A novel N-halamine monomer for preparing biocidal polyurethane coatings

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Summaries

A novel N-halamine monomer for preparing biocidal polyurethane coatings

A novel N-halamine monomer has been prepared which can be copolymerised with a commercial water-borne acrylic polyol and a commercial isocyanate to produce a polyurethane coating which can be applied to a broad variety of surfaces. After curing, the coating can be chlorinated with a source of free chlorine, such as bleach, to render it biocidal. Once the coating loses its chlorine loading, and hence its biocidal activity, regeneration is possible by further exposure to free chlorine. In one experimental observation a coating on a wall retained its biocidal activity for more than six months. The biocidal coating should have many applications, for example, in medical facilities, in food preparation areas, in the prevention of biofouling in aqueous and humid environments, etc.

Un nouveau monomère à la N-halamine pour la préparation de revêtements polyuréthaniques biocides

Un nouveau monomère à la n-halamine a été préparé qui peut être copolymérisé avec un polyol acrylique hydrodiluable commercial et un isocyanate commercial afin de produire un revêtement polyuréthanique qui peut être appliqué à une large variété de surfaces. Après séchage le revêtement peut être chloré en utilisant une source de chlore libre, telle que l'eau de Javel, pour le rendre biocide. Une fois que le revêtement perd sa charge de chlore, et donc son activité biocide, la régénération est possible par le moyen d'une autre exposition au chlore libre. Au cours d'une certaine observation d'expérience on a noté que le revêtement d'un mur a retenu son activité biocide pendant plus de six mois. Le revêtement biocide devrait avoir de nombreuses applications, par exemple, dans les établissements médicaux, dans les lieux de préparation des produits alimentaires, dans le domaine de la prévention de la biocontamination des environnements humides ou aqueux, etc.

Ein neuartiger N-Balaminmonomer für die Herstellung von Biozid-haltigen Polyurethanlacken

Wir haben einen neuartigen N-Balaminmonomer hergestellt, der durch ein handelsübliches acrylisches Polyol und ein Isocyanat copolymerisiert werden kann. Der so erhaltene Lack kann auf eine weite Reihe von Oberflächen aufgetragen werden. Nach dem Härteprozess kann der Lack mit einem Produzenten von freiem Chlor wie Bleiche chloriniert werden, um die Biozidwirkung zu aktivieren. Da der Lack mit der Zeit seinen Chlorgehalt verliert und damit seine Wirkungskraft, kann diese Behandlung nach Bedarf wiederholt werden. Eines unserer Experimente zeigte dass der Lack seine Biozidwirkung für über sechs Monate beibehalten kann. Dieser Biozidlack dürfte vielfältig Anwendung finden, z. B. in Krankenhäusern, Küchen, zum Verhindern von Pilzbefall in feuchten Räumen und so weiter.

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Introduction

Work at Auburn University since 1980 has focused on the development of novel biocidal N-halamine derivatives.[1] Water-soluble, cyclic N-halamine derivatives such as 1,3-dihalo-5,5-dimethylhydantoin and halogenated isocyanurates (eg Trichlor and Dichlor) have been employed as biocides for industrial and recreational water uses for many years, but the water-soluble N-halamine compounds produced at Auburn University (oxazolidinones and imidazolidinones) are unique because of their long-term stability in aqueous solutions and in dry storage (see Figure 1). This exceptional stability is a result of their chemical structures: all have electron-donating alkyl groups substituted on the heterocyclic rings adjacent to the oxidative NCl or NBr moieties, which prohibit significant release of 'free halogen' into aqueous solutions. The combined N-halamines thus serve as contact biocides.

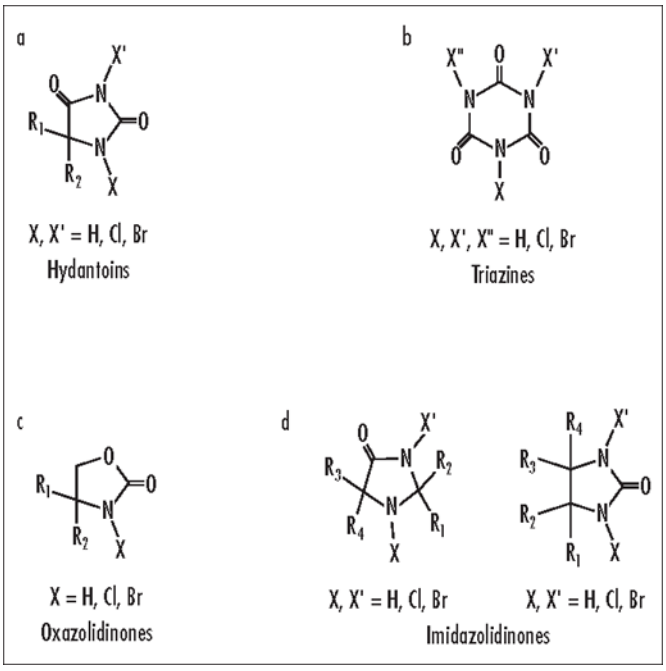

Figure 1: Water-soluble heterocyclic monomers used in the modification of polymers to render them biocidal

Although combined N-halamine monomers generally require longer contact times at a given halogen concentration than 'free halogen' to inactivate pathogens, it has been demonstrated in these laboratories that it is possible to concentrate N-halamine moieties on insoluble polymers, thus producing a substantial reservoir of combined halogen for enhanced disinfection purposes. Furthermore, the functionalised N-halamine polymers are superior in overall performance (taking into account biocidal efficacy, stability at varying pHs, and in the presence of organic receptors, rechargeability, lack of toxicity, and general cost) to other biocidal polymers which have been developed and marketed over the years, such as halogenated poly(styrene-divinylbenzene) sulphonamides,[2] polymeric phosphonium materials,[3] and polymeric quaternary ammonium compounds.[4]

Several commercial polymers have been functionalised with N-halamine moieties, rendering them biocidal upon surface contact with pathogens. These include: cellulose,[5,6] nylon,[6,7] PET (polyethylene terephthalate),[6,8] Kraton rubber,[9] various surface coatings,[10] and the N-halogenated poly(styrene) hydantoins.[11–15] The latter polymers are granular solids which are insoluble in water and which are packed into glass columns which function as cartridge filters. It was observed that the filters inactivated numerous species of bacteria, fungi, and even rotavirus in just seconds of contact time in flowing water.[11–15] Also, it was observed that the columns did not leach out decomposition products into the water,[14] and that the free chlorine and bromine concentrations leached into the flowing water were less than 0.1mg/L and less than 2.0mg/L, respectively. Furthermore, once the halogen supply was exhausted through various loss processes, it could be replenished on the polymers by simply exposing them to flowing aqueous free halogen (eg sodium hypochlorite bleach for the chlorinated derivative). It appears that the chlorinated polymer will be useful for potable water disinfection applications, and that the brominated poly-

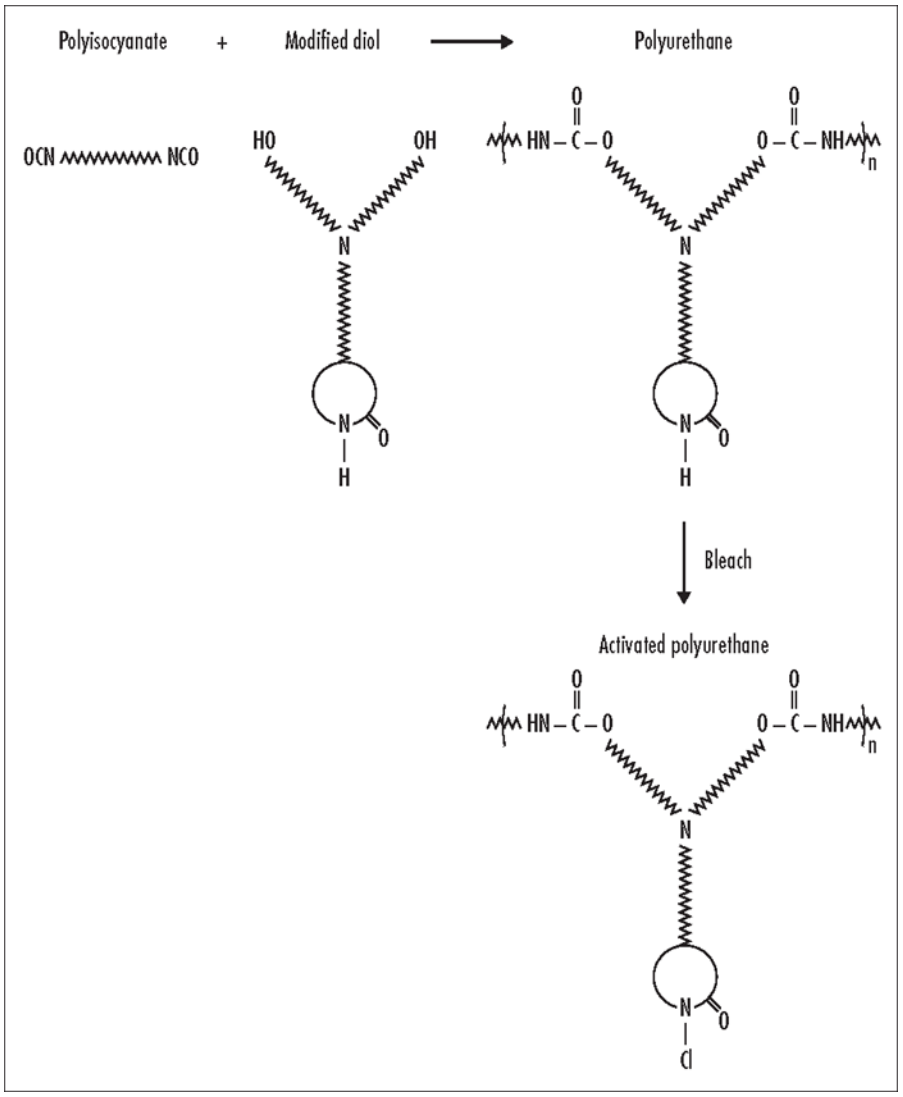

Figure 2: The concept of a biocidal polyurethane coating

mer will work well in disinfecting recreational water sources. Recently the products have been produced in the form of porous beads to enhance flow properties.

This work represents an extension of technology developed at Auburn University to the preparation of biocidal polyurethane coatings through the functionalisation of a reactive diol with a hydantoin moiety which can then be copolymerised with commercial polyols and isocyanates to form polyurethane. An application of free halogen (eg with household bleach) will then render the coating biocidal. The concept is illustrated in Figure 2, and the structure of the actual diol which has been developed in this work is shown in Figure 3.

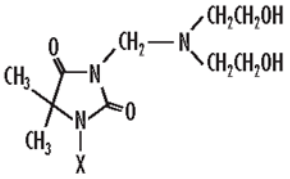

Figure 3: Diol monomer developed for polyurethane coatings

Experimental procedure

Preparation of diol monomer

The unhalogenated diol monomer was prepared by the reaction of 132.1g (1.0 mol) of 5,5-dimethylhydantoin, 106.2g (1.0 mol) of diethanolamine, and 81.16g (1.0 mol) of 37% formaldehyde solution in 400ml of methanol at an ambient temperature for two hours. Alternatively, it could be prepared by reaction of 3-hydroxymethyl-5,5-dimethylhydantoin with diethanolamine in methanol at 75°C. The water byproduct and methanol solvent were removed for characterisation purposes by vacuum evaporation. The viscous residue produced was then dissolved in ethyl acetate, and anhydrous sodium sulphate was added for further drying purposes. Following the removal of the sodium sulphate by filtration, the solution was refrigerated. After 12 hours, a white solid product precipitated from the ethyl acetate solution. The product, which was removed by filtration from the cold solution, exhibited a melting point of 74 to 76°C and was produced in 61 to 84% yield; it was identified as 5,5-dimethyl-3-(N,N-di-ß-hydroxyethylaminomethyl) hydantoin (see Figure 3). ^{1}H NMR (DMSO-d6) δ 1.28 (6H), 2.65 (4H), 3.40 (4H), 4.31 (2H), 4.39 (2H), 8.28 (1H); ^{13}C NMR (DMSO d_6) δ 24.8, 54.5, 57.6, 57.8, 59.2, 156.2, 178.7; IR (KBr) 1295, 1346, 1439, 1710, 1764, 2814, 2974, 3227, 3474 cm^{-1}.

Preparation and testing of polyurethane coatings

To 10g of commercial water-borne acrylic polyol formulation was added 0.7g of the unhalogenated diol monomer, prepared as described above, stirring until dissolution was complete. Then 2.45g of commercial isocyanate formulation was thoroughly mixed in, followed by the addition and mixing of 2.10g of distilled, deionised water. The resulting formulation was immediately spread on to the surfaces of several plastic Petri dishes, which were dried in air at an ambient temperature. The coatings were dry to the touch within four to five hours, but were allowed to cure further overnight at an ambient temperature before further treatment. The coatings were then chlorinated by exposure to commercial bleach (5.25% sodium hypochlorite) at several concentrations for three to twelve hours. After rinsing thoroughly with chlorine-demand-free water, the coatings were dried in air for six hours and then analysed for bound oxidative chlorine using an iodometric thiosulphate titration procedure.

Other coatings prepared in the same manner at the same time (cut to squares of 6.45cm^2 area) were challenged with *Staphylococcus aureus* bacteria for contact times of two hours. This was done by placing 25µl of bacterial suspension between two coated squares. Following quenching of disinfectant action with 0.02N sodium thiosulphate in a vortexed solution in a beaker, serial dilutions of the vortexed solution were plated on to trypticase soy agar, incubated for 48 hours at 37°C, and colony counts were made. Unchlorinated coatings served as controls. The analytical and microbiological evaluations were performed as a function of chlorination concentration and of time following chlorination.

In another experiment, strips of unhalogenated coatings were deposited on the stall doors of a rest-room at Tyndall AFB. Half of the strips were chlorinated with diluted bleach (20%) with the damp strips being thoroughly rinsed with water after five minutes; the other half were not chlorinated to serve as controls. After three months, sterile cotton swabs were used to challenge the strips with 9mµl aliquots of between 10^6 and 10^7CFU/ml of *Pseudomonas pseudoalcaligenes* JS45, and then again after six months without rechlorination. After contact times of five minutes, sterile cotton swabs moistened with sterile buffer were used to recover bacteria from the test sections. The recovered bacteria were inoculated on to trypticase soy agar plates, which were incubated at 30°C for 38 hours before colony enumeration.

Finally, polycarbonate strips were coated with the polyurethane and placed in a biofilm reactor at the Center for Biofilm Engineering at Montana State University; uncoated strips served as controls. Water containing nutrients which support biofilm growth was flowed through the reactor at a shear stress simulating a flow of 1ft/s (30.48cms^{-1}) in a four-inch pipe. After five weeks substantial biofilm development had occurred on all strips. At that time the water was doped with 1.0 to 1.2mgl^{-1} of free chlorine, and the flow was continued for five more weeks with the behaviour of the biofilms on the strips caused by planktonic bacteria continuously monitored microbiologically.

Results and Discussion

The data for *S aureus* inactivation are presented in Tables 1 and 2. Table 1 shows that a complete inactivation of the bacteria (>4.5 logs) in two hours of contact time was obtained after 5% and 10% bleach solutions were used for chlorination for three hours, and a 3.0 log inactivation occurred following exposure of the coating to 1% bleach solution for three hours. This was consistent with the trend of Cl atoms/cm^2 determined analytically for the three types of samples.

Table 1. Biocidal efficacy as a function of chlorination concentration

Bleach concentration in water (%)[a]	*Cl atoms/cm^2 surface*	*Log reduction* S aureus
10	1.34×10^{17}	>4.5 (no growth)
5	9.13×10^{16}	>4.5 (no growth)
1	3.69×10^{16}	3.0

a Household bleach containing about 5.25% sodium hypochlorite

Table 2 shows that the coatings retained their biocidal efficacies for at least 14 days (longer times were not tested in this particular experiment). It has also been demonstrated that biocidal

Table 2. Coating chlorine loadings and biocidal efficacies as a function of time following chlorination with 100% bleach for 12 hours

Time after chlorination in days	*Cl atoms/cm² surface*	*Log reduction* S aureus
0.25	3.53×10^{17}	>4.7 (no growth)
4.0	6.78×10^{16}	>4.7 (no growth)
14.0	2.33×10^{16}	>4.7 (no growth)

efficacy can be regenerated, once lost, by re-exposure to free chlorine solutions.

The results of the rest-room stall experiment performed at Tyndall AFB were very gratifying. No viable bacteria were recovered from the polyurethane strips which had originally been chlorinated even after six months without recharging. Viable bacteria were recovered from the control strips which had not been chlorinated.

Also gratifying were the results of the biofilm reactor study at Montana State University. When the small amounts of free chlorine (1.0 to 1.2mgl^{-1}) were present in the flowing water, the strips containing the polyurethane coating yielded 1 to 2 logs fewer biofilm microorganisms than did the polycarbonate strips not containing a polyurethane coating. Figure 4 contains photographs showing the polycarbonate strips with and without the polyurethane coating. The polycarbonate slides were subjected to biofilm formation over a period of five weeks in the presence of about 1mg/L free chlorine.

Figure 4: Polycarbonate annular reactor coupons used in the biofilm prevention study; the coupons contain the biocidal polyurethane coating (top) and no coating (bottom)

Conclusions

A novel hydantoinyl diol monomer has been prepared in a simple, inexpensive process. The monomer has been copolymerised with a commercial water-borne acrylic polyol and a commercial isocyanate to produce a polyurethane coating. The cured coating can be chlorinated with a source of free chlorine, such as household bleach, to render it biocidal. The coating loses its chlorine loading gradually, but it can be regenerated by further exposure to free chlorine. The biocidal coating should have many applications, including use in medical facilities, in food preparation areas, in prevention of biofouling, etc.

Acknowledgments

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