of epoxide **1d**, this procedure was carried out a total of 8 times and the reaction mixtures combined to give sufficient material to purify by flash chromatography (eluting with hexane: EtOAc, 8:1 to 1:1) to give cyclic carbonate **9d** (107.0 mg, 67%) as a colourless oil.

*Preparation of cyclic carbonate **9a**[13,114]:*



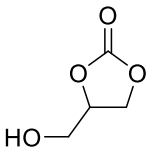
Obtained as a white solid. Mp 51-52 ^{o}C (lit.[13] = 49-52 ^{o}C); δ_H($CDCl_3$) 4.36 (1H, t, *J* 8.4 Hz, CH_2O), 4.82 (1H, t, *J* 8.4 Hz, CH_2O), 5.70 (1H, t, *J* 8.4 Hz, CHO), 7.3-7.5 (5H, m, ArH); δ_C($CDCl_3$) 71.3, 78.1, 126.0, 129.3, 129.8, 135.9, 154.9

*Preparation of cyclic carbonate **9b**[13,115]:*



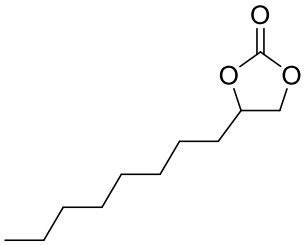
Obtained as a colourless oil. δ_H($CDCl_3$) 3.3-3.8 (2H, m, CH_2Cl), 4.40 (1H, dd *J* 9.0, 8.7 Hz, OCH_2), 4.59 (1H, dd *J* 8.7, 8.4 Hz, OCH_2), 5.0-5.49 (1H, m, OCH).

Preparation of cyclic carbonate ***9c***[13,115]*:*



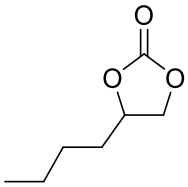
Obtained as a colourless oil. $\delta_H(CDCl_3)$ 3.65 (1H, br, OH), 3.72 (1h, dd, *J* 12.7, 3.5 Hz, CH_2OH), 4.04 (1H, dd, *J* 12.7, 3.5 Hz, CH_2OH), 4.4-4.5 (2H, m, OCH_2), 4.8-4.9 (1H, m, OCH).

Preparation of cyclic carbonate ***9d***[13,115]*:*



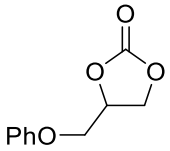
Obtained as a colourless oil. $\delta_H(CDCl_3)$ 0.89 (3H, t *J* 6.9 Hz, CH_3), 1.2–1.6 (12H, m, $(CH_2)_6$), 1.6–1.75 (1H, m, $CHCH_2$), 1.75–1.9 (1H, m, $CHCH_2$), 4.07 (1H, dd *J* 8.3, 7.4 Hz, OCH_2), 4.53 (1H, t *J* 8.3 Hz, OCH_2), 4.71 (1H, ddd *J* 13.0, 7.4, 5.5 Hz, OCH); $\delta_C(CDCl_3)$ 14.0, 22.6, 24.4, 29.0, 29.1, 29.3, 31.8, 33.9, 69.4, 77.0, 155.0; ν_{max}(ATR) 2926, 2856 and 1834 cm^{-1}.

Preparation of cyclic carbonate ***9f***[13,115]*:*



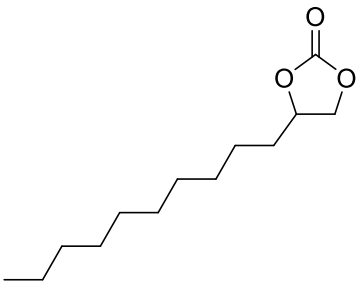
Obtained as a colourless oil in inseparable mixture with corresponding epoxide. $\delta_H(CDCl_3)$ 0.95 (3H, t, *J* 7.1 Hz, CH_3), 1.2-1.6 (4H, m, 2 x CH_2), 1.6-2.0 (2H, m, CH_2), 4.09 (1H, dd, *J* 8.4, 7.6 Hz, OCH_2), 4.46 (1H, t, *J* 7.6 Hz, OCH_2), 4.64 (1H, qd, *J* 7.6, 5.4 Hz, OCH).

Preparation of cyclic carbonate ***9h***[13,115]*:*



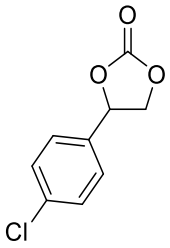
Obtained as a colourless oil in inseparable mixture with corresponding epoxide. $\delta_H(CDCl_3)$ 4.14 (1H, dd, *J* 10.6, 3.9 Hz, CH_2OPh), 4.24 (1H, dd, *J* 10.6, 3.9 Hz, CH_2OPh), 4.5-4.7 2H, m, OCH_2), 5.03 (1H, m, OCH), 6.6-7.0 (2H, m, ArH), 7.01 (1H, t, *J* 7.6 Hz, ArH), 7.3-7.4 (2H, m, ArH).

Preparation of cyclic carbonate ***9j***[ref]*:*



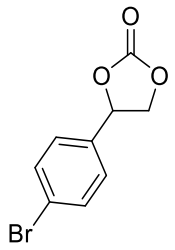
Obtained as a colourless oil in inseparable mixture with corresponding epoxide. $\delta_H(CDCl_3)$ 0.82 (3H, t, *J* 7.0 Hz, CH_3) 1.2-1.8 (18H, m, 9 x CH_2) 4.11 (1H, dd, *J* = 7.8, 8.4 Hz, CH), 4.54 (1H, t, *J* = 7.8 Hz, CH), 4.4-4.6 (1H, m, CH).

Preparation of cyclic carbonate ***9k***[13,116]*:*



Obtained as a colourless oil in inseparable mixture with corresponding epoxide. $\delta_H(CDCl_3)$ 4.3 (1H, t, *J* 8.4 Hz, OCH_2), 4.80 (1H, t, *J* 8.4 Hz, OCH_2), 5.66 (1H, t, *J* 8.4 Hz, OCH), 7.30 (2H, dd *J* 6.7, 1.8 Hz, ArH), 7.45 (2H, dd, *J* 6.7, 1.8 Hz, ArH).

Preparation of cyclic carbonate ***9l***[13,117]*:*



Obtained as a colourless oil in inseparable mixture with corresponding epoxide. $\delta_H(CDCl_3)$ 4.32 (1H, t, *J* 8.5 Hz, OCH_2), 4.83 (1H, t, *J* 8.5 Hz, OCH_2), 5.66 (1H, t *J* 7.8 Hz, CH), 7.27 (2H, dd *J* 8.2, 1.8 Hz, ArH), 7.61 (2H, dd, *J* 8.2, 1.8 Hz, ArH).

3.6 Thiocarbonates

General procedures for synthesis of cyclic di- and trithiocarbonates:

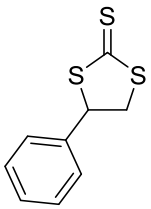
Reactions catalysed by complex **13a**/**47**/**57** and TBAB:

CS_2 (0.09 mL, 1.49 mmol), an epoxide (0.835 mmol), metal salen catalyst **13a/47/57** (0.5–5 mol%), and Bu_4NBr (0.5 – 5 mol%, 1.4 – 14 mg, 0.00417 – 0.0417 mmol) were placed in a sealed Young flask and stirred at 90^{o}C for 24 h. The solution was evaporated and, if necessary, the residue purified by column chromatography ($CHCl_3$/hexane 1/1) to give an unseparated mixture of the di- and trithiocarbonate except for **15a** which was obtained as the pure trithiocarbonate and **14b**/**15b** and **14o**/**15o** for which the di- and trithiocarbonates were separable by chromatography. The NMR data for the di- and trithiocarbonate mixtures matched those in the literature.

Reactions catalysed by complex **57** and tributylamine:

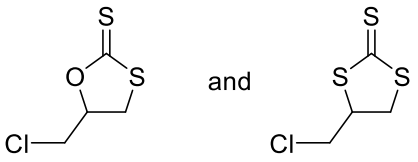
CS_2 (0.09 mL, 1.49 mmol), an epoxide (0.835 mmol), catalyst **57** (1 mol%, 10 mg, 0.00835 mmol), and Bu_3N (1 mol%, 1.5 mg, 0.00835 mmol) were placed in a sealed Young flask and stirred at 90°C for 24 h. The solution was evaporated and, if necessary, the residue purified by column chromatography ($CHCl_3$/hexane 1/1) to give an unseparated mixture of the di- and trithiocarbonate except for **15a** which was obtained as the pure trithiocarbonate.

*Preparation of trithiocarbonate **15a**[27]:*



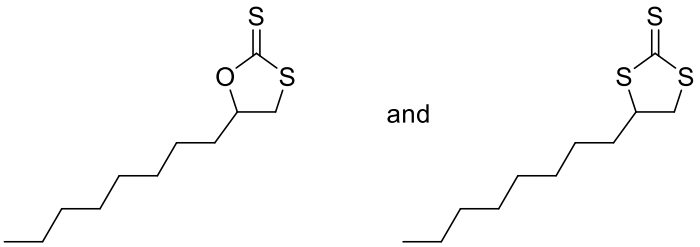
Obtained as a yellow solid. Mp 83-84 °C (lit.[27] 85–86 °C); $\delta_H(CDCl_3)$ 4.05 (1H, dd *J* 12.0, 6.0 Hz, CH_2), 4.20 (1H, dd *J* 12.0, 6.0 Hz, CH_2), 5.67 (1H, dd *J* 12.0, 6.0 Hz, CHS), 7.2–7.6 (5H, m, ArH); $\delta_C(CDCl_3)$ 49.6, 64.0, 127.4, 129.0, 129.1, 135.0, 227.2; ν_{max}(ATR) 3050 (m), 2918 (w), 1487 (s) and 1451 cm^{-1} (s).

*Preparation of dithiocarbonate **14b** and trithiocarbonate **15b**[27]:*



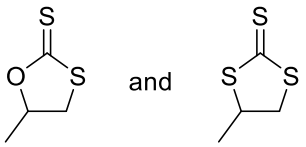
14b and **15b** obtained in an inseparable mixture as a yellow oil. $\delta_H(CDCl_3)$ 3.60 (1H, dd *J* 11.1, 6.9 Hz, ClCH, **15b**), 3.65 (1H, dd *J* 11.1, 7.0 Hz, ClCH, **14b**), 3.68 (1H, dd *J* 11.1, 6.9 Hz, ClCH, **15b**), 3.72 (1H, dd *J* 11.1, 7.0 Hz, ClCH **14b**), 3.82 (2H, d *J* 6.9 Hz, SCH, **15b**), 3.90 (2H, d *J* 7.0 Hz, SCH, **14b**), 4.8-4.9 (1H, m, OCH, **15b**), 5.2-5.4 (1H, m, OCH, **14b**).

*Preparation of dithiocarbonate **14d** and trithiocarbonate **15d**[27]:*



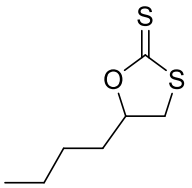
14d and **15d** obtained in an inseparable mixture as a yellow oil. $\delta_H(CDCl_3)$ 0.90 (3H, t *J* 5.9 Hz, CH_3, **14d** and **15d**), 1.2-1.6 (14H, m, CH, **14d** and **15d**), 1.8-2.1 (2H, m, CH_2, **14d** and **15d**) 3.41 (1H, dd *J* 8.9 Hz, 11.8 Hz, CH, **14d**), 3.60 (1H, dd *J* 8.9, 11.8 Hz, CH, **14d**), 3.73 (1H, dd *J* 9.3 Hz, 12.3 Hz, CH, **15d**), 4.00 (1H, dd *J* 9.3, 12.3 Hz, CH, **15d**), 4.4-4.5 (1H, m, CH, **15d**), 5.1-5.2 (1H, m, CH, **14d**).

*Preparation of dithiocarbonate **14e** and trithiocarbonate **15e**[27]:*



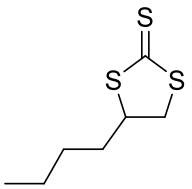
14e and **15e** obtained in an inseparable mixture as a yellow oil. $\delta_H(CDCl_3)$ 1.66 (3H, dd *J* 5.6, 3.2 Hz, CH_3, **14e** and **15e**), 3.39 (1H, dd *J* 5.6 Hz, 8.7 Hz, CH, **14e**), 3.66 (1H, dd *J* 8.7 Hz, 5.6 Hz, CH, **14e**), 3.70 (1H, dd *J* 11.5, 6.3 Hz, CH, **15e**), 4.01 (1H, dd *J* 11.5, 6.3 Hz, CH, **15e**), 4.5-4.6 (1H, m, CH, **15e**), 5.2-5.3 (1H, m, CH, **14e**).

*Preparation of dithiocarbonate **14f**[27]:*



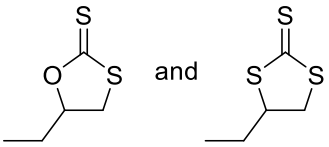
Obtained as a yellow oil. $\delta_H(CDCl_3)$ 0.87 (3H, t *J* 6.7 Hz, CH_3), 1.2-1.4 (4H, m, 2 x CH_2), 1.4-1.5 (1H, m, CH_2), 1.7-1.8 (1H, m, CH_2CH), 1.9-2.0 (1H, m, CH_2CH), 3.35 (1H, dd *J* 10.5, 6.3 Hz, CH_2S), 3.52 (1H, dd *J* 10.5, 6.3 Hz, CH_2S), 5.0-5.1 (1H, m, CHO); $\delta_C(CDCl_3)$ 13.8, 22.3, 27.4, 33.4, 39.3, 91.8, 212.1; ν_{max}(ATR) 2932 (m), 2861 (w) and 1647 cm^{-1} (w).

*Preparation of trithiocarbonate **15f**[27]:*



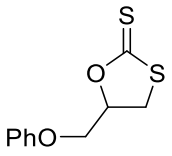
Obtained as a yellow oil. $\delta_H(CDCl_3)$ 0.86 (3H, t *J* 6.7 Hz, CH_3), 1.2-1.4 (4H, m, 2 x CH_2), 1.7-2.0 (2H, m, CH_2), 3.64 (1H, dd *J* 11.9, 8.0 Hz, CH_2S), 3.90 (1H, dd *J* 11.9, 8.0 Hz, CH_2S), 4.2-4.4 (1H, m, CHS); $\delta_C(CDCl_3)$ 13.8, 22.3, 30.3, 33.2, 48.2, 60.9, 227.9; ν_{max}(ATR) 2932 (m), 2861 (w) and 1350 cm^{-1} (m).

*Preparation of dithiocarbonate **14g** and trithiocarbonate **15g**[27]:*



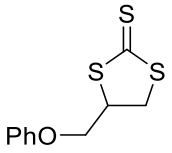
14g and **15g** obtained in an inseparable mixture as a yellow oil. $\delta_H(CDCl_3)$ 1.11 (3H, t *J* 9.0 Hz, CH_3, **14g** and **15g**), 1.8-2.2 (2H, m, CH_2, **14g**), 3.42 (1H, dd *J* 11.9, 8.9 Hz, CH, **14g**), 3.61 (1H, dd *J* 8.9, 5.9 Hz, CH, **14g**), 3.73 (1H, dd *J* 11.9 Hz, 6.1 Hz, CH, **15g**), 4.01 (1H, dd *J* 11.9 Hz, 6.1 Hz, CH, **15g**), 4.3-4.4 (1H, m, CH, **15g**), 5.1-5.2 (1H, m, CH, **14g**).

*Preparation of dithiocarbonate **14h**[27]:*



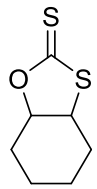
Obtained as a yellow oil. δ_H ($CDCl_3$) 3.67 (1H, dd *J* 11.2, 7.5 Hz, $ArOCH_2$), 3.74 (1H, dd *J* 11.2, 7.5 Hz, $ArOCH_2$), 4.22 (1H, dd *J* 10.3, 5.6 Hz, SCH_2), 4.26 (1H, dd *J* 10.3, 5.6 Hz, SCH_2), 5.3-5.5 (1H, m, OCH), 6.8-6.9 (2H, m, ArH), 6.9-7.0 (1H, m, ArH), 7.2-7.3 (2H, m, ArH); δ_C ($CDCl_3$) 36.3, 66.2, 87.7, 114.5, 121.9, 129.7, 157.7, 211.3; ν_{max} 2925 (w), 1597 (m), 1493 (m) and 1184 cm^{-1}.

*Preparation of trithiocarbonate **15h**[27]:*



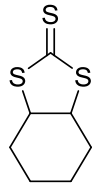
Obtained as a yellow oil. δ_H($CDCl_3$) 4.00 (1H, dd *J* 12.2, 5.4 Hz, $ArOCH_2$), 4.11 (1H, dd *J* 9.0, 5.4 Hz, $ArOCH_2$), 4.15 (1H, dd *J* 9.8, 5.4 Hz, SCH_2), 4.29 (1H, t *J* 9.8 Hz, SCH_2), 4.5-4.7 (1H, m, SCH), 6.8-6.9 (2H, m, ArH), 6.9-7.0 (1H, m, ArH), 7.2-7.3 (2H, m, ArH); δ_C 44.9, 57.2, 66.5, 114.6, 121.8, 129.7, 157.7, 226.4; ν_{max}(ATR) 2936 (w), 1598 (m), 1488 (m), 1461 (m) and 1033 cm^{-1} (s).

*Preparation of dithiocarbonate **14i**[27]:*



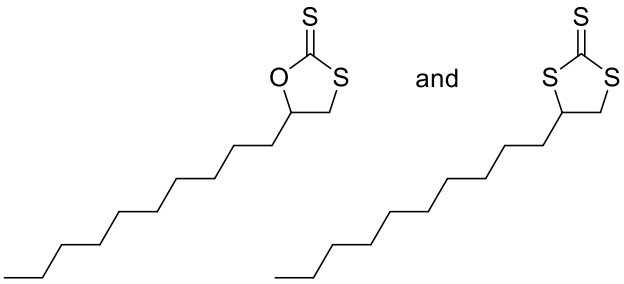
Obtained as a yellow solid. Mp 60–61 °C (lit.[27] 63–64 °C); $\delta_H(CDCl_3)$ 1.3-1.5 (2H, m, CH_2), 1.5-1.7 (1H, m, CH_2), 1.7-1.8 (1H, m, CH_2), 1.8-2.0 (2H, m, CH_2), 2.1-2.3 (1H, m, CH_2), 2.4-2.5 (1H, m, CH_2), 3.71 (1H, td *J* 11.9, 3.6 Hz, CHS), 4.33 (1H, td *J* 11.9, 3.6 Hz, CHO); $\delta_C(CDCl_3)$ 23.7, 25.1, 28.3, 29.8, 56.4, 94.7, 212.5; ν_{max}(ATR) 2940 (m), 2860 (m) and 1447 cm^{-1} (m).

*Preparation of trithiocarbonate **15i**[27]:*



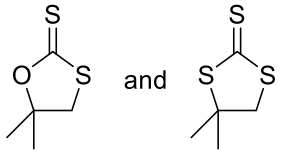
Obtained as a yellow solid. Mp 165–166 °C (lit.[27] 163–164 °C); $\delta_H(CDCl_3)$ 1.4-1.5 (2H, m, CH_2), 1.6-1.8 (2H, m, CH_2), 1.9-2.0 (2H, m, CH_2), 2.1-2.3 (2H, m, CH_2), 4.0-4.2 (2H, m, 2 x CH); $\delta_C(CDCl_3)$ 24.9, 29.0, 64.4, 227.1; ν_{max}(ATR) 2940 (m), 2859 (m) and 1643 cm^{-1}.

*Preparation of dithiocarbonate **14j** and trithiocarbonate **15j**[27]:*



14g and **15g** obtained in an inseparable mixture as a yellow oil. $\delta_H(CDCl_3)$ 0.9 (3H, t *J* 6.1 Hz, CH_3, **14g** and **15g**), 1.2-1.6 (16H, m, 8 x CH_2, **14g** and **15g**), 1.8-2.1 (2H, m, CH_2, **14g** and **15g**), 3.41 (1H, dd *J* 8.9, 12.0 Hz, CH, **14g**), 3.60 (1H, dd *J* 5.9, 9.2 Hz, CH, **14g**), 3.71 (1H, dd *J* 8.7, 12.1 Hz, CH, **15g**), 3.98 (1H, dd *J* 5.9, 11.2 Hz, CH, **15g**), 4.4-4.5 (1H, m, CH, **15g**), 5.1-5.2 (1H, m, CH, **14g**).

*Preparation of dithiocarbonate **14o** and trithiocarbonate **15o**[27]:*



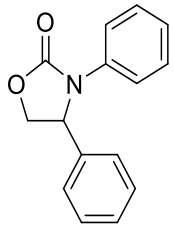
14o and **15o** obtained in an inseparable mixture as a yellow oil. $\delta_H(CDCl_3)$ 1.52 (6H, s, 2 x CH_3, **14o**), 1.61 (6H, s, 2 x CH_3, **15o**), 3.30 (2H, s, CH_2, **14o**), 3.40 (2H, s, CH_2, **15o**).

3.7 Oxazolidinones

General procedure for synthesis of oxazolidinones:

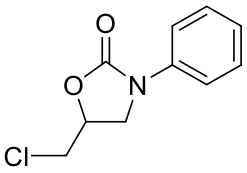
To a stirred solution of complex **56d** (0.00835–0.0418 mmol) and a cocatalyst (0.00835–0.0418 mmol) in toluene (0.5-2 ml) was added an epoxide (0.835 mmol) and isocyanate (0.835 mmol). The reaction was then heated to 80 °C and stirred for 5-24 hours. The reaction was cooled to room temperature and solvent removed in vacuo. CH_2Cl_2 (5 ml) was added to the residue and the mixture filtered through silica, washing with additional CH_2Cl_2 (5 ml) and the solvent was removed in vacuo. The conversion and ratio of regioisomeric oxazolidinones was determined by ^{1}H NMR spectroscopy, then the residue was purified as described for each compound below.

*Preparation of oxazolidinone **24a**[90,118]:*



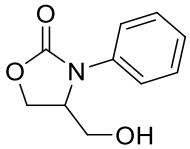
Obtained as a white solid after purification by flash chromatography using CH_2Cl_2:hexane (85:15) as solvent. Mp 128–129 ^{o}C (lit.[90] 128–129 °C); $\delta_H(CDCl_3)$ 4.22 (1H, dd *J* 8.7, 6.0 Hz, CH_2), 4.81 (1H, t *J* 8.7 Hz, CH_2), 5.42 (1H, dd *J* 8.7, 6.0 Hz, CH), 7.10 (1H, t *J* 7.4 Hz, ArH), 7.2–7.5 (9H, m, ArH); $\delta_C(CDCl_3)$ 60.9, 69.8, 121.0, 124.7, 126.3, 128.8, 128.9, 129.3, 137.3, 138.6, 155.8; ν_{max}(ATR) 1596, 1705, 1750, 2889, 2981, 3065 cm^{-1}.

Preparation of oxazolidinone ***23b***[90,118]*:*



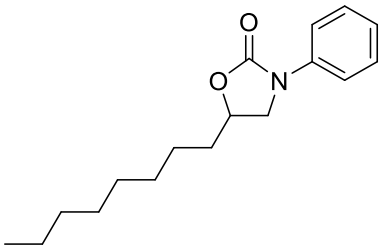
Obtained as a white solid after washing with Et_2O. mp 104–105 ^oC (lit.[90] 104–105 °C); $\delta_H(CDCl_3)$ 3.74 (1H, dd *J* 11.6, 6.6 Hz, CH_2Cl), 3.79 (1H, dd *J* 11.6, 4.2 Hz, CH_2Cl), 3.96 (1H, dd, *J* 9.0, 5.7 Hz, CH_2N), 4.17 (1H, t, *J* 9.0 Hz, CH_2N), 4.88 (1H, dddd, *J* 8.7, 6.5, 5.7, 4.1 Hz, CH), 7.17 (1H, t *J* 7.4, 1.1 Hz, ArH), 7.3–7.6 (4H, m, ArH); $\delta_C(CDCl_3)$ 44.5, 48.3, 70.9, 118.6, 124.4, 129.1, 138.0, 153.9; ν_{max}(ATR) 1599, 1734, 2917, 2981, 3040 cm^{-1}.

Preparation of oxazolidinone ***23c***[90,101a]*:*



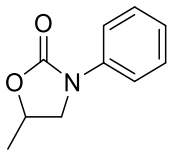
Obtained as a white solid after purification by flash chromatography using CH_2Cl_2 as solvent. mp 110–112 ^oC (lit.[90] 109–111 °C); $\delta_H(CDCl_3)$ 2.71 (1H, dd *J* 4.7, 2.6 Hz, CH_2O), 2.89 (1H, t *J* 4.7 Hz, CH_2O), 3.29 (1H, ddt *J* 6.6, 4.7, 2.8 Hz, CHN), 3.97 (1H, dd *J* 12.2, 6.6 Hz, CH_2O), 4.58 (1H, dd *J* 12.2, 2.8 Hz, CH_2O), 6.9–7.1 (2H, m, ArH + OH), 7.2–7.5 (4H, m, ArH); $\delta_C(CDCl_3)$ 44.6, 49.5, 65.8, 119.1, 123.8, 129.1, 137.7, 153.1; ν_{max}(ATR) 1599, 1737, 2889, 2981, 3082, 3137, 3271 cm^{-1}.

Preparation of oxazolidinone ***23d***[90,119]*:*



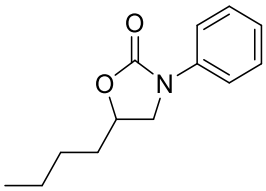
Obtained as a beige coloured solid after purification by flash chromatography using CH_2Cl_2:hexane (75:25) as solvent. mp 71–72 ^oC (lit.[90] 70–71 °C); $\delta_H(CDCl_3)$ 0.87 (3H, t *J* 6.9 Hz, CH_3), 1.2–1.6 (12H, m, $(CH_2)_6Me$), 1.6–1.8 (1H, m, CH_2), 1.8–2.0 (1H, m, CH_2), 3.64 (1H, dd *J* 8.6, 7.2 Hz, CH_2N), 4.07 (1H, t *J* 8.6 Hz, CH_2N), 4.6–4.7 (1H, m, CH), 7.14 (1H, tt *J* 7.3, 1.2 Hz, ArH), 7.3–7.5 (2H, m, ArH), 7.5–7.6 (2H, m, ArH); $\delta_C(CDCl_3)$ 13.9, 22.6, 24.6, 29.1, 29.3, 29.4, 31.8, 35.1, 50.7, 73.1, 118.4, 123.9, 129.0, 138.7, 154.9; ν_{max}(ATR) 1594, 1706, 2889, 2981 cm^{-1}.

Preparation of oxazolidinone ***23e***[31,90]*:*



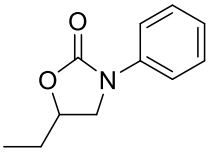
Obtained as a white solid after purification by flash chromatography using CH_2Cl_2:hexane (75:25) as solvent. mp 78–80 ^oC (lit.[90] 79–82 °C); $\delta_H(CDCl_3)$ 1.51 (3H, d *J* 6.3 Hz, CH_3), 3.60 (1H, dd *J* 8.7, 7.1 Hz, CH_2), 4.09 (1H, t *J* 8.7 Hz, CH_2), 4.6–4.8 (1H, m, CH), 7.11 (1H, t *J* 7.4 Hz, ArH), 7.36 (2H, t *J* 8.1 Hz, ArH), 7.51 (2H, dd *J* 8.7, 1.0 Hz, ArH); $\delta_C(CDCl_3)$ 20.7, 52.1, 69.5, 118.5, 124.1, 129.1, 138.6, 154.9; ν_{max}(ATR) 1599, 1670, 1740, 2884, 2981, 3036 cm^{-1}.

Preparation of oxazolidinone ***23f***[29b,90]*:*



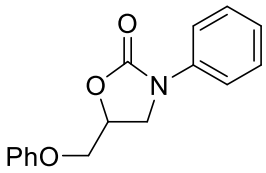
Obtained as a cream coloured solid after purification by flash chromatography using CH_2Cl_2:hexane (75:25) as solvent. mp 62–63 ^oC (lit.[90] 65–66 °C); $\delta_H(CDCl_3)$ 0.96 (3H, t *J* 7.2 Hz, CH_3); 1.3–1.6 (4H, m, CH_2CH_2Me), 1.7–1.8 (1H, m, CH_2), 1.8–2.0 (1H, m, CH_2), 3.66 (1H, dd *J* 8.8, 7.2 Hz, CH_2N), 4.09 (1H, t *J* 8.8 Hz, CH_2N), 4.5–4.7 (1H, m, CH), 7.14 (1H, tt *J* 7.4, 1.1 Hz, ArH), 7.39 (2H, t *J* 8.7 Hz, ArH), 7.56 (2H, dd *J* 8.7, 1.1 Hz, ArH); $\delta_C(CDCl_3)$13.8, 22.4, 26.7, 34.8, 50.7, 73.1, 118.4, 124.0, 128.0, 138.7, 154.9; ν_{max}(ATR) 1597, 1703, 1741, 2880, 2930, 2981, 3064 cm^{-1}.

Preparation of oxazolidinone ***23g***[46,90]*:*



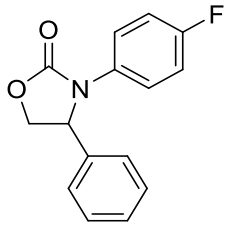
Obtained as a colourless oil after purification by flash chromatography using CH_2Cl_2:hexane (75:25) as solvent. $\delta_H(CDCl_3)$ 1.07 (3H, t *J* 7.5, CH_3), 1.7–2.0 (2H, m, $MeCH_2$), 3.65 (1H, dd *J* 8.7, 7.1 Hz, NCH_2), 4.07 (1H, t *J* 8.7 Hz, NCH_2), 4.5–4.7 (1H, m, CH), 7.13 (1H, t *J* 7.4 Hz, ArH), 7.38 (2H, t *J* 8.7 Hz, ArH), 7.57 (2H, dd *J* 7.4, 1.0 Hz, ArH); $\delta_C(CDCl_3)$ 8.7, 27.9, 49.9, 74.0, 118.0, 123.8, 128.9, 138.3, 154.9; ν_{max}(ATR) 1597, 1703, 1738, 2970, 3038 cm^{-1}.

Preparation of oxazolidinone ***23h***[54,72,90]*:*



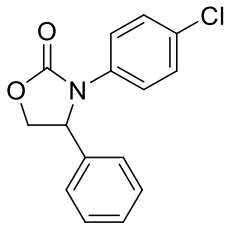
Obtained as a white solid after washing with Et_2O. Mp 139–140 ^oC (lit.[90] 139–140 °C); $\delta_H(CDCl_3)$ 4.06 (1H, dd *J* 8.9, 5.9 Hz, CH_2N), 4.1–4.3 (3H, m, CH_2O + CH_2N), 4.9–5.0 (1H, m, CH), 6.93 (2H, d *J* 7.3 Hz, ArH), 7.02 (1H, t *J* 7.3 Hz, ArH), 7.18 (1H, t *J* 7.3 Hz, ArH), 7.33 (2H, t *J* 7.3 Hz, ArH), 7.41 (2H, t *J* 8.5 Hz, ArH), 7.60 (2H, d *J* 7.7 Hz, ArH); $\delta_C(CDCl_3)$ 47.7, 68.4, 70.5, 115.0, 118.6, 122.0, 124.3, 129.1, 129.7, 138.4, 154.3, 158.3; ν_{max}(ATR) 1598, 1736, 2940, 3043 cm^{-1}.

Preparation of oxazolidinone ***24i***[90]*:*



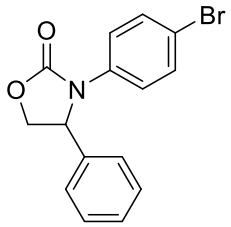
Obtained as a cream coloured solid after purification by flash chromatography using CH_2Cl_2:hexane (85:15) as solvent. mp 91–92 ^oC (lit.[90] 94–97 °C); $\delta_H(CDCl_3)$ 4.21 (1H, dd *J* 8.7, 6.3 Hz, CH_2), 4.78 (1H, t *J* 8.7 Hz, CH_2), 5.36 (1H, dd *J* 8.7, 6.3 Hz, CH), 6.95 (2H, dd *J* 9.2, 8.3 Hz, ArH), 7.2–7.4 (7H, m, ArH); $\delta_C(CDCl_3)$ 61.3, 69.8, 115.8 (d *J* 22 Hz), 116.3, 123.1 (d *J* 8 Hz), 126.4, 129.5, 130.3, 138.2, 156.0, 159.9 (d *J* 243 Hz); ν_{max}(ATR) 1509, 1710, 1744, 2889, 2981 cm^{-1}.

Preparation of oxazolidinone ***23j***[90,118,120]*:*



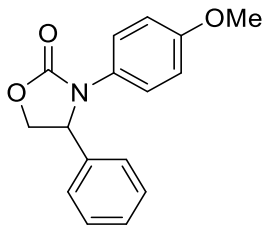
Obtained as a white solid after purification by flash chromatography using CH_2Cl_2:hexane (85:15) as solvent. mp 123–125 ^oC (lit.[90] 126–128 °C); $\delta_H(CDCl_3)$ 4.20 (1H, dd, *J* 8.6, 6.0 Hz, CH_2), 4.77 (1H, t *J* 8.6 Hz, CH_2), 5.35 (1H, dd *J* 8.7, 6.1 Hz, ArH), 7.0–7.5 (9H, m, ArH); $\delta_C(CDCl_3)$ 60.5, 69.7, 121.8, 126.1, 128.9, 129.0, 129.4, 129.8, 135.5, 137.7, 155.7; ν_{max}(ATR) 1597, 1700, 1737, 2960, 3040 cm^{-1}.

Preparation of oxazolidinone ***24k***[90]*:*



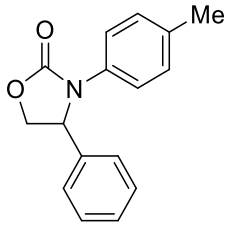
Obtained as a yellow solid after purification by flash chromatography using CH_2Cl_2:hexane (85:15) as solvent. mp 136–137 ^oC (lit.[90] 134–137 °C); $\delta_H(CDCl_3)$ 4.13 (1H, dd, *J* 8.6, 6.0 Hz, CH_2), 4.71 (1H, t *J* 8.6 Hz, CH_2), 5.29 (1H, dd *J* 8.6, 6.0 Hz, CH), 7.0–7.4 (9H, m, ArH); $\delta_C(CDCl_3)$ 60.8, 69.8, 117.7, 122.4, 125.2, 129.0, 129.5, 131.9, 136.5, 138.1, 155.5; ν_{max}(ATR) 1601, 1735, 2909, 2981 cm^{-1}.

Preparation of oxazolidinone ***24l***[90]*:*



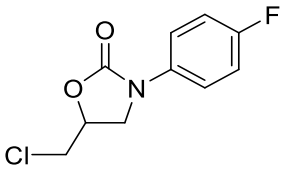
Obtained as a cream coloured solid after purification by flash chromatography using CH_2Cl_2:hexane (85:15) as solvent. mp 103–105 ^oC (lit.[90] 105–107 °C); $\delta_H(CDCl_3)$ 3.79 (3H, s, OCH_3), 3.92 (1H, t *J* 8.6 Hz, CH_2), 4.34 (1H, t *J* 8.8 Hz, CH_2), 5.62 (1H, t *J* 8.6 Hz, CH), 6.90 (2H, d *J* 8.4 Hz, ArH), 7.3–7.5 (7H, m, ArH); $\delta_C(CDCl_3)$ 55.3, 61.4, 69.6, 114.3, 123.3, 126.5, 128.7, 129.2, 130.2, 138.5, 156.2, 157.0; ν_{max}(ATR) 1734, 2923 cm^{-1}.

Preparation of oxazolidinone ***24m***[34a,90]*:*



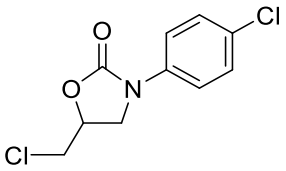
Obtained as a cream coloured solid after purification by flash chromatography using CH_2Cl_2:hexane (85:15) as solvent. mp 104–106 ^oC (lit.[90] 105–107 °C); $\delta_H(CDCl_3)$ 2.25 (3H, s, $ArCH_3$), 4.17 (1H, dd *J* 8.5, 6.0 Hz, CH_2), 4.74 (1H, t *J* 8.7 Hz, CH_2), 5.38 (1H, dd *J* 8.9, 6.2 Hz, CH), 7.06 (2H, d *J* 8.3 Hz, ArH), 7.2–7.6 (7H, m, ArH); $\delta_C(CDCl_3)$ 20.6, 60.9, 69.7, 121.2, 126.2, 128.6, 129.2, 129.4, 134.4, 134.7, 138.6, 155.9; ν_{max}(ATR) 1601, 1738, 2915, 2982, 3040 cm^{-1}.

*Preparation of oxazolidinone **23n**[90]:*



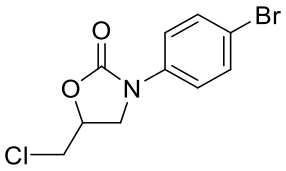
Obtained as a white solid after washing with Et_2O. mp 105–106 °C (lit.[90] 101–104 °C); $\delta_H(CDCl_3)$ 3.77 (1H, dd *J* 11.6, 6.4 Hz, CH_2Cl), 3.84 (1H, dd *J* 11.6, 7.4 Hz, CH_2Cl), 3.97 (1H, dd *J* 9.1, 5.7 Hz, NCH_2), 4.18 (1H, t *J* 9.1 Hz, NCH_2), 4.8–5.0 (1H, m, CH), 7.10 (2H, dd *J* 9.2, 8.2 Hz, ArH), 7.52 (2H, dd *J* 9.2, 4.6 Hz, ArH); $\delta_C(CDCl_3)$ 44.7, 48.1, 70.4, 115.7 (d *J* 22.3 Hz), 120.2, 133.8 (d *J* 5.2 Hz), 154.0, 160.9; ν_{max}(ATR) 1735, 2908, 2982 cm^{-1}.

*Preparation of oxazolidinone **23o**[90]:*



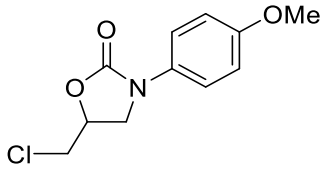
Obtained as a white solid after washing with Et_2O. mp 128–129 °C (lit.[90] 130–133 °C); $\delta_H(CDCl_3)$ 3.74 (1H, dd *J* 11.7, 6.2 Hz, CH_2Cl), 3.78 (1H, dd *J* 11.7, 4.3 Hz, CH_2Cl), 3.91 (1H, dd *J* 9.0, 6.0 Hz, NCH_2), 4.13 (1H, t *J* 9.0 Hz, NCH_2), 4.8–4.9 (1H, m, CH), 7.32 (2H, d *J* 9.0 Hz, ArH), 7.47 (2H, d *J* 9.0 Hz, ArH); $\delta_C(CDCl_3)$ 44.6, 48.1, 71.0, 119.6, 129.0, 129.6, 136.5, 153.7; ν_{max}(ATR) 1598, 1737, 2907, 3040 cm^{-1}.

Preparation of oxazolidinone ***23p***[90,121]*:*



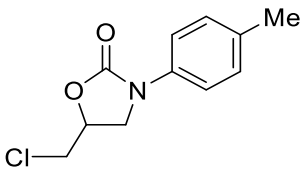
Obtained as a white solid after washing with Et_2O. mp 126–127 °C (lit.[90] 125–127 °C); $\delta_H(CDCl_3)$ 3.75 (1H, dd *J* 11.6, 6.4 Hz, CH_2Cl), 3.83 (1H, dd *J* 11.6, 4.2 Hz, CH_2Cl), 3.96 (1H, dd *J* 9.1, 5.7 Hz, NCH_2), 4.17 (1H, t *J* 9.1 Hz, NCH_2), 4.8–5.0 (1H, m, CH), 7.47 (2H, d *J* 9.1 Hz, ArH), 7.52 (2H, d *J* 9.1 Hz, ArH); $\delta_C(CDCl_3)$ 44.5, 48.0, 70.9, 117.2, 119.9, 132.0, 137.0, 153.6; ν_{max}(ATR) 1637, 1734, 2890, 2981, 3080 cm^{-1}.

Preparation of oxazolidinone ***23q***[90,122]*:*



Obtained as a white solid after washing with Et_2O. mp 103–105 °C (lit.[90] 105–107 °C); $\delta_H(CDCl_3)$ 3.7–3.9 (2H, m, CH_2Cl), 3.78 (3H, s, OCH_3), 3.95 (1H, dd *J* 9.1, 5.7 Hz, NCH_2), 4.16 (1H, t *J* 9.1 Hz, NCH_2), 4.82 (1H, dq *J* 8.8, 5.2 Hz, CH), 6.94 (2H, d *J* 9.1 Hz, ArH), 7.46 (2H, d *J* 9.1 Hz, ArH); $\delta_C(CDCl_3)$ 44.7, 48.7, 55.5, 70.9, 114.4, 120.6, 131.1, 154.1, 156.7; ν_{max}(ATR) 1598, 1731, 2841, 2904, 2973, 3030 cm^{-1}.

*Preparation of oxazolidinone **23r**[90]:*



Obtained as a cream coloured solid after washing with Et_2O. mp 101–103 °C (lit.[90] 104–107 °C); $\delta_H(CDCl_3)$ 2.36 (3H, s, $ArCH_3$), 3.75 (1H, dd, *J* 11.5, 6.6 Hz, CH_2Cl), 3.81 (1H, dd, *J* 11.5, 4.2 Hz, CH_2Cl), 3.96 (1H, dd, *J* 9.1, 5.7 Hz, NCH_2), 4.17 (1H, t *J* 9.1 Hz, NCH_2), 4.86 (1H, dddd, *J* 8.7, 6.6, 5.7, 4.2 Hz, CH), 7.21 (2H, d *J* 8.1 Hz, ArH), 7.44 (2H, d *J* 8.5 Hz, ArH); $\delta_C(CDCl_3)$ 20.7, 44.5, 48.6, 71.0, 118.8, 129.7, 134.3, 135.6, 154.0; ν_{max}(ATR) 1616, 1733, 2909, 3025 cm^{-1}.

3.8 Procedures for various kinetic experiments

*Procedure for measuring the kinetics of the reaction between epoxide **1a** and phenylisocyanate **5a** catalysed by complex **10**:*

Complex **10** (0.04–0.11 mmol) and styrene oxide **1a** (0.1 mL, 0.84 mmol) were dissolved in toluene (2 mL) and the solution was heated to 80 °C, after which phenylisocyanate **5a** (0.1 mL, 0.84 mmol) was added. An aliquot of the reaction mixture was removed and immediately quenched with $CDCl_3$ every 30 minutes for 4–5 hours. Each sample was analysed by ^1H NMR spectroscopy to determine the ratio of epoxide **1a** to oxazolidinones **23a**/**24a**.

*Procedure for measuring the kinetics of the reaction between epoxide **1a** and CO_2 catalysed by complex **10** and TBAB:*

Complex **10** (50 mg, 0.04 mmol) and Bu_4NBr (12.9 mg, 0.04 mmol) were placed in a test tube fitted with a side-arm and dissolved in propylene carbonate (0.5 mL). A round-bottom flask was filled with dry ice pellets and attached to the side–arm. The test tube was sealed with a suba seal pierced with an empty balloon. The CO_2 was allowed to flush the system and fill the balloon. The solution was then heated (20–40 ^oC), and styrene oxide **1a** (0.1 mL, 0.84 mmol) was added to the solution. An aliquot of the reaction mixture was removed and immediately quenched with $CDCl_3$ every 30 minutes for 4–5 hours. Each sample was analysed by ^1H NMR spectroscopy to determine the ratio of epoxide **1a** to cyclic carbonate **9a**.

*Procedure for measuring the kinetics of the reaction between epoxide **1h** and CS_2 catalysed by complex **10**:*

Complex **10** (50 mg, 0.04 mmol), Bu_4NBr (12.9 mg, 0.04 mmol) and 3-phenoxypropylene oxide **2b** (0.113 mL, 0.84 mmol) were dissolved in $CDCl_3$ (0.37 mL). The solution was added to an NMR tube followed by addition of carbon disulphide (0.09 mL, 1.5 mmol). The tube was inserted into the NMR spectrometer with the probe heated (35–50 ^oC). A ^1H NMR spectrum was collected every 30 min for 12.5 h and used to determine the ratio of epoxide **2b** to cyclic dithiocarbonate **10**.

*Procedure for measuring the kinetics of the reaction between epoxide **2a** and phenylisocyanate **7** catalysed by complex **22**:*

Complex **22** (5–13 mol%) and styrene oxide **1a** (0.1 mL, 0.84 mmol) were dissolved in toluene (0.5–2 mL) and the solution was heated to 80 ^{o}C, after which phenylisocyanate **5a** (0.1 mL, 0.835 mmol) was added. An aliquot of the reaction mixture was removed and immediately quenched with $CDCl_3$ every 30 minutes for 4–5 hours. Each sample was analysed by ^{1}H NMR spectroscopy to determine the ratio of epoxide **1a** to oxazolidinones **23a**/**24a**.

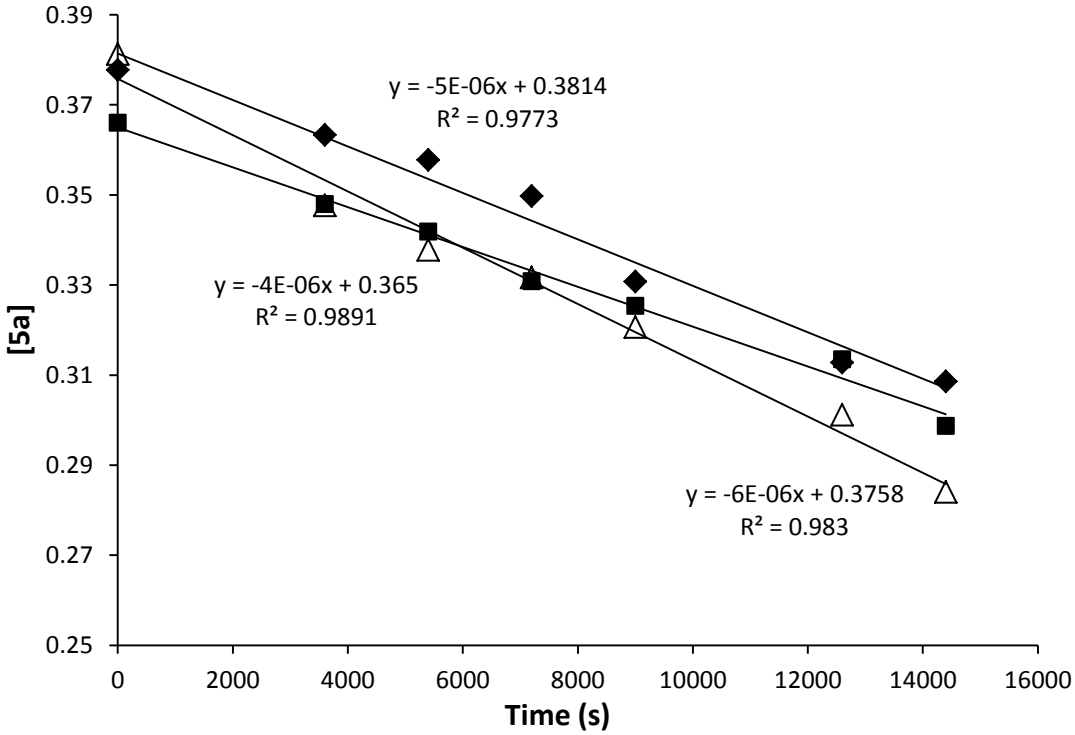
*Procedure for measuring the kinetics of the reaction between epoxide **1h** and carbon disulphide catalysed by complex **57**:*

The appropriate amounts of catalyst **57**, Bu_4NBr, and epoxide **1h** were dissolved in $CDCl_3$ (0.37 mL) to give the concentrations required for a particular experiment. The solution was added to an NMR tube, then the required amount of CS_2 was added. The NMR tube was kept in the 400 MHz NMR spectrometer with the probe heated to 50 ^{o}C. A ^{1}H NMR spectrum was collected every 30 min for 12.5 h and the relative intensities of the signals for unreacted epoxide, dithiocarbonate and trithiocarbonate were used to determine the extent of reaction.

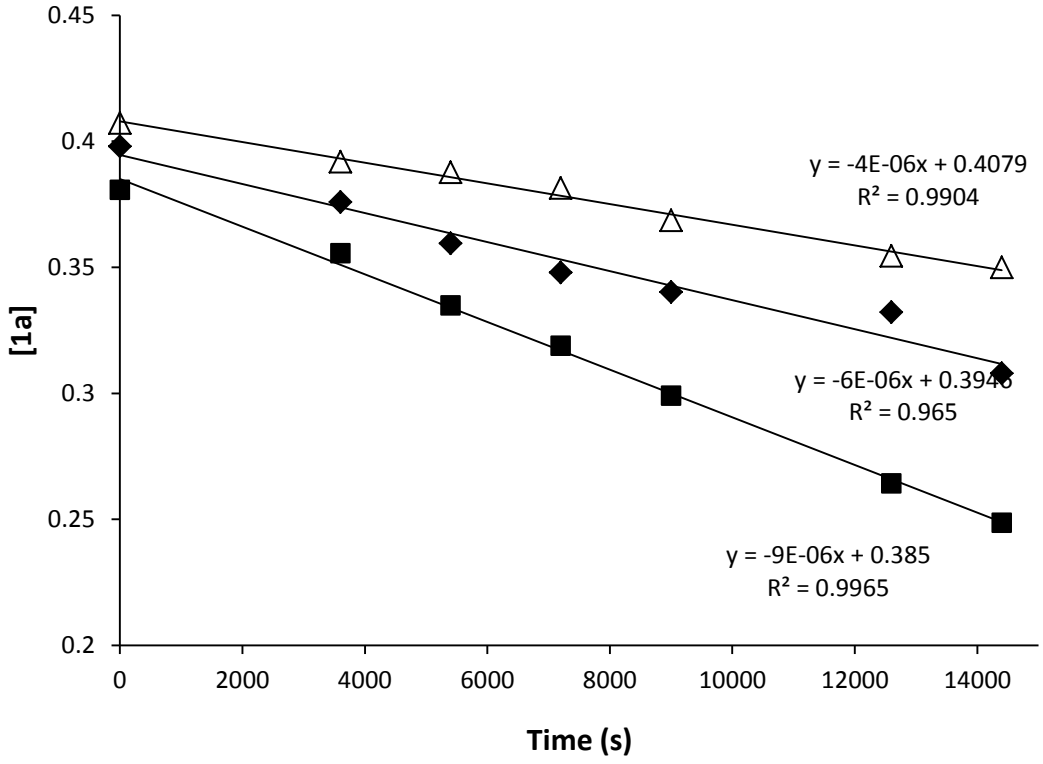
Chapter 4. Appendix

4.1 Complex 10 catalysed synthesis of oxazolidinones

*Reaction profile plot for synthesis of oxazolidinones (**23a**, **24b**) from styrene oxide (**1a**) and phenylisocyanate (**5a**), catalysed by complex **10** ([**10**] = 0.2 mM). $[\mathbf{5a}]_0$ = 0.42 M. Three different epoxide concentrations; filled diamonds $[\mathbf{1a}]_0$ = 0.4 M, empty triangles $[\mathbf{1a}]_0$ = 1.2 M, filled squares $[\mathbf{1a}]_0$ = 1.6 M.*



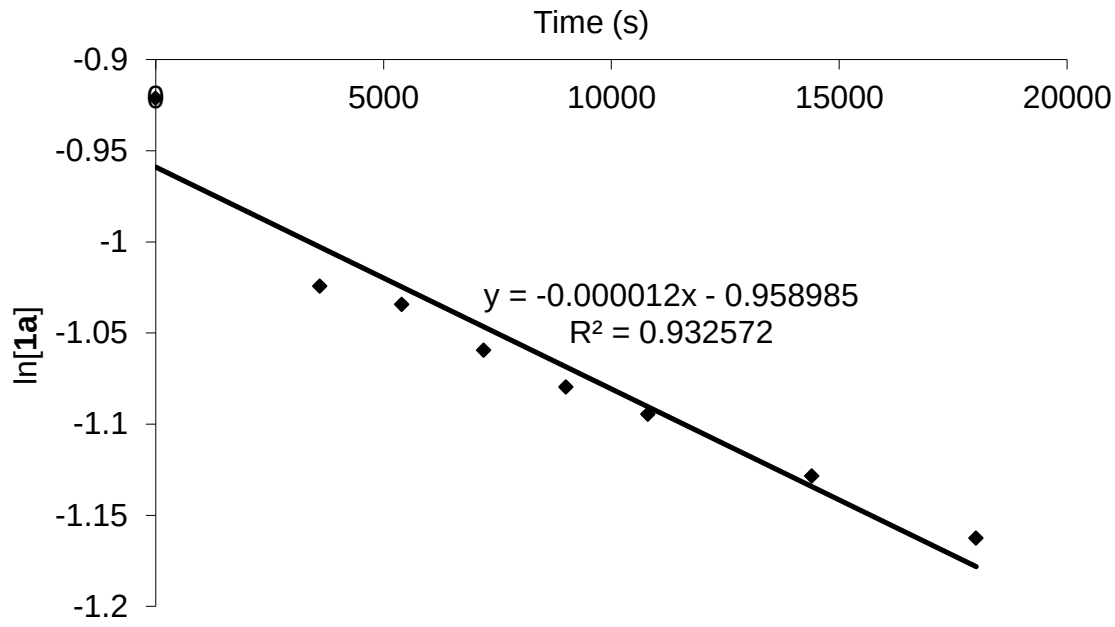
*Reaction profile plot for synthesis of oxazolidinones (**23a**, **24b**) from styrene oxide (**1a**) and phenylisocyanate (**5a**), catalysed by complex **10** ([**10**] = 0.2 mM). $[\mathbf{1a}]_0$ = 0.40 M. Three different isocyanate concentrations; filled diamonds $[\mathbf{5a}]_0$ = 0.42 M, empty triangles $[\mathbf{5a}]_0$ = 0.21 M, filled squares $[\mathbf{5a}]_0$ = 0.84 M.*



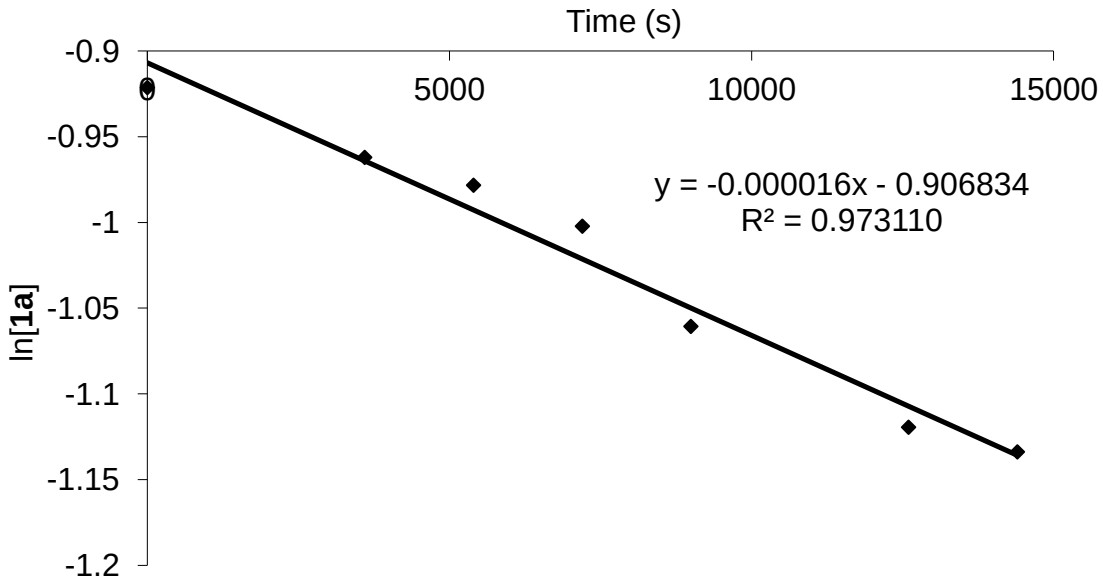
*First order kinetic plots for the synthesis of oxazolidinones **23a**/**24a** catalysed by complex **10***

[**10**] = 20 mM (5 mol%)

Run 1:

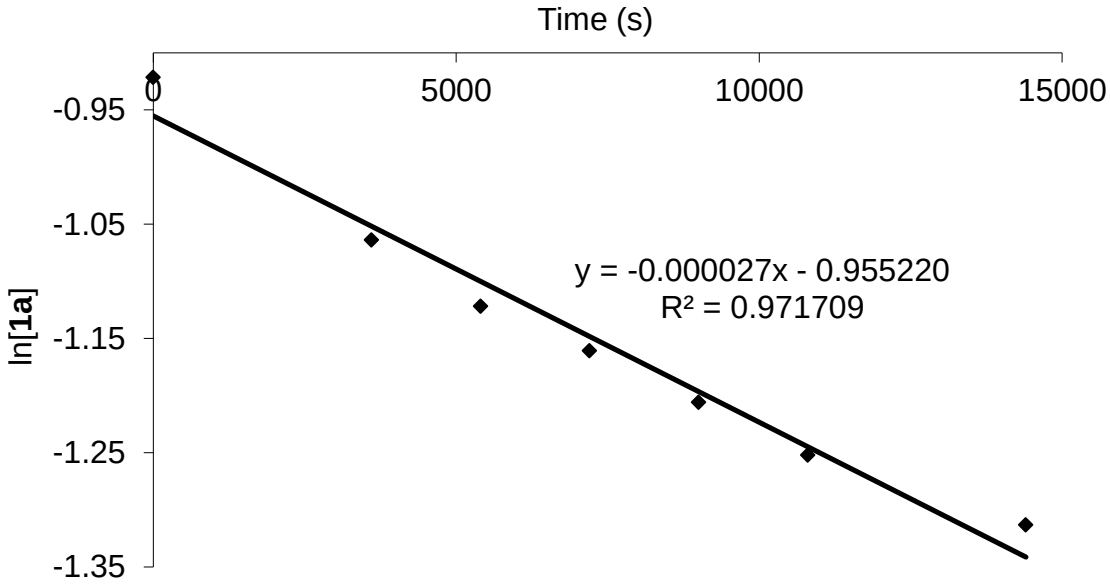


Run 2:

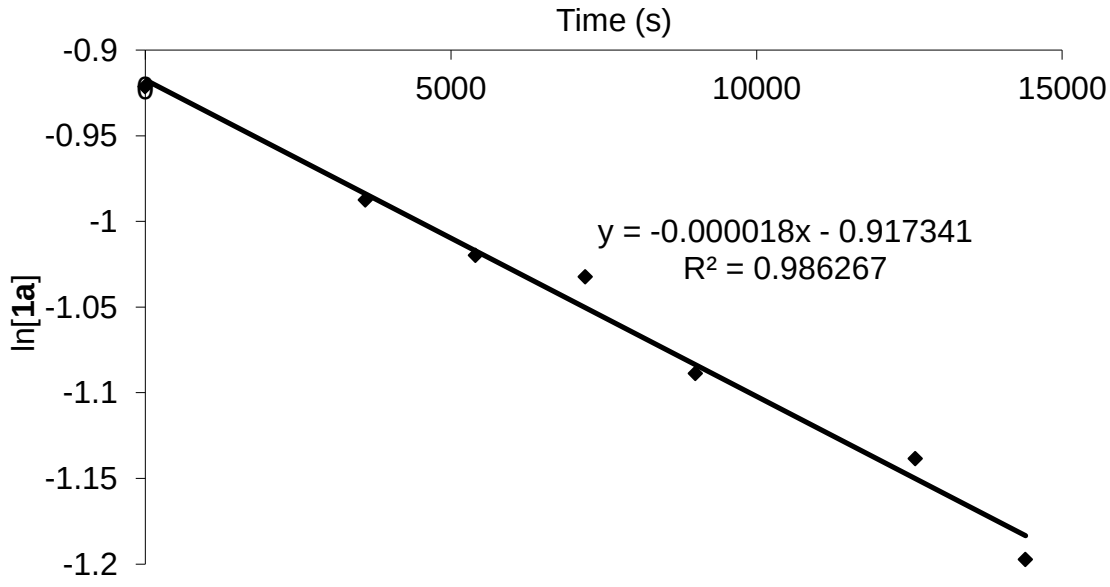


[**10**] = 28 mM (7 mol%)

Run 1:

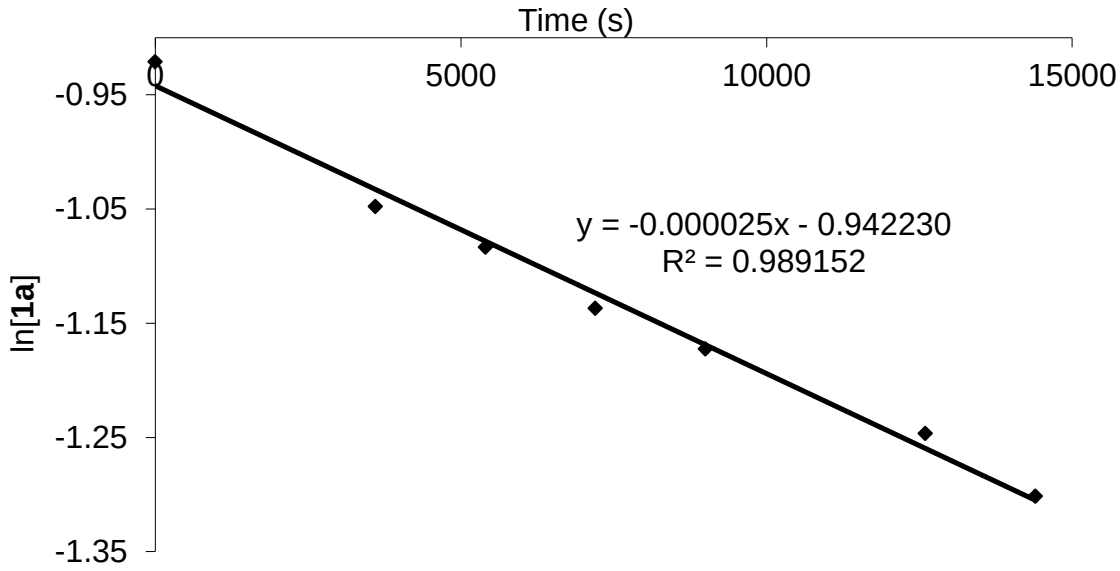


Run 2:

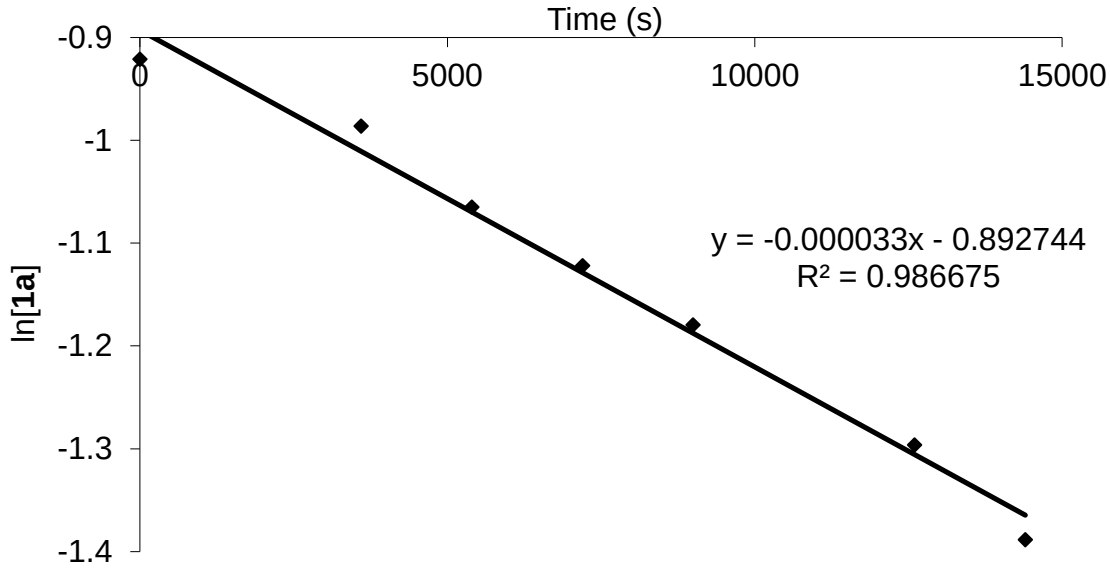


[**10**] = 40 mM (10 mol%)

Run 1:

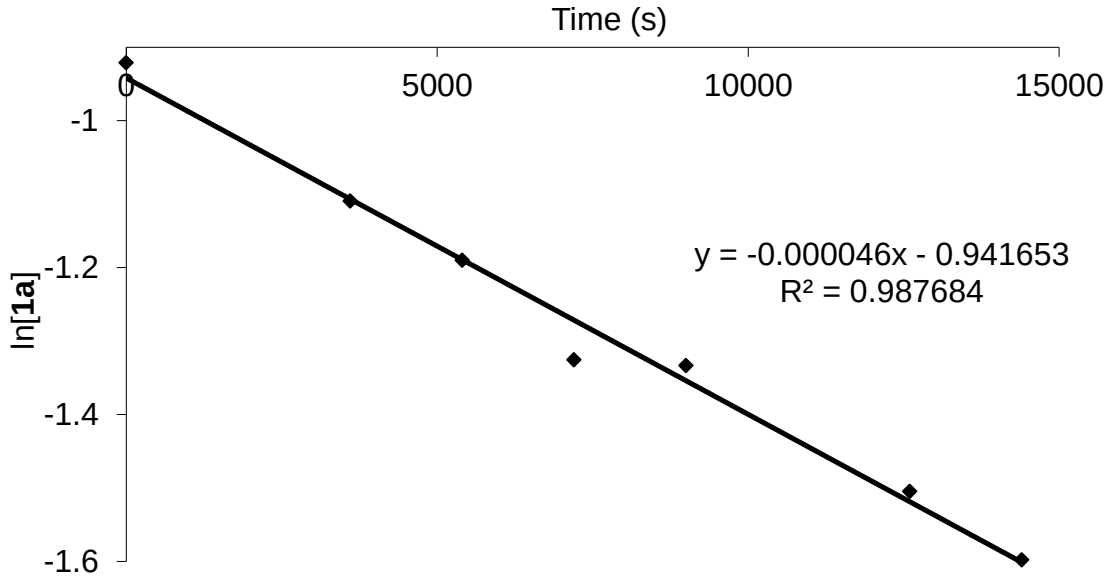


Run 2:

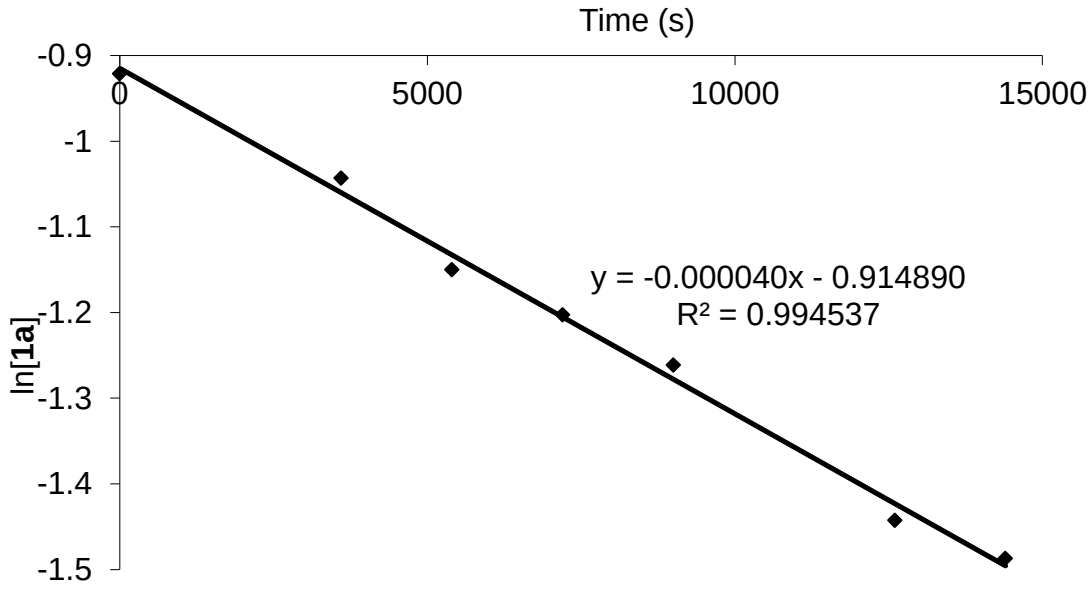


[**10**] = 52 mM (13 mol%)

Run 1:

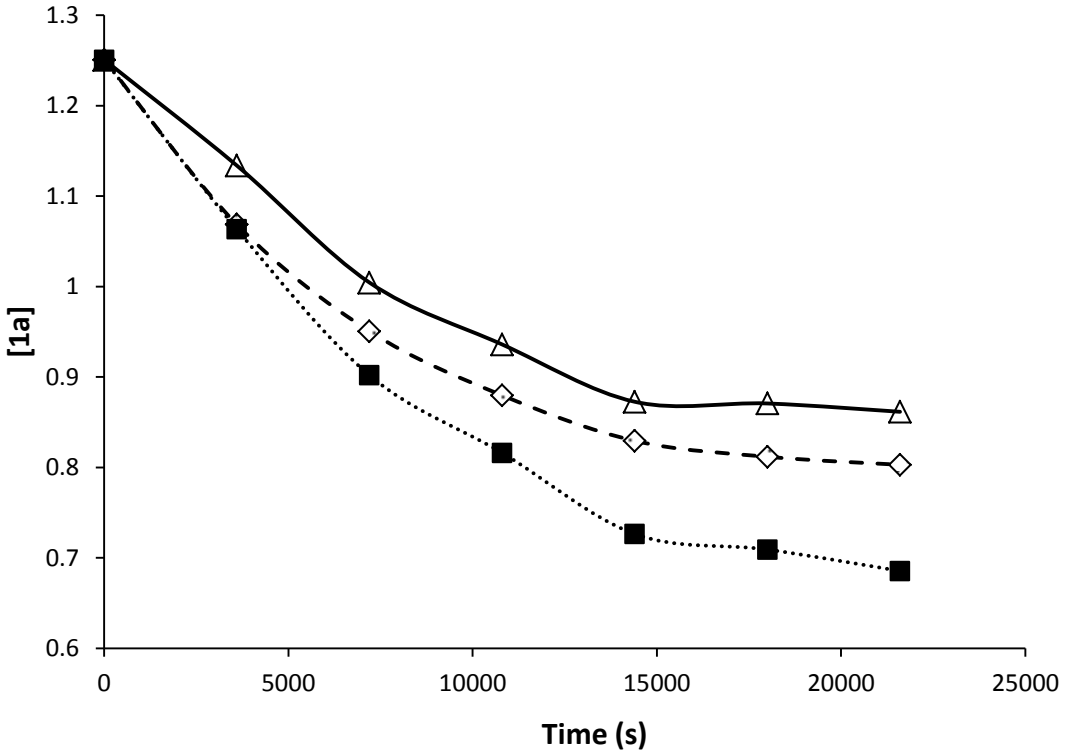


Run 2:

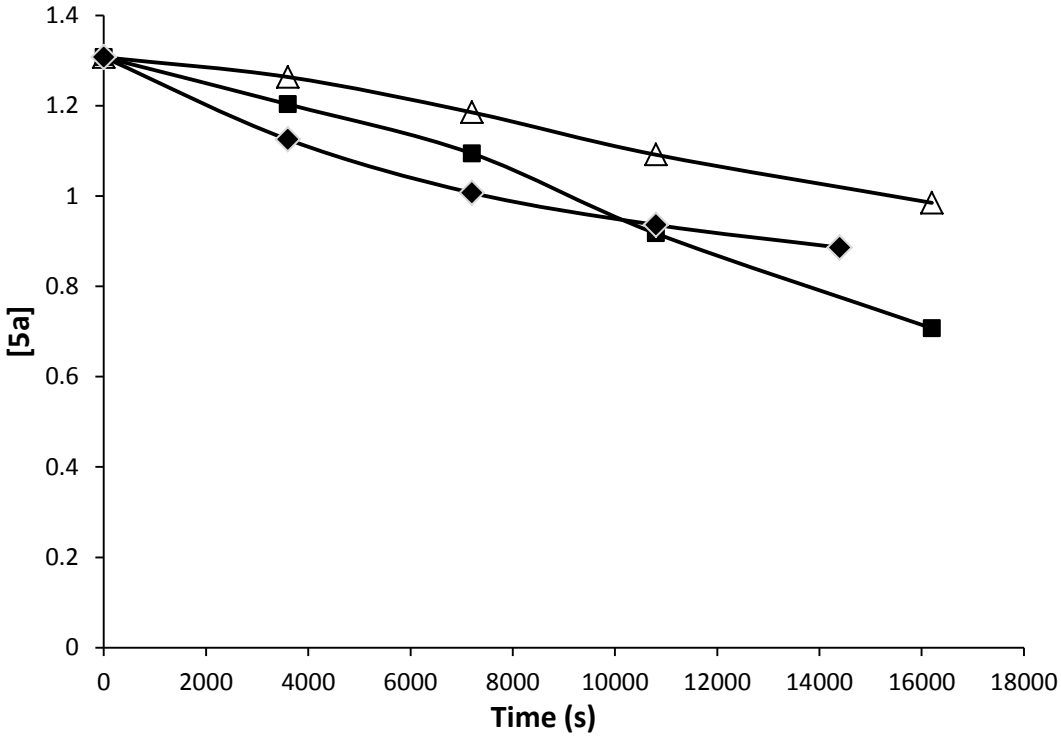


4.2 Complex 22 catalysed synthesis of oxazolidinones

*Reaction profile plot for synthesis of oxazolidinones (**23a**, **24a**) from styrene oxide (**1a**) and phenylisocyanate (**5a**), catalysed by complex **22** ([**22**] = 20 mM). [**5a**]$_0$ = 0.42 M. Three different epoxide concentrations; empty diamonds [**1a**]$_0$ = 0.2 M, empty triangles [**1a**]$_0$ = 0.4 M, filled squares [**1a**]$_0$ = 0.8 M.*



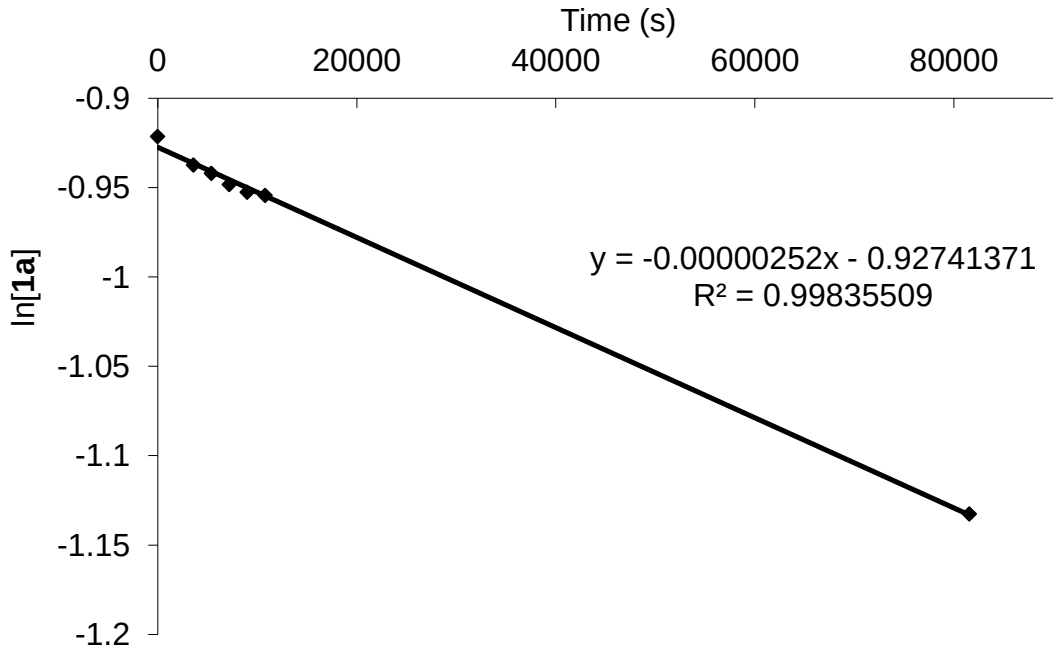
*Reaction profile plot for synthesis of oxazolidinones (**23a**, **24a**) from styrene oxide (**1a**) and phenylisocyanate (**5a**), catalysed by complex **22** ([**22**] = 20 mM). [**1a**]$_0$ = 0.40 M. Three different isocyanate concentrations; filled diamonds [**5a**]$_0$ = 0.42 M, empty triangles [**5a**]$_0$ = 0.21 M, filled squares [**5a**]$_0$ = 0.84 M.*



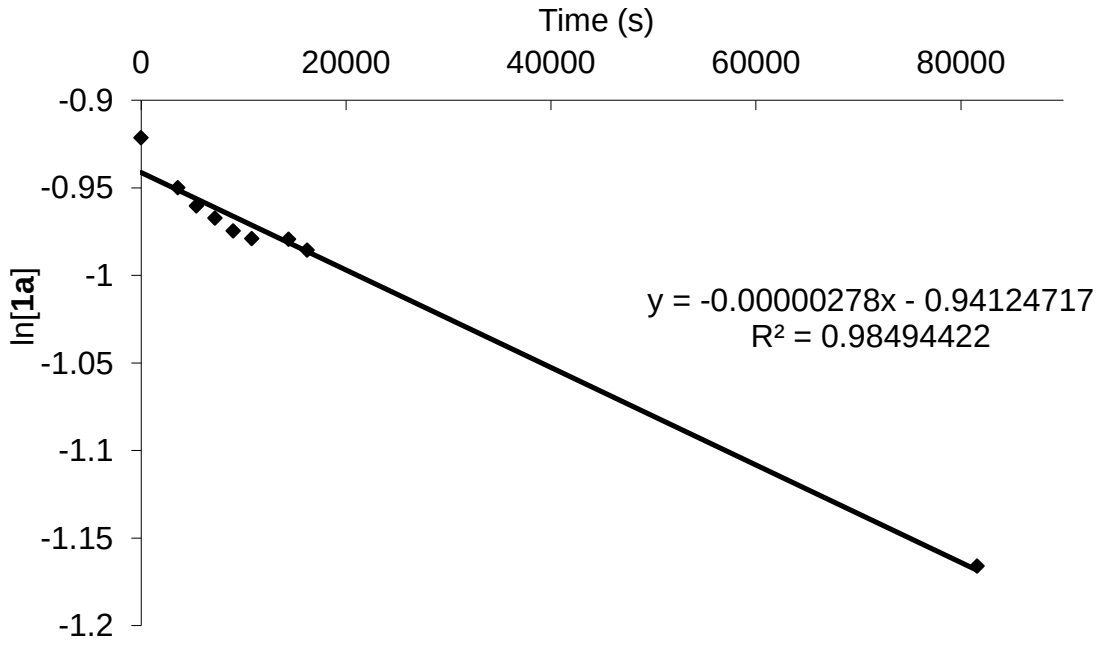
*First order kinetic plots for the synthesis of oxazolidinones **23a**/**24a** catalysed by complex **22***

[**22**] = 20 mM (5 mol%)

Run 1:

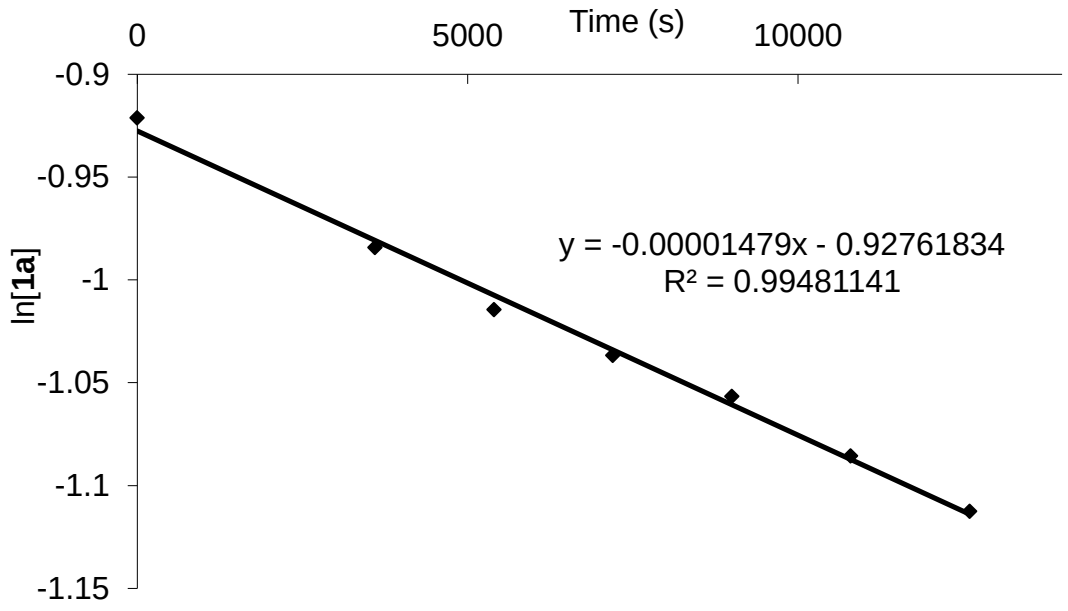


Run 2:

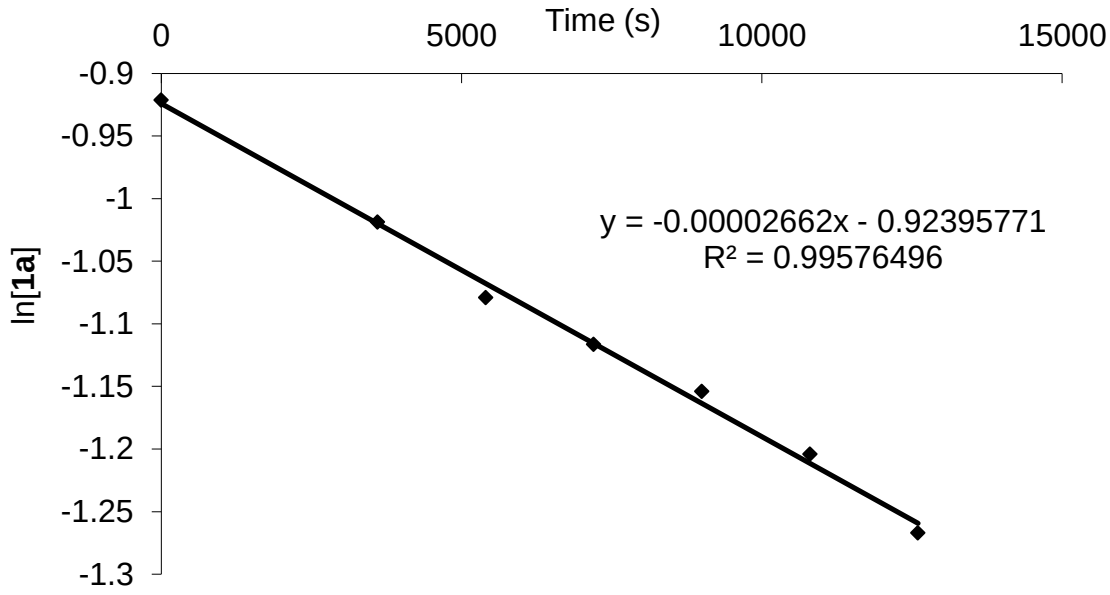


[**22**] = 32 mM (8 mol%)

Run 1:

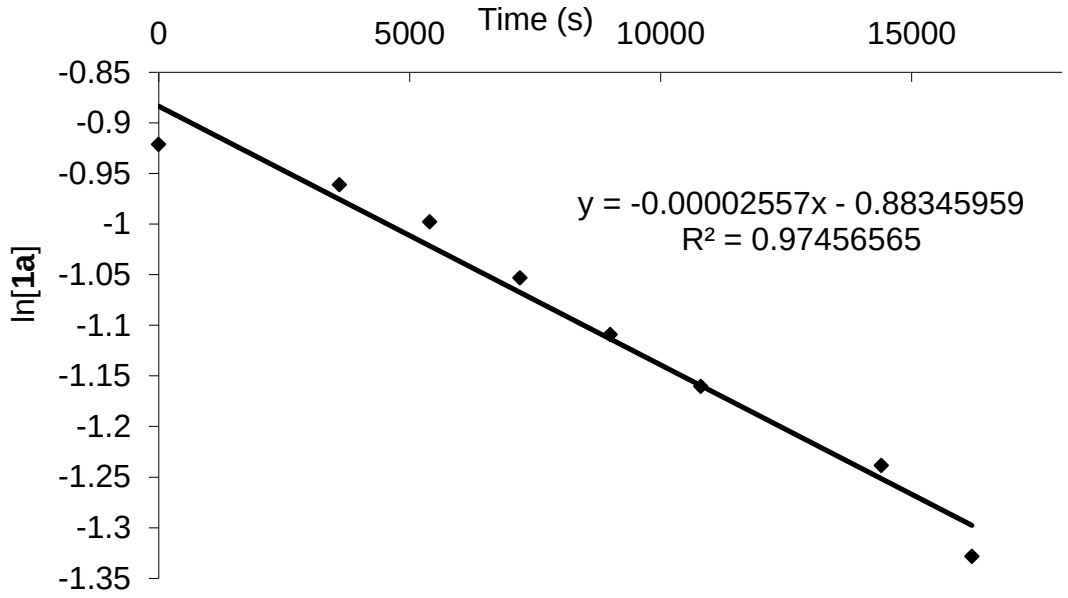


Run 2:

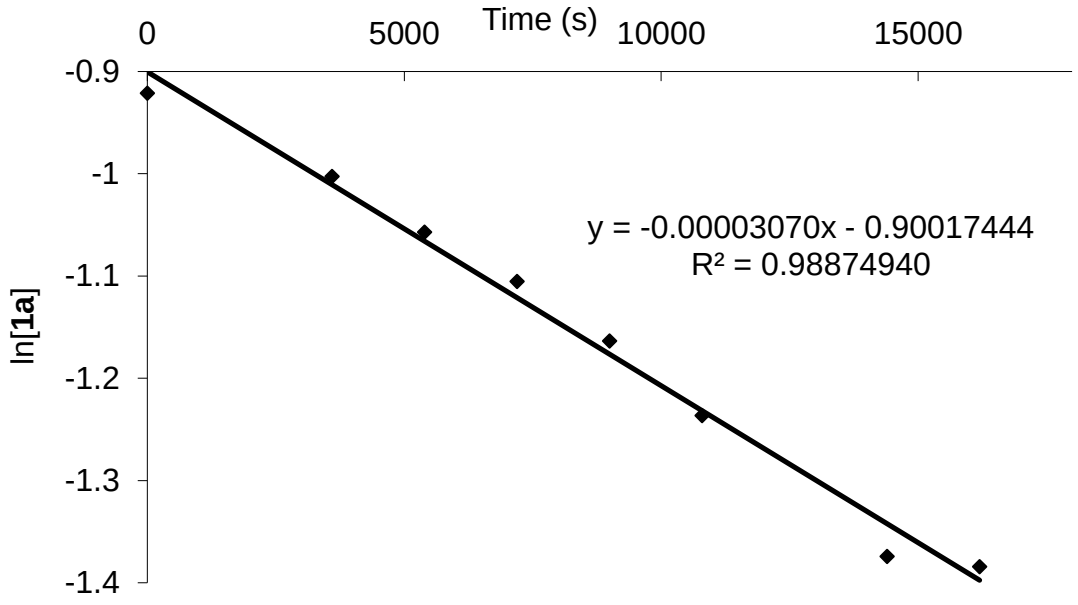


[**22**] = 44 mM (11 mol%)

Run 1:

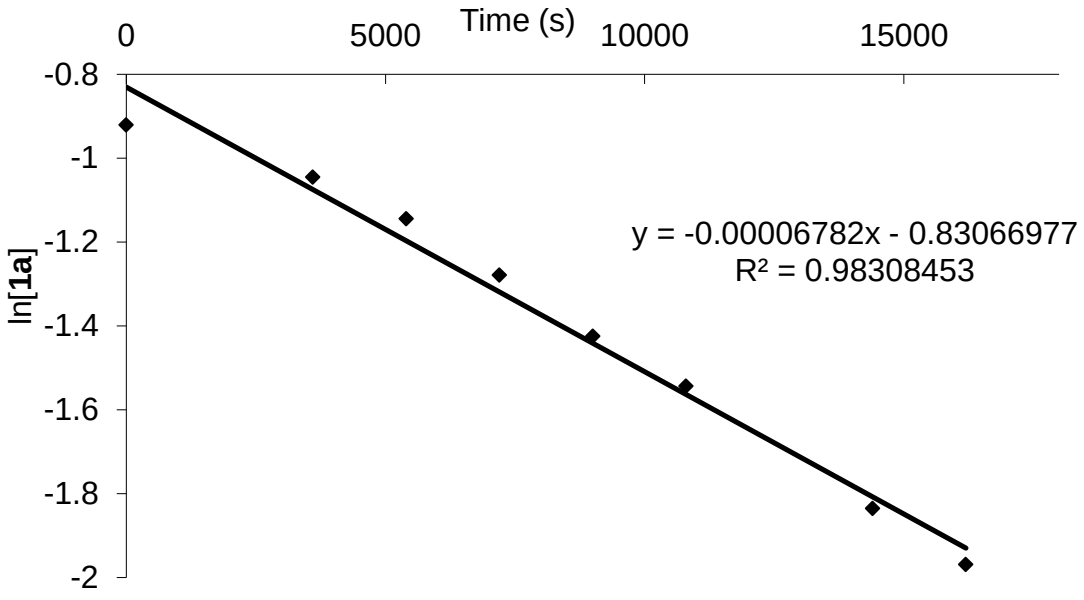


Run 2:

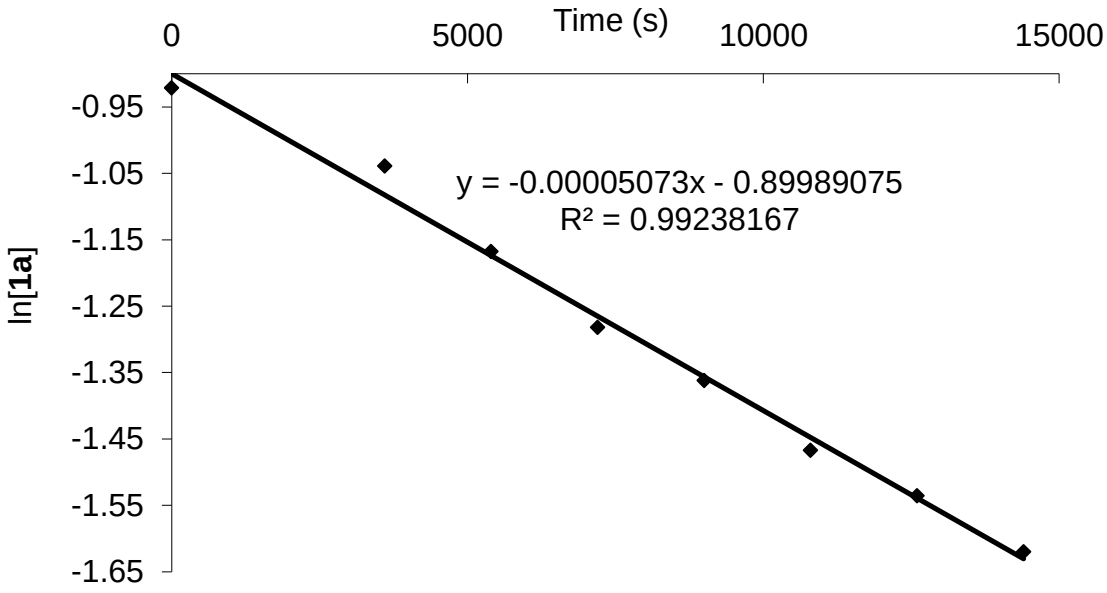


[**22**] = 56 mM (14 mol%)

Run 1:



Run 2:

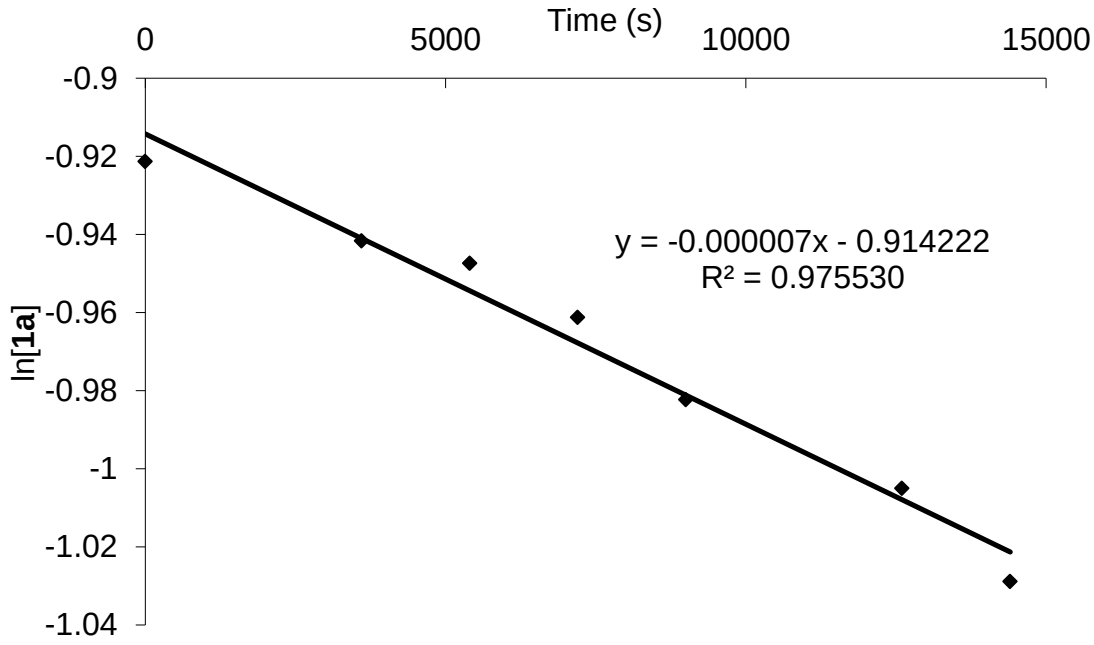


4.3 Variable temperature experiments

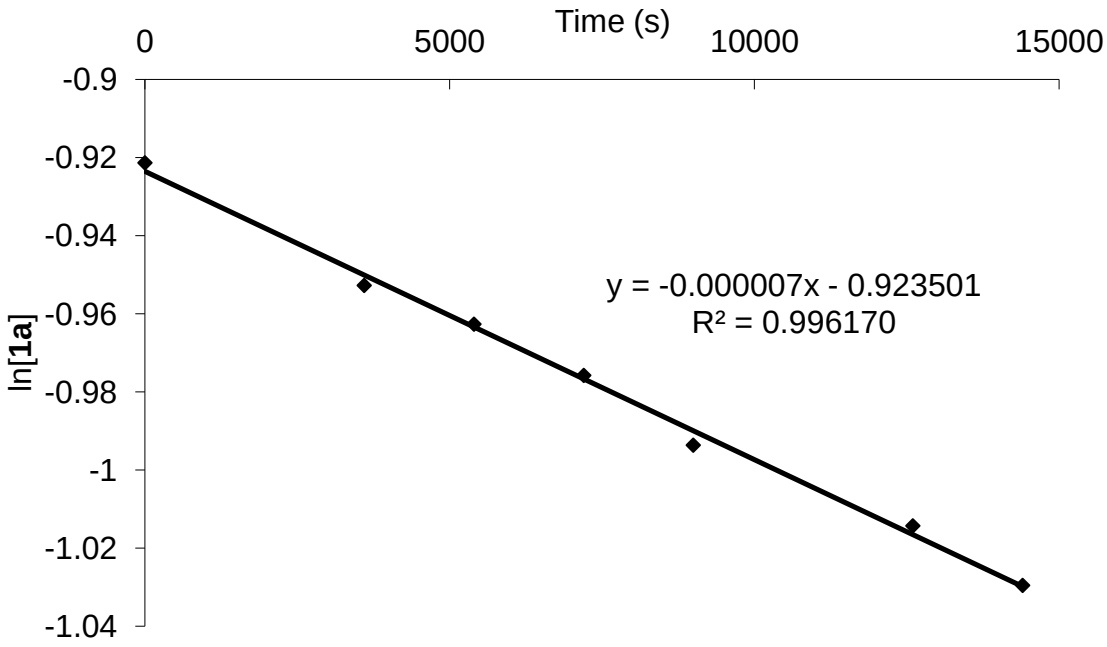
*First order kinetic plots for the varied temperature experiments in the synthesis of oxazolidinones **23a/24a** catalysed by complex **10***

70°C

Run 1:

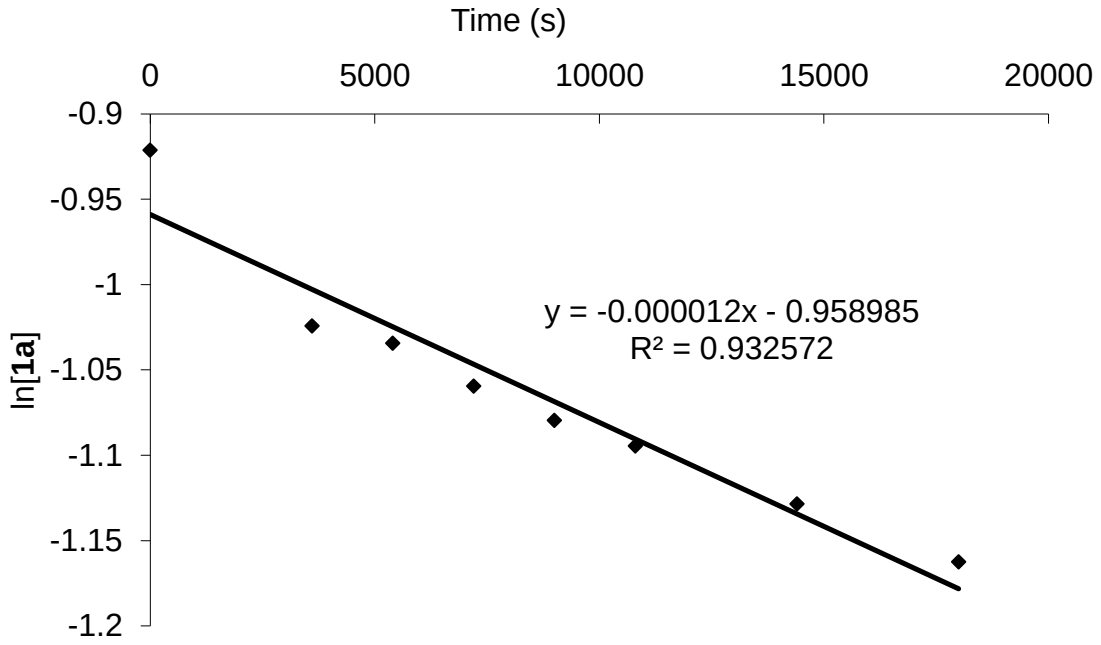


Run 2:

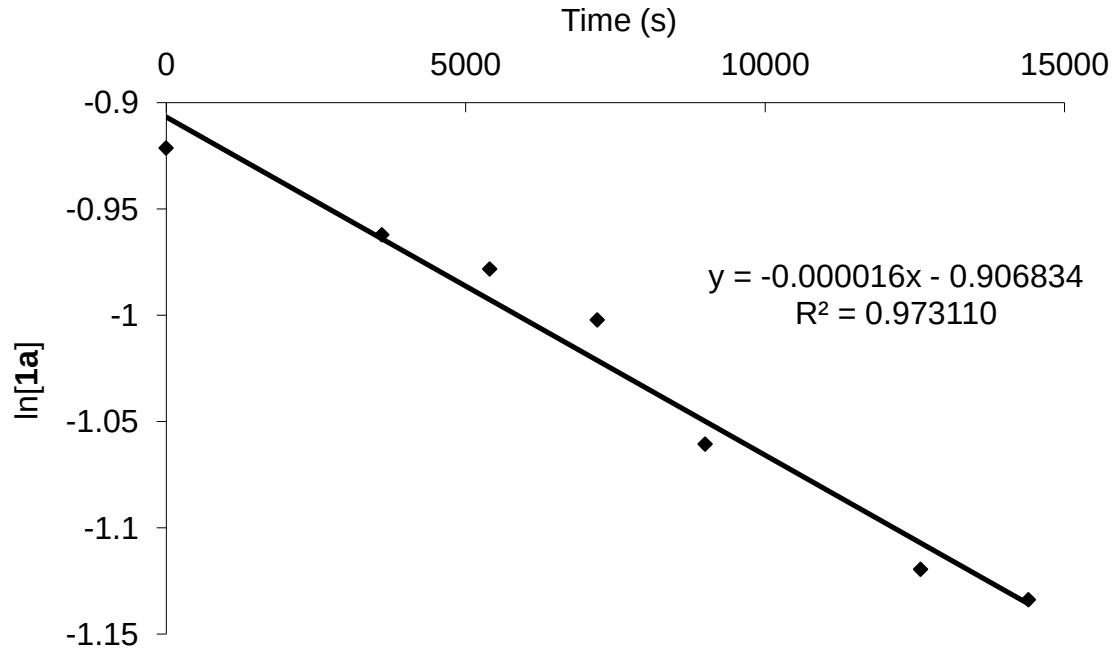


80°C

Run 1:

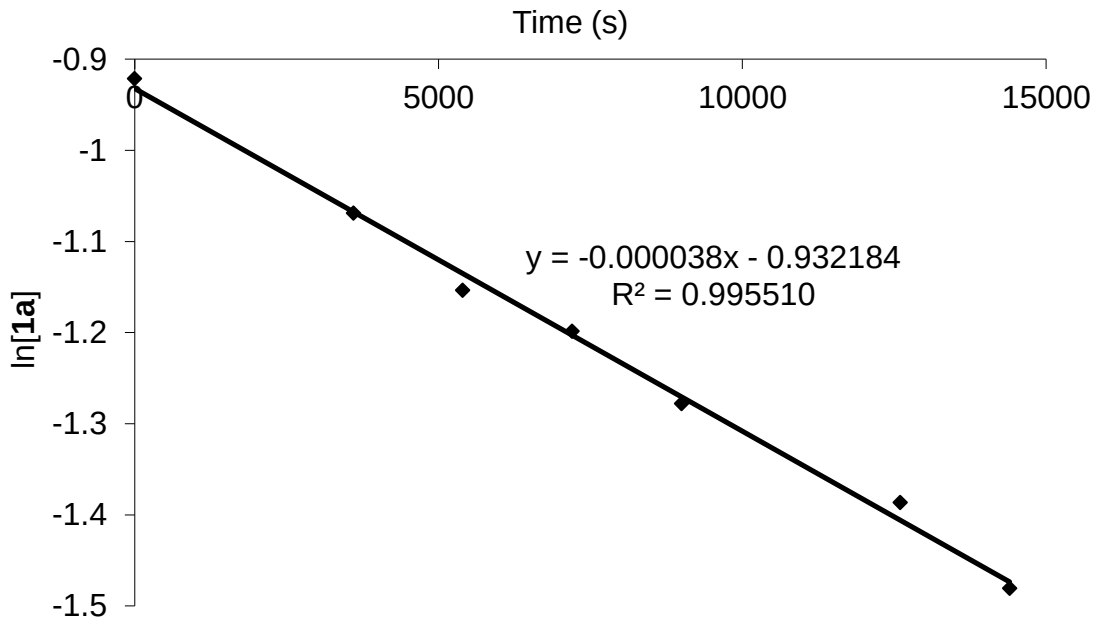


Run 2:

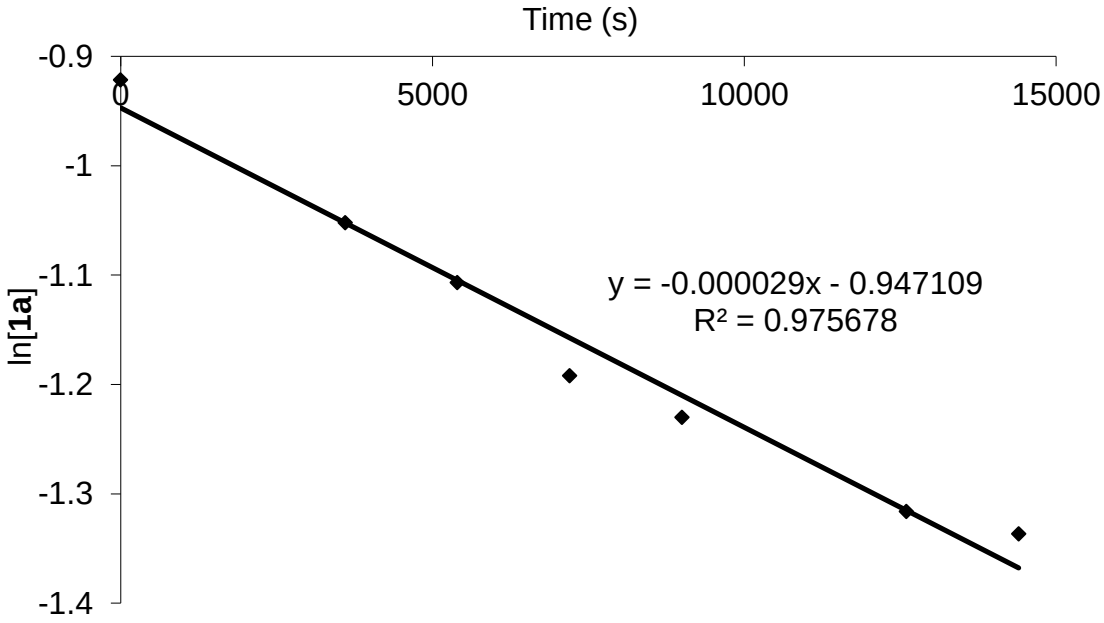


90°C

Run 1:

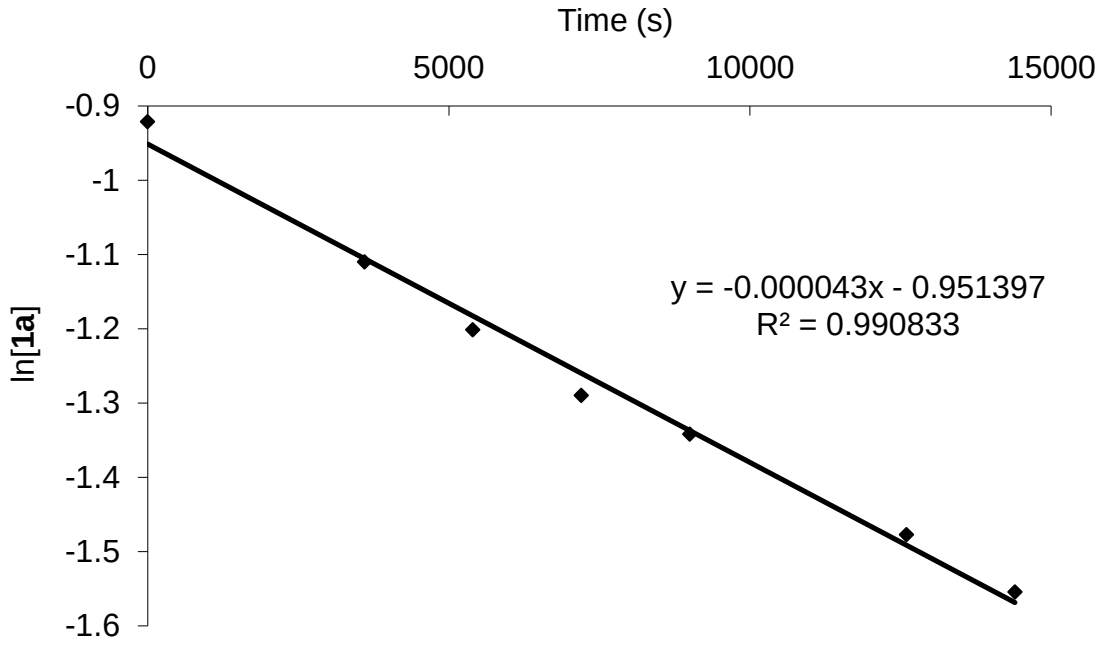


Run 2:

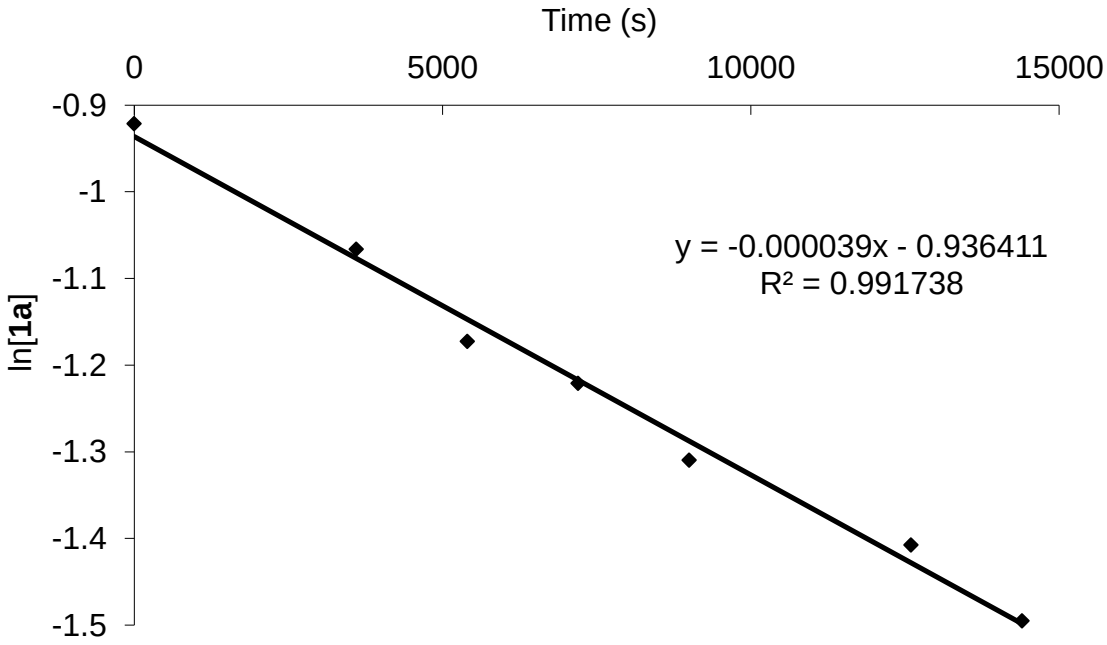


100 °C

Run 1:

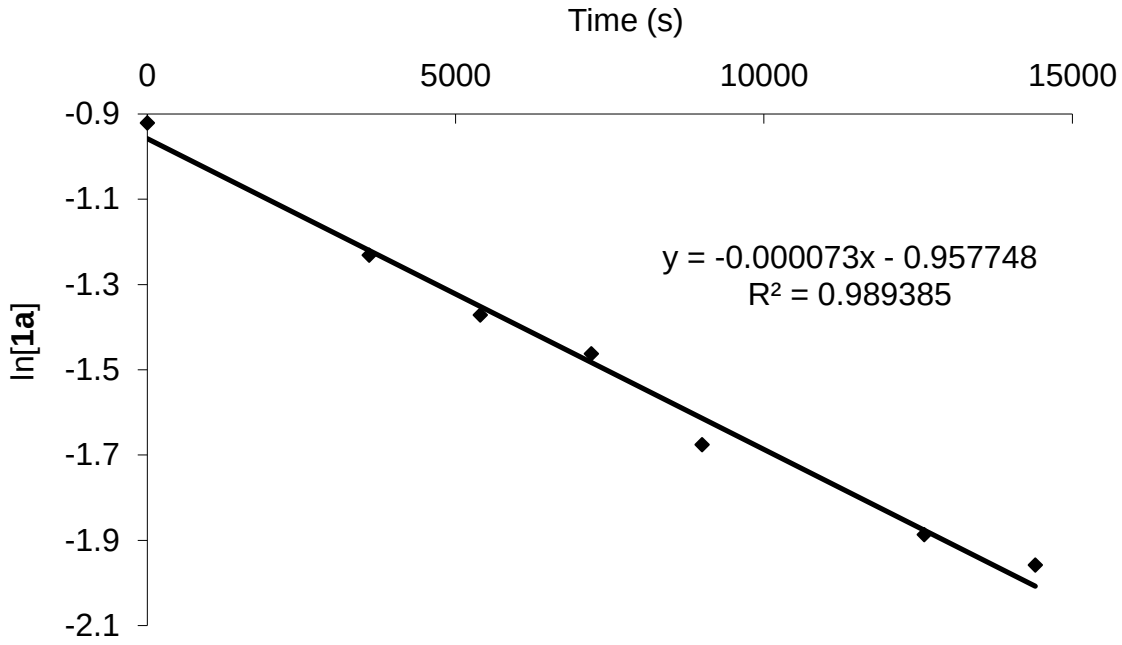


Run 2:

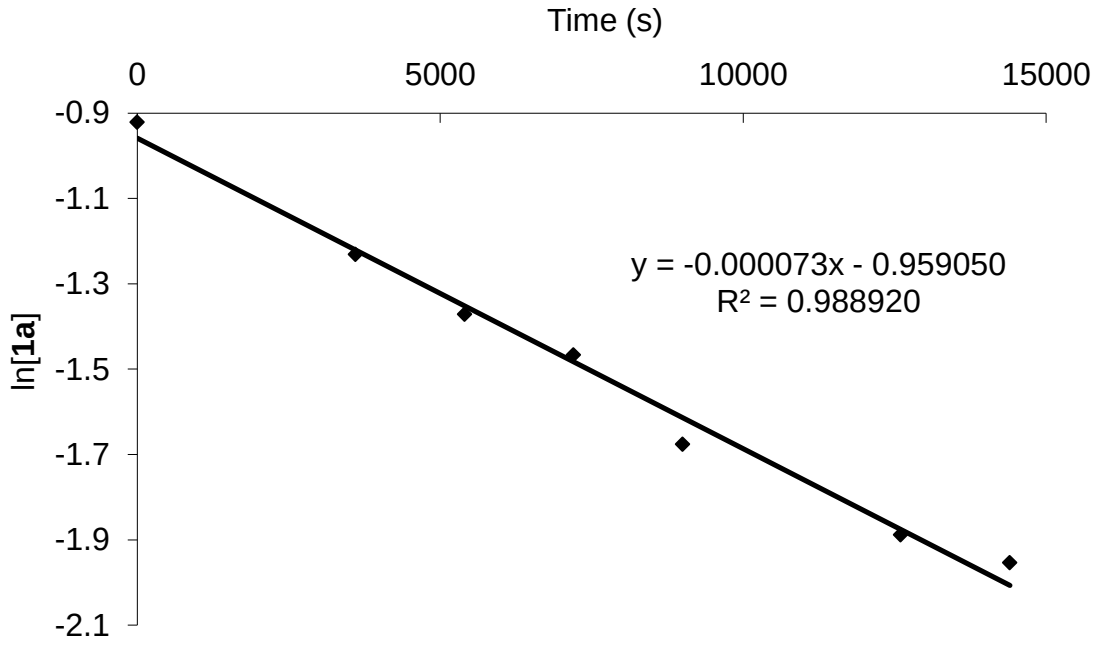


110 °C

Run 1:



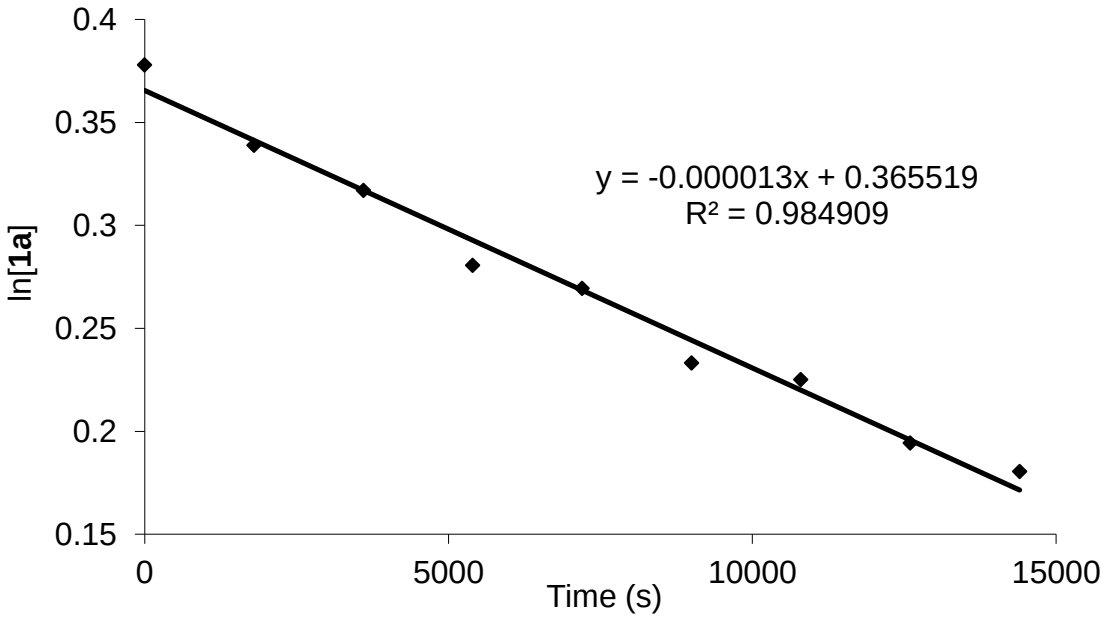
Run 2:



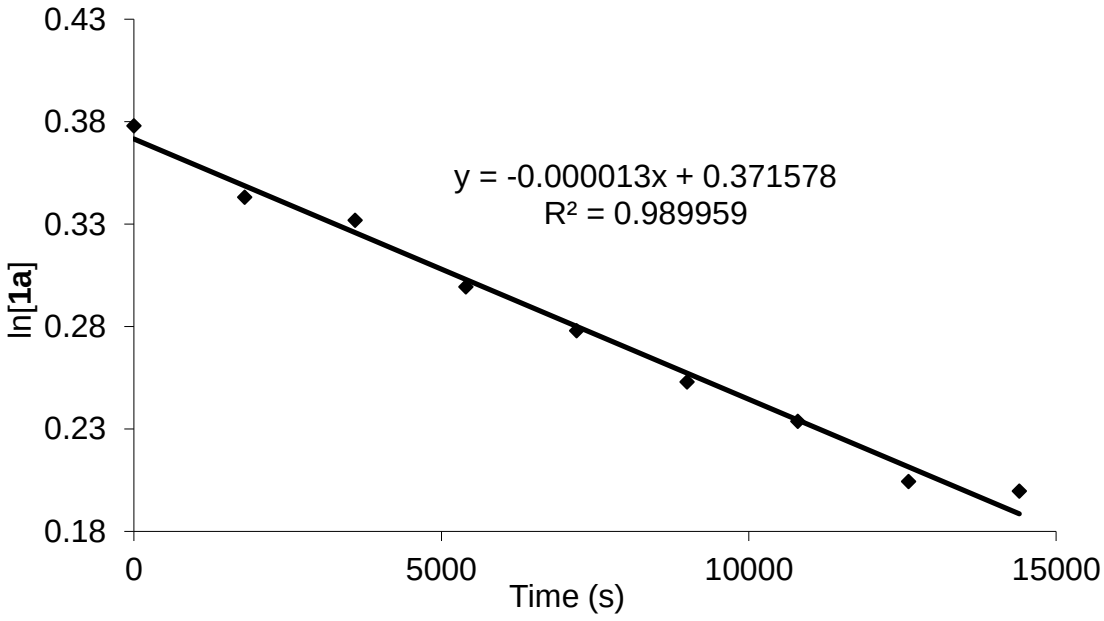
*First order kinetic plots for the varied temperature experiments in the synthesis of styrene carbonate **9a** catalysed by complex **10** and TBAB*

20 °C

Run 1:

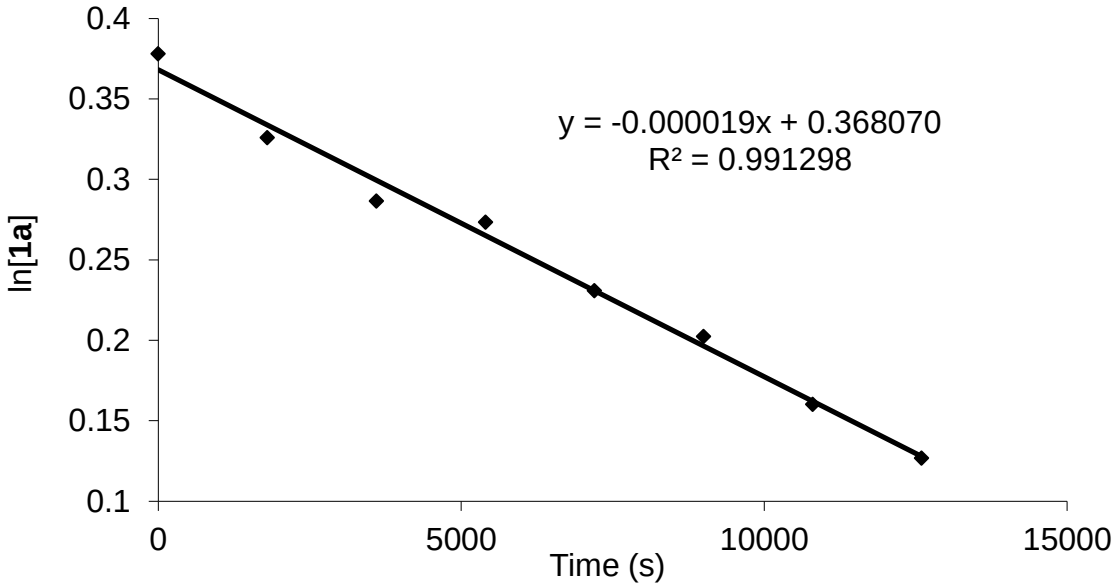


Run 2:

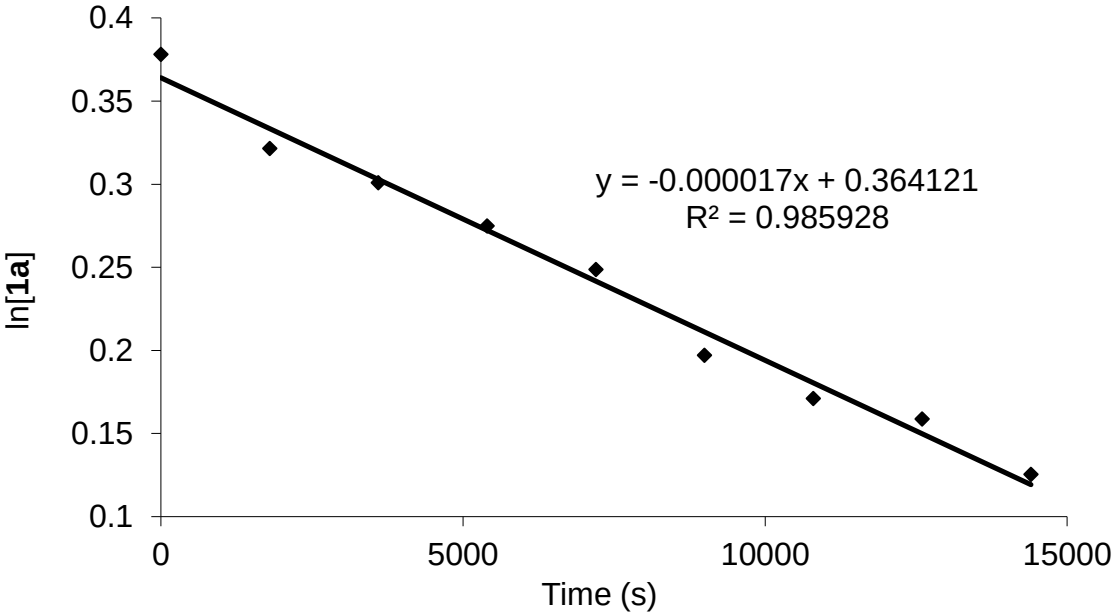


30 °C

Run 1:

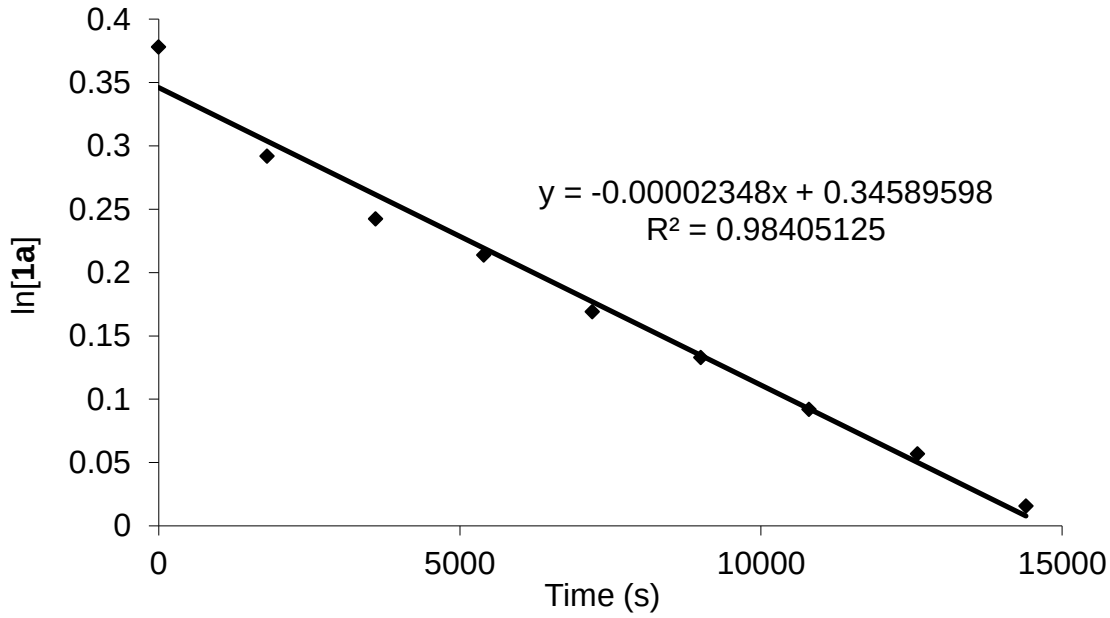


Run 2:

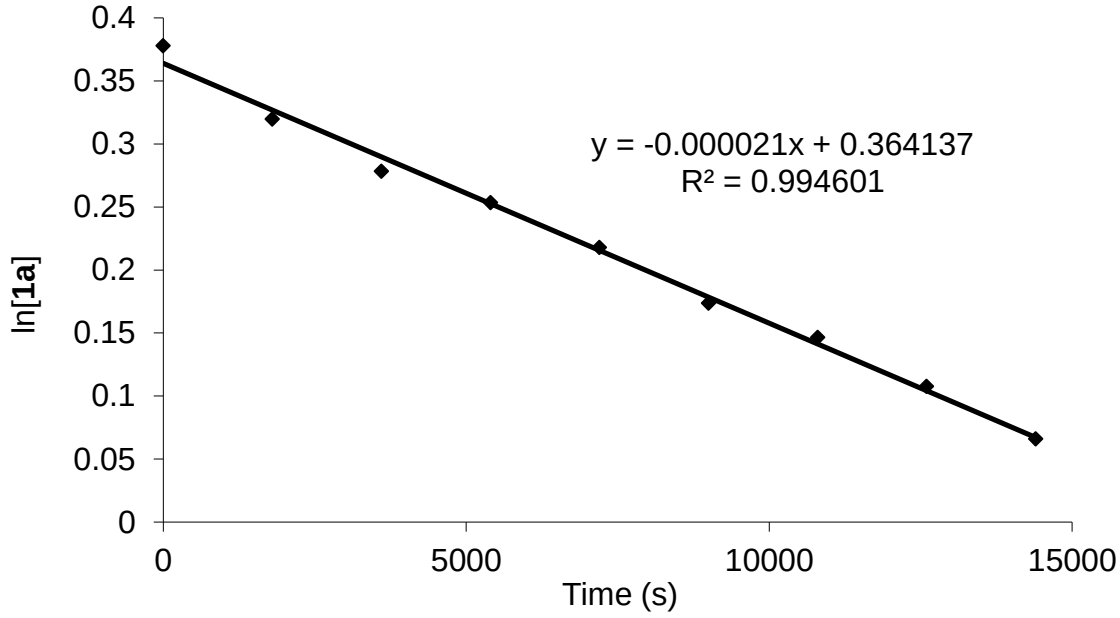


35 ^{o}C

Run 1:

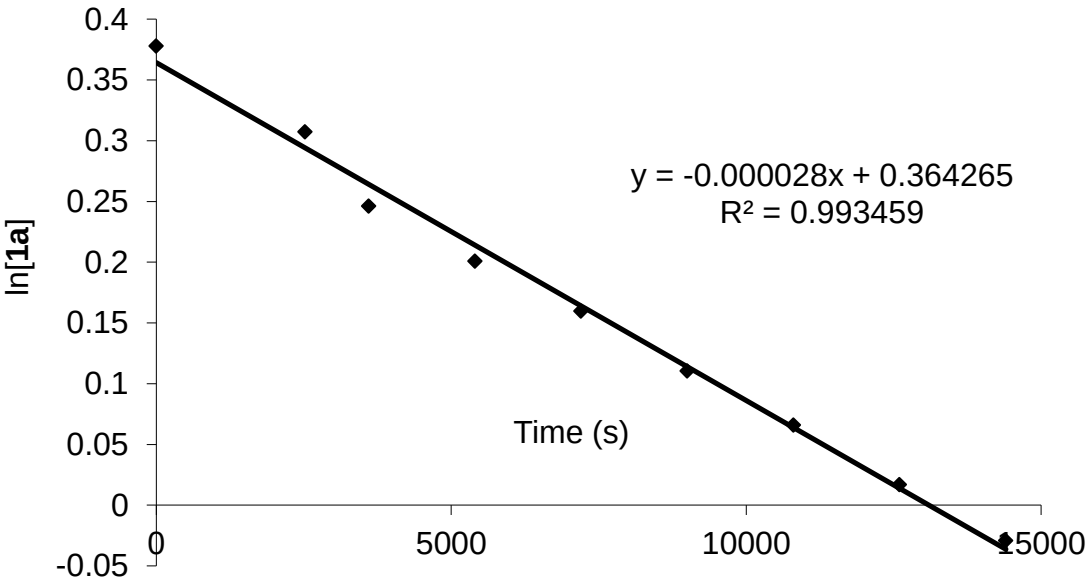


Run 2:

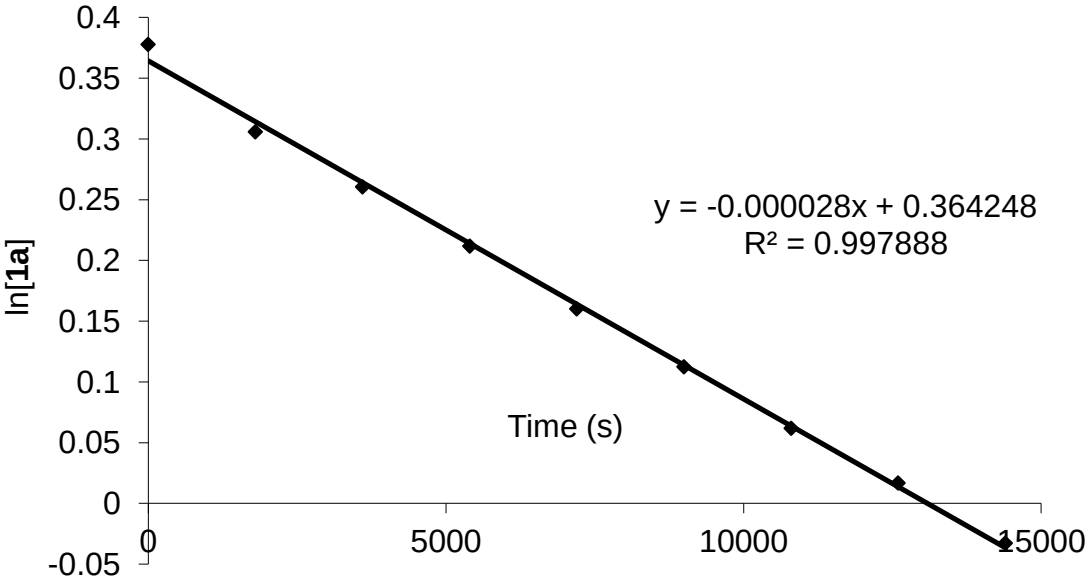


40 °C

Run 1:



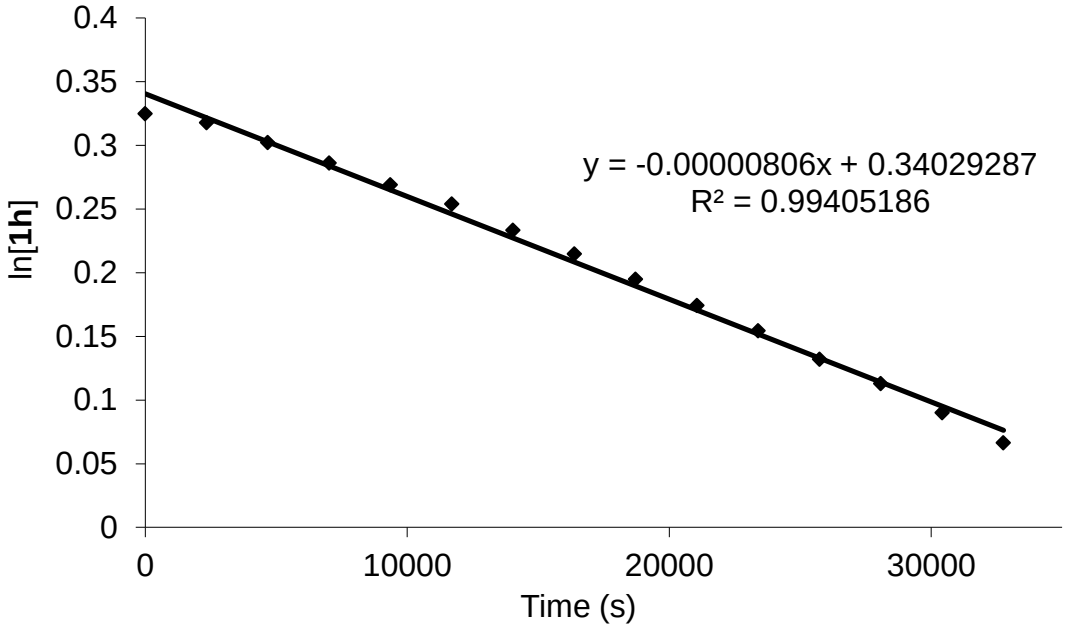
Run 2:



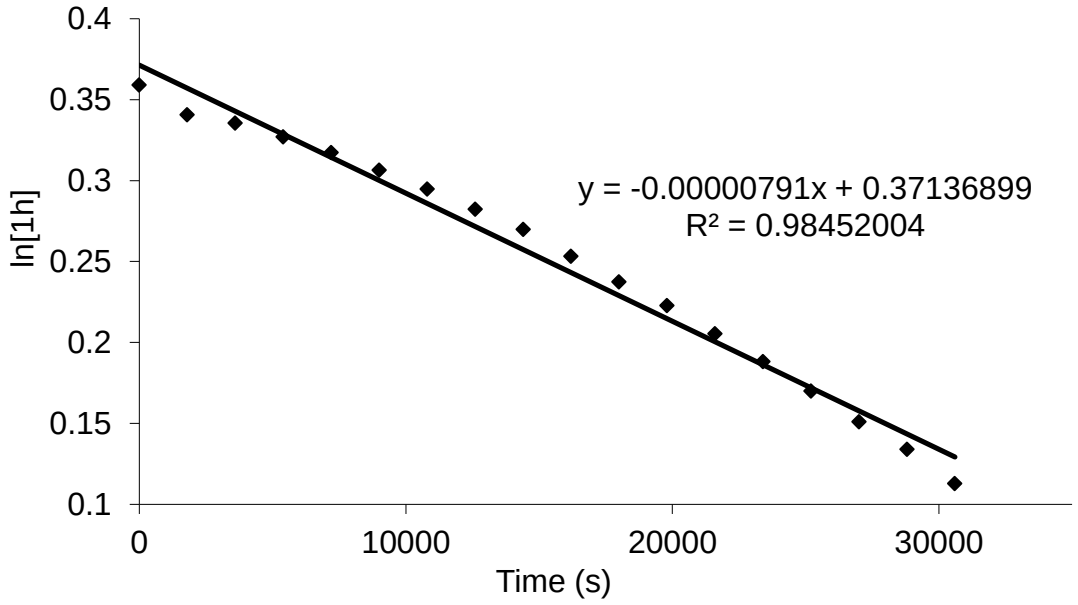
First order kinetic plots for the synthesis of dithiocarbonate ***14h*** *catalysed by complex* ***10***

35 ^{o}C

Run 1:

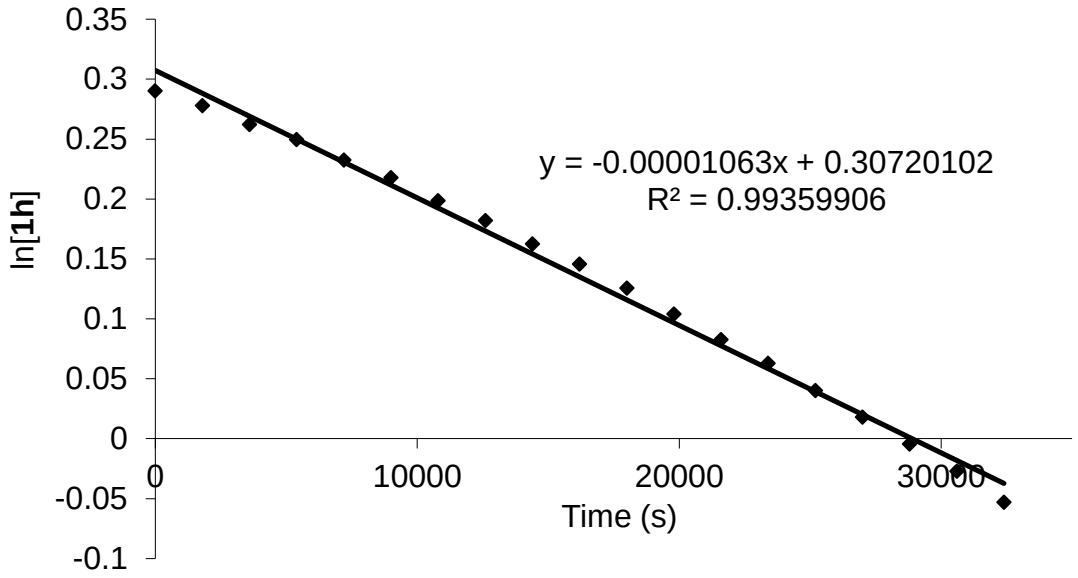


Run 2:

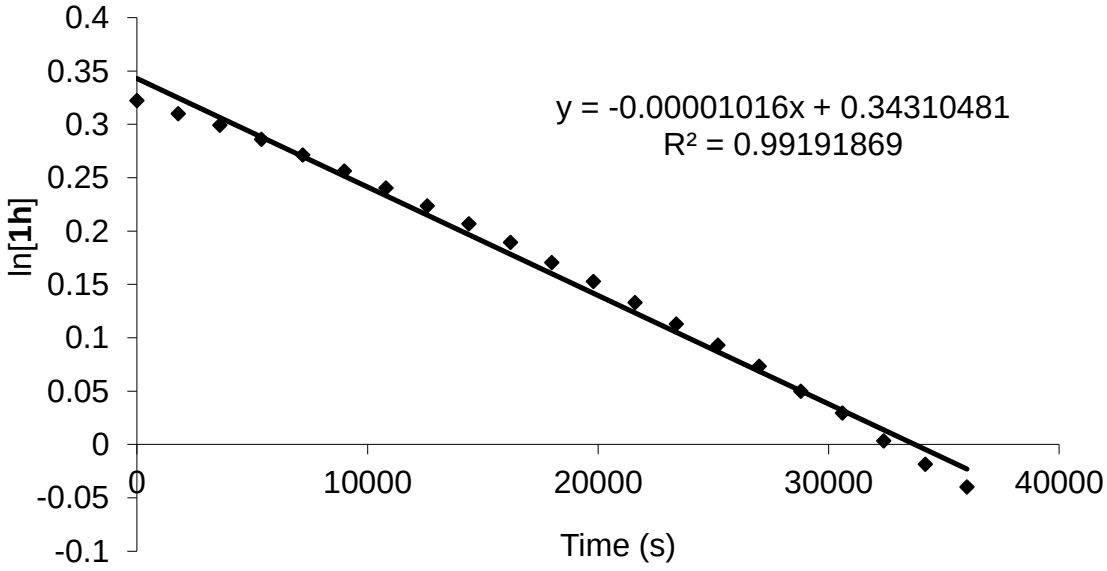


40 ^{o}C

Run 1:

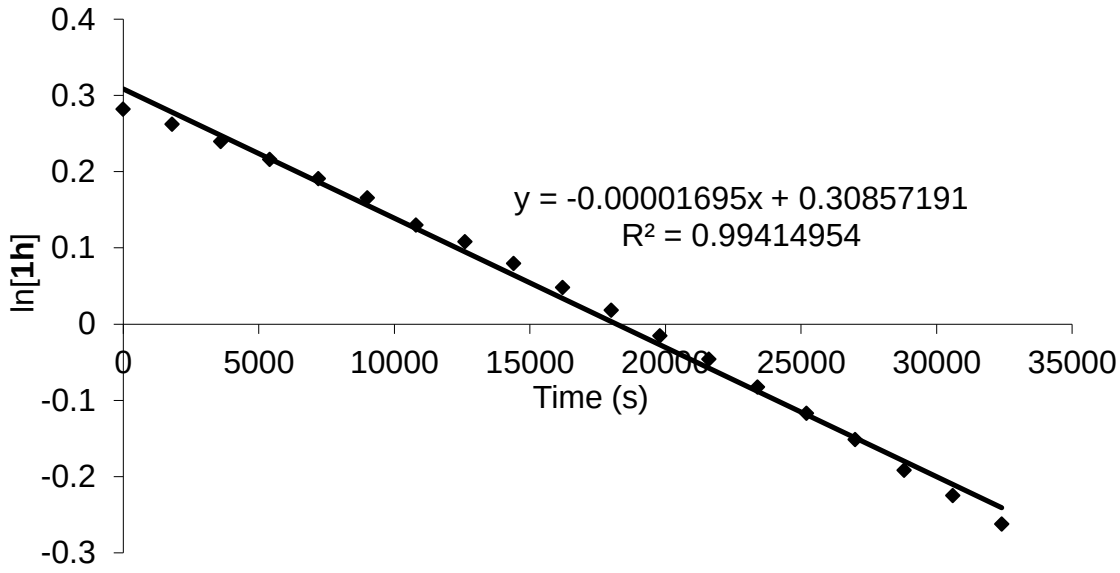


Run 2:

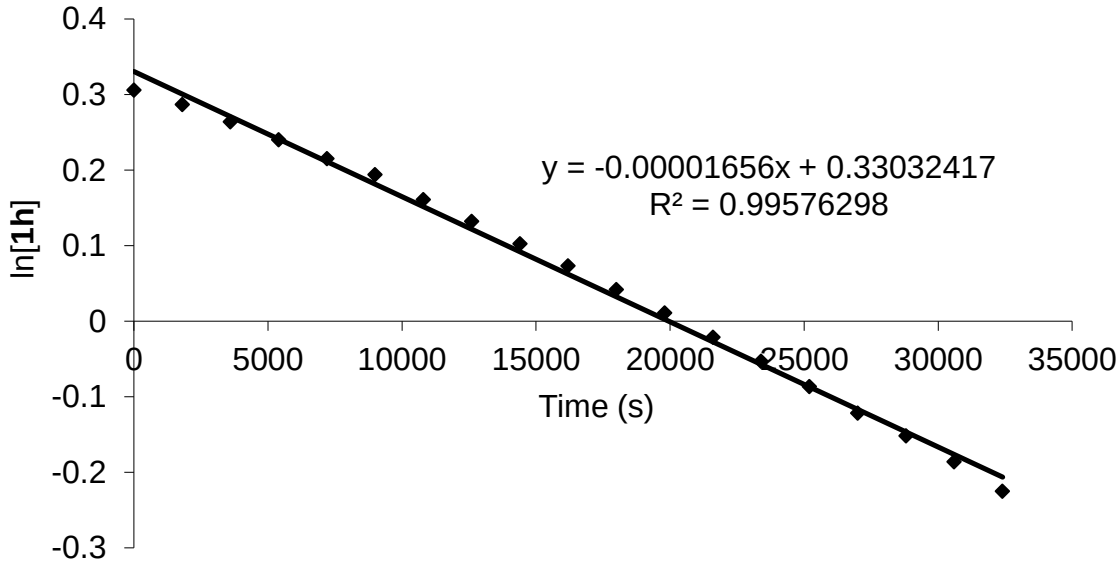


45 ^{o}C

Run 1:

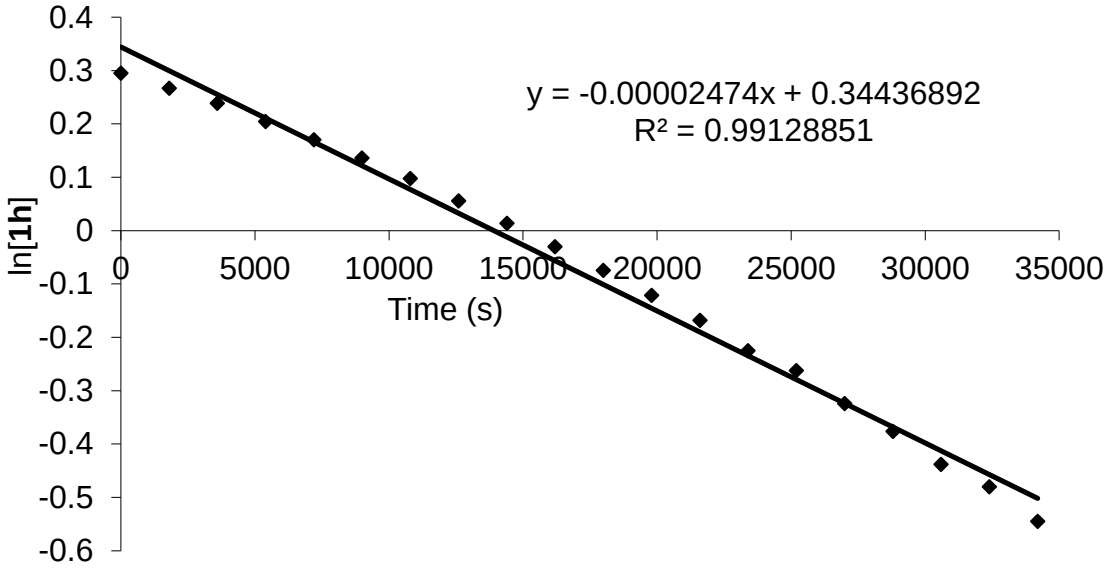


Run 2:

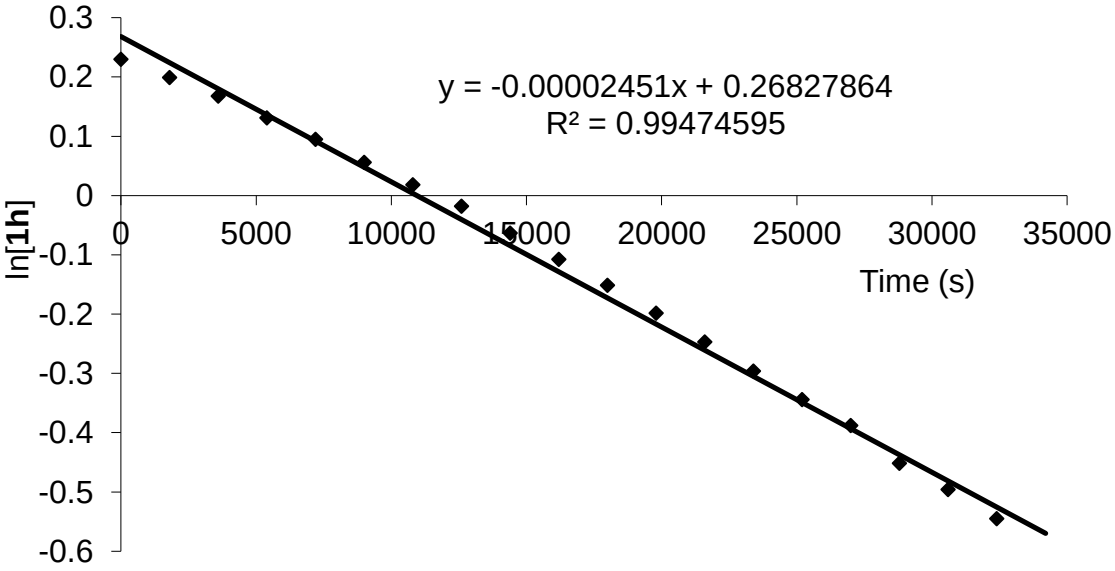


50 ^{o}C

Run 1:



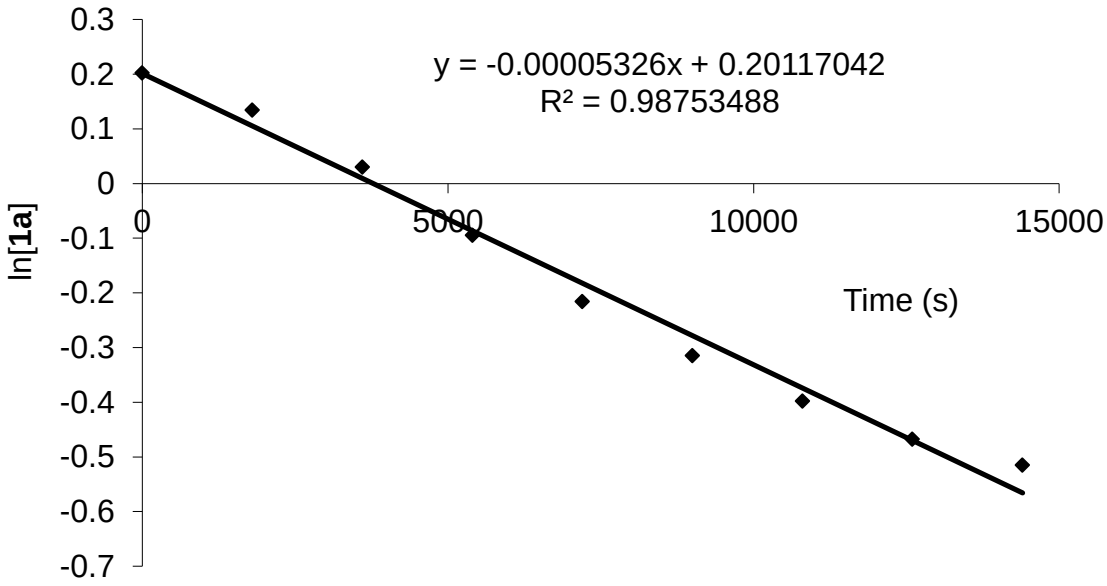
Run 2:



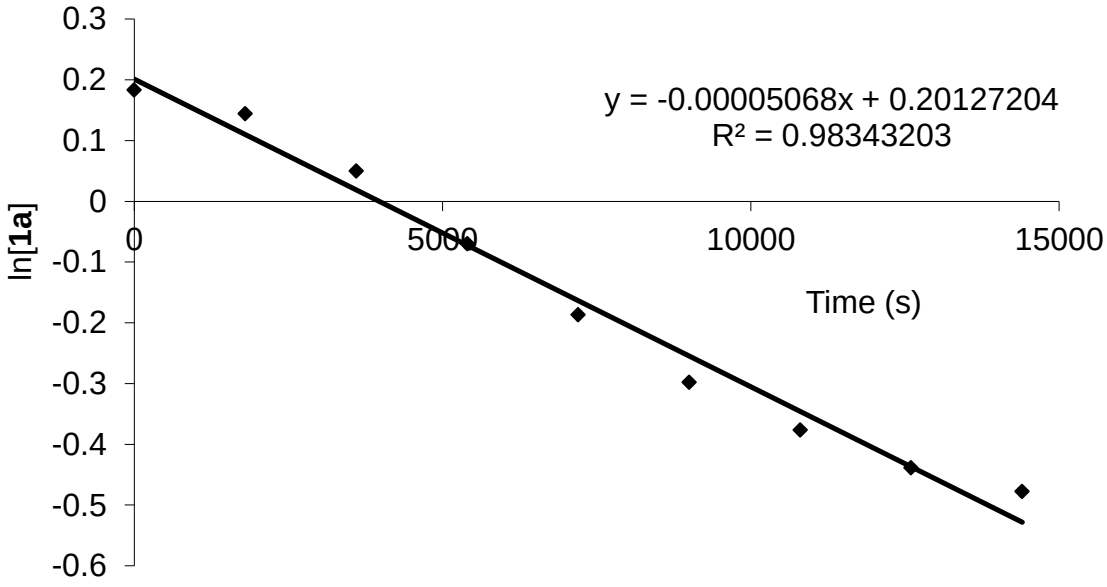
*First order kinetic plots for the varied temperature experiments in the synthesis of oxazolidinones **23a**/**24a** catalysed by complex **22***

80 °C

Run 1:

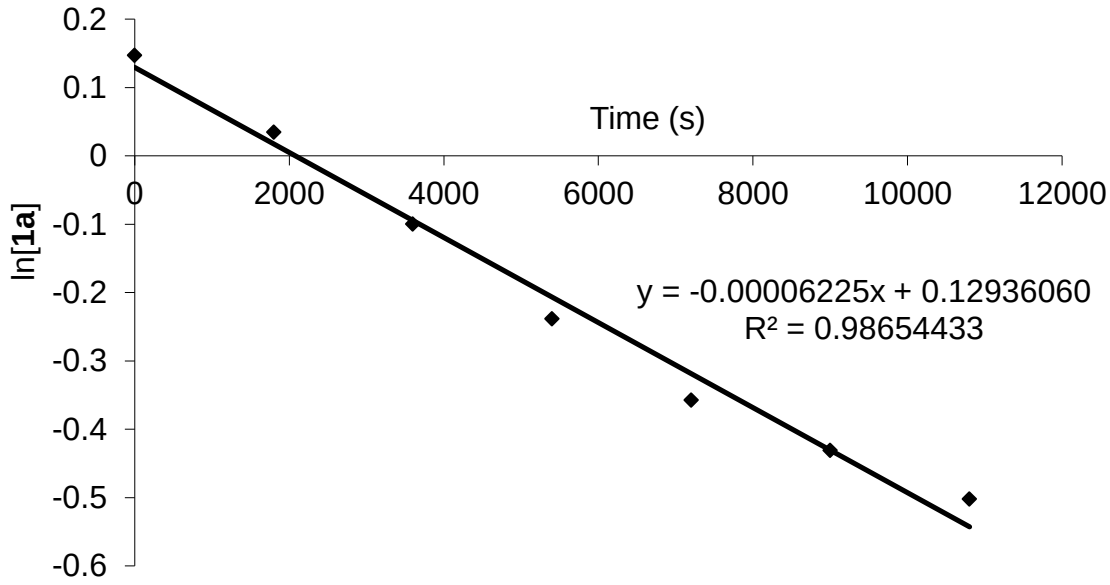


Run 2:

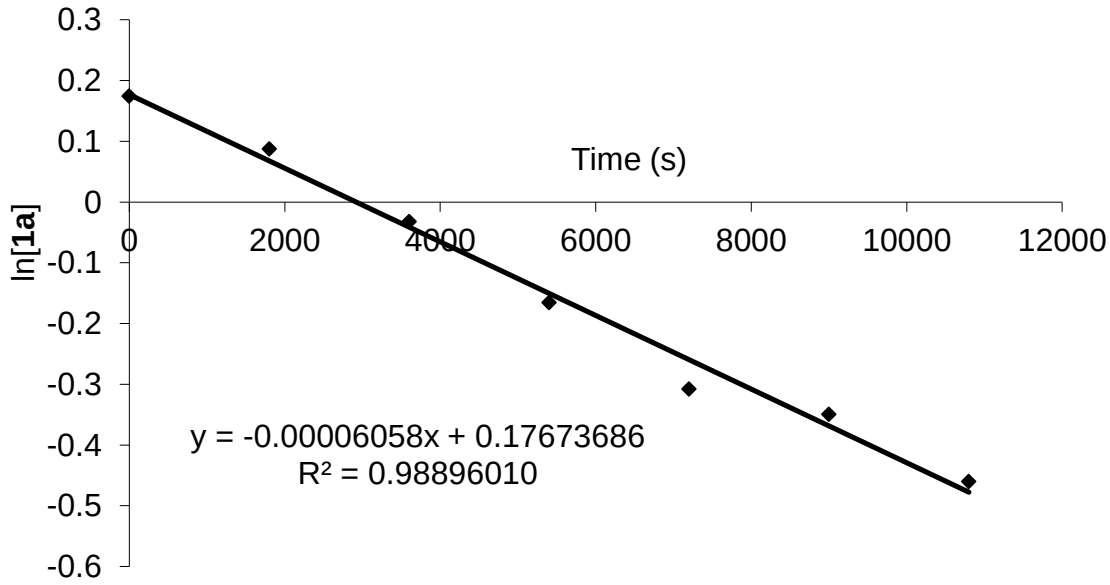


85 ^{o}C

Run 1:

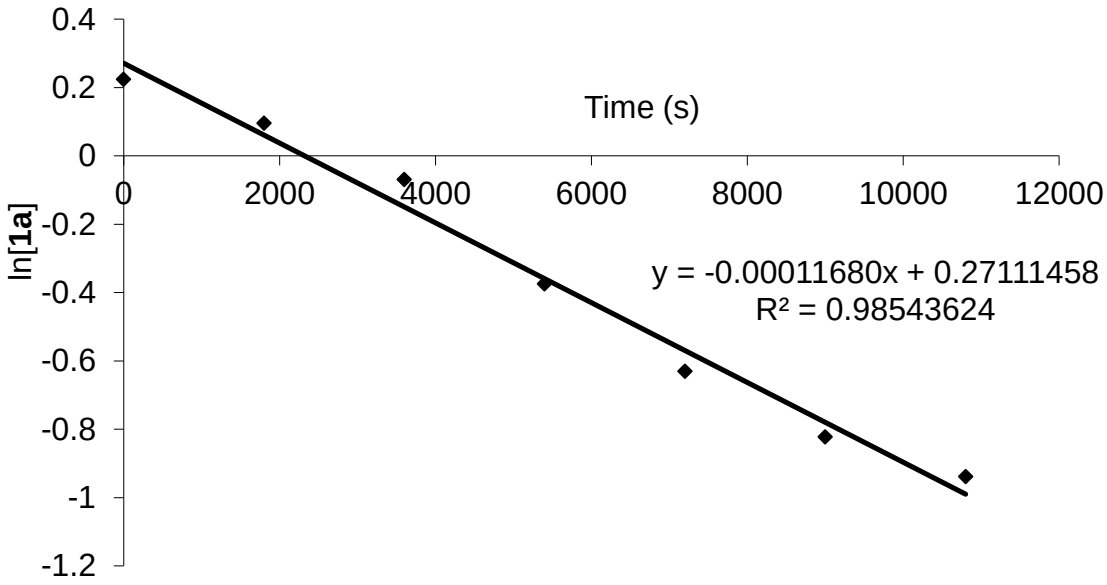


Run 2:

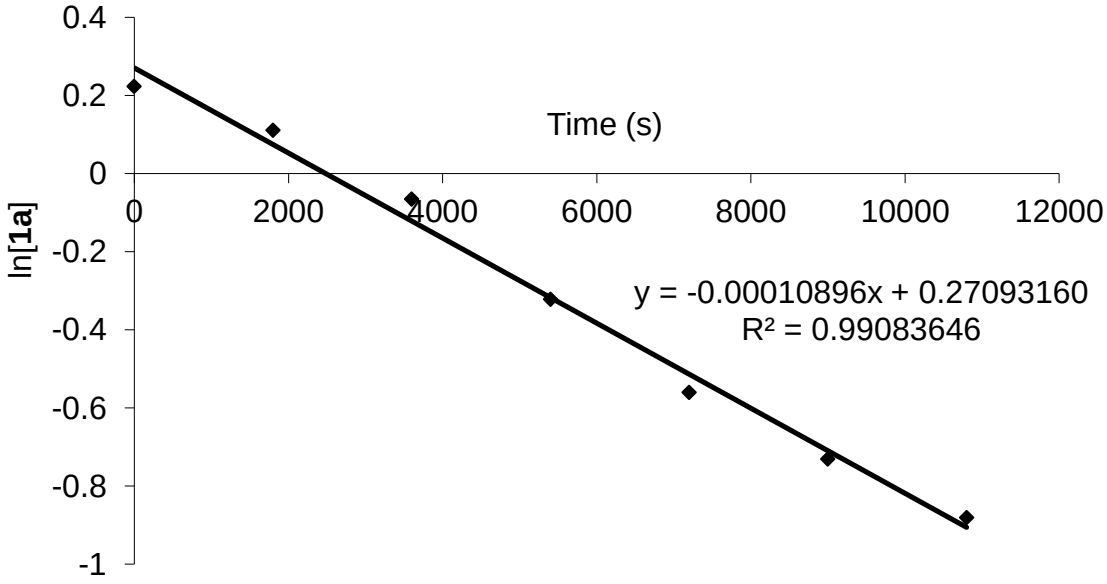


90 °C

Run 1:

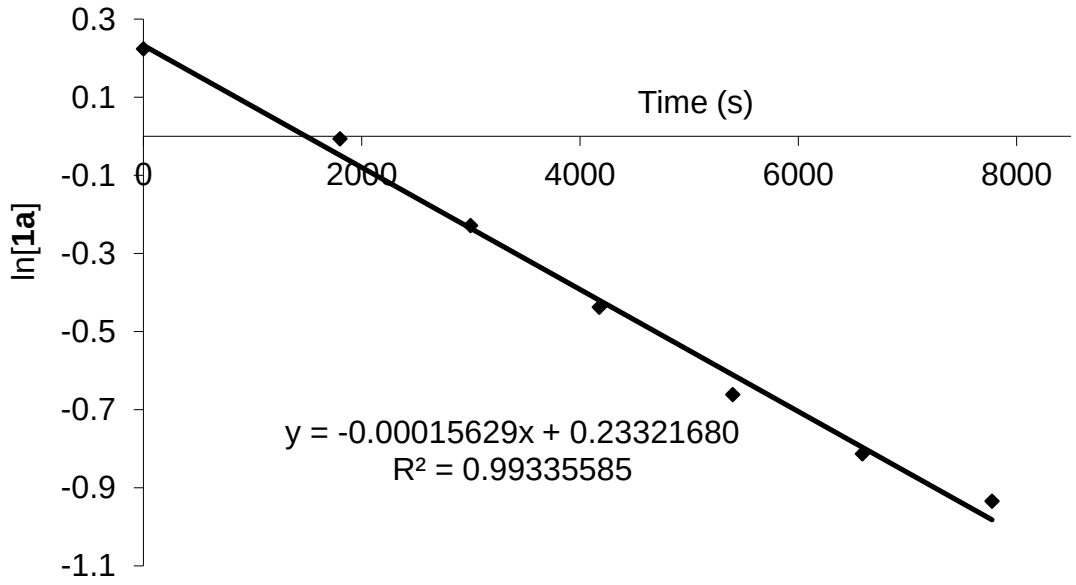


Run 2:

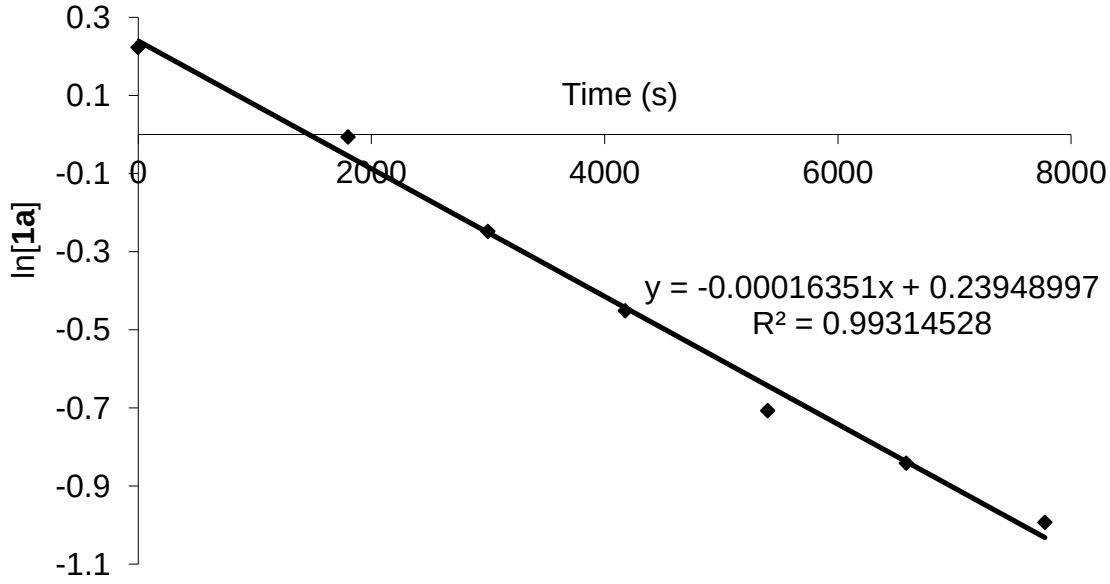


95 °C

Run 1:

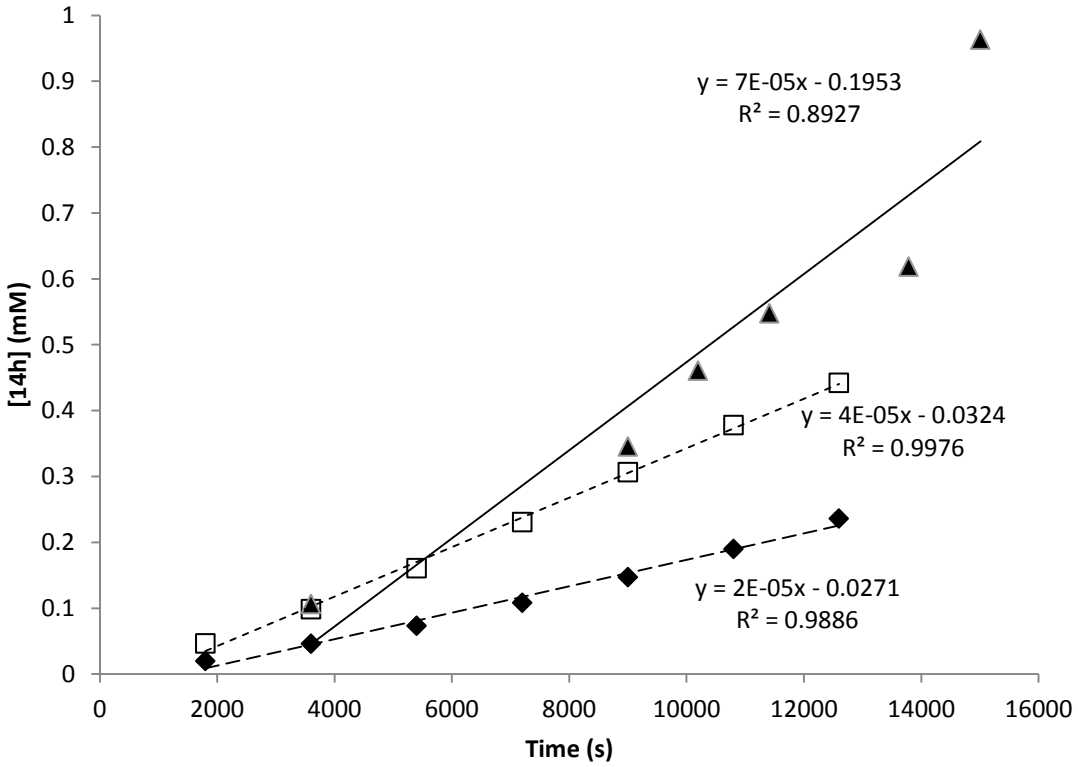


Run 2:

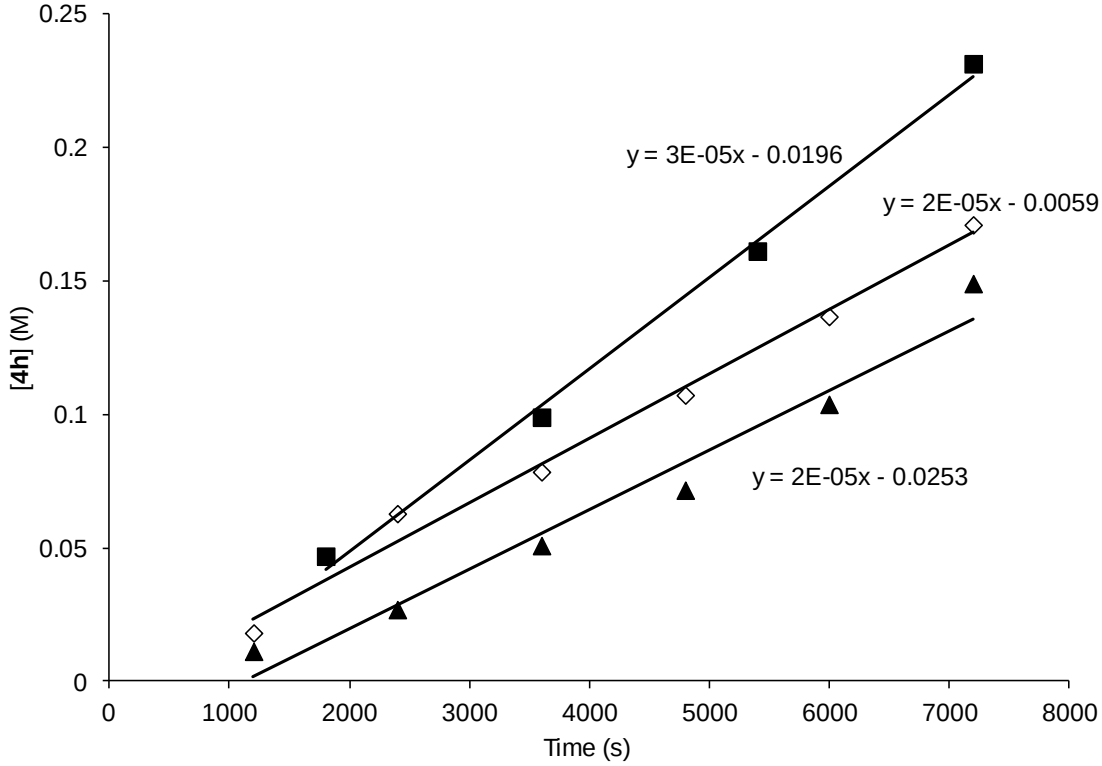


4.4 Complex 57 catalysed synthesis of dithiocarbonates

*Reaction profile plot for synthesis of thiocarbonate (**14h**) from phenyl glycidyl ether (**1h**) and CS_2, catalysed by titanium complex **57** and Bu_4NBr. [**57**] = 43 mM, [Bu_4NBr] = 71 mM, $[CS_2]_0$ = 2.6 M. Three different epoxide concentrations; filled diamonds $[\mathbf{1h}]_0$ = 0.7 M, empty squares $[\mathbf{1h}]_0$ = 1.4 M, filled traingles $[\mathbf{1h}]_0$ = 2.8 M.*



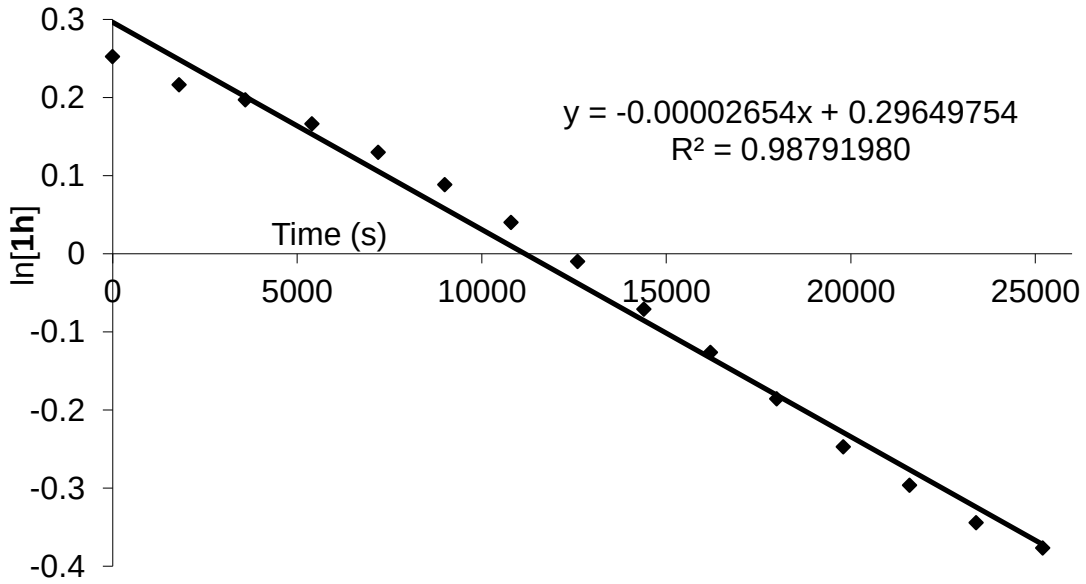
*Reaction profile plot for synthesis of thiocarbonate (**14h**) from phenyl glycidyl ether (**1h**) and CS_2, catalysed by titanium complex **57** and Bu_4NBr. [**57**] = 43 mM, [Bu_4NBr] = 71 mM, $[CS_2]_0$ = 2.6 M. Three different epoxide concentrations; empty diamonds $[\mathbf{1h}]_0$ = 0.7 M, filled squares $[\mathbf{1h}]_0$ = 1.4 M, filled traingles $[\mathbf{1h}]_0$ = 2.8 M.*



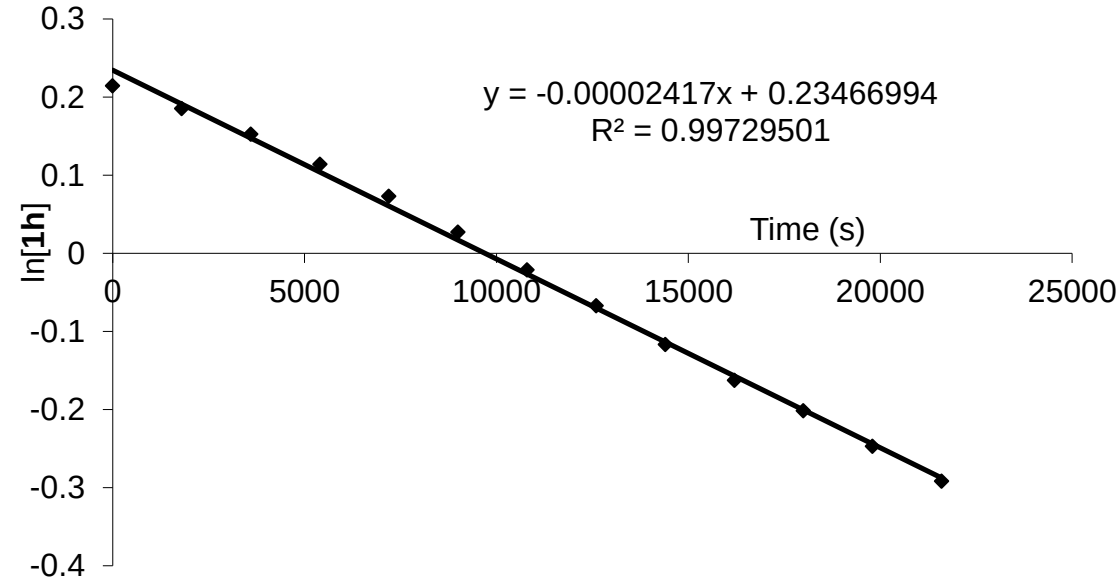
*First order kinetic plots for the synthesis of thiocarbonate **14h** catalysed by **57** and TBAB*

[**57**] = 28 mM (2 mol%)

Run 1:

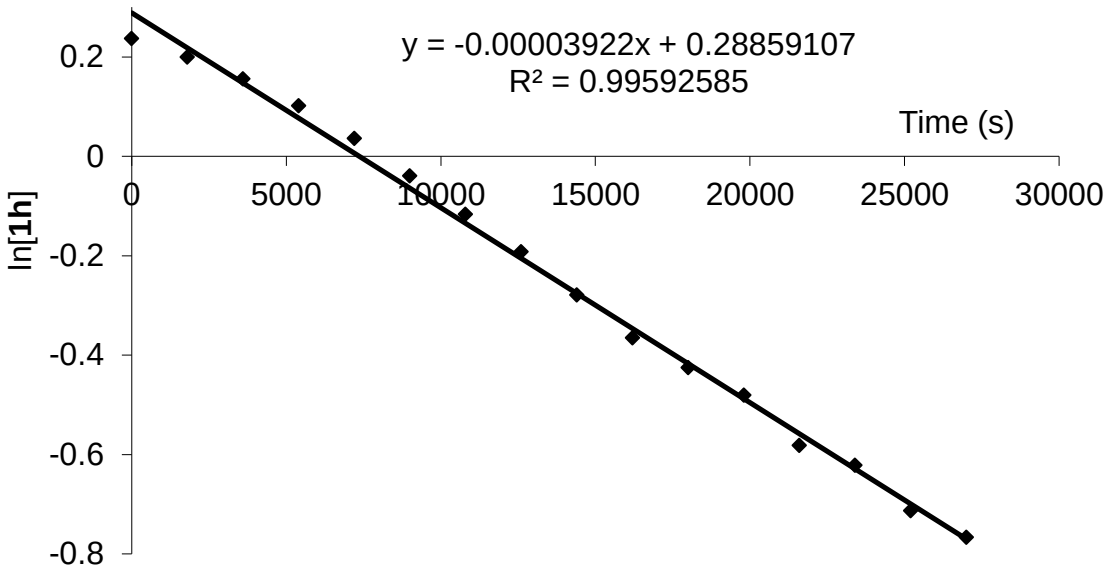


Run 2:

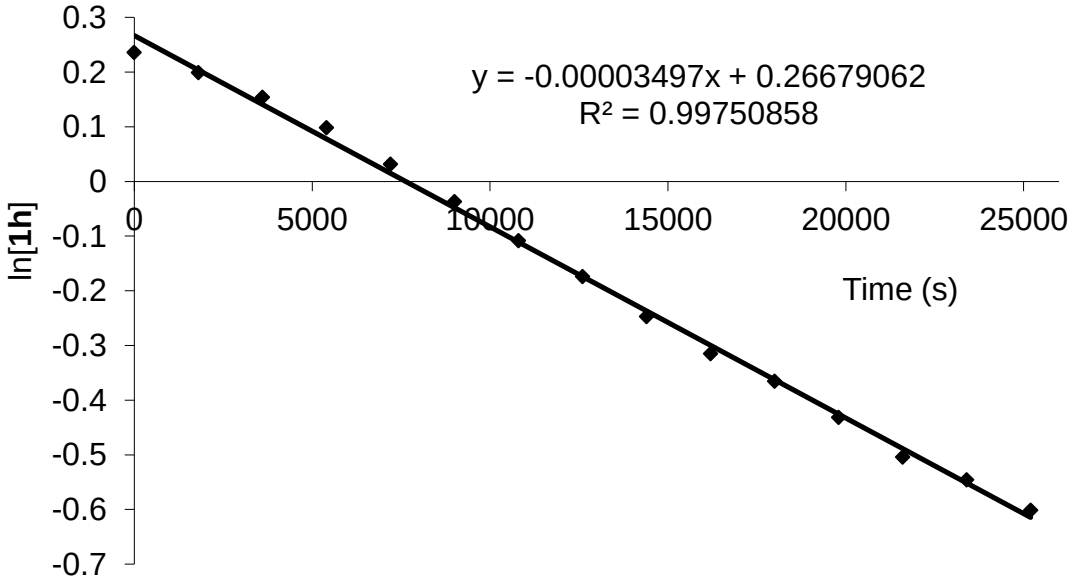


[**57**] = 43 mM (3 mol%)

Run 1:

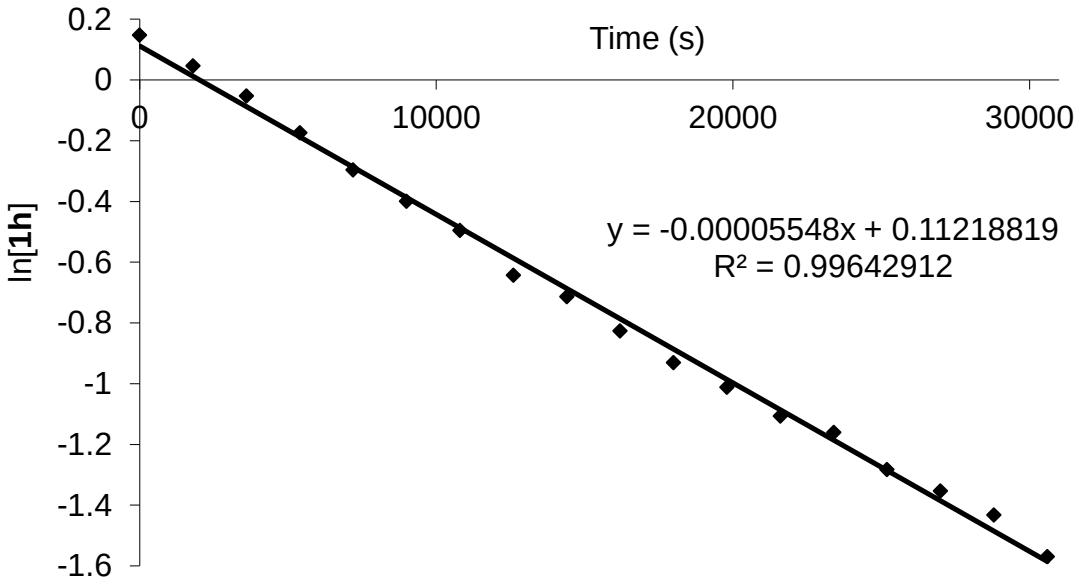


Run 2:

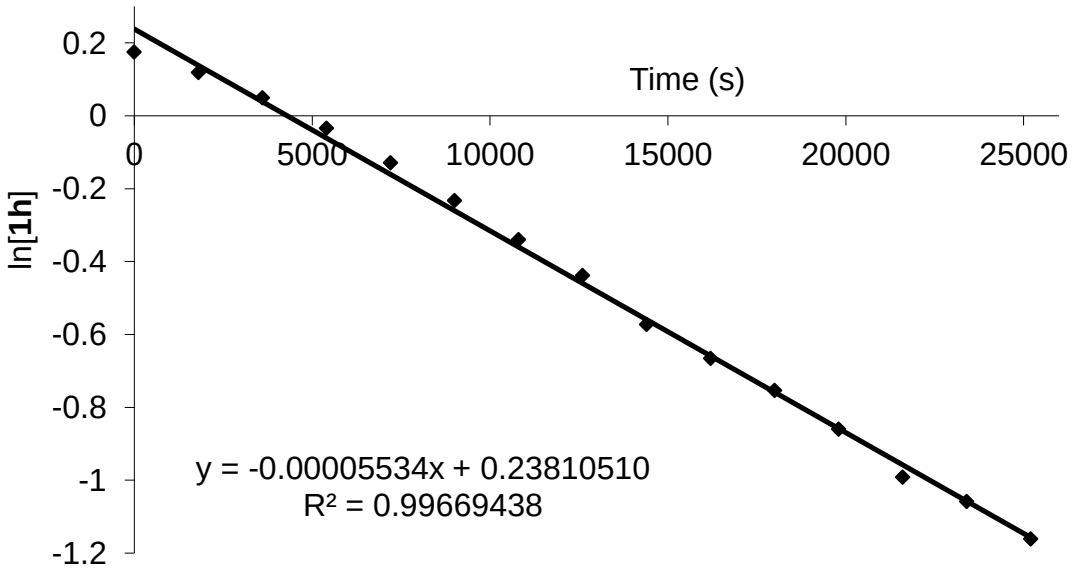


[**57**] = 57 mM (4 mol%)

Run 1:

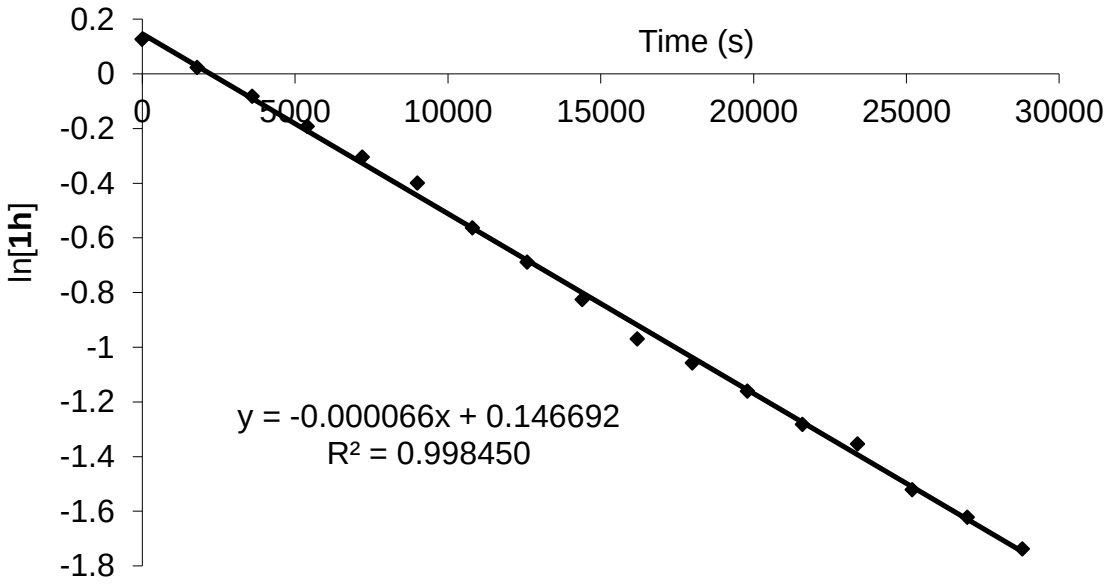


Run 2:

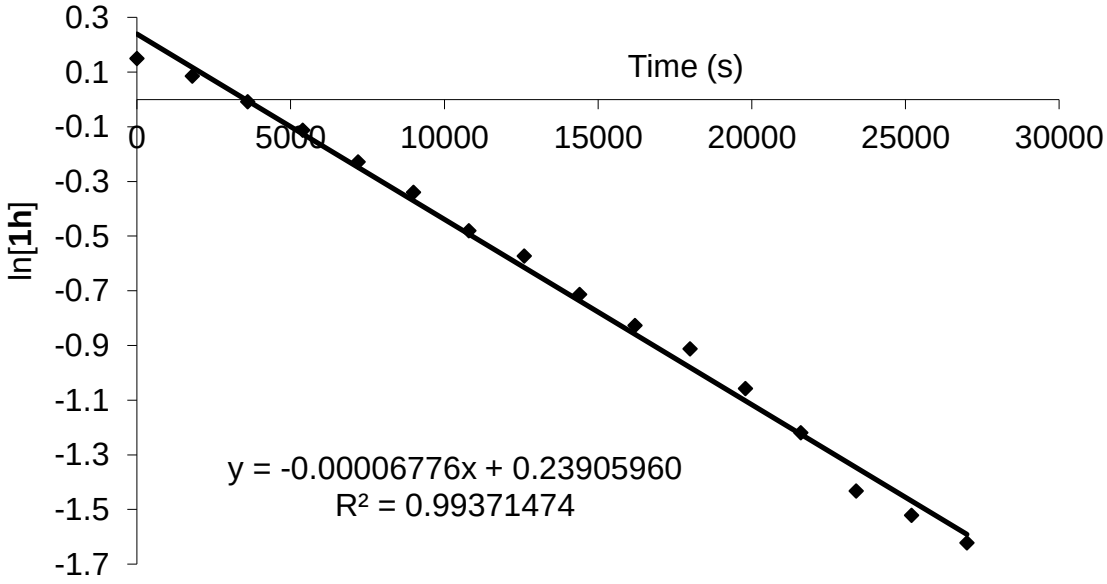


[**57**] = 71 mM (5 mol%)

Run 1:



Run 2:



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