Click Chemistry – A Route to Isocyanate-Free Polyurethane Coatings

By

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This thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

The preparation of a polyurethane liquid-applied membrane (LAM) coating system, which requires no isocyanate in the curing process, has been achieved. The synthesis of both azide- and alkyne-functional molecules affords the necessary building blocks to prepare both azide- and alkyne-functional polyurethanes.

The combination of the copper catalysed azide alkyne cycloaddition (CuAAC) reaction and azide/alkyne-functional polyurethanes allows for the creation of LAM systems, which can be prepared at ambient temperature and which do not have the disadvantages normally associated with traditional isocyanate-cured systems.

In the first instance, the PhD program was concerned with the preparation of azide/alkyne-functional molecules. Particular interest was given to the synthesis of azides and alkynes that contained alcohol or amine functionality. The subsequent azide/alkyne-functional amines and alcohols allow for their insertion into the preparation of polyurethane-based prepolymers.

Another aspect of the work was focused on various copper catalyst systems and their role in the preparation of LAM systems. A suitable catalyst system was found and applied to the curing of azide/alkyne-functional materials to provide a LAM system. The formulation of the non-isocyanate resins into LAM-type systems was attempted. Key performance criteria for the non-isocyanate systems, such as physical properties and the UV and light-stability of the formulated LAM, were measured alongside standard isocyanate-cured systems.

The necessary components for a truly non-isocyanate LAM system have been set in place. The improvement of the physical properties of the CuAAC crosslinked LAM systems will be extended in the future. The knowledge gained within this study has generated useful information which will potentially accelerate the transfer of CuAAC chemistry to a number of other technological areas, such as sealants and adhesives.

Acknowledgements

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I wish to thank my parents and my wife for their unerring support over the PhD project.

Abbreviations

2K	Two-component
4-DMAP	4-Dimethylaminopyridine
AEBDC	(O-(2-Azido-ethyl) S-Benzyl dithiocarbonate
AGE	Allyl glycidyl ether
$Al(OH)_3$	Aluminium hydroxide
ATRP	Atom-transfer radical polymerisation
BADGE	Bisphenol-A Diglycidylether
Bis A-DGE	Bisphenol-A Diglycidylether
Bis A-DTC	Bisphenol-A Dithiocarbonate
Bpy	2,2'-Bipyridine
$C18_6$TREN	*Tris* (2-dioctadecylaminoethyl) amine
CBC	Carbonylbiscaprolactam
COMBO	Carboxymethylmonobenzocyclooctyne
CTAs	Chain transfer agents
CuAAC	Copper-catalysed azide alkyne cycloaddition
DABCO	1,4-Diazabicyclo[2.2.2]octane
DGE	diglycidyl ether
DIBO	Dibenzocyclooctynyls
DIFO	Difluorinated cyclooctyne
DIPEA	N,N-Diisopropylethylamine
DMSO	Dimethyl sulfoxide

DPPD	2,2-Di(prop-2-ynyl)-propane-1,3-diol
DTC	Dithiocarbonates
DTC-Si	Dithiocarbonate-siloxane
EACDT	2-(3-Ethynylphenylazophenoxycarbonyl)prop-2-yl-9H-carbazole-9-carbodithioate
FT-IR	Fourier-transform infrared
GPC	Gel permeation chromatography
GPE	Glycidyl phenyl ether
HALS	Hindered Amine Light Stabiliser
HMTEA	1,1,4,7,10,10-Hexamethyltriethylenetetramine
HOAc	Acetic acid
ICI	Imperial Chemical Industries
Icy	N,N'-(Dicyclohexyl)imidazol-2-ylidene
IPDI	Isophorone diisocyanate
KOAc	Potassium acetate
MA	Methyl acrylate
MALDI-MS	Matrix-assisted laser desorption/ionisation - mass spectrometry
MDI	Methylene diphenyl diisocyanate
Me_2PPh	Dimethylphenylphosphine
MeCN	Acetonitrile
MEK	Methyl ethyl ketone

MMA	Methyl methacrylate
MPA	Methoxypropyl acetate
NaAsc	Sodium ascorbate
NBOC	Nitrobenzyloxycarbonyl
NCO	Isocyanate
NHC	N-Heterocyclic carbene
NMI	N-Methylimidazole
NMP	N-Methyl-2-pyrrolidone
NMR	Nuclear Magnetic Resonance
PBM	3,5-*bis*(Hydroxymethyl)-1-propargyloxybenzene
PETMP	Pentaerythritol tetra(3-mercaptopropionate)
Ph_3P	Triphenylphosphine
Phen	Phenanthroline
PhO-DTC	Phenoxy dithiocarbonate
PMA	Poly(methyl acrylate)
PMDETA	N,N,N′,N′′,N′′-Pentamethyldiethylenetriamine
PPG	Polypropyleneglycol
PTAs	Polytriazoles
PU	Polyurethane
RAFT	Reversible Addition-Fragmentation Chain Transfer
ROS	Reactive Oxygen Species

RT-FT-IR	Real time Fourier-transform infrared
SLP	Sika Liquid Plastics
SPAAC	Strain-Promoted Azide Alkyne Cycloaddition
sIMES	1,3-Dimesityl 4,5-dihydroimidazol-2-ylidenes
TATATO	Triallyl 1,3,5-triazine-2,4,6-trione
TBTA	*tris*-(Benzyltriazolylmethyl) amine
TEA	Triethylamine
THF	Tetrahydrofuran
THPTA	*tris*(3-Hydroxypropyltriazolylmethyl)amine
TiO_2	Titanium dioxide
$TMSN_3$	Trimethlsilyl azide
UV	Ultraviolet
VOC	Volatile Organic Component

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Chapter 2: Experimental

Chapter 3: Results and Discussion

1.0 Introduction and aims of the research

Sika Liquid Plastics (SLP) manufactures and sells liquid applied polyurethane (PU) prepolymers for roofing applications. The PU prepolymers can be chemically crosslinked and cured at ambient temperatures in a range of environmental conditions. The current technology employed by SLP involves using PU prepolymers that are isocyanate functional. Due to the high inherent reactivity of the isocyanate group these materials cure quickly and efficiently, in the presence of atmospheric moisture, to provide an impervious water barrier.

The current coating system is spray- or roller- applied in two coats and normally a polyester/glass fibre membrane is sandwiched between the two coatings (Figure 1.1). The spray/roller application results in an easy method of application, in addition the membrane adds strength and resistance to impact.

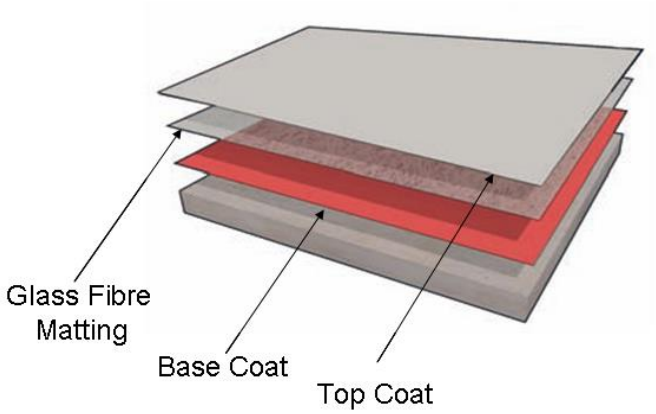

Figure 1.1: Schematic representation of current coating system used by SLP.

Despite the excellent performance of SLP products there is one significant drawback; the presence of monomeric diisocyanates.[1] The presence of residual isocyanate can have health implications for applicators working with the product, which includes occupational asthma.[2] The potential health effects that monomeric isocyanate-containing PU products can cause results in ever more stringent labelling regulations.[3] It is both the labelling and health implications of isocyanate containing materials which acts as the driving force for the investigation into alternatives to isocyanate-containing PU roof-coatings, ideally towards isocyanate-free PU systems. The challenge of the present PhD study was to investigate potential isocyanate-free PU materials, which would have scope for use in PU roofing materials.

There are a number of requirements that any isocyanate-free PU coating system must conform to if it is to have any potential as a commercially viable product. For example, the current technology employed by SLP can cure effectively at a range of temperatures from 4 °C to 80 °C. The tolerance towards a range of temperatures allows the product to be used globally in a range of climates and environments. Another advantageous aspect of the current technology is its fast cure, which allows for application in humid or wet climates. The previous two examples are illustrative of the need for an alternative chemistry which is as robust as the current technology, and therefore allows for use in a wide variety of environments and potentially unfavourable conditions. Other key considerations of any new isocyanate-free PU destined for roof coating applications include:

- Viscosity suitable for roller, spray and brush application
- Consider minimum use of Volatile Organic Component (VOC) in formulation
- Low toxicity in labelling
- Maintain existing PU performance characteristics
- UV, chemically and thermally stable
- Scalable
- Must be storage stable
- Lifetime of product should be comparable to current technology (25 years)

In essence, the research focus is on a robust coating chemistry that can be applied in a range of environments and conditions. The coating chemistry chosen should provide equal, if not better, performance than the current state-of-the-art in PU coatings for roofing, but also conform to the above mentioned performance requirements.

1.1 Polyurethanes

Polyurethanes are normally prepared from the step-growth polymerisation of diisocyanates with diols. This chemistry, and the resulting polymers, were developed by Otto Bayer as early as the 1940s.[4] The early commercial applications were based on millable elastomers, coatings and adhesives, however other applications based around flexible/rigid foams were subsequently found.[5]

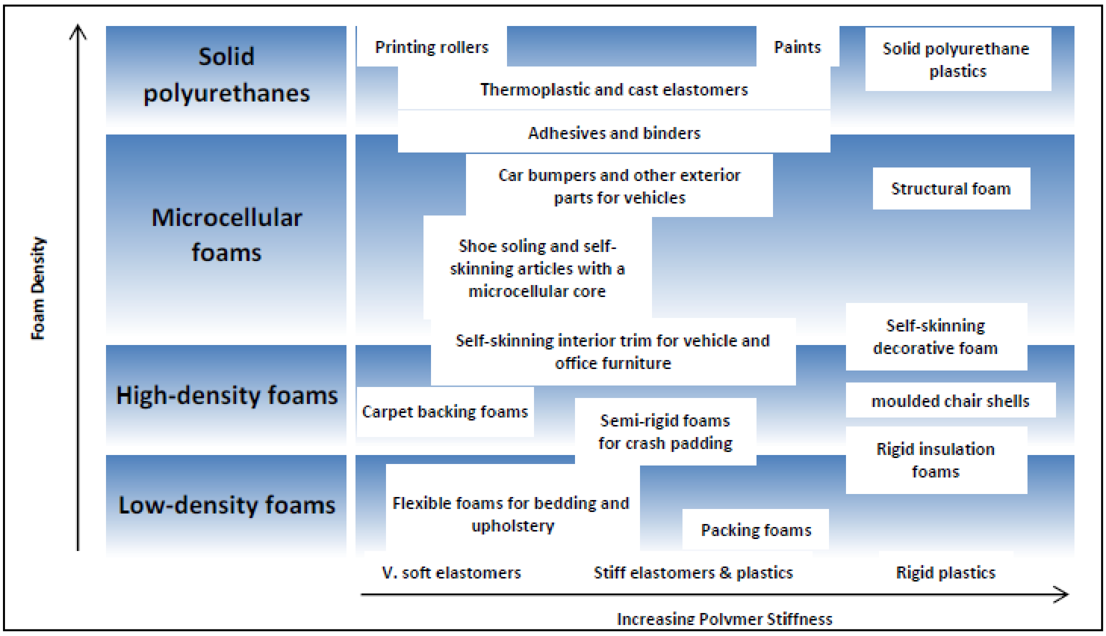

Figure 1.2: Applications of polyurethane materials. [5]

Polyurethane materials are now ubiquitous, with applications in a wide range of areas ranging from industrial building materials to fabrics containing polyurethane fibres.[5] Figure 1.2 indicates some of the applications that polyurethanes are commonly used in.

1.2 Isocyanate chemistry

The high reactivity of the isocyanate group is important to the chemistry of polyurethanes. Figure 1.3 shows the resonance forms of the isocyanate group; the most important of the resonance contributors is number **1.**

The electron deficiency of the carbon atom in resonance form **1** explains why the isocyanate group is susceptible to nucleophilic attack, with most reactions occurring at the carbonyl carbon.

Resonance form **4** becomes more important if the R group is aromatic. This further decreases the electron density on the carbon atom of the isocyanate group; it is for this reason that aromatic isocyanates are more reactive than their aliphatic counterparts.

Any electron-withdrawing substituent on the R group will reduce the electron density at the isocyanate carbon, thereby increasing the reactivity of the isocyanate to nucleophilic attack. In contrast, electron-donating groups will decrease the reactivity of the isocyanate.

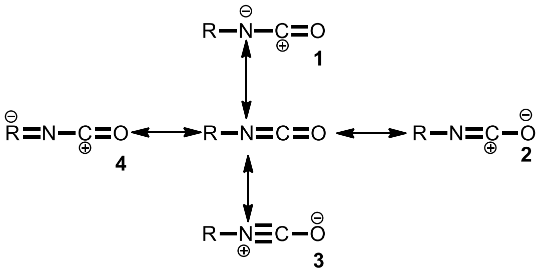

Figure 1.3: Resonance forms of the isocyanate functional group.

In the context of polyurethane chemistry, isocyanates react with molecules such as alcohols, water, amines, urea and urethanes. In addition, there is also the possibility of isocyanate reacting with itself. All of these important reactions are discussed in the following pages.

1.2.1 Isocyanates and alcohols

A key reaction, with respect to polyurethanes, is the reaction between an alcohol and an isocyanate group (Figure 1.4). The reaction product is known as a urethane when dealing with high molecular weight polymers.

The reaction between an alcohol and isocyanate is exothermic and reversible. Isocyanate and alcohol are returned. The back reaction for aliphatic urethanes begins at 250 °C, and for aromatic alcohols it begins at the lower temperature of around 200 °C.[6]

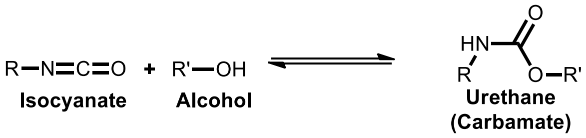

Figure 1.4: Reaction (reversible) between isocyanate and alcohol to form a urethane.

Blocked or hindered isocyanates can be prepared from the slower reaction of a phenol and an isocyanate; the resulting urethane that is formed dissociates readily at around 180 °C for aliphatic isocyanates and at 120 °C for the aromatic variants.[7] The resulting blocked isocyanates are more moisture resistant and better storage stable compared to the more reactive isocyanate. [7]

Blocked isocyanates can react with active hydrogen containing molecules in two different ways. The first involves thermal dissociation of the urethane to yield a free isocyanate, which can then react with an active hydrogen containing molecule. Alternatively, direct bimolecular displacement is another route by which a blocked isocyanate may react with an active hydrogen containing molecule. [7]

The alcohol and isocyanate reaction can be catalysed by the addition of bases (tertiary amines) and metal complexes (organo tin compounds). Catalysts are also available which decrease the temperature at which blocked isocyanates become deblocked.[7]

1.2.2 Isocyanates and water

The reaction of isocyanates with water to produce an amine and carbon dioxide is highly exothermic. This reaction proceeds *via* a carbamic acid which breaks down to the amine and carbon dioxide (Figure 1.5). The resulting amine then reacts with another molecule of isocyanate to form a symmetric urea. As carbon dioxide is formed during the reaction between isocyanate and water, this reaction has been used as the basis of a blowing agent in the production of polyurethane foams.

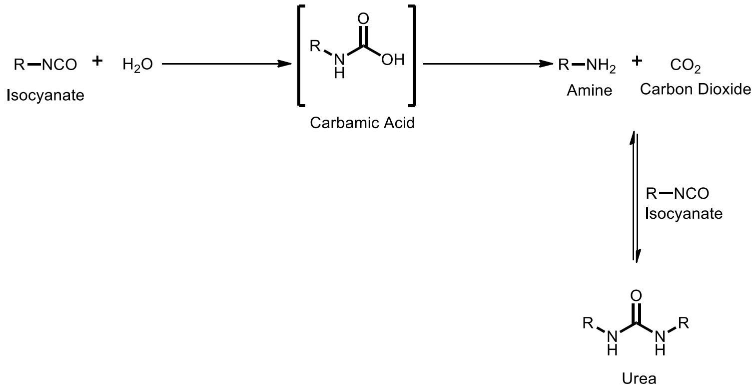

Figure 1.5: The reaction between water and isocyanate which generates amine and subsequently urea.

1.2.3 Isocyanates and amines

Isocyanates react with primary and secondary amines to yield di- and tri-substituted ureas, respectively (Figure 1.6). These conversions, as with the isocyanate/alcohol reactions, are exothermic. Diamines are used as chain-extending and curing agents in polyurethane production. The polyurea segments increase the potential for crosslinking.

The reaction between unhindered isocyanates with primary amines at room temperature can be up to 100 to 1,000 times faster than the reaction between primary alcohols and isocyanates. The reactivity increases with increasing basicity, therefore aliphatic amines are more reactive than aromatic amines.

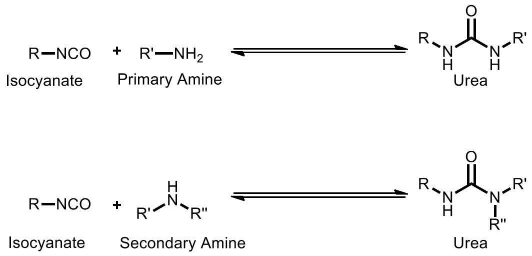

Figure 1.6: The reaction between primary and secondary amines with isocyanate to yield substituted ureas.

1.2.4 Isocyanates and other active hydrogen containing moieties

In addition to the alcohol, water and amine reactions outlined, isocyanates can take part in a range of reactions with other active hydrogen containing molecules such as ureas and urethanes, to form biurets and allophonate, respectively (Figure 1.7). These reactions require elevated temperatures of around 100-140 °C, and they have the effect of increasing the crosslinking within a system. The thermal stability of the linkages decrease as follows: Urea > urethane > biuret > allophonate. Aliphatic compounds have enhanced thermal stability over their aromatic counterparts.[8]

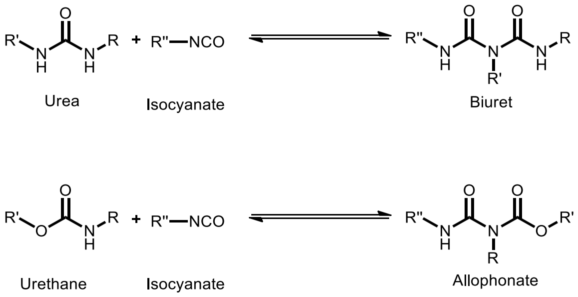

Figure 1.7: Reversible formation of biuret and allophonate linkages.

1.2.5 Isocyanates and isocyanates

Isocyanates are capable of reacting with themselves to form dimers (**5**) and trimers (**6**) as well as uretonimines (**8**) *via* a carbodiimide (**7**) (Figure 1.8). [8]

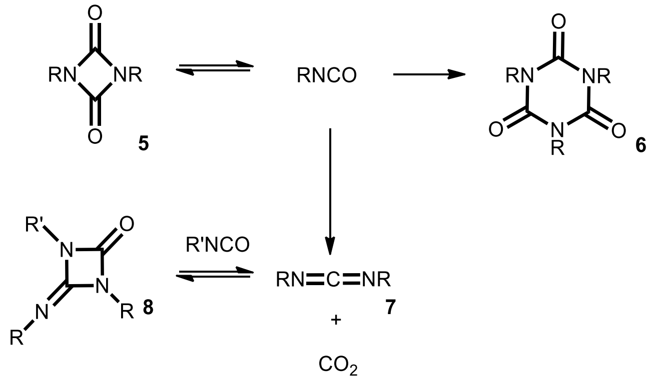

Figure 1.8: Reaction products of isocyanate when reacted with itself.

1.3 Preparation of polyurethanes

The three main components of a PU coating are polyol, diisocyanate and a chain-extending agent. It is because of the wide range and availability of these three building blocks that polyurethanes can be engineered to have a broad range of properties and benefits.[5]

PUs are prepared in what could be called a rearrangement polymerisation between a diisocyanate and a multifunctional alcohol species. PUs became industrially relevant in 1947 as Otto Bayer investigated these materials as an alternative to DuPont’s patented Nylon-6,6.[4,5]

Based on the chemistry shown in the previous sections it can be envisioned how PU pre-polymers that are end-capped with isocyanates can then be chain-extended using water, glycols and amines. The reaction with water evolves carbon dioxide and the crosslink is a urea linkage, from the carbamic acid. An alternative is the crosslinking with a diol to form two urethane linkages. The same process can be used for a diamine and the result is a double urea linkage between the two pre-polymers (Figure 1.9).

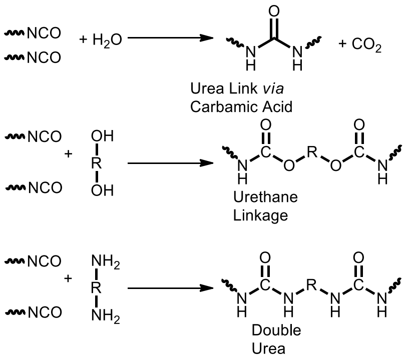

Figure 1.9: Chain extension using water, diols or diamines.

1.3.1 Diisocyanates

The diisocyanate component of a PU can be aliphatic or aromatic; typical examples are shown in Figure 1.10. The reactivites tend to differ for these isocyanates with the aromatic diisocyanates being typically the more reactive of the two classes. The aromatic monomers have poor ultraviolet and oxidative resistance compared to the aliphatic monomers.[9] The choice of monomer is important as the aromatic monomers lend the polymer a more rigid backbone.

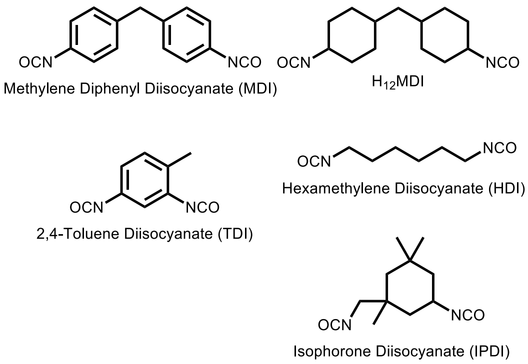

Figure 1.10: Typical diisocyanate monomers used in the polyurethane industry.

1.3.2 Polyols, chain extenders and catalysts

There is a wide range of diols that can be used, from short-chain aliphatic diols, which can be used as chain extending agents, to polyether, polyglycol and polycarbonate polyols.[8] Both diamines and diols can be used as chain extenders. They act as hard segments in the polymer chain due to their short-chain aliphatic structure which leads to polymers which are more rigid. Water can also be used as a chain extender. Catalysts are chosen for their ability to drive a specific reaction between the isocyanate and either water or polyol. The types of catalyst used include tertiary amines and organometallic species.[8]

1.4 Alternative synthetic routes to isocyanate-free polyurethane-based materials

In most examples from the literature concerning alternative synthetic routes to non-isocyanate PU materials, researchers are interested in replacing the isocyanate/alcohol reaction which is important in the traditional route of preparing linear PUs.[10] The aim of the present PhD study was to investigate methods of crosslinking PU prepolymers without using isocyanate functionality. Therefore, there is some overlap between the two research streams. Previously investigated routes for the preparation of non-isocyanate PUs include cyclic carbonate[11] and silane-terminated PU polymers.[12]

1.4.1 Blocked isocyanates

Blocked isocyanates have been mentioned briefly already. They are of interest to researchers because, upon thermal dissociation, they essentially provide a molecule with isocyanate functionality without the negative health aspects and increased reactivity (more side-products) associated with free isocyanate.[13]

Blocked isocyanates are also of interest when two-component (2K) formulations are disfavoured because of the need to mix them near to or at the site of application and the relatively short pot life.[13] Conveniently, blocked isocyanates can be mixed with co-reactants and no significant reaction will occur, until the isocyanate is liberated from the blocked isocyanate *via* thermal dissociation. However, there are some issues with the use of blocked isocyanates, such as the high temperatures needed for curing and the possibility of any toxic blocking agents escaping.

Unfortunately, the technical requirements of the current PhD program prohibit the use of a heat source (which could potentially pose a fire hazard) in the final formulated product. Nevertheless, the chemistry of blocked isocyanates is interesting and has been investigated by a number of groups as a route to non-isocyanate based coatings and polyurethanes.[7,13,14,15,16]

Maier *et al.* were interested in isocyanate- and phosgene-free routes towards the preparation of PUs. The approach taken by Maier was to use carbonyl*bis*caprolactam (CBC) (Figure 1.11) which could react with hydroxyl and amine functional molecules to afford caprolactam blocked isocyanates.[16]

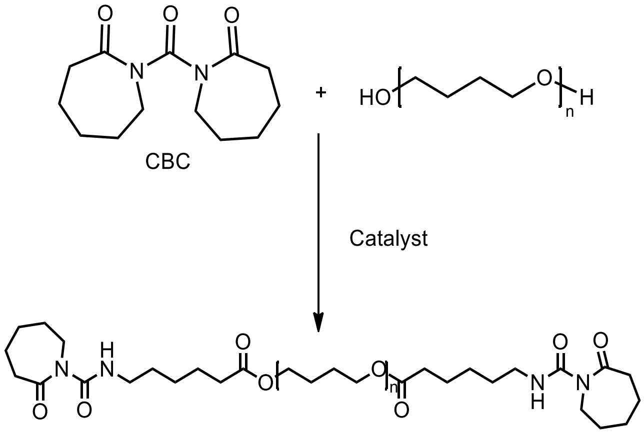

Figure 1.11: Example of the reaction of CBC with a diol.[16]

CBC was reacted with amine and hydroxyl functional molecules in either a ring-opening pathway or a ring-elimination pathway. Amine functional nucleophiles tended to react in a ring-elimination pathway (eliminating a molecule of caprolactam) whereas hydroxyl nucleophiles reacted in a ring-opening pathway. Ultimately, the chemistry afforded isocyanate-free ureas and urethanes. The unfortunate aspect of this approach is that there is a need for elevated temperatures (100-150 °C) and the presence of catalyst (in the case of hydroxyl nucleophiles) to promote the reaction.[16]

Ubaghs *et al.* used the novel blocked isocyanate **9** (Figure 1.12), and the reactions **9** underwent with amino alcohols, to prepare AB-type monomers.[14] Interestingly, Ubaghs noted that **9** can function in two ways. The first is to act as an activated urethane where upon attack by a nucleophile a tetrahedral intermediate is formed, which is then followed by elimination of a blocking agent. The second function is that of an intramolecular blocked isocyanate which dissociates to yield isocyanate functionality (which is subsequently reacted with a nucleophile) and accordingly a urethane group where the blocking group becomes part of the product.[14]

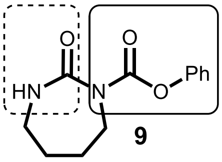
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Figure 1.12: Novel isocyanate capable of acting as an activated urethane (lined box) and also an intramolecular blocked isocyanate (dashed box).[14]

The new AB-type monomers formed could then undergo polycondensation reactions to afford poly (urea urethanes). Unfortunately, the polycondensations required elevated temperatures and the presence of catalyst to form the poly(urea urethanes).[14] Interestingly, the reaction of **9** and the amino alcohols was carried out at ambient temperature and there was no need for a catalyst.[14] The reaction between the activated urethane **9** and the amine of the amino alcohol could be a potential route for crosslinking PU polymers which are terminated with **9** and reacting with multi-functional amines to yield a crosslinked polymer.

Although the need for elevated temperatures is prohibitive, there has been some progress in removing the need for thermal dissociation and regenerating isocyanate *via* chemical means. Blencowe *et al*. report the synthesis of linear polyurethanes, prepared from symmetrical diisocyanates generated from a blocked isocyanate.[15] The blocking agent used in this study was of the 1,2,4- dithiazolidine-3,5-dione type (Figure 1.13) which was then incorporated into A_2- type monomers.

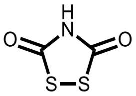

Figure 1.13: 1,2,4- Dithiazolidine-3,5-dione blocking agent.[15]

The A_2- type monomers (Figure 1.14) were co-polymerised with a range of diols in the presence of triphenylphosphine. The polymerisations were carried out in anhydrous dioxane under reflux for 48 hours, and resulted in a number of PU products (Figure 1.15).

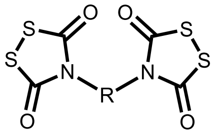

Figure 1.14: A_2- type monomer, blocked with 1,2,4-dithiazolidine-3,5-dione.[15]

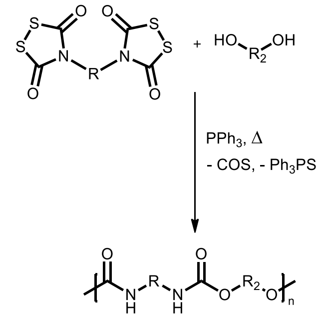

Figure 1.15: Polyurethane prepared *via* the use of the blocked isocyanates. [15]

Blencowe *et al.* have successfully used blocked isocyanates that are de-blocked using chemical means (PPh_3), but there is a need for elevated temperatures during the preparation of the polyurethanes. There has been no investigation into how the chemically liberated isocyanate reacts with an alcohol or amine at ambient temperatures. This could possibly be one method for crosslinking polyurethane prepolymers which have been functionalised with dithiazolidine dione moieties; in the presence of triphenylphosphine the dithiazolidine dione is converted into isocyanate *in-situ,* and the latter can then undergo a rapid reaction with an amine or alcohol.

A possible issue with this method of polyurethane preparation is the release of the toxic and flammable carbonyl sulphide. Carbonyl sulphide is converted into carbon dioxide and hydrogen sulphide in the presence of atmospheric water, which is liable to cause foaming or bubbling (as CO_2 is released) in any product this chemistry may be formulated into.

1.4.2 Cyclic carbonates

Cyclic carbonates can be described as reactive intermediates which can react with a range of aromatic and aliphatic amines, alcohols and thiols. Cyclic carbonates have been used previously to alkylate active hydrogen containing aromatics, such as phenol, thiophenol and aniline. The reactions involve the nucleophilic attack on the alkyl carbon followed by the loss of carbon dioxide, which results in the formation of the alkylated active hydrogen species in a 50/50 mixture of primary and secondary alcohols. These alkylations typically require elevated temperatures of 100-200 °C.[17]

Five-membered ring cyclic carbonates can react with primary and some secondary amines at room temperature, but in most cases elevated temperatures (30-50 °C) are required. In addition, the reaction between a cyclic carbonate and amine results in an exotherm,[17] which requires careful addition of one component to another. The use of some alkalis can be used to promote the reaction at sub-ambient temperatures.[18]

In most cases presented in the literature, there is a requirement for elevated temperatures (80-120 °C), to either promote the amine/cyclic carbonate reaction or to speed up the curing process of any coating system based upon this chemistry.[19,20] This requirement renders the cyclic carbonate chemistry unacceptable for any application where elevated temperatures are prohibited. In addition, the polyhydroxyurethanes formed from the reaction of cyclic carbonates and amines are reported to have high water absorption, which is another drawback for applications that require materials which are resistant to hydrolysis.[21]

Cyclic carbonates have been investigated as alternatives to the conventional isocyanate/alcohol reaction of preparing urethane-containing materials. Hydroxypropylcarbamate was prepared *via* the reaction between propylene carbonate and ammonia (Figure 1.16).[22]

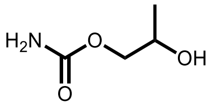

Figure 1.16: Hydroxypropylcarbamate, used to prepare urethane functional polymers. [22]

The hydroxypropylcarbamate was then reacted with polyacrylates containing isocyanate functionality, to afford carbamate functional polymers. The carbamate functional polymers were then crosslinked using crosslinking agents containing methoxy functionality (Figure 1.17). The subsequent coatings were baked at 140 °C for 30 minutes.

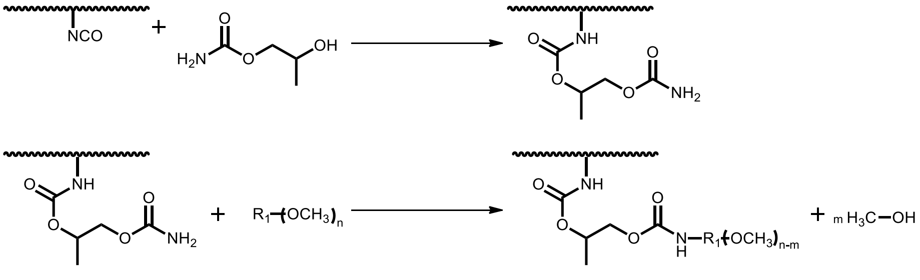

Figure 1.17: Urethane cross linked coating, avoiding the use of isocyanate in cross-linking step.[22]

The use of hydroxypropylcarbamate resulted in the formation of a urethane cross-linked coating, without using the conventional isocyanate/alcohol chemistry. This route to non-isocyanate coatings avoids the use of isocyanates, and the subsequent health hazards associated with them, as the isocyanate is converted safely under laboratory conditions to a carbamate functional polymer.

Another example of cyclic carbonates being applied within a non-isocyanate route to polyurethanes was investigated by King Industries.[23] The researchers replaced a toxic diisocyanate with its equivalent diamine; the diamine could then be reacted with cyclic carbonate to yield difunctional hydroxyalkyl urethanes (Figure 1.18).

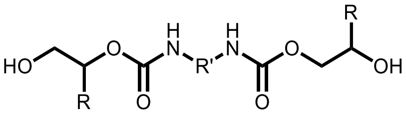

Figure 1.18: Difunctional hydroxyalkyl urethane.[23]

The difunctional hydroxyalkyl urethane acts as a blocked isocyanate, which when deblocked at temperatures of 160 °C in the presence of a tin catalyst and polyester polyol resulted in the desired polyurethane.[23]

Glycerol carbonate is an interesting cyclic carbonate molecule since it contains both hydroxyl and cyclic carbonate functionality. Since it contains an active hydrogen containing functional group (hydroxyl), it can be reacted with isocyanates to provide cyclic carbonate functionalised urethanes (Figure 1.19). Researchers from ICI made use of this chemistry to react glycerol carbonate with multifunctional, polymeric MDI, to create a multifunctional cyclic carbonate.[24] The multifunctional cyclic carbonate can then be reacted with aliphatic diamines to prepare polyurethane resins (Figure 1.19).[24]

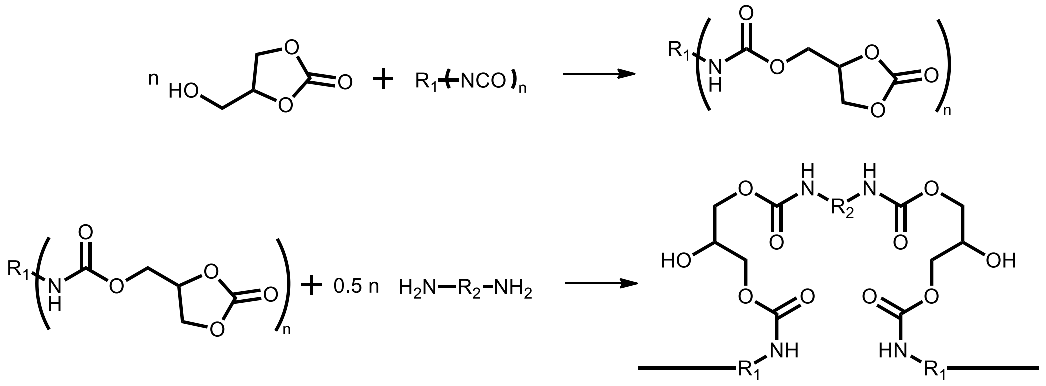

Figure 1.19: Glycerol carbonate providing a route to a crosslinked polyurethane resin.[24]

Cyclic carbonates have been reacted with isophorone diamine to prepare amine-containing polyurethanes which can be used as crosslinking agents.[25] The authors of this work made use of the significant difference in reactivity of the aliphatic amine compared to the cycloaliphatic amine of isophorone diamine (Figure 1.20), such that only the aliphatic amine reacts with the cyclic carbonate. The remaining cycloaliphatic amine is then capable of reacting with epoxy resins to provide urethane materials not requiring the use of toxic isocyanate in their production.[25]

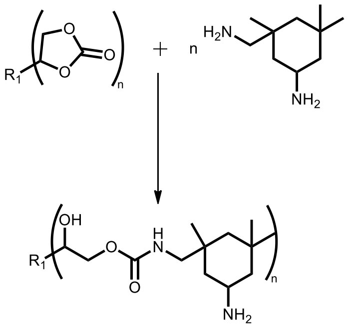

Figure 1.20: Selective reaction of an aliphatic diamine and a cyclic carbonate to yield a urethane product which can react further with epoxy-type molecules.[25]

1.4.3 Dithiocarbonates

Analogous to the preparation of cyclic carbonates *via* epoxides and carbon dioxide, carbon disulphide can be reacted with epoxide groups to deliver five-membered ring cyclic dithiocarbonates (DTC).[26] The reaction of DTC with amines proceeds smoothly to produce thiourethanes bearing a thiol moiety. *Bis*(cyclic dithiocarbonates) can react with diamines to yield poly(mercaptothiourethane)s; the poly(mercaptothiourethane)s can then be further modified *via* oxidative coupling of the thiol groups to yield crosslinked polymers. In addition, the thiol group can be further functionalised *via* acetylation of the thiol group.[26]

Suzuki *et al.* prepared trifunctional, five-membered ring dithiocarbonates and cyclic carbonates (Figure 1.21) and described their reactions with diamines to yield thiourethane and hydroxyurethane polymers, respectively.[26] The epoxide was reacted with carbon disulfide in the presence of LiBr in acetonitrile for 24 hours to precipitate the trifunctional, five-membered ring cyclic dithiocarbonate in an 84% yield.[26]

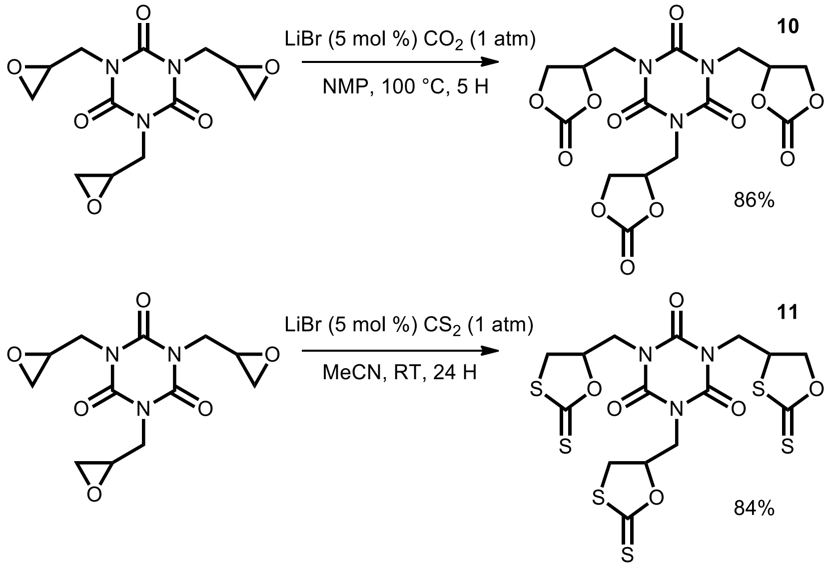

Figure 1.21: Preparation of trifunctional cyclic carbonate and dithiocarbonate.[26]

Crosslinking reactions were carried out with *p*-xylenediamine or hexamethylenediamine with **10** and **11**. The cyclic carbonate variant was reacted with the diamines in DMSO at 100 °C for 48 hours. The dithiocarbonate was reacted with diamine in THF at room temperature for 24 hours, followed by acetylation with acetic anhydride and triethylamine to afford the crosslinked polymer in an 80% yield (Figure 1.22). Longer reaction times (48 hours) enhanced the yield of crosslinked polymer.

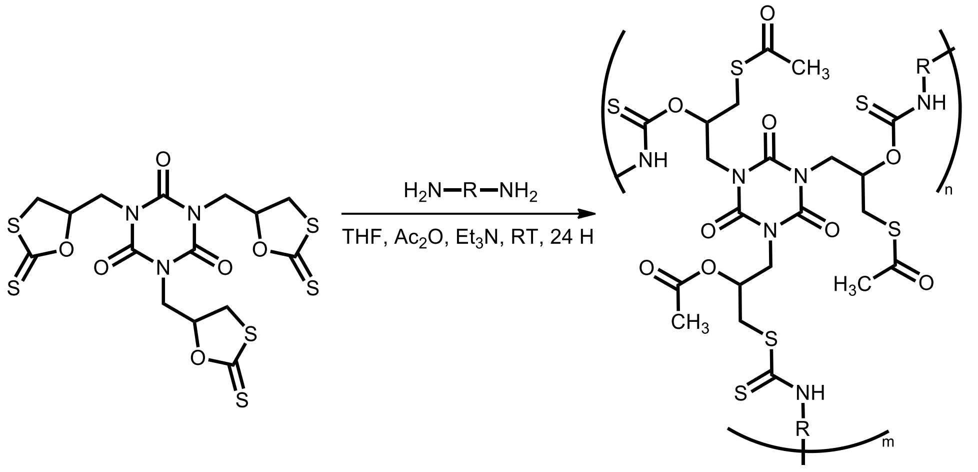

Figure 1.22: Reaction between a diamine and tri-functional dithiocarbonate to afford a crosslinked polymer.[26]

The use of cyclic and dithiol carbonates is one method of preparing hydroxyurethanes and thiourethanes *via* a non-isocyanate route. As a crosslinking method, the reaction between the carbonate tends to be slow (24 to 48 hours). The cyclic dithiocarbonates are more reactive than cyclic carbonates, as evidenced by the absence of heat needed during the ring-opening of the dithiocarbonate.[26]

Uenishi *et al.* made use of a DTC-siloxane hybrid (DTC-Si) (Figure 1.23) which underwent the previously described ring-opening with amine functional molecules, irrespective of the siloxane moiety. The siloxane moiety in the side-chain can then undergo self-condensation under exposure to moisture, which provides a facile method to crosslink DTC-derived polymers.[27]

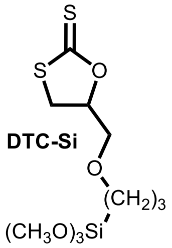

Figure 1.23: Dithiocarbonate with pendant siloxane moiety.[27]

DTC-Si was used to prepare poly(thiourethanes)s having siloxane side-chains. The resulting thiols were reacted in a polyaddition reaction with diisocyanates (Figure 1.24). The polyaddition was performed for 40 hours to ensure sufficient chain-extension in the late stages of polymerisation.

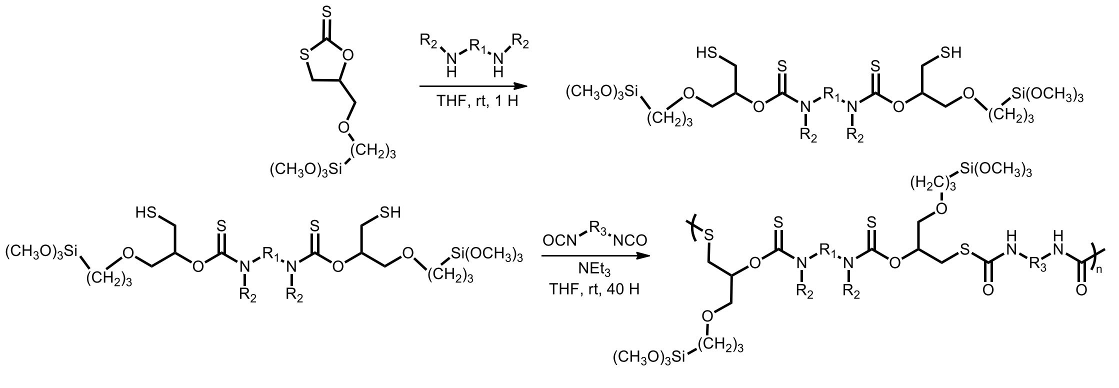

Figure 1.24: Incorporation of siloxane functionality into a polyurethane chain *via* the use of dithiocarbonate.[27]

The resulting polymers were soluble in organic solvents, such as tetrahydrofuran and chloroform, but upon storage in air they underwent hardening because of the crosslinking condensation of the siloxane groups in the side-chains. The poly(thiourethane)s were coated on a glass surface and baked at 50 °C for 12 hours under air.[27]

This chemistry is attractive because it does not require isocyanate chemistry to cure the resulting polymers. Instead, the crosslinking reaction is carried out *via* the siloxane moiety in the side-chain. The deficiencies of this system are based on storage problems associated with the siloxane moiety. In addition, the curing/baking reaction was carried out at 50 °C for 12 hours; this increased temperature, required for full cure, is another practical deficiency of this system.

The use of multifunctional amines and multifunctional epoxides is widely applied in many curing systems; one drawback is the reaction's moderate curing rates.[28] DTC was again used by Horikiri *et al.* in an epoxy/amine curing system, and the accelerating effects of the DTC investigated. Since the corresponding thiourethane formed (from the reaction of DTC and amine) has a thiol group, it can take part in other reactions with epoxide or isocyanate electrophiles.[28]

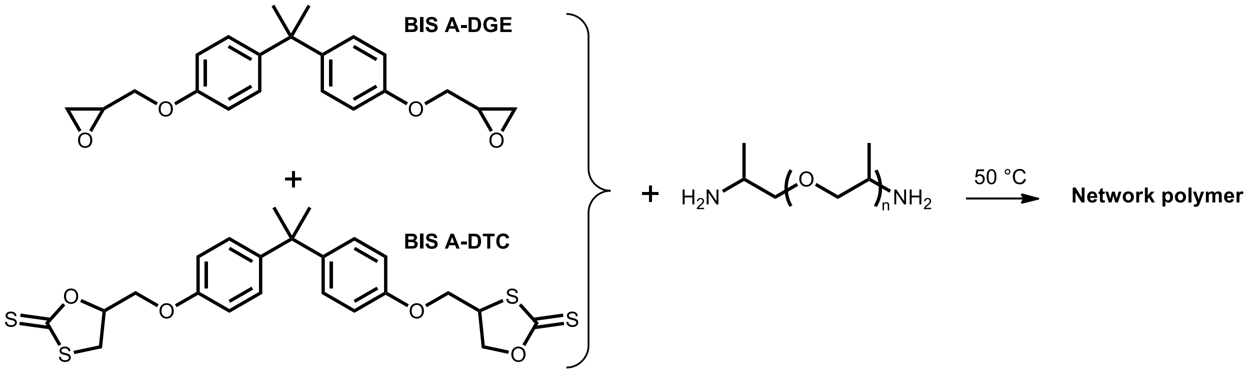

Figure 1.25: Reaction between an amine and epoxy in the presence and absence of DTC.[28]

The effect that a difunctional DTC having a bisphenol A structure (Bis A-DTC) (Figure 1.25) had on a model epoxy/amine curing system was investigated. In the absence of Bis A-DTC, the epoxy and amine were cured at 50 °C. After 6 hours, the non Bis A-DGE sample began to form a network polymer, however in the presence of Bis A-DTC the network formation began only after 2 hours.[28]

Horikiri *et al.* attributed the remarkable decrease in time needed to form a network to the formation of the polythiourethane.[28] The polythiourethane has two functions: initially when it has formed, the thiol may react rapidly with an epoxide functional group (GPE = Glycidyl Phenyl Ether) to give a polythiourethane adduct of the type shown in Figure 1.26; the second function of the polythiourethane is based on its proton-donating nature, as it is believed that the thiourethane would be more acidic than its urethane analogue. The acidic thiourethane may then promote the epoxide/amine reaction *via* protonation of the epoxide group.[28]

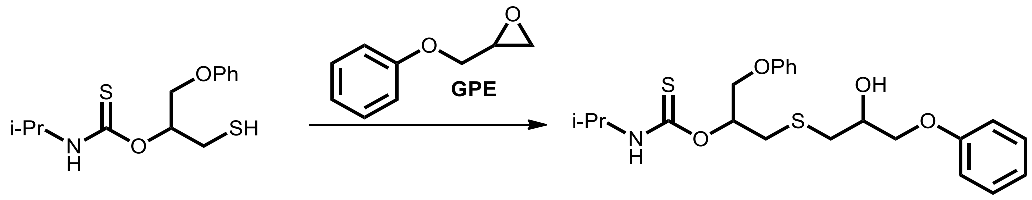

Figure 1.26: Polythiourethane adduct formed from the reaction between a thiourethane and GPE.[28]

The thiourethane was shown to have a catalytic effect by use of a model thiourethane compound (**12**) (Figure 1.27). Indeed, the model compound showed increased conversion similar to a DTC-containing molecule, indicating that the thiourethane formed *in-situ* was indeed the catalytic species.

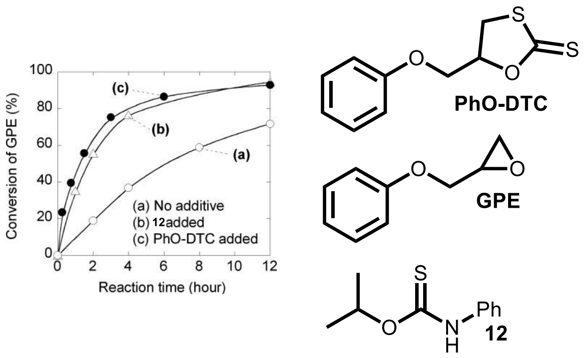

Figure 1.27: Conversion (%) of GPE against reaction time; the thiourethane additive (12) has a similar effect on conversion as the PhO-DTC dithiocarbonate.[28]

Research work carried out into alternatives to the isocyanate/alcohol curing reaction has generally relied on elevated temperatures, either to promote the reaction between cyclic carbonates/dithiocarbonates or alternatively to deblock a blocked isocyanate. Therefore, an alternative cure mechanism must be found that is not reliant on elevated temperatures.

1.4.4 Silane-terminated polyurethanes

Trialkoxysilanes, such as those shown in Figure 1.28, react in a stepwise manner where the alkoxysilanes hydrolyse in the presence of atmospheric moisture to silanols. The silanols then condense to siloxanes.[29]

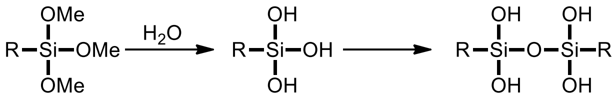

Figure 1.28: Hydrolysis and condensation of alkoxysilanes to form siloxanes.[29]

Emmerling *et al*. disclosed the use of alkoxysilane-containing functional groups capable of reacting with isocyanate functional prepolymers.[30] Emmerling *et al*. noted that alkoxysilanes can improve adhesion and, in some applications, the alkoxysilanes can be used to crosslink the system.[30] An advantage of alkoxysilane functional PU is its ability to crosslink with the absence of “bubbling”, which is a problem with isocyanate functional PU.

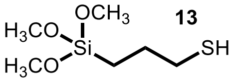

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Figure 1.29: Silane used by Emmerling *et al.* to improve the elasticity of polyurethanes.[30]

Emmerling *et al.* used (3-mercaptopropyl) trimethoxysilane (**13**) (Figure 1.29) to terminate isocyanate-functional PU. The resulting product had improved elasticity and an absence of bubbles associated with an isocyanate-based cured mechanism.[30]

Frisch *et al.* also applied reactive silanes to isocyanate-free PUs.[31] Initially, an amine was reacted with a maleate type ester to afford **14** which could be reacted subsequently with isocyanate functional monomers or isocyanate functional PU pre-polymers (Figure 1.30).

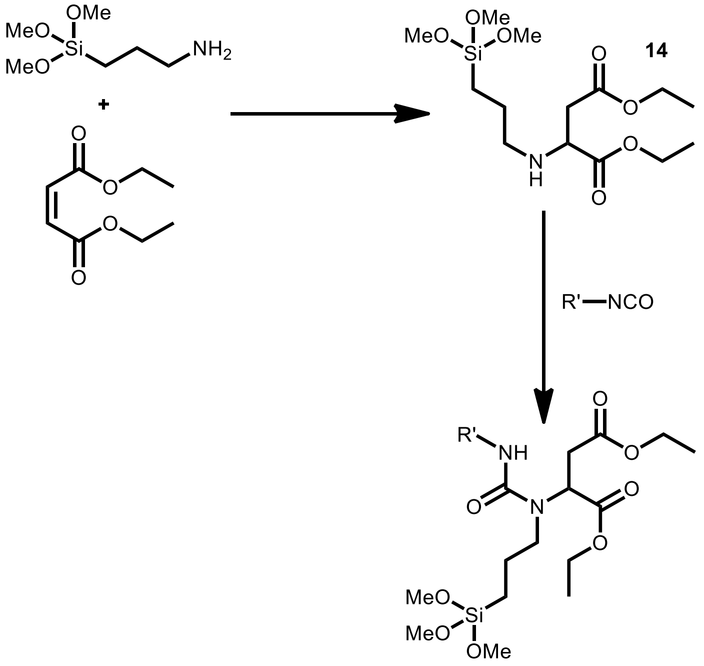


Figure 1.30: Use of reactive silane (14) to end-cap isocyanate functional molecules.[31]

The resulting silane-functional PUs could then be crosslinked *via* the hydrolysis and condensation of the silane groups by atmospheric moisture.[31]

Nomura *et al.* also investigated the use of PUs end-capped with alkoxysilanes for adhesive applications.[32] Their strategy involved the preparation of two silane end-cappers derived from the Michael addition of methyl acrylate and aminosilanes (Figure 1.31).[32]

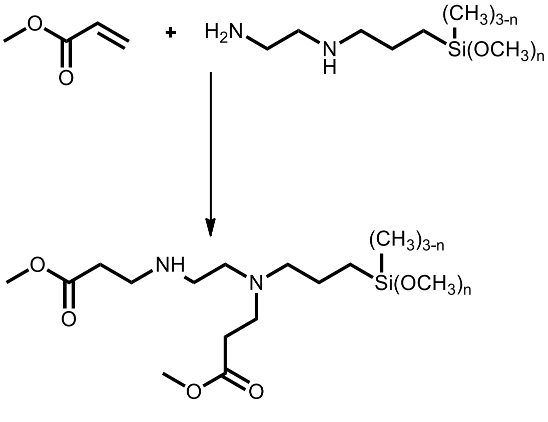


Figure 1.31: Preparation of alkoxysilane for reaction with isocyanate functional PU.[32]

The newly formed alkoxysilanes could then be used to end-cap isocyanate functional PU. There was a number of silane terminated PUs prepared and it was found that the viscosity and physical properties were determined by the length of the PU chain and also the structure of the silane end-capper used to remove the isocyanate functionality.[32]

Silane functionalization of PUs does provide a route towards a truly isocyanate-free crosslinking method for PU. Unfortunately, much research has been carried out in this area and products based on reactive silane terminated PUs are available on the market.[33] Therefore, an alternative approach was necessary for our search for a novel and patentable isocyanate-free PU crosslinking mechanism.

1.5 Click chemistry as a route to isocyanate-free polyurethanes

Previous approaches towards isocyanate-free PUs include blocked isocyanates and the use of reactive intermediates such as cyclic carbonates and alkoxysilanes. Progress has been made in a number of these areas, to the point where products based on the aforementioned technologies are commercially available. It would be difficult to realise the aspect of novelty needed to completely satisfy the technical requirements of the PhD programme if these alternative technologies were to be investigated further. Therefore, click chemistry was chosen as an alternative to the previous chemistries mentioned. Motivations for this choice of click chemistry include past experience with click chemistry within the Polymer Group at Strathclyde, and a limited number of examples of click chemistry being used with PU materials.

1.5.1 Click chemistry - the concept

Click chemistry was a term coined by Sharpless *et al.* in 2001;[34] Sharpless and co-workers aimed to mimic nature by joining small molecules together with heteroatom links, and they defined a number of criteria that a reaction must satisfy in order to be classed as a click-type reaction:

- Modular
- Wide in scope
- *Very high yields*
- *Inoffensive by-products (removed by non-chromatographic methods)*
- Stereospecific
- *Simple reaction conditions (insensitive to water and oxygen)*
- *Readily available starting materials and reagents*
- *No solvent or benign solvent which is easily removed*
- *Simple product isolation*

The italicised requirements highlighted in the list are of particular benefit when considering click reactions as a synthetic method for the crosslinking of polymeric roof coatings. More generally speaking, any reactions which meet these requirements are going to be of wide interest to various areas of science. This is certainly the case as the number of papers which use click chemistry has increased dramatically since the introduction of click chemistry in 2001, and click-type reactions have found various applications in material science.[35]

1.5.2 Copper-catalysed Azide-Alkyne Cycloaddition (CuAAC)

The copper-catalysed azide alkyne cycloaddition (CuAAC) is such an example of a click reaction. The original azide-alkyne cycloaddition reported by Huisgen[36] in 1963 was carried out in the absence of a copper catalyst, it required elevated temperatures and it gave a mixture of products (1,4 and 1,5 substituted triazoles; Figure 1.32). The Cu(I) catalysed cycloaddition was introduced independently by Sharpless[34] and Meldal[37] in 2001. The benefits of the copper catalysed system were that the reactions could be performed at room temperature, and they resulted in the exclusive formation of the 1,4-substituted triazole product. The ruthenium-catalysed version of the reaction gives solely the 1,5-substituted triazole[38] (Figure 1.32). A further advantage of the chemistry is that the azide and alkyne moieties are generally unreactive with a wide range of functional groups and thus negate the need for protecting group chemistry, further enhancing its popularity in a number of scientific areas such as the biomedical arena[39] and in materials science.[35]

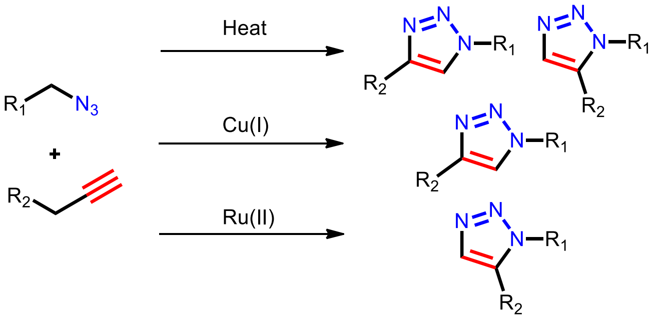


Figure 1.32: The non-catalysed (upper) and catalysed (middle and lower) Huisgen reactions.

The accepted mechanism for CuAAC reactions involves a stepwise mechanism, whereas the thermal cycloaddition proceeds *via* a concerted mechanism. The lowest activation energy barrier found for the concerted process is 99.2 kJ mol^{-1} but this is too high for this to be an acceptable mechanism. However, the Cu(I) species lowers the activation energy barrier by about 46 kJ mol^{-1} relative to the uncatalysed process, and this explains the rate enhancement observed for the Cu(I) catalysed process compared to the non-catalysed process.[40]

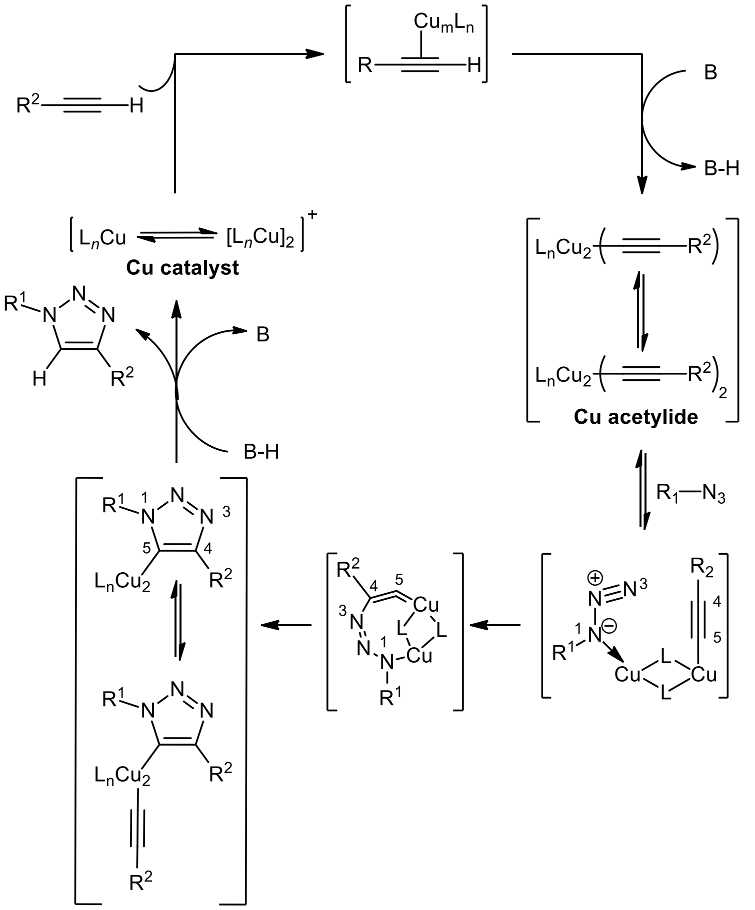


Figure 1.33: The proposed mechanism for Cu(I) catalysis in CuAAC.[40]

The postulated mechanism for the Cu(I) process (Figure 1.33) has a number of key steps: the formation of the Cu(I) acetylide species is the start of the stepwise mechanism. The function of the second copper atom is to activate the azide**.** Azide displacement of one ligand can occur and the species is activated to nucleophilic attack at Carbon 4 by Nitrogen 3 which subsequently generates a metallocycle. The metallocycle is then well positioned for subsequent attack by the azide nitrogen lone pair (N1) on C(5) - Cu π* orbital. Collapse of the metallocycle followed by protonation and dissociation of the product ends the reaction and regenerates the catalyst.[40]

1.5.3 Copper-catalysed reactions

The active oxidation state of copper used in CuAAC is Cu(I). Practically, this is used as a copper halide with a stabilising ligand, or as copper (II) sulphate in conjunction with sodium ascorbate as a reducing agent.[41]

Cu(I) is the catalytic species in the CuAAC click reaction and there is a need to protect it from oxidation. Typical ligands used to complex the Cu(I) include amines, thiols and halides. An issue with some of these ligands (halides and amines) is that they can tend to be too labile, and are unable to prevent oxidation. Conversely, in the case of some other ligands (nitriles) they bond too strongly, therefore hampering the catalytic activity of Cu(I).[42]

The problem described in the previous paragraph has led to research into alternative Cu(I) catalysts beyond the two most popular catalyst systems used widely in the literature: Cu(I) halide or $CuSO_4$/reducing agent.

Alternative copper catalysts have been an area of active research. In a paper from Novák *et al.* from 2010,[43] the copper catalyst in question was a copper (I) carboxylate, and the reaction was found to be effective in the presence of 0.005-0.05 mol % catalyst at ambient temperature (25 °C). In addition to the copper catalyst, the presence of phosphine ligands and base were also found to be important in enhancing the click reaction.[43] The click reaction monitored was that between benzyl azide and phenylacetylene (Figure 1.47).

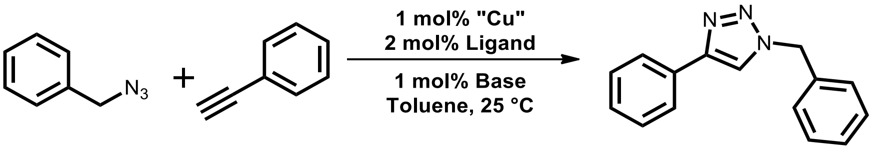


Figure 1.34: Model reaction between benzyl azide and phenylacetylene.[43]

Novák *et al.* screened the efficiency of a range of copper catalysts, which resulted in the optimised click reaction between benzyl azide and phenylacetylene reaching full conversion in as little as one hour at 25 °C. During this optimisation process, a number of important factors were found to aid the efficiency of the CuAAC click reaction.

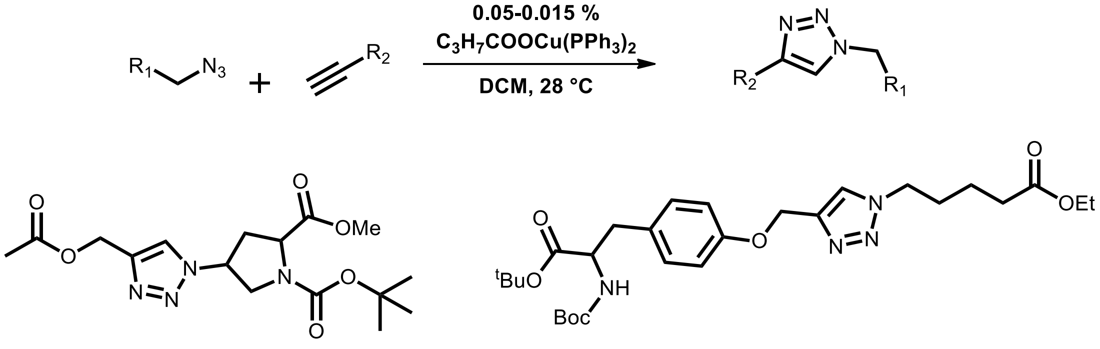
The first copper sources investigated were copper halides (CuI, CuBr, and CuCl) and CuCN. These copper sources were found to have no catalytic effect on the click reaction, even after twenty four hours. This was thought to be due in part to the low solubility of these copper salts in the reaction solvent (toluene).

To aid the solubility of the copper salts, triphenylphosphine was used to dramatic effect in the case of the CuI salt. The presence of the phosphine ligand resulted in 41% conversion of substrate after only three hours. The triphenylphosphine ligand has a dual role when used in the presence of copper (II) salts; the phosphine ligand increases the solubility and reduces copper (II) to copper (I).

The copper (II) salt that was found to give the best performance was copper (II) acetate. When used in conjunction with the triphenylphosphine ligand, the click reaction reached complete conversion within one hour at 25 °C. It is interesting to note there seems to be an aspect of tuneability to the time in which the reaction reaches complete conversion. This is accomplished by varying the mole per cent of the copper catalyst used; as the mole per cent of the copper (II) acetate is reduced to 0.5 and then to 0.05 mol%, the reaction reaches full conversion within seven and 24 hours, respectively.

From this exciting result, Novák suggested that the carboxylate anion has some role to play in accelerating the click reaction.[43] To investigate this hypothesis, different carboxylate additives were used together with copper (I) salts. The presence of the carboxylate anion has a marked effect on the reaction rate; as an example, CuI catalyst in the presence of KOAc increases the conversion from 41% (in the absence of KOAc) to 75% after three hours of reaction.

The optimisation led to a copper phosphine complex ($C_3H_7COOCu(PPh_3)_2$) which showed excellent activity. The scope of this catalyst was then investigated using a range of structurally diverse azides and alkynes (Figure 1.35).



12 h, 85%

8 h, 96%

Figure 1.35: The yields and reaction times for the formation of the triazole between interesting azides and alkynes.[43]

There are other reports of alternative copper catalysts which promote the click reaction. One such example from Candelon *et al.* makes use of [Cu(C18$_6$TREN)]Br (C18$_6$TREN = *tris*(2-dioctadecylaminoethyl) amine) (Figure 1.36). A benefit of this catalyst is that it can be recycled if the correct solvents are used.[44] A number of reactions were carried out using the [Cu(C18$_6$TREN)]Br catalyst.

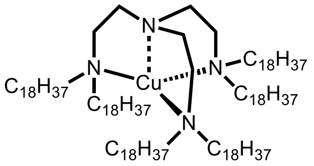


Figure 1.36: [Cu(C18$_6$TREN)]Br.[44]

It is interesting to note that although the use of the copper TREN catalyst does result in high yields, the reactions were carried out at 60 °C, a temperature that diminishes any potential benefits of the catalyst and interferes with the aim of finding a catalyst system that proceeds at room temperature.

Another catalyst system investigated has been *N*-heterocyclic carbenes (NHCs).[45] Nolan investigated the activity of a range of [(NHC)$_2$CuX] complexes (Figure 1.37).

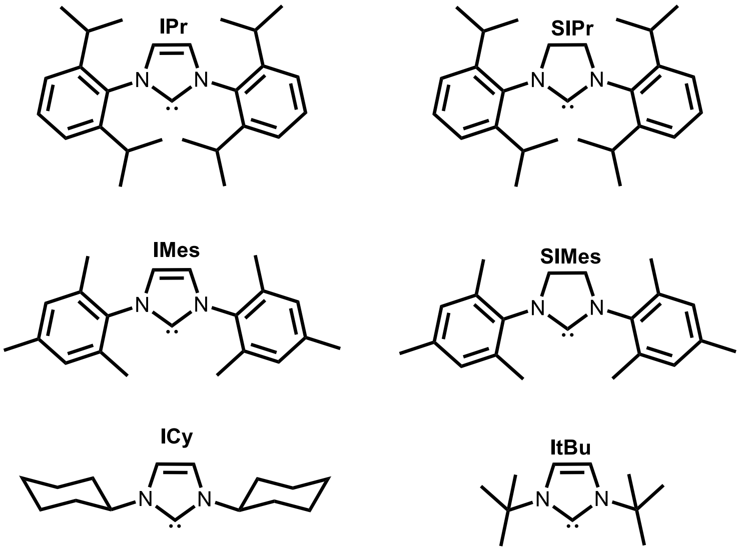


Figure 1.37: ***N*-heterocyclic carbenes prepared by Nolan.**[45]

The best performing NHC (ICy) enabled the cycloaddition reaction between benzyl azide and phenylacetylene within 90 minutes at room temperature. Acetonitrile was shown to be the best solvent for ICy and, accordingly, decreased the reaction time to 12 minutes. It was noted that there appeared to be no copper disproportionation or oxidation, highlighting the ability of the NHC to stabilise Cu(I).

The amount of copper catalyst needed to promote the CuAAC was then investigated. It was found that as the catalyst loading was decreased, there was a need for elevated temperatures (40-50 °C). The reactions performed at elevated temperatures were faster than those carried out at room temperature.

Teyssot *et al.* also made use of NHCs in tandem with external *N*-donor aromatic ligands.[46] The purpose of this was to mimic the binding mode of *tris*-(benzyltriazolylmethyl)amine (TBTA) type ligands (Figure 1.44). The strong σ-donor ligand of the NHC acts to replace the tertiary nitrogen of TBTA. In an effort to mimic the effect of the three triazoles in TBTA, external *N*-donor aromatic ligands were investigated. The best performing ligands were found to be 4-dimethylaminopyridine (4-DMAP) and phenanthroline (Phen) (Figure 1.38).

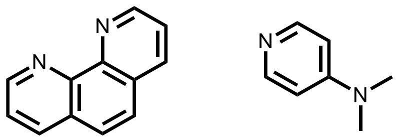


Figure 1.38: Phen (left) and 4-DMAP (right).[46]

The [CuCl(SIMes)] NHC catalyst of Teyssot *et al.* was used to prepare a range of simple triazole-containing molecules (Figure 1.39). Aromatic, electron-rich and electron-poor groups were incorporated into triazole products after 18 hours reaction time at room temperature, using only 1 mol% of [CuCl(SIMes)] and either 1 or 2 mol% of Phen or 4-DMAP, respectively.

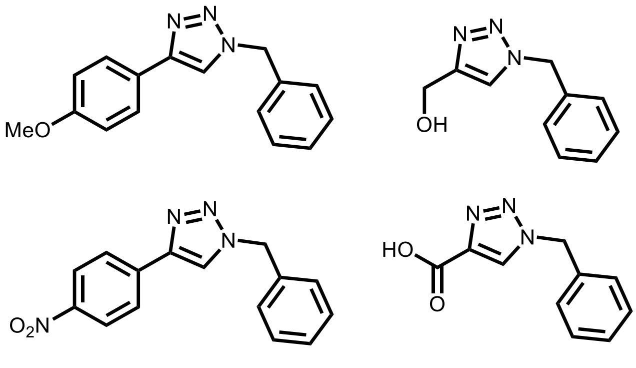


Figure 1.39: Triazoles prepared with NHC copper catalysts.[46]

To benchmark the effectiveness of their catalyst system, a comparison was run with the previously described TBTA co-ligand and copper sulfate (1:1). The results (Figure 1.40) led to a classification based on reaction rates: 4-DMAP > Phen > TBTA > NMI. The best performing ligand, 4-DMAP, afforded the formation of triazole product in 100 % yield after only 1.7 hours.

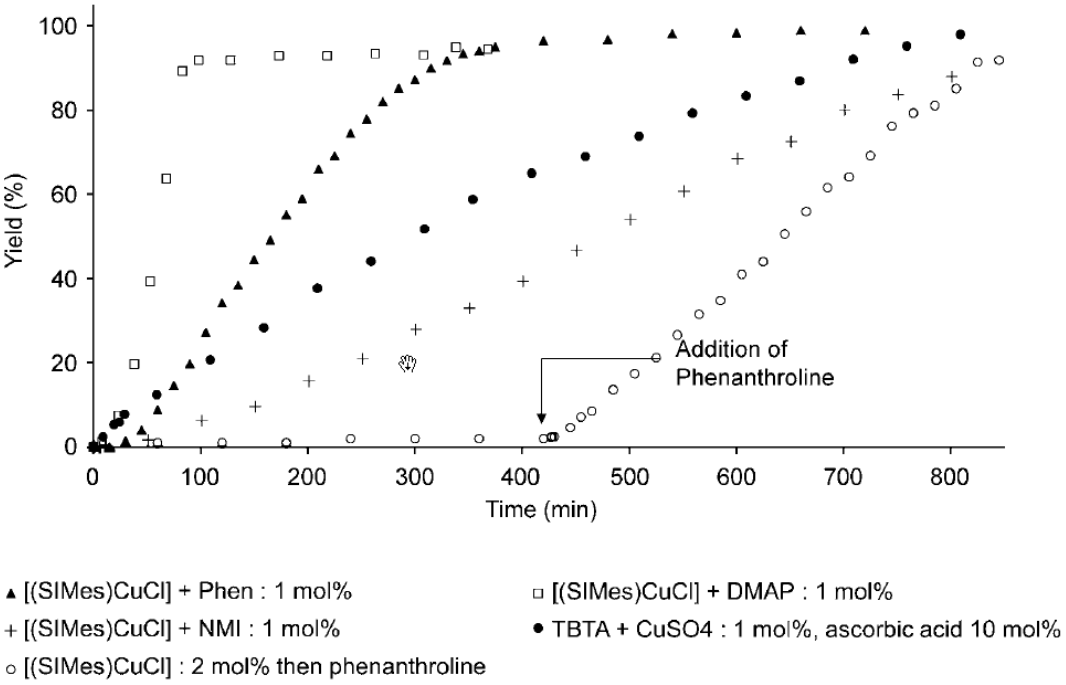


Figure 1.40: Kinetic study showing the formation of triazole over time.[46]

Another interesting catalyst system (Figure 1.40) is that comprising the NHC copper complex [(SIMes) CuCl] and phenanthroline as a co-ligand. It is interesting to note that the NHC has no catalytic activity until at around 400 minutes when 2 mol% of the phenanthroline is added, at which point in time the yield of the triazole shows a marked increase.

Gautier *et al*. have cleverly used both an alternative catalyst (NHC) and developed the use of co-ligands for their catalytic system. The result is the formation of triazole products, albeit with simple model compounds, in relatively short times at low catalyst loadings.[46]

Lal *et al.* investigated the air stable and organic solvent compatible Cu(I) catalyst [47]. Initially, they investigated the model reaction of benzyl azide and phenylacetylene in a number of solvents. Optimum results were obtained in water and water/*tert*-butanol mixtures. Other organic solvents exhibited increased reaction times, and in the case of methanol and ethanol the reactions did not go to completion within eight hours.[47]

The [47] catalysed reaction of benzyl azide and phenylacetylene could be carried out in the absence of solvent and this allowed for lower loadings of the catalyst. Interestingly, when CuBr was used as a source of Cu(I) there was no triazole product formed. The utility of the [47] catalyst allowed for the three-component preparation of triazoles where the organic azide was generated *in-situ*.[47] The *in-situ* generation of organic azides is one method of circumventing some of the hazards that these materials are known to have.[48]

Alternatives to Cu(I) (either from copper halide, or from Cu(II) where Cu(I) is generated *in-situ* from a reducing agent) include Cu(0) nanoparticles. Alonso *et al.*[49] used copper nanoparticles as an alternative catalyst system for alkyne and azide cycloaddition. The authors claim that the copper nanoparticles used in their experiments are prepared easily from commercially available materials and are formed under mild reaction conditions.

The workers claim milder conditions (65 °C) than most other alkyne-azide cycloadditions. Benzyl azide and cyclohexacetylene were used as model substrates (Figure 1.41). Triethylamine was found to be essential to the reaction. The copper nanoparticles were found to be superior to other sources of copper and, with more than one equivalent of NEt_3, reduced the reaction time to 30 minutes at 25 °C.

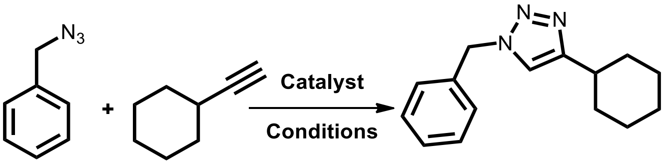


Figure 1.41: Reaction carried out with copper nanoparticles.[49]

One potential issue with copper nanoparticles is the sensitivity to air of the nanoparticles; when the reaction was carried out in air there was a lower yield, even with an increased temperature (65 °C) and reaction time (24 hours) compared to reactions carried out under an argon atmosphere.[49] This would negate the effectiveness of the catalyst in systems which are exposed to the atmosphere.

1.5.4 Promotion of the CuAAC Click Reaction

An important influencing factor on the rate of reaction is the ligand type used in the Cu(I) catalysis.[41] It is known that the nature of the ligand influences the catalytic activity of Cu(I). As click chemistry has branched out into other areas, such as polymer science, a need for a Cu(I) system that works in a range of organic solvents has developed. Matyjaszewski compared the effect of both aliphatic and pyridine-based ligands on the catalytic performance of Cu(I). The ligands of interest are shown in Figure 1.42; the authors found that aliphatic amine ligands had a faster reaction rate compared to pyridine-based ligands.[50]

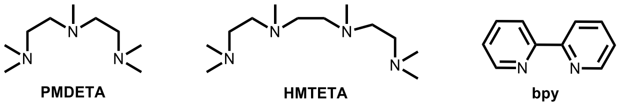


Figure 1.42: Aliphatic and pyridine based ligands.[50]

The ligands were used in the model reaction shown in Figure 1.43, which is a model reaction between diazido-terminated polystyrene and propargyl ether. It was found that for the aliphatic ligands the coupling reactions were essentially complete after 30 minutes, yet when compared to the coupling reactions with the pyridine-based ligands the reaction rate was actually slower than when no ligand was present. The authors suggest that other factors, such as the increased basicity and increased lability of aliphatic amines over pyridine ligands, may be responsible for the increased reaction rate. The authors also found that non-coordinating solvents increased the reaction rate compared to non-coordinating solvents.[50]

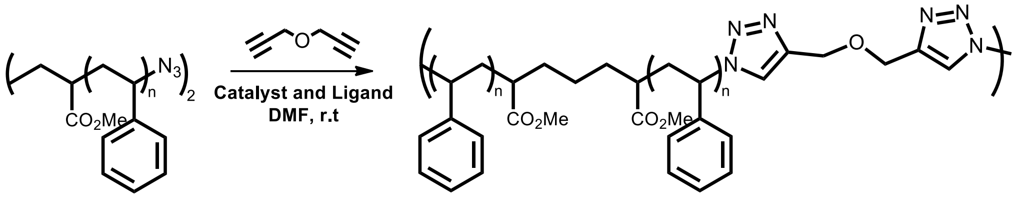


Figure 1.43: Reaction Used to Investigate Ligand Effects.[50]

Chan *et al.* found that when synthesising polyvalent triazole containing molecules the reaction rates were faster than expected; one possible explanation for this observation was that the reaction was autocatalytic.[42] This would involve the polytriazole containing molecules acting as rate-accelerating ligands for the Cu(I) catalysts. The ligands which performed best were those that were derived from a propargylamine core and contained triazole groups. These molecules are thought to be capable of acting as multi-dentate ligands that can bind to metals *via* the central amine core, and the N-3 nitrogen of the triazole. The best performing ligand identified during the study was found to be the tetradentate TBTA (Figure 1.44)

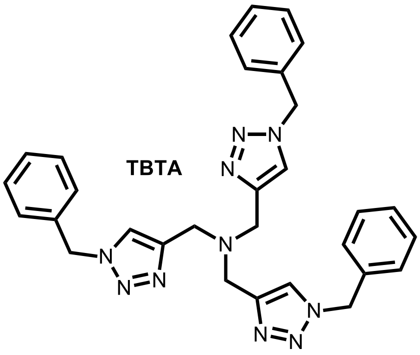


Figure 1.44: TBTA containing three triazoles around tertiary nitrogen centre.[42]

The tetradentate nature of TBTA allows for the complete envelopment of the Cu(I) centre. The more basic, tertiary nitrogen can provide additional electron density to the copper centre, whereas the triazole nitrogens are more labile and come off temporarily, to allow the formation of the Cu(I) acetylide species. It is the combination of these ligands which protect the copper from oxidation, whilst also promoting the azide-alkyne cycloaddition.

One aim of the PhD study described herein was to find a system and set of parameters that allow the CuAAC click reaction to proceed efficiently at room temperature and below. It was therefore heartening to see an example in the literature of the click reaction proceeding efficiently in spite of these temperature constraints.

In a paper by Wang *et al.* the researchers make use of the TBTA ligand to promote the click reaction between azide/alkyne containing dye molecules and a corresponding azide/alkyne containing protein (Figure 1.45).[51]

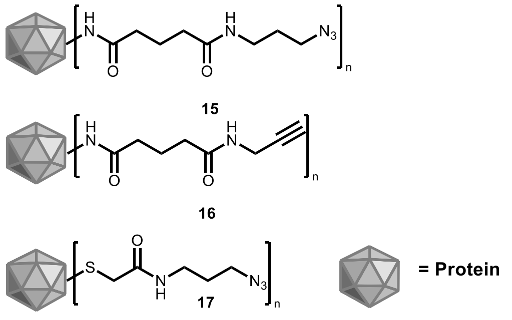


Figure 1.45: Azide/alkyne coupling in the presence of proteins.[51]

The protein of interest was functionalised with azide and alkyne groups (**15-17**) which were then subsequently reacted with a complementary partner which contained a fluorescein dye (Figure 1.46).

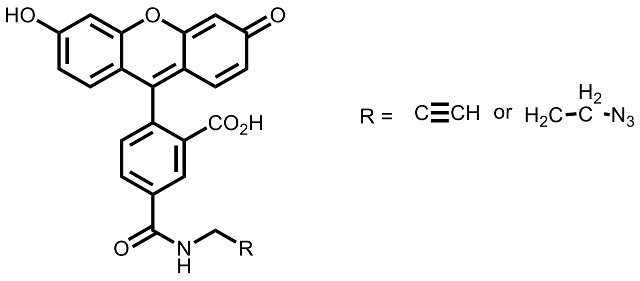


Figure 1.46: Azide/alkyne functionalised dyes.[51]

The bioconjugations performed *via* the CuAAC click reaction were carried out for 16 hours at 4 °C in a potassium phosphate buffer (pH 8) containing 5% *tert*-butyl alcohol. The addition of TBTA to the reaction mixture resulted in an increased reaction rate to the extent that all azide and alkyne groups were converted to triazoles.

Phosphoramidite co-ligands for catalysis of the CuAAC click reaction have been investigated by Feringa *et al.*[52] A number of phosphoramidite ligands were investigated. The best performing phosphoramidite ligand was able to return a 98 % yield in only two hours (Figure 1.47):

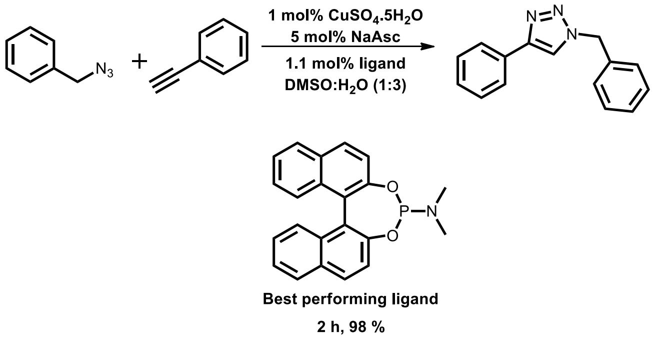


Figure 1.47: Best performing phosphoramidite ligand investigated for the reaction between benzyl azide and phenylacetylene.[52]

Phosphoramidites are used as monodentate ligands, which demonstrate the ligand accelerating effects. Phosphoramidites are known to be inexpensive, easily modified, remarkably stable and readily accessible.[52]

Feringa *et al.* found phosphoramidites to be high yielding and easily recovered ligands. Benzyl azide and phenylacetylene were used as a model system. The catalyst system used was $CuSO_4$/NaAsc, and all reactions were performed in DMSO/H_2O (1:3, v/v).

In the absence of any co-ligands the model reaction required 30 hours to reach completion. The most effective phosphoramidite ligand was able to reduce the reaction time to two hours at a 1 mol% loading of copper. It was possible to increase the catalyst loading to 10 mol%, which decreased the time to reach full conversion to 30 minutes.

The phosphoramidites were used in conjunction with a range of commonly available copper (I) salts in aqueous solution, and it was found that use of the phosphoramidite led to excellent reaction times and yields. This was attributed to the stabilising effect which the phosphoramidite may have on stabilising the catalytically active Cu(I) oxidation state.[52]

It has been reported by Wang and Hu that carboxylic acids are capable of promoting the copper catalysed azide-alkyne cycloaddition.[53] The workers found that in the presence of carboxylic acids the CuAAC reaction was promoted. The proposed rationale of the reaction promotion is due to the ability of some carboxylic acids to chelate to the Cu(I) centre and generate a highly active catalyst $[(RCO_2Cu)_m]_n$ (Figure 1.48).

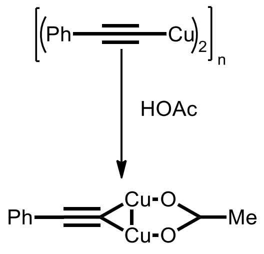


Figure 1.48: Proposed Cu(I) carboxylate catalyst system.[53]

Interestingly, the authors found that non-carboxylic acids could not function as promoters of the CuAAC reaction, and this was also the case for ligands with strong chelating ability to the Cu(I) ion.

Further work by Wang and Hu involved optimising the well-known CuI/amine catalyst system.[54] The authors note that there are significant drawbacks to the popular CuI/amine catalyst system, foremost of which is the production of by-products. Despite this drawback, there is still significant interest in the CuI/amine catalyst system as it can be used in non-aqueous or non-protic solvents. The workers developed a catalyst system based on CuI, *N,N*-diisopropylethylamine (DIPEA) and acetic acid (HOAc). It was found that the CuI/DIPEA/HOAc catalyst system was capable of carrying out the CuAAC reaction in organic solvents such as chloroform and cyclohexane, amongst others. This is encouraging as this is an extremely effective catalyst system that works well in organic solvents and provides an alternative to the constraints of the aqueous $CuSO_4$/NaAsc system that has found application routinely in CuAAC.

1.5.5 Copper-free azide-alkyne cycloaddition

The ultimate aims of the PhD research programme have been discussed previously, but it is well worth reiterating the point that the success of the research work is dependent on the removal of isocyanate functionality. The need to remove isocyanate is dictated by the toxicity of this functional group (particularly in unreacted monomers). The belief is that the substitution of the isocyanate functionality with functional groups capable of taking part in CuAAC will ultimately reduce the toxicity and labelling issues associated with any non-isocyanate/CuAAC crosslinked product.

To this end it is worth reviewing the literature to investigate if there is any aspect of CuAAC that may prove to be a stumbling block for our desire to use CuAAC chemistry as a replacement for the traditional isocyanate materials.

To date, the commercial exploitation of CuAAC chemistry has been limited, but there are commercially available azide-containing products available from companies such as Sigma-Aldrich.[55,56] If focus is diverted to polymeric materials then the indications are positive, with most polymeric azides having little or no risk or hazard phrases. This is reassuring as it would be anticipated that this would result in less off-putting labels and warnings on any polymeric azide containing product.

Indeed, within the relevant literature it is noted that azide and alkyne functional groups are bio-orthogonal and will thus tend to be unreactive with a range of functional groups in a biological or cell environment.[57] In fact, the real concern for researchers is the presence of cytotoxic copper which is capable of generating reactive oxygen species (ROS).[58]

The presence of free copper is such an issue that alternatives to using CuAAC have been investigated.[59] To this end, strain promoted azide-alkyne cycloaddition (SPAAC) has been investigated. This strategy attempts to make use of ring-strain and electron withdrawing/donating groups to increase the reactivity of the azide and alkyne components in the SPAAC reaction and thereby negate the need for copper.

Ning *et al.* describe the use of a dibenzocyclooctynyls (DIBO) such as those shown in Figure 1.49. Confining an alkyne within an eight-membered ring generates 18 kcal mol^{-1} of strain, strain which is released in the reaction with an azide.[60] The outcome of this is that the reaction between a strained alkyne and an azide will occur at room temperature without the need for a catalyst. Boons *et al.* report that an azide-alkyne reaction occurred at 4 °C with the strained cyclooctyne after only fifteen minutes.[60]

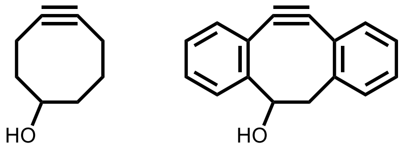


Figure 1.49: Two examples of ring-strained cycloctynyls.[60]

Another approach to increasing the speed of the copper-free azide-alkyne cycloaddition involves using electron-withdrawing groups in the alpha position of a cyclooctyne derivative (Figure 1.50). This method was used by Agard *et al.* to give very fast and efficient azide-alkyne cycloadditions;[61] the electron-withdrawing groups used in the work were fluorine groups due to the inertness of such groups in a biological environment, but other electron-withdrawing groups may be used were the need for inertness not thought to be an issue, such as in some polymer applications.

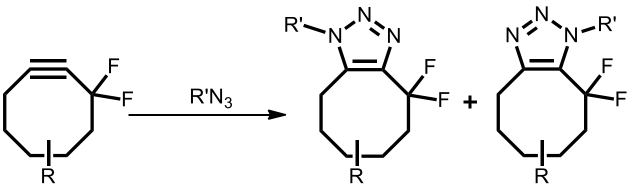


Figure 1.50: Electron-withdrawing groups and ring strain.[61]

If the CuAAC proves to be sluggish at below ambient temperatures (25 °C) then ring-strain and electron-withdrawing groups may prove to be a useful tool for speeding up the azide-alkyne cycloaddition, especially in the presence of a ruthenium catalyst,[38] as there are now two possible rate-enhancing drivers for promoting the cycloaddition reaction. The ring-strain promoted method of copper-free azide-alkyne cycloaddition does have some issues that do make it less attractive: the difluorinated cyclooctyne (DIFO) used in the work by Agard required a twelve-step synthesis and was isolated in an overall yield of 1 %. Fortunately, Codelli has introduced a second-generation of DIFO molecules (Figure 1.51), which are claimed to be easier to synthesise. This will allow for more widespread use of copper-free azide-alkyne cycloaddition.[62]

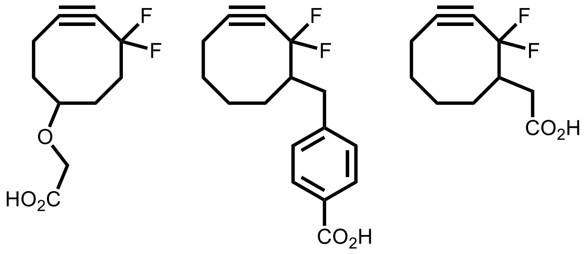


Figure 1.51: Second generation of DIFO molecules.[62]

Varga *et al.* wished to promote SPAAC to levels that were comparable to CuAAC. They prepared a monobenzocyclooctyne derivative; carboxymethylmonobenzocyclooctyne (COMBO) (Figure 1.52).[63]

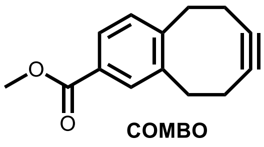


Figure 1.52: Monobenzocyclooctyne prepared by Varga *et al.*[63]

COMBO lacks the fluorine substituents of the DIFO molecules discussed earlier,[62] but does have carboxylic group for further modification.[63] COMBO was reacted with benzyl azide in a model reaction. In a polar medium (H_2O:MeCN [3:4 v/v]) COMBO showed a quicker reaction with benzyl azide over both DIFO and DIBO.[60,62] The absence of fluorine in the cyclooctyne reduces the number of synthetic steps, and also affords a more economical route to an alkyne capable of partaking in a SPAAC.[63]

Another example of the use of the electron withdrawing group strategy is shown by Clark *et al.,* in which they use an electron-deficient dialkyne crosslinker (which is water-soluble) to crosslink multivalent azide polymers, resulting in the formation of hydrogel networks under mild conditions.[64]

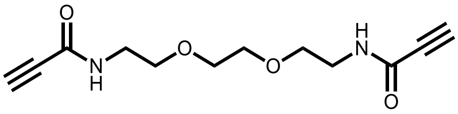


Figure 1.53: Crosslinking with an electron deficient alkyne.[64]

This method requires increased reaction times; the authors show that the time taken for even 10% cycloadduct formation takes around thirty hours with the dialkyne molecule shown in Figure 1.53.[64] This relatively slow reaction rules it out as an effective crosslinker for roofing applications where faster reaction times are needed.

Although some research has been carried out into the metal-free AAC/SPAAC click reaction, the difficult synthesis of the ring-strained molecules and the need for elevated temperatures negate the effectiveness of this non-metal catalysed process when applied to a coating system. In addition, it has been found that even for the fastest strained cyclooctyne systems the rate of cycloaddition is more than ten times slower than the corresponding CuAAC process.[65]

Other approaches to the copper problem involve making use of ligands which are water soluble such as *tris*(3-hydroxypropyltriazolylmethyl)amine (THPTA) (Figure 1.54).[66]

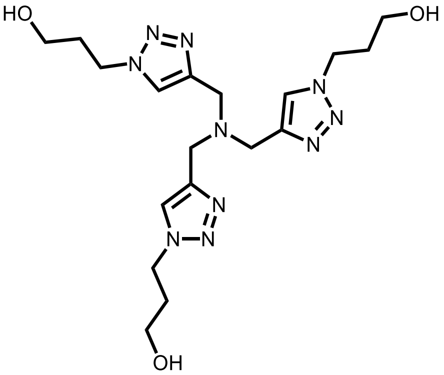


Figure 1.54: THPTA ligand for use in cell compatible CuAAC.[66]

The THPTA ligand acts to increase the rate of CuAAC whilst also acting as a sacrificial reductant and therefore reducing the cell toxicity associated with copper and ROS. The THPTA ligand is generally used at a level of five equivalents relative to copper, following this protocol along with others allows for bioconjugation to be carried out.[66]

An alternative approach reported by Uttamapinant *et al.* focused on the reduction of the copper concentration. This strategy reduces the cell toxicity in tandem with a decrease in the CuAAC reaction rate. To combat this reduction in reactivity, the authors prepared a number of azide molecules that also contained internal copper-chelating moieties (Figure 1.55).[65]

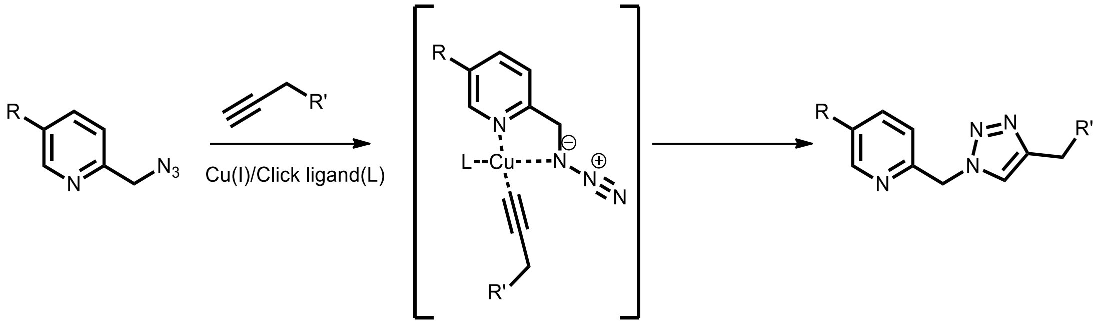


Figure 1.55: Function of the internal copper chelator.[65]

It was found that the use of the chelating azides resulted in a dramatic acceleration of CuAAC under cell compatible conditions. The main advantage of this system is that the concentrations of copper needed is greatly reduced (10-100 µM), resulting in reduced cell toxicity.[65]

It can be seen from the examples presented here that there appears to be a desire to obtain a SPAAC or Cu-free AAC reaction with all the beneficial properties of the conventional CuAAC but without the cytotoxicity of the copper. This work lends credence to our strategy of replacing the isocyanate group with azide or alkynes with the aim of reducing the toxicity, in view of the fact that CuAAC has been shown to proceed in biological systems with reduced cell toxicity.[65]

1.5.6 Organic azides for polymeric applications

Bräse *et al.* carried out a comprehensive review on the chemistry of organic azides.[67] To summarise, there are five principal routes for the preparation of organic azides:[68]

- Insertion of azide moiety *via* substitution or addition
- Diazo transfer
- Diazotisation
- Degradation of triazines and their analogues
- Rearrangement of azides

The discussion here of these routes is limited to methods which are suitable for polymeric applications. Due to the challenges associated with the purification and processing of many polymeric materials, only reactions with high yields typically find use in polymer chemistry. One such example of this is the direct substitution of halides with sodium azide. This direct substitution is particularly useful in the case of polymers prepared by ATRP where halide (chain end) functional polymers are commonly prepared.[68] This direct substitution is by far the most utilised method for preparing azide functional materials. This approach has been used to prepare monomers that can be used to introduce azide functionality into step-growth polymers.[69]

Another less utilised method for the preparation of azide functional molecules is the diazotisation of amines followed by nucleophilic substitution with sodium azide. Another amine to azide interconversion is diazo transfer; this reaction is normally carried out under mild conditions and in high yields, and returns a range of alkyl and aryl azides.[67]

Guerin *et al.* investigated the azidation of α,β-unsaturated carbonyl compounds towards the preparation of β-amino acids.[70] The authors report mild conditions for the preparation of β-azido carbonyl compounds, which proceed in high yields and at ambient temperatures. The reaction is catalysed with common and readily available amines. In addition, the source of azide is from the stable trimethylsilyl azide (TMSN$_3$), as opposed to the potentially unstable sodium azide or hydrazoic acid.[70]

The authors recognised the hazards associated with using hydrazoic acid and elevated temperatures from the prior art.[70] In place of using a stock solution of hydrazoic acid, the authors generated hydrazoic acid *in-situ* from TMSN$_3$ and acetic acid. The presence of catalytic quantities of amines in the reaction mixture provided a route to azide functional cyclohexenone. The authors investigated the scope of the substrate and found the reaction to be applicable to a range of substrates (Figure 1.56).[70]

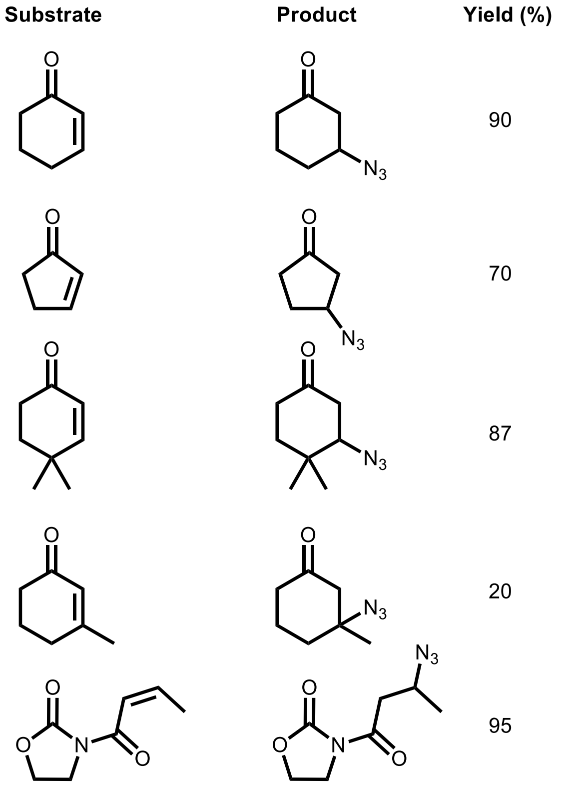


Figure 1.56: Substrate scope for the preparation of β-azido carbonyl compounds.[70]

The work described previously is interesting as it provides a relatively direct route into azide functional molecules under mild conditions. One potential downside to this approach to azide functional molecules is that the explosive and toxic hydrazoic acid is generated during the course of the reaction.

An alternative route towards azide functional molecules has been investigated by Waser *et al.,* and this is a route which involves using a cobalt catalyst and a Schiff base to mediate the reaction between tosyl azide and a range of olefins (Figure 1.57).[71]

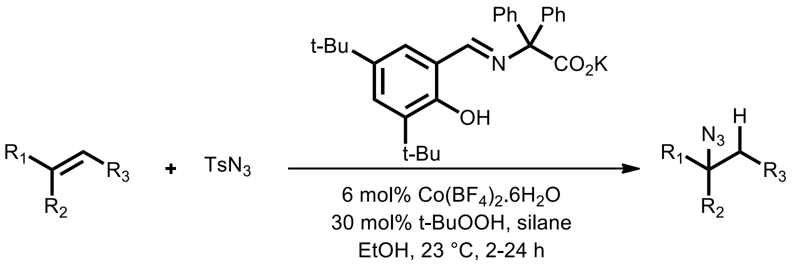


Figure 1.57: Cobalt catalysed azidation of alkenes.[71]

The benefit of the approach of Waser *et al.* is that the hydroazidation can be carried out on unactivated olefins. This is interesting as it provides access to a wider range of azide functional molecules then can be accessed *via* the chemistry of Guerin *et al.*[70] ; the Guerin approach requires activated alkene functionality for hydroazidation. Waser *et al.* also highlight the mildness of this hydroazidation process by reaction of the newly formed azides without isolation or purification of the azides. This was shown by reaction of 4-phenylbutene in the hydroazidation process, followed subsequently by CuAAC with ethynylbenzene in the presence of Cu and a reducing agent.[71]

1.5.7 Organic alkynes for polymeric applications

A number of routes have been investigated for the insertion of alkyne functionality into a range of polymers. The route chosen to introduce alkyne functionality can sometimes be dependent on the chosen method of polymerisation. As previously discussed, in the case of polymers prepared *via* RAFT, the resulting polymers can be prepared using alkyne functional CTAs resulting in alkyne terminated polymers.[72]

Alternatively, for step-growth polymerisations alkyne functional monomers can be prepared that allow for alkyne functionality to be incorporated into polymer chains.[73] Examples of these techniques are best highlighted by the illustrative examples shown in the following sections.

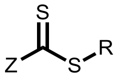
1.5.8 CuAAC in polymer applications

There are a large number of papers and comprehensive reviews[74,75,76] detailing the use of click chemistry in polymer science applications. Examples where click chemistry has been used as a crosslinking mechanism for polyurethane polymers are of special interest.

CuAAC was investigated initially as a method for the preparation of linear polymers in a step-growth or polyaddition processes.[77] However, the area in which the most impact has been made in materials science is in fact the modification of pre-existing polymers.[74] Some of these approaches to triazole functional molecules and the modification of polymeric materials will be discussed in further depth in the following sections.

1.5.8.1 Controlled radical polymerisations and CuAAC

Reversible addition-fragmentation chain-transfer (RAFT) polymerisation is an example of a radical polymerization mediated by the presence of a reversible chain-transfer agent. Examples of reversible chain-transfer agents include dithioesters (Figure 1.58).



Z = aryl, alkyl, SR',OR',NR'$_2$
R = good leaving group

Figure 1.58: Dithioester chain transfer agent.

RAFT polymerisation involves a number of key steps (Figure 1.59), summarised as: initiation, addition-fragmentation, reinitiation and equilibriation.

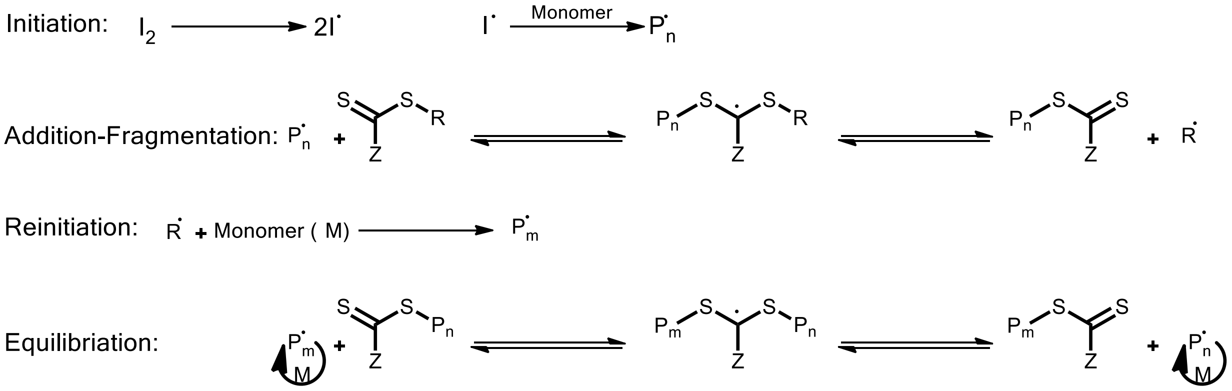


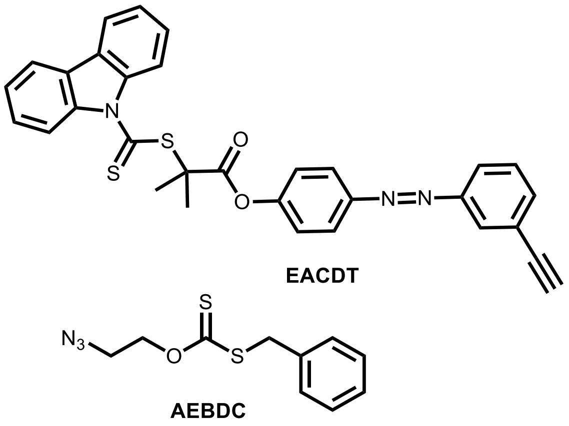
Figure 1.59: Key steps in a RAFT polymerisation.[78]

The key step in the RAFT polymerisation process is the addition-fragmentation step which traps the propagating species in an unreactive thiocarbonyl compound. This trapping of the propagating species reduces the likelihood of termination reactions occurring. The benefits of this approach are controlled molecular weight polymers with low polydispersites.[78]

One particular benefit of the RAFT polymerisation process is its ability to harbour click functional molecules either in monomers or RAFT chain-transfer agents (CTAs) or allow them to be introduced *via* post-polymerization chemical modification.[72] This range of entry points for the introduction of click functionality ensures that RAFT polymerisation and CuAAC continue to be investigated as routes to building a variety of chemically elaborate and structurally interesting polymeric materials.

As mentioned previously, both the clickable azide and alkyne functionalities can be readily introduced into the polymer by using either an azide or alkyne functional CTA. Harvison and Lowe gave a brief review of the uses of these CTAs.[72]

One example of the use of both alkyne and azide functional CTAs is illustrated in the work of Xue *et al.*, where both an alkyne- and azide-containing CTAs were prepared and exploited (Figure 1.60).[79]



EACDT

AEBDC

Figure 1.60: Alkyne terminal CTA (EACDT) and azide terminal CTA (AEBDC).[79]

These CTAs were used in a RAFT polymerisation to prepare alkyne-terminal polystyrene and azide-terminal poly(vinyl acetate). These CuAAC clickable functionalities were then reacted together to prepare a block copolymer.[79]

Atom transfer radical polymerization (ATRP) is another method of controlled radical polymerization. ATRP reactions have a number of key components, which include an alkyl halide and a transition metal halide catalyst. The transition metal halide catalyst abstracts a halogen from the alkyl halide and generates alkyl radicals (initiation) which can react subsequently with monomer to yield polymer (*via* propagation) (Figure 1.61).[78]

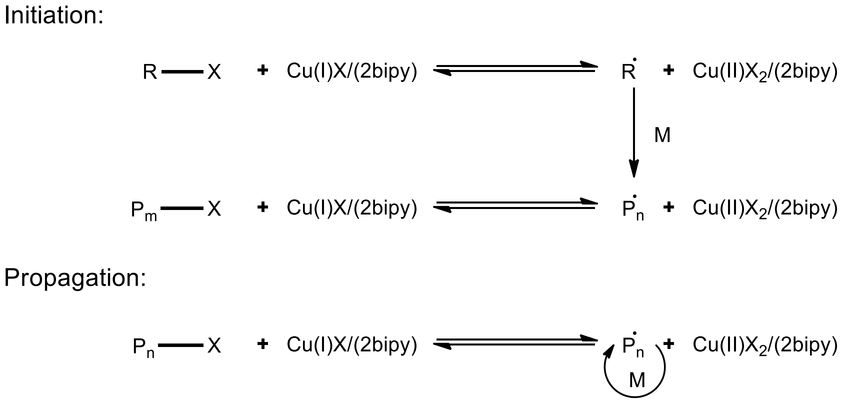


Figure 1.61: Key steps in ATRP polymerisation.[78]

Similarly to the RAFT polymerisation, ATRP allows for the synthesis of polymers with predetermined molecular weight and low polydispersites. Polymers prepared *via*

ATRP can be modified easily to introduce azide functionality; this is accomplished *via* nucleophilic substitution of terminal halide with sodium azide.[80]

An example of the successful combination of ATRP and CuAAC was shown by Lutz and co-workers; they successfully prepared polystyrene *via* ATRP and subsequently carried out a nucleophilic substitution of the bromine terminated polystyrene.[76] This afforded azide functional polystyrene which was capable of undergoing CuAAC chemistry with various alkyne functional groups (Figure 1.62).[76]

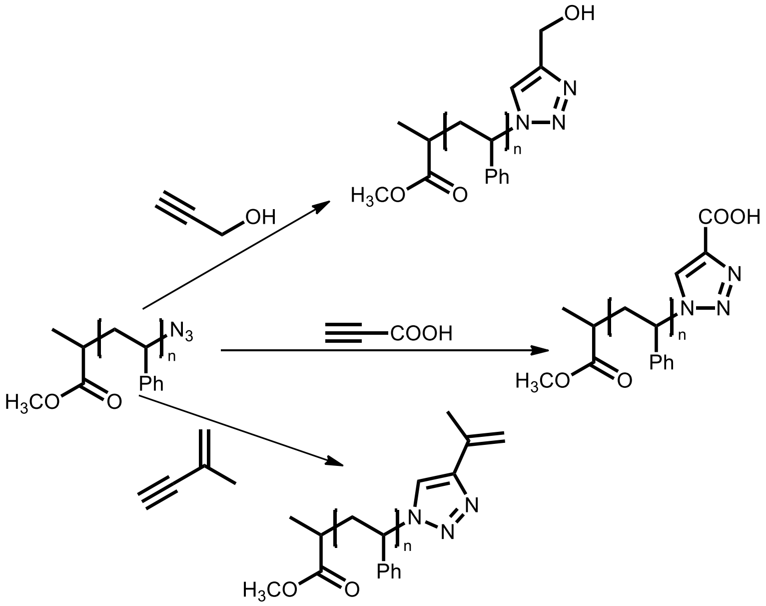


Figure 1.62: Azide functional polystyrene and subsequent CuAAC chemistry.[76]

1.5.8.2 Step-growth polymerisations and CuAAC

Polyurethanes are examples of step-growth polymers of the polyaddition type. The chemistry of polyurethanes has been discussed previously. The combination of polyurethanes and CuAAC is of special interest because this is the chemistry that we have investigated during the course of the current research program.

Examples of the blending of polyurethanes can be seen in the work of DuPrez *et al.*,. Du Prez and coworkers were primarily interested in the functionalization and preparation of polyurethanes with CuAAC clickable moieties.[73,81,82]

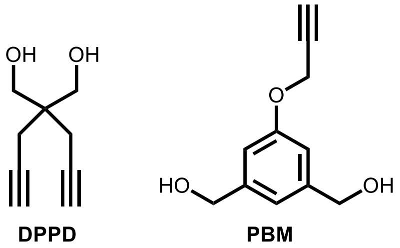


Figure 1.63: Alkyne functional diols for the preparation of alkyne-functional PUs.[73]

DPPD and PBM (Figure 1.63) are examples of di-functional and mono-functional alkyne diols, with respect to the alkyne moieties, which were incorporated into linear polyurethanes. Specifically, linear polyurethanes were prepared using 1, 4-butanediol in combination with alkyne functional PBM/DPPD as the diols and hexamethylene diisocyanate as the diisocyanate.

The materials were characterised *via* ^{1}H NMR spectroscopy, and the NMR spectra clearly showed the insertion of the alkyne-functional diols into the polyurethane.[73] Subsequently, the alkyne functional polyurethane was treated with a number of azide functional molecules under CuAAC click chemistry conditions (Figure 1.64).

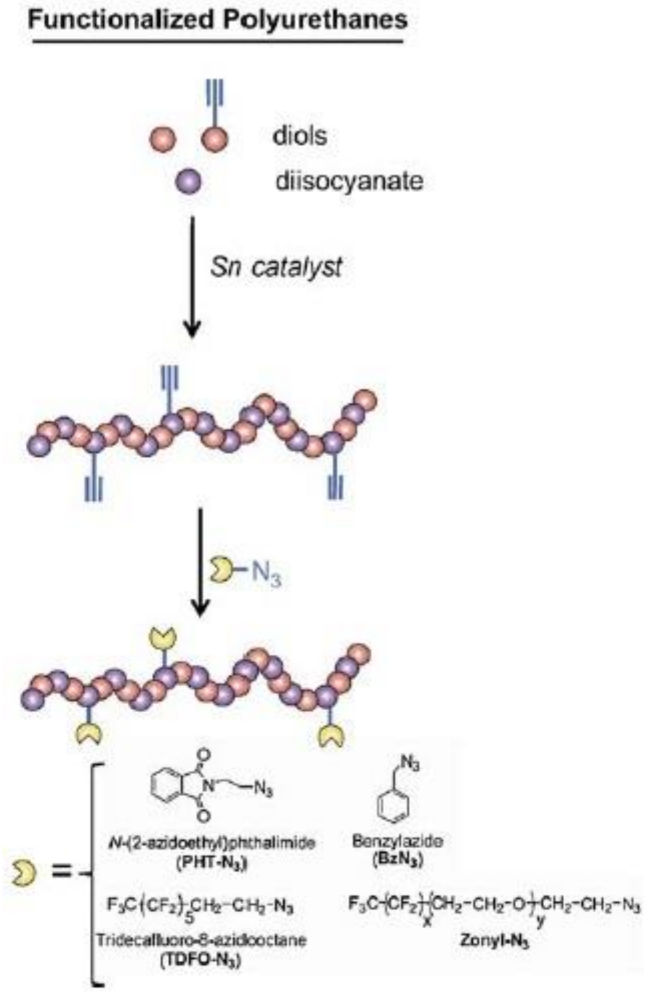


Figure 1.64: Combination of step-growth polymerization and CuAAC click chemistry.[73]

The post-polymerization modification of the PU was successful and highlights the ease with which “clickable” polyurethanes can be prepared and subsequently modified. One benefit of employing CuAAC chemistry is that there is no need for protection/deprotection of functional groups due to the orthogonality associated with the azide and alkyne functional groups.

The post-polymerization protocol was extended to already crosslinked polyurethane materials.[82] Du Prez *et al.* were able to functionalise alkyne-containing polyurethane films and foams with a number of azide-containing molecules which had the ability to change the surface properties of the films (Figure 1.65).

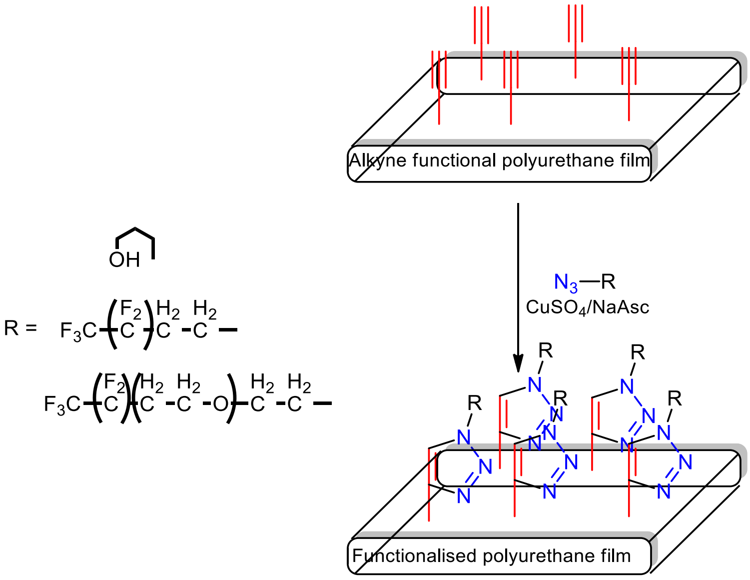


Figure 1.65: Modification of alkyne-containing film with various azide functional molecules.[82]

Du Prez and co-workers have reported previously upon the preparation of alkyne-containing polyurethanes. The preparation of the polyurethanes involved using an alkyne-functional diol as the hard segment of the polyurethane.[73] Alternatively, Du Prez was able to exploit the cationic ring-opening of THF in the presence of glycidyl propargyl ether and 1,4-butanediol. This afforded a polydiol with alkyne functionality which acted as the soft segment of a linear polyurethane. The alkyne functional polydiol was used in the preparation of linear polyurethane and could be reacted with a range of azide functional molecules.[81]

Another example of the combination of polyurethanes and CuAAC can be seen in the work of Baier *et al.* who prepared azide functional polyurethane nanocapsules *via* an inverse miniemulsion technique. Owing to the azide functionality on the polyurethane nanoparticles, it was possible to modify the surfaces of the nanoparticles using both a copper-free process and a copper-catalysed variant.[69]

The copper-free version of the surface functionalization of the nanoparticles involved reaction of the azide functionality with the electron deficient propiolic acid. This copper-free process is interesting because there is no need for elevated temperatures to promote the cycloaddition. To investigate the copper-free reaction further, the azide monomer used to prepare the azide functional polyurethane was itself reacted with propiolic acid at room temperature in the absence of catalyst. The reaction was monitored *via* ^{1}H NMR spectroscopy and it was found that after approximately 48 hours the reaction was complete. As expected, there was a mixture of regio-isomers associated with a non-copper catalysed reaction. The workers noted that the copper-free cycloaddition between azide nanocapsules and alkyne functional molecules shows promise for biological applications.[69]

In addition to the previously described work involving polyurethane materials, the suitability of other step-growth polymers has been explored with CuAAC. Two examples which investigated siloxane polymers and CuAAC come from the work of Gongaza *et al.*; in these examples, alkyne and azide functional siloxanes were prepared[83] and subsequently crosslinked.[84]

Nucleophilic substitution of halogenated siloxanes with sodium azide resulted in the formation of an azide functional disiloxane and a polymeric azido-siloxane (Figure 1.66).[83]

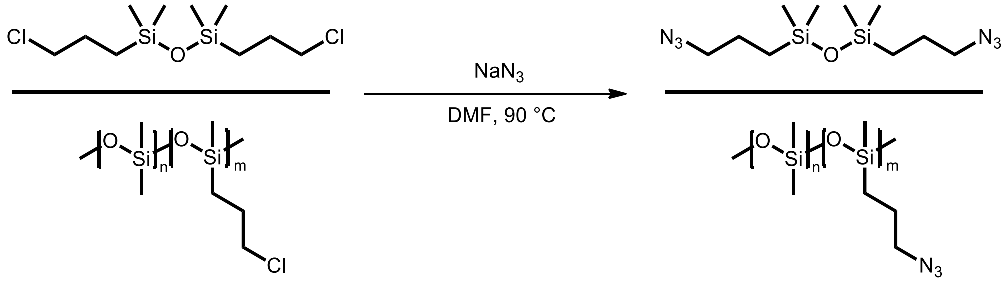


Figure 1.66: Nucleophilic substitution of halogenated siloxanes to afford azide functional siloxanes.[83]

The azide functional siloxanes were subjected to CuAAC with a range of alkyne-containing molecules. In addition, the azide- and alkyne-containing molecules were reacted together under thermal conditions, in the absence of a Cu catalyst.[83]

Both thermal and CuAAC reactions resulted in high yields and, in the case of CuAAC, selectivity. Key findings of the work were that there is no need for the biotoxic Cu catalyst to be used in situations where the use of elevated temperatures can be tolerated. In addition, it was found that when the alkyne and azide components were mixed at room temperature in the absence of catalyst there was no reaction;

the authors highlight this as a beneficial finding as it allows for the preparation of one-pot formulations that would only undergo cycloaddition upon addition of catalyst or application of a heat source.[83]

In further work from Gongaza *et al.* the ability of azide and alkyne functional siloxanes to act as precursor materials for elastomer formation was investigated. The function of the azide and alkyne was to crosslink the siloxane materials. This was achieved in a catalyst-free process at elevated temperature (Figure 1.67).[84]

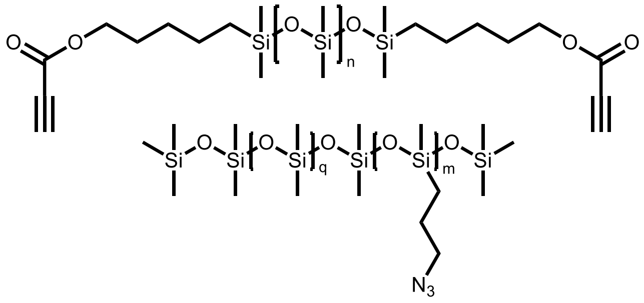


Figure 1.67: Azide and alkyne siloxanes for the preparation of polysiloxane elastomers.[84]

This work is exciting as it provides an example of how azide and alkyne functional molecules can be used to crosslink polymeric materials. One interesting result arising from the work was the ability to form an elastomer at room temperature with no Cu catalyst. Unfortunately, the rates of elastomer formation were not spectacular, with reactions between azide and alkyne occurring at room temperature within 30-48 h. These interesting results are reported to be due to the electron-deficient nature of the alkynes used.[84]

1.5.8.3 Preparation of polytriazoles

The previously discussed examples of the union of CuAAC and polymer chemistry have related to the use of the CuAAC chemistry as either a method for post-polymerisation functionalization or as a crosslinking strategy. Alternatively, azide and alkyne functionalities can be used to prepare polymers with triazole residues in the backbones of the polymers; this class of materials have been termed polytriazoles (PTAs).

One such example of the use of polytriazoles is evident in the work of Finn *et al.* in which a range of multi-functional azides and alkynes that could be reacted under CuAAC conditions to provide adhesive materials.[85] The properties and performance of the resulting products are based solely on the polytriazole chain.

The use of azide and alkyne functional molecules can be extended to the preparation of linear polymers and other architectures. One such example of the formation of linear PTAs is seen in the work of van Steenis *et al.* where the authors were interested in using the CuAAC reaction to prepare conjugated polymers.[86] This involved the preparation of a number of azide and alkyne functional monomers and end-cappers (Figure 1.68).

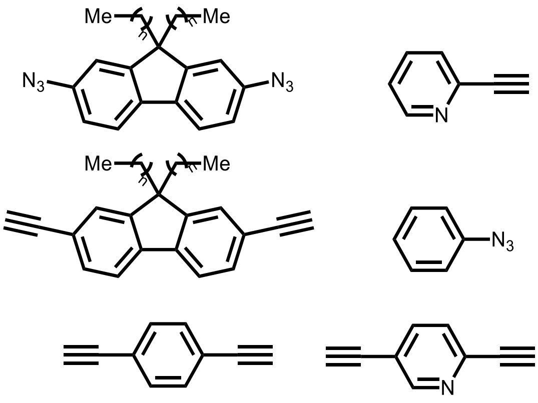


Figure 1.68: Azide and alkyne functional monomers used in the preparation of polytriazoles.[86]

The bulk of the polymerisations were carried out at room temperature and a number of high molecular weight polymers were formed. An interesting result arising from the work was the ability to carry out the CuAAC polymerisations at sub-ambient temperatures (-10 °C) and still achieve products with relatively high molecular weights (M_w = 59,000).[86]

Moving away from A_2/B_2 azide and alkyne systems it is also possible to prepare A-B type monomers.[87] Binauld *et al.* prepared three of these A-B type monomers and were able to copolymerise these to afford a range of co-polymers with tuneable structures and properties (Figure 1.69). Importantly, the monomers were stable to storage (at -4 °C and in the absence of a Cu(I) catalyst) even after prolonged periods of time.[87]

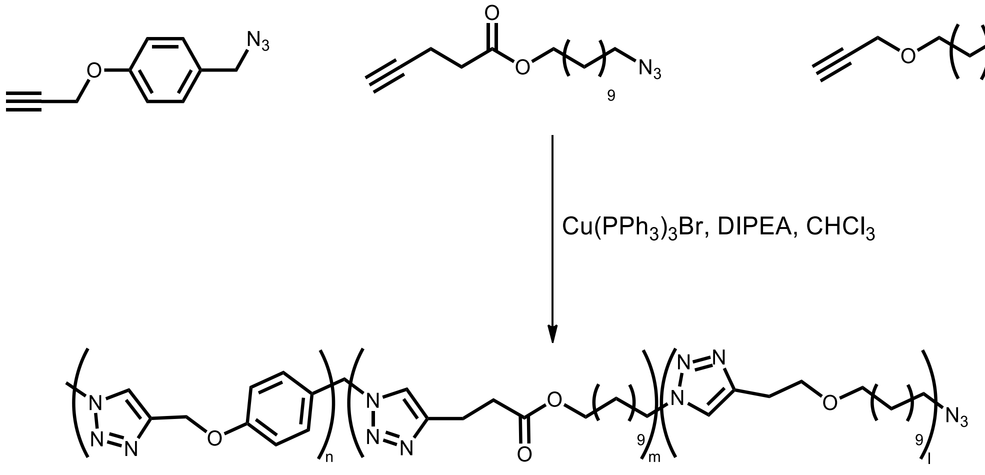


Figure 1.69: Copolymerisation of A-B monomers *via* CuAAC.[87]

The preparation of PTAs continues to be investigated as a route towards functional materials. This is because the CuAAC reaction provides a route to interesting polymers with heteroaromatic backbones which would be difficult to synthesise in any other way.[87]

1.5.9 Interesting aspects and developments of CuAAC

The application of our azide and alkyne functional polymers has to be considered. Most likely, the fully crosslinked system will be exposed to a variety of external, environmental conditions that will be capable of causing degradation of the coating. A review of the literature presents very few examples of either mechanical, chemical or photochemical investigations into the stability of materials prepared *via* CuAAC. The reason for this lack of research could be attributed to the fact that the triazole is known to be broadly stable to most chemical treatments. In addition, the triazole moiety is seemingly inert in aqueous or biological environments and can also tolerate high temperatures and normal UV-light.[88]

That being said, there is a limited number of examples of investigations into the stability of triazoles. One such example from Brantley *et al.* used mechanical force to promote a retro-cycloaddition of the triazole ring to afford both azide and alkyne functionalities.[89] The authors prepared a poly(methyl acrylate) (PMA) polymer bearing a central triazole ring. After ultrasonication for two hours at 0 °C it was shown by gel permeation chromatography (GPC) that the molecular weight of the polymer had decreased by half. Also, the infrared spectrum of the ultrasonicated polymer showed bands associated with both azide and alkyne functionality. The mechanical scission of the triazole ring could be used to beneficial effect in material applications were a reversible cycloaddition of the azide and alkyne would be of benefit.[89]

The photostability of the triazole groups has been studied indirectly by a number of groups.[59, 90] Johnson *et al.* used SPAAC chemistry to prepare photodegradable star polymers; these star polymers possessed a photocleavable tetra-nitrobenzyloxycarbonyl (NBOC) group in the polymer chain. It was shown that upon photoirradiation (350 nm for 2 days) the triazole links were not affected.[59] Johnson *et al.* applied conventional CuAAC with ATRP to prepare monomers which could be used to prepare a photocleavable network; the NBOC group was again used as the photocleavable group. It was found that for UV irradiation at 350 nm, several days were needed for complete degradation to occur.[90]

The previously mentioned examples of studies that have directly or indirectly investigated the stability (chemical or photochemical) of triazole groups are very encouraging. They show that the extreme of an extended period of ultrasonication is required for triazole degradation, whilst also suggesting that there is little or no photodegradation of triazole rings when they are exposed to extended period of UV irradiation.

In some instances, when CuAAC does not proceed as expected the culprit is most likely acetylinic homocoupling.[40] Small and unhindered amines are likely to mediate the acetylinic homocoupling as they stabilise intermediates (Figure 1.70).[91]

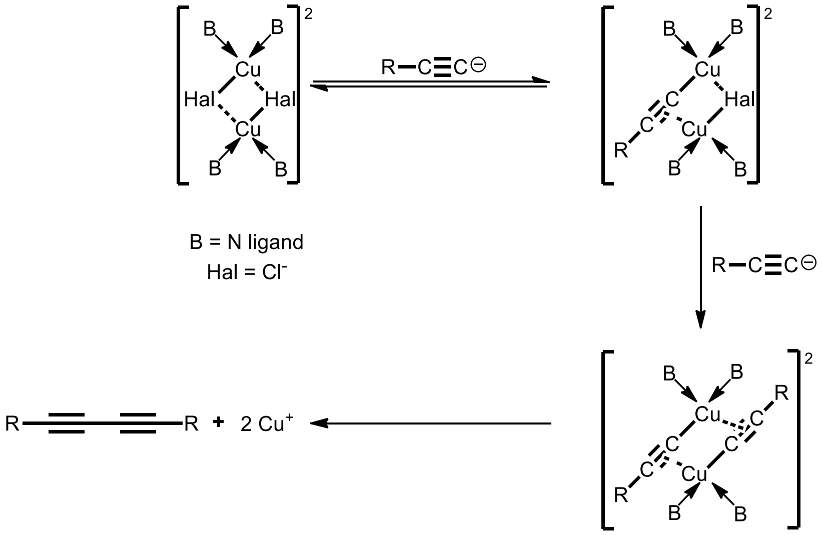


Figure 1.70: Proposed mechanism for Cu-catalyzed acetylenic coupling.[40]

Increasing the steric bulk of the amine base will reduce its ligand donor properties and will, in turn, reduce the stabilisation of the intermediates (Figure 1.70) and supress the unwanted homocoupling of the alkyne groups.[91]

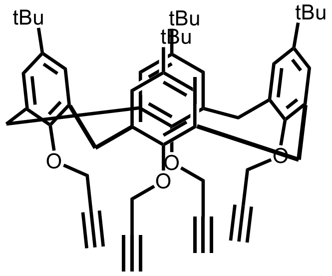


Figure 1.71: Polyalkyne calixarene prepared by Ryu *et al.* which was incapable of CuAAC reaction.[92]

Another possible source of failure in the CuAAC reaction comes from the over-saturation of the Cu centre.[40] This was the case for a polyalkyne prepared by Ryu *et al.* (Figure 1.71) where the Cu(I) centre was saturated through chelation.[92] Even upon an increase of the reaction temperature to 60 °C, only a complicated mixture of products resulted. Preparation of triazole functional calixarenes was achieved by substituting the pendent alkyne groups for pendent azides.[92]

A recent interesting communication by McNulty *et al.* described a silver-catalysed azide-alkyne cycloaddition.[93] They found that a P-O type ligand/silver complex (Figure 1.72) was capable of catalysing an azide-alkyne cycloaddition.[93]

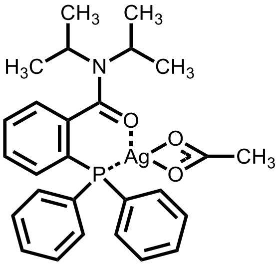


Figure 1.72: Ligand/silver complex capable of catalysing reactions between azides and alkynes.[93]

The silver-catalysed reaction between phenyl acetylene and benzyl azide was found to proceed at room temperature in the presence of 10 mol. % of the silver complex, returning a 9-10 % yield of product. The addition of additives and optimisation of reaction conditions afforded the triazole product in 98 % yield within 48 hours.[93]

Dohler *et al.* investigated the auto-catalytic effect of the CuAAC reaction with respect to crosslinking of azide- and alkyne-containing molecules.[94] The authors wished to exploit the 1, 3 – triazole rings that are formed in the CuAAC reaction and the ability of the triazole rings to act as ligands which have been found to accelerate the rate of subsequent CuAAC reactions.[94]

Auto-catalysis was observed in a number of cases and a few key findings were observed. Increased reaction rates in the presence of an increased number of functional groups were observed. In addition, it was found that molecular mobility was related to CuAAC reactivity with increased reaction rates recorded for lower molar mass substrates.

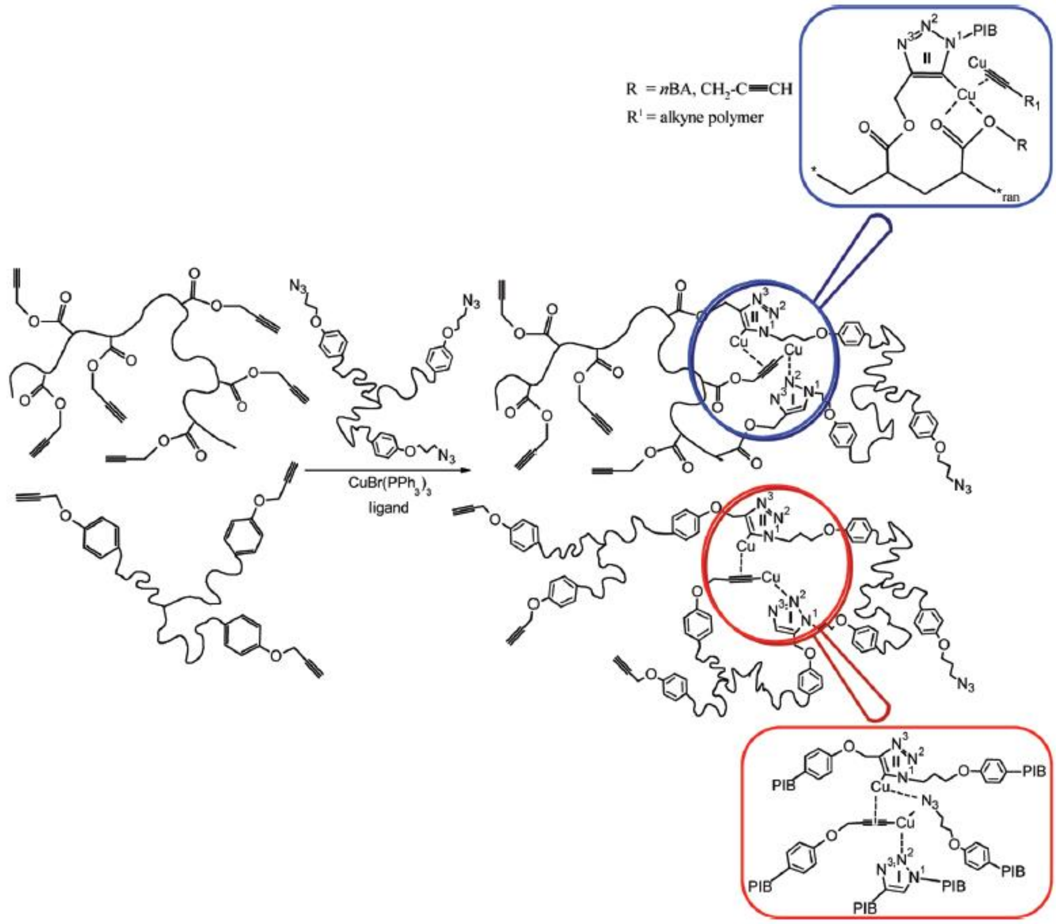


Figure 1.73: Auto-catalytic function of triazole group.[94]

The mechanism proposed for their observed auto-catalysis was based on the ability of the triazole ring to function in either one of two ways. In the first instance, a triazole ring is capable of acting as an internal ligand whilst using the N2 or N3 atoms of the triazole ring. This is thought to push electron density onto the Cu centre and promote the formation of Cu(I) acetylide species (Figure 1.73 (**I**)). The second postulated function of the triazole ring is to act to preorientate the azide and alkyne functionalities close to the Cu(I) centre leading to rapid formation of the next triazole ring (Figure 1.73 (**II**)).

1.5.10 CuAAC and polymeric applications – patent literature

A review of the patent literature affords a number of patent applications where CuAAC chemistry has been investigated. Focus is given to patents that relate in some way to the application we are interested in pursuing using CuAAC, such as coatings, polyurethanes and general polymeric applications.

Fokin *et al.* investigated CuAAC as a method for preparing adhesives. Fokin prepared a range of azide and alkyne functional monomers which could be applied to a solid surface, or specifically to a solid surface that is copper or an alloy containing copper.[95] Ritter *et al.* worked on the preparation of elastomers based on polysiloxanes that contain alkyne or azide functionality, with the preferred application being for coatings or sealants.[96] Du Prez *et al.* focused on preparing isocyanate functional polymer materials that were also functionalised with azide or alkyne moieties. The isocyanate functional PUs were processed into films or foams using conventional means, but owing to the latent azide or alkyne functionality could be modified using CuAAC chemistry.[97]

Manzara *et al.,* from 3M, disclose compositions and molecules that can be used to carry out post-polymerisation functionalization of a polymer.[98] The molecules used to functionalise the polymer had azide or alkyne functionality, and the azide or alkyne functional polymer could subsequently undergo crosslinking *via* azide-alkyne cycloaddition.[98]

Typical modifying compounds possess a reactive functional group such as aziridine amide, isocyanate, alcohol, epoxy or amine. The second functional group was either alkyne or azide. Typical modifying compounds are shown in Figure 1.74. Types of polymers suitable for this modification include poly(meth)acrylates, polyurethanes, polyesters and polysiloxanes amongst others.[98]

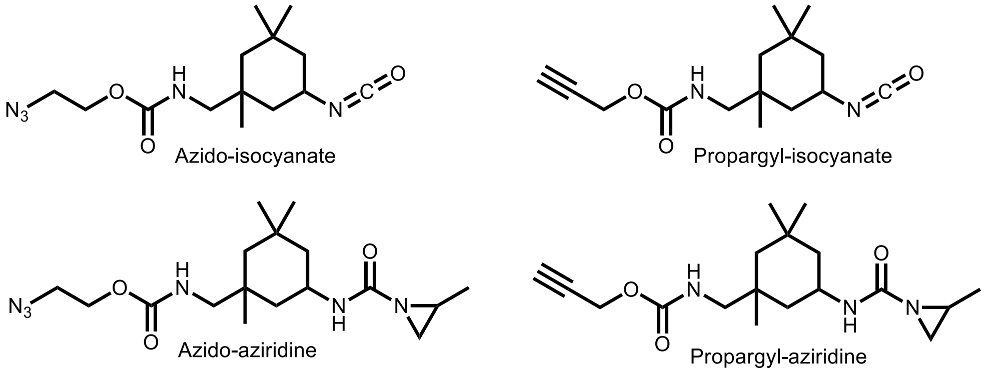


Figure 1.74: Modifying compounds used to functionalise polymers with azide or alkyne groups.[98]

An earlier example of the preparation of CuAAC compatible polymers, which pre-dates the work of Sharpless on the "click" chemistry concept, is seen in the work of Chen *et al.* in which they prepared alkyne-containing polymers which could be subsequently crosslinked.[99]

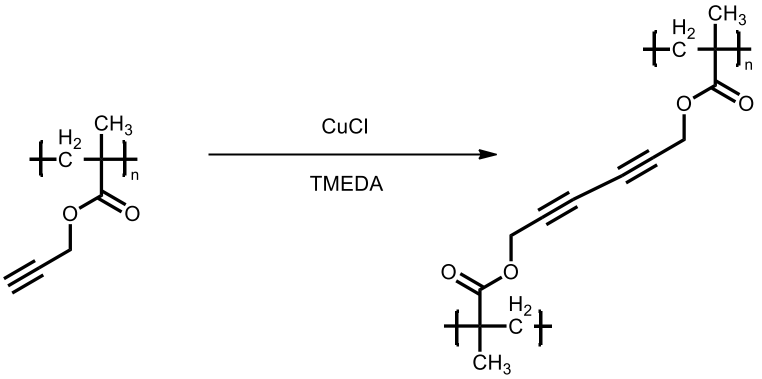


Figure 1.75: Hay coupling used to crosslink acetylene containing polymers.[99]

Interestingly, there was no need for an external crosslinker. Instead, Hay coupling was carried out between the acetylene groups (Figure 1.75).[99]

1.5.11 Alternative click reactions to CuAAC

As mentioned previously, a number of reactions conform to the requirements set out by Sharpless *et al.* that determine if a reaction qualifies as a click-type reaction.[34] Some of these reactions and their applications (particularly in polymer chemistry) are discussed in the following sections.

The term thiol-ene relates to the addition of a thiol across an alkene double bond (Figure 1.76).[100]

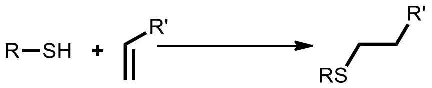


Figure 1.76: Thiol-ene reaction.[100]

The thiol-ene reaction has been used frequently for the preparation of near-perfect networks and films by a number of researchers.[101,102,103] The thiol-ene reaction has recently become a hot topic as it emerges that the reaction has a number of properties that allow the thiol-ene reaction to be classed as a "click" type reaction.[100]

The thiol-ene reaction can proceed under a range of conditions *via* one of three possible mechanisms:

- Radical-mediated thiol-ene reaction
- Base-catalysed thiol-ene reaction
- Nucleophile-catalysed thiol-ene reaction

Regardless of the promotion method used, thiol-ene reactions tend to occur extremely rapidly at ambient temperature and pressure. The reaction is also tolerant of a wide range of environmental conditions including oxygen and moisture. [100]

The radical-mediated version of the thiol-ene reaction is by far the most studied (Figure 1.77).[100] The reaction is commonly photochemically induced, but thermolysis of the S-H bond can also be used to generate the thiyl radical.

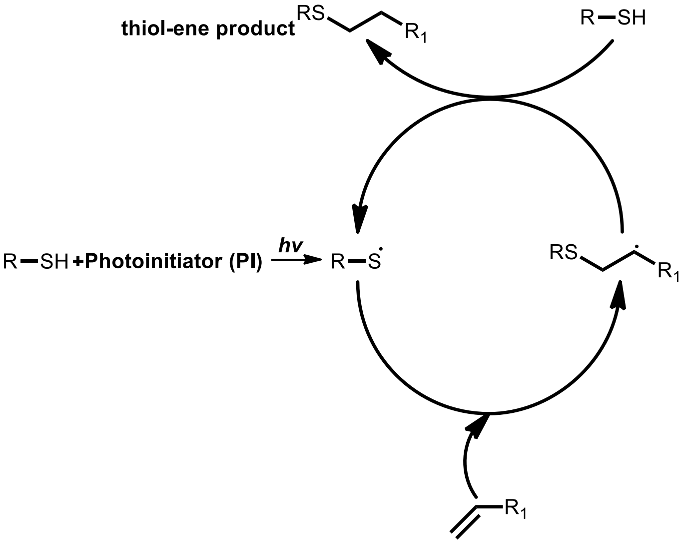


Figure 1.77: Radical-mediated thiol-ene reaction.[100]

Figure 1.77 shows the key steps involved in the radical-mediated thiol-ene reaction. Initially, a photoinitiator species is used to generate the thiyl radical which then adds to the carbon-carbon double bond to give a carbon-centred radical which allows for chain-transfer to another thiol molecule. The process results in the hydrothiolation of a carbon-carbon double bond in an *anti*-Markovnikov fashion.[100]

Bearing in mind the aim of the current PhD programme, the thiol-ene reaction initially seemed attractive as it has a set of properties that make it a rather robust and efficient reaction. Unfortunately, the radical-mediated version of the thiol-ene reaction does not lend itself to use on a large scale, where the potential application environment will prohibit the use of UV lamps for curing.

Fortunately, an alternative to the radical-promoted thiol-ene reaction exists in the form of the base/nucleophile-catalysed variants of the thiol-ene reaction. These reactions allow for the thiol-ene reaction to occur without the need for a photoinitiator or UV lamps. The base- and nucleophile-catalysed reactions also involve the addition of a thiol group across an alkene double bond. The reaction is most effective when the alkene is "activated", that is to say that it is attached to an electron-withdrawing group (Figure 1.78).[100]

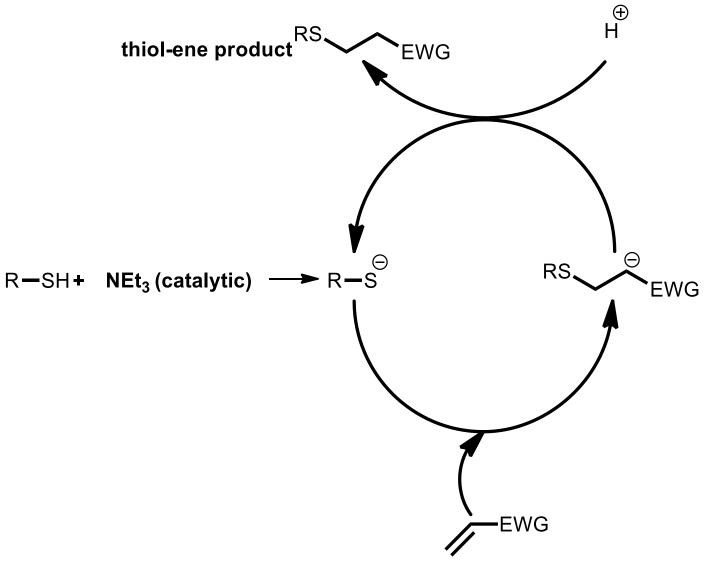


Figure 1.78: Base-catalysed thiol-ene reaction.[100]

Figure 1.78 shows the proposed route of the base-catalysed thiol-ene reaction. Initially, the base abstracts a proton from the thiol. This generates a thiolate anion which can attack the carbon-carbon double bond in the β-position to generate a carbon-centred anion. This anion can pick up a proton from another thiol molecule, or the ammonium cation, to give the thiol-ene hydrothiolation product in an *anti*-Markovnikov fashion. In essence, a relatively weak base is used to generate the much stronger carbon-centred anion (a very strong base).[100]

In addition to the base-catalysed system, use of a nucleophile provides an alternative route to the thiol-ene reaction. Certain amines and phosphines act as strong nucleophiles and can attack the activated alkene to generate an enolate species which can deprotonate thiol and thus generate the thiolate anion (Figure 1.79).[100]

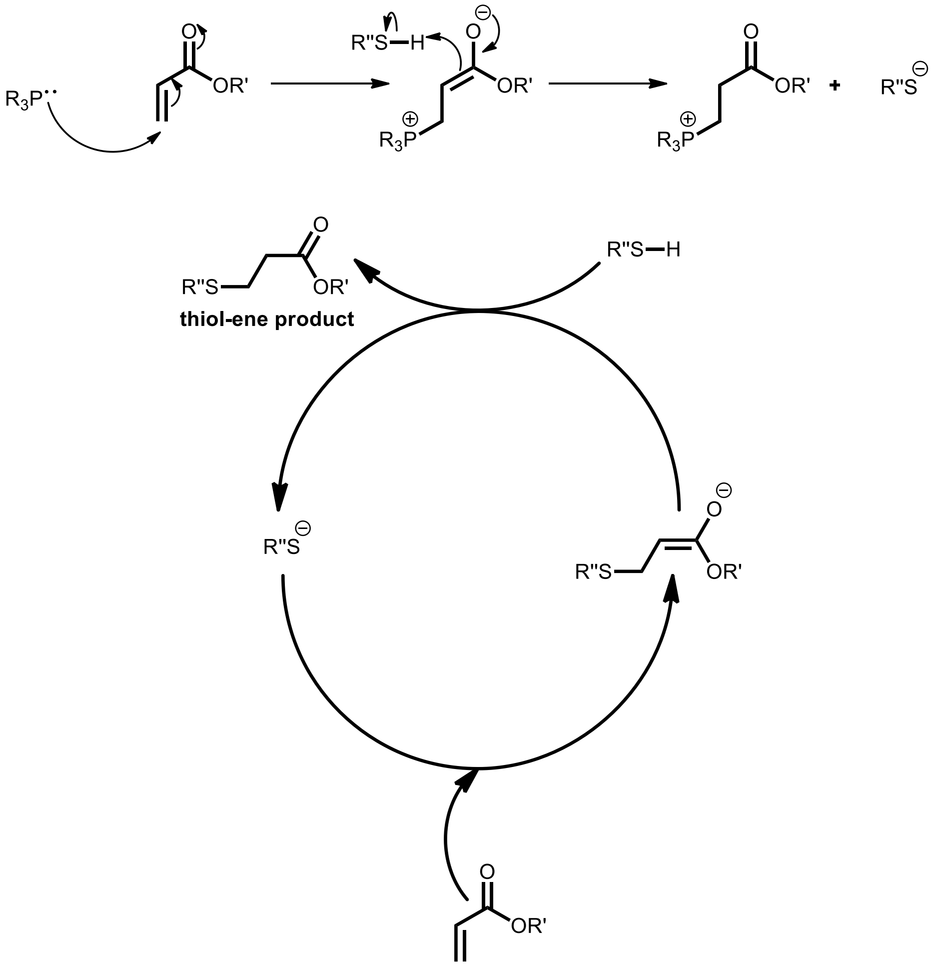


Figure 1.79: Proposed nucleophilic mechanism for thiol-ene reaction.[100]

Once generated, the thiolate anion can take part in the anionic chain mechanism resulting in the formation of the thiol-ene product. One can note that primary and secondary amines are both potent catalysts, and weakly basic dimethylphenylphosphine (Me_2PPh) is a superior nucleophilic catalyst.[100]

Thiol-ene chemistry has been used extensively for the formation of perfect networks and films.[100-103] To date, most work has centred on the radical-mediated thiol-ene reaction, with relatively little work on the base/nucleophile version of the reaction.

Chan *et al.* describe, in their 2009 paper, the use of the phosphine-catalysed nucleophilic thiol-ene reaction, which is sequentially coupled with a radical-mediated thiol-yne reaction. The work made use of the extremely rapid and quantitative reaction of a thiol with an activated alkene in the presence of Me_2PPh as catalyst.[104]

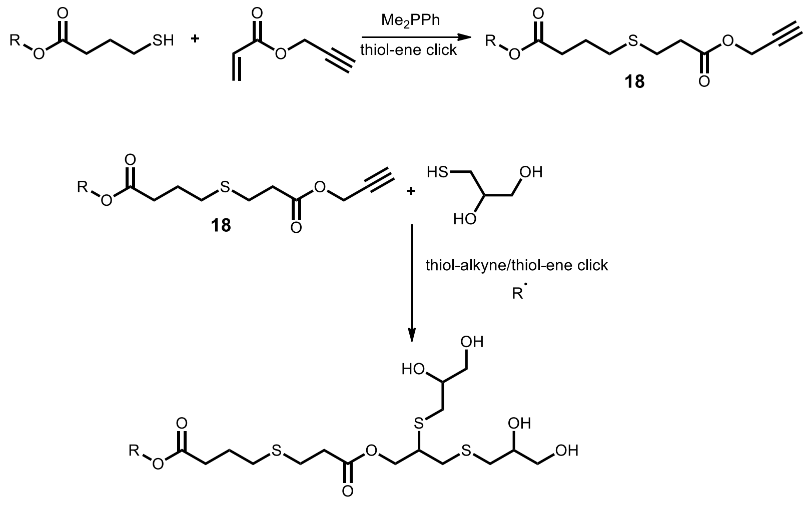


Figure 1.80: Model reaction carried out between thiol-ester and propargyl acrylate.[104]

The model reaction shown in Figure 1.80 between a thiol-ester and propargyl acrylate was carried out at ambient temperature and pressure. It was observed that there was rapid and selective addition of the thiol across the alkene to yield the thioether diester (**18**) in 100% yield. Approximately 90% conversion of substrate was observed within 2.5 minutes, and the reaction was complete after only 17 minutes. It was found that increasing the catalyst concentration increased the reaction rate considerably.[104]

The reaction between the thiol-ester and propargyl acrylate to yield **18** was tracked using real-time FT-IR spectroscopy to monitor the disappearance of the acrylate and thiol signals at 810 and 2,570 cm^{-1}, respectively (Figure 1.81).[104]

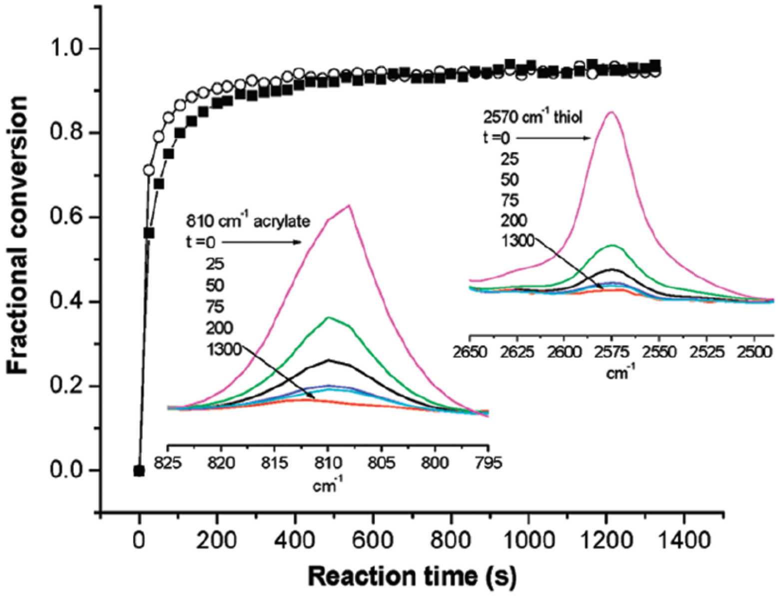


Figure 1.81: RT-FT-IR spectroscopy (■) acrylate conversion (○) thiol conversion.[104]

Figure 1.81 highlights the speed with which the phosphine-mediated thiol-ene reaction occurs; within 200 seconds integration of both the acrylate and thiol peaks indicate greater than 60% conversion.[104]

In addition to the model reaction shown in Figure 1.80, the researchers also prepared multi-functional thioethers *via* a similar phosphine-promoted thiol-ene reaction (Figure 1.82).[104]

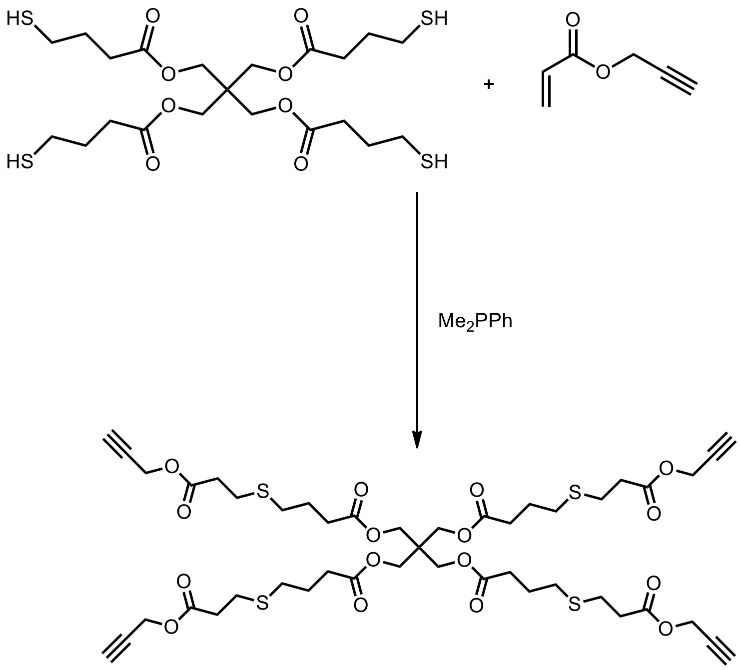


Figure 1.82: Multi-functional thio-ethers.[104]

The tetra-functional alkyne was prepared by mixing pentaerythritol tetramercaptoprionate with propargyl acrylate and the reaction was left for one hour to allow for complete conversion. This research emphasises the utility of the nucleophilic thiol-ene reaction. It also illustrates the speed at which the thiol-ene reaction can occur, and highlights the high conversion rates.[104]

In another paper from 2009 by Shin *et al.*, use was made of the phosphine-catalysed thiol-ene reaction to prepare thiol-terminated oligomers (Figure 1.83). The thiol-terminated oligomers were then used to react with diisocyanate monomers in a base-catalysed process.[105]

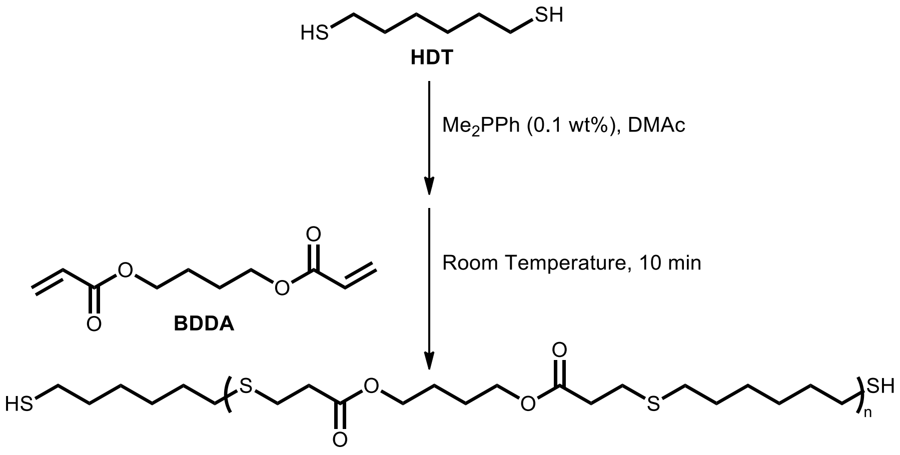
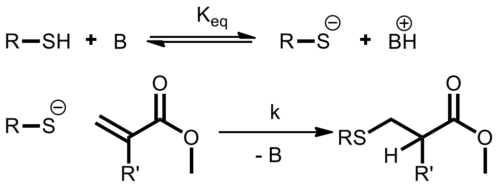


Figure 1.83: Preparation of thiol-terminated oligomers *via* nucleophile-catalysed thiol-ene reaction.[105]

The speed at which the phosphine-catalysed thiol-ene reactions occurred was monitored *via* RT-FT-IR spectroscopy. Three samples with differing number average molecular weights (theoretical) show how extremely fast and efficient the thiol-ene reaction is, with acrylate conversions of 98, 96 and 94% being recorded after only 300 seconds.

The examples from the literature described so far have concerned the thiol-ene reaction catalysed *via* a nucleophile, but there are also examples of base-catalysed thiol-ene chemistry in the literature. One such example is from Tomasi *et al.*, who attempted to prepare poly(ester sulphides) from oligo(oxyethylene) dithiols and *bis*(acrylates).[106] The researchers initially prepared *tetra*(ethylene glycol) dithiols which could undergo a base-catalysed (TEA and DABCO) thiol-ene reaction with methyl methacrylate (MMA) and methyl acrylate (MA) (Figure 1.84).



R' = H, CH$_3$; B = base (TEA or DABCO)

Figure 1.84: Base-catalysed mechanism for the formation of β-thioesters.[106]

There was an observed higher reactivity of the MA over the MMA upon reaction with oligo(oxyethylene) dithiol. The difference in reactivity is believed to be due to the difference in the stability of the intermediate. In the case of MA the anion is located on a secondary carbon atom, whereas for MMA there is less resonance stabilisation due to the anion being located on a tertiary carbon which is less stable than the secondary carbanion of MA (Figure 1.85).

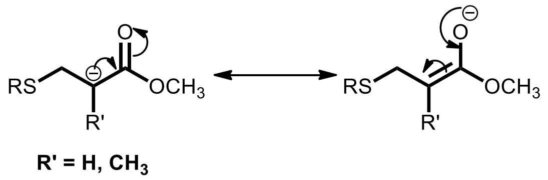


Figure 1.85: Resonance stabilisation on MA and MMA.[106]

Three oligo(ethylene glycol) dithiols and three *bis*(acrylates) were combined to prepare a number of different polymer samples (Figure 1.86). The polymerisations were carried out for 140 hours at 30 °C to allow for complete conversion. Data disclosed in the paper indicates high conversions after only 5 hours for reactions between the dithiols and MA.

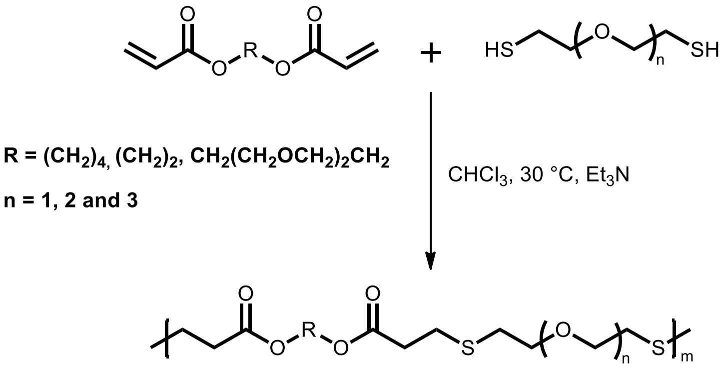


Figure 1.86: Preparation of poly(β-thioesters).[106]

All reactions were carried out under identical conditions (30 °C for 140 hours in chloroform using a stoichiometric amount of triethylamine). It was noted that there was a distinct difference in molecular weight between the samples considering that they were prepared under nominally identical experimental conditions. This shows that the reaction is somewhat sensitive to changes to the experimental parameters.

A paper by Carioscia *et al.* from 2007 describes the use of base-catalysis in the reaction between thiols and epoxy groups.[107] The thiol-epoxy reaction can proceed *via* a base- or nucleophile-catalysed pathway. Generally, the base creates a thiolate anion as it reacts with the thiol group. The thiolate anion can then attack an epoxide group.

In addition, the reaction between the amine and the epoxy group can create an oxygen anion. In the presence of a hydrogen donor, such as a thiol or alcohol group, hydrogen abstraction can occur to create the alcohol and return the tertiary amine.

This reaction was teamed with the photo-initiated thiol-ene reaction to prepare thiol-ene/thiol-epoxy hybrid networks. The monomers used during the work are shown in Figure 1.87; they are pentaerythritol *tetra*(3-mercaptopropionate) (PETMP), triallyl 1,3,5-triazine-2,4,6-trione (TATATO) and bisphenol A diglycidyl ether (Bis A-DGE).[107]

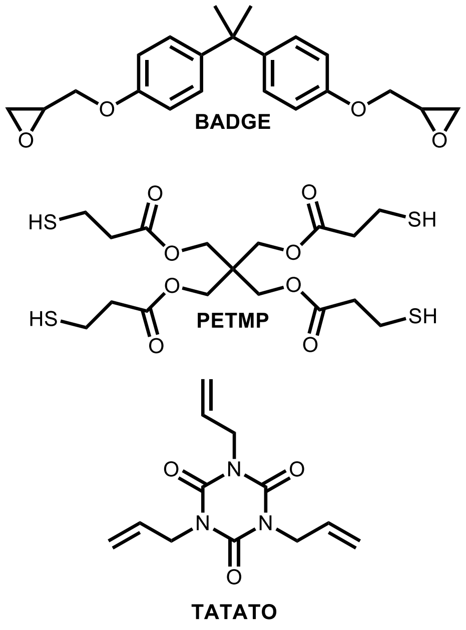


Figure 1.87: Monomers used to prepare thiol-ene/thiol-epoxy hybrid networks.[107]

During the study the composition of the thiol-ene/thiol-epoxy hybrid mixtures was varied and the resulting polymers analysed. One experiment of interest studied the effect of the sequential curing for two hybrid mixtures of the thiol-epoxy/thiol-ene monomers at 50/50 wt% and 75/25 wt% (Figure 1.88).[107]

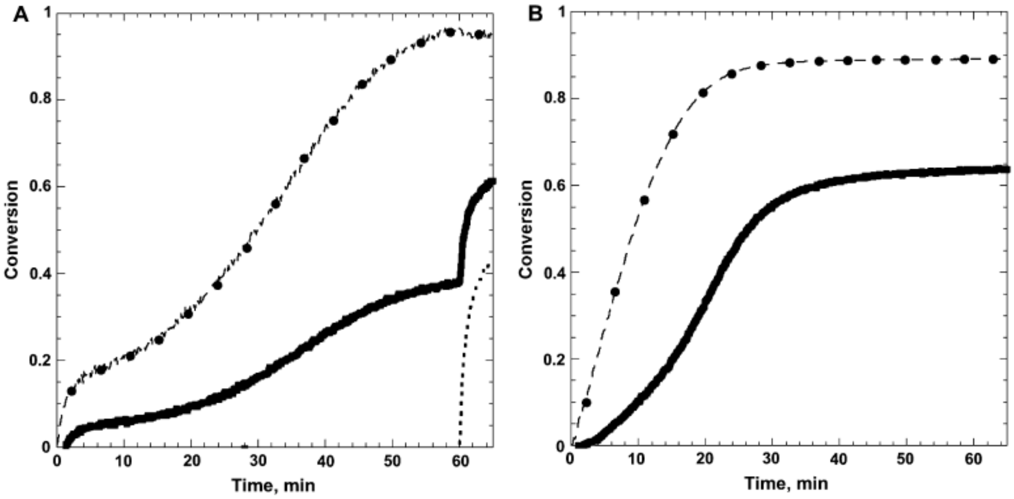


Figure 1.88: Graphs showing functional group conversion against time for 50/50 (A) and 75/25 (B) wt% thiol-epoxy/thiol-ene hybrid mixtures. The graphs depict (--●--) epoxy conversion, (●) thiol conversion, and (¨¨¨) ene conversion.[107]

The samples depicted in Figure 1.88 were subjected to sequential curing; initially, the samples were dark-cured in the presence of amine catalyst, and then after 60 minutes subjected to UV curing for 300 seconds with 15 mW/cm^2 320-500 nm light. It can be seen that there is no conversion of the ene component in the 75/25 wt% hybrid mixture due to the formation of a highly crosslinked network. It is interesting to note that there is no conversion of the ene *via* the nucleophile/base thiol-ene reaction; this is most likely due to the fact that the ene moiety of TATATO is not activated. [107]

During the study the researchers investigated the effect of the catalyst concentration; a 50/50 wt% thiol-epoxy/thiol-ene mixture was cured for 300 seconds with 15 mW/cm^2 of 320-500 nm light. The catalyst concentration was varied from 5 wt% to 10 wt%, and it was found that this increased the epoxy polymerisation rate but did not affect the thiol conversion (Figure 1.89).

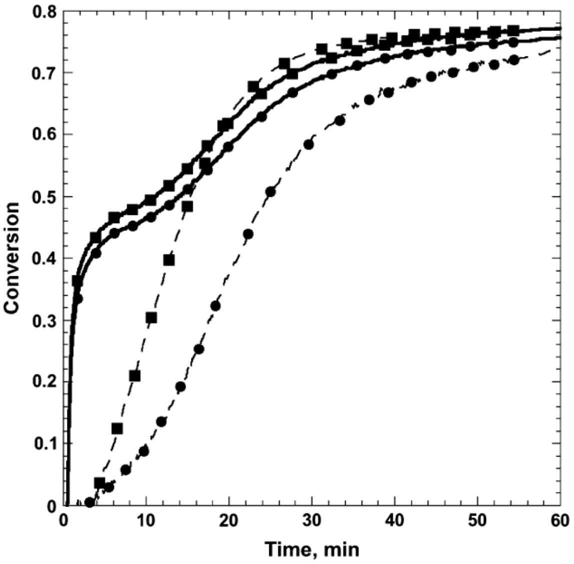


Figure 1.89: The effect of increasing the amine catalyst concentration with (●) 5 wt% amine or (■) 10 wt% amine. The graph depicts (—) thiol conversion and (---) epoxy conversion.[107]

A recent paper which highlights the effectiveness of phosphine-mediated reactions from Jones *et al.,* describes the use of water-soluble phosphine catalysts with a two-fold function.[108] Initially, the phosphine reagent acts as a reducing agent for the reduction of a disulfide bond in a protein to two thiol groups. The same phosphine catalyst is then capable of catalysing the thiol-ene reaction between the thiol groups and poly(monomethoxy ethylene glycol) methacrylates in a one-pot procedure (Figure 1.90) at ambient temperature and pressure.[108]

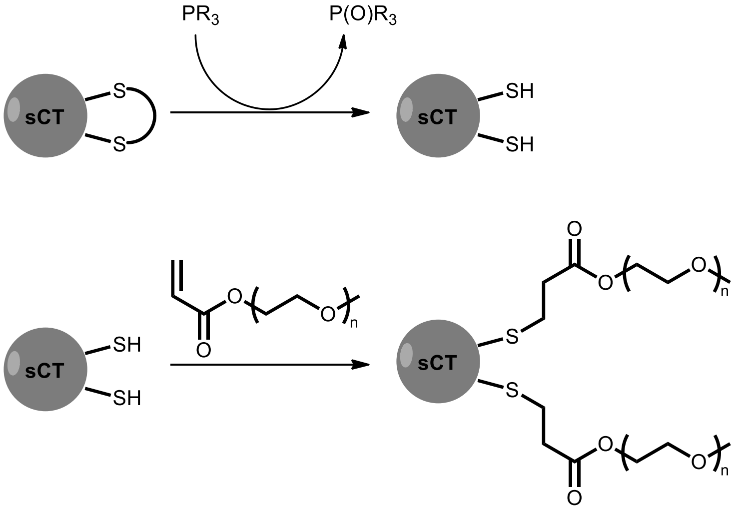


Figure 1.90: Reduction of a disulfide bridge in salmon calcitonin (sCT) and subsequent catalysis of thiol-ene reaction.[108]

The thiol-ene reaction represents a reaction which shows promise as a method for the crosslinking of thiol- or alkene-terminated PUs. The thiol-ene reaction proceeds at room temperature and in short reaction times.[108]

Diels-Alder cycloaddition is a common reaction used in organic chemistry, and was invented by Otto Diels and Kurt Alder.[109] The reaction is a [4 + 2] cycloaddition between electron-rich dienes and electron-poor dieneophiles to form stable, unsaturated, cyclic products.[110]

In some applications, the thermal reversibility and the fact that the decomposition reaction of the cyclic system can be controlled by temperature are valuable attributes.[111] Some Diels-Alder reactions conform to some of the qualifying criteria for a click reaction.[112]

Diels-Alder chemistry has been used in a wide number of polymeric applications.[111] Particularly advantageous are the high reaction yields, absence of side reactions and no need for additional metal catalysts. The reactive moieties are inert to most functionalites, such as acid, alcohol, amine and biomolecules.[112]

Another reaction that can be classed as a click type reaction is the cycloaddition between nitrile oxides and alkynes to generate isoxazoles. This isoxazole generating chemistry has a number of advantages.[113] Amongst these advantages are the ease of preparation of the nitrile oxides,[114] faster kinetics than azide-cycloadditions,[115] and regioselectivity.[116] Isoxazoles are stable but can be subjected to further manipulations which unmask hidden functionalities within the isoxazole,[117] and there are limited issues with the nitrile oxides with respect to health and safety (compared to azide-functional molecules).[67] There are some issues associated with nitrile oxides such as nucleophile trapping and dimerization,[118] but these issues can be overcome by *in-situ* generation of nitrile oxide and careful selection of the reaction partner.[113]

Another reaction that could be classed as a click-type reaction is that between a thio acid and a sulfonyl azide, as developed by Williams and coworkers (Figure 1.91).[119]

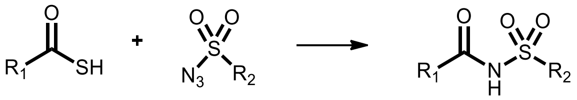


Figure 1.91: Reaction of a thio acid and sulfonyl azide to yield sulphonamide.[119]

Rijkers *et al.* classed the reaction shown in Figure 1.91 as "sulfo-click".[120] They used the sulfo-click reaction as a way to chemically ligate peptide-based thio acids and an amino acid derived sulfonyl azide.[120] Typical experiments involved solubilising the sulfonyl azide in a suitable solvent and then adding the thio acid component. The reactions were carried out at room temperature and were complete within fifteen minutes.[120] One potential drawback would be that in the presence of free sulfhydryl groups (cysteine) the sulfonyl azide can be reduced to the sulphonamide without coupling occuring.[120]

1.6 Introduction – conclusions

At the outset of the research program, the aim was to investigate potential synthetic routes into non-isocyanate polyurethane coatings, with an eye on formulating any new materials prepared into a liquid-applied membrane suitable for roofing applications.

Any potential chemistry used to meet the aims of the research programme must conform to a number of crucial requirements:

- The new chemistry should be isocyanate free (thereby removing or reducing any labelling concerns of the finished product).
- There should be no hazards, or at the very least less hazard, than the current isocyanate chemistry/technology.
- The new chemistry should not be prohibitive in terms of cost.
- The new chemistry must provide finished products that meet or exceed the state-of-the-art in important areas such as UV and thermal stability.
- Ideally, the application method of any finished product should be similar to the current isocyanate-based technology (brush or roller applied).

The strategy that was decided upon to best meet the aim of the research was to utilise currently prepared polyurethane pre-polymers that were isocyanate functional. The isocyanate group would provide an excellent functional handle (due to the reactivity of isocyanates with active hydrogen containing molecules) for efficiently functionalising the PU pre-polymer with alternative reactive functional groups, whilst also removing the isocyanate functionality and simultaneously reducing the hazards associated with the isocyanate functional pre-polymers.

Following an extensive literature survey, the chemistry that was believed to be the most promising with regards to meeting the goals and requirements of the research programme was CuAAC chemistry.

2.0 Experimental

2.1 Chemical list, instrumentation used and structural elucidation methods

List of Chemicals Used

Reagent	Purity	Source	Purification
1,4- Butanediol	NA	Industrial source – provided by industrial collaborators	Used as received
1,4-Phenylene diamine	99%	Aldrich	Used as received
1- Bromohexane	98%	Aldrich	Used as received
2,2-Aminoethoxy ethanol	98%	Aldrich	Used as received
2,2-Chloroethoxy ethanol	99%	Aldrich	Used as received
4,4-Methylene diphenylene diisocyanate (MDI)	98%	Aldrich	Used as received
Allyl glycidyl ether	99%	Aldrich	Used as received
Aluminium hydroxide	99%	Aldrich	Used as received
Ammonium chloride	99%	Aldrich	Used as received
Araldite DY-F	NA	Industrial source – provided by industrial collaborators	Used as received
Benzoic acid	99%	Aldrich	Used as received
Benzyl azide	NA	prepared in house	NA
Benzyl chloride	99%	Sigma	Used as received
*Bis*phenol-A diglycidyl ether	NA	Industrial source – provided by industrial collaborators	Used as received
Branched isocyanate-functional pre-polymer	NA	Industrial source – provided by industrial collaborators	Used as received
Copper(II)bromide	98%	Aldrich	Used as received
Cu(II)acetate.monohydrate	98%	Aldrich	Used as received
Cu(II)sulfate.pentahydrate	98+%	Aldrich	Used as received
Dibutyltin dilaurate	NA	Industrial source – provided by industrial collaborators	Used as received
Glycidol	99%	Aldrich	Used as received
Grilonit F704	NA	Industrial source – provided by industrial collaborators	Used as received
Hexyl azide	NA	prepared in house	NA
Isophorone diisocyanate	NA	Industrial source – provided by industrial collaborators	Used as received

Isophorone diisocyanate trimer	NA	Industrial source – provided by industrial collaborators	Used as received
Linear isocyanate-functional pre-polymer	NA	Industrial source – provided by industrial collaborators	Used as received
Lutidine	98%	Aldrich	Used as received
N-Methyl propargylamine	95%	Aldrich	Used as received
O-Cresyl glycidyl ether	NA	Industrial source – provided by industrial collaborators	Used as received
Pentaerythritol	98%	Aldrich	Used as received
Polypropylene glycol polyol	NA	Industrial source – provided by industrial collaborators	Used as received
Potassium carbonate	98%	Aldrich	Used as received
Potassium hydroxide	99%	Aldrich	Used as received
Propargyl alcohol	99%	Aldrich	Used as received
Propargyl Amine	98%	Aldrich	Used as received
Propargyl bromide (80 wt% in toluene)	80%	Aldrich	Used as received
Sodium ascorbate	98+%	Sigma	Used as received
Sodium azide	99%	Acros	Used as received
Sodium hydroxide	99%	Aldrich	Used as received
Sodium iodide	99%	Aldrich	Used as received
Titanium dioxide	NA	Industrial source – provided by industrial collaborators	Used as received
Tolonate HDT LV	NA	Industrial source – provided by industrial collaborators	Used as received
Triethylamine	99%	Aldrich	Used as received
Triphenylphosphine	99%	Aldrich	Used as received
Uvinul 3039	NA	Industrial source – provided by industrial collaborators	Used as received

Equipment

FT-IR spectra were recorded using a Perkin Elmer Spectrum One FT-IR Spectrometer using either a diamond cell or KBr discs prepared in a RIIC press, in the range from 400 to 4000 cm^{-1}. A Bruker Alpha-P FT-IR instrument with a diamond ATR unit was used to record FT-IR spectra of solid and liquid samples.

Electrospray mass spectrometry was performed on an LCQ DUO Thermo-Finnigan ion-trap with a spray voltage of 4.5 kV and capillary temperature of 230 °C. The analysis was carried out by Patricia Keating of the Mass Spectrometry Service at the University of Strathclyde.

MALDI-MS was performed on a Shimadzu Biotech Axima-CFR TOF MS. The analysis was carried out by Patricia Keating of the Mass Spectrometry Service at the University of Strathclyde.

SEC was recorded within the analytical laboratory at Incorez. The SEC system used a refractive index detector and pump (Knauer). The mobile phase was anhydrous THF. The sample (0.5 g) was dissolved in THF (10 mL) and toluene (25 µL). The injection loop was 20 µL. The SEC columns used were (2x) MesoPore 300 x 7.5 mmol columns, and the column oven temperature was set at 30 °C. The flow rate was 1 mL/min and the system was calibrated using polystyrene standards (EasiVial PS-L).

Proton (^{1}H) NMR experiments were performed at 400.13 MHz on Bruker DPX400 and 500.16 MHz on Bruker DRX500 and Carbon NMR (^{13}C) spectra were recorded at 125 MHz or 100 MHz. The chemical shifts (δ) are quoted in parts per million (ppm). Multiplicities are abbreviated as: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet for the ^{1}H NMR spectra. The coupling constants (j) are reported in Hertz (Hz). In cases where superimposition of the signals of two, or more, isomers occurred, the signals have been reported as multiplets (m), unless the coupling constants of each isomer could be ascertained.

Melting points were recorded on a Gallenkamp melting point apparatus.

The UV weathering and tensile testing of azide-based resin systems was only begun upon complete conversion of azide to triazole. The conversion of azide was conveniently tracked via the disappearance of azide signal (2100 cm^{-1}) in the FT-IR spectrum of the resulting polymer film.

Dumbbell shaped samples for tensile testing were cut out of polymer films using a template. Samples were then subjected to tensile testing using an Lloyd LRX

Tensometer. The thickness of the samples were measured prior to testing. The samples were mounted between rubber-padded grips and tested at room temperature under a constant strain rate of 2 mm/min.

Isocyanate handling

Isocyanate exposure can lead to long-term asthma and dermatitis if a person becomes sensitised. Sensitisation is a condition in which breathing or skin conditions can return with increasing severity with any further exposure to the original sensitising agent, or similar substances, even at very low exposures. Sufficient ventilation should be provided to ensure that the atmospheric concentration of isocyanate vapours does not exceed the occupational exposure limit.

In the event of small spills of isocyanate a general formulation for a neutralisation solution is as follows; sodium carbonate 5-10 %; liquid detergent (soap solution) 0.2-2 %; water to make 100 %.

General note on the preparation and handling of azides

Organic azides are potentially-explosive substances that can and will decompose with the slightest input of energy from external sources (heat, light, pressure). Additionally, small molecules containing the azido functionality tend to decompose violently which may result in injury if proper safety precautions are not utilized.

Care should be taken when preparing organic azides. Equation 1 should be used to evaluate the suitability and stability of the organic azide before synthesis is attempted.

$$\frac{N_C + N_O}{N_N} \geq 3$$

Equation 1: N_c + N_o (The number of carbon and oxygen atoms in molecule)/ N_n (The number of nitrogen atoms in molecule) should be greater than or equal to 3 for the organic azide to be safely prepared and handled.

Heavy-metal azides that are highly explosive under pressure or shock are formed when solutions of NaN_3 or HN_3 vapours come into contact with heavy metals or their salts. Heavy-metal azides can accumulate under certain circumstances, for example, in metal pipelines and on the metal components of diverse equipment (rotary evaporators, freeze-drying equipment, cooling traps, water baths, waste pipes), and thus lead to violent explosions.[67]

General note on the purification of chemicals.

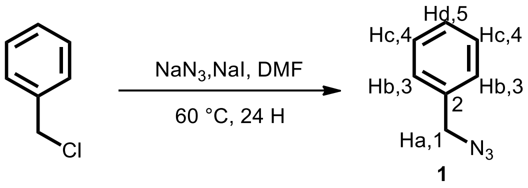
Integral to the success of the project was that any synthetic chemistry investigated and developed during the PhD programme should be scalable and applicable to the facilities contained within the laboratory/factory of the industrial collaborators.

Separation of complex mixtures is not currently possible at Incorez. Therefore it was of importance to prioritize reactions which could be carried out without significant purification. Chromatographic separations were carried out only when necessary to facilitate further synthetic steps or to separate reaction products from residual starting material.

2.2 Preparation of azide-functional molecules

2.2.1 Preparation of simple azide-containing molecules

Benzyl azide[121](**1**)



1

To a round-bottomed flask containing a magnetic stirrer bar, sodium azide (1.95 g, 0.03 mol) and sodium iodide (0.14 g, 1 mmol) were added. DMF (10 mL) was then added to the reaction vessel. Finally, benzyl chloride (1.15 mL, 0.01 mol) was added to the reaction vessel and the vessel contents stirred for 24 hours at 60 °C. Upon cooling to room temperature, distilled water (20 mL) was added to the reaction flask and then the contents of the reaction flask were decanted into a separating funnel. The reaction mixture was washed with ethyl acetate (20 mL x 3) and the organic fractions pooled and washed with distilled water (20 mL x 2) and brine (20 mL). The organic fractions were combined and dried over sodium sulphate, subsequently filtered and the ethyl acetate removed under reduced pressure.

Appearance: Yellow liquid

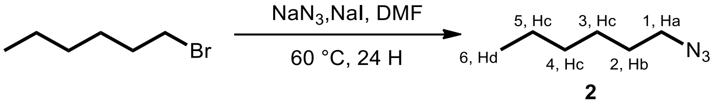
Yield: 1.33 g, (100%)

FT-IR $\bar{\upsilon}/cm^{-1}$*:* (Diamond cell) 2098 cm^{-1} (-N_3)

^1H NMR (500 MHz, DMSO-*d_6*) δ ppm 4.43 (s, 2H, *Ha*), 7.31 - 7.46 (m, 5H, *Hb,Hc&Hd*)

^{13}C NMR (125 MHz, chloroform-*d*) δ ppm 54.8(C1), 128.2(C5), 128.3(C3), 128.9(C4), 135.4(C2)

Hexyl azide[122](**2**)



To a round-bottomed flask containing a magnetic stirrer bar, sodium azide (5.85 g, 0.09 mol) and sodium iodide (0.45 g, 3 mmol) were added. DMF (10 mL) was then added to the reaction vessel. Finally, 1-Bromohexane (4.21 mL, 0.03 mol) was added to the reaction vessel and the vessel contents stirred for 24 hours at 60 °C. Upon cooling to room temperature, distilled water (20 mL) was added to the reaction flask and then the contents of the reaction flask were decanted into a separating funnel. The reaction mixture was washed with ethyl acetate (20 mL x 3) and the organic fractions pooled and washed with distilled water (20 mL x 2) and brine (20 mL). The organic fractions were combined and dried over sodium sulphate, subsequently filtered and the ethyl acetate removed under reduced pressure.

Appearance: Yellow liquid

Yield: 2.06 g, (54%)

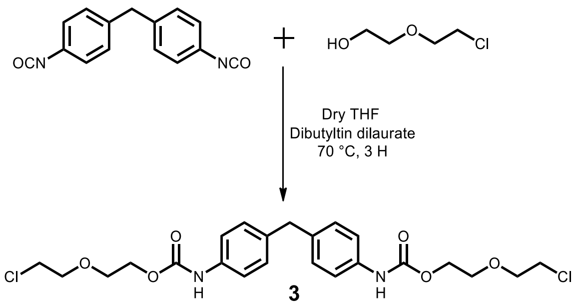
FT-IR $\bar{\upsilon}/\mathrm{cm}^{-1}$*:* (Diamond cell) 2861, 2105 (-N_3), 1458

^{1}H NMR (500 MHz, chloroform-*d*) δ ppm 0.82 (t, J=7.2 Hz, 3H, *Hd*), 1.20 - 1.32 (m, 6H, *Hc*), 1.52 (m, 2H, *Hb*), 3.17 (t, J=7.2 Hz, 2H, *Ha*)

^{13}C NMR (125 MHz, chloroform-*d*) δ ppm 13.3 (C6), 21.9 (C5), 25.8 (C3), 28.2 (C2), 30.8 (C4), 50.9 (C1).

2.2.2 Preparation of azide-functional molecules based on MDI

Halide functional MDI (**3**)

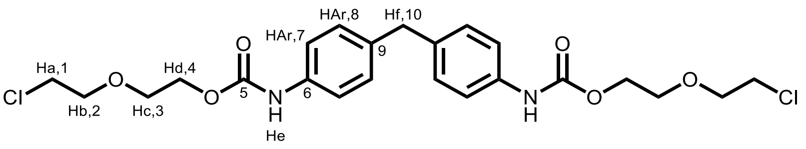


To a Radleys reaction vial containing a magnetic stirrer bar, MDI (0.1 g, 0.39 mmol) was added along with 2,2-chloroethoxy ethanol (88 µL ; 2.1 eq. 0.84 mmol) and dibutyltin dilaurate (23 µL ; 0.1 eq. 0.04 mmol). Then 5 mL of dry THF was added to the reaction vessel. The reaction vessel was heated to 70 °C for 6 hours, and then cooled to room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (10 mL x 3) and the combined aqueous layers washed with ethyl acetate (10 mL x 2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure.

Appearance: White solid.

Yield: 0.16 g (80%)



^{1}H NMR (500 MHz, chloroform-*d*) δ ppm 3.65 (t, *J*=6.0 Hz, 4H, *Ha*), 3.77 (m, 8H, *Hb,Hc*), 3.90 (s, 2H, *Hf*), 4.20 (*t, J*=5.0 Hz, 4H*, Hd*), 6.64 (s, 2H, *He*), 7.10 (d, *J*=8.5 Hz, 4H, *HAr*), 7.27 (d, *J*=8.5 Hz, 4H, *HAr*)

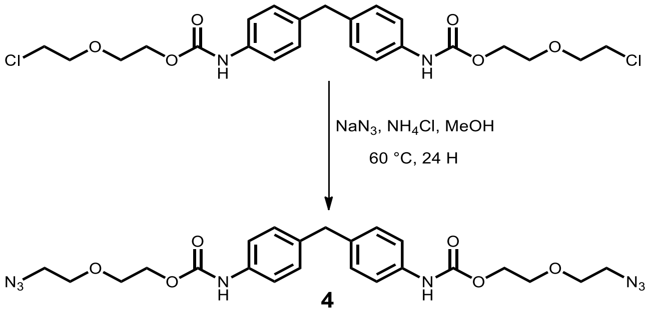
^{13}C NMR (100 MHz, acetone-d_6) δ ppm 39.7 (C10) 42.4 (C1) 63.1 (C4) 68.6 (C3) 70.4 (C2) 118.0 (C7) 128.5 (C8) 135.5 (C9) 136.8 (C6) 153.0 (C5)

Mass Spec: expected 498.1; Found: 499.1 $(M + H)^+$

FT-IR $\bar{\upsilon}$*/cm*$^{-1}$: (Diamond cell) 3350, 3302, 2891, 1720, 1695, 1531

Melting Point: 92-94 °C

Azide-functional MDI from halide-functional MDI (**4**)



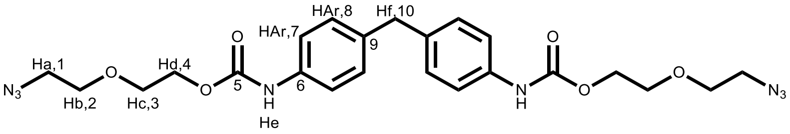
4

To a Radleys reaction vial containing a magnetic stirrer bar, **3** (0.1 g, 0.2 mmol) was added along with sodium azide (78 mg, 6 eq., 1.2 mmol) and ammonium chloride (64 mg, 6 eq., 1.20 mmol) then 20 mL of methanol was added to the reaction vessel. The reaction vessel was heated to 60 °C for 24 hours, and then cooled to room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (15 mL x 3) and the combined aqueous layers were washed with ethyl acetate (15 mL x 2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure.

Appearance: White solid

Yield: 0.10 g, 98%



^{1}H NMR (500 MHz, chloroform-*d*) δ ppm 3.42 (t, *J*=5 Hz, 4H, *Ha*), 3.71 (t, *J*=5 Hz, 4H, *Hb*), 3.77 (t, *J*=5 Hz, 4H, *Hc*), 3.91 (s, 2H, *Hf*), 4.35 (*t, J*=5 Hz, 4H*, Hd*), 6.65 (s, 2H, *He*), 7.11 (d, *J*=8.5 Hz, 4H, *HAr*), 7.28 (d, *J*=8.5 Hz, 4H, *HAr*)

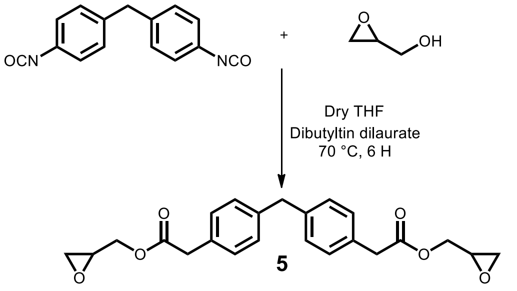
^{13}C NMR (125 MHz, chloroform-*d*) δ ppm 40.1 (C10) 50.1 (C1) 63.5 (C4) 68.9 (C3) 69.5 (C2) 118.5 (C7) 128.9 (C8) 135.3 (C9) 135.9 (C6) 152.9 (C5)

Mass Spec: expected; 512.21 Found: 535.27 $(M + Na)^+$

FT-IR $\bar{\upsilon}/cm^{-1}$: (Diamond cell) 3309, 2945, 2098, 1720, 1697, 1593, 1529

Melting Point: 51-53 °C

Epoxide-functional MDI[123] (**5**)

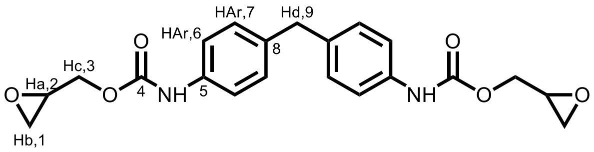


To a Radleys reaction vial containing a magnetic stirrer bar, MDI (1 g, 4 mmol) was added along with glycidol (557 µL ; 2.1 eq., 8.4 mmol) and dibutyltin dilaurate (236 µL ; 0.1 eq., 0.4 mmol), then 5 mL of dry THF was added to the reaction vessel. The reaction vessel was heated to 70 °C for 6 hours, and then cooled to room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (10 mL x3), and the combined aqueous layers washed with ethyl acetate (10 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure.

Appearance: White solid

Yield: 0.12 g, 75%



^{1}H NMR (400 MHz, DMSO-d_6) δ ppm 2.67 (dd, *J*=4.5, 2.5 Hz, 2H, *Hb*), 2.81 (t, *J*=4.5 Hz, 2H, *Hb*), 3.24 (m, 2H, *Ha*), 3.81 (*s,* 2H*, Hd*), 3.85 (dd, *J*=12, 7 Hz, 2H, *Hc*), 4.44 (dd, *J*=12, 2.5 Hz, 2H, *Hc*), 7.11 (d, *J*=8.0 Hz, 4H, *HAr*), 7.37 (d, *J*=8.0 Hz, 4H, *HAr*), 9.69 (br. s., 2 H, *NH*)

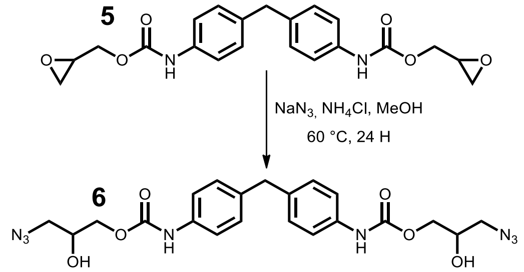
^{13}C NMR (101 MHz, DMSO-d_6) δ ppm 39.5 (C9) 43.8 (C1) 49.3 (C2) 65.1 (C3) 118.4 (C6) 128.9 (C8) 135.6 (C7) 136.9 (C5) 153.1 (C4)

Mass spec: expected 398.1; found: 399.1 $(M + H)^+$

FT-IR $\bar{\upsilon}/cm^{-1}$: (Diamond cell) 3316, 2934, 1741, 1530

Melting point: 108-110 °C

Azide-functional MDI from epoxide-functional MDI (**6**)

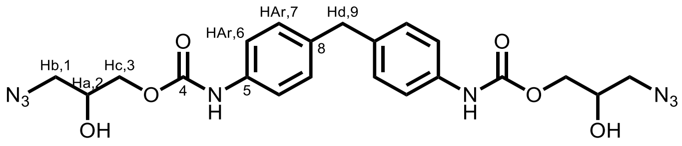


To a Radleys reaction vial containing a magnetic stirrer bar, **5** (0.1 g, 0.25 mmol) was added together with sodium azide (97.9 mg, 6 eq., 1.5 mmol) and ammonium chloride (80.6 mg, 6 eq., 1.5 mmol), then 10 mL of methanol was added to the reaction vessel. The reaction vessel was heated to 60 °C for 24 hours, and then cooled to room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (10 mL x3) and the combined aqueous layers washed with ethyl acetate (10 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure.

Appearance: Off-white solid

Yield: 0.07 g, 55%



^{1}H NMR (400 MHz, acetone-*d$_6$*) δ ppm 3.31 - 3.47 (m, 4H, *Hb,OH*), 3.90 (s, 2H, *Hd*), 4.03 - 4.24 (m, 6H, *Ha,Hb,Hc*), 4.58 (d, *J*=4.5 Hz, 2H, *Hc*), 7.17 (d, *J*=8 Hz, 4H, *HAr*), 7.48 (d, *J*=8 Hz, 4H, *HAr*), 8.60 (br. s., 2H, *NH*)

^{13}C NMR (101 MHz, acetone-*d$_6$*) δ ppm 39.7 (C9) 53.0 (C1) 65.2 (C3) 68.3 (C2) 117.9 (C6) 128.6 (C8) 135.5 (C7) 136.6 (C5) 152.9 (C4)

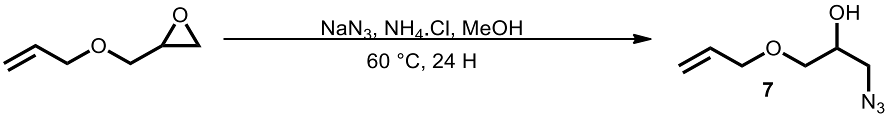
Mass spec: Expected 484.1; Found: 502.1 (M + NH_4^+)

FT-IR $\bar{\upsilon}$*/cm*$^{-1}$: (Diamond cell) 3300, 2952, 2095, 1703

Melting point: 76-78 °C

2.2.3 Azide-functional alcohols and polyols

Azide-functional alcohol from allyl glycidyl ether[124] (**7**)

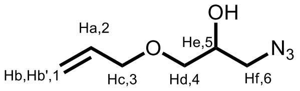


To a Radleys reaction vial containing a magnetic stirrer bar, allyl glycidyl ether (2 g, 17.5 mmol) was added together with sodium azide (3.42 g, 3 eq., 52.6 mmol) and ammonium chloride (2.81 g, 3 eq., 52.6 mmol) then 20 mL of methanol was added. The reaction vessel was heated to 60 °C for 24 hours, and then cooled to room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (15 mL x3) and the combined aqueous layers were washed with ethyl acetate (15 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure.

Appearance: Slightly viscous yellow liquid

Yield: 1.90 g, 69%



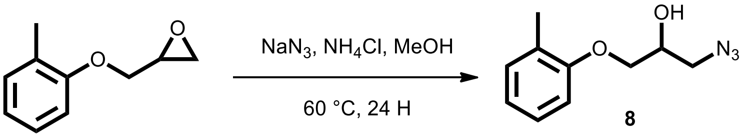
^{1}H NMR (500 MHz, chloroform-*d*) δ ppm 3.02 (br. s, 1H, *Hg*), 3.33 (dd, *J*=12.7, 6.3 Hz, 1H, *Hd*), 3.35 (dd, *J*=12.7, 4.8 Hz, 1H, *Hd'*), 3.43 (dd, *J*=9.7, 6.1 Hz, 1H, *Hf*), 3.46 (dd, *J*=9.7, 4.35 Hz, 1H, *Hf'*), 3.92 (m, 1H, *He*), 4.00 (dt, *J*=4.6, 1 Hz, 2H, *Hc*), 5.17 - 5.20 (dd, *J*=10.4, 1.5 Hz, 1H, *Hb*), 5.23 - 5.28 (dd, *J*=17, 1.2 Hz, 1H, *Hb'*), 5.88 (m, 1H, *Ha*)

^{13}C NMR (125 MHz, chloroform-*d*) δ ppm 53.1 (C6) 69.1 (C5) 70.8 (C3) 71.9 (C4) 117.1 (C1) 133.7 (C2)

Mass spec: expected 157.09, the molecular ion was not found but a peak was found[124] at 141 $(M - H_2O + H_2)^+$ [124]

FT-IR $\bar{\upsilon}$*/cm*$^{-1}$: (Diamond cell) 3354, 2910, 2864, 2096, 1645, 1444, 1348, 1271, 1190, 927

Azide-functional alcohol from O-cresyl glycidyl ether[125](**8**)

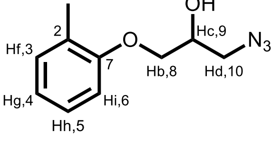


To a Radleys reaction vial containing a magnetic stirrer bar, *O*-Cresyl glycidyl ether (1 g, 6.1 mmol) was added together with sodium azide (1.19 g, 3 eq., 18.3 mmol) and ammonium chloride (0.98 g, 3 eq., 18.3 mmol), then 10 mL of methanol/water (8:1, v/v) was added to the reaction vessel. The reaction mixture was stirred overnight under reflux.

After the vessel was cooled to room temperature, water (20 mL) was added to dissolve residual solid material. The resulting homogeneous solution was decanted to a separating funnel. The organic component was extracted using ethyl acetate (20 mL x 2). The organic component was then washed with distilled water (20 mL x2), the organic component dried over sodium sulphate and then finally the organic solvent removed under reduced pressure.

Appearance: Pale yellow oil

Yield: 1.1 g, (87 %)



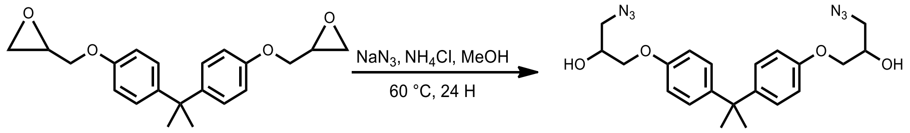
^{1}H NMR (500 MHz, chloroform-*d*) δ ppm 2.27 (s, 3H, *Ha*), 2.45 (s, 1H, *He*), 3.54 (dd, *J*=12.7, 6 Hz, 1H, *Hd*), 3.58 (d, *J*=12.7, 4.5 Hz, 1H, *Hd'*), 4.05 (d, *J*=6 Hz, 2H, *Hb*), 4.25 (m, 1H, *Hc*), 6.85 (d, *J*=6 Hz, 1H, *Hf*), 6.92 (m, 1H, *Hi*) 7.19 (m, 2H, *Hg,Hh*)

^{13}C NMR (125 MHz, chloroform-*d*) δ ppm 15.7(C1) 45.7(C10) 68.6(C8) 69.0(C9) 110.8(C6) 120.7(C4) 126.2(C2) 126.5(C5) 130.4(C3) 155.8(C7)

Mass spec: expected 207.1; Found: 180.5 $(M - N_2 + H)^+$

FT-IR $\bar{\upsilon}/cm^{-1}$: (Liquid film) 3382, 3026, 2927, 2874, 2096, 1601, 1590

Azide-functional diol from bisphenol-A diglycidyl ether (BADGE)[126] (**9**)



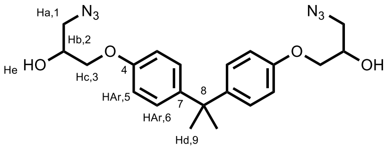
9

To a Radleys reaction vial containing a magnetic stirrer bar, bisphenol-A diglycidyl ether (15 g, 44.1 mmol) was added together with sodium azide (17.2 g, 6 eq., 264 mmol) and ammonium chloride (17.2 g, 6 eq., 264 mmol), then 50 mL of methanol was added to the reaction vessel. The reaction mixture was stirred overnight under reflux.

After the vessel was cooled to room temperature, water (100 mL) was added to dissolve residual solid material. The resulting homogeneous solution was decanted to a separating funnel. The organic component was extracted using ethyl acetate (80 mL x 2). The organic component was then washed with distilled water (80 mL x2) and then the organic component was dried over sodium sulphate. Finally, the organic solvent was removed under reduced pressure.

Appearance: Viscous brown oil

Yield: 11.31 g, (70 %)



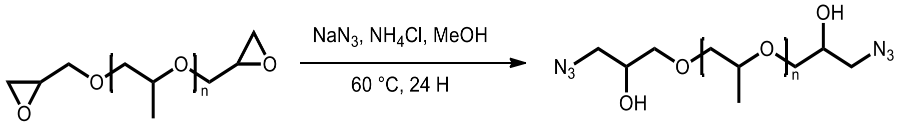
^{1}H NMR (400 MHz, DMSO-d_6) δ ppm 1.56 (s, 6H, *Hd*), 3.37 (dd, *J*=12.7, 6.4 Hz, 2H *Ha*), 3.39 (dd, *J*=12.7, 3.8 Hz, 2H *Ha*), 3.89 (m, 4H, *Hc*), 3.97 (m, 2H, *Hb*), 5.50 (d, *J*=5.2 Hz, 2H, *He*), 6.81 (d, *J*=8.9 Hz, 4H, *HAr*), 7.08 (d, *J*=8.9 Hz, 4H, *HAr*)

^{13}C NMR (101 MHz, DMSO-d_6) δ ppm 31.2 (C9) 41.6 (C8) 53.8 (C1) 68.8 (C3) 69.7 (C2) 114.4 (C5) 127.9 (C6) 143.3 (C7) 156.6 (C4)

Mass spec: expected 426.2; Found: 399.2 $(M - N_2 + H)^+$

FT-IR $\bar{\upsilon}/cm^{-1}$: (Liquid film) 3372, 2971, 2932, 2871, 2098, 1607, 1508

Azide-functional polyols from epoxide polyol (Grilonit F704) (**10**)



10

n = 7-10

To a round-bottomed flask, fitted with condenser and magnetic stirrer bar was added Grilonit F704 (10 mL, 19.8 mmol) together with sodium azide (7.71 g, 6 eq., 118 mmol) and ammonium chloride (6.3 g, 6 eq., 118 mmol). Then, 50 mL of methanol was added. The reaction vessel was heated to 60 °C for 24 hours on an oil bath, and then cooled to room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (30 mL x3) and the combined aqueous layers were washed with ethyl acetate (30 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure.

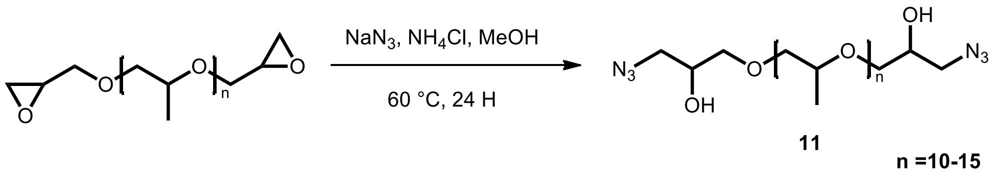
Appearance: Slightly viscous yellow liquid

Yield: 8.61 g, 70%

MALDI MS: expected 622-796; found $(M+Na)^+$ 645

FT-IR $\bar{\upsilon}/cm^{-1}$: (Liquid film) 3419, 2973, 2870, 2098, 1644, 1086

Azide-functional polyols from epoxide polyol (Araldite DY-F) (**11**)



To a round-bottomed flask fitted with condenser and magnetic stirrer bar was added Araldite DY-F (200 g, 0.21 mol) together with sodium azide (82.1 g, 6 eq., 1.26 mol) and ammonium chloride (67.5 g, 6 eq. 1.26 mol) then 500 mL of methanol was added to the reaction vessel. The reaction vessel was heated to 60 °C for 24 hours on an oil bath, and then cooled to room temperature.

The resulting organic product was worked-up into diethyl ether and washed with distilled water (300 mL x3) and the combined aqueous layers were washed with diethyl ether (300 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure to afford a slightly viscous yellow liquid.

Appearance: Slightly viscous yellow liquid

Yield: 128.71 g, 77%

MALDI MS expected range 796- 1086; found 604-894

FT-IR $\bar{\upsilon}/cm^{-1}$: (Liquid film) 3422, 2972, 2871, 2099, 1642, 1083

2.3 Preparation of azide-functional polyurethanes

2.3.1 Linear azide-containing polyurethane (PU1)

To a reaction flask was added MPA (67.7 g), IPDI (65.4 g, 0.29 mol) plus a calculated excess of IPDI needed to compensate for the water content of the starting materials. Dibutyltin dilaurate (0.16 g, 0.25 mmol) and 1,4-butanediol (3.40 g, 0.04 mol) were added and allowed to react at 45-50 °C for approximately 30 minutes. This was then followed by drop-wise addition of **11** (113.3 g, 0.12 mol). The temperature was increased to 90 °C and the reaction allowed to proceed for a period of time until the isocyanate content was close to the expected theoretical isocyanate value. Finally, and to ensure complete removal of isocyanate, end-capping was carried out using methanol (9.43 g) until disappearance of the isocyanate signal in the FT-IR spectrum was observed.

FT-IR $\bar{\upsilon}$/cm^{-1}: (Liquid film) 3340, 2873, 2100, 1708, 1528, 1458

MALDI-MS: 1128

GPC: $\overline{\mathrm{Mn}}$ *(1590),* $\overline{\mathrm{Mw}}$ *(3370),* $Đ_M$ *(2.1)*

2.3.2 Branched azide-containing polyurethane (PU2)

To a reaction flask was added MPA (13.93 g), IPDI (43.60 g, 0.04 mol) plus a calculated excess of IPDI needed to compensate for the water content of the starting materials. Dibutyltin dilaurate (0.03 g, 0.05 mmol) was added. This was then followed by drop-wise addition of **11** (134.7 g, 0.13 mol). The temperature was increased to 90 °C and the reaction allowed to proceed for a period of time until the isocyanate functional group had disappeared in the FT-IR spectrum.

FT-IR $\bar{\upsilon}$/cm^{-1}: (Liquid film) 3371, 2971, 2930, 2874, 2099, 1735, 1693, 1526

MALDI-MS: 2048

GPC: $\overline{\mathrm{Mn}}$ (1690), $\overline{\mathrm{Mw}}$ (7930), $Đ_M$ (4.7)

2.3.3 End-capping of standard linear polyurethane polymers (PU3)

To a reaction flask was added MPA (16.00 g), linear isocyanate-functional pre-polymer (48.77 g, 0.03 mol). Dibutyltin dilaurate (2.44 g, 3.86 mmol) was added and allowed to react at 45-50 °C for approximately 30 minutes. This was then followed by drop-wise addition of **8** (12.80 g, 0.06 mol). The temperature was increased to 90 °C and the reaction allowed to proceed for a period of time until the isocyanate functional group had disappeared in the FT-IR spectrum.

FT-IR $\bar{\upsilon}$/cm^{-1}: (Liquid film) 3345, 2971, 2929, 2874, 2102, 1731, 1590, 1523

MALDI-MS: 1887

GPC: $\overline{\mathrm{Mn}}$ (1450), $\overline{\mathrm{Mw}}$ (3090), $Đ_M$ (2.1)

2.3.4 End-capping of standard branched polyurethane polymers (PU4)

To a reaction flask was added MPA (20.00 g), branched Isocyanate-functional pre-polymer (53.33 g, 0.04 mol). Dibutyltin dilaurate (2.67 g, 4.23 mmol) was added and allowed to react at 45-50 °C for approximately 30 minutes. This was then followed by drop-wise addition of **8** (24.01 g, 0.12 mol). The temperature was increased to 90 °C and the reaction allowed to proceed for a period of time until the isocyanate functional group had disappeared in the FT-IR spectrum.

FT-IR $\bar{\upsilon}$/cm^{-1}: (Liquid film) 3342, 2931, 2101, 1731, 1603, 1518

MALDI-MS: 1576

GPC: $\overline{\mathrm{Mn}}$ (1360), $\overline{\mathrm{Mw}}$ (3950), $Đ_M$ (2.9)

2.3.5 End-capping of standard polyurethane polymers (PU5)

To a reaction flask was added MPA (18.94 g), IPDI (37.49 g, 0.035 mol) plus calculated excess of IPDI needed to compensate for water content of starting materials. Dibutyltin dilaurate (0.94 g, 1.48 mmol) was added and allowed to react at 45-50 °C for approximately 30 minutes. This was then followed by drop-wise addition of **8** (22.64 g, 0.11 mol). The temperature was increased to 90 °C and the reaction allowed to proceed for a period of time until the isocyanate functional group had disappeared in the FT-IR spectrum.

FT-IR $\bar{\upsilon}$/cm^{-1}: (Liquid film) 3380, 2927, 2096, 1601

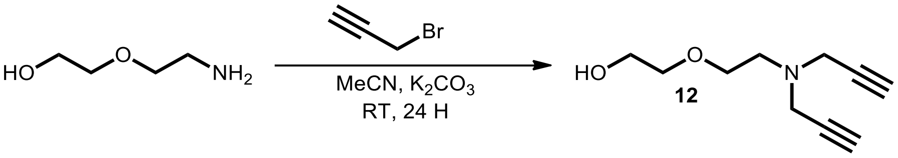
MALDI-MS: 1310

GPC: $\overline{\mathrm{Mn}}$ (1490), $\overline{\mathrm{Mw}}$ (4130), $Đ_M$ (2.8)

2.4 Preparation of alkyne-functional molecules

2.4.1 Preparation of simple alkyne-functional molecules

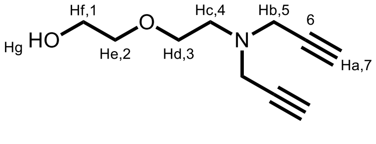
N-Alkylation of 2,2-aminoethoxy ethanol[127] (**12**)



To a three-necked, round-bottomed flask, fitted with dropping funnel and magnetic stirrer bar, was added 2,2-aminoethoxy ethanol (0.95 mL, 9.51 mmol) together with potassium carbonate (3.29 g, 2.5 eq., 23.8 mmol). Acetonitrile (20 mL) was then added to the reaction vessel and stirred for approximately 15 minutes. Finally, a solution of propargyl bromide (80 wt% in toluene) (2.6 mL, 2.5 eq., 30.2 mmol) in acetonitrile (10 mL) was added drop-wise. The resulting reaction mixture was allowed to react for 24 hours at room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (30 mL x3), and the combined aqueous layers washed with ethyl acetate (30 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The solvent was then removed under reduced pressure. Column chromatography was used to separate the products (5% MeOH in DCM).

Appearance: clear liquid, slight yellow colouration.



***R**f* (5% MeOH in DCM) = 0.54

^{1}H NMR (500 MHz, chloroform-*d*) δ ppm 2.25 (t, *J*=2.4 Hz, 2H, *Ha*), 2.80 (t, *J*=5.3 Hz, 2H, *Hc*), 3.51 (d, *J*=2.5 Hz, 4H, *Hb*), 3.58 (t, *J*=4.7 Hz, 2H, *Hf*), 3.64 (t, *J*=5.5 Hz, 2H, *Hd*), 3.71 (t, *J*=4.1 Hz, 2H, *He*).

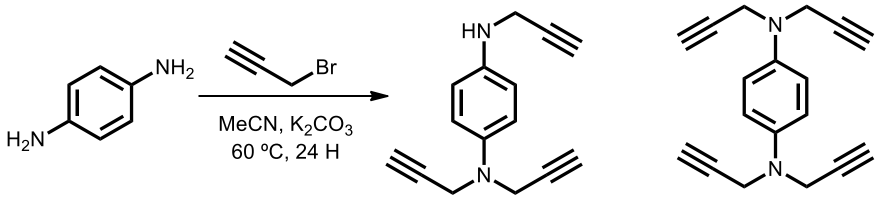
^{13}C NMR (126 MHz, chloroform-*d*) δ ppm 42.6(C5) 52.3(C4) 61.9(C1) 68.8(C3) 72.4 (C2) 73.4(C7) 78.5(C6)

Yield: 0.95 g, 55%

Mass Spec: expected 181.11; found 182.07 $(M + H)^+$

FT-IR $\bar{\upsilon}$/cm^{-1}: (Liquid film) 2100 and 3300

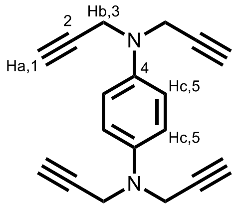
N-Alkylation of 1,4-phenylene diamine – lower equivalents of propargyl bromide[128](**13 and 14**)



13 **14**

To a round-bottomed flask fitted with condenser and magnetic stirrer bar, was added 1,4-phenylene diamine (0.1 g, 0.92 mmol) together with potassium carbonate (0.52 g, 4.1 eq., 3.79 mmol) and acetonitrile (10 mL). This mixture was stirred at room temperature for fifteen minutes. Propargyl bromide (80 wt% in toluene) (0.45 g, 4.1 eq., 3.79 mmol) was added drop-wise to the reaction vessel. The reaction vessel was heated to 60°C for 24 hours on an oil bath, and then cooled to room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (30 mL x3), and the combined aqueous layers washed with ethyl acetate (30 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure to afford brown oil. Column chromatography was used to separate the products (5% MeOH in DCM).



R$_f$ (5% MeOH in DCM) = 0.39

^{1}H NMR (500 MHz, chloroform-*d*) δ 2.23 (t, *J*=2.4 Hz, 4H, *Ha*), 4.07 (d, *J*=2.4 Hz, 8H, *Hb*), 6.98 (s, 4H, Hc)

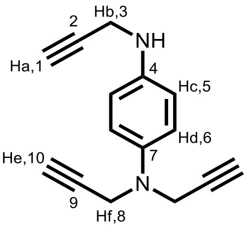
^{13}C NMR (100 MHz, chloroform-*d*) δ 40.6(C3) 72.3(C1) 78.9(C2) 117.6(C5) 141.8(C4)

Yield: 0.10 g, 42%

Mass Spec: expected 260.1; found 261.2 (M +H)$^{+}$

FT-IR $\bar{\upsilon}$/cm^{-1}: (ATR) 3305, 2256

Melting Point: 72-74°C



R_f (5% MeOH in DCM) = 0.14

^{1}H NMR (400 MHz, chloroform-*d*) δ ppm 2.23 (t, *J*=2.3 Hz, 1H, *Ha*), 2.26 (t, *J*=2.3 Hz, 2H, *He*), 3.70 (s, 1H, N*H*), 3.92 (d, *J*=2.3 Hz, 2H, *Hb*), 4.03 (d, *J*=2.3 Hz, 4H, *Hf*), 6.70-6.68 (dd, *J*=6.6, 2.3 Hz, 2H, *Hc*), 6.98-6.96 (dd, *J*=6.6, 2.3 Hz, 2H, *Hd)*

^{13}C NMR (100 MHz, chloroform-*d*) δ ppm 34.3(C3) 41.6(C8) 72.8(C10, C1) 79.4(C9, C2) 114.6(C6) 119.7(C5) 141.6(C4, C7)

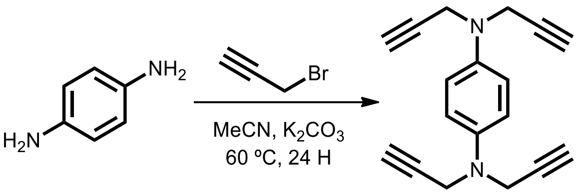
Yield: 0.12 g, 58%

Mass Spec: expected 222.1; found 223.1 (M +H)$^{+}$

FT-IR $\bar{\upsilon}$/cm^{-1}: (Liquid film) 3398, 3294, 3031, 2925, 2248, 2118, 1613, 1523

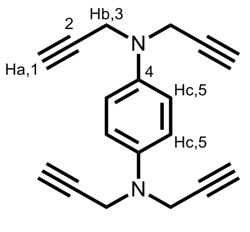
N-Alkylation of 1,4-phenylene diamine – higher equivalents of propargyl bromide[128]

(**14**)



To a round-bottomed flask fitted with condenser and magnetic stirrer bar, was added 1,4-phenylene diamine (0.1 g, 0.92 mmol) together with potassium carbonate (1.02 g, 8 eq., 7.40 mmol) and acetonitrile (10 mL). This mixture was stirred at room temperature for fifteen minutes. Propargyl bromide (80 wt% in toluene) (0.88 g, 8 eq., 7.40 mmol) was added drop-wise to the reaction vessel. The reaction vessel was heated to 60 °C for 24 hours on an oil bath, and then cooled to room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (30 mL x3), and the combined aqueous layers were washed with ethyl acetate (30 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure to afford brown solid. The solid was recrystallized from methanol.



R

R_f (5% MeOH in DCM) = 0.39

^{1}H NMR (500 MHz, chloroform-*d*) δ ppm 2.23 (t, *J*=2.4 Hz, 4H, *Ha*), 4.07 (d, *J*=2.4 Hz, 8H,*Hb*), 6.98 (s, 4H, *Hc*)

^{13}C NMR (100 MHz, acetone-*d*$_6$) δ ppm 40.6(C3) 72.3(C1) 78.9(C2) 117.6 (C5)

141.8(C4)

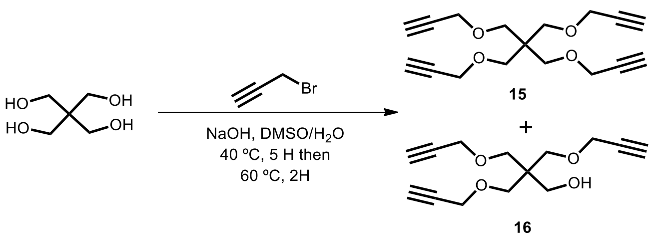
Yield: 0.20 g, 83%

Mass Spec: expected 260.1; found 261.2 $(M + H)^+$

Melting Point: 72-74 °C

FT-IR $\bar{\upsilon}$/cm^{-1}: (ATR) 3305, 2256

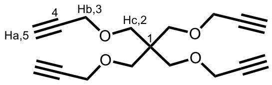
O-Alkylation of pentaerythritol - lower equivalents of propargyl bromide[129] (**15 and 16**)



To a Radleys reaction flask was added pentaerythritol (2 g, 14.7 mmol), together with NaOH (2.6 g in 10 mL H_2O, 66.1 mmol, 4.5 eq). To these reactants was added DMSO (15 mL), then propargyl bromide (80 wt% in toluene) (9.85 g, 66.1 mmol, 4.5 eq.) was added to the reaction flask drop-wise. After complete addition of propargyl bromide the reaction flask was taken to 40 °C and held at this temperature for 5 hours. After 5 hours the reaction mixture was cooled to room temperature and left overnight. The following day the reaction mixture was heated to 60 °C for a further 2 hours. The reaction mixture was worked up into ethyl acetate (3 x 30 mL), then the organic layers combined, washed with brine and subsequently dried over sodium sulphate (48 hours). The organic solvent was removed under reduced pressure. Column chromatography was used to separate the products (20% ethyl acetate/ Pet. Ether (40-60) °C).

Appearance: White solid

Yield: 0.21 g, 5 %



R_f (20% ethyl acetate/ Pet. Ether (40-60) °C) = 0.38

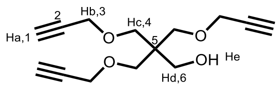
^{1}H NMR (500 MHz, chloroform-*d*) δ ppm 2.43 (t, *J*=2.4 Hz, 4H, *Ha*), 3.53 (s, 8H, *Hc*), 4.12 (d, *J*=2.4 Hz, 8H, *Hb*).

^{13}C NMR (126 MHz, chloroform-*d*) δ ppm 80.1(C4) 74.1(C5) 69.0(C2) 58.7(C3) 44.8(C1)

Mass Spec: expected 288.1; found 289.1 (M +H)$^+$

FT-IR $\bar{\upsilon}$/cm^{-1}: (ATR) 3290, 2126

Melting point: 53-55 °C



R_f (20% ethyl acetate/ Pet. Ether (40-60 °C) = 0.18

^{1}H NMR (400 MHz, chloroform-*d*) δ ppm 2.43 (t, *J*=6.5 Hz, 1H, *He*), 2.44(t, *J*=2.4 Hz, 3H, *Ha*), 3.59 (s, 6H, *Hc*), 3.65 (d, *J*=6.4 Hz, 2H, *Hd*), 4.16 (d, *J*=2.4 Hz, 6H, *Hb*)

^{13}C NMR (100 MHz, chloroform-*d*) δ ppm 79.8(C2) 74.0(C1) 69.5(C4) 64.2(C6) 58.2(C3) 44.2(C5)

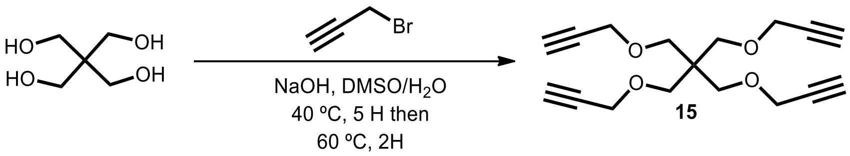
Mass Spec: expected 250.1; found 251.2 (M +H)$^+$

Yield: 3.60 g, 85 %

Appearance: pale yellow oil

FT-IR $\bar{\upsilon}$*/cm*$^{-1}$: (Liquid film) 3515, 3290, 2115

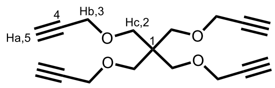
O-Alkylation of pentaerythritol - higher equivalents of propargyl bromide[129] (**15**)



To a Radleys reaction flask was added pentaerythritol (2.5 g, 14.7 mmol), together with KOH (8.2 g in 20 mL H_2O, 146 mmol, 8 eq). To these reactants was added DMSO (30 mL), then propargyl bromide (80 wt. % solution) (17.4 g, 146 mmol, 8 eq.) was added to the reaction flask drop-wise. After complete addition of propargyl bromide, the reaction flask was taken to 40 °C and held at this temperature for 5 hours. After 5 hours the reaction mixture was cooled to room temperature and left overnight. The following day the reaction mixture was heated to 60 °C for a further 2 hours.

The reaction mixture was worked up into ethyl acetate (3 x 30 mL), then the organic layers combined, washed with brine and subsequently dried over sodium sulphate (48 hours). The organic solvent was removed under reduced pressure to afford a yellow oil. Column chromatography was used to separate the products (20% ethyl acetate/ Pet. Ether (40-60) °C).

Appearance: white solid



R_f (20% ethyl acetate/ Pet. Ether (40-60 °C) = 0.38

^{1}H NMR (500 MHz, chloroform-*d*) δ ppm 2.43 (t, *J*=2.4 Hz, 4H, *Ha*), 3.53 (s, 8H, *Hc*), 4.12 (d, *J*=2.4 Hz, 8H, *Hb*).

^{13}C NMR (126 MHz, chloroform-*d*) δ ppm 80.1(C4) 74.1(C5) 69.0(C2) 58.7(C3) 44.8(C1)

Yield: 3.40 g, 80 %

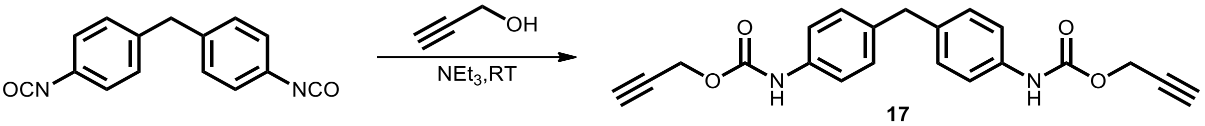
Mass Spec: expected 288.1; found 289.1 $(M+H)^+$

Melting point: 53-55 °C

FT-IR $\bar{\upsilon}$/cm^{-1}: (ATR) 3290, 2126

2.4.2 Preparation of alkyne molecules from isocyanate-based starting materials

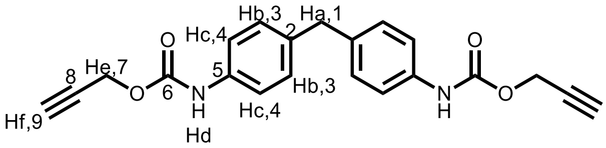
Alkyne-functional MDI[130] (**17**)



To a round-bottomed flask containing a magnetic stirrer bar was added MDI (10 g, 40 mmol), propargyl alcohol (5.1 mL, 2.2 eq., 88 mmol), triethylamine (5.6 mL, 40 mmol), and dry THF (25 mL). The reaction vessel was immersed in an ice bath initially, but this was subsequently removed. The reaction was stirred for 24 hours and then quenched by the addition of 2M aqueous HCl (30 mL). The aqueous layer was washed with ethyl acetate (20 mL x3), and then the combined organic layers dried over sodium sulphate and subsequently filtered. The solvent was then removed under reduced pressure.

Appearance: Off-white solid

Yield: 10.6 g, 73%



^{1}H NMR (500 MHz, DMSO-*d*$_6$) δ ppm 3.53 (t, J=2.5 Hz, 2H, Hf), 3.80 (s, 2H, Ha), 4.73 (d, J=2.5 Hz, 4H, He), 7.11 (d, J=8.5 Hz, 4H, Hb), 7.34 (d, J=8.2 Hz, 4H, Hc), 9.73 (br. s., 2H, Hd)

^{13}C NMR (125 MHz, acetone-*d*$_6$) δ ppm 152.7 (C6 x2), 136.9 (C5 x2), 136.3 (C3 x4), 129.1 (C2 x2), 118.6 (C4 x4), 78.5 (C8 x2), 75.2 (C9 x2) 51.7 (C7 x2), 40.2 (C1).

Mass spectrometry: expected 362.13; found $(M+Na)^+$ 385.13

FT-IR $\bar{\upsilon}$/cm^{-1}: (KBr) 3326, 3292 (alkyne C-H stretch), 3131, 2919, 2115 (alkyne C-C stretch), 1723 (urethane C=O stretch), 1544, 1432.

Melting point: 162-164 °C

*Preparation of **17** in NMP and MPA Solvents*

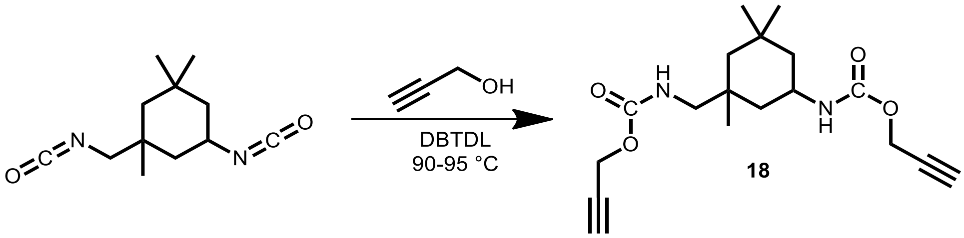
To a round-bottomed flask containing a magnetic stirrer bar was added MDI (1 g, 4.0 mmol), propargyl alcohol (484 µL, 2.1 eq., 8.4 mmol) and triethylamine (56 µL, 0.4 mmol). Then NMP or MPA (10 mL) was added to the reaction vessel. The flask contents were stirred for 24 hours and then quenched with 2M HCl (20 mL) the aqueous layer was washed with ethyl acetate (20 mL x3) and the combined organic layers were dried over sodium sulphate and subsequently filtered. The solvent was then removed under reduced pressure to afford an off-white solid.

Analysis (MPA as solvent): as for **17** discussed previously.

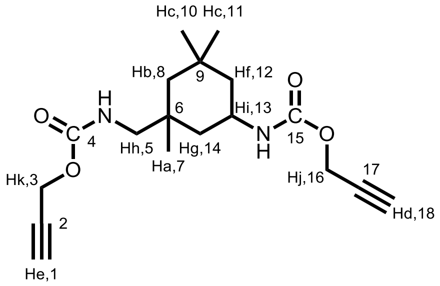
Yield (MPA as solvent): 0.83 g, 78%

*The preparation of **17** in NMP solvent was unsuccessful. This was because the NMP solvent had high residual water content.*

Alkyne-functional IPDI[131] (**18**)



To a reaction flask was added IPDI (222.3 g, 1 mole), together with propargyl alcohol (117 g, 2.1 moles). To these reactants was added MPA (85 g) and dibutyltin tin dilaurate (0.22 g, 0.35 mmol), and the reaction allowed to proceed at 90-95 °C and periodically monitored *via* FT-IR analysis. After approximately 48 hours reaction time at 90-95 °C, the isocyanate peak had disappeared from the FT-IR spectrum.



^{1}H NMR (400 MHz, chloroform-*d*) δ ppm 0.95 (s, 3H, *Ha*), 1.06 (s, 1H, *Hb*), 1.08 (s, 6H, *Hc*), 1.21 (t, *J*=2.1 Hz, 1H, *Hd*), 1.24 (t, *J*=2.4 Hz, 1H, *He*), 1.73 (m, 3H, *Hb,Hf,Hg*), 2.49 (m, 2H, *Hg,Hh*), 2.95 (m, 2H, *Hf,Hh*), 3.84 (m, 1H, *Hi*), 4.67 (d, *J*=2.1 Hz, 2H, *Hj*), 4.69 (d, *J*=2.4 Hz, 2H, *Hk*)

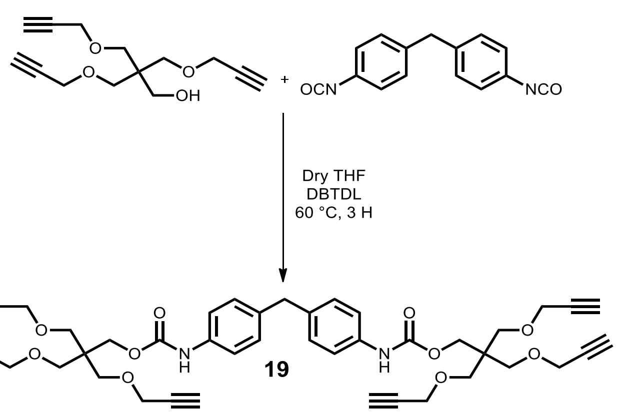
^{13}C NMR (100 MHz, chloroform-*d*) δ ppm 23.1(C6) 27.4(C9) 31.4(C7) 34.9(C10) 36.2(C11) 41.2(C13) 44.1(C14) 45.3(C5) 46.5(C12) 51.2(C8) 51.4(C16) 54.3(C3) 76.9(C18) 77.0(C1) 79.4(C17) 79.5(C1) 154.4(C15) 155.9(C4)

Yield: 267.53 g, 80%

MALDI-MS expected 334.19; found: 357.26 (M + Na)$^+$, 373.23 (M + K)$^+$

FT-IR $\bar{\upsilon}$*/cm*$^{-1}$: (Liquid film) 3338, 3294, 2951, 2125, 1716, 1529, 1456, 1238

Multi-functional alkyne using MDI (**19**)



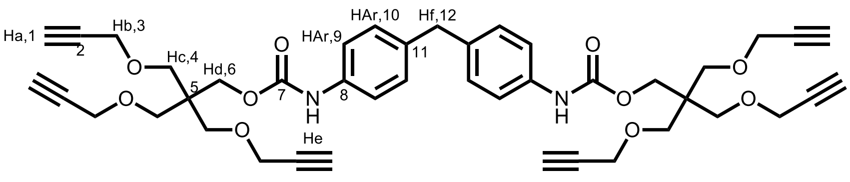
19

To a Radleys reaction vial containing a magnetic stirrer, MDI (0.2 g, 0.8 mmol) was added together with **16** (0.42 g, 2.1 eq. 1.7 mmol) and dibutyltin dilaurate (47 µL ; 0.1 eq., 0.08 mmol). Finally dry THF (5 mL) was added to the reaction vessel. The reaction vessel was heated to 60 °C for 3 hours, and then cooled to room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (30 mL x3). The combined aqueous layers were washed with ethyl acetate (30 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure.

Appearance: Highly viscous orange oil

Yield: 0.47 g, 78%



^{1}H NMR (400 MHz, chloroform-*d*) δ ppm 2.40 (t, *J*=2.4 Hz, 6H, *Ha*), 3.58 (s, 12H, *Hc*), 3.90 (s, 2H, *Hf*), 4.14 (d, *J*=2.4 Hz, 12H, *Hb*), 4.16 (s, 4H, *Hd*), 6.57 (s, 2H, *He*), 7.13 (d, *J*=8.5 Hz, 4H, *HAr*), 7.29 (d, *J*=8.5 Hz, 4H, *HAr*)

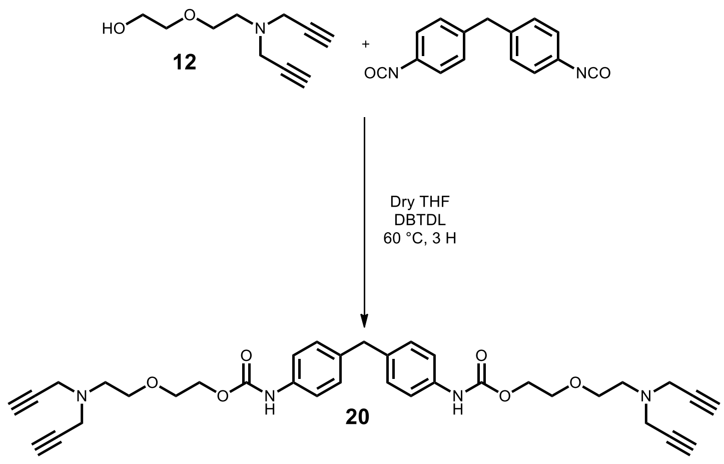
^{13}C NMR (100 MHz, chloroform-*d*) δ ppm 40.1(C5) 43.7(C12) 58.2(C4) 63.9(C6) 68.4(C3) 73.8(C1) 79.3(C2) 118.5(C10) 128.5(C9) 135.5(C8) 135.8(C11) 152.9(C7)

Mass spectrometry: expected 750.32; found (M+ Na) 773.05

Melting Point: 86-88 °C

FT-IR $\bar{\upsilon}$ */cm*$^{-1}$: (Liquid film) 3292, 2115, 1717

Multi-functional alkyne using MDI (**20**)

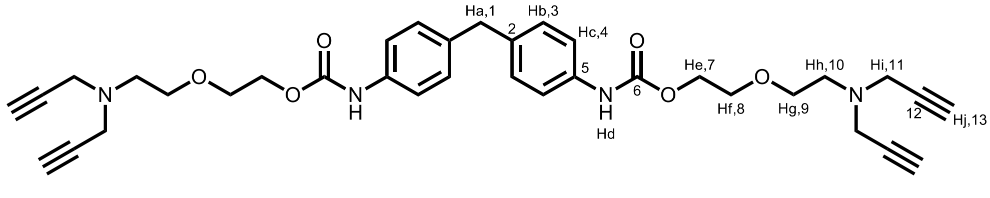


To a Radleys reaction vial containing a magnetic stirrer bar MDI (0.1 g, 0.40 mmol) was added together with **12** (145 µL, 2.1 eq., 0.84 mmol) and dibutyltin dilaurate (24 µL, 0.1 eq., 0.04 mmol). Finally, dry THF (5 mL) was added to the reaction vessel. The reaction vessel was heated to 60 °C for 3 hours, and then cooled to room temperature.

The resulting organic product was worked-up into ethyl acetate and washed with distilled water (30 mL x3). The combined aqueous layers were washed with ethyl acetate (30 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure.

Appearance: Highly viscous orange oil

Yield: 0.21 g, 87%



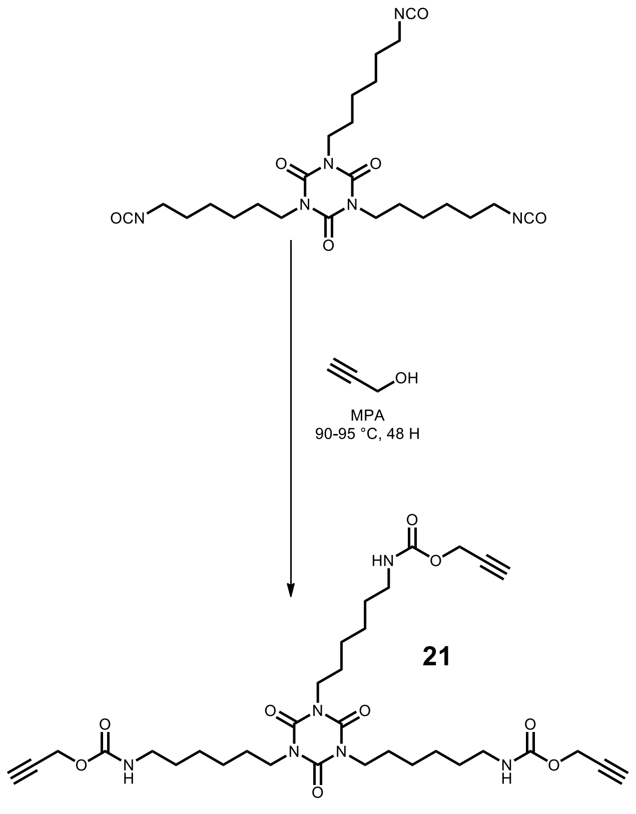
^{1}H NMR (500 MHz, DMSO-d_6) δ ppm 2.62 (t, *J*=6 Hz, 4H, *Hh*), 3.12 (t, *J*=2 Hz, 4H, *Hj*), 3.38 (d, *J*=2 Hz, 8H, *Hi*), 3.52 (t, *J*=6 Hz, 4H, *Hg*), 3.61 (t, *J*=5 Hz, 4H, *Hf*), 3.78 (s, 2H, *Ha*), 4.16 (t, *J*=5 Hz, 4H, *He*), 7.08 (d, *J*=8 Hz, 4H, *Hc*), 7.35 (d, *J*=8 Hz, 4H, *Hb*), 9.61 (br. s., 2 H, *Hd*)

^{13}C NMR (125 MHz, acetone-d_6) δ 39.7(C1) 41.8(C11) 51.5(C10) 63.2(C7) 68.5(C9) 69.1(C8) 72.9(C13) 78.6(C12) 118.0(C4) 128.5(C3) 135.5(C5) 136.9(C2) 153.1(C6)

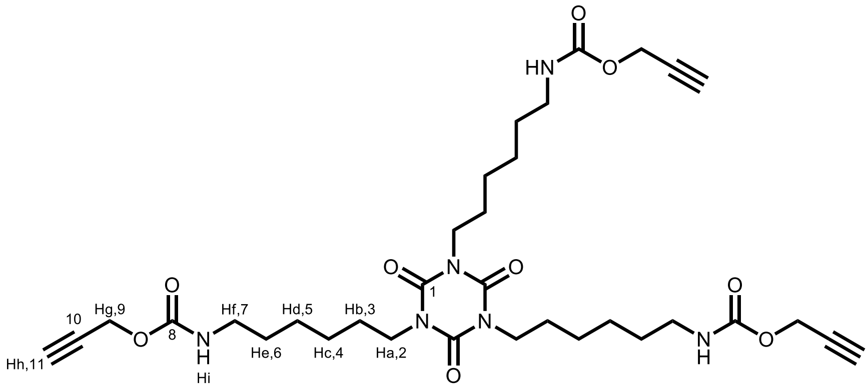
MALDI MS: expected 612.3; found $(M+H)^+$ 613.3

FT-IR $\bar{\upsilon}/cm^{-1}$: (Liquid film) 3288, 2922, 2160, 1701, 1597, 1527, 1220, 1066

Multi-functional alkyne using HMDI[132] (**21**)



To a Radleys reaction flask was added Tolonate HDT LV (10 g, 0.02 moles), together with propargyl alcohol (3.67 g, 0.07 moles). To these reactants was added MPA (64 g). The mixture was then allowed to proceed at 90-95 °C and periodically monitored *via* FT-IR analysis. After 48 hours reaction time at 90-95 °C the isocyanate peak had disappeared. No purification was attempted and **21** was used as a 77% solution.



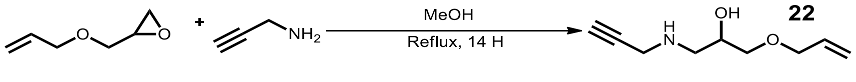
^{1}H NMR (400 MHz, chloroform-*d*) δ ppm 1.33 (m, 12H, *Hc + Hd*), 1.49 (m, 6H, *He*), 1.60 (m, 6H, *Hb*), 2.5 (t, *J*=2 Hz, 3H, *Hh*), 3.16 (m, 6H, *Hf*), 3.84 (m, 6H, *Ha*), 4.6 (d, *J*=2 Hz, 6H, *Hg*), 4.9 (m, 3H, *Hi*)

^{13}C NMR (100 MHz, chloroform-*d*) δ 25.6(C4) 25.7(C5) 27.2(C6) 29.2(C3) 40.5(C7) 42.3(C2) 51.9(C9) 74.0(C11) 77.9(C10) 148.5(C1) 155.0(C8)

MALDI MS: expected 672.3; found (M+Na)$^{+}$ 695.2

FT-IR $\bar{\upsilon}/cm^{-1}$: (Liquid film) 3350, 3294, 2934, 2860, 2126, 1678, 1524, 1460, 1239

2.4.3 Preparation of alkyne molecules from other methods



22

To a Radleys reaction vial containing a magnetic stirrer bar, allyl glycidyl ether (AGE) (103 µL, 0.88 mmol) along with propargyl amine (168 µL, 3 eq., 2.63 mmol) and methanol (20 mL) was added. The reaction vessel was heated to reflux for 14 hours, and then cooled to room temperature.

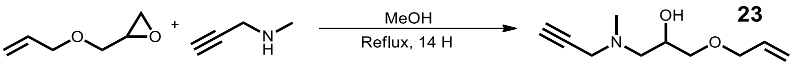
The reaction vial was left for over a weekend and was worked upon the next working day; the reaction mixture showed no appreciable colour change.

The resulting crude organic product was worked-up into ethyl acetate and washed with distilled water (15 mL x3) and the combined aqueous layers washed with ethyl acetate (15 mL x2). The organic layers were combined and dried over sodium sulphate and subsequently filtered. The organic solvent was then removed under reduced pressure to afford a slightly viscous yellow liquid.

TLC analysis indicated two different products in the worked-up material, flash column chromatography was attempted, but only one product was isolated in sufficient yield to allow for ^{1}H NMR spectroscopy.

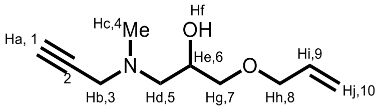
The results are discussed in the results and discussion section.

Alkyne functional alcohol from AGE[133] (**23**)



To a Radleys reaction vial containing a magnetic stirrer bar, allyl glycidyl ether (AGE) (52 µL, 0.44 mmol) along with N-methyl propargyl amine (74 µL, 2 eq., 0.88 mmol) and methanol (5 mL) was added to the reaction vessel. The reaction vessel was heated to reflux for 14 hours, and then cooled to room temperature.

The reaction mixture was moved to a round-bottomed flask and the solvent was removed under vacuum. No further purification was carried out.



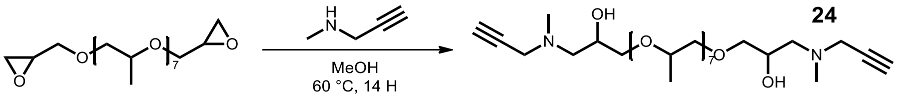
^{1}H NMR (500 MHz, chloroform-*d*) δ ppm 2.23 (t, *J*=2.3 Hz, 1H, *Ha*), 2.36 (s, 3H, *Hc*), 2.48 (dd, *J*=12.6, 3.8 Hz, 1H, *Hd*), 2.54 (dd, *J*=12.6, 3.8 Hz, 1H, *Hd*), 3.13 (s, 1H, *Hf*), 3.39 (d, *J*= 2.3 Hz, 2H, *Hb*), 3.43 (dd, *J*=9.7, 4.0 Hz, 1H, *Hg*), 3.50 (dd, *J*=9.7, 4.1 Hz, 1H, *Hg*), 3.83 - 3.89 (m, 1H, *He*), 4.03 (dt, *J*=5.0, 1.5 Hz, 2H, *Hh*), 5.19 (dq, *J*=10.4, 1.3 Hz, 1H, *Hj*), 5.28 (dq, *J*=17.3, 1.6 Hz, 1H, *Hj*), 5.87 - 5.96 (m, 1H, *Hi*)

^{13}C NMR (126 MHz, chloroform-*d*) δ ppm 41.7 (C4) 46.1 (C3) 58.2 (C5) 67.0 (C6) 72.4 (C8) 72.5 (C1) 73.3 (C7) 78.3 (C2) 117.2 (C10) 134.6 (C9)

Mass Spec: expected 183.1; found $(M+Na)^+$ 206.2

Yield: 0.05 g, 63%

FTIR (cm^{-1}): (Liquid film) 3437, 3299, 2852, 2106 (w), 1644, 1450



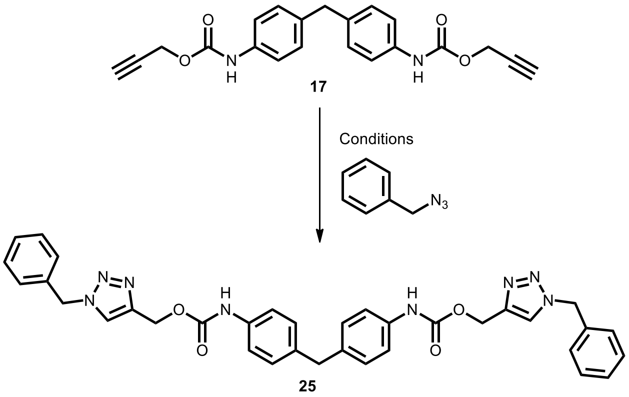
To a Radleys reaction vial containing a magnetic stirrer bar, Grilonit F704 (94 µL, 0.19 mmol) along with N-methyl propargyl amine (66 µL, 4.2 eq., 0.78 mmol) and methanol (5 mL) was added. The reaction vessel was heated at reflux for 14 hours, and then cooled to room temperature.

The reaction mixture was moved to a round-bottomed flask and the solvent was removed under vacuum. No further purification was carried out.

Mass Spec: expected 675.4; found $(M+H)^+$ 606.4 (*consistent with only one epoxide ring-opening*)

2.5 CuAAC click reactions

2.5.1 CuAAC click reaction to give triazole-functional molecules (25)



A typical CuAAC click reaction to give **25** involved the addition of **17** into a reaction flask. To this was added a source of copper (either Cu(I) or Cu(II)) and a suitable reducing agent. A suitable solvent was then added to dissolve all the reaction components. Finally, benzyl azide was added to the reaction flask.

The conversion of the starting materials to products was monitored over a range of timescales by ^{1}H NMR spectroscopy. Typically, a small aliquot was taken from the reaction vessel and the product of the reaction was extracted into diethyl ether, which was then evaporated to dryness under nitrogen; the residue remaining was then dissolved in a deuterated solvent and a ^{1}H NMR spectrum acquired.

Conversion of **17** was measured conveniently *via* the disappearance of the triplet signal associated with the alkyne groups of **17,** and the appearance of new signals within the ^{1}H NMR spectrum, at around 5.1 and 5.5 ppm, associated with the methylene groups adjacent to the triazole rings in **25.**

2.5.1.1 CuBr (10 mol%) and lutidine

To a Radleys carousel reaction tube was added **17** (0.2 g, 0.55 mmol), CuBr (8 mg, 0.1 eq., 0.055 mmol) and a few drops of lutidine. DMSO (5 mL) was added to solubilise the reactants. Finally, benzyl azide (172 µL, 2.5 eq., 1.38 mmol) was added and the reaction allowed to proceed for 15 hours at room temperature.

Conversion: negligible after 15 hours as judged *via* ^{1}H NMR spectroscopy.

2.5.1.2 CuBr (20 mol%) and lutidine in solvent alternatives to DMSO

To a Radleys carousel reaction tube was added **17** (0.05 g, 0.14 mmol), CuBr (4 mg, 0.2 eq., 0.028 mmol) and a few drops of lutidine. Solvent (5 mL) was added to solubilise the reactants. Finally, benzyl azide (43 µL, 2.5 eq. 0.34 mmol) was added and the reaction was allowed to proceed for 24 hours at room temperature. The reaction vessel was heated subsequently at 60 °C for 4 hours.

Conversion: negligible after 24 hours as judged *via* ^{1}H NMR spectroscopy for all solvents.

Solvents investigated: Acetone, DMF, THF, ethyl acetate, MEK

2.5.1.3 Cu(II) acetate (10 mol%)

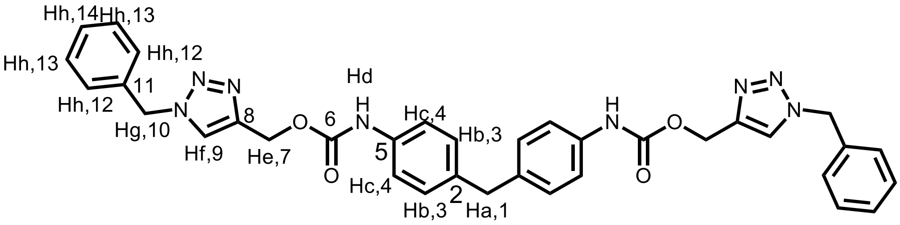
To a Radleys carousel reaction tube was added **17** (0.1 g, 0.28 mmol), Cu(II) acetate (5.1 mg, 0.1 eq. 0.028 mmol) and triphenylphosphine (14.5 mg, 0.2 eq., 0.055 mmol). DMSO (5 mL) was added to solubilise the reactants. Finally, benzyl azide (72 µL, 2.1 eq., 0.58 mmol) was added and the reaction allowed to proceed for 6 hours at room temperature.

2.5.1.4 Cu(II) acetate (1 mol%)

To a Radleys carousel reaction tube was added **17** (0.1 g; 0.28 mmol), Cu(II) acetate (0.6 mg, 0.01 eq., 0.0028 mmol) and triphenylphosphine (1.5 mg, 0.02 eq., 0.0055 mmol). DMSO (5 mL) was added to solubilise the reactants. Finally, benzyl azide (72 µL, 2.1 eq., 0.58 mmol) was added and the reaction allowed to proceed for 6 hours at room temperature.

After the allotted reaction time for both reactions, the crude product was partitioned into ethyl acetate (10 mL) and the organic phase washed with distilled water (20 mL x3). The aqueous layers were then washed with ethyl acetate. The organic fractions were combined, dried overnight over sodium sulphate, filtered and the organic solvent removed under reduced pressure to yield an orange/brown coloured viscous liquid. The solubilised reaction mixture was purified *via* column chromatography to yield a white crystalline solid.

Column chromatography was used to separate the products (1:1 pet. ether: ethyl acetate).



R_f (50% ethyl acetate/Pet. Ether (40-60 °C) = *0.23*

Melting point: 171-173 °C

Conversion: Variable dependent on conditions.

FT-IR $\bar{\upsilon}$/cm^{-1}: (KBr) 3247, 3151, 2957, 2854, 1723 (urethane C=O stretch), 1602, 1544.

^{1}H NMR: (400 MHz, DMSO-d_6) δ ppm 3.79 (s, 2H, *Ha*), 5.16 (s, 4H, *He*), 5.61 (s, 4H, *Hg*), 7.09 (d, J=8.5 Hz, 4H, *Hb*), 7.31 - 7.39 (m, 14H, *Hh, Hc*), 8.23 (s, 2H, *Hf*), 9.62 (s, 2H, *Hd*)

^{13}C NMR: (125 MHz, acetone-d_6) δ ppm 153.4 (C6 x2), 143.3 (C8 x2), 137.2 (C5 x2), 136.1 (C11 x2), 129.3 (C3 x4), 128.8 (C13 x4), 128.3 (C12 x4, C2 x2), 128.1 (C14 x2), 124.1 (C9 x2), 118.4 (C4 x4), 57.6 (C7 x2), 53.3 (C10 x2) 40.2 (C1).

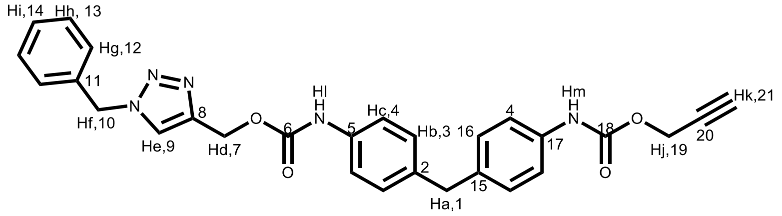
*Yield of **25**: 0.12 g, (73%*); (10 mol % catalyst)*

Mass spec: expected 628.25; found (M+Na)$^+$ 651.20, (M+K)$^+$ 667.13

Elemental microanalysis: Expected C, 66.9; H, 5.1; N, 17.8; Found C, 65.8; H, 4.5; N, 16.6

** Low recovered yield due to difficult separation of triphenylphosphine oxide from the product. In addition, 6.4 mg of the **mono-reacted 17** was recovered, the identity of which was confirmed via ^{1}H NMR spectroscopy.*

*Yield of **25**: 0 g (0%) (1 mol % catalyst); 20.2 mg of unreacted **17** returned together with > 20.5 mg of mono-reacted **17***



R_f (50% ethyl acetate/Pet. Ether (40-60 °C) = 0.86

^{1}H NMR: (400 MHz, DMSO-d_6) δ ppm 3.54 (t, J=2.00 Hz, 1H, *Hk*), 3.80 (s, 2H, *Ha*), 4.74 (d, J=2.01 Hz, 2H, *Hj*), 5.16 (s, 2H, *Hd*), 5.61 (s, 2H, *Hf*), 7.11 (dd, J=8.53, 5.02 Hz, 4H, *Hb*), 7.31 - 7.39 (m, 9H, *Hc, Hg,h,i*), 8.23 (s, 1H, *He*), 9.62 (s, 1H, *Hl*), 9.73 (s, 1H, *Hm*)

^{13}C NMR: (125 MHz, acetone-d_6) δ ppm 153.4 (C6), 152. 7 (C18), 143.3 (C8), 137.2 (C5), 137.0 (C17), 136.3 (C2), 136.1 (C15), 136.0 (C11), 129.1 (C16 x2), 129.1 (C3 x2), 128.8 (C13 x2), 128.3 (C12 x2), 128.1 (C14), 124.1 (C9), 118.5 (C4 x4), 78.5 (C20), 75.2 (C21), 57.6 (C7), 53.3 (C10), 51.7 (C19), 40.2 (C1).

Mass spectrometry: expected 495.19; found (M+Na)$^+$ 518.20

Column chromatography was used to separate the products (1:1 pet. ether: ethyl acetate).

2.5.1.5 Cu(II) acetate (5 mol%)

To a Radleys carousel reaction tube was added **17** (0.2 g, 0.55 mmol), Cu(II) acetate (5.5 mg, 0.05 eq., 0.028 mmol) and triphenylphosphine (31.8 mg, 0.22 eq., 0.12 mmol); DMSO (5 mL) was added to solubilise the reactants. Finally, benzyl azide (151 µL, 2.2 eq., 1.2 mmol) was added and the reaction allowed to proceed for 90 minutes at room temperature.

Analysis: as for **25**

Conversion: 82% after 90 minutes as judged from the ^{1}H NMR spectrum.

2.5.1.6 Cu(II) acetate (20 mol%)

To a Radleys carousel reaction tube was added **17** (0.1 g, 0.28 mmol), Cu(II) acetate (11.0 mg, 0.2 eq., 0.055 mmol) and triphenylphosphine (14.5 mg, 0.4 eq., 0.11 mmol); DMSO (5 mL) was added to solubilise the reactants. Finally, benzyl azide (72 µL, 2.1 eq., 0.58 mmol) was added and the reaction allowed to proceed for 90 minutes at room temperature.

Analysis: as for **25**

Conversion: 100% after 90 minutes as judged from the ^{1}H NMR spectrum.

2.5.1.7 Cu(II) acetate (10 mol%) in DMF at sub-ambient temperatures

To a round-bottomed flask was added **17** (0.1 g, 0.28 mmol), Cu(II) acetate (5.1 mg, 0.1 eq., 0.028 mmol) and triphenylphosphine (14.5 mg, 0.2 eq., 0.055 mmol). DMF (5 mL) was added to solubilise the reactants. Finally, benzyl azide (72 µL, 2.1 eq., 0.58 mmol) was added and the reaction allowed to proceed for 90 minutes. The reaction flask was held in an ice bath for the duration of the reaction.

Analysis: as for **25**

Conversion: 49% after 90 minutes as judged from the ^{1}H NMR spectrum.

2.5.1.8 Cu(II) acetate (10 mol%) in ethyl acetate at sub-ambient temperatures

To a round-bottomed flask was added **17** (0.1 g, 0.28 mmol), Cu(II) acetate (5.1 mg, 0.1 eq., 0.028 mmol) and triphenylphosphine (14.5 mg, 0.2 eq., 0.055 mmol). Ethyl acetate (5 mL) was added to solubilise the reactants. Finally, benzyl azide (72 µL, 2.1 eq., 0.58 mmol) was added and the reaction allowed to proceed for 90 minutes. The reaction flask was held in an ice bath for the duration of the reaction.

Analysis: as for **25**

Conversion: negligible after 90 minutes as judged from the ^{1}H NMR spectrum.

2.5.1.9 Cu(II) acetate (10 mol%) with TBTA co-ligand

To a Radleys carousel reaction tube was added **17** (0.2 g, 0.55 mmol), Cu(II) acetate (1.10 mg, 0.01 eq, 0.0055 mmol), triphenylphosphine (6.4 mg, 0.044 eq., 0.025 mmol) and TBTA (2.93 mg, 0.01 eq., 0.0055 mmol). DMSO (5 mL) was added to solubilise the reactants. Finally, benzyl azide (151 µL, 2.2 eq., 1.21 mmol) was added and the reaction allowed to proceed for 90 minutes at room temperature.

Analysis: as for **25**

Conversion: 3% after 90 minutes as judged from the ^{1}H NMR spectrum.

2.5.1.10 Cu(II) acetate (10 mol%) with sodium ascorbate as reducing agent

To a Radleys carousel reaction tube was added **17** (0.1 g, 0.28 mmol), Cu(II)acetate (2.8 mg, 0.05 eq., 0.014 mmol) and sodium ascorbate (4.8 mg, 0.1 eq., 0.028 mmol). DMSO (5 mL) was added to solubilise the reactants. Finally, benzyl azide (72 µL, 2.1 eq., 0.58 mmol) was added and the reaction allowed to proceed for 6 hours at room temperature.

Analysis: as for **25**

Conversion: 10% after 90 minutes as judged from the ^{1}H NMR spectrum and 56% after 6 hours as judged from the ^{1}H NMR spectrum.

2.5.1.11 Cu(II) sulphate (20 mol%)

To a Radleys carousel reaction tube was added **17** (73.4 mg, 0.16 mmol), Cu(II) sulphate (8.21 mg, 0.2 eq., 0.033 mmol) and sodium ascorbate (4.8 mg, 1 eq., 0.16 mmol). DMSO (5 mL) was added to solubilise the reactants. Finally, benzyl azide (43 µL, 2.1 eq., 0.35 mmol) was added and the reaction allowed to proceed for 14 hours at room temperature.

Analysis: as for **25**

Conversion: 55% after 14 hours as judged from the ^{1}H NMR spectrum.

2.5.2 CuAAC click reaction to give triazole-functional molecules in NMP and MPA Solvents

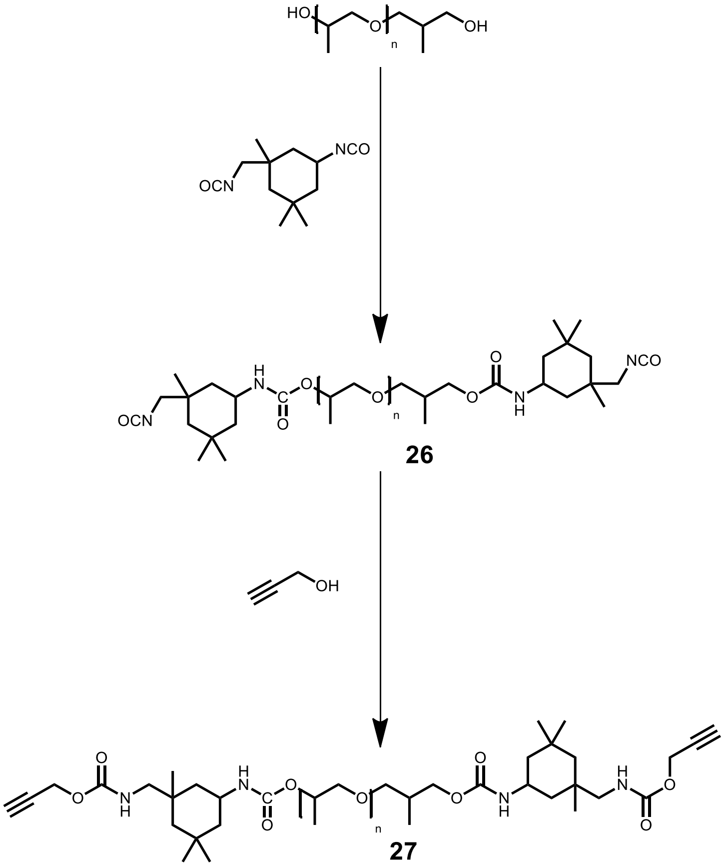
To a Radleys carousel reaction tube was added **17** (0.1 g, 0.28 mmol), Cu(II) acetate (5.1 mg, 0.1 eq., 0.028 mmol) and triphenylphosphine (14.5 mg, 0.2 eq., 0.055 mmol). Either NMP or MPA (5 mL) was added to solubilise the reactants. Finally, benzyl azide (72 µL, 2.1 eq., 0.58 mmol) was added and the reaction allowed to proceed for 6 hours at room temperature.

Conversion (MPA): 69% after 6 hours as judged from the ^{1}H NMR spectrum.

Conversion (NMP): Full conversion after 6 hours as judged from the ^{1}H NMR spectrum.

2.5.3 The preparation and subsequent CuAAC reaction of simple azide- and alkyne-containing oligomers

2.5.3.1 Alkyne-functional IPDI oligomer



To a reaction flask was added IPDI (127.47 g, 0.57 moles), and to this was added MPA (100 g) and dibutyltin tin dilaurate (0.12 g, 0.19 mmoles). To these, PPG polyol (0.5 eq., 276.81 g, 0.28 moles) was added drop-wise. The NCO content was measured periodically over a period of time (48 hours) until it approached the theoretical NCO content expected. Propargyl alcohol (2.1 eq., 42.79 g, 0.76 moles) was then added drop-wise. The disappearance of the NCO group was monitored *via* FT-IR spectroscopy.

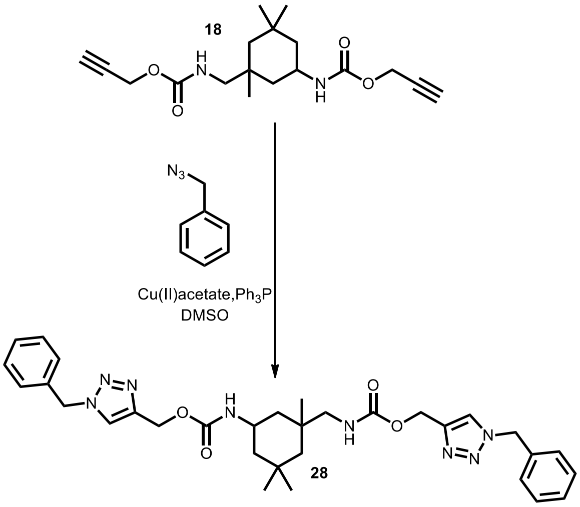
^{1}H NMR: discussed in Results and Discussion

MALDI-MS expected range from 1500 to 2000; found: 1178 to 1898

FT-IR $\bar{\upsilon}/cm^{-1}$: (Liquid film) 3334, 3315, 2931, 1716, 1529, 1236, 1097

2.5.3.2 CuAAC-promoted reactions of benzyl azide- and alkyne-functional urethanes.

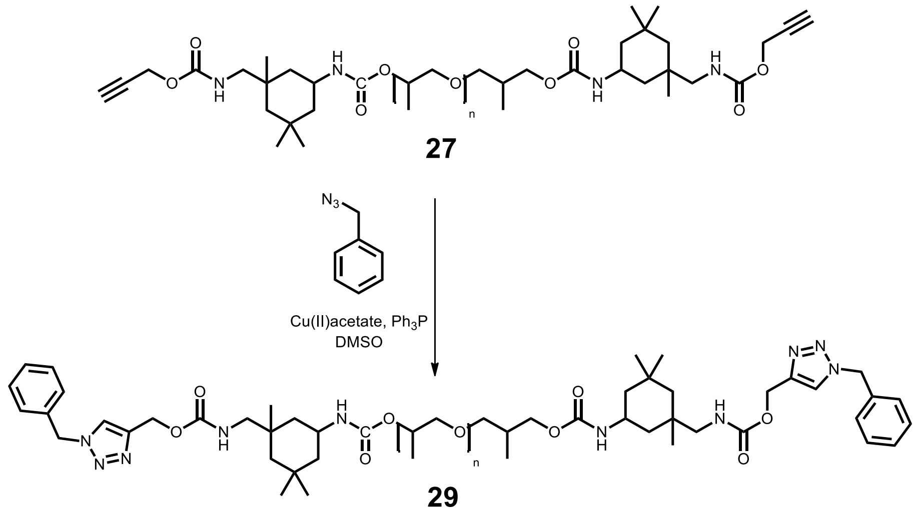
*CuAAC reaction of **18** with benzyl azide*



To a Radleys carousel reaction vial, containing a magnetic stirrer bar, was added **18** (0.1 g, 0.30 mmol). To this was added a solution of Cu (II) acetate (0.1 eq., 6 mg, 0.03 mmol) and triphenyl phosphine (0.2 eq., 15.7 mg, 0.06 mmol) in DMSO (5 mL). This mixture was stirred for ten minutes, and then benzyl azide (2.1 eq., 83.6 mg, 0.63 mmol) added.

^{1}H NMR: discussed in Results and Discussion

*CuAAC reaction of **27** with benzyl azide*



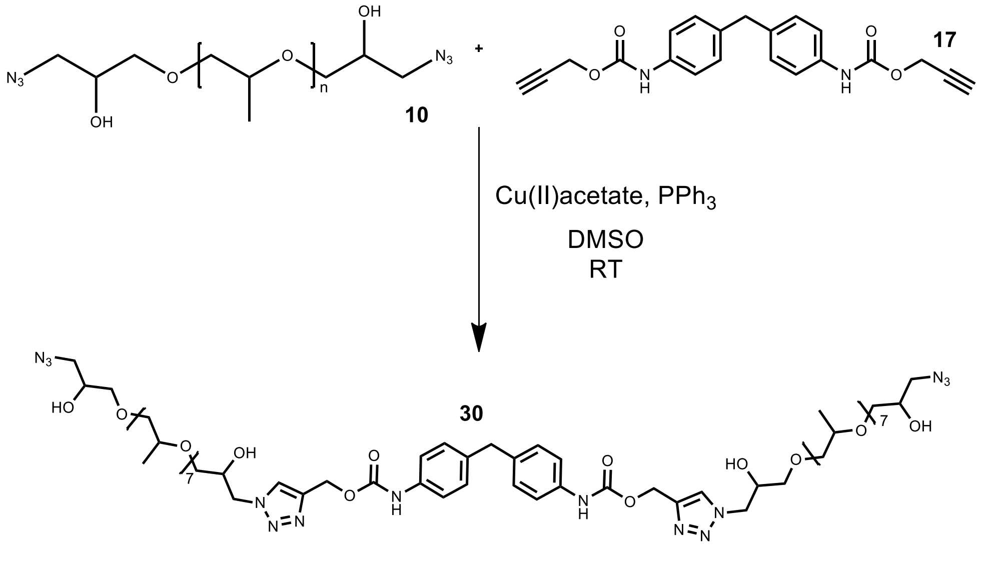
At the time of carrying out this reaction the molecular weight range of the alkyne-containing polyurethane oligomer was unknown. Therefore, the amount of benzyl azide, Cu (II) acetate and triphenyl phosphine needed was calculated relative to the amount of propargyl alcohol used in the preparation of the alkyne-containing polyurethane oligomer.

To a Radleys carousel reaction vial, containing a magnetic stirrer, was added **27** (0.1 g, 0.14 mmol *relative to propargyl alcohol*). To this was added a solution of Cu (II) acetate (0.1 eq., 2.8 mg, 0.014 mmol) and triphenyl phosphine (0.2 eq., 5.6 mg, 0.028 mmol) in DMSO (5 mL). This mixture was stirred for ten minutes, and then benzyl azide (1 eq., 18.6 mg, 0.14 mmol) added.

^{1}H NMR: discussed in Results and Discussion

MALDI-MS: expected range from 1619 to 2141; found: 1618 to 2200

2.5.3.3 Reaction of azide polyol (10) with 17

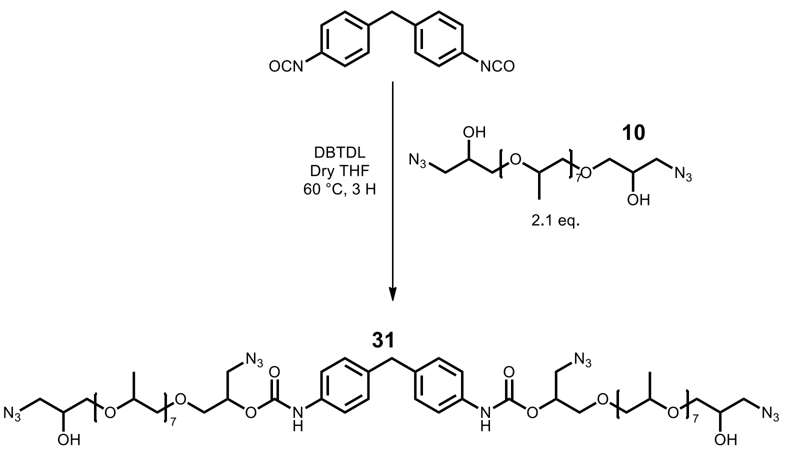


To a Radleys reaction vial containing a magnetic stirrer bar, azide ring-opened Grilonit F704 (**10**) (471 µL, 0.80 mmol) was added together with **17** (145 mg, 0.5 eq., 0.40 mmol) Cu(II)acetate (9.3 mg, 0.1 eq., 0.040 mmol) and triphenyl phosphine (21.1 mg, 0.2 eq., 0.080 mmol) in DMSO (5 mL) was then added to the reaction vessel. The reaction vessel was left stirring at room temperature for 16 hours.

A liquid/liquid extraction into ethyl acetate was performed, and this allowed for the ^{1}H NMR of the resulting viscous product to be obtained. In addition, a small amount of sample was placed in a glass reaction vial and left in vacuum oven overnight to drive off residual DMSO solvent.

MALDI-MS: expected from around 900; found: 752 to 1452

2.5.3.4 Reaction between MDI and azido-polyol



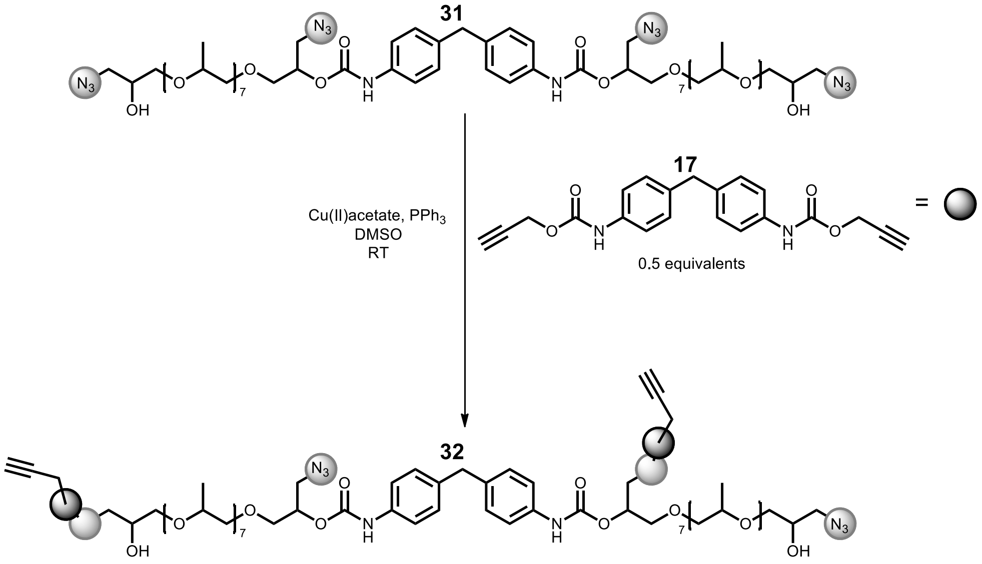
To a Radleys reaction vial containing a magnetic stirrer bar was added MDI (0.2 g, 0.80 mmol) to this was added dibutyltin tin dilaurate (0.05 g, 0.1 eq., 0.08 mmol) and dry THF (5 mL). To this was added **10** (2.1 eq., 1.04 g, 1.68 mmol) drop-wise. The disappearance of the isocyanate functionality was monitored *via* FT-IR spectroscopy.

^{1}H NMR: discussed in Results and Discussion section

MALDI-MS: expected range from 1400; found: 1400 to 1800

FT-IR $\bar{\upsilon}$*/cm*$^{-1}$: 3359, 2971, 2874, 2099, 1736, 1598, 1534

2.5.3.5 Reaction of 31 with 17



To a Radleys reaction vial containing a magnetic stirrer bar was added **31** (0.2 g, 0.13 mmol). To this was added **17** (0.5 eq., 0.02 g, 0.07 mmol) and a solution of Cu (II) acetate (2.67 mg, 0.01 mmol) and triphenyl phosphine (7.02 mg, 0.03 mmol) in either DMSO (5 mL) or acetonitrile (5 mL). The mixture was allowed to react overnight at room temperature.

FT-IR $\bar{\upsilon}$*/cm*$^{-1}$: (Liquid film) 3253, 2930, 2107, 1725, 1602, 1512

2.6 Other experiments

2.6.1 UV and weathering testing

Preparation of two pigment blends A and B

Two pigment blends were prepared. Pigment blend A was prepared on a 1.5 kg scale and included no UV additives. Pigment blend B was prepared on a 1.6 kg scale and included both a HALS additive and one other UV additive (Uvinul 3039). The compositions of both pigment blends are shown in Table 2.1.

Table 2.1: Components for the preparation of pigment blend A and B.

	% of blend	
Components	Pigment blend A	Pigment blend B
TiO_2	**20**	**18.75**
$Al(OH)_3$	**46.67**	**43.75**
NMP	**33.33**	**31.25**
HALS	**-**	**3.13**
Uvinul 3039	**-**	**3.13**
Total mass of blend (g)	**1500**	**1600**

The solvent used in the preparation of both pigments was NMP. The pigment blends were prepared as follows; the components of the blends were added to a suitable container which was capable of holding all of the components and which allowed for mixing *in-situ* using an overhead stirrer.

Preparation of pigmented (with and without UV additives) azide-functional polyurethanes and standard (non-azide) polyurethane controls for coating of test panels and subsequent UV-weathering analysis

Two azide-functional polyurethanes were used. The first was **PU1,** which was discussed earlier (2.3.1). The second azide-containing polyurethane was based on a branched system **PU2** (2.3.2). The alkyne cross linker used in both systems was **21** (2.4.2)**.** The linear and branched azide-containing systems are described in Table 2.2 and Table 2.3, respectively. For both systems it was decided to make both clear-coats and pigmented systems (with and without UV additives). In addition the concentration of the Cu(II)acetate catalyst used was varied from 10 to 1 mol %. Included for completeness were samples in which there was no copper present.

Table 2.2: Linear azide polyurethane (PU1) (with and without UV additives).

Name	Pigmented	UV additives	Cu catalyst	Cure mechanism
1.1 i	Yes	No	No	Thermal
1.2 i	Yes	No	10 mol%	CuAAC
1.3 i	Yes	No	1 mol%	CuAAC
2.1 i	Yes	Yes	No	Thermal
2.2 i	Yes	Yes	10 mol%	CuAAC
2.3 i	Yes	Yes	1 mol%	CuAAC
3.1 i	No	No	No	Thermal
3.2 i	No	No	10 mol%	CuAAC
3.3 i	No	No	1 mol%	CuAAC

Table 2.3: Branched azide polyurethane (PU2) (with and without UV additives).

Name	Pigmented	UV additives	Cu catalyst	Cure mechanism
1.1 ii	Yes	No	No	Thermal
1.2 ii	Yes	No	10 mol%	CuAAC
1.3 ii	Yes	No	1 mol%	CuAAC
2.1 ii	Yes	Yes	No	Thermal
2.2 ii	Yes	Yes	10 mol%	CuAAC
2.3 ii	Yes	Yes	1 mol%	CuAAC
3.1 ii	No	No	No	Thermal
3.2 ii	No	No	10 mol%	CuAAC
3.3 ii	No	No	1 mol%	CuAAC

Control system (with and without UV additives)

The control system was based on a standard isocyanate-functional polyurethane which was reacted with a tetra-functional amino-alcohol crosslinker at ambient temperature. A number of controls were prepared using this system (C1-C6). The controls consisted of pigmented systems with and without the presence of UV additives, and also non-pigmented clear-coats. Copper was added at a 1 mol% loading level to three of the controls (C4-C6). Descriptions of the control samples are shown in Table 2.4 and the masses of components used to prepare the controls are listed in Table 2.5.

Table 2.4: Isocyanate-cured polyurethane controls with and without copper catalyst.

Name	Description
C1	Clear coat, no copper catalyst
C2	Pigmented system, no UV additives, no copper catalyst
C3	Pigmented system, with UV additives, no copper catalyst
C4	Clear coat, 1 mol% catalyst
C5	Pigmented system, no UV additives, 1 mol% catalyst
C6	Pigmented system, with UV additives, 1 mol% catalyst

The 1 mol % referred to in Table 2.4 is related to the amount of Cu(II)acetate and triphenyl phosphine that would have been used in a corresponding azide-functional sample (10 g).

Table 2.5: Isocyanate-cured polyurethane controls with and without copper catalyst.

	Polymer mixture (g)	Pigment blend A (g)	Pigment blend B (g)	Cu(II)acetate (g)	Ph_3P (g)
C1	10	-	-	-	-
C2	10	3.75	-	-	-
C3	10	-	3.59	-	-
C4	10	-	-	0.027	0.079
C5	10	3.75	-	0.027	0.079
C6	10	-	3.59	0.027	0.079

The resulting azide-containing polyurethanes and the control systems were deposited onto Q-panel test plates using a 120 µM applicator bar. The samples which contained copper were allowed to react at room temperature for 24 hours and then subsequently placed in an oven at 120 °C for 2 hours to allow for complete reaction and also to allow for complete evaporation of solvent. The samples which contained no copper were cured thermally at 120 °C for 2 hours. The polyurethane controls, with and without copper, were cured at room temperature for 24 hours and then placed in an oven at 120 °C for 2 hours.

All panels underwent cycles of condensation and UV-A weathering at 60 °C for 576 hours.

2.6.2 Leaching testing

To a 4 mL screw-top vial was added prepolymer **PU1** (0.5 g, 0.76 mmol (of azide groups)), together with acetonitrile (0.25 mL) and **16** (0.063 g, 0.76 mmol (of alkyne groups)). To this was added Cu (II) acetate at various loadings (1, 5 and 10 mol %) (Table 2.6). Finally, a solution of triphenyl phosphine in acetonitrile (0.75 mL) was added.

Table 2.6: Cu(II) acetate and triphenyl phosphine added to prepare three films with various loadings of copper.

mol % of Cu catalyst	Cu(II)acetate (mg)	Triphenyl phosphine (mg)
1	1.37	3.96
5	6.87	19.84
10	13.7	39.68

The mixture was stirred by hand until homogeneous and then subsequently decanted into a polypropylene mold. The mixture was allowed to form a uniform film at room temperature overnight. The films formed were then subsequently placed in an oven at 109 °C for two hours to ensure complete reaction, which was confirmed *via* disappearance of azide signal (2100 cm^{-1}) in the FT-IR spectrum of the films.

The thin films were cut into portions (0.5 g) placed in screw-top vials and then subsequently submerged in distilled water (1 mL). The samples were prepared in triplicate and the amount of copper leached was measured using ICP-MS after 7, 43 and 181 days.

2.6.3 Mechanical testing of CuAAC crosslinked polyurethane films

2.6.3.1 PU2 and 21 - 5 mol % Cu catalyst in aqueous solution.

To a plastic beaker was added **PU2** (5 g, 14.5 mmol of azide) and **21** (4.21 g, 14.5 mmol of alkyne). This mixture was stirred until homogeneous. To the mixture was added Cu(II)acetate solution (2 mL, 0.36 Molar), this was stirred until homogeneous. Finally a saturated solution of NaAsc (0.46 mL, 3.1 Molar) was added. The mixture was stirred rapidly to allow for an even distribution of the NaAsc solution, and then finally decanted into a suitable mold and allowed to form a film at room temperature.

2.6.3.2 PU2 and 21 - 5 mol % Cu catalyst in organic solution.

To a plastic beaker was added **PU2** (5 g, 14.5 mmol of azide) and **21** (4.21 g, 14.5 mmol of alkyne). This mixture was stirred until homogeneous. To the mixture was added Cu(II)acetate solution (2.8 mL, 0.26 Molar), this was stirred until homogeneous. Finally a saturated solution of NaAsc (0.46 mL, 3.13 Molar) was added. The mixture was stirred rapidly to allow for an even distribution of the NaAsc solution, and then finally decanted into a suitable mold and allowed to form a film at room temperature.

To investigate the effect of residual solvent upon the mechanical properties of the thin films prepared, a section of the film was subsequently placed in an oven at 80 °C overnight. After removal from the oven the mechanical properties were then tested.

2.6.3.3 PU2 and 21 - thermal cure

To a plastic beaker was added **PU2** (5 g, 14.5 mmol of azide) and **21** (4.21 g, 14.5 mmol of alkyne). This mixture was stirred until homogeneous. Finally, the mixture was decanted into a suitable mold and allowed to form a film at 80 °C overnight.

2.6.3.4 PU2 and 21 with 9 for improved physical properties

Mix A 1:1 Thermal cure

To a plastic beaker was added **PU2** (2.5 g, 7.23 mmol of azide) together with **9** (2.5 g, 11.72 mmol of azide) and **21** (5.51 g, 18.94 mmol of alkyne). This mixture was stirred until homogeneous. Finally, the mixture was decanted into a suitable mold and allowed to form a film at 80 °C overnight.

Mix B 3:1 Thermal cure

To a plastic beaker was added **PU2** (3.75 g, 10.84 mmol of azide) together with **9** (1.25 g, 5.86 mmol of azide) **21** (4.86 g, 16.71 mmol of alkyne). This mixture was stirred until homogeneous. Finally, the mixture was decanted into a suitable mold and allowed to form a film at 80 °C overnight.

Mix C 1:3 Thermal cure

To a plastic beaker was added **PU2** (1.25 g, 3.61 mmol of azide) together with **9** (3.75 g, 17.59 mmol of azide) and **21** (6.17 g, 21.20 mmol of alkyne). This mixture was stirred until homogeneous. Finally, the mixture was decanted into a suitable mold and allowed to form a film at 80 °C overnight.

Mix D 1:1 ambient temperature cure, 4 mol % Cu catalyst (aqueous solution)

To a plastic beaker was added **PU2** (2.50 g, 7.23 mmol of azide) together with **9** (2.50 g, 11.72 mmol of azide) and **21** (5.51 g, 18.94 mmol of alkyne). This mixture was stirred until homogeneous. To the mixture was added Cu(II)acetate solution (2.11 mL, 0.36 Molar), and this was stirred until homogeneous. Finally a saturated solution of NaAsc (0.48 mL, 3.1 Molar) was added. The mixture was stirred rapidly to allow for an even distribution of the NaAsc solution, and then finally decanted into a suitable mold and allowed to form a film at room temperature.

Mix E 3:1 ambient temperature cure, 4 mol % Cu catalyst (aqueous solution)

To a plastic beaker was added **PU2** (3.75 g, 10.84 mmol of azide) together with **9** (1.25 g, 5.86 mmol of azide) and **21** (4.86 g, 16.71 mmol of alkyne). This mixture was stirred until homogeneous. To the mixture was added Cu(II)acetate solution (1.86 mL, 0.36 Molar), and this was stirred until homogeneous. Finally a saturated solution of NaAsc (0.43 mL, 3.1 Molar) was added. The mixture was stirred rapidly to allow for an even distribution of the NaAsc solution, and then finally decanted into a suitable mold and allowed to form a film at room temperature.

Mix F 1:3 ambient temperature cure, 4 mol % Cu catalyst (aqueous solution)

To a plastic beaker was added **PU2** (1.25 g, 3.61 mmol of azide) together with **9** (3.75 g, 17.59 mmol of azide) and **21** (6.17 g, 21.20 mmol of alkyne). This mixture was stirred until homogeneous. To the mixture was added Cu(II)acetate solution (2.36 mL, 0.36 Molar), this was stirred until homogeneous. Finally a saturated solution of NaAsc (0.54 mL, 3.1 Molar) was added. The mixture was stirred rapidly to allow for an even distribution of the NaAsc solution, and then finally decanted into a suitable mold and allowed to form a film at room temperature.

*Mix G **9** ambient temperature cure, 2.5 mol % Cu catalyst (aqueous solution)*

To a plastic beaker was added **9** (5 g, 23.45 mmol of azide) and **21** (6.82 g, 23.45 mmol of alkyne). This mixture was stirred until homogeneous. To the mixture was added Cu(II)acetate solution (1.63 mL, 0.36 Molar), and this was stirred until homogeneous. Finally, a saturated solution of NaAsc (0.37 mL, 3.1 Molar) was added. The mixture was stirred rapidly to allow for an even distribution of the NaAsc solution, and then finally decanted into a suitable mold and allowed to form a film at room temperature.

*Mix H **9** ambient temperature cure, 0.75 mol % Cu catalyst (aqueous solution)*

To a plastic beaker was added **9** (5 g, 23.45 mmol of azide) and **21** (6.82 g, 23.45 mmol of alkyne). This mixture was stirred until homogeneous. To the mixture was added Cu(II)acetate solution (0.49 mL, 0.36 Molar), and this was stirred until homogeneous. Finally a saturated solution of NaAsc (0.11 mL, 3.1 Molar) was added. The mixture was stirred rapidly to allow for an even distribution of the NaAsc solution, and then finally decanted into a suitable mold and allowed to form a film at room temperature.

2.6.4 Benzoic acid as an additive in the reaction between 11 and 17

*Twelve reactions were carried out to investigate the effect of benzoic acid as an additive on the reaction of an azide-functional polyol **11** and **17**. The role of the reducing agent was also investigated in this series of mixtures. The reaction solvent was DMSO and this was kept constant in each of the mixtures.*

A: 10 mol % Cu catalyst with Ph_3P reducing agent and 10 mol % loading of benzoic acid

To a 4 mL screw-top vial was added **11** (0.1 g, 0.25 mmol of azide), together with DMSO (1 mL) and **17** (0.046 g, 0.25 mmol of alkyne). To this was added Cu (II) acetate (5 mg, 25 µmol), Ph_3P (13 mg, 50 µmol) and benzoic acid (3.1 mg, 25 µmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

B: 1 mol % Cu catalyst with Ph_3P reducing agent and 10 mol % loading of benzoic acid

To a 4 mL screw-top vial was added **11** (0.1 g, 0.25 mmol of azide), together with DMSO (1 mL) and **17** (0.046 g, 0.25 mmol of alkyne). To this was added Cu (II) acetate (0.5 mg, 2.5 µmol), Ph_3P (1.3 mg, 5.0 µmol) and benzoic acid (3.1 mg, 25 µmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

C: 0.1 mol % Cu catalyst with Ph_3P reducing agent and 10 mol % loading of benzoic acid

To a 4 mL screw-top vial was added **11** (0.2 g, 0.5 mmol of azide), together with DMSO (1 mL) and **17** (0.092 g, 0.5 mmol of alkyne). To this was added Cu (II) acetate (0.1 mg, 0.25 µmol), Ph_3P (0.26 mg, 0.5 µmol) and benzoic acid (3.1 mg, 25 µmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-

IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

D: 0 mol % Cu catalyst with Ph_3P reducing agent (at 10 mol %) and 10 mol % loading of benzoic acid

To a 4 mL screw-top vial was added **11** (0.1 g, 0.25 mmol of azide), together with DMSO (1 mL) and **17** (0.046 g, 0.25 mmol of alkyne). To this was added Ph_3P (13 mg, 50 µmol) and benzoic acid (3.1 mg, 25 µmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

E: 10 mol % Cu catalyst with Ph_3P reducing agent and no benzoic acid

To a 4 mL screw-top vial was added **11** (0.1 g, 0.25 mmol of azide), together with DMSO (1 mL) and **17** (0.046 g, 0.25 mmol of alkyne). To this was added Cu (II) acetate (5 mg, 25 µmol) and Ph_3P (13 mg, 50 µmol).The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

F: 1 mol % Cu catalyst with Ph_3P reducing agent and no benzoic acid

To a 4 mL screw-top vial was added **11** (0.1 g, 0.25 mmol of azide), together with DMSO (1 mL) and **17** (0.046 g, 0.25 mmol of alkyne). To this was added Cu (II) acetate (0.5 mg, 2.5 µmol) and Ph_3P (1.3 mg, 5.0 µmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

G: 0.1 mol % Cu catalyst with Ph_3P reducing agent and no benzoic acid

To a 4 mL screw-top vial was added **11** (0.2 g, 0.50 mmol of azide), together with DMSO (1 mL) and **17** (0.092 g, 0.50 mmol of alkyne). To this was added Cu (II) acetate (0.1 mg, 0.25 μmol) and Ph_3P (0.26 mg, 0.5 μmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

H: 0 mol % Cu catalyst with Ph_3P reducing agent (at 10 mol %) and no benzoic acid

To a 4 mL screw-top vial was added **11** (0.1 g, 0.25 mmol of azide), together with DMSO (1 mL) and **17** (0.046 g, 0.25 mmol of alkyne). To this was added Ph_3P (13 mg, 50 μmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

I: 10 mol % Cu catalyst with NaAsc reducing agent and 10 mol % loading of benzoic acid

To a 4 mL screw-top vial was added **11** (0.1 g, 0.25 mmol of azide), together with DMSO (1 mL) and **17** (0.046 g, 0.25 mmol of alkyne). To this was added Cu (II) acetate (5 mg, 25 μmol), NaAsc (9.96 mg, 50 μmol) and benzoic acid (3.1 mg, 25 μmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

J: 0 mol % Cu catalyst with NaAsc reducing agent and 10 mol % loading of benzoic acid

To a 4 mL screw-top vial was added **11** (0.1 g, 0.25 mmol of azide), together with DMSO (1 mL) and **17** (0.046 g, 0.25 mmol of alkyne). To this was added NaAsc (9.96 mg, 50 μmol) and benzoic acid (3.1 mg, 25 μmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

K: 10 mol % Cu catalyst with NaAsc reducing agent and no benzoic acid

To a 4 mL screw-top vial was added **11** (0.1 g, 0.25 mmol of azide), together with DMSO (1 mL) and **17** (0.046 g, 0.25 mmol of alkyne). To this was added Cu (II) acetate (5 mg, 25 µmol) and NaAsc (9.96 mg, 50 µmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

L: 0 mol % Cu catalyst with NaAsc reducing agent and no benzoic acid

To a 4 mL screw-top vial was added **11** (0.1 g, 0.25 mmol of azide), together with DMSO (1 mL) and **17** (0.046 g, 0.25 mmol of alkyne). To this was added NaAsc (9.96 mg, 50 µmol). The mixture was shaken by hand and allowed to react overnight (18 hours). The FT-IR spectrum of the mixture was taken and investigated for the appearance of a signal at around 2100 cm^{-1} associated with the azide moiety.

3.0 Results and discussion

3.1 Preparation of azide-containing molecules

The first aim of the PhD study was to prepare azide-containing molecules which could partake in CuAAC click-type reactions with alkynes. There was a requirement for the preparation of organic azides to take part in CuAAC click reactions, as these are not normally commercially available. The lack of commercial availability is due to the hazards associated with their storage and transportation.

3.1.1 Simple azide-containing molecules

Benzyl azide **1** and hexyl azide **2** (Figure 3.1) were prepared from halide precursors *via* treatment with sodium azide and sodium iodide in DMF. ^{1}H NMR spectroscopy was used to confirm the successful substitution of halide for azide. The conversion of benzyl chloride to benzyl azide was quantitative, but the conversion of hexyl bromide to hexyl azide only afforded a yield of 54%.

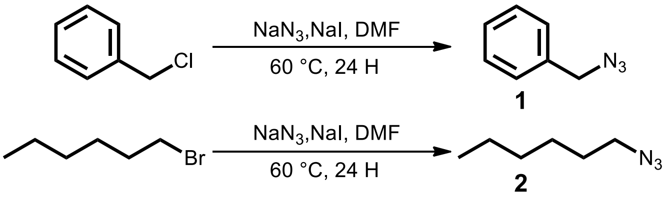


Figure 3.1: Simple azide-containing molecules (aliphatic and aromatic) prepared from halide precursors.

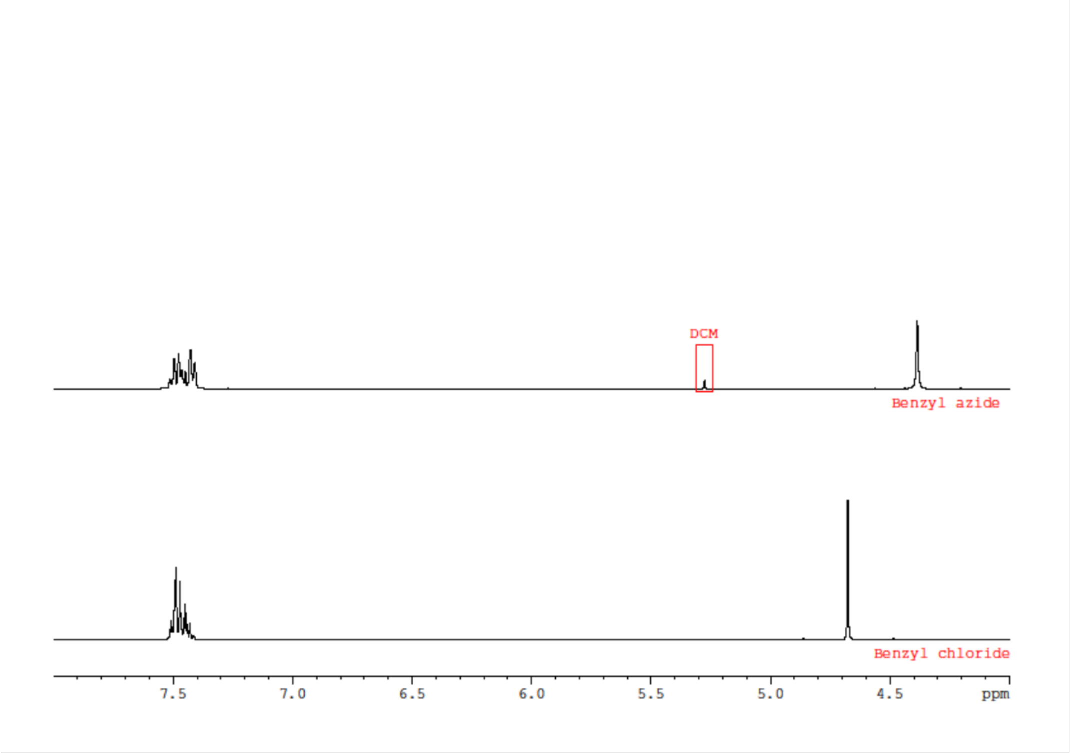


Figure 3.2: ^{1}**H NMR spectra of benzyl chloride (lower) and benzyl azide (Upper).**

^{1}H NMR spectroscopy was used to confirm the substitution of halide for azide in the case of benzyl chloride (Figure 3.2) and 1-bromohexane (Figure 3.3). In the case of benzyl chloride (Figure 3.2), there was a small upfield shift of the methylene protons adjacent to the azide group (from 4.68 to 4.39 ppm). This was also the case for the methylene protons adjacent to the azide group in hexyl azide (from 3.40 to 3.17 ppm). These simple spectra are presented here because the changes in the NMR spectra which occur upon substitution with azide are very diagnostic and extremely useful in monitoring cognate reactions, including reactions involving structurally much more complex starting materials, e.g., prepolymers.

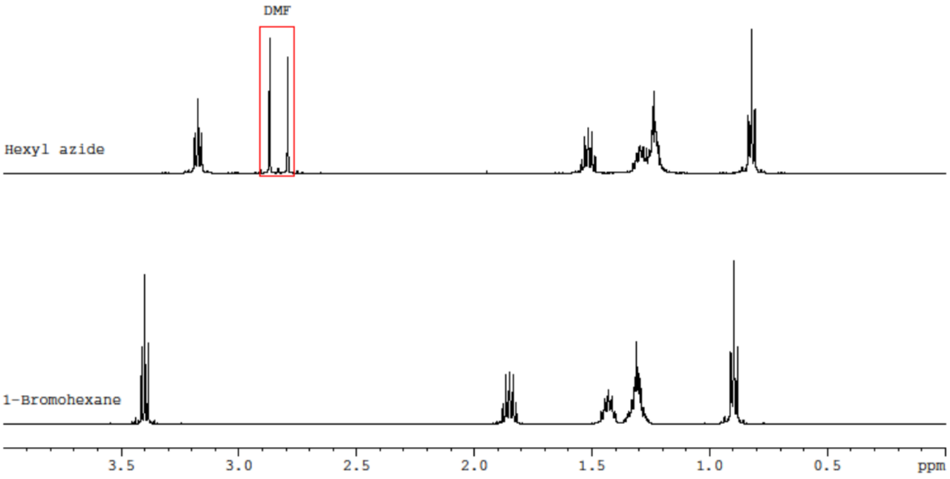


Figure 3.3: ^{1}**H NMR spectra of 1-bromohexane (lower) and hexyl azide (upper).**

Both of these azide-containing molecules had a very strong FT-IR absorption band at around 2,100-2,090 cm^{-1}, which is consistent with successful introduction of the azide moiety. This band was absent in both of the halide starting materials.

3.1.2 Preparation of azide containing molecules based on MDI

Methylene diphenyl diisocyanate (MDI) was used as a scaffold for the preparation of azide-containing molecules for a number of reasons, the first being the higher molecular weight of MDI which facilitates the safe handling of the resulting organic azides. In addition, the presence of the urethane group in the scaffold is significant as subsequent click chemistry reactions will be carried out in the presence of urethane groups, so this route includes the functional groups that the CuAAC click reaction will need to tolerate.

One potential route taken towards the preparation of azide-functional molecules was the reaction of MDI with a halide containing alcohol, such as 2,2 chloroethoxyethanol. This would provide a route towards halogen functional MDI molecule **3**. The chlorides on **3** could then be substituted with azide to afford a *bis*-azide functional molecule based on MDI (**4**) (Figure 3.4).

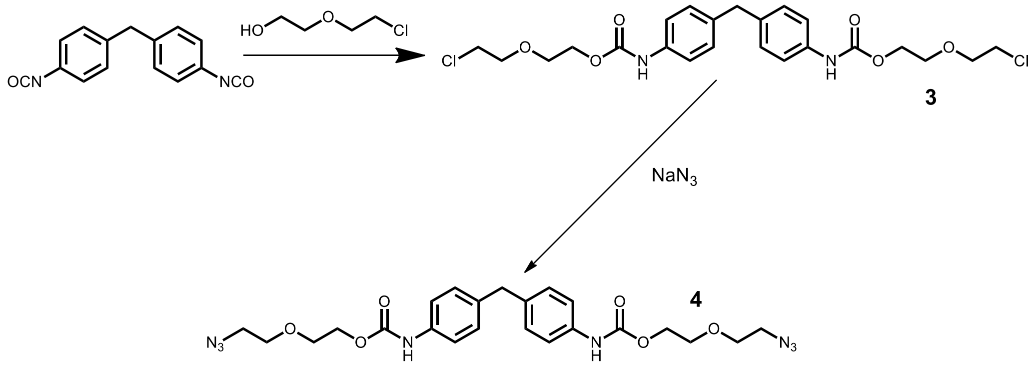


Figure 3.4: Preparation of halogen-functional MDI and the corresponding azide-functional MDI.

This route provides pathways to *bis*-azide functional molecules, and in addition the *bis*-azide molecules have any possible hazards associated with organic azides compensated for with the relatively high molecular weight of the molecules and the increased presence of carbon and oxygen molecules which dilutes the nitrogen content of the azide molecules.

The *bis*-azide molecule prepared could possibly act as a chain-extender with an alkyne-containing pre-polymer, but **4** lacks any other chemical functionality that could be used to incorporate the molecule into a pre-polymer.

In any case, the synthetic strategy was to functionalise a polyurethane pre-polymer (with all the beneficial properties it enjoys) with azide or alkyne functional groups and then use CuAAC chemistry as a replacement for the reaction of an isocyanate with an active hydrogen containing crosslinker.

One possible synthetic route to an azide which does have the functionality that would allow for incorporation into a pre-polymer, involves the addition of glycidol to MDI followed by ring-opening of the epoxide with sodium azide. This would allow for the preparation of an azide-functional molecule which would also bear hydroxyl functionality (Figure 3.5). **6** could then potentially be used to react with diisocyanate monomers *en route* to the preparation of azide-containing pre-polymers.

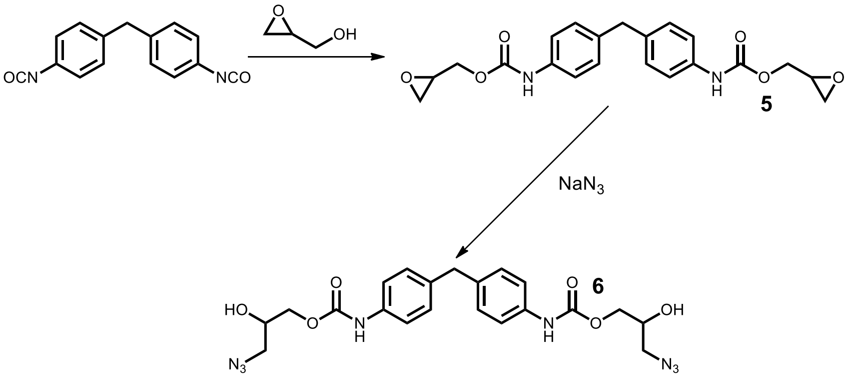


Figure 3.5: Synthetic route for the preparation of a diol with pendent azide functionality.

Through exploiting the sodium azide ring-opening of epoxide molecules, it is possible to take simple epoxides and react them with sodium azide to reveal hydroxyl functionality. This hydroxyl functional molecule also possesses azide functionality and is therefore ideally suited for reactions with diisocyanates as a potential pathway to introducing the azide moiety into urethanes (Figure 3.6).

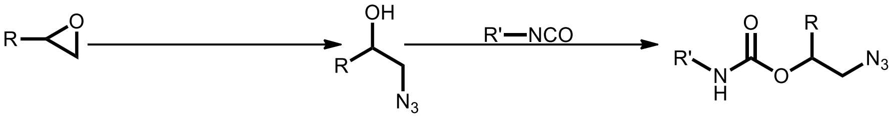


Figure 3.6: Potential route to "end-cap" isocyanates with an azide-functional alcohol.

The introduction of azides to diisocyanates will, in itself, provide a pathway to multifunctional azides, but it can also be envisioned that the azido alcohol prepared *via* the reaction between an epoxide and sodium azide could be used effectively to end-cap isocyanate functional polyurethane pre-polymers (Figure 3.7).

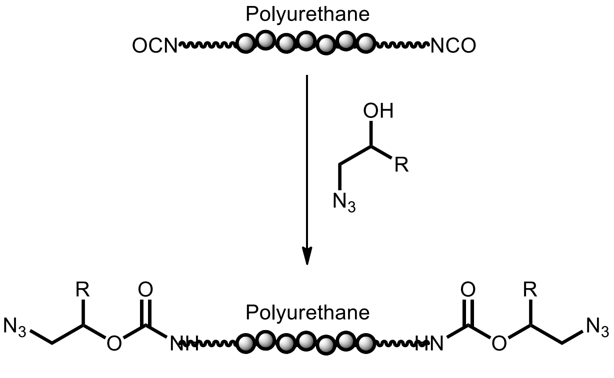


Figure 3.7: "End-capping" of isocyanate functional pre-polymers to afford azide-functional polyurethane pre-polymers.

This would afford azide-functional polyurethane pre-polymers. This azide functional polyurethane pre-polymer could then be subsequently crosslinked with a multi-functional alkyne. This route is particularly attractive as the possible hazards associated with the azide functionality are compensated for by its incorporation into the pre-polymer which has relatively high molecular weight.

This route was investigated in the first instance using allyl glycidyl ether (**AGE**) and sodium azide to furnish azido alcohol **7** (Figure 3.8).

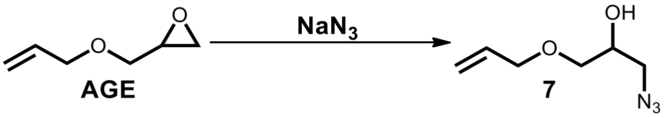


Figure 3.8: Preparation of azide-functional alcohol 7 from AGE.

^{1}H NMR spectroscopy was used to confirm that the expected product **7** had been formed.

A strong absorption band at 2096 cm^{-1} in the infra-red spectrum of the product was also indicative of the presence of the azide group on **7**. In addition to the azide band at 2096 cm^{-1}, a broad band at around 3300 cm^{-1} indicated the presence of the hydroxyl group (Figure 3.9). The resulting azido alcohol was recovered in a reasonable 69 % yield.

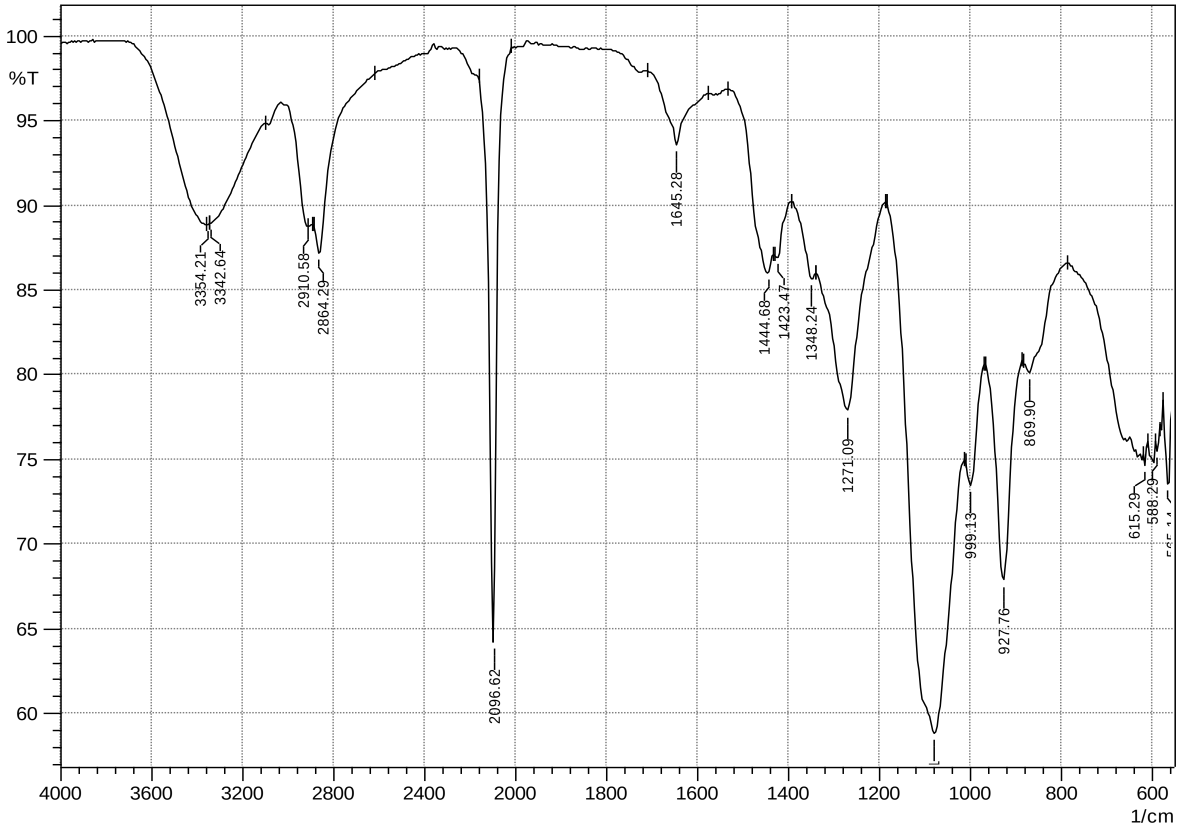


Figure 3.9: FT-IR spectrum of 7; the intense band at 2096 cm^{-1} is indicative of azide functionality.

The azido alcohol **7** was reacted with MDI monomer under a range of conditions, but did not afford the expected product **7a**.

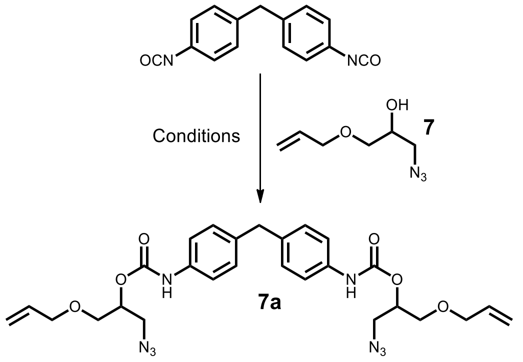


Figure 3.10: Reaction between MDI and 7 to afford 7a.

The catalyst used to promote the reaction between the isocyanate and alcohol was investigated. This investigation involved using triethylamine and dibutyltin dilaurate as catalyst. In both instances the catalyst was not successful in promoting the reaction between **7** and MDI.

The initial hypothesis prepared to explain the failure of **7** to react with MDI was based on the potential for the presence of residual water in **7**. Residual water will react with the diisocyanate. An alternative hypothesis to explain the failure of the reaction between **7** and MDI was suggested by the mass spectrum of **7**, acquired after prolonged storage. This mass spectrum did not show the expected parent ion, and indeed when an NMR spectrum of **7** of the molecule was reacquired it was found that there was significant broadening of the signals at around 3.5 ppm. This broadening suggests the possibility of side reactions, and indicates that **7** is not suitable for further investigations if it is unstable during storage.

3.1.2.1 Preparation of azide-containing molecules: conclusions

The key results and findings arising from the small azide molecule study are as follows:

Nucleophilic substitution of an organic halide with azide is a viable method to prepare organic azides. During the course of the research programme a dihalide based on MDI was converted to the corresponding diazide. A drawback of this chemistry is that there is no active hydrogen to react with isocyanate functional pre-polymers. Therefore, the function of **4** would be solely as a chain-extender for alkyne-functional polyurethane pre-polymers.

An alternative to the nucleophilic substitution of an organic halide with azide is the sodium azide ring-opening of epoxides. One particular benefit of such reactions is that upon introduction of azide functionality, hydroxyl functionality is introduced simultaneously. This hydroxyl functionality is well-suited to reacting with isocyanate functional molecules. In the case of **6,** the two hydroxyl groups in **6** mean that it could be used to replace conventional diols or polyols in the preparation of polyurethane pre-polymers. This approach would introduce azide functionality directly into the backbone of the polyurethane pre-polymer.

The reaction of **7** with MDI proved to be unsuccessful, and this is likely to be down to a number of possible factors, such as increased water content of **7** or side-reactions involving **7**, which would lead to unpredictable reactions with MDI. The strategy remains a viable way to “end-cap” isocyanate terminated polyurethane pre-polymers whilst also introducing azide functionality.

3.1.3 Other azide-functional alcohols and polyols

The sodium azide ring-opening reaction used in the preparation of 7 was extended to two other starting materials, namely *O*-cresyl glycidyl ether and BADGE, to afford 8 and 9, respectively (Figure 3.11).

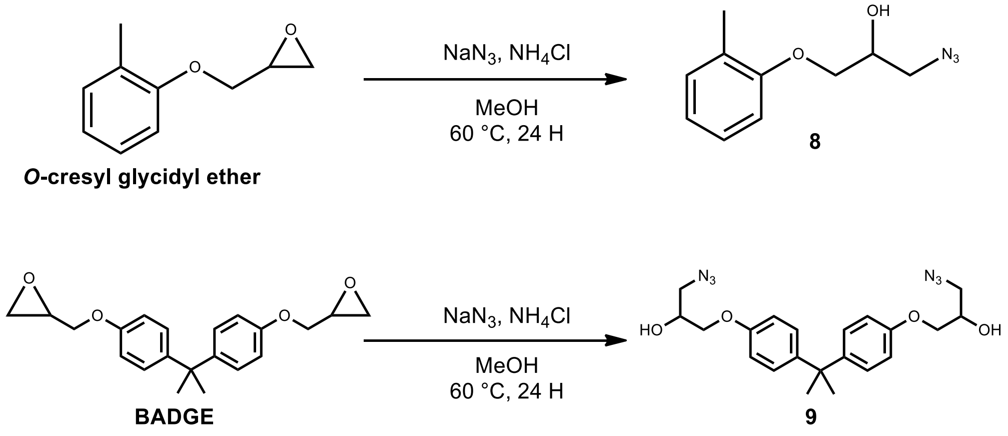


Figure 3.11: Sodium azide ring-opening of O-cresyl glycidyl ether and BADGE.

Both of the azide-functional molecules **8** and **9** were characterised by ^{1}H NMR spectroscopy and FT-IR spectroscopy.

Molecules **8** and **9** both had strong absorption bands at around 2100 cm^{-1} in the FT-IR spectra associated with the presence of the azide moiety. Also present was a broad signal at around 3300 cm^{-1} which is associated with the hydroxyl functionality.

The mono-functional azido alcohol **8** is of particular interest as it could be used as mentioned earlier (Figure 3.7) to end-cap isocyanate functional pre-polymers. More interesting still is the opportunity for **9** to be introduced into the preparation of a polyurethane pre-polymer. The introduction of **9** into a polyurethane pre-polymer is made possible due to the two azido alcohol groups present, which allows for **9** to act as a chain-extender in the preparation of a polyurethane, whilst at the same time introducing azide functionality into the polymer chain.

The sodium azide ring-opening of small azide molecules was extended to poly(propylene glycol) (PPG) diglycidyl ethers to afford two azide polyols, 10 and 11.

Two examples of this reaction were attempted with varying PPG chain lengths (Figure 3.12).

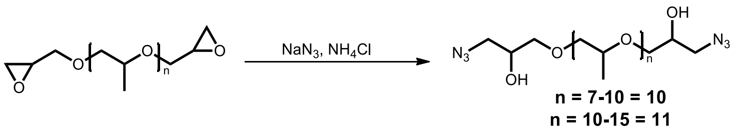


Figure 3.12: Sodium azide ring-opening of PPG diglycidyl ethers.

Both of the attempted reactions resulted in the successful instillation of azide and hydroxyl functionality. These azide and alcohol functional PPGs represent an interesting set of materials. This is because they are analogous to current polyols used to prepare polyurethane pre-polymers, but with the added benefit of introducing azide functionality into the backbone of the pre-polymer.

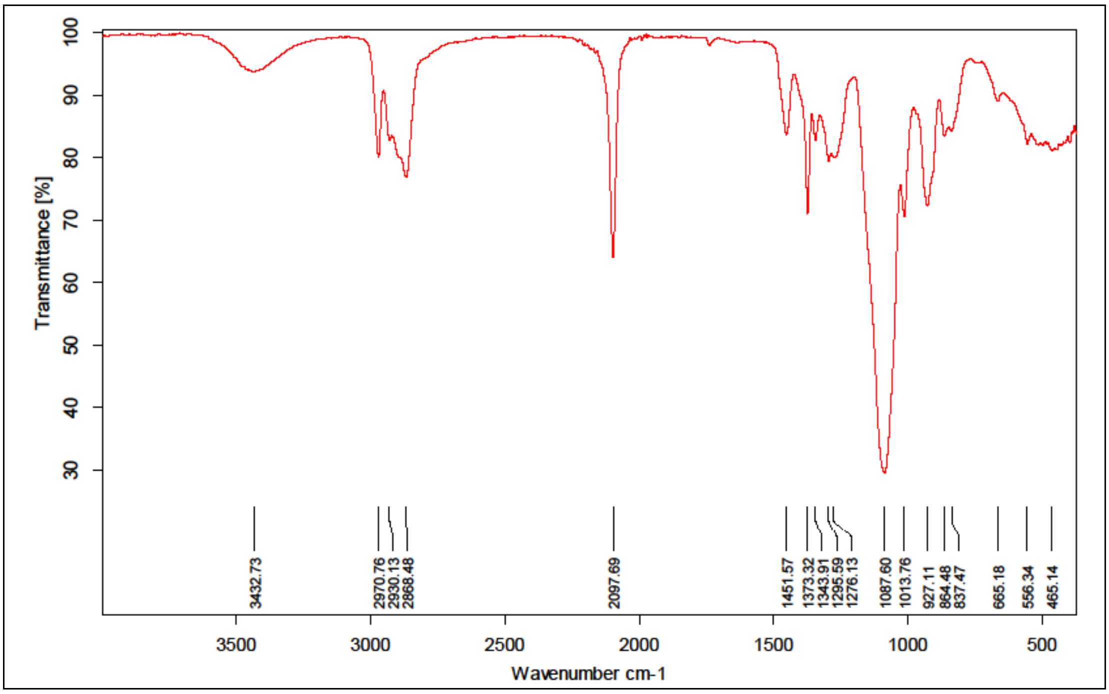


Figure 3.13: The FT-IR spectrum of *bis*-azido polyol based on PPG diglycidyl ether with 7-10 PPG repeat units (10).

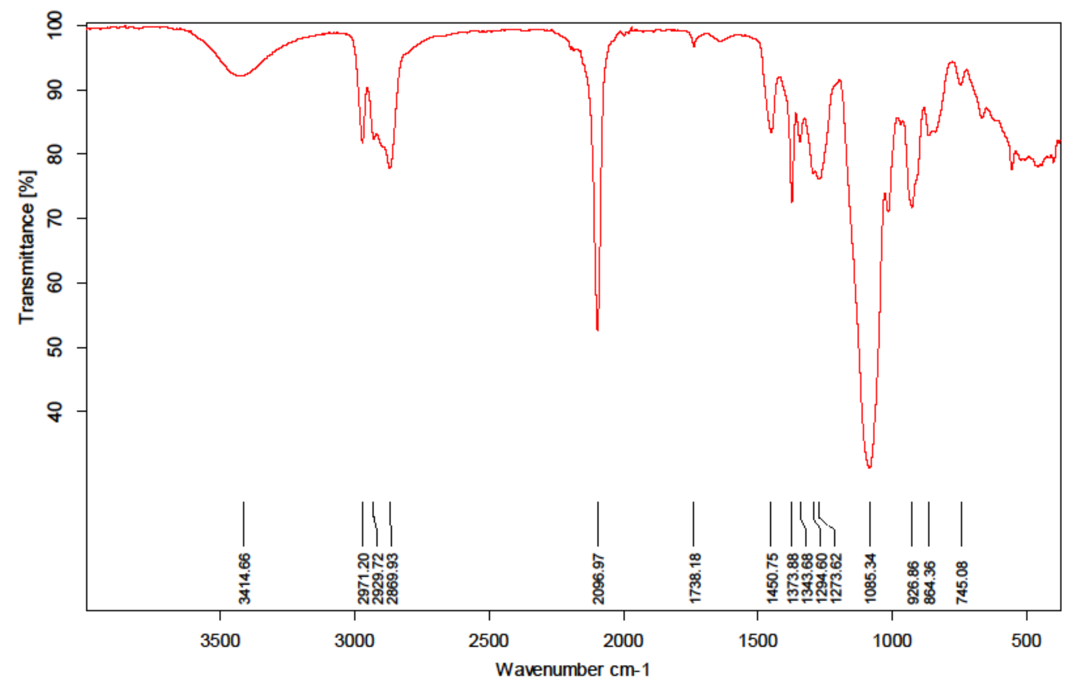


Figure 3.14: The FT-IR spectrum of *bis* azido polyol based on PPG diglycidyl ether with 10-15 PPG repeat units (11).

The FT-IR spectra of the *bis*-azide polyols (Figure 3.13 and Figure 3.14) show intense peaks at 2096 and 2097 cm^{-1}, respectively, which indicates that azide functionality has been inserted successfully.

The azide ring-opening of PPG diglycidyl ethers has been shown to be a rapid route to an azide functional polyol. This azide functional polyol is ideally suited to replacing currently used azide-free polyols. One particular benefit of the azide ring-opening of PPG diglycidyl ethers is the commercial availability of the PPG DGE starting materials.

The preparation of the azide polyols is straightforward. Complications do exist, for example the reaction mixture is purified *via* aqueous work-up. The preparation of the azide polyols also requires three equivalents of sodium azide per epoxide group. This can be problematic as there will be an excess of sodium azide which must be removed, and this is a time-consuming process. In addition, the azide polyol must be worked up *via* a liquid/liquid extraction; this work-up process introduces water into the azide polyol, thus the azide polyol must be dried so that it has a water content of below 500 ppm prior to use, which is another time-consuming step necessary to ensure that the azide polyols are suitable for reaction with isocyanate materials.

General conclusions

The nucleophilic substitution of organic halides with azide has been used to prepare organic azides. The sodium azide ring-opening of both small molecule epoxide-containing molecules and PPG diglycidyl ethers provides a route to hydroxyl functional azide molecules. These azide functional polyols have been found to have applications towards the preparation of azide-containing polyurethane pre-polymers.

3.2 Preparation of azide-functional polyurethanes

3.2.1 Preparation of linear and branched azide-functional polyurethanes

One synthetic strategy towards the preparation of azide-functional polyurethanes involved the use of an azide polyol (**11**). Azide polyol **11** was used in much the same way that a conventional polyol would be used in the preparation of conventional polyurethane pre-polymer (Figure 3.15).

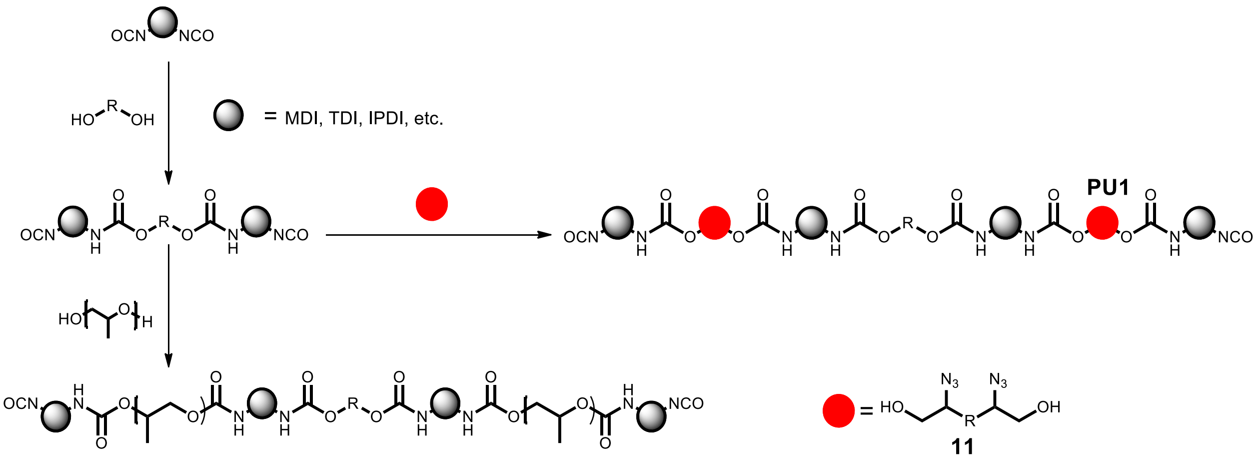


Figure 3.15: Method for preparing a conventional polyurethane pre-polymer and the method for the preparation of a azide-functional polyurethane pre-polymer PU1.

The preparation of **PU1** was accomplished by using **11** in a standard polyurethane synthesis. This process involves the addition of an isocyanate monomer (in this case isophorone diisocyanate, IPDI) along with a chain-extender used to increase the molecular weight. In addition, a polyol is added to provide soft segments in the polymer chain.

In the case of **PU1** (Figure 3.15), the polyol used was the azide functional PPG **11**. The attractiveness of this approach for the preparation of azide-containing polyurethanes is that it involves no significant changes to the pre-polymer process that is currently used on a large scale in the polyurethane industry, besides the addition of an azide-functional polyol (**11**).

One other attractive feature of this process for the preparation of azide-containing polyurethanes is the ease with which the process can be monitored using a simple IR spectrometer. This ease of characterisation is aided by the distinctive signals associated with some of the functional groups especially the azide, urethane carbonyl and the isocyanate functional groups.

It should be noted that in Figure 3.15 the process for the preparation of **PU1** shows an azide-functional polyurethane, but it also has isocyanate functionality. The presence of the isocyanate is unfortunate because the aim of this work is to avoid the presence of isocyanate functionality. It is fortunate, then, that the isocyanate can be reacted with any suitable active hydrogen-containing molecule. The reaction between the isocyanate and the active hydrogen-containing molecule removes the isocyanate functional group and affords an azide-functional polyurethane pre-polymer.

An FT-IR spectrum of **PU1** prior to the end-capping process is shown in Figure 3.16. It can be seen in Figure 3.16 that there is an intense signal at 2259 cm^{-1} ascribable to the isocyanate functional group.

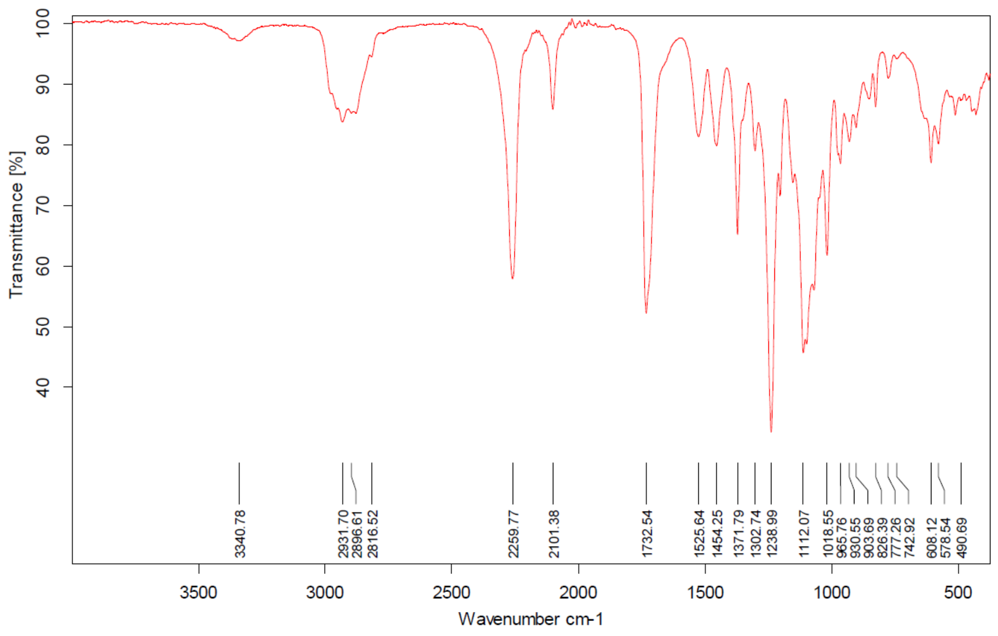


Figure 3.16: PU1 before the end-capping process, showing both isocyanate (2259 cm^{-1}) and azide (2100 cm^{-1}) signals.

Upon reaction of the isocyanate-functional **PU1** with methanol it can be seen that there is a disappearance of the signal in the FT-IR spectrum associated with the isocyanate functional group (Figure 3.17).

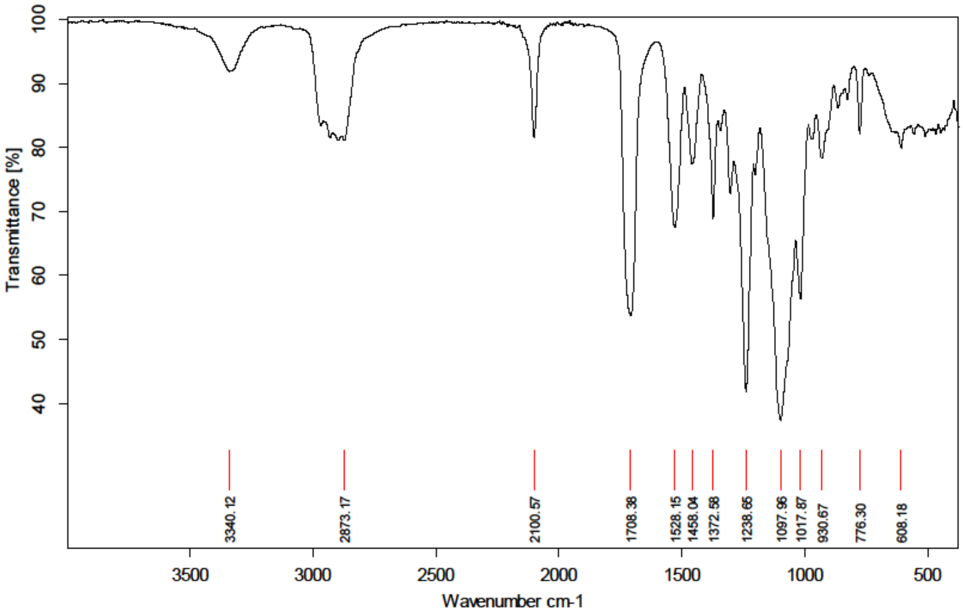


Figure 3.17: PU1 after the end-capping process; signals associated with isocyanate are absent and a signal associated with azide is apparent (2100 cm^{-1}).

The end-capped **PU1** is an example of a linear polyurethane which has azide functionality and more importantly no isocyanate functionality. This was the first azide functional polyurethane pre-polymer prepared during the course of the research programme.

As an alternative to the linear **PU1,** a branched azide-containing polyurethane pre-polymer was prepared using an isocyanate trimer based on IPDI in combination with **11** (Figure 3.18).

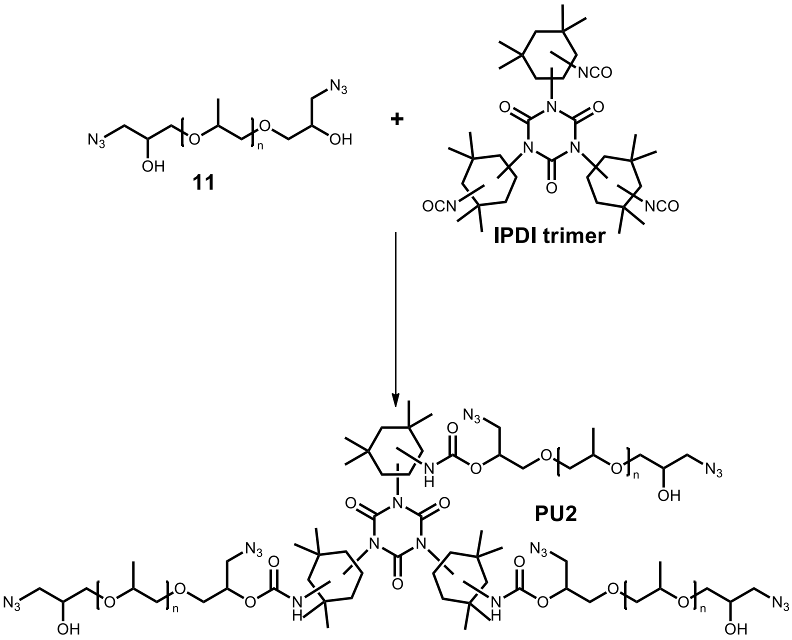


Figure 3.18: Preparation of PU2 using IPDI trimer and 11.

Again, and similar to the situation for **PU1** the conversion of **11** and the IPDI trimer to **PU2** could be tracked easily by monitoring the reaction mixture *via* FT-IR spectroscopy. Upon completion of the reaction it can be seen clearly that there is a signal associated with azide functionality at 2100 cm^{-1} but no signal associated with the isocyanate moiety (Figure 3.19).

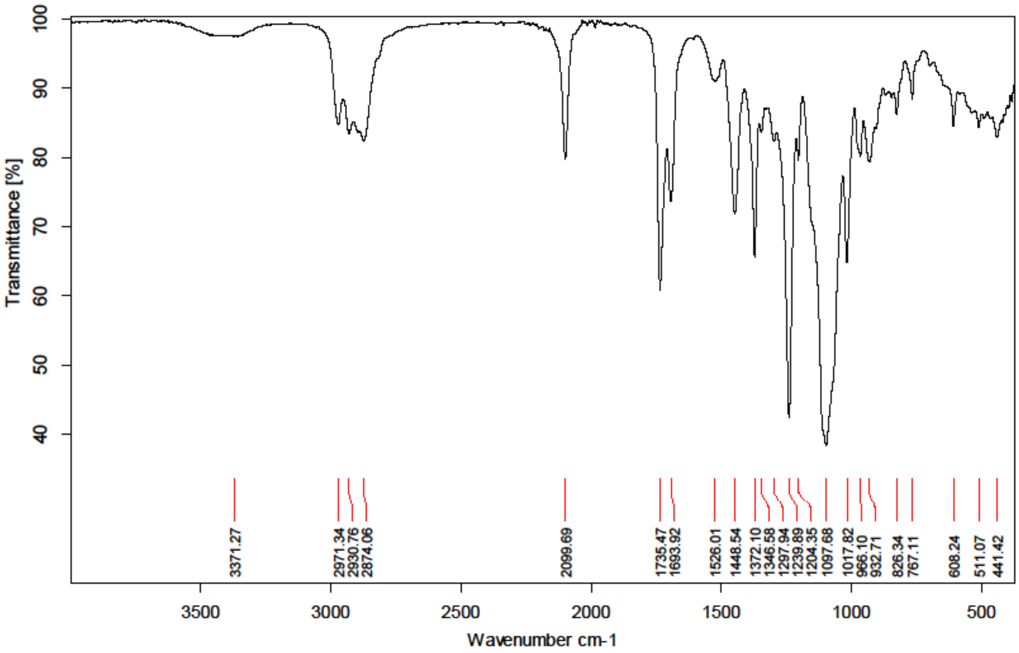


Figure 3.19: FT-IR spectrum of PU2 upon complete reaction of 11 with the IPDI trimer.

General conclusions

The main advantages of these pre-polymers (**PU1** and **PU2**) revolve around the simplicity with which the azide functionality can be introduced into the polymer chains. The synthesis of the newly formed linear azide-containing polyurethane (**PU1**) requires only the substitution of the standard polyol for an azide-functional polyol. In addition, the same polyol used in the preparation of **PU1** can be used in the preparation of the branched **PU2**. Both of the azide-functional polymers are now capable of reacting with alkyne-functional crosslinkers in a Cu-mediated process to afford crosslinked polyurethane polymers where isocyanate is absent completely from the crosslinking process.

3.2.1 “End-capping” strategy towards azide-functional polyurethanes

Step-growth polymerisation was used in the preparation of **PU1**. The step-growth polymerisation allowed for introduction of azide functionality into the backbone of the polymer chain. Alternatively, it was possible to take isocyanate-functional polyurethane pre-polymers and react the isocyanate functional groups present in the pre-polymer with an azido alcohol, such as **8**, in an “end-capping” process (Figure 3.20).

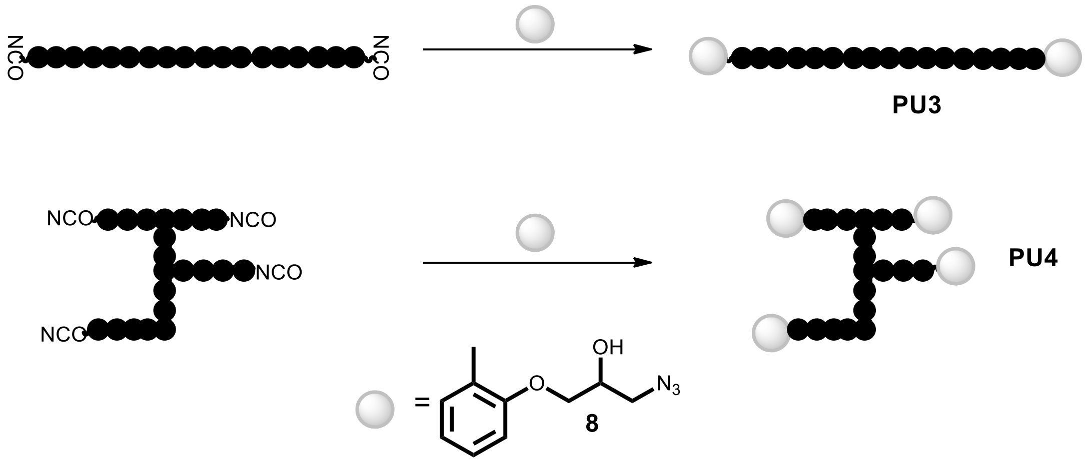


Figure 3.20: “End-capping” strategy for the preparation of azide-functional pre-polymers.

The end-capping process was carried out with linear, isocyanate-containing polyurethane pre-polymer and **8** to afford **PU3**. A similar process was followed using a branched, isocyanate-containing polyurethane pre-polymer and **8** to afford branched, azide-containing polyurethane pre-polymer **PU4**.

Azido alcohol **8** was also used to remove the isocyanate functionality from an IPDI trimer, similar to the process used to prepare **PU2**. The reaction of the IPDI trimer with **8** was tracked easily using FT-IR spectroscopy, and afforded **PU5**.

General conclusions

One attractive feature of this end-capping approach is that it can be applied to any isocyanate-containing pre-polymer. The utility of the end-capping means that it may be possible to take a range of isocyanate-containing pre-polymers, which possess well defined physical and chemical properties, and in one additional synthetic step carry out an end-capping step with an azide-functional alcohol, which ultimately removes the hazardous isocyanate group whilst simultaneously introducing the azide moiety. The azide group can then be used to crosslink polyurethane pre-polymers in an isocyanate-free process. The step-growth polymerisation that afforded **PU1** and **PU2**, along with the end-capping approach that allowed for the preparation of **PU3**, **PU4** and **PU5** led to products with a range of molecular weights and polydispersities ($Đ_M$), as is summarised in Table 3.1.

Table 3.1: Molecular weight and polydispersities of the five azide-functional pre-polymers prepared.

Pre-polymer	Mn	Mw	$Đ_M$
PU1	1590	3370	2.12
PU2	1690	7930	4.69
PU3	1450	3090	2.14
PU4	1360	3950	2.91
PU5	1490	4130	2.80

3.3 Preparation of alkyne-functional molecules

As was stated previously the global aim of the research programme is to investigate alternative routes to non-isocyanate polyurethane coatings. The success of the azide synthesis work has shown that it is possible to introduce azide functionality into a pre-polymer through the use of the azide molecules described in the previous section.

The insertion of azide functionality into polyurethane pre-polymers necessitates the need for multi-functional alkynes to act as crosslinkers. The preparation of multi-functional alkynes using N-alkylation and O-alkylation of a propargyl halide has therefore been investigated as a direct route to multi-functional alkynes.

3.3.1 Preparation of simple alkyne molecules

A multi-functional alkyne was prepared *via* the reaction of aminoethoxy ethanol with propargyl bromide. This reaction resulted in the formation of a di-functional alkyne with hydroxyl functionality (**12**) (Figure 3.21). The hydroxyl functionality of **12** allows for subsequent reactions with diisocyanates.

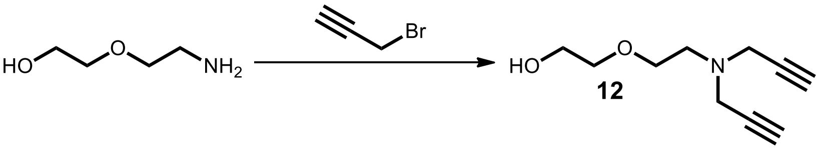


Figure 3.21: N-alkylation of aminoethoxyethanol with propargyl bromide.

The ^{1}H NMR spectrum of **12** shows a doublet (at 3.5 ppm) and a triplet (2.2 ppm) which confirms that the alkyne functionality is present and the reaction to prepare **12** proceeded as planned (Figure 3.22).

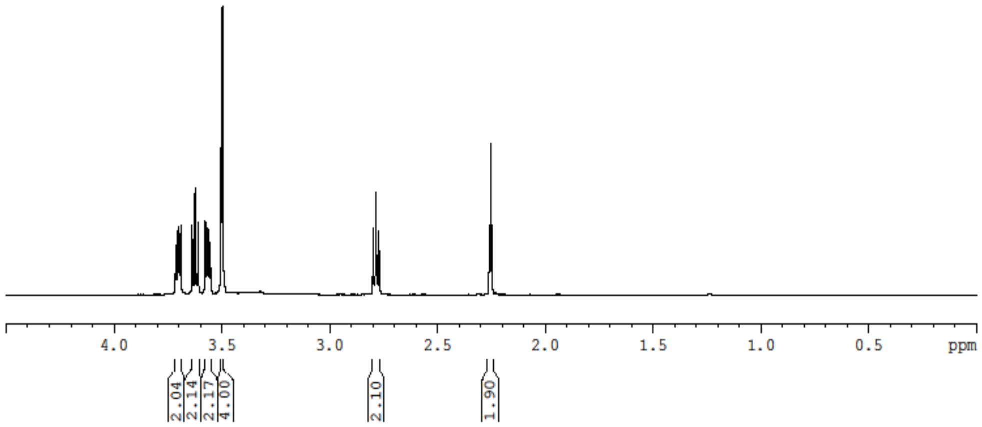
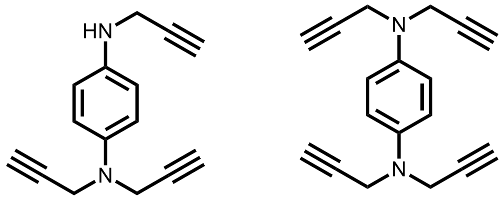


Figure 3.22: ^{1}H NMR spectrum of 12.

N-Alkylation of a multi-functional amine is another possible route towards multi-functional alkynes. This route was investigated using 1,4-phenylene diamine and propargyl bromide. A successful outcome from this reaction would result in a tetra-functional alkyne **14** in one step. In addition, by reducing the number of equivalents it is possible to recover an enhanced amount of the amine functional alkyne **13** (Figure 3.23).



13 **14**

Figure 3.23: Tri- and tetra-functional alkynes prepared from 1,4-phenylenediamine and propargyl bromide.

The secondary amine in **13** is interesting because it can react with a diisocyanate in a 2:1 mole ratio to yield a hexa-functional alkyne.

Similarly, to the N-alkylation chemistry, O-alkylation of propargyl bromide provides direct routes to both small molecule multi-functional alkyne **15** and multi-functional alkynes with hydroxyl functionality **16** (Figure 3.24).

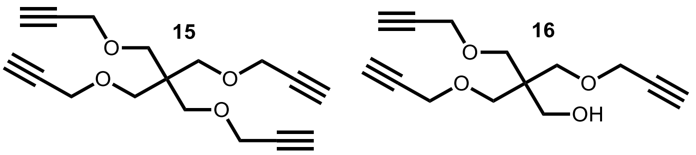


Figure 3.24: O-Alkylation of pentaerythritol with propargyl bromine affords multi-functional alkynes 15 and 16.

Both **15** and **16** can be prepared easily from pentaerythritol and propargyl bromide in good yields. Similarly to molecule **13**, **16** has an active hydrogen containing functional group (OH) which allows for reaction with isocyanate functional molecules.

General conclusions

The N-alkylation and O-alkylation chemistry has proven to be a direct route towards the preparation of multi-functional alkynes. Making use of the reactivity of isocyanates with reactive hydrogen containing molecules, such as 12, 13 and 16, allows for the preparation of small molecule, multi-functional alkynes. This is not the limit of the extent to which 12, 13 and 16 could be applied; the hydroxyl/amine functionality of these molecules would allow for “end-capping” of an isocyanate-tipped polyurethane. This would introduce alkyne functionality to previously prepared polyurethane pre-polymers (Figure 3.25).

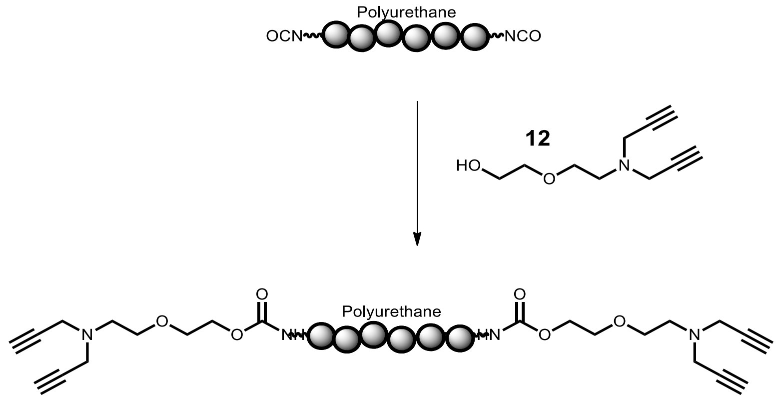


Figure 3.25: A potential “end-capping” strategy that could be carried out with 12 and an isocyanate-functional polyurethane pre-polymer.

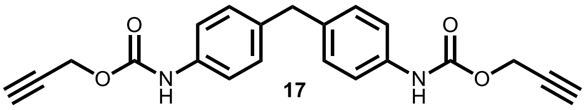
This alkyne functionalization strategy is attractive because it allows for the preparation of polyurethane pre-polymers with well-defined physical properties, but also because upon reaction with a molecule such as **12** the isocyanate functionality is removed together with all the associated hazards that go along with it. Unfortunately, this route loses some of its attractiveness when the need for a small molecule multi-functional azide to act as crosslinker for this type of system is considered.

A drawback of the O-alkylation and N-alkylation strategies is the expense of the propargyl bromide needed to alkylate the amine and alcohol starting materials. This cost may be prohibitive when the chemistry is required to be scaled-up, but does offer routes to a wide variety of alkyne structures that may beneficially alter the properties of any resulting polymeric films.

3.3.2 Preparation of alkyne-containing molecules based on isocyanate starting materials

Monomeric MDI was selected as one starting material because it is a commonly used monomer in the polyurethane industry and because it has a relatively low vapour pressure when compared to other possible monomeric diisocyanate starting materials. This was important as it reduced the risk of exposure to the hazardous isocyanate, and since it is a solid this made the chemical handling operations simpler.

Functionalization of the MDI was accomplished easily; using the high reactivity of the isocyanate group of MDI, it was possible to introduce propargyl alcohol residues (an active hydrogen containing molecule with alkyne functionality) into MDI (Figure 3.26). This approach was beneficial as the coupling reactions involved the formation of a urethane group. The significance of the urethane group is that all subsequent CuAAC click chemistry reactions will be carried out in the presence of urethane groups, and **17** would be representative of the types of functional groups present in crosslinking reactions that the CuAAC click reaction would need to tolerate.



17

Figure 3.26: Alkyne-functional MDI (17).

FT-IR spectroscopy was a convenient method for tracking the conversion of MDI to **17**. A band at around 2,400 cm^{-1} is indicative of an NCO stretch. This band is present in MDI but had disappeared in **17**. In **17** there were also new bands at 1,723 cm^{-1}, assigned to the urethane groups, and 2,115 and 3,292 cm^{-1}, assigned to the alkyne groups.

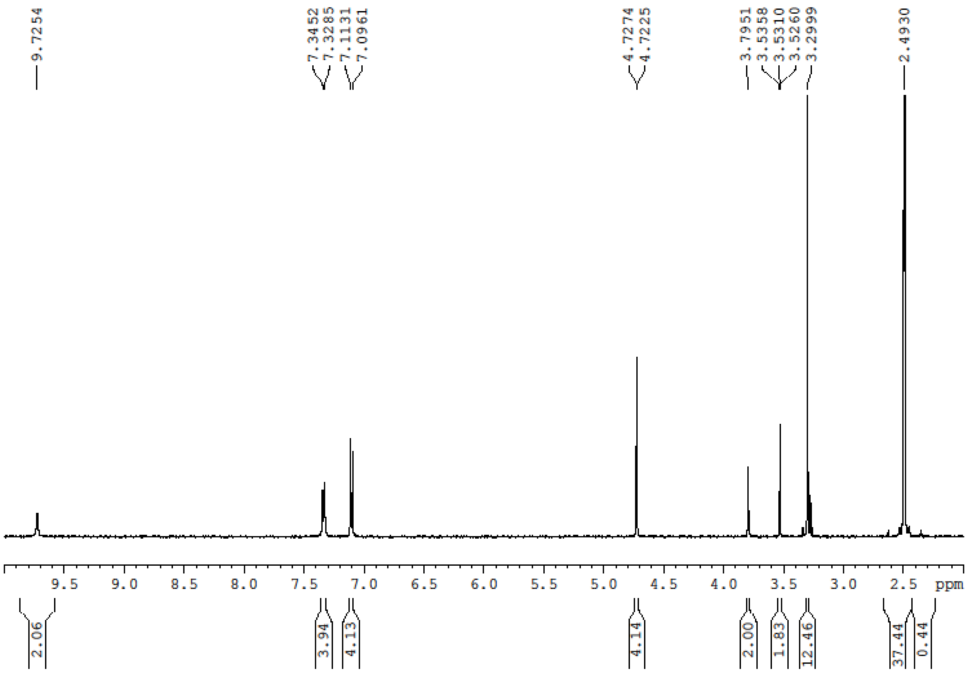


Figure 3.27: ^{1}H NMR spectrum of 17.

The ^{1}H NMR spectrum of **17** (Figure 3.27) clearly supports the incorporation of propargyl alcohol into the MDI molecule. The triplet at 3.53 ppm and the doublet at 4.72 ppm can be assigned to the alkyne residues and methylene groups, respectively. These signals are of particular diagnostic importance because they would be expected to disappear upon formation of a triazole ring in a CuAAC click reaction and be replaced by resonances assignable to a methylene residue with a different chemical shift and a vinyl residue.

Also of interest was the use of alternative solvents for the preparation of **17**. The alternative solvents under investigation were *N*-methylpyrrolidone (NMP), methoxy propyl acetate (MPA) and two naphtha-based solvents. These solvents were of interest as they are used currently in industry for the formulation of polyurethane-based coatings.

In the first instance, the suitability of the solvents listed was investigated for the reaction between propargyl alcohol and MDI to afford **17**. It was found that only methoxy propyl acetate and NMP were suitable for solubilising the MDI starting material (Table 3.2), therefore the reaction between the propargyl alcohol and MDI was carried out in these two solvents but not the others.

Table 3.2: Solubility of MDI, 17 and the click reaction catalysts in various solvents: (✓) soluble and (✗) insoluble.

Reagent / Solvent	MDI	Cu(II) acetate	Triphenyl phosphine	17
NMP	✓	✓	✓	✓
MPA	✓	✓	✓	✓
Naphtha-based solvent (1)	✗	✗	✗	✗
Naphtha-based solvent (2)	✗	✗	✗	✗

The preparation of **17** in MPA proceeded smoothly and in high yields. The ^{1}H NMR spectrum of the resulting product (Figure 3.28) shows all the characteristic signals associated with **17**, including a doublet and triplet at 4.72 and 3.53 ppm, respectively.

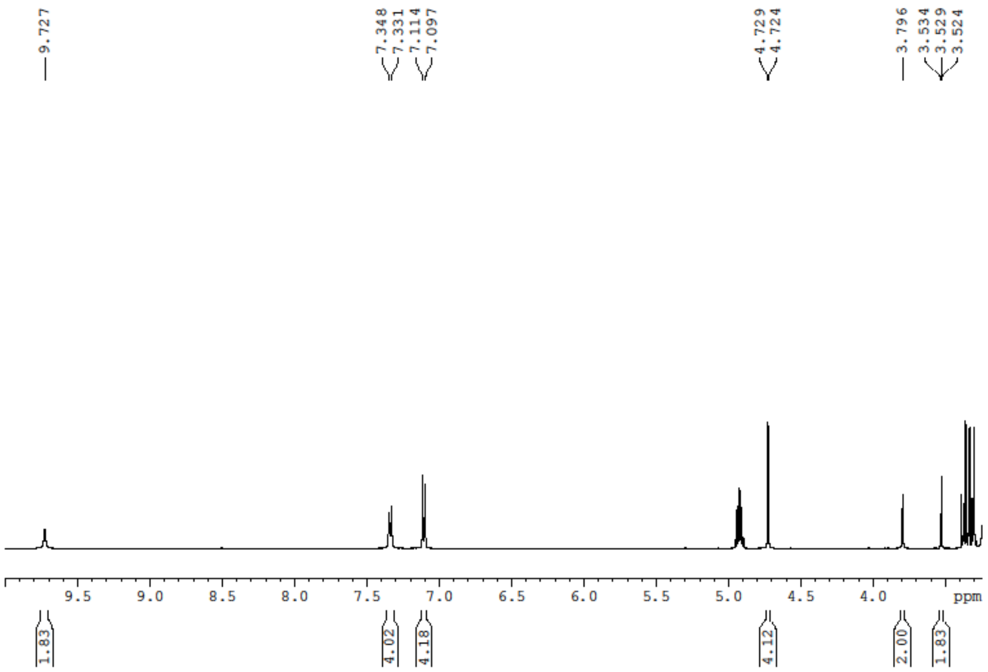


Figure 3.28: ^{1}H NMR spectrum of 17 prepared in MPA.

The ^{1}H NMR spectrum of **17** prepared in NMP (Figure 3.29) showed the characteristic signals at 3.5 and 4.72 ppm; in addition, there was an intense signal at 8.5 ppm. This is likely to be from the reaction of MDI with water which is present in the hygroscopic NMP solvent. Therefore, NMP is not a suitable solvent for the preparation of **17**, due to its hygroscopic nature. This was not an issue with the MPA solvent.

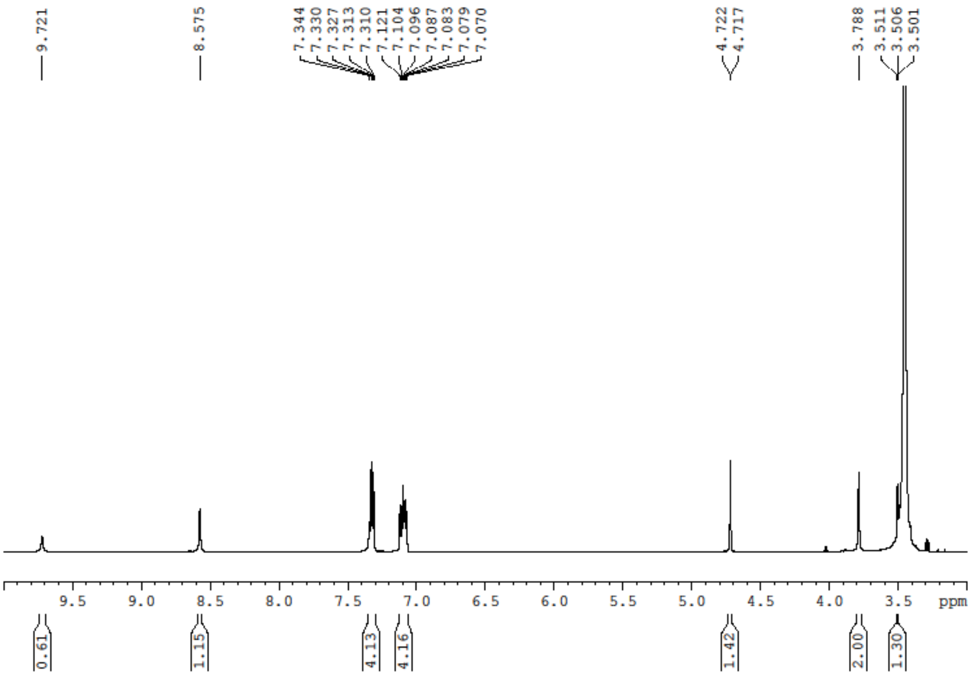
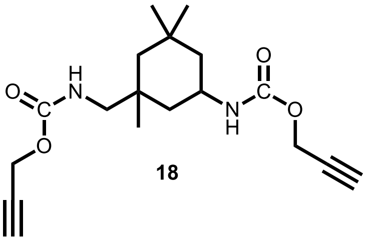


Figure 3.29: ^{1}H NMR spectrum of 17 prepared in NMP, showing a new signal at 8.5 ppm most likely arising from a side-reaction between MDI and residual water present in NMP which generates amine functionality.

As opposed to the aromatic diisocyanate used in the preparation of **17** an aliphatic diisocyanate (IPDI) was investigated in the preparation of an aliphatic-based alkyne molecule (**18**) (Figure 3.30).



18

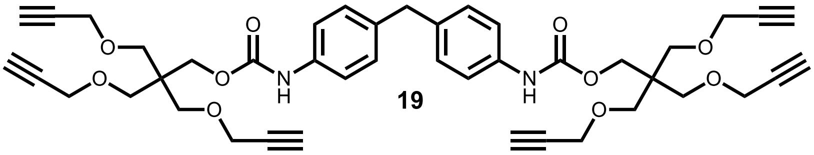
Figure 3.30: Alkyne-functional IPDI (18).

The need for an alternative to the aromatic-based alkyne arises because both aromatic and aliphatic based polyurethanes are used commonly within the polyurethane industrial sector.

The ability to prepare both aromatic (**17**) and aliphatic alkynes (**18**) is encouraging. The alkynes can be prepared easily from commercially available isocyanates and propargyl alcohol. This ease of synthesis and commercial availability is advantageous when compared to the N- and O-alkylation chemistry where the cost of the propargyl halide is prohibitive.

Building upon the difunctional alkynes **17** and **18** discussed, there was a need for multi-functional alkynes, which could be used to crosslink azide-functional polyurethane pre-polymers.

One approach to a multi-functional alkyne involved taking the OH-containing *tri*-functional alkyne **16** and reacting with the isocyanate functionalites in MDI to give **19** (Figure 3.31).



19

Figure 3.31: Hexa-functional alkyne prepared from 16 and MDI monomer.

The reaction product of **16** and MDI provides a route to a hexa-functional alkyne in two steps. This highlights the ease with which the O-alkylation can be used to prepare a range of functional alkynes. This control of functionality is extremely important as it may be critical to the properties exhibited by any PU film derived therefrom.

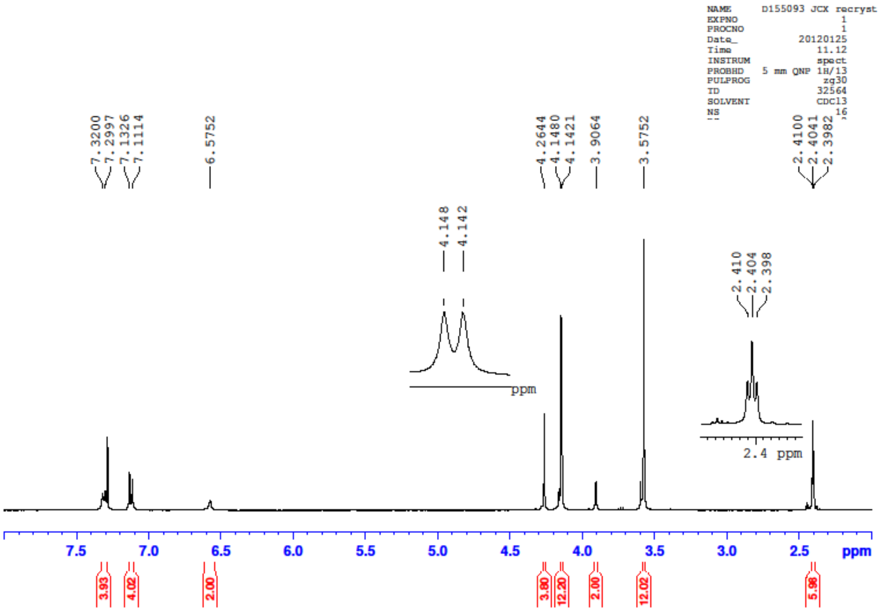


Figure 3.32: ^{1}H NMR spectrum of 19.

The ^{1}H NMR spectrum of **19** (Figure 3.32) shows clearly the doublet and triplet associated with alkyne functionality. The synthetic route to **19** is a relatively quick route to a multi-functional alkyne which is capable of acting as a crosslinker for azide-functional molecules.

The multi-functional alkyne **20** was also prepared easily from **12** and MDI in one step. This is an example of how the N-alkylation chemistry can provide a relatively direct route to a multi-functional alkyne, whilst also exploiting the reactivity of the isocyanate group.

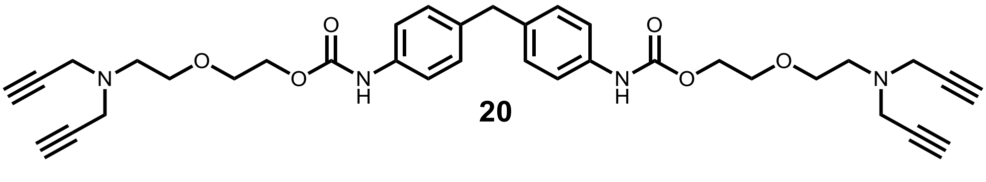
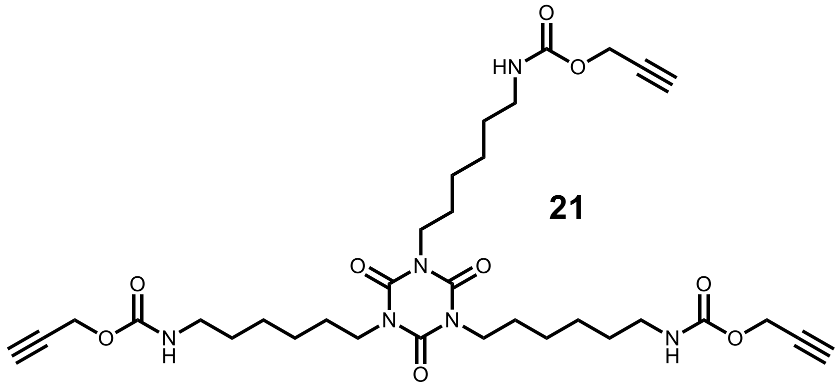

20

Figure 3.33: The preparation of tetra-functional alkyne 20 from 12 and MDI.

The N- and O-alkylation of various staring materials has been shown to be suitable for preparing a range of multi-functional alkynes. Unfortunately, the cost of the propargyl halide alkylating agents is a serious drawback of this route. Alternatively, a more cost-effective route than the alkylation route would be to use propargyl alcohol (which is less expensive and more readily available) in a reaction with a multi-functional isocyanate. This more cost-effective route was used to prepare **21** from hexamethylene diisocyanate (HDI) trimer and propargyl alcohol (Figure 3.34).



21

Figure 3.34: Reaction product of HDI trimer with propargyl alcohol.

Fortunately, due to the presence of the isocyanate group, the reaction between HDI trimer and propargyl alcohol can be tracked easily *via* infra-red spectroscopy and returns a tri-functional alkyne capable of acting as a crosslinker for azide-functional pre-polymers.

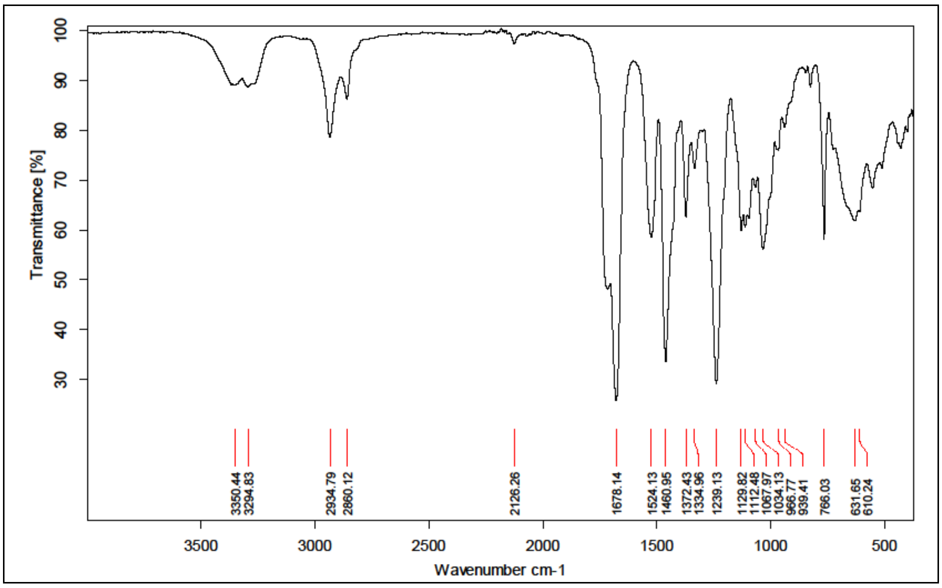


Figure 3.35: FT-IR spectrum of 21 showing peaks at 2126 and 3350 cm^{-1} from the alkyne moiety.

The absence of a peak at around 2200 cm^{-1} indicates that the isocyanate group of the HDI trimer has reacted successfully with propargyl alcohol (Figure 3.35). This finding is supported when the peaks at 2126 and 3350 cm^{-1} are considered; both of these peaks are associated with the presence of the alkyne moieties.

General conclusions

The benefits of this approach include the variety of isocyanate trimers available, which easily allows for facile manipulation of the alkyne-functionality of the crosslinker. In addition, the commercial availability of the isocyanate trimers and propargyl alcohol also increase the attractiveness of this approach compared to the relatively expensive alkylation chemistry described previously.

3.3.3 Preparation of other alkyne-containing molecules

As a preliminary investigation into the preparation of *bis*-alkyne polyols, which could be used to replace currently used polyols, propargyl amine was used to ring-open AGE to give **22** (Figure 3.36). The ultimate aim was to replicate this reaction on the PPG diglycidyl ethers and therefore allow for the preparation of *bis*-alkyne PPG polyols.

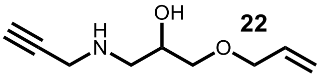

22

Figure 3.36: Reaction product of AGE and propargyl amine to afford alkyne-functional alcohol 22.

A ^{1}H NMR spectrum of the crude product was obtained by extracting the reaction mixture into diethyl ether and removing the diethyl ether solvent under nitrogen purge. The ^{1}H NMR spectrum suggested that the reaction had proceeded as expected (Figure 3.37). It can be seen in the spectrum that there is a broad singlet at 4.7 ppm, and this can be attributed to the secondary amine that is formed upon the successful ring-opening of AGE. In addition, the methine proton of the epoxide group has undergone a significant downfield shift to 3.9 ppm. This is also consistent with successful ring-opening of the epoxide molecule.

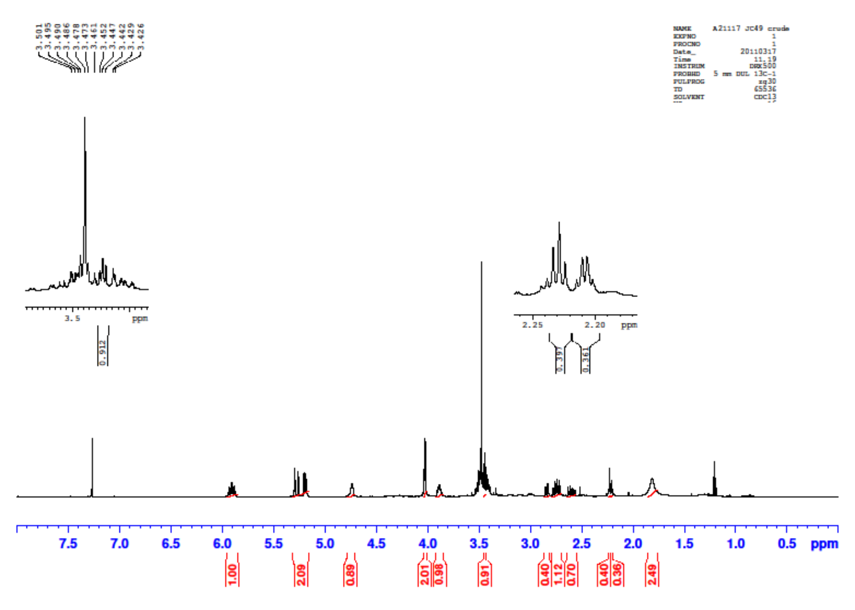


Figure 3.37: ^{1}H NMR spectrum of the crude product arising from the reaction between AGE and propargyl amine.

Further TLC analysis of **22**, which was stored at room temperature for 48 hours at ambient temperature, indicated two different products were present. Flash column chromatography was attempted on **22**, but only one product was isolated in sufficient yield to allow for ^{1}H NMR analysis. The ^{1}H NMR spectrum of the product indicated the disappearance of the broad singlet at 4.7 ppm attributed to the secondary amine proton (Figure 3.37). This disappearance indicates that the secondary amine had undergone reaction with unreacted AGE in the reaction vessel.

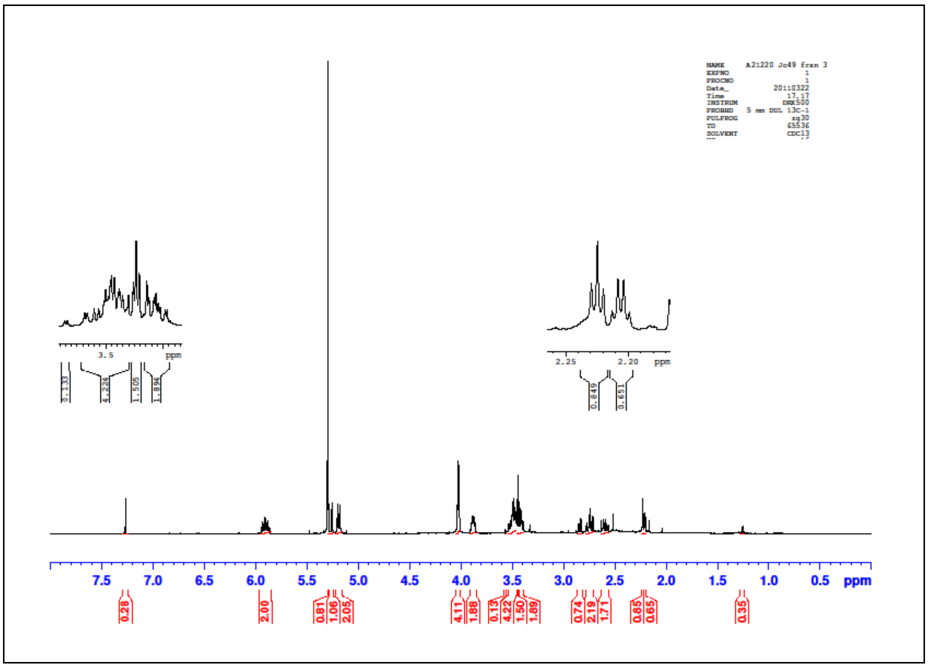


Figure 3. 38: ^{1}H NMR spectrum of one fraction of the columned reaction mixture between AGE and propargyl amine showing the disappearance of the amine signal.

Mass spectrometry and ^{1}H NMR spectroscopy evidence seems to indicate that the reaction has occurred as expected with the M + H mass being found at 170. It also indicates that there were side-reactions occurring in the reaction mixture which was left to react over a weekend. An ion at 284 is indicative of reactions between the secondary amine formed during the epoxide ring-opening and unreacted AGE to afford a diol which has a pendent alkyne group (Figure 3.39).

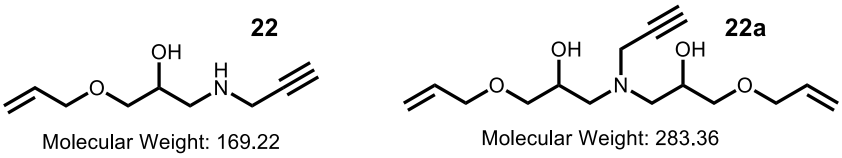


Figure 3.39: Expected product 22 (left) and possible side product 22a (right).

The results of this epoxide-opening with propargyl amine are encouraging; they suggest that the reaction does occur as expected. Unfortunately, due to the extended reaction time there appears to be subsequent reaction of the secondary amine and AGE to afford an unwanted reaction product.

To avoid the formation of the unwanted side products seen in the preparation of **22,** N-methyl propargyl amine was reacted with AGE to afford **23** (Figure 3.40). The benefit of using this amine would be that it could only react with one equivalent of AGE and would avoid any side-products forming. The infra-red spectrum of the reaction product (Figure 3.41) indicated that the reaction had proceeded as expected.

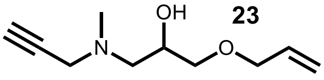


Figure 3.40: Reaction product of AGE and N-methyl propargyl amine.

The signals at 3300 and 2106 cm^{-1} in the FT-IR spectrum are indicative of the presence of alkyne functionality. In addition, the broad signal at 3437 cm^{-1} indicates that N-methyl propargyl amine has reacted with AGE and liberated the hydroxyl functional group.

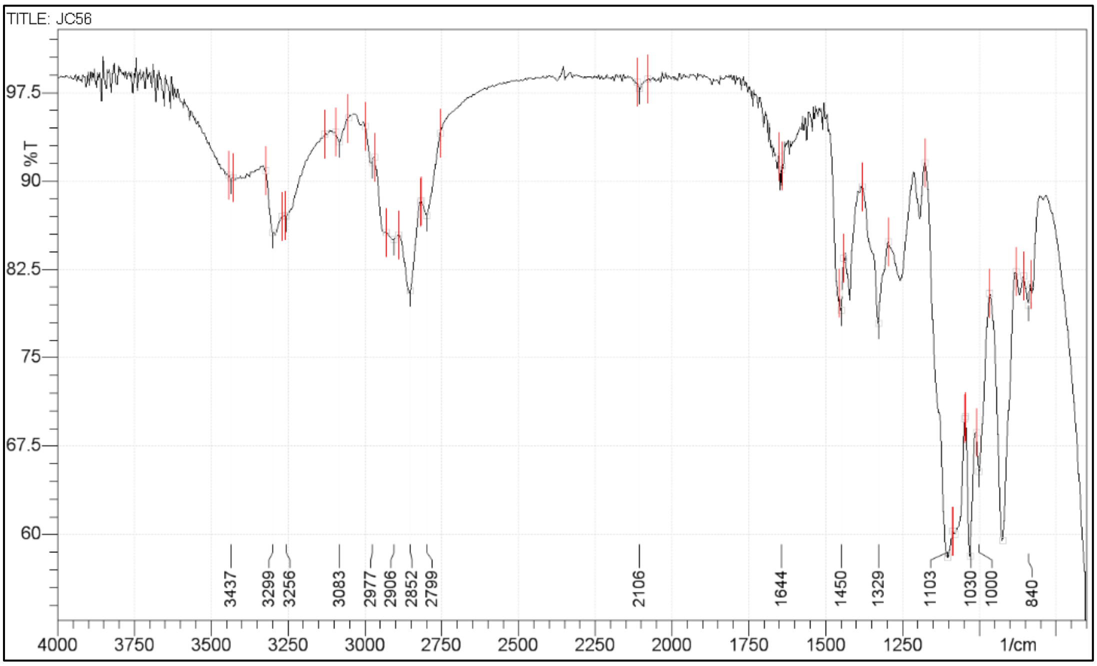
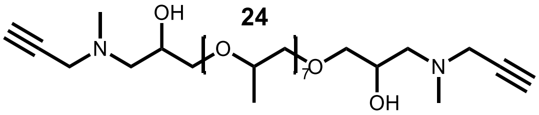


Figure 3.41: FT-IR spectrum of 23 showing peaks associated with alkyne functionality.

N-Methyl propargyl amine was then used to prepare *bis*-alkyne polyols (similar to the azide polyols) from PPG diglycidyl ethers. A successful outcome from such a reaction would allow for the preparation of polyols that possess alkyne functionality such as **24** (Figure 3.42), which could be used to prepare alkyne-functional polyurethane pre-polymers.



24

Figure 3.42: Alkyne polyol 24 prepared from treatment of a PPG polyol with N-methyl propargyl amine.

The infra-red spectrum of **24** does have peaks associated with alkyne groups. The signal at 2100 cm^{-1} is extremely weak, but there is a strong peak at 3300 cm^{-1}. Unfortunately, the MALDI-MS analysis indicated that the reaction had not gone to completion. When compared to MALDI-MS of the PPG diglycidyl ether, it is evident that there is only an increase in mass by 69 mass units. This is consistent with only one epoxide group being opened by N-methyl propargyl amine. These results were disappointing, since if alkyne polyols were to be prepared then complete reaction would be required. In the case of the reaction between N-methyl propargyl amine and PPG diglycidyl ether (Figure 3.42) only 4.2 equivalents of N-methyl propargyl amine were used relative to the PPG diglycidyl ether. It may be the case that a higher number of equivalents of amine and/or extended reaction times will be required for the preparation of *bis*-alkyne polyols.

General conclusions

Mixed results were obtained when using alkyne-functional amines to ring-open both AGE and PPG diglycidyl ethers. The major drawbacks of this route are the need for an excess of the amine reagent. This is unattractive due to the high cost associated with both propargyl amine and N-methyl propargyl amine. Indeed, alternative and more direct routes to alkyne-functional polyurethane pre-polymers could be completed by “end-capping” of isocyanate-tipped polyurethane pre-polymers.

3.3.4 Preparation of alkyne-containing molecules: conclusions

A range of multi-functional alkynes have been prepared, which vary in terms of structural complexity and functionality. The multi-functional alkynes can be used in a variety of ways, from “end-capping” of isocyanate-tipped polyurethane pre-polymers, to being used to build up a polyurethane pre-polymer with alkyne functionality and acting as multi-functional alkynes to crosslink non-isocyanate azide functional pre-polymers.

The range of materials which has been prepared with ease is extremely encouraging. It will ultimately allow for a flexible approach to formulation of the physical properties of any liquid-applied membrane which includes these alkynes in its formulation.

3.4 CuAAC click reactions

The reaction between **17** and benzyl azide (Figure 3.43) was selected as a model reaction for developing a base of knowledge on CuAAC click chemistry. **17** is based on MDI, which is a monomer used commonly in the polyurethane industry, and therefore begins to reflect the types of monomers that the CuAAC click chemistry must be tolerant of. Another beneficial aspect of selecting **17** as a model was the ease with which the successful conversion of **17** to **25** could be tracked *via* ^{1}H NMR spectroscopy (Figure 3.44).

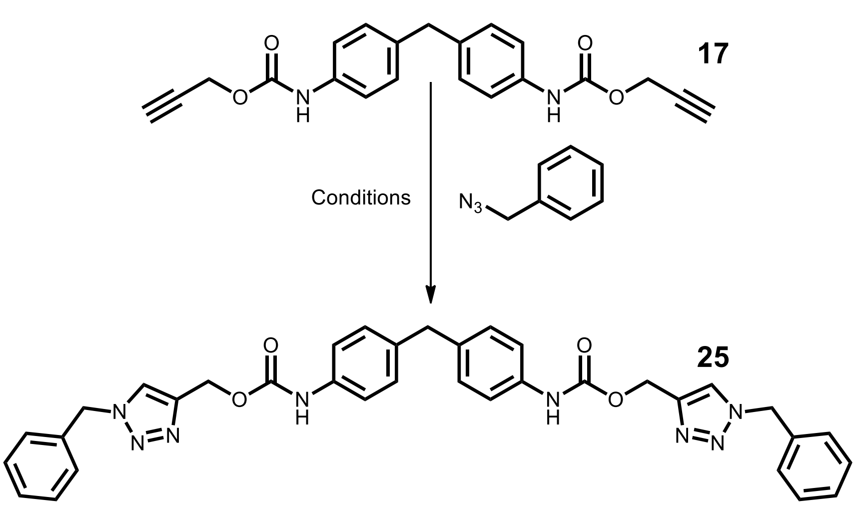


Figure 3.43: The model CuAAC system used to investigate a range of reaction conditions.

Figure 3.44 shows a comparison of the ^{1}H NMR spectra of **17** and **25**. It can be seen that upon completion of the CuAAC click reaction there are three new key signals appearing in the NMR spectrum. The signals at 5.16 and 5.56 ppm are indicative of the formation of the triazole ring, as is the signal at 8.23 ppm. Also indicative of the formation of the triazole ring is the disappearance of the triplet signal at 3.52 ppm assigned to the terminal alkyne proton of **17** (inset, Figure 3.44). Tracking these changes in the spectra provided a convenient method for monitoring conversions over time as **17** was converted to its triazole derivative **(25)**.

Figure 3.44: ^{1}H NMR spectra of 17 and 25, showing clearly the disappearance and appearance of a number of diagnostic signals, which is useful for determining conversion w.r.t time.

Practical CuAAC work began by looking at CuBr as the catalyst for the click reaction between **17** and benzyl azide, in DMSO, and at room temperature. A CuBr catalyst loading of 10 mol% relative to **17** was investigated. In addition, lutidine was used as a base to co-ordinate to the Cu(I) centre and protect it from oxidation. Unfortunately, the CuBr-catalysed reaction between benzyl azide and **17** was found to be extremely sluggish, even with extended reaction times in excess of 15 hours. Initially, it was suspected that this was due to the poor solubility of CuBr in DMSO, therefore a number of other solvents were investigated, including DMF, THF and MEK. The catalyst loading was increased from 10 to 20 mol% in all of these alternative solvents, however there was little or no conversion of **17** to **25** even after 24 hours reaction time. After 24 hours the reaction vessels were heated at 60 °C for 4 hours, and it was only then that characteristic signals at 5.15 and 5.56 ppm became apparent in the ^{1}H NMR spectra of the crude reaction mixtures (Figure 3.45).

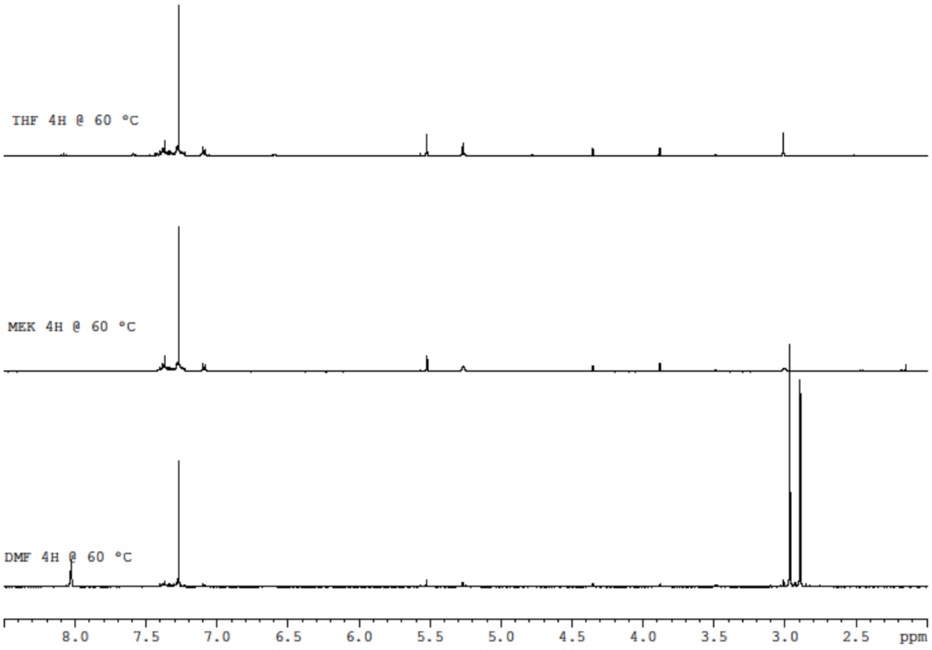


Figure 3.45: ^{1}H NMR spectra showing the appearance of signals at ~ 5.1 and 5.5 ppm associated with triazole formation upon the heating at 60 °C.

This was a rather disappointing outcome, since it seemed that with CuBr as the catalyst the CuAAC click reactions only proceeded at elevated temperatures. Given that one of the goals of the research was to evolve a click reaction that would proceed to high conversion in short timescales at sub-ambient temperatures, an alternative catalyst system was sought.

Attention was transferred to copper(II) sulphate in conjunction with sodium ascorbate as a reducing agent.[134] The loading level of the catalyst was fixed initially at 2 mol% relative to **17**, but unfortunately it was found that at this catalyst loading the conversion of **17** to **25** was negligible; therefore, the catalyst loading was increased to 20 mol% and the crude reaction mixture analysed by NMR spectroscopy (Figure 3.46).

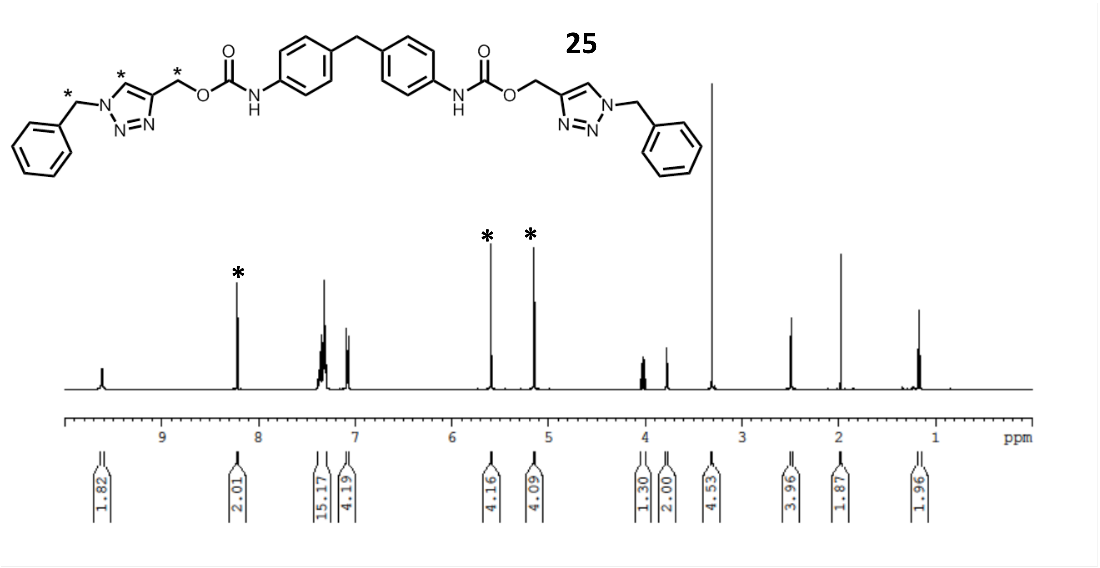


Figure 3.46: ^{1}H NMR spectrum of a crude reaction mixture showing conversion of 17 to 25 after 14 hours with Cu(II) sulphate as catalyst; triazole signals are evident at 5.15 and 5.56 ppm.

This change to the catalyst loading returned a reasonable conversion of **17** to **25** of 55% after 14 hours. This was the first promising conversion, on a reasonable timescale, of **17** to **25** at room temperature. In Figure 3.46 it can be seen that the diagnostic signals consistent with the formation of the triazole ring are present at 5.15, 5.56 and 8.21 ppm.

Although the Cu(II) sulphate/sodium ascorbate catalyst system showed signs of promise, it was hoped that the click reaction would have proceeded to higher conversion within a shorter period of time. Therefore, a more thorough literature review was carried out, and this review highlighted the use of the simple Cu(II) acetate/triphenylphosphine catalyst system.[43] This catalyst system led to a step-change in reaction rate. Using a 10 mol% loading of Cu(II) acetate, it was found that conversion of **17** to **25** was approaching 75% after only 90 minutes (Figure 3.47).

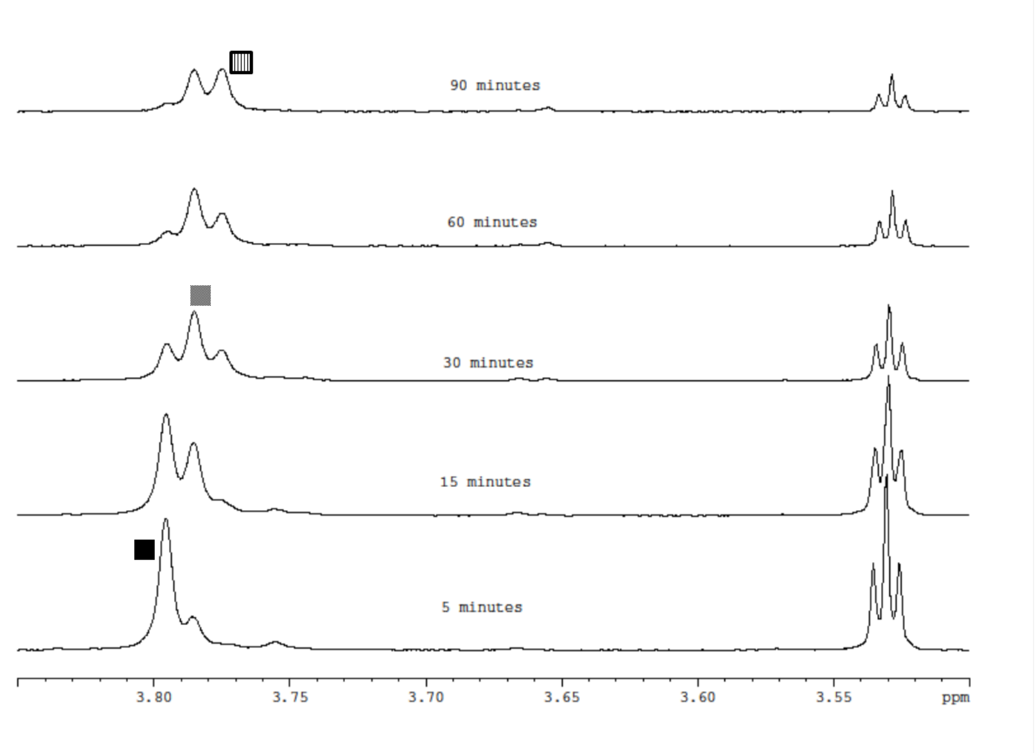


Figure 3.47: ^{1}H NMR spectra showing the conversion of 17 (black box) to 25 (lined box) *via* 17a (dotted box) over 90 minutes with the Cu(II) acetate catalyst system.

The singlet centred at around 3.80 ppm (Figure 3.47 and Figure 3.48) is assigned to the two protons of the methylene bridge between the aromatic rings of the alkyne end-capped MDI starting material. This signal shifts upfield as the unsubstituted starting material (black box) is converted to the mono- and di-substituted triazole-containing compounds (dotted box and lined box, respectively) (Figure 3.47).

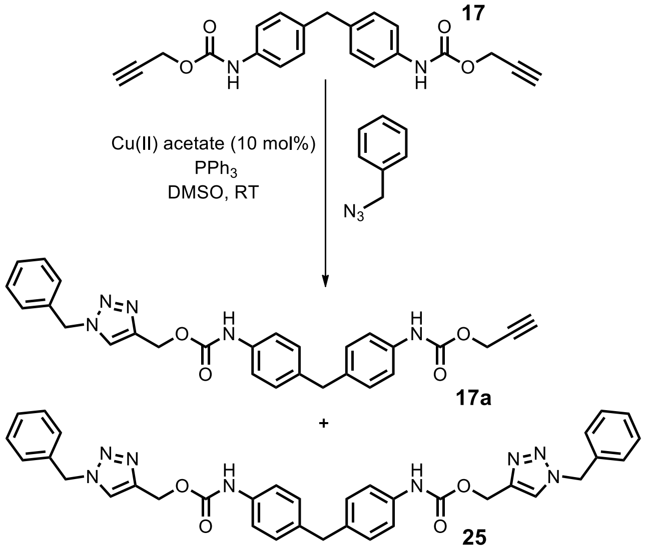


Figure 3.48: Possible products of the Cu(II) acetate catalysed reaction.

From the ^{1}H NMR spectra it appears that there is formation of the mono-substituted product, which is then gradually converted to the disubstituted product. After five minutes of reaction time there is no signal associated with the disubstituted product. In addition, it can be seen that after 90 minutes there is very little of the starting material remaining and an approximately equal amount of the mono- and disubstituted products.

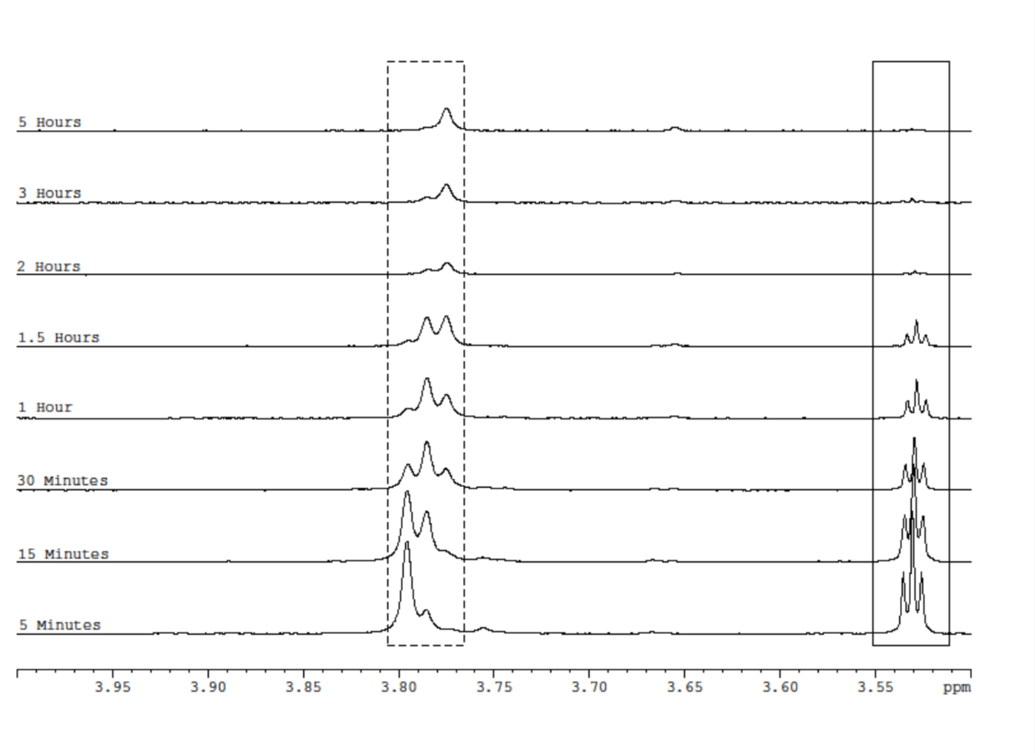


Figure 3.49: ^{1}H NMR spectra showing the conversion of 17 to 25 (dashed line) and the disappearance of the triplet of the alkyne group (solid line).

Figure 3.49 shows a 10 mol% reaction timed to 5 hours; it also indicates the formation of **17a** (Figure 3.50) before going on to form the *bis*triazole **25** in a stepwise manner. This shows that after approximately 2-5 hours the triplet signal of the alkyne group has almost disappeared, and that there is only one signal associated with **25**. The 10 mol% Cu(II) acetate reaction was repeated and, after column chromatography, **25** was recovered in a yield of 73%. In addition, some of the monosubstituted **17a** was recovered.

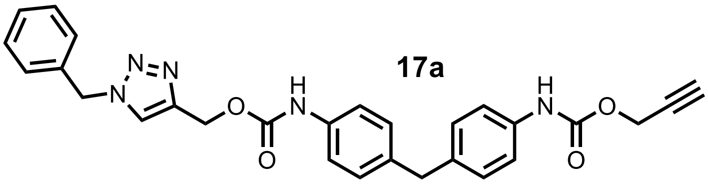


Figure 3.50: Monosubstituted 17a.

The click reaction between **17** and benzyl azide was repeated with a 1 mol% loading of the Cu catalyst. After 6 hours, there was some unreacted starting material returned, and the predominant product was the monosubstituted **17a** (Figure 3.51).

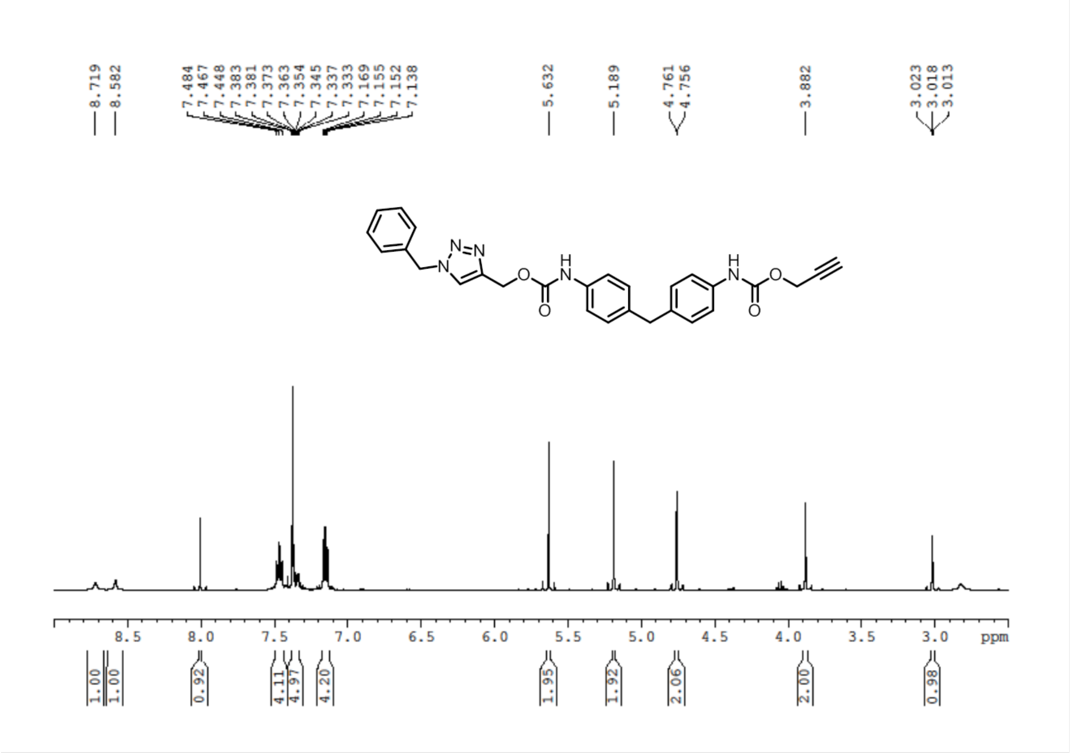


Figure 3.51: ^{1}H NMR spectrum of monosubstituted 17a

The ^{1}H NMR spectrum of monosubstitued **17a** (Figure 3.51) shows a number of key signals that can be assigned to functional groups within the molecule. There are two downfield signals at 9.73 and 9.66 ppm; these are assigned to the substituted and non-substituted protons of the urethane linkages at the substituted and non-substituted sides of the molecule. In addition, there is a signal at 8.2 ppm which is assigned to the proton of the triazole linkage. This integrates to one proton, indicating that only one triazole linkage has formed. In addition, a triplet and doublet associated with the unreacted alkyne functional group on **17** are apparent, as well as two new signals at 5.15 and 5.60 ppm associated with triazole formation.

The 1 mol% catalyst loading reaction returned none of the **25** product. This is in good agreement with the conversions noted for a 1 mol% loading of Cu(II) acetate catalyst, which showed negligible conversion of **17** to **25** after 90 minutes. This is in contrast to the 10 and 5 mol % reactions which show reasonable-to-good conversions after the same reaction time (75 and 82%, respectively).

It is interesting to note that there is an increased conversion of **17** to **25** when the catalyst concentration is dropped from 10 to 5 mol%. This may be due to the formation of copper aggregates as the concentration of the Cu catalyst is increased.[41] It is also interesting to note that there is very little conversion of **17** to **25** after 90 minutes when the catalyst loading is held at 1 mol %. This is quite surprising, since with a 5 mol% catalyst on the same timescale the conversion is good. This could be in part due to the ability of triazole molecules to co-ordinate to Cu.[42] This is not an issue for the higher loadings of catalyst, but as the concentration of catalyst is decreased it leaves less Cu free to catalyse the click reaction as the triazoles are beginning to form.

Based on the poor conversion of the 1 mol% Cu(II) acetate reaction it was decided to repeat the experiment with tetradentate *tris*(benzyltriazolylmethyl)amine (TBTA).**[42]** The structure of TBTA promotes electron density on the copper centre whilst also increasing the solubility of the metal in organic solvents and protecting it from oxidation. However, it was found that the addition of TBTA had no significant effect on the conversion of **17** to **25**; the conversion was only around 3% after 90 minutes.

The effect of the reaction temperature on the CuAAC click reaction between **17** and benzyl azide was investigated using a 10 mol% loading of Cu(II) acetate and triphenylphosphine as reducing agent. The reaction vessel was immersed in an ice/water bath. Since DMSO is not a suitable solvent for reactions below room temperature (m.pt. of DMSO = 16-19 °C), one reaction was carried out in ethyl acetate and the other in DMF.

For the reaction carried out in ethyl acetate, it was noted that at sub-ambient temperature conditions there is very little product formation. In contrast, for the reaction carried out under the same conditions, but with DMF as solvent, there was significant conversion of the alkyne functionality into the triazole (44% conversion after only 90 minutes). This further highlights the utility of the Cu(II) acetate catalyst system, even when operating at sub-ambient temperatures. One caveat to bear in mind is that no reaction was observed when ethyl acetate was used as reaction solvent, indicating that the solvent plays a significant role in the successful completion of the click reaction.

The reducing agent in all the previous Cu(II) acetate reactions was triphenylphosphine. One potential drawback of this reducing agent is the formation of triphenylphosphine oxide, a side-product which can be difficult to remove from the final product. If the formation of triphenylphosphine oxide proves to be an issue in the longer term, there would be a need for an alternative reducing agent.

To this end, sodium ascorbate was used with Cu(II) acetate. The loading of the Cu(II) acetate was kept constant at 5 mol% and the sodium ascorbate was added at 10 mol %. Unfortunately, it was found that there was a decrease in reactivity when the reducing agent was changed to sodium ascorbate. In fact, only 10% conversion of **17** to **25** was observed after 1.5 hours, compared to 82% conversion when the reducing agent was kept as triphenylphosphine (also at a 5 mol% loading of Cu(II) acetate). After six hours, the conversion was increased to 56%. All reactions were carried out at room temperature, with DMSO as solvent.

Also of interest was the use of alternative solvents as reaction media for the conversion of **17** to **25.** The alternative solvents under investigation were *N*-methylpyrrolidone (NMP) and methoxy propyl acetate (MPA). These solvents were investigated as reaction media for the click reaction between **17** and benzyl azide. The Cu(II) acetate catalyst was kept at a 10 mol% loading in both solvents. It was found that NMP was as good as DMSO as a reaction solvent, affording full conversion of **17** to **25** within five hours. The conversion of **17** to **25** was more modest in MPA; 69% conversion within five hours.

Based on the promising results with MPA as reaction solvent for the preparation of **17** and the click reaction, a “one-pot” process was attempted, were MPA would act as the solvent for both the preparation of **17** and the conversion of **17** to **25**. Alkyne-functional **17** was prepared *via* the reaction between MDI and propargyl alcohol, in the absence of any triethylamine catalyst at 60 °C for four hours. A sample of the crude reaction mixture was then treated with benzyl azide for one hour, in the presence of a 10 mol% loading of Cu(II) acetate, to afford **25**. A ^{1}H NMR spectrum of the resulting product (Figure 3.52) shows the characteristic signals for **25** at 5.15, 5.56 and 8.2 ppm suggesting, the successful preparation of **17** and showing that the subsequent CuAAC click reaction proceeded smoothly to yield **25**.

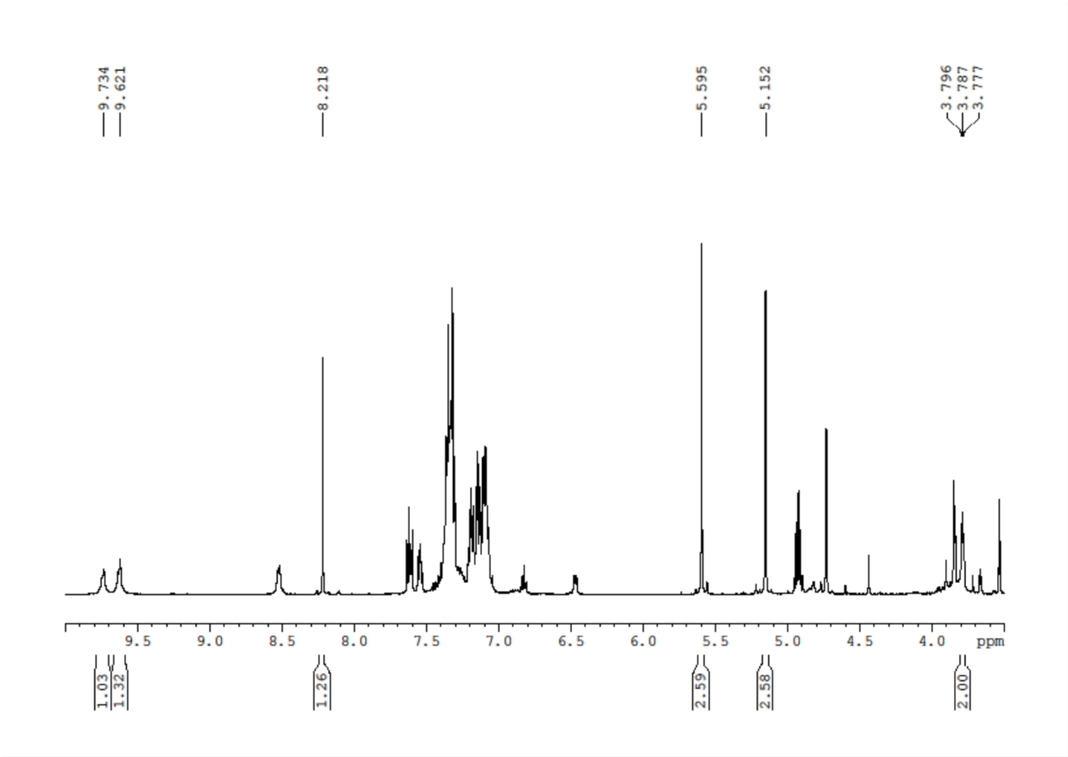


Figure 3.52: ^{1}H NMR spectrum of the product from the "one-pot" process, showing the characteristic signals at 5.15, 5.56 and 8.20 ppm which indicate that the triazole has formed successfully.

General conclusions

The alkyne-containing molecule **17** has been investigated in a number of CuAAC click reactions. Initial click reactions using CuBr and Cu(II) sulphate as catalyst were found to be sluggish, and one of the major successes was the use of a Cu(II) acetate catalyst system to afford good conversions of alkyne and azide to triazole in relatively short periods of time. The conversion of the alkyne and azide to triazole has been shown to be conveniently monitored *via* ^{1}H NMR spectroscopy. In addition, a model system has been used to gain an understanding of the various reaction variables, such as temperature and catalyst loading. This work was used to provide a springboard for the next phase of research. The Cu(II) acetate system will be used in future work with more complex polymeric systems.

3.5 Preparation of oligomeric azides and alkynes

A range of azide- and alkyne-functional molecules have been prepared. Some of these materials are suited for use in the preparation of polyurethane pre-polymers which contain azide or alkyne functionality. Other materials are designed for use as crosslinkers for these azide or alkyne functional pre-polymers.

Azide-containing pre-polymers are the most attractive of the systems to pursue; this is because the presence of azide in the pre-polymer reduces the hazards normally associated with the azide functional group. An alternative approach was to functionalise polyurethane pre-polymers with alkyne functional groups. The alkyne functionalization was investigated in the first instance.

3.5.1 CuAAC click reactions of oligomeric azides and alkynes

Prior to the preparation of azide-functional pre-polymers, an alkyne-containing oligomer and monomer were prepared. The alkyne functional monomer was prepared from isophorone diisocyanate (IPDI) and propargyl alcohol to afford 18 (Figure 3.30). The oligomeric system was prepared using a PPG polyol in combination with IPDI and propargyl alcohol (Figure 3.53).

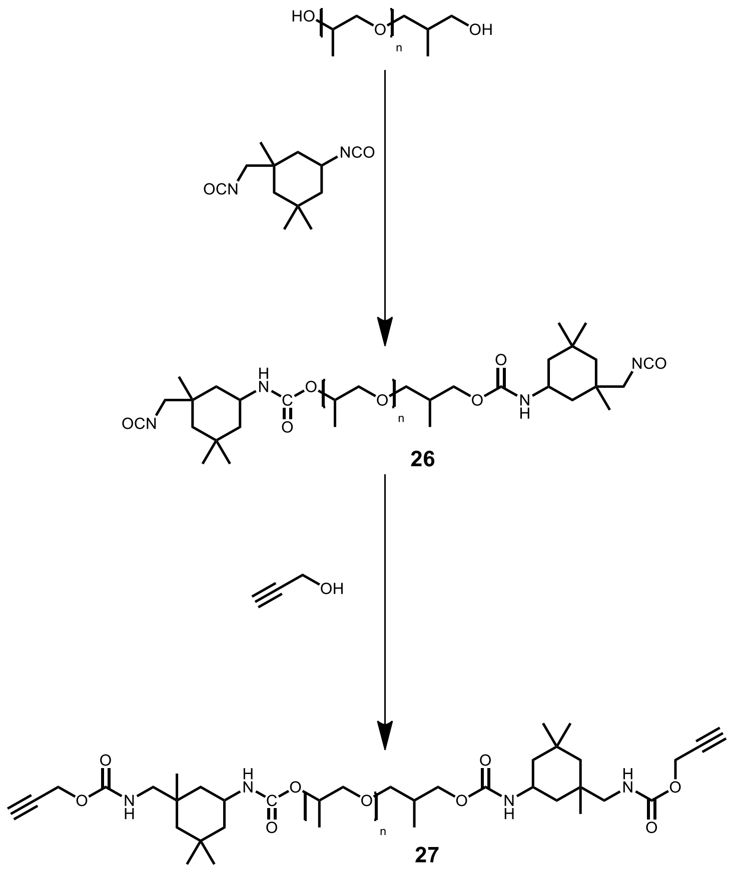


Figure 3.53: Preparation of alkyne-functional IPDI oligomer 27.

IPDI was used as a starting material and as a key part of the oligomer formation as it is a commonly used monomer for the preparation of polyurethane pre-polymers. In addition, it is the first aliphatic diisocyanate monomer used to investigate the CuAAC chemistry in the course of this work.

The ^{1}H NMR spectra of the resulting aliphatic products **18** and **27** were complicated by the aliphatic nature of IPDI, and this complexity was heightened by the fact that industrial sources of IPDI were used. This use of industrial quality IPDI may be responsible for introducing unexpected signals in the NMR spectra. It is because of these extra signals that it is difficult to fully assign the ^{1}H NMR spectra of both **18** and **27**. Fortunately, it is possible to assign peaks in the ^{1}H NMR spectrum for both **18** and **27** that are likely to arise from the presence of alkyne functionality.

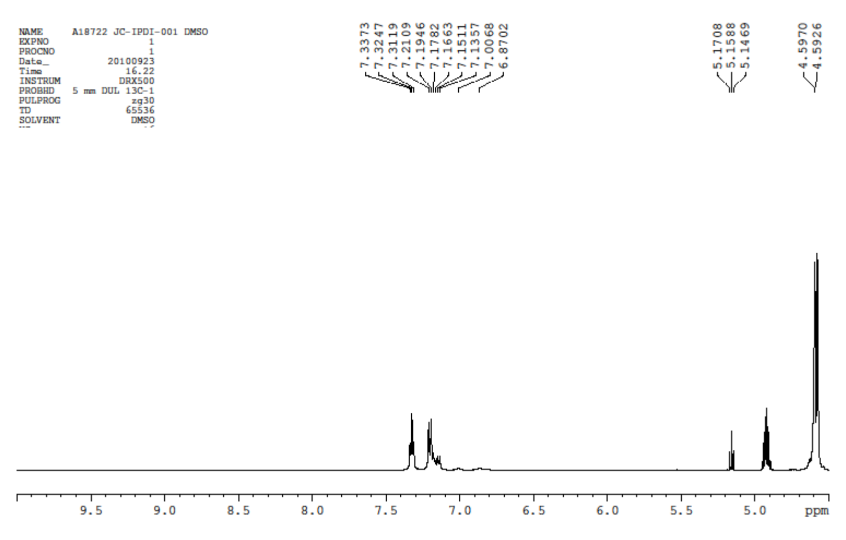


Figure 3.54: ^{1}H NMR spectrum of 18.

The signals at around 4.5 ppm are likely to be from the alkyne functional group (Figure 3.54), and these signals are mirrored in the ^{1}H NMR spectrum of **27** (Figure 3.55).

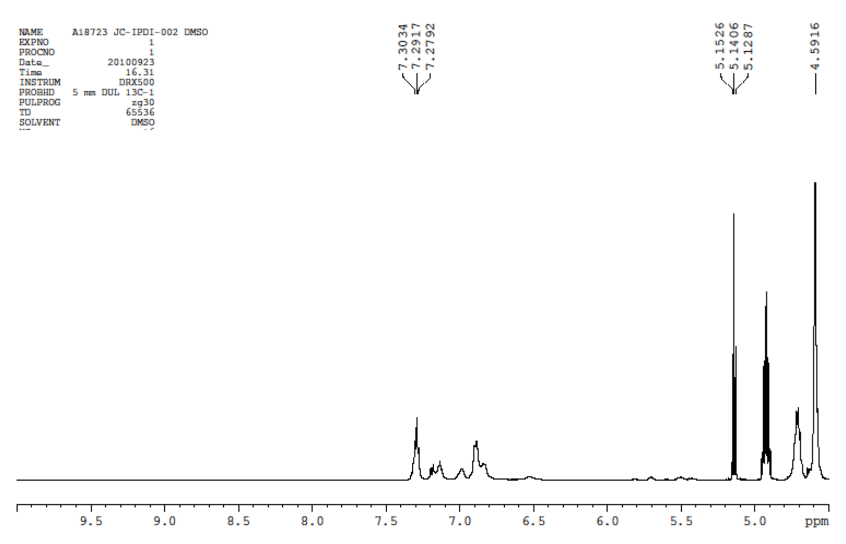


Figure 3.55: ^{1}H NMR spectrum of 27.

The aim then was to use the newly formed alkyne materials (**18** and **27**) to investigate the CuAAC click reaction, both with aliphatic-based alkynes and the larger and more structurally complex, alkyne oligomer. It was hoped that there would be no decrease in reactivity as the transition was made from small molecule alkynes to the larger oligomers.

As noted previously, the ^{1}H NMR spectra of the resulting products are difficult to fully assign, but there are peaks that can be used diagnostically to show if the CuAAC reaction has proceeded as expected. Therefore, prior to investigating CuAAC chemistry using the alkyne-containing polyurethane oligomer **27**, the CuAAC reaction was investigated using the alkyne-functional IPDI (**18**) (Figure 3.56). The reason for this sequence of reactions was to determine the peaks appearing in NMR spectra which are associated with formation of the triazole group, and this task would be easier to complete with the simpler alkyne-functionalised IPDI.

A CuAAC reaction was carried out between **18** and benzyl azide with a 10 mol% loading of copper catalyst (Cu (II) acetate). Upon completion of the reaction one can observe the complete disappearance of the signals at 4.7 and 3.5 ppm in the ^{1}H NMR spectrum associated with the alkyne functional group. In addition, there are new peaks present at around 8.1 and 5.5 ppm; this is consistent with the proton of the triazole ring formed upon successful reaction of alkyne with azide, and the downfield shift of the methylene group present in benzyl azide as it forms the triazole group (Figure 3.56).

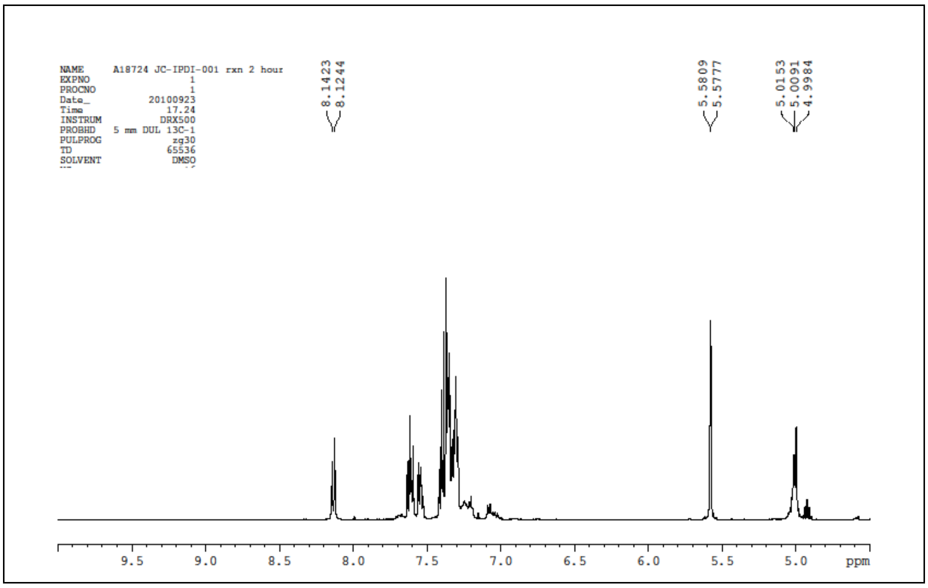


Figure 3.56: ^{1}H NMR of reaction product between 18 and benzyl azide.

New peaks are found at 8.1 ppm which are associated with the proton in the triazole ring. In addition to the signal at 8.1 ppm there is a new peak at 5.5 ppm associated with the methylene group next to the triazole group. It can also be seen that the signal associated with alkyne functionality at 4.5 ppm has disappeared completely.

The aforementioned peaks in the ^{1}H NMR spectrum of the reaction product of **18** and benzyl azide are mirrored in the reaction of the alkyne oligomer **27** and benzyl azide. MALDI-MS also suggests that there is successful reaction of **27** and benzyl azide; under the conditions of the reaction, there is an increase in molecular weight of 266 compared to the parent ion and this is equivalent to two molecules of benzyl azide.

The ^{1}H NMR and MALDI-MS results are encouraging because they suggest that the CuAAC reaction proceeds as expected with the larger oligomeric alkyne (which resembles a conventional polyurethane pre-polymer), and lends confidence to the belief that CuAAC is a suitable reaction to pursue and meet the ultimate aim of the research work.

Prior to the incorporation of an azide polyol into a polyurethane pre-polymer, the reactivity of the azide polyols was investigated. The reactivity of **10** was investigated with **17** using a 10 mol% loading of Cu (II) acetate as catalyst and triphenyl phosphine as reducing agent (Figure 3.57). Stoichiometry was controlled (2:1 azide/alkyne) so as to limit the amount of alkyne functional groups able to react with the azide groups in the azide polyol. This control of stoichiometry was carried out to ensure that chain-extension did not occur, which would increase the difficulty of analysing the ^{1}H NMR spectroscopy and MALDI-MS data.

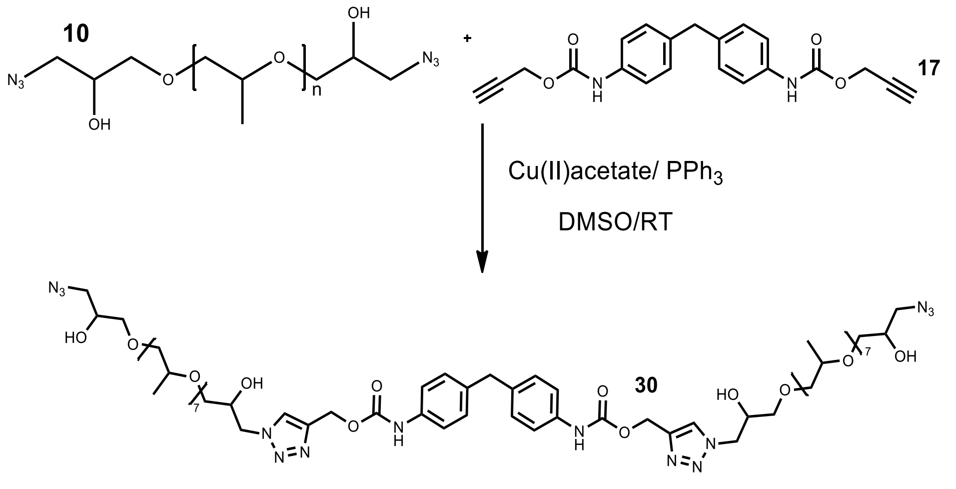


Figure 3.57: CuAAC between 10 and 17 to afford 30.

As seen in previous examples of ^{1}H NMR spectra of the reaction products from the CuAAC of azide and alkyne functional groups, there are a number of key peaks formed (Figure 3.58).

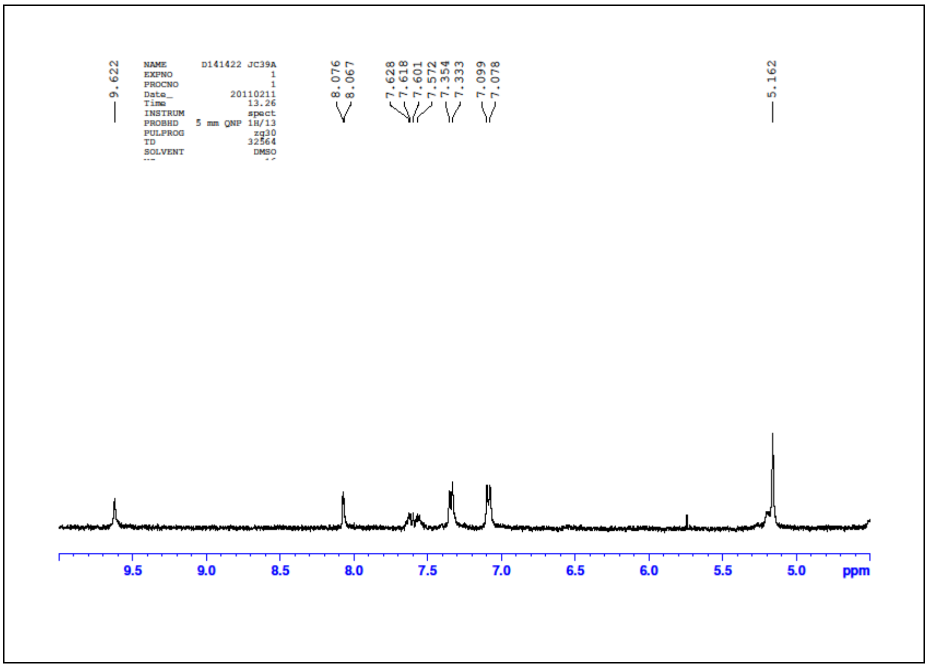


Figure 3.58: ^{1}H NMR spectrum of the reaction product of 10 and 17.

Principal peaks are found again at 8.0 and 5.1 ppm, suggesting that the reaction has proceeded as expected. The MALDI-MS is also in agreement showing a range of molecular weights greater than that of the alkyne MDI and the azide polyol. The NMR and MS results indicate that the reaction has proceeded as expected. In addition, a small amount of sample was placed in a glass reaction vial and left in a vacuum oven overnight to drive-off residual DMSO solvent. The resulting product was a slightly tacky solid that remained in position as the glass vial was inverted (Figure 3.59). This gives some reassurance that the azide polyol when formulated into polyurethane pre-polymer should be capable of reacting with multi-functional alkynes, as there appears to be no decrease in reactivity, to provide routes to non-isocyanate polyurethane films.

Figure 3.59: Residue left upon removal of DMSO solvent.

To investigate further the reactivity of more complex azide functional pre-polymers, reactions involving an azide polyol and MDI monomer were studied (Figure 3.60).

The aim was to prepare a more complicated analogue of a polyurethane pre-polymer. The azide polyol would be analogous to a traditional PPG polyol and MDI would act as a diisocyanate monomer. The stoichiometry was controlled (2:1 azide/alkyne) so that effectively each molecule of MDI would be “end-capped”, and the structure of the resulting pre-polymer analogue would resemble that shown in Figure 3.60.

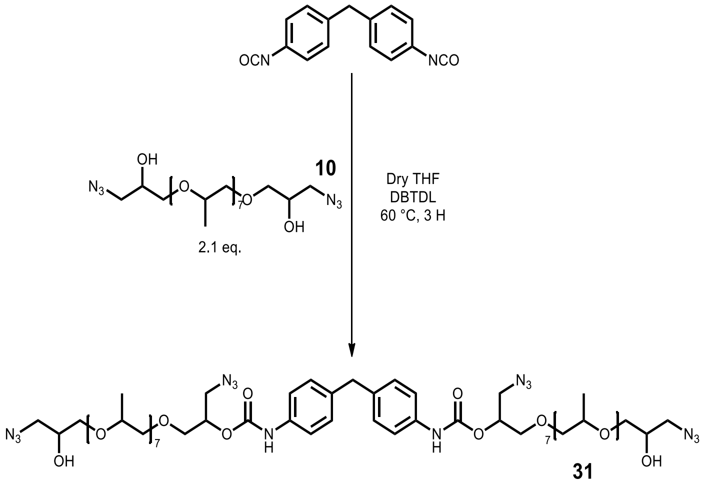


Figure 3.60: “End-capping” of MDI with 10 to afford azide-functional 31.

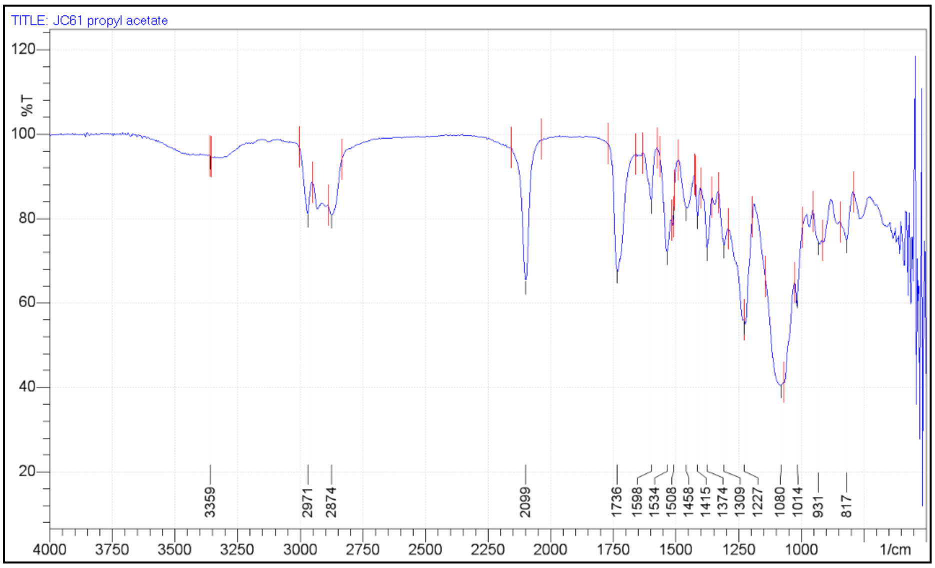


Figure 3.61: FT-IR spectrum of 31.

The FT-IR spectrum of **31** (Figure 3.61) shows peaks that can be attributed to both the azide (2099 cm^{-1}) and the carbonyl of the urethane group (1735 cm^{-1}). This suggests that there has been successful "end-capping" of MDI. The azide functionality is an excellent handle for monitoring the CuAAC reaction, because as azide is converted to triazole the intensity of the azide band decreases in the FT-IR spectrum.

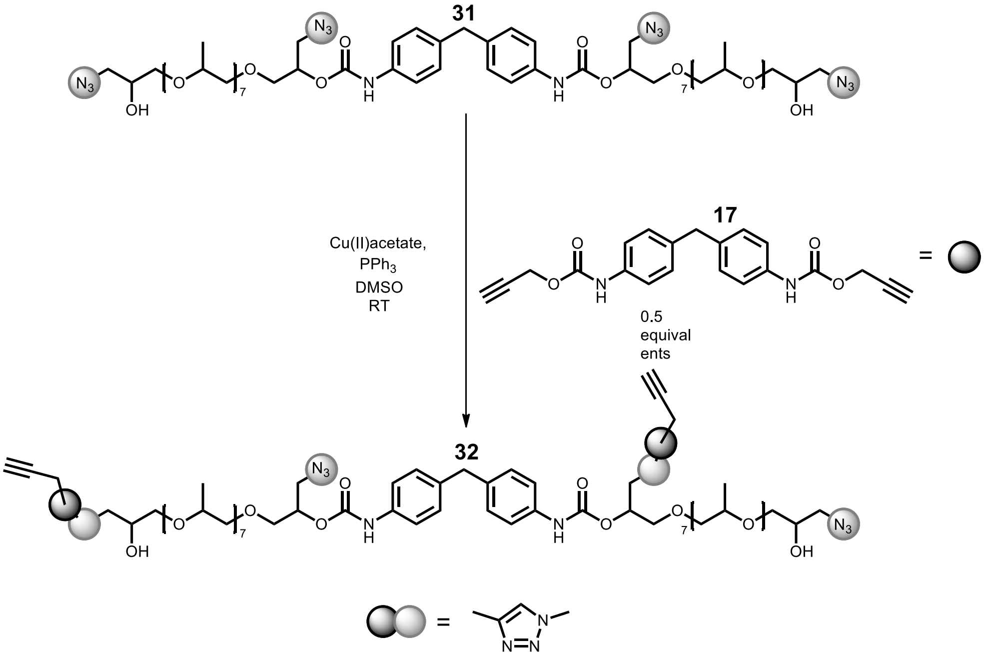


Figure 3.62: CuAAC reaction of 31 with 17.

The reaction of 31 with 17 (Figure 3.62) was carried out under CuAAC conditions. The stoichiometry of the reactants was controlled. The aim was to react a portion of the azide functional groups in **31** and hopefully observe a decrease in the intensity of the azide band in the FT-IR spectrum (Figure 3.63).

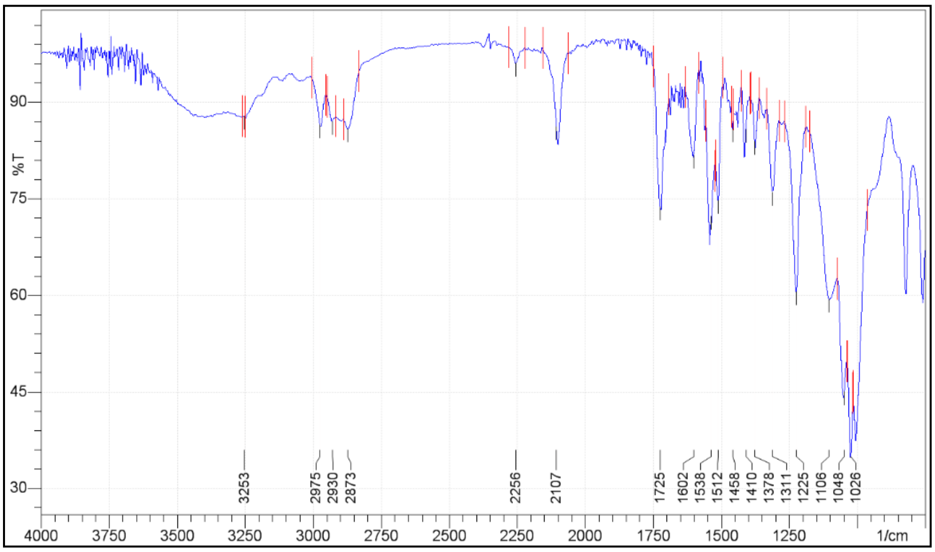


Figure 3.63: FT-IR spectrum of the product from the reaction between 31 with 17, showing a decrease in azide intensity relative to Figure 3.61.

It can be seen clearly that the azide signal at 2107 cm^{-1} has decreased in intensity suggesting that the CuAAC reaction has occurred as expected. Again, it must be emphasised how important that this result is; it indicates clearly that the azide and alkyne have no issues reacting with one another, even when a move is made away from small molecule chemistry towards more complicated pre-polymer systems.

Based on these encouraging results it was attempted to use a more functional alkyne cross-linker. The result of using a more-functional alkyne crosslinker such as **19** (Figure 3.31) or **14** (Figure 3.23) with **31** was the formation of thin films (Figure 3.64)**.**

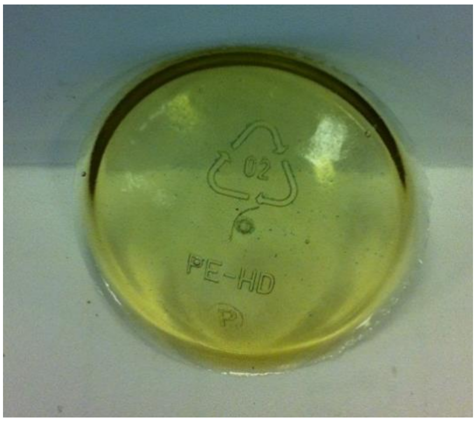


Figure 3.64: Example of a self-standing thin film formed from the reaction of 31 with multi-functional alkynes.

Thin film formation is a major step towards meeting the goals of the PhD study. The CuAAC in this case has shown to be a viable chemistry for crosslinking an azide “pre-polymer” with alkyne-functional molecules. It should be highlighted that there is no isocyanate functionality involved in the film formation step; this non-isocyanate aspect to the preparation of thin films clearly conforms to one of the major requirements set out at the outset of the present work.

General conclusions

At the outset of the research program it was envisioned that a number of distinct routes may be investigated to achieve the ultimate aim of preparing non-isocyanate polyurethane liquid-applied membranes. Upon careful consideration of all routes that would meet the aims of the study, it was decided to investigate CuAAC.

To this end a number of azide and alkyne functional molecules have been prepared. The functions of the molecules are varied. Some are designed to act as crosslinkers for polymers, whereas others are capable of being incorporated into polyurethane pre-polymers. There are a number of strategies in which these azide and alkyne functional molecules can be used to achieve the aims of the study.

The strategy that has been investigated most intensely involves the incorporation of azide functionality into the backbone of polyurethane pre-polymers, and subsequently crosslinking with a multi-functional alkyne molecule. This strategy has been shown to be successful in meeting some of the aims of the study.

Polyurethane films that which have no isocyanate involved in the curing process have been prepared. In this respect, CuAAC has proven to be a viable way to provide non-isocyanate polyurethane films.

3.6 Physical and chemical testing of PU thin films

Polyurethane films which have been crosslinked *via* a CuAAC process can now be prepared at will. The ability to prepare these films allows for the investigation of any chemical or physical limitations that the new CuAAC crosslinked PU films have when compared to the state-of-the-art in conventional isocyanate-cured PU films.

Specific areas of interest involve tests which mimic conditions that the final formulated products may be exposed to when used in real-world applications. Testing of the light stability of the coatings was accomplished *via* the use of specialised UV-weathering machines which test the coatings resistance to periods of UV and water exposure. The hydrolysis resistance of the CuAAC crosslinked polyurethanes was investigated by following the leaching of copper from a number of films upon storage in water.

3.6.1 Testing of the UV and weathering resistance of CuAAC polyurethane films

The UV and weather resistance of two PU films derived from pre-polymers prepared in earlier work were investigated. The pre-polymers used were **PU1** and **PU2**. The alkyne-functional crosslinker used to crosslink both pre-polymers was **21** (Figure 3.65).

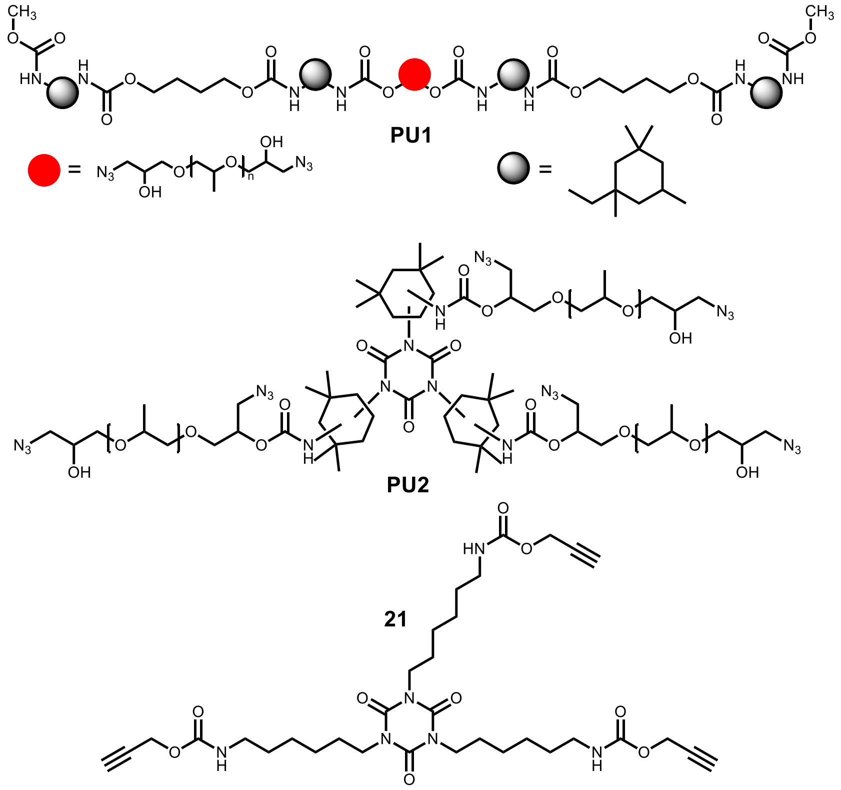


Figure 3.65: The pre-polymers (PU1 and PU2) and alkyne crosslinker (21) used in the investigation of the performance of the new CuAAC crosslinked polymers.

These pre-polymers were selected for study because they allowed for a comparison of both a linear azide-containing polyurethane (**PU1**) and a branched azide-containing polyurethane (**PU2**). It was thought that there may be a difference in performance between the two systems related to the crosslink density and the linear and branched nature of the two prepolymer systems. The alkyne crosslinker **21** was kept constant for both systems.

A method for introducing a consistent amount of additives and pigment can be achieved by preparing a blend of the required pigments and additives in solvent or plasticiser and mixing at high shear. Two such pigment blends were prepared. Both of the pigment blends were formulated using NMP as the solvent. NMP was used as a solvent to promote the solubility of the copper catalyst used to crosslink the azide functional pre-polymers. Titanium dioxide and aluminium hydroxide were added to represent typical additives present in a typical blend that may be used for a conventional isocyanate-functional polyurethane product. As mentioned previously, two pigment blends prepared. The first pigment blend had only the aforementioned titanium dioxide and aluminium hydroxide present. The second pigment blend also had UV additives present (Uvinul 3039 and a hindered amine light stabiliser) which would be present normally in a final formulated polyurethane product destined for use in roofing applications. In addition to the two pigmented blends discussed it was also interesting to investigate how a non-pigmented system would perform, also of particular interest was the role that copper may play, if any, in the degradation and the performance of both polymer systems. The role that copper plays was investigated by varying the concentration of copper catalyst used in the preparation of the crosslinked polyurethane films from 10 to 1 and then to 0 mol%.

The performance of the two CuAAC crosslinked polymers was compared against a conventional isocyanate-cured polyurethane film. The conventional polyurethane film samples were also prepared in pigmented (with and without UV additives) and a non-pigmented variation similar to the CuAAC cross-linked samples. The role of copper on the degradation of the conventional isocyanate-cured films was investigated by adulterating the conventional polyurethane controls with a 1 mol% loading of copper catalyst (Cu (II) acetate).

The samples were tested by applying the formulated polymers onto a Q-panel (Figure 3.66) using a 120 µm application bar to form thin films. The coated Q-panels were then placed in a UV weathering machine and monitored periodically for signs of degradation.

Figure 3.66: Typical Q-panel used as substrate for the application of polymer samples.

The polyurethane films crosslinked *via* a CuAAC method were cured at room temperature for 24 hours. Prior to the weathering testing the absence of free azide within the system was determined *via* FT-IR (Figure 3.67).

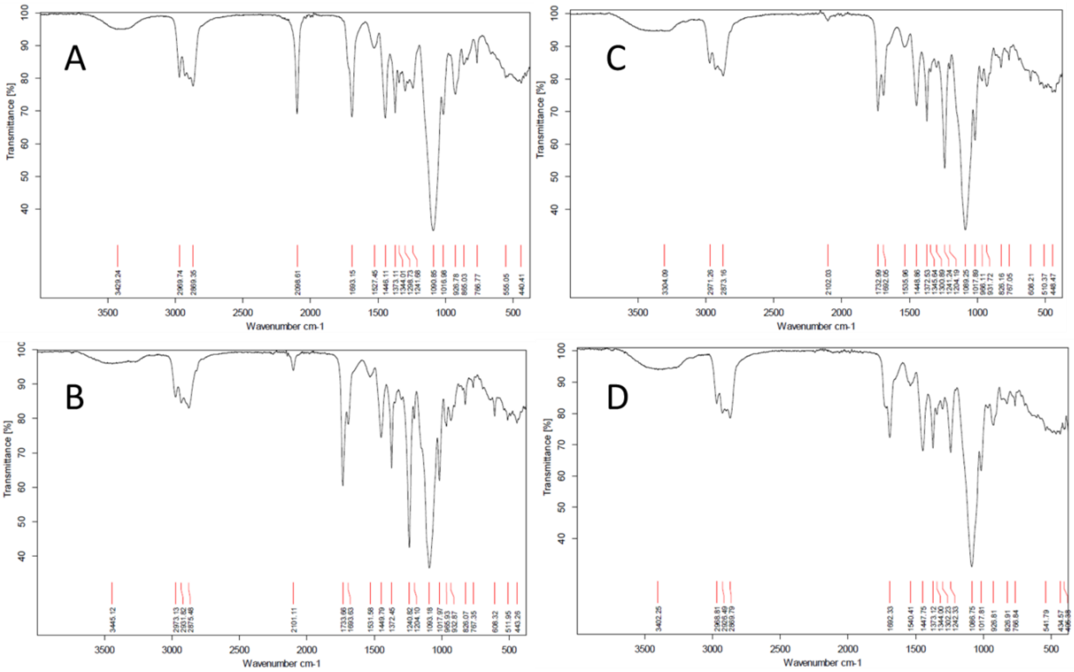


Figure 3.67: The FT-IR spectrum of A) Azide pepolymer (PU2) with azide signal at 2100 cm^{-1}. B) Mixture of PU2 and 21 in the presence of Cu (II) acetate catalyst after 1.5 hours. C) Mixture of PU2 and 21 in the presence of Cu (II) acetate catalyst after 4 hours. D) Mixture of PU2 and 21 in the presence of Cu (II) acetate catalyst after 24 hours showing no azide signal.

The samples which had no copper catalyst present were cured in a thermal process at 80 °C for 24 hours. One potential issue with the thermal cure is that the thermal process yields a mixture of the 1,4- and 1,5-triazoles. The mixture of regioisomers may lead to differences in performance when compared to the copper-promoted process where only the 1,4- triazole is formed. The isocyanate-cured controls were cured at room temperature for 24 hours and then placed in an 80 °C oven overnight to allow for the evaporation of residual solvent. Upon the full cure of both the new CuAAC cured materials and isocyanate controls the Q-panels were placed in a weatherometer for 576 hours and underwent cycles of condensation and UV-A weathering. The temperature within the weatherometer was held at 60 °C throughout.

Upon the completion of the testing period the coated Q-panels were removed from the weatherometer, visually inspected and any significant changes in the films was noted.

Control samples

The control samples were tested at the same time as the CuAAC cured films. An image of the three controls prior to the weathering testing is shown in Figure 3.68.

Figure 3.68: Isocyanate cured systems prior to weathering: C1 - non-pigmented, C2 - pigmented system and C3 - pigmented system with UV additives.

In C1 to C3 there was no copper present. To investigate the role copper plays in the degradation of the conventional isocyanate cured system controls were prepared, which were doped with a 1 mol% loading of copper (Cu (II) acetate) (C4-C6) again with a non-pigmented sample and two pigmented samples with and without UV additives (Figure 3.69).

Figure 3.69: Isocyanate cured systems with copper (Cu (II) acetate) prior to weathering: C4 - non-pigmented, C5 - pigmented system and C6 - pigmented system with UV additives.

After testing the samples for 576 hours there was a clear difference between the controls which had copper present and the controls where no copper was present (Figure 3.70 and Figure 3.71).

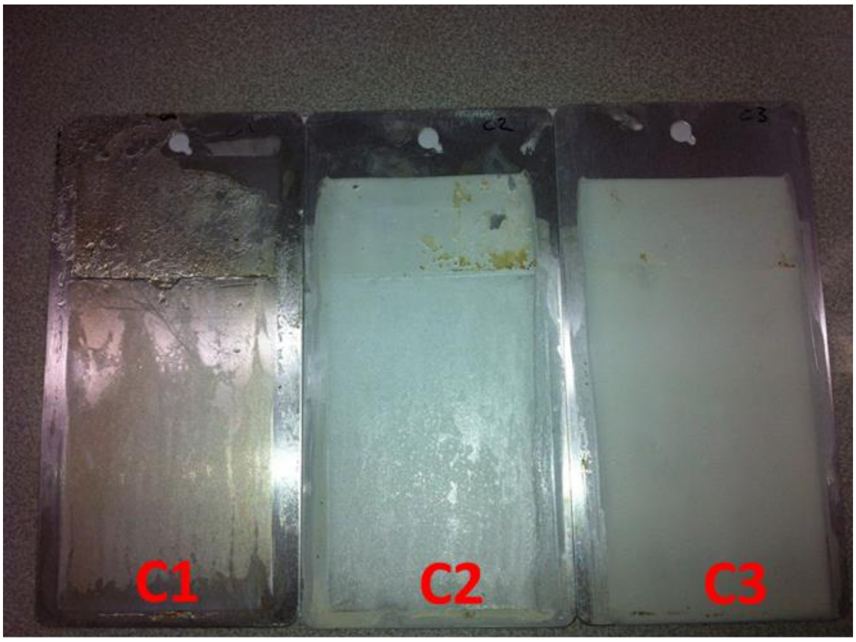


Figure 3.70: Isocyanate cured systems after weathering: C1 - non-pigmented, C2 - pigmented system, and C3 - pigmented system with UV additives.

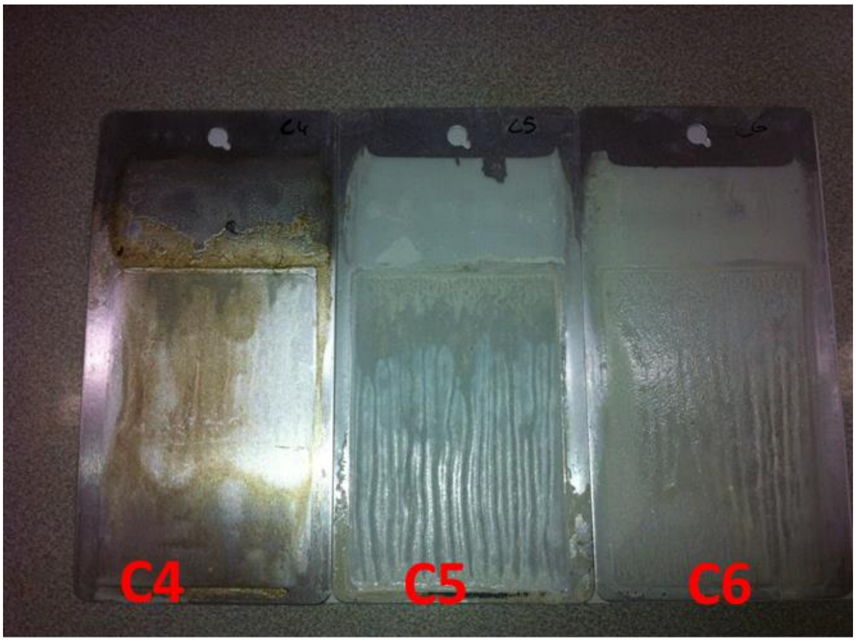


Figure 3.71: Isocyanate cured systems with copper (Cu (II) acetate) after weathering: C4 - non-pigmented, C5 - pigmented system, and C6 - pigmented system with UV additives.

It can be seen in Figure 3.70 that the pigmented controls have performed well, but it can also be seen that the non-pigmented control has performed poorly (total degradation of the non-pigmented control was observed).

It is also interesting to compare the controls without copper (C2-C3) to those with copper (C5-C6). It can be seen that the samples without copper have survived the weathering testing, but the analogous systems with copper present have undergone an increased amount of degradation. It is possible for polymers to degrade *via* an autoxidation process which generates hydroperoxide species.[135,136] The presence of the redox-active copper is likely to catalyse the decomposition of hydrogen peroxide,[137] which generates more radicals and a possible increased rate of polymer degradation. This increased degradation highlights the effect that the presence of copper can have on the conventional isocyanate-cured materials.

CuAAC samples

For the CuAAC cured films increased degradation due to the presence of copper was not observed. In contrast, the performance of the CuAAC crosslinked samples was uniformly excellent in the case of the pigmented (with and without UV additives) samples (Figure 3.72 and Figure 3.73).

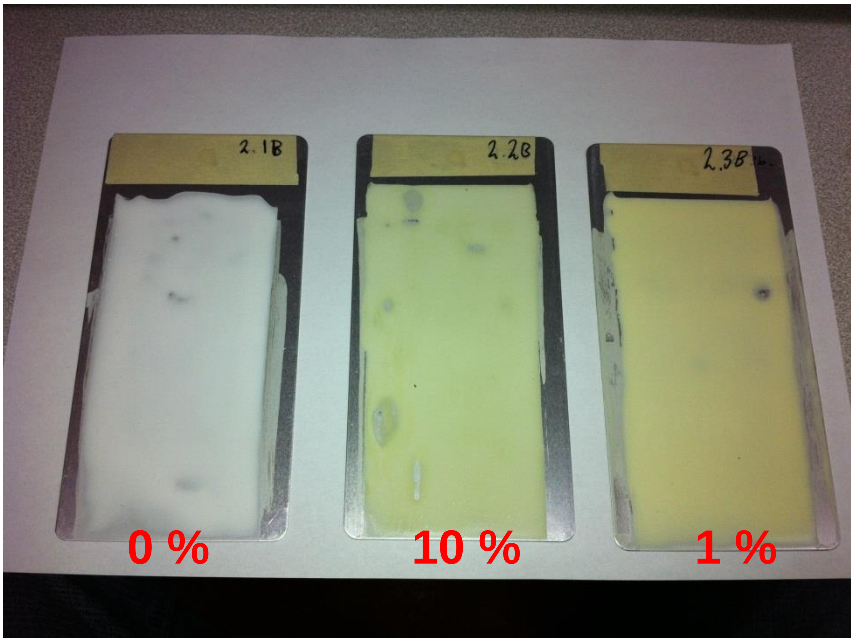


Figure 3.72: CuAAC cured samples (PU2 and 21) with differing loadings of Cu (II) acetate from 0 to 10 and 1 mol%, prior to weathering testing.

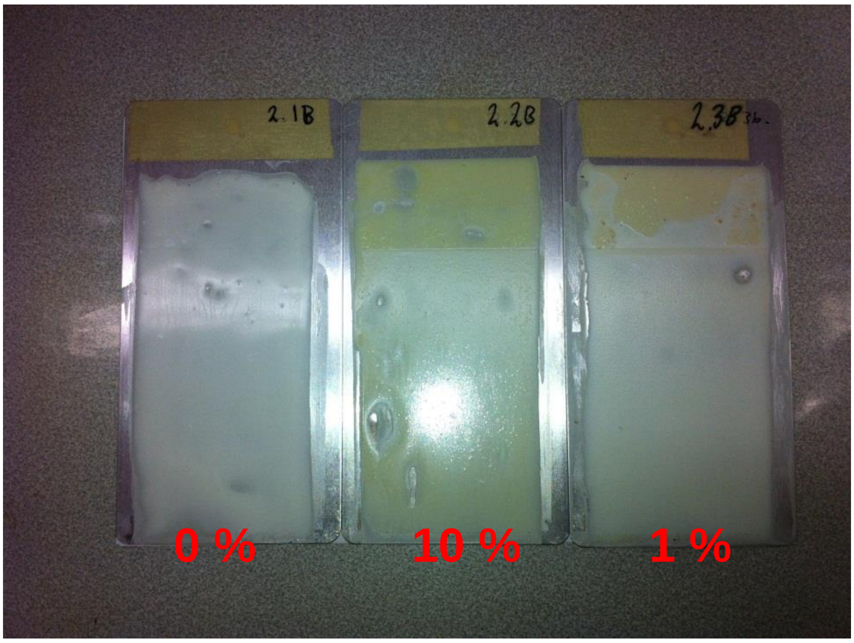


Figure 3.73: CuAAC cured samples (PU2 and 21) with differing loadings of (Cu (II) acetate) from 0 to 10 and 1 mol%, after weathering testing.

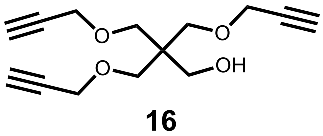
It can be seen in Figure 3.72 and Figure 3.73 that there is no significant degradation noted for the CuAAC crosslinked samples. This lack of degradation is particularly interesting in the sample with a 10 mol% loading of copper catalyst, which is a ten-fold increase in the copper loading compared to the copper loading which led to significant degradation in the standard isocyanate-cured controls (C4-C6).

General conclusions

From the preliminary results obtained it can be noted that there has been an improved performance of the CuAAC coatings over the conventional isocyanate cured coatings. The reason for the improved performance may be due to the presence of the triazole rings which are formed upon reaction of the azides and alkynes; triazoles are known to be UV absorbers, and have recently been used as such in the preparation of ophthalmic lenses.[138] The results reported here are very encouraging but will require further investigation with a wider range of azide and alkyne materials.

3.6.2 Leaching of copper from CuAAC crosslinked polyurethane films

An important factor under investigation was the leaching of copper from the films. To test the leaching of Cu from thin films, three polymer films were formed. The films were prepared from **PU1** and **16** (Figure 3.74), and crosslinked using CuAAC chemistry using three different loadings of the copper catalyst (1, 5 and 10 mol%).



16

Figure 3.74: Alkyne-functional crosslinker used to prepare films for hydrolysis testing.

Three films were formed using three different loadings of copper catalyst. The films were cut into equal weighted portions and placed in vials and completely submerged in 1 mL of distilled water at room temperature. The concentration of copper in the water was measured using ICP-MS after 7, 43 and 181 days (Table 3.3).

Table 3.3: Cu concentration (ppb) observed for three different polymer films with various loadings of copper.

	Cu concentration (ppb)		
Days	1 mol %	5 mol %	10 mol %
7	0	410	1460
43	0	3952	2708
181	12240	53480	70550

It can be seen in Table 3.3 that for the film prepared using a 1 mol% loading of Cu there was no significant leaching of copper at both 7 and 43 days, but after 181 days immersion in water there was a significant concentration of copper found. Both the 5 and 10 mol% experiments indicated that there was leaching after 7 and 43 days, and as was the case for the 1 mol% sample after 181 days it was noted that there was a significant amount of copper leached.

General conclusions

The leaching of copper from CuAAC crosslinked product of **PU1** and **16** was initially promising, which was especially the case for the 1 mol% sample where no copper was detected at either 7 or 43 days. Unfortunately, it can be seen that with an increased immersion time of 181 days all samples show a significant amount of copper leached from the polymer film into the water. It should be noted that these results are based upon one system only (**PU1** and **16**) and further research will need to be carried out into the performance of a range of other polyurethane resin systems. In addition, there is a need to investigate the consequences that hydrolysis would have upon the physical properties of CuAAC cured resin systems.

3.7 Mechanical performance of polymer films

Polyurethane films prepared from azide-functional pre-polymers and alkyne-functional crosslinkers can be formed at room temperature in a CuAAC promoted process. An important performance characteristic of these new CuAAC crosslinked films upon which they will be judged is their mechanical properties.

The CuAAC crosslinking method introduces some issues that can adversely affect the physical appearance and mechanical properties of the new CuAAC crosslinked films. For example, in a situation where the copper catalyst (Cu(II) acetate) is introduced as an aqueous solution to the azide-functional pre-polymer and alkyne-functional crosslinker, optically opaque films are formed (Figure 3.75).

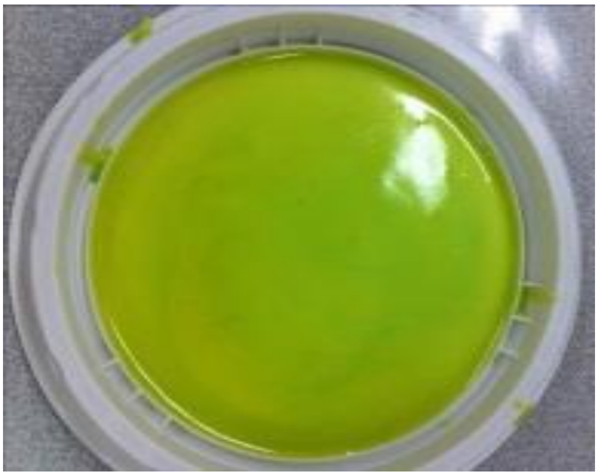


Figure 3.75: An example of an opaque film formed from the use of an aqueous solution of the copper catalyst.

In addition to the formation of opaque films, the use of an aqueous based catalyst solution adversely affects the physical properties of the CuAAC crosslinked films. The reason for the inferior mechanical properties is likely to be linked to the increased volume of solvent acting as a pseudo-plasticiser, and resulting in a softer product. The issue of the opaque nature of films using an aqueous-based catalyst can be overcome if an organic solvent such as NMP is used (Figure 3.76). Unfortunately, the films prepared using organic solvents require an increased volume of the catalyst solution and this again leads to poorer mechanical performance.

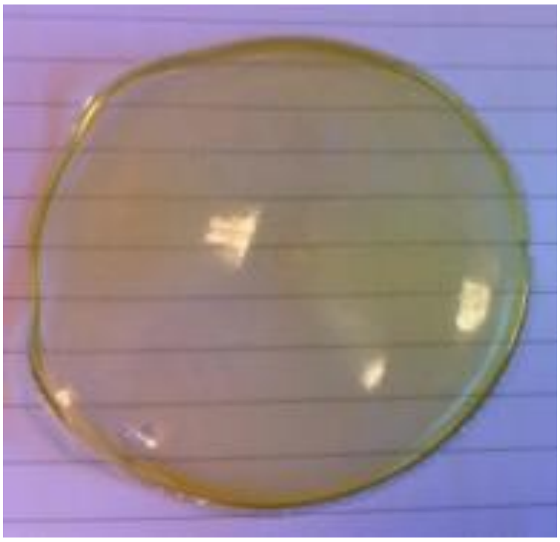


Figure 3.76: An example of a clear film formed *via* the use of an organic solvent solution of the copper catalyst.

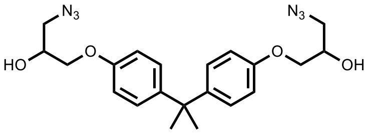
Three films were prepared to investigate the role that the aqueous or organic solvent plays in the mechanical properties of the CuAAC crosslinked films. The azide-functional pre-polymer used was the branched **PU2** system and the alkyne-functional crosslinker used was **21**. One film was prepared in a thermally-promoted process where there was no copper or additional solvent present. The other two films were prepared using a 5 mol% loading of Cu(II) acetate in either an aqueous solution or organic solution.

Table 3.4: Stress and elongation observed for films prepared from PU2 and 21 under a range of conditions. * Film cured overnight in oven (80 °C) ** Film cured at ambient temperature for 24 hours and then placed in oven (80 °C) overnight.

	Thermally cured*	**Aqueous Cu soln.**	**Organic Cu soln.**	**Organic Cu soln. then oven cure****
Stress (MPa)	**1.58**	**0.34**	**0.24**	**0.88**
Elongation at break (%)	**337**	**274**	**194**	**410**

The results shown in Table 3.4 indicate that improved tensile properties were observed in systems which were exposed to thermal cure. Both of the room temperature cured systems showed decreased tensile properties in comparison to the thermally cured film. It was interesting to find that the organic-based copper catalyst film exhibited improved tensile properties when the initial room temperature cure for 24 hours was followed by an overnight period in an 80 °C oven. The improved performance could possibly be attributed to the enhanced rate at which the solvent had been driven from the polyurethane film.

In an effort to improve the physical properties obtainable from the CuAAC crosslinked materials the system comprising of **PU2** and **21** was modified. Instead of the azide-functionality coming from **PU2** alone the azide-functional diol **9** (Figure 3.77) was added. It was hoped that the presence of **9** would deliver a stronger polymer film and eventually allow for tailoring of physical properties.



9

Figure 3.77: Azide-functional diol (9) used in the preparation of stronger polyurethane films.

To investigate the effect of **9** on the physical properties, different ratios of azide components were prepared (1:1, 3:1 and 1:3). Table 3.5 shows the different ratios and components that made up mixtures A to H.

Table 3.5: Mixtures of azide and alkyne prepared to investigate the physical properties achievable from PU2, 9 and 21.

Mixture	**PU2** (g)	**9** (g)	**21** (g)	Azide : Alkyne Ratio	Aqueous Cu (II) acetate solution (0.36 M) (mL)	Aqueous sodium ascorbate solution (3.13 M) (mL)	Cure conditions
A	**2.50**	**2.50**	**5.51**	**1:1**	**-**	**-**	**Thermal**
B	**3.75**	**1.25**	**6.17**	**1:1**	**-**	**-**	**Thermal**
C	**1.25**	**3.75**	**4.86**	**1:1**	**-**	**-**	**Thermal**
D (4 mol%)	**2.50**	**2.50**	**5.51**	**1:1**	**2.11**	**0.48**	**Ambient**
E (4 mol%)	**3.75**	**1.25**	**6.17**	**1:1**	**2.36**	**0.54**	**Ambient**
F (4 mol%)	**1.25**	**3.75**	**4.86**	**1:1**	**1.86**	**0.43**	**Ambient**
G (2.5 mol%)	**0.00**	**5.00**	**6.82**	**1:1**	**1.63**	**0.37**	**Ambient**
H (0.75 mol%)	**0.00**	**5.00**	**6.82**	**1:1**	**0.49**	**0.11**	**Ambient**

Mixture A, which comprises a 1:1 mixture of **PU2** and **9**, showed an impressive tensile strength for the thermally-promoted film. Mixture D (analogous to mixture A) was prepared to investigate the effect that a CuAAC promoted process (with a 4 mol% loading of the Cu (II) acetate catalyst) would have on the physical properties. In-line with the results observed in mixture A, the room temperature cured mixture D showed a gradual improvement in performance over the system comprised solely of **PU2** without the addition of **9**. It was found that when the film was placed overnight in an 80 °C oven, after 24 hours at room temperature, there was an enhancement in physical properties. Also of interest was that upon an extended period of room temperature cure (7 days) there was a slight increase in the tensile properties (Table 3.6).

Table 3.6: Stress and elongation observed for films prepared from PU2:9 mix (1:1) and 21 under a range of conditions. * Film cured overnight in oven (80 °C) , Measured after 24 hours of ambient cure, *** Film cured at ambient temperature for 24 hours and then left in oven (80 °C) overnight, **** Measured after 7 days of ambient cure.**

PU2 : 9 **1:1**	**Mix A***	**MIX D (4 mol%)****	**MIX D (4 mol%)/ oven*****	**MIX D (4 mol%)******
Stress (MPa)	6.28	0.41	2.42	0.64
Elongation (%)	232	190	158	225

Mixture C, which comprised of a 1:3 blend of **PU2** and **9** showed a startling increase in tensile stress and an equally startling decrease in elongation. The pattern noticed for the room temperature cured mixture D is mirrored in mixture F, which showed an increase in tensile properties after an extended room temperature cure (7 days) and also when the room temperature cured film was placed overnight in an oven at 80 °C (Table 3.7).

Table 3.7: Stress and elongation observed for films prepared from PU2:9 mix (1:3) and 21 under a range of conditions. * Film cured overnight in oven (80 °C) , Measured after 24 hours of ambient cure, *** Film cured at ambient temperature for 24 hours and then left in oven (80 °C) overnight, **** Measured after 7 days of ambient cure.**

PU2 : 9 **1:3**	**Mix C***	**MIX F (4 mol%)****	**MIX F (4 mol%)/ oven*****	**MIX F (4 mol%)******
Stress (MPa)	29.39	0.86	7.23	2.6
Elongation (%)	9	167	52	238

Based on the positive results obtained by using a blend of **PU2** and **9,** further work was carried out. This work involved the use of **9** as the sole azide component and complete removal of **PU2** (mixture G and H, Table 3.5). The alkyne crosslinker was kept constant as **21**. It was found that the CuAAC crosslinkable materials (**9** + **21**) were able to be crosslinked at significantly lower loadings of Cu catalyst (2.5 mol% and 0.75 mol%).

The physical properties of polymer films based on **9** and **21** using a 0.75 mol% loading of catalyst are shown in Table 3.8.

Table 3.8: Stress and elongation observed for films prepared from 9 and 21 under a range of conditions. * Measured after 24 hours of ambient cure, Film cured at ambient temperature for 24 hours and then left in oven (80 °C) overnight, *** after 7 days of ambient cure**

	MIX H (0.75 mol%)*	**MIX H (0.75 mol%)/ oven****	**MIX H (0.75 mol%)*****
Stress (MPa)	0.86	20.74	2.19
Elongation (%)	412	10	365

Particularly notable is the high tensile stress and low elongation observed using this system. It should be noted that there was a significant exotherm noticed, which was possibly due to the decrease in the volume of solvent added to the system due to the decrease in the amount of the copper catalyst used and also due to the more azide-rich nature of **9**.

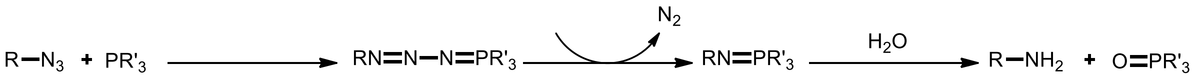
General Conclusions

The ability to tailor the mechanical properties of simple CuAAC crosslinked polyurethane films has been shown. The tailoring of the physical properties highlights that there is scope for the preparation of a system which gives physical performance at least on a par with what is currently achievable with conventional isocyanate-cured films. To date, the work has only been carried out on one simple system, but it is hoped that with the investigation into other systems a range of physical properties should be obtained.

3.8 The use of benzoic acid as an additive to promote the CuAAC reaction

Two areas were under investigation in this portion of the work. The first was to investigate if benzoic acid would promote the CuAAC reaction between azides and alkynes as discussed recently in the literature.[53] The second area of investigation was the propensity of some films formed using CuAAC chemistry to exhibit significant bubbling (Figure 3.78) when triphenyl phosphine was used as the reducing agent. It was thought likely that the triphenyl phosphine was reacting with the azide functional groups in the azide-functional pre-polymers (Figure 3.79). The nitrogen gas generated is likely to be the cause of the bubbling seen within the polyurethane films.

Figure 3.78: The bubbling effect witnessed in some CuAAC cross-linked films when triphenyl phosphine was used as the reducing agent.



$$R{-}N_3 + PR'_3 \longrightarrow RN{=}N{-}N{=}PR'_3 \xrightarrow{N_2} RN{=}PR'_3 \xrightarrow{H_2O} R{-}NH_2 + O{=}PR'_3$$

Figure 3.79: The reaction of organic azide and phosphine to generate an amine and phosphine oxide as well as nitrogen gas.

To investigate both the role of benzoic acid and the bubbling phenomena a number of CuAAC reactions were attempted (Table 3.9) using azide polyol **11** and alkyne-functional **17**.

Table 3.9: Reactions used to investigate the role of benzoic acid and triphenyl phosphine on the CuAAC promoted reaction between 11 and 17.

Reaction	DMSO reaction solvent (mL)	Cu(II)acetate loading (mol %)	Reducing agent	Benzoic acid (mol %)	FT-IR results after 18 hours	FT-IR results after 100 hours
A	1	10	Ph_3P	10	Azide not present	-
B	1	1	Ph_3P	10	Azide present	Azide not present
C	1	0.1	Ph_3P	10	Azide present	Azide present
D	1	0	Ph_3P	10	Azide present	Azide present
E	1	10	Ph_3P	-	Azide not present	-
F	1	1	Ph_3P	-	Azide not present	-
G	1	0.1	Ph_3P	-	Azide present	Azide present
H	1	0	Ph_3P	-	Azide present	Azide present
I	1	10	NaAsc	10	Azide not present	-
J	1	0	NaAsc	10	Azide present	Azide present
K	1	10	NaAsc	-	Azide not present	-
L	1	0	NaAsc	-	Azide present	Azide present

Reactions A-D varied the copper catalyst in the presence of benzoic acid. The benzoic acid loading was kept constant at 10 mol%. Reactions E-H were analogous to A-D, but in the absence of benzoic acid. The reactions were monitored using FT-IR spectroscopy and the signal at 2100 cm^{-1} attributed to the azide moiety of **11.** The FT-IR spectra were obtained after 18 and 100 hours of reaction time.

The reactions A to D showed that after 18 hours of reaction time only the 10 mol% reaction (A) had gone to completion (as evidenced by the complete disappearance of azide signal in the FT-IR spectrum). Reactions B and C, with lower loadings of copper catalyst (1 and 0.1 mol% respectively) still had azide-functionality after 18 hours. The 1 mol% reaction did eventually proceed to completion after an extended period of reaction (100 hours). Even after the extended period of reaction the 0.1 mol% reaction was incomplete and as expected, reaction D without copper catalyst present showed no difference in the azide signal intensity.

In the reactions E to H, both E and F had reacted completely after 18 hours. As in the case of the previously discussed reactions, the 0.1 mol% and catalyst-free reactions did not go to completion even after 100 hours of reaction time. It is interesting to note that based upon these results the use of benzoic acid in reaction B has had an opposite effect to that desired, which is evidenced by reaction F going to completion in the absence of benzoic acid.

Reactions I and K indicate that sodium ascorbate is a more than adequate replacement for triphenyl phosphine if the reaction between triphenyl phosphine and azide-functional molecules proves to be a problem. Reactions D and H are also interesting as the both reactions suggest that there was no appreciable reaction of azide and triphenyl phosphine, even after 100 hours of reaction.

General conclusions

It is premature to draw concrete conclusions on the effectiveness of the use of benzoic acid based on the limited examples discussed here. It should also be noted that the literature reference made use of aqueous-based solvents. The use of aqueous-based solvent systems was not possible in this work, which was due to the low solubility of **17** in water.

4.0 Conclusions and future work

Conclusions

At the outset of the research program a number of synthetic routes were envisioned to achieve the ultimate aim of preparing non-isocyanate polyurethane liquid-applied membranes. After careful consideration of all the potential routes, which would meet the aims of the research programme, it was decided to investigate CuAAC chemistry in detail.

To this end, a number of azide- and alkyne-functional molecules have been prepared. The functions of the molecules are variable. Some are suited to acting as crosslinkers for polymers, whereas others are capable of being incorporated into polyurethane pre-polymers. There are a number of ways in which these azide- and alkyne-functional molecules could be exploited to deliver upon the aims of the study. Particularly exciting is the way that the azides and alkynes disclosed within this thesis can be prepared from commodity materials under very simple reaction conditions. The ease of synthesis of these molecules increases the likelihood that commercial products reliant on CuAAC could become a viable alternative to isocyanate-based systems.

The strategy that has been investigated most intensely involves the incorporation of azide functionality into the backbone of polyurethane pre-polymers, and subsequently crosslinking with a multi-functional alkyne molecule. This strategy has been shown to be successful in meeting some of the aims of the work.

CuAAC has proven to be an effective way to provide non-isocyanate polyurethane films which require absolutely no isocyanate in the curing process under ambient conditions. The physical properties achievable from these films have been investigated, and there is good scope for the tailoring properties for different application requirements.

Future work

The strategy of incorporating azide functionality into a polyurethane pre-polymer and cross-linking with a multi-functional alkyne has proven to be a sound one. There still remains a large volume of work to be carried out in a number of areas:

- The preparation of additional azide- and alkyne-functional molecules; this will allow for fine control of the physical and chemical properties of the resulting films.
- Quantification of the hazards associated with the azide and alkyne materials. It is presumed that they are less hazardous than the current isocyanate-based technology. This has to be verified.
- The weathering performance of triazole-containing polyurethane films is of the upmost importance. To this end, the UV and hydrolysis performance of the resulting films remains to be investigated fully with a range of materials.
- The CuAAC chemistry has been shown to be suitable for preparing non-isocyanate liquid-applied membranes although to date this has only been proven in relatively simple systems. An area of further research will to investigate how the CuAAC chemistry performs in a fully-formulated system where a range of fillers and adducts are present.
- Another area of interest is what role copper may play in the chemical stability of the liquid-applied membranes. This requires further investigation in tandem with UV and hydrolysis stability for a range of systems.

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