

The Institute of Paper Chemistry

Appleton, Wisconsin

Doctor's Dissertation

**The Design, Preparation, Characterization, and
Preliminary Reactions of an Insoluble Lignin Model**

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June, 1986

THE DESIGN, PREPARATION, CHARACTERIZATION, AND PRELIMINARY
REACTIONS OF AN INSOLUBLE LIGNIN MODEL

A thesis submitted by

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in partial fulfillment of the requirements
of The Institute of Paper Chemistry
for the degree of Doctor of Philosophy
from Lawrence University
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ABSTRACT

A heterogeneous (insoluble) lignin model which contains a basic reactive unit of lignin attached to a cross-linked polymer network has been prepared. Such a polymer-support model incorporates various polymeric characteristics which may more adequately mimic a chemically reacting lignin.

Three lignin model dimers have been synthesized toward the preparation of the heterogeneous model. These unique lignin-related compounds are: 1-(4-hydroxy-3-methoxy-5-[γ -hydroxypropyl]-phenyl)-2-(2,6-dimethoxy-4-methylphenoxy)ethanol (I), 4-hydroxy-3-methoxy- β -(2-methoxy-4-[γ -hydroxypropyl]phenoxy)-acetophenone (II), and 2-(2-methoxyphenoxy)-1-(3-methoxy-4-hydroxyphenyl)-1,5-pentanediol (III).

Each new model is similar to lignin models which have been routinely studied, but unique in that they all incorporate a propyl alcohol handle into their respective dimer, each at a different position. The handle was incorporated so that the model could be attached to a polystyrene matrix via a polymer-bound triphenylmethyl (trityl) ether.

The propyl alcohol handle of compound I resisted soluble tritylation, presumably because of the configuration between the phenol and primary hydroxyl, and, therefore, I was not appropriate for polymer attachment. Both phenacyl aryl ether II and β -aryl ether III, however, were easily tritylated; either compound was thus appropriate for polymer-bound tritylation.

Compound III was attached to a macroreticular polystyrene by means of a polymer-bound trityl to primary hydroxyl bond. The polymer-supported dimer thus constituted an insoluble lignin model; the extent of model loading was determined by gravimetric analysis and Zeisel methoxyl content analyses.

Subsequently, the insoluble model was reacted under simulated kraft pulping conditions to afford moderate yields of guaiacol, a fragmentation product. The addition of 28.5% p-dioxane or DMSO drastically depressed the yield of guaiacol from the insoluble model. The trityl ether attachment was not as alkali-stable as its soluble counterpart and, therefore, portions of the guaiacol production from the insoluble model are from homogeneous reactions.

The behavior of the insoluble model was compared to the homogeneous reactions of the analogous soluble tritylated analog of III, as well as to the reactions of soluble III itself. The soluble tritylated III degraded in a manner similar to other β -aryl ether models.

However, compound III underwent cyclization reactions which competed with ordinary fragmentation; the nonderivatized primary hydroxyl cyclized by capturing quinonemethides (which are key reactive intermediates in the reactions of β -aryl ethers). The nonderivatized handle of III may yet prove useful as an internal mechanistic probe, in an attempt to differentiate between ionic and electron-transfer reaction mechanisms.

INTRODUCTION

Lignin is a random, three dimensional, cross-linked polymer which is based upon p-coumaryl-, coniferyl-, and sinapyl alcohols.¹ Native lignin is deposited between the cells and throughout the cell walls of woody tissue.^{2,3} Lignin in wood is insoluble in neutral solvents,⁴ presumably because of its high molecular weight and because the polymer is locked into the macroscopic continuum of wood by lignin-lignin covalent bonds.²

The goal of the chemical pulping of wood is to selectively remove the insoluble lignin. Reaction rates and mechanisms of chemically reacting lignin are generally very difficult to quantify and characterize because reactions of lignin are usually heterogeneous, that is to say, there are at least two dissimilar phases involved.^{5,6} The phases involved during pulping consist of solid- or gel-liquid interfaces of lignin and pulping liquor;⁷ this concept is supported by findings that lignin dissolution is accelerated when large surface areas are exposed to cooking liquor and decelerated when the interface available for reaction is decreased.⁸

Lignin model compounds are designed to approximate the chemical reactivity of the predominant structural units in lignin while avoiding the experimental difficulties associated with the complex structure of the polymer. The model compounds are generally soluble in the reaction medium, are chemically distinct, and products from their chemical reactions are relatively simple to detect and measure.

Lignin models are favorably regarded as a tool with which the basic underlying chemistry of delignification can be elucidated. It is questionable, however, whether these simple, soluble models can mimic the various polymeric

characteristics of a chemically reacting native lignin. A review of some general aspects of heterogeneous reactions will highlight the limitations of simple model compounds.

CHARACTERISTICS OF REACTIONS OCCURRING AT SOLID- OR GEL-LIQUID INTERFACES

Accessibility

In any chemical reaction involving a solid polymer, the degree to which the polymer molecules are available to the reagents determines the ease and extent of the reaction. With this concept in mind, Nakano and Schuerch compared the rates and extent of chlorination of soluble model compounds, spruce lignin, and wood meal.⁹ Chlorine substitution on the soluble model compounds was comparatively fast in all solvents, whereas the rate of chlorine substitution observed with the spruce lignin or wood meal was relatively slow, except when performed in good lignin solvents. Specifically, for example, the rate of chlorination of lignin in wood meal by aqueous chlorine was quite slow, while soluble phenols reacted instantaneously with chlorine water.^{9,29}

Based on the data above, it appears that water is a poor lignin solvent, and at least for chlorination, the physical process of diffusion is rate controlling.²⁶ However, even in cases when diffusion is not a limiting factor and there is sufficient solid-liquid interface for reactions to proceed, the mobility of reactive units at the surfaces of the solid phase must be considered.

The effects of different solvent systems on the "availability" of molecules covalently bound to insoluble polymer matrices has been studied extensively.^{24,25} In general, those solvent systems which swell polymer matrices the most will impart the greatest mobility and thus availability of reagents to surface bound

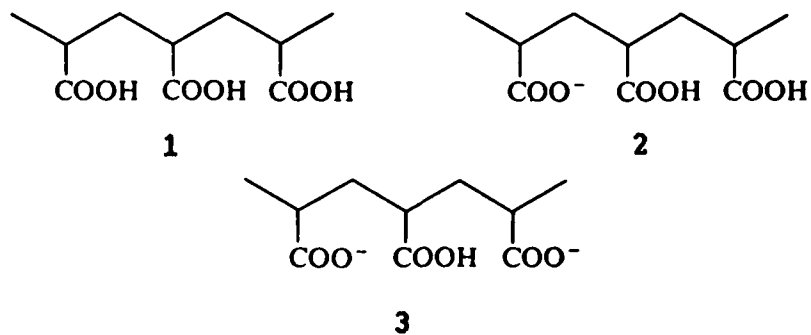
molecules. Also, the restricted mobility of the insoluble component of the reaction imposes a loss in entropy on the transition state of such a reacting system.^{10,11}

In the case of alkaline pulping, native lignin exhibits very little swelling in aqueous alkali.^{7,22} During the initial stages of delignification, particularly at lower temperatures, the lignin at the solid- or gel-liquid interface has a restricted mobility - a molecular inflexibility.²² The physical restraints on swelling and molecular mobility may make it more difficult to form key intermediates or transition state complexes and represent a resistance to delignification.

Microenvironmental Effects

Polyelectrolytic behavior must be kept in mind when investigating heterogeneous reactions. A simple example of a polyelectrolytic neighboring-group effect is seen in the ionization of carboxylic acid groups on a polymeric molecule, such as in polyacrylic acid. Qualitatively, the ease of proton release will decrease as the degree of ionization increases because the polymer backbone becomes progressively more negatively charged. The acidity of a carboxylic acid flanked by two un-ionized groups should be greater than those flanked by one or two ionized groups (Fig. 1).^{12,31}

Moreover, the acidity of polymer-bound carboxylic acid and phenol can be mutually influenced by hydrogen-bond formation between the two (Fig. 2).^{12,32} The hydrogen bond formed between the phenol and ionized acid group is stronger than with the un-ionized acid. The acidity of the carboxylic acid is thus enhanced, while that of the phenol is reduced.



$$K_1 > K_2 > K_3$$

Figure 1. Relative acidities of carboxylic acid groups on a polymer.^{12,31}

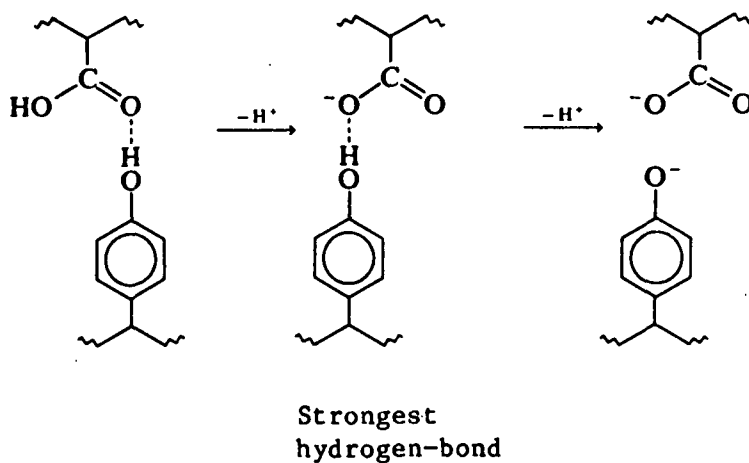


Figure 2. Neighboring-group effect with polymer-bound carboxylic acids and phenols as neighbors.^{12,32}

In the instance of pulping, Schuerch has postulated an effect, called the ion-exclusion effect, which is similar to the neighboring-group effect and which may be operative during delignification processes.²⁶ Schuerch was specifically looking at the sulfite process, but the conceptual scheme may be valid for alkaline pulping.

During alkaline pulping processes, the degrading lignin becomes negatively charged. The reactive pulping chemicals in alkaline processes are themselves negatively charged species, namely hydroxide ion (OH^-), hydrosulfide ion (SH^-), and anthrahydroquinone dianion (AHQ^{2-}).

According to the Donnan equilibrium effect, polyelectrolytes tend to electrostatically exclude ions of the same charge; this leads to an unequal distribution of diffusable ions around the polyelectrolytic domain.³⁰ The polyelectrolytic nature of partially degraded lignin may tend to repel negative ions and prevent the completion of reactions by this Donnan equilibrium or "ion-exclusion" effect.

Lignin model compounds are not polymeric in nature; rather they are usually aliphatic-aromatic monomers or dimers, and they are generally soluble in the reaction media of interest. It seems clear that simple models cannot mimic the polymeric characteristics of a chemically reacting lignin. In light of the inadequacies of simple models, and considering the difficulties in characterizing reactions as they occur in actual lignin, we initiated thesis research to design an insoluble/heterogeneous lignin model.

THESIS OBJECTIVES

The goal of the thesis was to design, synthesize, and characterize a heterogeneous/insoluble lignin model. The heterogeneous model was to be comprised of a basic reactive unit of lignin, a β -aryl ether dimer,¹ covalently attached to a polymer network by means of a polymer-bound protecting group.^{13,14} The model would be used to study lignin fragmentation reactions relative to soluble models.

The insoluble model has the advantages of (1) a definable structure, which actual lignin does not, and (2) the incorporation of various polymeric characteristics, which simple models lack.

EXPERIMENTAL APPROACH

A macroreticular polystyrene was functionalized to a polymer-bound triphenylmethyl (trityl) chloride and characterized by elemental analyses. This functionalized resin would be used to preferentially form a trityl ether linkage with a primary alcohol group on a lignin model.^{28,29} Such groups (propyl alcohol handles) were incorporated into several reactive lignin model dimers; the synthesis of these unique compounds proved to be the most formidable portion of the thesis.

A heterogeneous model was prepared from one of the appropriate lignin dimers and was characterized (as to the extent of loading) by gravimetric analyses and Zeisel methoxyl content analyses. This heterogeneous model was subsequently reacted under kraftlike pulping conditions and the results were compared to the reactions of analogous soluble lignin dimers.

ADDITIONAL BACKGROUND INFORMATION

Polymer-bound Protecting Groups

The last two decades have seen the rise in popularity of the simple, yet far-reaching idea of attaching chemically reactive species to insoluble supports.¹⁵ The most popular support is generally cross-linked polystyrene, of various cross-link ratios and morphologies. Premanufactured polymer-supports, often called resins, are available in both functionalized and unfunctionalized forms from various suppliers. Functionalized polystyrene resins are obtained

by either (1) polymerizing styrene and divinylbenzene along with a functionalized monomer, or (2) performing reactions on premade polystyrene.¹²

Functionalized polymers, often in the form of polymeric analogs to protecting group (organic derivative) reagents, have been used extensively during the synthesis of various kinds of molecules. For example, a polymer-supported triphenylmethyl (trityl) chloride preferentially forms an alkali-stable polymer-supported trityl ether at the primary hydroxyl (C-6) of a monosaccharide.^{17,18} Chemists have prepared glycosides, di- and trisaccharides, as well as a variety of other modified carbohydrate molecules from monosaccharides attached to a polymer at C-6. The supported ether linkage can be hydrolyzed with acid after the chosen synthetic procedures are complete to liberate the modified product into the bulk solution phase.^{13,14,18}

Morphology of Polymer Supports

Cross-linked polystyrene supports can be prepared or purchased with a variety of physical characteristics, generally in bead form and with a thermal stability of 250°C or greater. Most polystyrene supports are prepared by the "suspension copolymerization" of styrene and divinylbenzene, differing in the type or amount of solvent in which the polymerization is carried out. There are basically three general categories in which most cross-linked polystyrene resins can be classified.^{12,16,19,20}

Microporous gel-type resins have negligible internal surface area and dry porosity, and they will not accept "nonsolvents" (solvents which do not solvate styrene). However, upon addition of a good solvent, such as benzene or toluene, considerable porosity is reestablished; the microporous gel can swell because the cross-link ratio (% divinylbenzene) is commonly 2% or less. With nonsolvent

systems (water, aqueous alkali, methanol and others) these resins display little tendency to expand, and the transport of reagents within such an interior is analogous to a diffusional process within a polymer solid.

Macroporous gel-type resins are similarly swellable in appropriate solvents (though not as much as microporous gels because the cross-link ratio is commonly 20% or more). They have a moderate dry porosity and internal surface area, allowing the penetration of some nonsolvents (methanol, heptane, acetonitrile, but not water or aqueous alkali) into their internal voids.

Macroreticular resins have a definitive and permanent internal porous structure with a well defined surface area. They will absorb significant quantities of all solvent systems by simply filling the available voids, although they do not exhibit significant swelling with any solvent. Macroreticular resins can be envisioned as spongelike, where the interior volume is responsible for the absorption of liquid and the highly entangled volume of polymer material is penetrated only by a good solvent.

A relatively new type of polystyrene, which is not prepared by suspension copolymerization, has some interesting properties. Macronet isoporous gels are made by cross-linking linear polystyrene.²¹⁻²³ These gels have the ability to increase their volume in any solvent to give a high interior surface area. Macronet gels are not currently commercially available, and information on their physical and thermal stability is not widely known.

A macroreticular polystyrene, Amberlite XE-305, was chosen for the purposes of this thesis.³³ Polystyrene resembles lignin, superficially at least, in that it is an aliphatic-aromatic polymer. This particular resin should allow all aqueous pulping reagents to come into contact with polymer-bound lignin models; the

pores are very large (1000 Å) relative to the size of alkaline pulping reagents and should reduce the potential importance of diffusion as a limiting process.

DESCRIPTION OF THE DISSERTATION FORMAT

The format of this manuscript consists of the thesis introduction, as above, followed by two articles prepared for publication. The articles include their own introductions, the significant results of the thesis, and the experimental methods employed to obtain the results. Following the articles are general thesis conclusions and suggested future work, and two brief appendices.

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INSOLUBLE LIGNIN MODELS (I): SYNTHESIS OF UNIQUE LIGNINLIKE
DIMERS WITH PRIMARY ALCOHOL HANDLES

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ABSTRACT

Three unique lignin model dimers, compounds 10, 11, and 12b, have been synthesized; each was designed to have a propyl alcohol handle by which the model could be attached to a polymer matrix via a polymer-bound trityl ether. Compound 10, which has a γ -hydroxypropyl group ortho to a phenol, could not, however, be tritylated. Phenacyl aryl ether 12b, which has a para γ -hydroxypropyl group on the phenoxy substituent, was easily tritylated. The β -aryl ether 11, which has a γ -hydroxypropyl group incorporated through the alkyl β -carbon, was also tritylated in a straightforward manner and has subsequently been used for the preparation of a polymer-bound lignin model dimer.

INTRODUCTION

In order to elucidate the role(s) of various chemicals in removing lignin from wood (delignification), researchers have quite often examined the reactions of lignin model compounds. These simple models are designed to simulate the chemical reactivity of the predominant reactive units in lignin and, thereby, to avoid experimental difficulties associated with the complex, random, cross-linked structure of the polymer.¹ Extensive studies employing model dimers, such as structures 1 and 2 (Fig. 1) have provided an abundance of information about the possible reactions of lignin during alkaline pulping.²⁻⁴

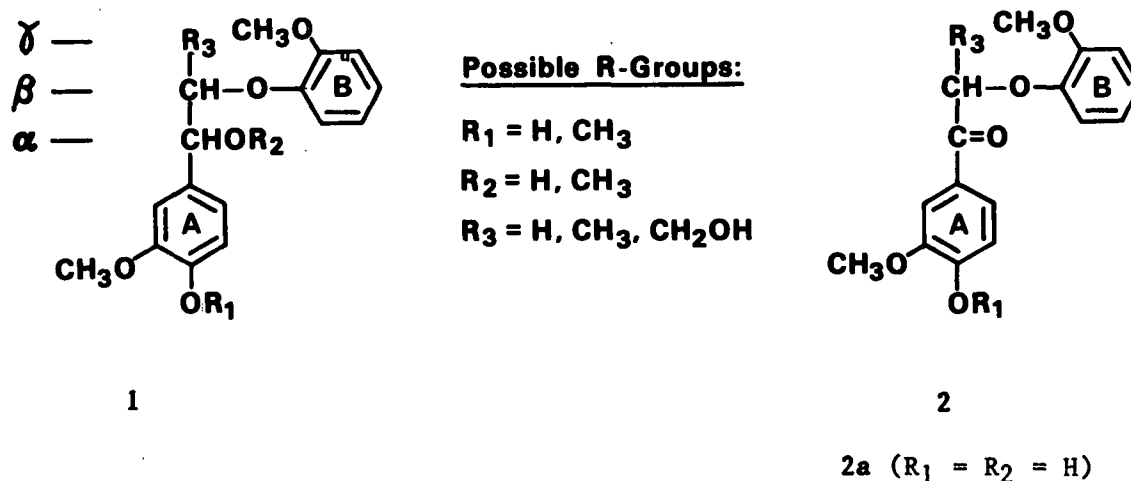


Figure 1. General lignin model dimers, with aryl rings A and B, and side-chain positions α , β , and γ annotated.

The objective of our recent synthetic efforts has been to prepare lignin model dimers which are attached to an insoluble polymer matrix; a lignin model dimer covalently bound to a polymer would constitute a heterogeneous (insoluble) lignin model which may provide the lignin chemist with an additional method by which to study alkaline delignification. The synthesis of polymeric lignin model compounds requires lignin model dimers similar to the "conventional" lignin dimers illustrated in Fig. 1, but unique in that they include a primary alcohol side-chain incorporated onto the molecule at either ring A or B, or through the β -position. This report describes the model syntheses; a publication to follow describes the polymer model syntheses, characterization, and reactions.⁶

The impetus behind preparing these unique types of models is that primary alcohols can be preferentially derivatized in the presence of secondary and tertiary alcohols and phenols, with alkali-stable/acid labile triphenylmethyl (trityl) ether protecting groups.⁷ Polymer-supported trityl chlorides are easily prepared and provide a means to bond primary alcohol substrates to a polymer. This technique has frequently been used to immobilize monosaccharides

by forming the polymer-bound trityl ether at the C-6 hydroxyl.^{8,9} Likewise, it should be possible to covalently attach a lignin model containing a primary alcohol handle to an insoluble polymer backbone via a polymer bound trityl ether.^{10,11}

The two principal considerations which need to be addressed when designing a model with a primary alcohol handle are the location and the length of the handle. These considerations are, of course, complicated by the restrictions of synthetic ingenuity and convenience, and by the type of lignin dimer that is to be studied.

The most predominant reactive unit in lignin (and the type of most interest to this study) is the β -aryl ether unit.¹ The general alkaline pulping chemistry of β -aryl ethers is demonstrated by reactions of simple model 3,^{2,3} as illustrated in Fig. 2. During alkaline pulping, models such as 3 (and presumably lignin as well) give rise to vinyl ethers 4 and, in the presence of certain additives, cleavage products - a styrene phenolate ion 5 and a simple phenolate ion 6.

The inherent chemistry of the heterogeneous β -aryl ether model should be unaffected by the polymer linkage. The attachment should not sterically hinder the usual reactions, should survive alkaline pulping conditions, and should be easily detached by acid hydrolysis.

Three different types of β -aryl ether structures, which would constitute lignin dimers with primary alcohol handles, are illustrated in Fig. 3. If the handle (and subsequent polymer attachment) is on the A-ring (7) or through the β -position (8), an alkaline β -ether fragmentation reaction of the polymer-bound model would liberate into solution a simple phenol, which should be easily quantified.¹² Conversely, a polymer attachment through the B-ring (9) would liberate,

upon fragmentation, a compound analogous to 5 which, because it is a styrenelike molecule, can polymerize and may thus be difficult to analyze quantitatively.

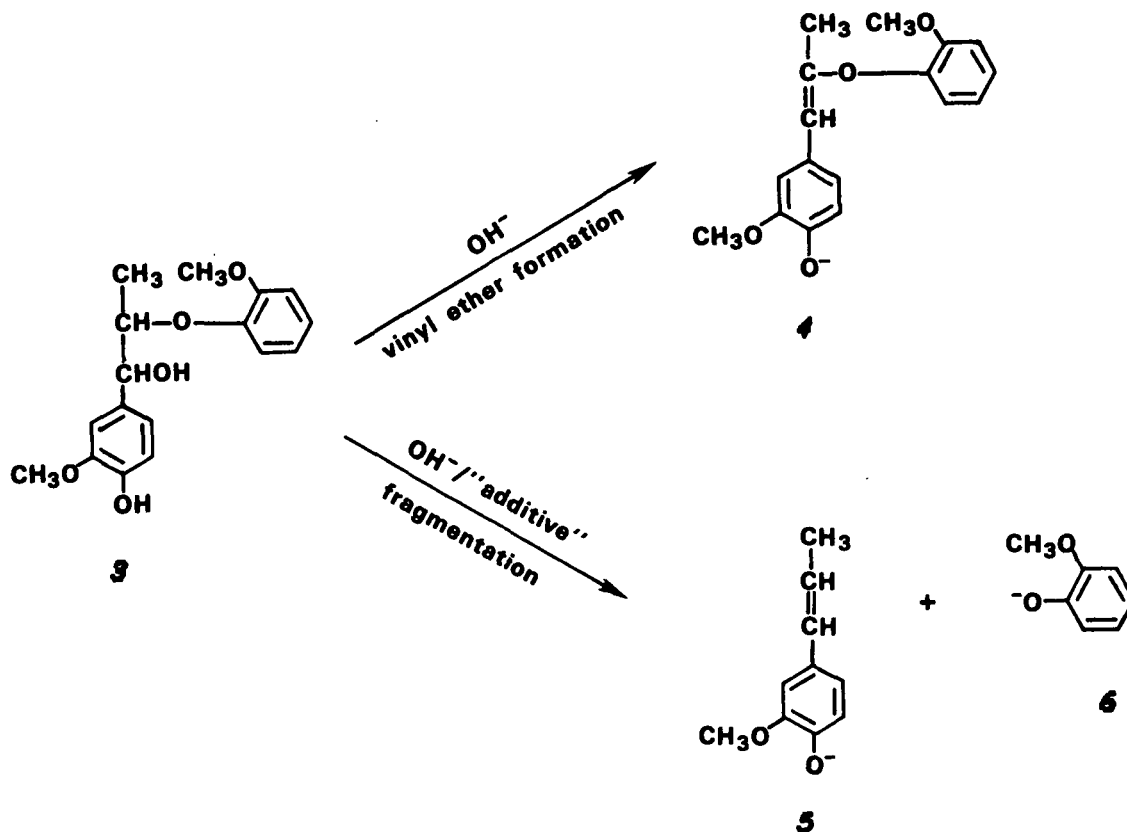


Figure 2. Generalized alkaline reactions of β -aryl ether 3, with and without "additives."

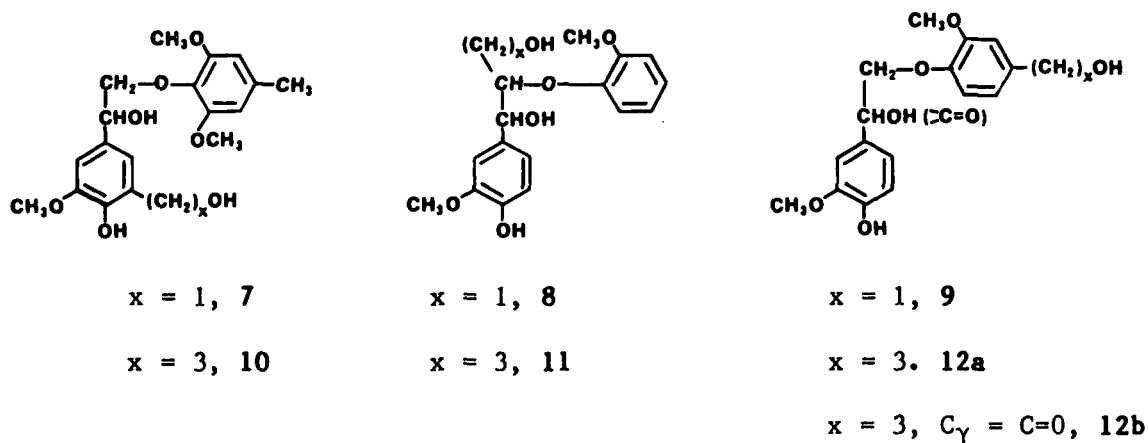


Figure 3. Three β -aryl ether dimers with primary alcohol handles.

A suitable length for the alkyl side-chain ($[\text{CH}_2]_x$) of the handle, was chosen on the basis of two factors. The trityl ether is a large protecting group; in order to prevent steric interference with the anticipated delignification chemistry it was decided that an appropriate alkyl side-chain $[\text{CH}_2]_x$ should have $x > 1$. Additionally, an examination of the possible alkaline chemistry of the tritylated versions of 7, 8, and 9 (when $x = 1$) reveals that the trityl ethers may not maintain their expected alkaline stability. Structures 7 and 9 are set-up for detritylation via ortho- or para-quinonemethide generation (Fig. 4a and 4b); similarly, the vinyl ether analog of 8 is also a likely candidate for premature detachment via quinonemethide generation (Fig. 4c), because the γ -carbon is a "vinylogous" benzyl carbon.

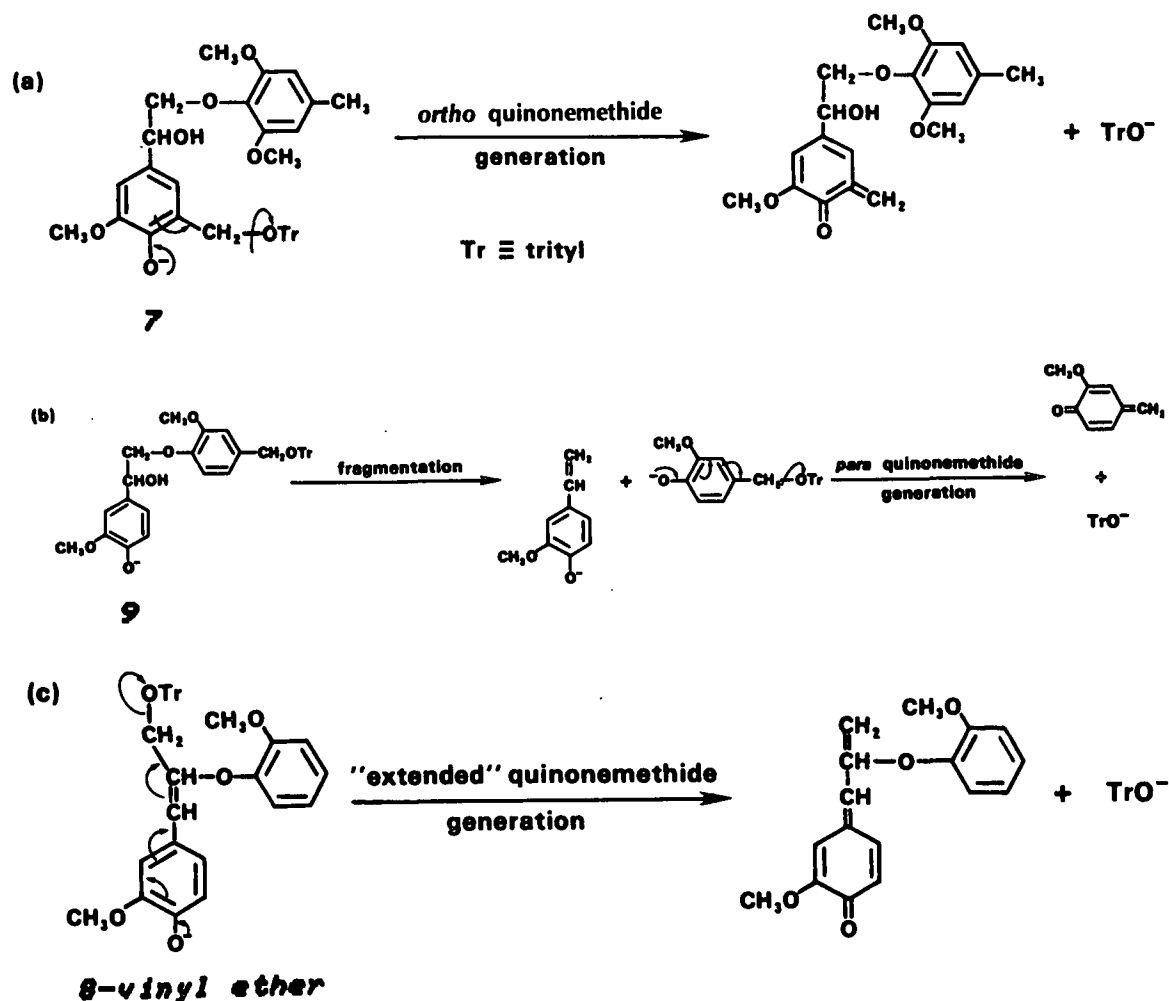


Figure 4. Possible alkali-promoted detritylation reactions of three tritylated lignin model dimers.

Finally, after a consideration of the above-mentioned factors and an overview of possible synthetic schemes, we decided that the synthesis of compounds 10, 11, and 12a (when $x = 3$ inch $[\text{CH}_2]_x$) would be the objective of our study. Each of these compounds with primary alcohol handles should be appropriate for the eventual preparation of insoluble lignin models.

RESULTS AND DISCUSSION

A-Ring Handle Model

Preparation of Compound 10

An ideal synthetic scheme for our purposes would be a generic procedure which would start with any of a variety of already prepared conventional lignin dimers and add a propyl alcohol handle to it. Scrutiny of possible synthetic routes to an A-ring handle model directed our attention toward coumarin syntheses (Fig. 5.)^{13,14} Coumarin-type structures, their precursors, and reduction products all resemble the desired A-ring handle model 10, in that they include an ortho configuration between a phenoxy oxygen and a three-carbon alkyl-oxy side-chain.

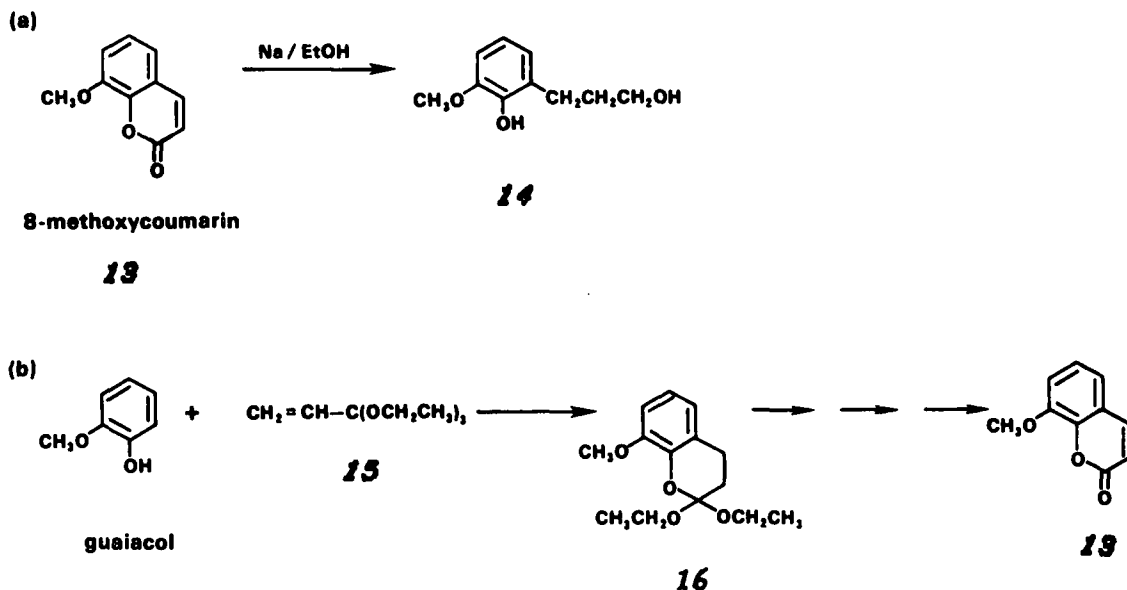
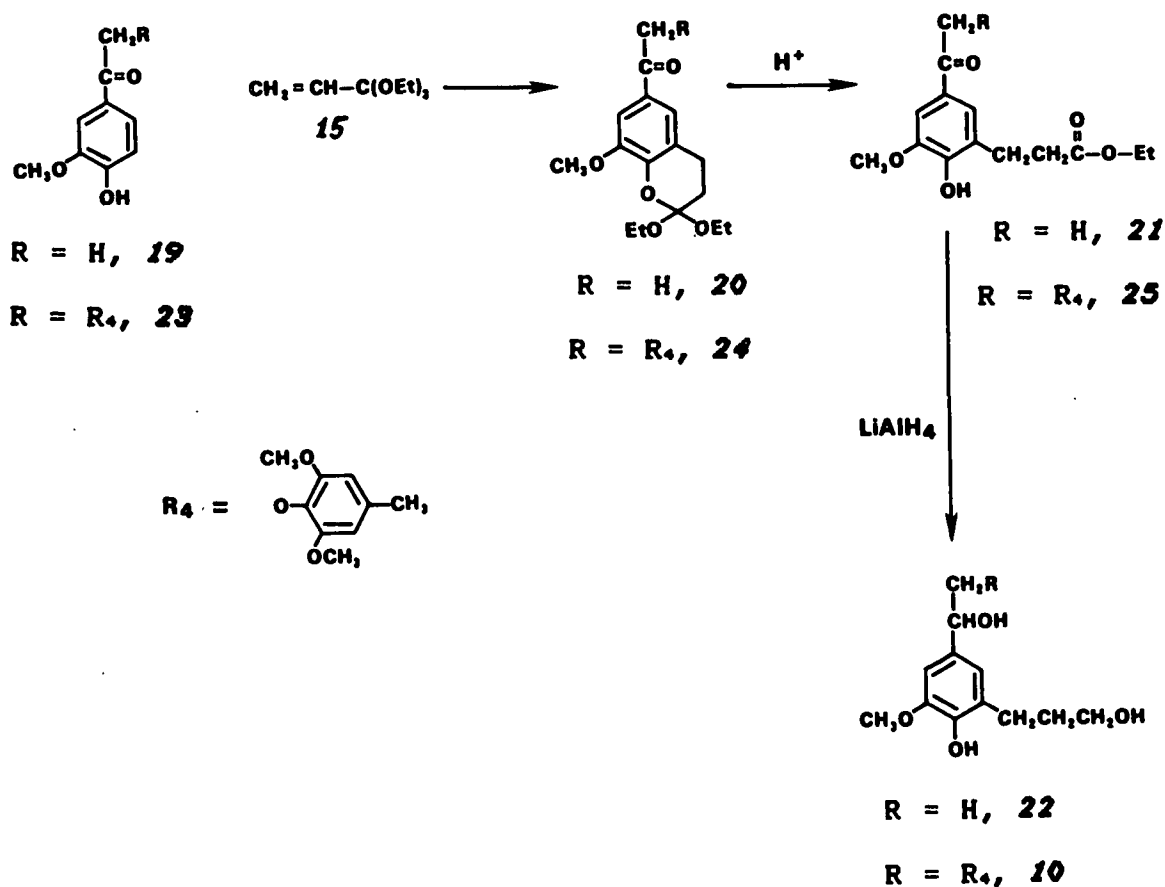


Figure 5. A) Structure of 8-methoxycoumarin (13) and its Bouveault-Blanc¹⁴ reduction product (14). B) Generalized schematic of Panetta and Rapoport's¹⁵ coumarin synthesis.

Portions of a recently described coumarin synthesis appear suitable for our synthetic requirements. Panetta and Rapoport report that when triethylorthoacrylate is reacted with guaiacol, the 2,2-diethoxychroman 16 is formed (Fig. 5b).¹⁵ If a diethoxychroman structure can be prepared with a para-acyl phenol, the synthesis of the desired A-ring handle model 10 appears possible (Scheme 1).



Scheme 1. Adaptation of Panetta and Rapoport's¹⁵ coumarin synthesis for the introduction of a propyl alcohol handle to acetoguaiacone (19) and lignin dimer 23.

Scheme 1 was attempted initially with a readily available para-acyl phenol, acetoguaiacone (19). The diethoxychroman 20 was indeed formed in excellent yield (ca. 74%) and was subsequently hydrolyzed with HCl to give the ester 21. The simultaneous reduction of the α -carbonyl and ethyl ester of 21 was effected with

LiAlH_4 in THF giving compound 22, a lignin model monomer with a primary alcohol handle.

Similarly, the phenacyl β -aryl ether 23 was subjected to the identical synthetic sequence. (Conventional lignin model 23 can be prepared by any one of several routinely used synthetic coupling techniques.^{16,17}) The desired compound 10 was successfully prepared in an overall yield of 58% (3-steps, from 23). This synthetic sequence should be applicable for introducing a primary alcohol handle to a variety of other lignin dimers with different β -aryl groups and/or β -alkyl substituents.

Tritylation of Compound 10

The preferential tritylation of the propyl alcohol handle (using either a soluble or polymer-bound tritylating reagent) is central to the usefulness of the unique lignin dimer 10. However, reaction of 10 with trityl chloride/pyridine^{7,18} or tritylpyridinium tetrafluoroborate (TPFB)¹⁹ failed to give a tritylated product. Similarly, the simpler monomer 22 could not be tritylated.

This resistance toward tritylation is in stark contrast to the behavior of another phenolic compound with a primary alcohol handle; 3-(3-methoxy-4-hydroxyphenyl)-1-propanol (27), was easily tritylated using the TPFB method. A possible explanation for the unexpected behavior of compounds 10 and 22 could be that the primary alcohol group is deactivated toward tritylation because of an intramolecular hydrogen bond between the phenol and primary hydroxyl (involving an eight-membered ring). Alternatively, the trityl ether may have indeed been formed, but subsequently hydrolyzed by an intramolecular proton transfer from the phenol.

Clearly, the unexpected behavior of lignin dimer 10 limits its potential utility. Variation of the original synthesis (Scheme 1) could make tritylation of a modified 10 possible. Prior to the LiAlH_4 reduction of structure 25, the phenol could be protected with a β -(trimethylsilyl)ethoxymethyl (SEM) ether.²⁰ The protected phenol dimer could be reduced and then tritylated. Selective removal of the SEM group would then be accomplished by treating with fluoride ion. While this modified approach seems promising, the course of the research progressed toward alternative models rather than pursuing the above-mentioned variation.

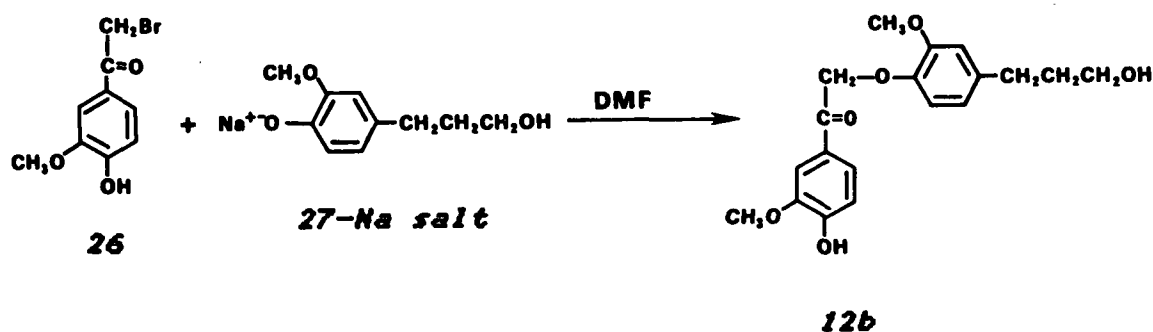
B-Ring Handle Model

Preparation of Compound 12b

As mentioned previously, the alkaline fragmentation of a polymer-bound model based on dimer 12a would liberate a styrenelike molecule which may be difficult to analyze quantitatively. Alternatively, a B-ring handle model which has an α -carbonyl rather than an α -hydroxyl (such as structure 12b - a phenacyl β -aryl ether) could be studied. The alkaline degradation of phenacyl aryl ethers are also of interest to lignin chemists;²¹ the alkaline fragmentation of a polymer-bound 12b should liberate acetoguaiacone (19) which can be easily quantified.

Compound 12b was prepared using procedures which have been commonly employed for the preparation of other lignin model dimers. Employing the method of Hosoya, et al.,¹⁶ acetoguaiacone was brominated on the β -carbon to give 26, which was coupled with the sodium salt of 3-(3-methoxy-4-hydroxyphenyl)-1-propanol (27) resulting in ketone 12b in ca. 60% yield (Scheme 2). (Although it was not prepared, β -aryl ether 12a should be easily made by employing a NaBH_4 reduction

procedure.⁵⁾ The precursor 27 was prepared via a two-step synthesis from ferulic acid. The latter was easily hydrogenated over palladium on carbon and the resulting dihydroferulic acid reduced with borane-tetrahydrofuran complex (or LiAlH_4) to give precursor 27.



Scheme 2. Coupling reaction¹⁶ giving lignin model dimer 12b, which has a propyl alcohol handle on the B-ring.

Tritylation of Compound 12b

Compound 12b was tritylated in a straightforward manner employing the TPFB method;¹⁹ after a chromatography the yield of 12b-Tr was a modest ca. 35%. (Similarly, we would expect compound 12a to be tritylated without complication.)

Beta-Position Handle Model

Preparation of Compound 11

The alkylation of lignin dimers (such as 2a) with methyl or hydroxymethyl groups at the β -position is a procedure which has been successfully and frequently employed by Dimmel, et al. (Fig. 6).⁵ Treatment of 2a with a strong base, lithium diisopropylamine (LDA), effectively generates a carbanion at a β -carbon; this nucleophile can be alkylated by methyl iodide to give the methylated product 2b, or by formaldehyde (an aldol condensation) to give the hydroxymethylated product 2c.

The above-mentioned alkylation technique could, perhaps, be adopted as a way to introduce a carbon side-chain (with $X > 1$ in $[\text{CH}_2]_X$) through the β -position of lignin dimer **2a**. Dimmel, *et al.*, found, however, that the scope of this reaction was limited; ethyl, propyl, and benzyl halides would not alkylate **2a**.⁵ Possible explanations for this behavior include the greater bulk of the above halides and the possibility of competing elimination reactions with the ethyl and propyl halides. Nevertheless, allyl bromide might be an effective alkylating agent because of two factors: a competing elimination reaction (by the loss of HBr) is impossible, and the reactivity of allylic substrates is relatively high.²²

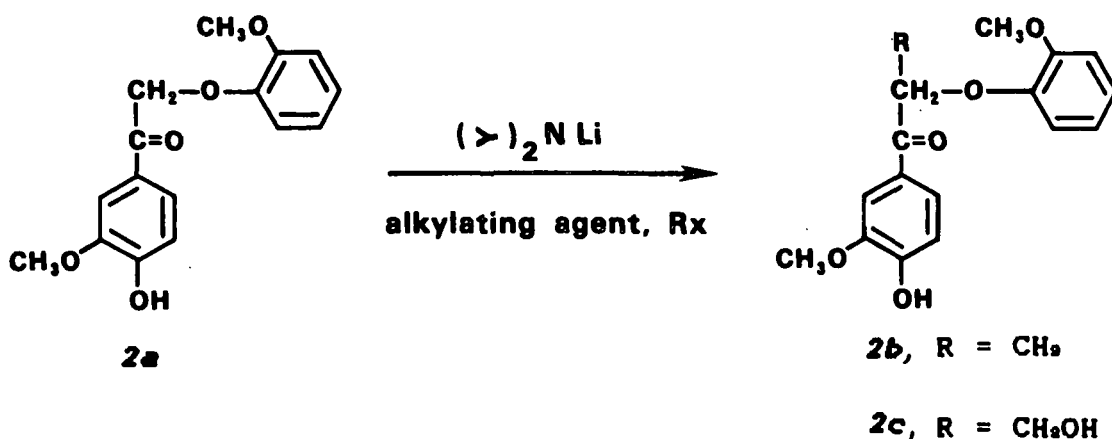


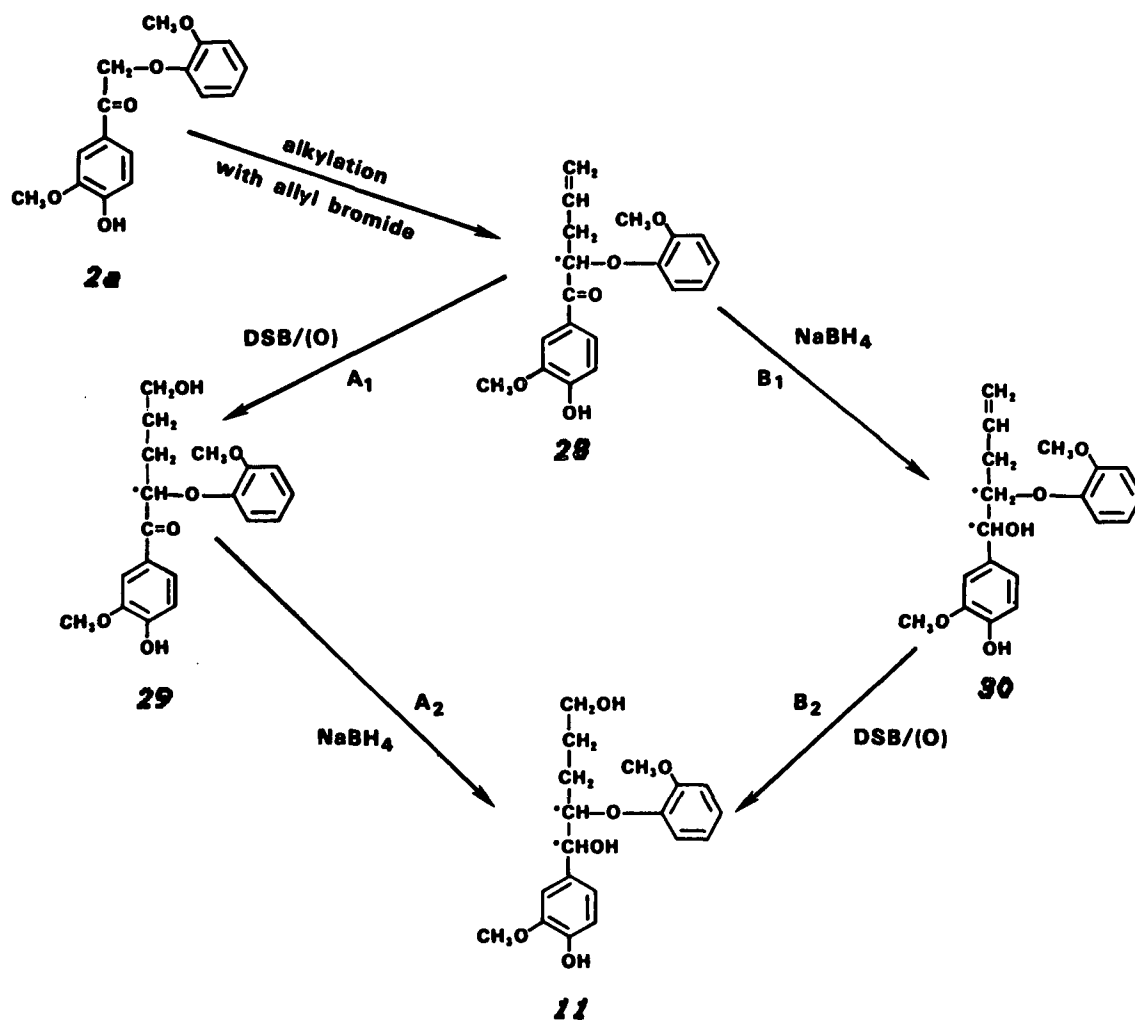
Figure 6. Alkylation of lignin model dimer **2a**.⁵

Indeed, **2a** was alkylated with allyl bromide to give compound **28**. The subsequent transformation of **28** to the desired **11** requires two separate steps: (1) the terminal olefin must be hydroborated and oxidized to give a terminal alcohol (using the stereoselective disiamylborane [DSB] and hydrogen peroxide as the oxidant [O])²³ and (2) the α -carbonyl must be reduced with sodium borohydride.

Transformation of **28** to **11** can be accomplished via either route A or B (Scheme 3); the two routes differ only in the particular order in which the DSB/[O] step and borohydride reduction take place. Either route involves the introduction of a second asymmetric carbon (step 5_2 or B_1) and the likelihood of producing

mixtures of erythro/threo diastereomers. Often, such similar isomers are difficult to separate and/or purify by chromatographic or crystallization methods.

The overall conversion of **28** to **11** was effected via either routes A or B on a small scale. Samples of **11** obtained by route A were chromatographically isolated as oils and, based on spectral evidence, were mixtures of diastereomers. Conversely, the intermediate alcohol **30** from step B₁ was chromatographically isolated as an oil and shown by NMR to be a single isomer (see Experimental). The final step, B₂, converted **30** to the desired **11**; the latter was obtained as a pure, crystalline solid (which was, clearly, also a single isomer).



Scheme 3. Utilization of an alkylation reaction⁵ as the initial step for the preparation of a lignin dimer with a γ -hydroxypropyl handle incorporated through the alkyl β -carbon.

In the case of step B₁, it is not overly surprising that a single isomer was obtained; Cram's rule predicts that, based on steric considerations, a particular diastereomer will predominate for certain additions (such as a hydride ion) to carbonyls which are adjacent to an asymmetric carbon.²⁴ Many reactions of this type are known; in some the extent of selectivity approaches 100%.^{25,26} The sodium borohydride reduction of 28 (step B₁) aptly illustrates this kind of selectivity.

Conversely, the sodium borohydride reduction of 29 (step A₂) apparently must involve factors other than the spatial relationship of substituents on the chiral β -carbon. The primary alcohol of 29 can react with a BH₄⁻ group; thus, a hydride ion can be delivered to the carbonyl carbon from both an intra- and intermolecular hydride source. The borohydride reduction of 29 is, therefore, predictably less stereoselective.

Finally, based upon the fortuitous selectivity of step B₁, the overall synthetic route B was repeated on a multigram scale to afford a quantity of compound 11 which was sufficient for the intended purpose.⁶ The respective yields of products from the large scale synthesis were: alkylation step - 68%, step B₁ - 65%, and step B₂ - 64%, for an overall three-step yield of 11 from 2a of 28%. Compound 11, if easily tritylated, should be a very appropriate lignin dimer with a primary alcohol handle with which to manufacture and study an insoluble lignin model.

Tritylation of Compound 11

The trityl chloride-pyridine method^{7,18} with compound 11 proceeded in a straightforward manner, and the tritylated analog of 11 (11Tr) was obtained as a crystalline solid in ca. 64% yield. Similarly, the analogous polymer-bound

trityl chloride was reacted with 11 to afford a polymer-bound 11.⁶ The preparation and characterization of this insoluble (heterogeneous) lignin model will be described in a publication to follow.⁹

SUMMARY

Three unique lignin model dimers have been prepared. Each new model is similar to lignin models which have been routinely studied, but unique in that they all incorporated a propyl alcohol handle onto their respective dimer, each at a different position.

The synthetic routes leading to β -aryl ethers 10 and 11 are both generic techniques by which to introduce a propyl alcohol handle to a variety of available lignin models. Compound 10, the A-ring handle model, could not be tritylated, presumably due to the unique configuration between the phenol and primary hydroxyl; therefore, compound 10 appears inappropriate for attachment to a polymer via a polymer-bound trityl ether. Conversely, compound 11, the β -position handle model, tritylates in a straightforward manner and appears appropriate for the preparation of a polymer-bound lignin dimer.

Finally, a third synthesis has provided a way to prepare a B-ring handle model, phenacyl β -aryl ether 12b; this synthetic scheme is rather specific, however, and does not add the propyl alcohol side-chain to an already prepared lignin model. Nevertheless, 12b tritylates easily and may be an appropriate substrate for the preparation of a polymer-bound lignin model dimer.

EXPERIMENTAL

General Information

Proton and ¹³C-NMR were recorded on a Jeol FX-100 spectrometer using CDCl₃ or d₆-DMSO as a solvent and TMS as an internal reference. Infrared spectra were

recorded on a Perkin-Elmer Model 700 infrared spectrometer and standardized with polystyrene. Electron impact mass spectra were obtained at 70 eV using a direct insertion probe (DIP) with a Hewlett-Packard 5985 mass spectrometer. Elemental analyses were performed by Micro-Tech Laboratories, Skokie, Illinois.

All solvents employed, unless indicated otherwise, were A.C.S. reagent grade. Reagents and starting materials were obtained from Aldrich Chemical Co., Milwaukee, Wisconsin. All melting points recorded are uncorrected.

4-Hydroxy-3-methoxy- β -(2,6-dimethoxy-4-methylphenoxy)acetophenone (23)

The phenacyl β -aryl ether 23 was prepared according to the general method of Miksche;¹⁷ its specific preparation is detailed elsewhere.²⁷

Triethylorthoacrylate (15)

This reagent was prepared in a manner identical to that used by Stetter and Uerdinger,²⁶ in which triethylorthopropionate is brominated (with Br₂ in pyridine) to give 2-bromo-triethylorthopropionate, which in turn is dehydrobrominated with potassium-*t*-butoxide to give 15.

6-Acetyl-2,2-diethoxy-8-methoxychroman (20)

Into 150 mL toluene was dissolved 15.0 g (90.4 mmol) of acetogualacone (19), 9.2 g (90.4 mmol) of pivalic acid, and 31.5 g (180.8 mmol) of 15. The mixture was refluxed for 24 hours, cooled, and diluted with 300 mL Et₂O. The combined organic layer was separated and washed with 1N NaOH, water, and saturated aqueous NaCl, dried (Na₂SO₄), and concentrated in vacuo to give a gold oil which crystallized upon standing. (Acidification and ether extraction of the NaOH was allowed for the recovery of ca. 0.9 g of starting material.) Recrystallization of the gold solid from hexane gave 19.8 g (74.2%) of light yellow crystals of 20: m.p. 81.0-84.0°C; IR (mull) cm⁻¹ 1680 (C=O); ¹H-NMR

(CDCl₃) δ 1.19 (t, J = 7 Hz, 6 OCH₂CH₃), 2.12 (t, J = 7, Hz, 2, ArCH₂CH₂), 2.55 (s, 3, COCH₃), 2.91 (t, J = 7 HZ 2, ArCH₂), 3.72 (q, J = 7 Hz, 2, OCH₂CH₃), 3.74 (q, J = 7 Hz, 2, OCH₂CH₃), 3.85 (s, 3, OCH₃, and 7.35 (s, 2, aryl).

Ethyl 5-acetyl-2-hydroxy-3-methoxydihydrocinnamate (21)

Into 200 mL of Et₂O was dissolved 12.0 g (40.5 mmol) of 20. To this mixture was added 200 mL of 10% aqueous HCl and the 2 phase mixture was stirred for 2.25 hours. The reaction mixture was separated and the aqueous layer extracted with Et₂O. The combined organic layers were washed with water and saturated aqueous NaCl, dried (Na₂SO₄), and evaporated on a steam cone to give 11.5 g of an oil which hardened upon standing to orange-gold crystals of 21: m.p. 64.0-65.0°C; IR (mull) cm⁻¹ 3350 (OH), 1730 (ester C=O), 1670 (ketone C=O), and 1600 (aryl); ¹H-NMR (CDCl₃) δ 1.22 (t, J = 7, 3, CH₂CH₃), 2.54 (s, 3, ArCOCH₃), 2.67 (t, 2, ArCH₂), 3.08 (t, 2, ArCH₂CH₂), 3.92 (s, 3, OCH₃), 4.13 (q, 2, COOCH₂CH₃), 6.59 (s, 1, OH), and 7.43 (s, 2, aryl).

1-(3-Methoxy-4-hydroxy-5-[γ -hydroxypropyl]phenyl)ethanol (22)

A slurry of 0.86 g (22.7 mmol) of LiAlH₄ in 35 mL of dry, freshly distilled THF was stirred while a solution of 2.0 g (8.8 mmol) of 21 in 35 mL THF was dripped in over 1 hour. The mixture was brought to and kept at reflux for 1.5 hours and then allowed to come to room temperature with stirring overnight. The reaction was quenched by the addition of saturated aqueous Na₂SO₄, until effervescing stopped and a nearly colorless granular solid was obtained. The mixture was filtered through a fine porosity filter funnel and the residue rinsed with fresh, dry Et₂O. The organic filtrate was reduced in vacuo to give 0.5 g of 22 as an oil: IR (neat) cm⁻¹ 3350 (broad, OH), no carbonyl absorbances, and 1600 (aryl); ¹H-NMR (d₆-DMSO) δ 1.28 (d, J = 6 Hz, 3, CH₃), 1.64 (m, 2,

ArCH₂CH₂), 2.53 (t, J = 8 Hz, 2, ArCH₂), 3.40 (t, J = 7 Hz, 2, CH₂OH), 3.76 (s, 3, OCH₃), 4.58 (q, J = 6.5 Hz, 1, ArCHOH), 5.38 (broad s, 3, 3 OH), 6.64 (s, 1 aryl), and 6.75 (s, 1, aryl).

The solid (aluminum salts) residue from above was dissolved in 1N H₂SO₄, and the acidic mixture was extracted with Et₂O. The ether extracts were washed with water, dried (Na₂SO₄), and reduced in vacuo to give ca. 0.3 g of an oil with spectra identical to the product 22 described above.

6-(2,6-Dimethoxy-4-methylphenoxy)acetyl-2,2-diethoxy-8-methoxychroman (24)

Compound 23 was subjected to the identical procedure for preparing diethoxychromans (as described above) with the following quantities: 12.0 g (32.1 mmol) of 22, 1.64 g (6.05 mmol) of pivalic acid, and 11.2 g (64.2 mmol) of triethyl orthoacrylate. The diethoxychroman 24, 17.5 g, was obtained as an oil and used without further purification: IR (neat) cm⁻¹ 1690 (C=O), and 1590 (aryl); ¹H-NMR (CDCl₃) δ 1.19 (t, J = 7 Hz, 6, CH₂CH₃), 2.11 (t, J = 7 Hz, 2, ArCH₂CH₂), 2.32 (s, 3, ArCH₃), 2.89 (t, J = 6.5 Hz, 2, ArCH₂CH₂), 3.44 (m, 4, OCH₂CH₃), 3.79 (s, 6, ArOCH₃), 3.88 (s, 3, ArOCH₃), 5.09 (s, 2, ArCOCH₂), 6.4 (s, 2, aryl), 7.22 (s, 1, aryl), and 7.50 (s, aryl).

Ethyl 5-(2,6-dimethoxy-4-methylphenoxy)acetyl-2-hydroxy-3-methoxydihydrocinnamate (25)

All of the crude product 24 from the previous procedure was dissolved in 100 mL of Et₂O and stirred for 3 hours with 100 mL 10% HCl. While this reaction proceeded, a fine white powder crystallized out of the ether phase. The entire reaction mixture was chilled, and the white powder was collected on a fine porosity filter funnel and washed with cold water and ether to give 7.1 g of 25. The filtrate was separated and the ether layer washed with water and saturated

aqueous NaCl, dried (Na₂SO₄), and concentrated on a steam cone until slightly cloudy; upon cooling another 3.0 g of product was collected, to give a total of 9.1 g (72.7% two-step yield from 23) of 25: m.p. 111.5-113.0°C; IR (mull) cm⁻¹ 3400 (OH), 1590 (aryl), 1660 (ketone C=O), and 1710 (ester C=O); ¹H-NMR (CDCl₃) δ 1.22 (t, J = 7 Hz, 3, CH₂CH₃), 2.32 (s, 3, ArCH₃), 2.64 (t, J = 6 Hz, 2, CH₂COO), 2.99 (t, J = 6 Hz, 2, CH₂CH₂COO), 3.80 (s, 6, ArOCH₃), 3.93 (s, 3, ArOCH₃), 4.11 (q, J = 7 Hz, 2, CH₂CH₃), 5.08 (s, 2, CH₂OAr), 6.40 (s, 3, 2 aryl & OH), and 7.21 (d, 2, aryl); ¹³C-NMR (CDCl₃) δ 14.2 (q, CH₂CH₃), 21.8 (q, ArCH₃), 25.4 (t, CH₂CH₂COO), 33.8 (t, CH₂COO), 55.9 (q, 2 ArOCH₃), 56.1 (q, ArOCH₃), 60.3 (CH₂CH₃), 75.1 (t, CH₂OAr), 105.8 (d, aryl C-3,5), 108.6 (d, aryl C-6), 124.0 (d, aryl C-2), 125.6, 126.9, 133.8, 133.9 (all d, aryl), 146.2, 148.3, 152.5 (all s, aryl), 172.7 (s, COO), and 193.2 (s, ArCO); MS (DIP) m/e (%) 432 (15.6, M⁺), 167 (100.0), 251 (38.4), and 77 (13.8).

1-(4-Hydroxy-3-methoxy-5-[γ-hydroxypropyl]phenyl)-2-(2,6-dimethoxy-4-methylphenoxy)ethanol (10)

The LiAlH₄ reduction procedure (which has already been described for the reduction of (21) was repeated with the following quantities and conditions: 5.0 g (11.6 mmol) of 25 and 1.2 g (32.4 mmol) of LiAlH₄; the mixture was refluxed for 21.5 hours. The reaction was quenched by the addition of saturated aqueous Na₂SO₄, giving a suspension of grey-white solid in the THF. The mixture was filtered and rinsed with copious quantities of Et₂O. Additional product was recovered by rinsing the residue with CH₂Cl₂. The filtrates were washed with water and dried (Na₂SO₄) and concentrated in vacuo to give oils which were crystallized from Et₂O to give a total of 3.7 g (82%) of 10: m.p. 110.0-111.0°C; IR (mull) cm⁻¹ 3223, 3450 (OH), 1595 (aryl), and no C=O absorbances; ¹H-NMR (d₆-DMSO)(60°C) δ 1.69 (m, 2, CH₂CH₂), 2.25 (s, 3, ArCH₃), 2.56 (t, J = 7 Hz

[with further fine splitting], 2, ArCH₂), 3.42 (t, J = 7 Hz, 2, CH₂OH), 3.6-4.1 (broad signal, 1, OH), 3.75, 3.77 (2 s, 6 + 3, ArOCH₃), 3.79 (d of d, J = 7.5 & 10 Hz, 1, CH_ACH_BOAr), 3.96 (d of d, J = 4.5 & 10 Hz, 1, CH_ACH_BOAr), 4.5-4.9 (broad signal, 1, OH), 4.71 (d of d, J = 4.5 & 7.5 Hz, 1, CHOH), 5.6-7.2 (broad signal, 1, OH), 6.47, 6.48 (2s, 1 + 1, aryl), 6.70 (d, J = 2 Hz, 1, aryl), and 6.82 (d, J = 2 Hz, 1, aryl); ¹³C-NMR (d₆-DMSO) δ 21.3 (q, ArCH₃), 26.2 (t, CH₂CH₂CH₂), 32.8 (t, ArCH₂), 55.6 (q, ArOCH₃), 55.8 (q, 2 ArOCH₃), 60.5 (t, CH₂OH), 71.5 (d, CHOH), 78.5 (t, CH₂OAr), 106.3, 107.6, 119.7, 134.5 (all d, aryl), and 127.9, 131.9, 132.8, 142.9, 146.8, 152.3 (all s, aryl); MS (DIP) m/e (%) 392 (1.6, M⁺), 182 (5.20, 168 (100, ArOH⁺), and 77 (4.6).

Elemental analysis, calcd. for C₂₁H₂₈O₇ (%): C, 64.27; H, 7.19; O, 28.54; found: C, 63.50; H, 7.17; O, 28.46.

3-(3-Methoxy-4-hydroxyphenyl)-1-propanol (27)

Into 700 mL of absolute ethanol was dissolved 50.0 g of ferulic acid, after which ca. 1.5 g of 10% Pd on carbon was added. The mixture was stirred while hydrogen was supplied to the reaction mixture from a balloon (equipped with a 3-way stopcock), which could be periodically recharged with the gas; the reaction was allowed to proceed until no more hydrogen was consumed. The solution was filtered through CELITE, concentrated in vacuo to give a light brown oil, and crystallized from CH₂Cl₂/hexane to give 42.8 g (84.8%) of dihydroferulic acid as light-brown needles: m.p. 88.0-90.5°C (Lit.²⁹ 89-90°C).

Dihydroferulic acid, 40.0 g (20.4 mmol), was dissolved into 200 mL of dry, freshly distilled THF; all glassware was oven-dried and all operations, until the workup, were under dry nitrogen. To the dihydroferulic acid solution was added (in 5 portions using a syringe) a total of 245 mL (24.5 mmol) of 1.0M

BH₃-THF complex. After ca. 75% of the reagent had been added the reaction mixture formed an unstirrable gel. The mixture was heated at reflux for 1 hour, allowed to cool, and diluted with 400 mL water to give a clear, yellow-brown solution. This quenched reactions mixture was extracted with Et₂O and the ether extracts were washed with 5% aqueous NaHCO₃, saturated aqueous NaCl, dried (Na₂SO₄) and concentrated in vacuo to give 31.3 g crude **29** (84% yield, ca. 100% conversion). From the bicarbonate wash was recovered ca. 8 g dihydroferulic acid.

Vacuum distillation of 18.9 g of crude **29** yielded 13.2 g of purified **29**: b.p. 178-180°C (1 mm Hg); IR (neat) cm⁻¹ 3400 (OH), 1600 (aryl), and 1520; ¹H-NMR (CDCl₃, δ 1.82 (m, 2, CH₂CH₂OH), 2.59 (t, J = 7 Hz, 2, ArCH₂), 3.62 (t, J = 7 Hz, 2, CH₂OH), 3.76 (s, 3, ArOCH₃), and 6.5-6.9 (multiplets, 3, aryl).

The sodium salt of **29** was prepared by dissolving 5.6 g (30.6 mmol) of the phenol in 30.6 mL of 1.00N aqueous NaOH; the methanol and water were removed in vacuo. Two 50 mL portions of 1,2-dichloroethane were added and evaporated in vacuo to remove residual moisture; the vacuum was always purged with nitrogen, and the contents chilled to ca. 0°C between 1,2-dichloroethane additions. The residual sodium salt of **29** was a fluffy off-white solid which was desiccated for 24 hours over fresh P₂O₅ before its subsequent use.

4-Hydroxy-3-methoxy-β-(2-methoxy-4-[γ-hydroxypropyl]phenoxy)-acetophenone (12b)

The dimer **12b** was prepared by the general coupling technique of Hoysoya, et al.¹⁶ as modified by Dimmel et al.⁵ Three equivalents of the sodium salt of **29** (30.6 mmol) were dissolved in 25 mL dry DMF (dried over molecular sieves) and stirred under nitrogen while 2.5 g (10.2 mmol) of β-bromoacetoguaiacone (**26**) in 25 mL DMF was added dropwise over 1 hour, while the reaction mixture was kept at

50°C. Stirring was continued for 1 hour after complete addition of 26, after which the mixture was diluted with 250 mL water and acidified with HCl. The mixture was extracted with CHCl₃, and the organic layer was washed with large amounts of water to remove excess DMF. The chloroform layer was concentrated in vacuo; the residual sirup was diluted with two 50 mL portions of xylenes and concentrated under high vacuum (ca. 1 mm Hg) leaving 6.8 g of organic material.

A portion of the above material (4.1 g), which was a mixture of product 12b and excess 29, was subjected to column chromatography (silica gel 60, hexane/acetone 1:1) to give a 2.6 g portion of 12b, as a sirup. The sirup was crystallized from i-PrOH to give 1.3 g (61%) of 12b as light-yellow needles: m.p. 94.5-96.0°C; IR (mull) cm⁻¹ 3500 (OH), 1665 (C=O), and 1590 (aryl); ¹H-NMR (CDCl₃) δ 1.65 (broad s, 1, CH₂OH), 1.84 (m, 2, CH₂CH₂OH), 2.64 (t, J = 7 Hz, 2, ArCH₂), 3.66 (t, J = 6.5 Hz, 2, CH₂OH), 3.85, 3.92 (2 s, 6, ArOCH₃), 5.25 (s, 2, CH₂OAr), 6.36 (broad s, 1, ArOH), 6.6-7.0 (m, 4, aryl), and 7.58 (m, 2, aryl); ¹³C-NMR (CDCl₃) δ 31.7 (t, CH₂CH₂OH), 34.2 (t, ArCH₂), 56.1 (q, 2 ArOCH₃), 62.1 (t, CH₂OH), 72.6 (t, CH₂OAr), 110.6, 113.2, 114.1, 115.6, 120.4, 123.3 (all d, aryl), 127.6, 136.2, 145.9, 146.8, 149.7, 151.1 (all s, aryl), and 193.2 (s, C=O); MS (DIP) m/e (%) 346 (26.5, M⁺) 347 (5.6), 181 (1.3), 151 (100), and 137 (14.1).

4-Hydroxy-3-methoxy-β-(2-methoxy-4-[γ-trityloxypropyl]phenoxy) acetophenone (12b-Tr)

Tritylpyridinium tetrafluoroborate reagent (TPFB) was prepared according to the method of Hanessian and Staub.¹⁹ Into 25 mL of spectroscopic grade acetonitrile was dissolved 0.5 g (1.44 mol) of 12b and 0.9 g (1.5 equiv.) of TPFB. The solution was kept at 55-60°C and after 24 hours the reaction progress seemed sluggish (by tlc); two more 0.5 g portions of TPFB were added on successive days.

After 5 days the entire reaction mixture was evaporated to dryness in vacuo and the solid residue was extracted with CHCl_2 . The chloroform extracts were washed with water, dried (Na_2SO_4), and concentrated in vacuo to give an oily residue which was visually contaminated with trityl alcohol crystals. This crude product was chromatographed on alumina (Alumin-AR CC-10, CH_2Cl_2 /methanol 40:1 to 20:1) to give a 0.3 g fraction (35%) of 12b-Tr as a colorless oil: IR (neat) cm^{-1} 1690 (C=O), and 1595 (aryl); $^1\text{H-NMR}$ (CDCl_3) δ 1.87 (m, 2, $\text{CH}_2\text{CH}_2\text{OTr}$), 2.66 (t, $J = 7$ Hz, 2, ArCH_2), 3.10 (t, $J = 6$ Hz, 2, CH_2OTr), 3.80, 3.90 (2s, 6, ArOCH_3), 5.21 (s, 2, CH_2OAr), 6.5-7.0 (m, 2, aryl), and 7.2-7.6 (m, 19, aryl).

3-(3-Methoxy-4-hydroxyphenyl)-1-trityloxypropane (27Tr)

The TPFB procedure was repeated with 27, with the following quantities: 1.2 g (6.6 mmol) of 27 and 2.9 g (1.1 equiv.) of TPFB. Following workup, 1.7 g of a crude solid was recovered, which was twice recrystallized from CHCl_3 /hexane: m.p. 109.0-111.0°C; $^1\text{H-NMR}$ δ (CDCl_3) 1.90 (m, 2, ArCH_2CH_2), 2.66 (t, $J = 7$ Hz, 2, ArCH_2), 3.10 (t, $J = 7$ Hz, 2, CH_2OTr), 3.79 (s, 3, ArOCH_3), 5.44 (s, 1, ArOH), 6.5-6.8 (m, 3, aryl), and 7.1-7.7 (m, 15, trityl).

3-Methoxy-4-hydroxy- β -(2'-methoxyphenoxy)acetophenone (2a

Phenacyl aryl ether 2a was prepared by the general method of Hosoya, et al.¹⁶ as adapted by Dimmel, et al.⁵

2-(2-Methoxyphenoxy)-1-(3-methoxy-4-hydroxyphenyl)-4-pentene-1-one (28)

The following alkylation procedure⁵ employed oven-dried glassware, freshly distilled anhydrous solvents, and nitrogen atmospheres. To 150 mL of ice-cooled THF was added 224 mL (0.347 mol) of 1.55M $n\text{-BuLi}$ in hexane and 35.1 g of diisopropylamine. After stirring 15 min, the solution was cooled to -70°C and 25.0 g 2a (86.7 mmol) dissolved in 150 mL THF was added dropwise. The stirred mixture

was then allowed to warm to room temperature for 1 hour, followed by cooling again to -70°C ; to this mixture, 42.0 g (0.347 mol) of allyl bromide (dissolved in 100 mL THF) was added dropwise. After complete addition of the allyl bromide, the mixture was allowed to warm to room temperature and stirred for several hours. The reaction mixture was quenched by the addition of 0.5N H_2SO_4 . The organic layer was separated, and the aqueous layer was extracted with Et_2O . The combined THF/ether extracts were extracted with 1N NaOH ; these NaOH extracts were acidified and extracted with CH_2Cl_2 . The CH_2Cl_2 extracts were washed with water and saturated aqueous NaCl , dried (Na_2SO_4), and concentrated in vacuo to give ca. 30 g of a brown oil. The oil was chromatographed (silica gel 60, $\text{CHCl}_3/\text{EtOAc}$ 6:1) to give 19.4 g (68.1%) of 28 as a gold oil: IR (neat) cm^{-1} 3400 (OH), 3190, and 1635 ($\text{CH}=\text{CH}_2$), 1670 ($\text{C}=\text{O}$), and 1590 (aryl); $^1\text{H-NMR}$ (CDCl_3) δ 2.81 (t, $J = 7$ Hz [with further fine splitting] 2, $\text{CH}_2\text{CH}=\text{CH}_2$), 3.77, 3.87 (2 s, 6, ArOCH_3), 5.0-5.4 (m, 3, CHOAr & $\text{CH}=\text{CH}_2$), 5.8-6.2 (m, 1, $\text{CH}=\text{CH}_2$), 6.39 (s, 1, OH), 6.85 (m, 5, aryl), and 7.70 (m, 2, aryl); $^{13}\text{C-NMR}$ (CDCl_3) δ 37.7 (t, $\text{CH}_2\text{CH}=\text{CH}_2$), 55.6 (q, ArOCH_3), 81.4 (d, CHOAr), 113.9 (t, $\text{CH}=\text{CH}_2$), 132.7 (d, $\text{CH}=\text{CH}_2$), 110.7, 112.4, 116.1, 117.6, 120.5, 122.1, 123.8 (all d, aryl), 126.9, 146.5, 146.8, 149.5, 150.8 (all s, aryl), and 196.1 (s, $\text{C}=\text{O}$); MS (DIP) m/e (%) 328 (24.0, M^+), 151 (100), 123 (15.), 177 (15.4), 77 (11.0), and 205 (9.6).

2-(2-Methoxyphenoxy)-1-(3-methoxy-4-hydroxyphenyl)-4-penten-1-ol (30)

Into 300 mL of absolute EtOH was dissolved 20.0 g (60.9 mmol) of 28. Six equivalents (13.8 g) of NaBH_4 were quickly dissolved in 150 mL water/50 mL EtOH and added dropwise to the substrate solution. After 1 hour, the solution was quenched by the dropwise addition of 3N HCl , diluted with more water, and extracted with CH_2Cl_2 . The organic extracts were dried (Na_2SO_4) and concentrated

in vacuo to leave 20.4 g of an oil. The crude product was chromatographed (silica gel 60, CH₂Cl₂/EtOAc 20:1 to 5:1) to give a major fraction of 13.0 g (64.7%) of **30**, as a colorless oil: IR (neat) cm⁻¹ 3100 (OH), 1650 (C=C), no C=O absorbance, and 1600 (aryl); ¹H-NMR (CDCl₃) δ 2.0-2.2, 2.4-2.7 (2 m, 1 + 1, non-equiv. CH₂CH=CH₂), 3.8-3.9 (broad signal, 1, OH), 3.87 (s, 6, ArOCH₃), 4.1-4.3 (m 1, CHOAr), 4.80 (d, J = 3 Hz, 1, CHOH), 4.9-5.1 (m, 2, CH=CH₂), 5.74 (s, 1, ArOH), 5.7-6.0 (m, 1, CH=CH₂), and 6.67-7.13 (m, 7, aryl); ¹³C-NMR (CDCl₃) δ 32.7 (t, CH₂CH=CH₂), 55.9, 56.0 (2 q, ArOCH₃), 72.8 (d, CHOH), 87.2 (d, CHOAr), 117.0 (t, CH=CH₂), 131.4 (d, CH=CH₂), 108.8, 112.0, 114.0, 119.0, 120.5, 121.4, 123.6 (all d, aryl), and 135.0, 144.6, 146.4, 147.0, 151.5 (all s, aryl); MS (DIP) m/e (%) 330 (10.2, M⁺), 153 (100.0), 124 (51.8), 178 (51.8), 177 (20.2), 206 (14.7), and 137 (18.7).

Disiamylborane (DSB)

A kit supplied by Aldrich Chemical³⁰ provided a rapid and simple method for preparation of the reagent; equal volumes of a 1M BH₃/THF solution were combined with a 2M THF solution of 2-methyl-2-butene to give a 0.5M THF solution of bis(3-methyl-2-butyl)borane (DSB).²³

2-(2-Methoxyphenoxy)-1-(3-methoxy-4-hydroxyphenyl)-1,5-pentanediol (11)

All procedures, until workup, employed oven-dried glassware, freshly distilled anhydrous solvent, and nitrogen atmospheres. Into 100 mL of THF was dissolved 12.0 g (36.3 mmol) of **29**; the mixture was chilled in an ice bath and 600 mL (8.2 equiv.) of 0.5M DSB in THF was added to the solution over 1 hour. The mixture was kept at ca. 0°C for 3 hours, after which 130 mL water was added to decompose residual hydride. The organoborane was oxidized in situ at room temperature by adding 220 mL of 3N NaOH, followed by the dropwise addition of

183 mL of 30% H₂O₂. The aqueous phase was saturated with K₂CO₃ and the THF layer was separated. The aqueous layer was then extracted with additional THF and the combined THF was washed with saturated aqueous NaCl, dried (Na₂SO₄), and concentrated under high vacuum (ca. 1 mm Hg) to leave 14.7 g of a crude yellow oil. The crude product was subjected to three successive column chromatographies (silica gel 60, CH₂Cl₂/MeOH 50:1 to 20:1) to give 11.4 g of a colorless oil which crystallized upon standing for several days; the product was recrystallized from benzene to yield 8.1 g (64.3%) of compound 11: m.p. 108.5-109.0°C; IR (mull) cm⁻¹ 3450, 3225 (OH), and 1590 (aryl); ¹H-NMR (CDCl₃) δ 1.5-2.1 (m, 5, CH₂CH₂ & OH), 3.55 (broadened t, J = 6 Hz, 3, CH₂OH & OH), 3.81, 3.82 (2 s, 6, ArOCH₃), 4.25 (m, 1, CHOAr), 4.80 (d, J = 3, 1, CHOH), 5.74 (s, 1, ArOH), and 6.7-7.1 (m, 7, aryl) [The ¹H-NMR assignments were verified with homonuclear decoupling experiments]; ¹³C-NMR δ (CDCl₃) 24.5, 29.3 (2 t, CH₂CH₂), 56.1 (s, 2, ArOCH₃), 62.8 (t, CH₂OH), 73.1 (d, CHOH), 86.4 (d, CHOAr), 109.5, 112.7, 114.2, 119.2, 119.4, 121.4, 123.1 (all d, aryl), and 132.0, 145.0, 146.6, 147.4, 151.4 (all s, aryl); MS (DIP) m/e (%) 348 (13.9, M⁺), 71 (100.0), 124 (75.5), 153 (68.0), 196 (27.4), 224 (16.2), and 137 (15.5).

Elemental analysis, calcd. for C₁₉H₂₄O₆ (%): C 65.50; H 6.94; O 27.55; found: C 65.78; H 6.96; O 27.26 (by difference).

2-(2-Methoxyphenoxy)-1-(3-methoxy-4-hydroxy)-5-trityloxy-1-pentanol (11Tr)

Into 75 mL freshly distilled, anhydrous pyridine was dissolved 1.53 g (4.39 mmol) of 11 and 2.41 g (2 equiv.) of trityl chloride. The reaction mixture was maintained at ca. 50°C for 5 days, and then diluted with 75 mL water. The aqueous pyridine solution was extracted with toluene, which was in turn washed repeatedly with water (until the wash was neutral), washed with saturated

aqueous NaCl, dried (Na₂SO₄), and concentrated in vacuo to leave 4.7 g of an oil. The crude product was chromatographed on alumina (AluminAR CC-10, CH₂Cl₂/MeOH, pure CH₂Cl₂ to 20:1) to give 2.17 g of a colorless oil, which was crystallized from warm MeOH to yield 1.67 g (64.5%) of 11Tr: m.p. 109.5-111.0°C; IR (mull) cm⁻¹ 3450, 3270 (OH), 1600, and 1580 (aryl); ¹H-NMR (CDCl₃) δ 1.4-2.1 (m, 4, CH₂CH₂), 3.04 (t, J = 6 Hz, 2, CH₂OTr), 3.66 (d, J = 3 Hz, 1, OH), 3.77, 3.84 (2 s, 6, ArOCH₃), 4.13 (m, 1, CHOAr), 4.76 (t, J = 3 Hz [d after D₂O wash], 1, CHOH), 5.65 (s, 1, ArOH), 6.6-7.0 (m, 7, aryl), and 7.0-7.4 (m, 15, trityl); ¹³C-NMR (CDCl₃) δ 24.2, 26.3 (2 s, CH₂CH₂), 55.8 (q, 2 ArOCH₃), 62.9 (t, CH₂OH), 72.6 (d, CHOH), 86.1 (s, CAr₃), 86.7 (d, CHOAr), 108.7, 111.9, 114.0, 118.8, 119.9, 121.3, 123.2 (all d, aryl), 126.6, 127.5, 128.4 (all d, trityl aryl), 144.0 (s, trityl aryl), and 131.4, 144.5, 146.4, 146.8, 151.4 (all s, aryl); MS (DIP) m/e (%) 243 (100.0, Tr⁺), 71 (23.7), 244 (22.4), 153 (36.4), 165 (24.7), and 223 (16.8).

Elemental analysis, calcd. for C₃₈H₃₈O₆ (%): C 77.26; H 6.48; O 16.25; found: C 76.87; H 6.54; O 16.59 (by difference).

5-Hydroxy-2-(2-methoxyphenoxy)-1-(3-methoxy-4-hydroxyphenyl)-1-pentanone (29)

The DSB procedure described above was repeated with compound 28, using the following quantities: 4.8 g (14.6 mmol) of 28, 88 mL (3 equiv.) of 0.5M DSB, and the appropriate amounts of NaOH and H₂O₂ during the workup. The crude product, 5.5 g, was chromatographed (silica gel 60, CH₂Cl₂/MeOH 30:1 to 10:1) to yield 1.8 g (36%) of 29 as an oil: IR (neat) cm⁻¹ 3400 (OH), 1670 (C=O), 1590 (aryl), and no C=C absorbances; ¹H-NMR (d₆-DMSO) δ 1.65, 1.89 (2 m, 4, CH₂CH₂), 3.46 (t, J = 6 Hz, 2, CH₂OH), 3.76, 3.93 (2 s, 6, ArOCH₃), 4.48 (broad s, 1, OH), 5.63 (t, J = 5 Hz, 1, CHOAr), 6.94 (m, 4, aryl), 7.62 (m, 2, aryl), and

10.15 (broad s, 1, ArOH); ^{13}C -NMR (d_6 -DMSO) δ 28.2, 29.7, ($\underline{\text{CH}_2\text{CH}_2}$), 55.8 (ArOCH_3), 60.4 ($\underline{\text{CH}_2\text{OH}}$), 80.3 ($\underline{\text{CHOAr}}$), 112.3, 113.3, 115.0, 115.4, 120.5, 121.4, 123.1, 126.4, 147.1, 147.3, 149.4, 151.9 (aryl), and 195.5 ($\underline{\text{C=O}}$).

Compound 11 (Alternate Preparation)

The NaBH_4 reduction procedure described above was repeated with compound 29, using the following quantities: 2.9 g (8.4 mmol) of 29 and 1.9 g (6 equiv.) of NaBH_4 . The crude product, 2.8 g, was chromatographed (silica gel 60, $\text{CH}_2\text{Cl}_2/\text{MeOH}$ 50:1 to 30:1) to yield 1.4 g (48%) of 11 as an oil which was a mixture of diastereomers: IR (neat) cm^{-1} 3400 (OH), no C=O absorbance, and 1595 (aryl); ^1H -NMR (CDCl_3) 1.4-2.0 (m, 4, $\underline{\text{CH}_2\text{CH}_2}$), 2.10 (s, 1, OH), 3.60 (t, $J = 6$ Hz, 2, $\underline{\text{CH}_2\text{OH}}$), 3.83, 3.85 (2s, 6, ArOCH_3), 4.1-4.2 (m, 1, $\underline{\text{CHOAr}}$), 4.74 (d, $J = 8$ Hz, 0.3, $\underline{\text{CHOH}}$), 4.82 (d, $J = 3$ Hz, 0.7, $\underline{\text{CHOH}}$), 5.29 (s, 1, OH), 5.77 (broad s, 1, ArOH), and 6.6-7.1 (m, 7, aryl); ^{13}C -NMR (CDCl_3) 24.2, 29.1 ($\underline{\text{CH}_2\text{CH}_2}$, major) 27.4, 28.1 ($\underline{\text{CH}_2\text{CH}_2}$, minor), 55.7 (2 ArOCH_3), 62.5 ($\underline{\text{CH}_2\text{OH}}$), 72.6 ($\underline{\text{CHOH}}$, major), 76.1 ($\underline{\text{CHOH}}$, minor), 86.5 ($\underline{\text{C HOAr}}$), 108.8, 112.0, 114.0, 118.7, 119.1, 121.2, 123.0 (aryl, major), 109.4, 117.8, 119.4, 120.7, 121.0, 122.4 (aryl, minor), 131.5, 144.5, 146.3, 146.7, 151.0 (aryl, major), and 131.8, 145.2, 148.2, 148.1, 150.0 (aryl, minor); DS (DIP) $\underline{\text{m/e}}$ (%) 348 (2.5, M^+), 71 (100.0), 124 (52.5), 153 (45.7), 196 (15.9), 137 (12.8), and 224 (9.8).

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INSOLUBLE LIGNIN MODELS (II): PREPARATION, CHARACTERIZATION,
AND PRELIMINARY REACTIONS OF A POLYMER-BOUND β -ARYL
ETHER/QUINONEMETHIDE PRECURSOR

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ABSTRACT

A unique lignin model dimer 2-(2-methoxyphenoxy)-1-(3-methoxy-4-hydroxy-phenyl)-1,5-pentanediol (11) was attached to a macroreticular polystyrene by means of a polymer-bound trityl to model primary alcohol bond. The extent of model loading was determined by gravimetric analysis and Zeisel methoxyl content. The insoluble model, 11Tr-P, was reacted under simulated kraft pulping conditions, to afford moderate yields of guaiacol, a fragmentation product. The addition of 28.5% of p-dioxane drastically depressed the yield of guaiacol from 11Tr-P. The trityl ether attachment was not as alkali-stable as its soluble counterpart, and portions of the guaiacol yield from 11Tr-P are from soluble reactions. The behavior of the insoluble model was compared to the reactions of 11 and to the reactions of the analogous soluble tritylated model dimer 11Tr.

INTRODUCTION

Lignin model compounds are designed to approximate the chemical reactivity of the predominant structural units in lignin, and as such are regarded as tools with which the basic, underlying chemistry of delignification can be elucidated. The model compounds are generally soluble in the reaction medium, are chemically distinct, and products from their chemical reactions are relatively simple to detect and measure.

Chemical reactions of native lignin are, on the other hand, usually heterogeneous; that is to say, there are at least two dissimilar phases involved.^{2,3} The phases involved during pulping consist of solid-liquid interfaces of lignin and pulping liquor,^{4,5} and the reaction rates and mechanisms of the degrading lignin are very difficult to quantify and characterize.

The goal of chemical pulping is the selective removal of the insoluble native lignin. Studies of the chemistry of soluble lignin model compounds have, in general, suggested that the selective degradation and dissolution of lignin during alkaline pulping is controlled by the cleavage of several different types of alkyl-aryl ether bonds.⁶⁻⁸

However, it has been argued that the rate of delignification might also be influenced by factors other than the ease (or rate) of ether bond cleavages. Some such factors include: (a) accessibility of reactants to lignin in different morphological regions,⁹ (b) polyelectrolytic behavior of the degrading polymer, postulated by Schuerch as an "ion-exclusion" (Donnan equilibrium) effect,¹⁰⁻¹¹ and (c) diffusion-, transport-, adsorption-, and desorption-phenomena.^{2,3,7}

Moreover, investigators of other polymeric systems have shown that the intrinsic ease or difficulty of a chemical reaction in which one of the reactants is part of an insoluble matrix may be quite different than the analogous homogeneous system; the insoluble reactant can impose a loss in entropy on the transition state of such a reacting system.^{12,13} Another operative factor in heterogeneous reactions is the molecular mobility of the insoluble matrix. Influenced by temperature and solvent, those conditions which impart greater

flexibility to a polymer backbone enhance the availability (reactivity) of the polymer-bound substrate.^{14,15}

Clearly, soluble lignin model compounds cannot mimic the various polymeric characteristics of a chemically reacting native lignin. In light of the inadequacies of simple models, and the difficulties in characterizing reactions as they occur with actual lignin, we initiated an experimental program to design, synthesize, characterize, and employ insoluble (heterogeneous) lignin models. The heterogeneous models will be comprised of a basic reactive unit of lignin attached to a polymer network by means of an alkali-stable polymer-bound protecting group¹ and will have the advantages of (1) a definable structure, which actual lignin does not, and (2) heterogeneity, which soluble models lack.

Design Criteria and Limitations

The design of the insoluble model described herein will follow a polymer-bound protecting group methodology.¹ Premanufactured macroreticular polystyrene can be functionalized to a triphenylmethyl (trityl) chloride. The polymer-bound trityl chloride preferentially forms a trityl ether linkage with primary alcohol groups; such groups (propyl alcohol handles) have been incorporated into reactive lignin model dimers. The general design of the insoluble model should allow us to study its chemistry in a variety of alkaline systems.

Polystyrene was chosen because insoluble, cross-linked polystyrene supports (often called resins) are commercially available with a variety of physical characteristics, generally in a convenient bead form and with a thermal stability of 250°C or more. Also, polystyrene resembles lignin, superficially at least, in that it is a cross-linked, aliphatic-aromatic polymer.

Macroreticular polystyrene was chosen to insure maximum solid-liquid interface of the insoluble model and cooking liquor. The definitive internal porous structure of macroreticular resins allows them to absorb significant quantities of virtually all solvents.^{1,16,17} The structure of macroreticular resins can be envisioned as spongelike, where the interior volume is responsible for the absorption of liquid, and the highly entangled volume of polymer material is penetrated only by a good polymer-swelling solvent.

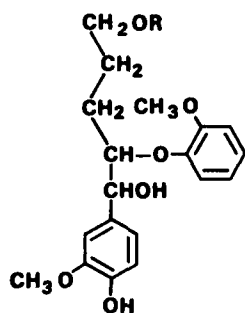
The choice of the trityl ether protecting group was in part based on its reported stability at pH > 12 and 150°C;¹⁸ clearly, the model-polymer attachment should be stable to the conditions under which the insoluble model will be studied. Bulky trityl ethers are not seen as reacting by S_N² processes, so the addition of a nucleophilic additive (such as hydrosulfide, in a kraft system) would not be expected to affect trityl ether stability.

It is convenient that trityl ethers are preferentially formed with primary alcohols;¹⁹ in general, there is no need to block other alcohols or phenols in polyhydroxylic compounds. Two lignin model dimers with primary propyl alcohol handles were prepared (Fig. 1).²⁰ Both compounds, phenacyl aryl ether 12b and β-aryl ether 11, are considered appropriate substrates to support on a polymer via a polymer-bound trityl ether because they could be conventionally tritylated without complication. For the purposes of this study, only dimer 11 was employed for the preparation of an insoluble lignin model.

For the purposes of this paper, the insoluble model (based on dimer 11) has been briefly studied only under simulated kraft pulping conditions. Similarly, the chemistry of analogous soluble lignin model dimers has been studied.

Tr \equiv trityl

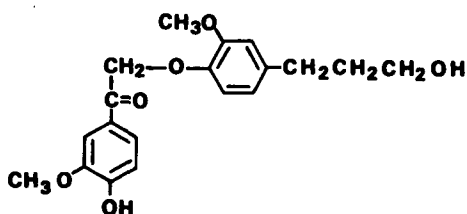
(P)Tr \equiv polystyrene-bound trityl



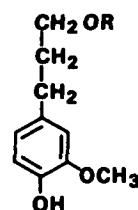
R = H, 11

$$R = Tr, \quad 11Tr$$

R = Tr-P, 11Tr-P



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R = H, 27

$$R = Tr, 27Tr$$

R = Tr-P, 27Tr-P

Figure 1. Structures of various compounds referred to in the text.

RESULTS AND DISCUSSION

Selection, Purification, and Stability Checks of the Polystyrene Support

The specific macroreticular polystyrene chosen for this study was selected from among three commercially available Amberlite resins (Table I). Amberlite XE-305 was chosen on the basis of its large average pore diameter which should insure that the transport of reagents and products, in and out of the macroreticular network, will not be restrictive. Also, Amberlite XE-305 is unusual, among macroreticular resins, in that it has a low degree of cross-linking (4% divinylbenzene).³⁵

Amberlite XE-305 is available only as an industrial-grade resin, so a purification was required. A multistage procedure suggested by Merrifield²¹ was employed, which produces what may be considered an analytical-grade resin.

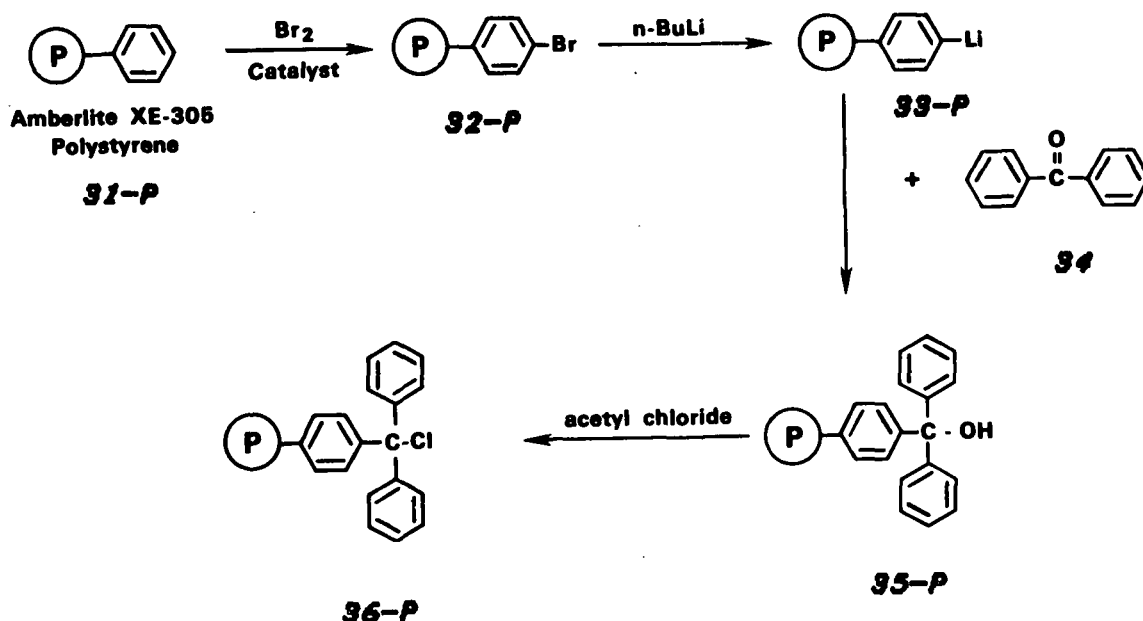
Table 1. Characteristics of three commercially available Amberlite resins.³⁷⁻³⁹

Resin	Average Pore Diameter, ^a Å	Surface Area, ^a m ² /g
XE-305	1000	35
XAD-2	90	300
XAD-4	40	725

^aBased on the BET method.^{40,41}

The stability of Amberlite XE-305 under high temperature alkaline conditions was confirmed in several ways. Portions of the polymer were subjected to aqueous 1N NaOH at 150°C for three hours, after which they were quantitatively recovered, thoroughly washed, dried under vacuum, and weighed to show no weight loss had occurred. Each cooking liquor was extracted with ether and chloroform, and gas chromatographic analysis of the extracts showed no polystyrene degradation products. There were no macroscopically observable differences between the thermally treated and untreated resin samples, and in a separate experiment²² there were no significant microscopic differences between untreated resin and resin heated for seven days at 175°C, in 1N NaOH.

Amberlite XE-305 (31-P) was functionalized to the polymer-bound trityl chloride (36-P) employing the synthetic route shown in Scheme 1.²³ The bromine content of product 32-P was 1.36%, which corresponds to one bromine per 4.4 polystyrene aryl rings. The chlorine content of the final product 36-P represents 60.5% of the theoretical maximum (based on the original amount of bromine), and corresponds to 1 chlorine per 8.5 polystyrene aryl rings, or 0.91 milliequivalents of chlorine per gram of product. Table 2 shows the elemental analyses of the various polymer products.



Scheme 1. Functionalization of polystyrene (31-P) to a polymer-bound trityl chloride (36-P).

Table 2. Elemental analyses of purified Amberlite XE-305 (31-P) and functionalized polymer products 32-P, 35-P, and 36-P.

Sample	%C	%H	%O	%Br	%Cl
31-P	91.47	7.75	1.36	—	—
32-P	77.78	6.47	1.93	14.67	—
35-P	89.48	7.36	2.99	0.67	—
36-P	88.12	7.22	1.63	—	3.22

What appears to be the limiting factor(s) with regard to the incorporation of chlorine? It is unlikely that a poor conversion in the final chlorination step could account for the large deviation from the maximum expected chlorine; the conversion of trityl alcohol to trityl chloride typically gives a yield of 95% or greater.²⁴

Only a small portion of the bromine from 32-P was not reacted; elemental analysis of 35-P showed a trace (0.67%) of bromine. However, a semiempirical mass balance between 32-P and 35-P indicates that the decrease in bromine is not balanced by an increase in oxygen.

Side reactions of the lithiated intermediate 33-P could account for the yield discrepancies. Undesirable oxidations of 33-P could give phenols, and protonation could generate starting units, 31-P. Moreover, the best agreement between predicted and actual elemental analyses of 35-P is based on the representation that a portion of 33-P reverts to an unsubstituted aryl unit, via protonation.

It is consistent then that the major limiting factor with regard to chlorine incorporation is not the incomplete chlorination of 35-P. If a greater loading of chloride is desired, either the original bromine content must be increased or the source of protons (probably trace water) and oxygen must be reduced. Related inference based on the above analyses is that the majority of oxygen that remains in product 36-P was originally present in the Amberlite XE-305.

Preparation of a Polymer-Bound Monomer (27Tr-P)

The monomer 3-(3-methoxy-4-hydroxyphenyl)-1-propanol (27) has previously been tritylated to give 3-(3-methoxy-4-hydroxyphenyl)-1-trityloxypropane (27Tr).²⁰ Preparation of the analogous polymer-bound monomer, 27Tr-P, was accomplished by reacting a portion of polymer-bound trityl chloride (36-P) with a threefold excess of compound 27 in dry pyridine. The loading of monomer on the polymer product 27Tr-P was determined to be 0.26 milliequivalents per gram of product, based on gross weight differences between 36-P and the product; this loading was confirmed by an acid hydrolysis study. While the trityl ether attachment is presumably stable to alkali, it can be readily cleaved with acid. The quantity of

27 which was liberated upon treatment of 27Tr-P with trifluoroacetic acid (TFAA) corresponded to 102% of the loading value based on the gravimetric analysis.

Alkaline Stability of the Trityl Ether in 27Tr and 27Tr-P

Trityl ethers are reported to be stable at 150°C in 0.1-1.0N NaOH (pH > 12).²⁵ Nevertheless, we checked the stability of the tritylated monomer 27Tr and the polymer-bound monomer 27Tr-P under the kraftlike conditions in which the lignin models would be studied. Portions of 27Tr were reacted for up to 2 hours at 150°C in a 0.11M NaOH/0.021M NaSH system; an aqueous medium employing 28.6% p-dioxane was used to insure solubility of 27-Tr. No trityl ether cleavage was observed.

However, the analogous polymer-bound trityl ether of 27Tr-P was not as stable. Portions of 27Tr-P were reacted at both 135°C and 150°C under similar conditions as described above (except that the aqueous medium contained no cosolvent); cleavage of polymer-bound trityl ether gave the yield of compound 27 shown in Table 3. Examination of this data shows that the fraction of polymer-bound trityl ether being cleaved levels off at ca. 25% (at 150°C).

A possible explanation for the above behavior is that a fraction of polymer-bound trityl groups are intrinsically strained (being part of a cross-linked polymer), and form relatively weak trityl ethers with primary alcohol substrates. These weak ethers cleave more readily than a soluble trityl ether; the remaining fraction of polymer-bound ethers may be relatively unstrained and maintain an alkaline stability similar to their soluble counterparts. Nevertheless, the data regarding polymer-bound trityl ether stability will be taken into account when interpreting data on the reactions of the polymer-bound lignin model dimer.

Table 3. Relative yield of 27 liberated from polymer-bound monomer 27Tr-P upon exposure to kraftlike conditions.

Time, min	At 135°C %27	At 150°C %27
15	4.5	13.5
30	7.8	17.9
45	--	20.6
60	11.6	25.3
90	14.6	23.0
120	15.0	24.3
240	17.0	25.4

Preparation of a Polymer-Bound Lignin Model Dimer (11Tr-P)

Lignin model dimer 11 was selected as an appropriate compound with which to prepare an insoluble lignin model. The propyl alcohol handle of 11 could be conventionally tritylated with trityl chloride to give 11Tr;²⁰ the analogous heterogeneous synthesis employing a polymer-bound trityl chloride will attach model 11 to the polymer, thus constituting an insoluble lignin model compound. The position of the propyl handle attachment is convenient because, upon a typical kraft-promoted fragmentation,^{6,7} guaiacol (2-methoxyphenol) will be liberated into solution, where its production can be easily measured.²⁶

Preparation of the polymer-bound lignin model, 11Tr-P, was accomplished by reacting a portion of 36-P with a sixfold excess of 11 in dry 33% dry benzene/pyridine. The benzene was added to assist in swelling the macroreticular polymer backbone and, perhaps, promote a greater loading of 11. Based solely on gross weight differences between 36-P and the polymer product, the loading of dimer on product 11Tr-P was determined to be 0.41 millimoles per gram of product. Further characterization was desired.

Characterization of Insoluble Lignin Model 11Tr-P

Reliable weight differences are difficult to obtain when working with polymer beads; quantitative delivery from vessel to vessel is awkward and complicated by the fact that functionalized polymer beads often take on a static electrical charge. Clearly, it would be useful to find a specific analytical technique for determining the loading of model dimer on 11Tr-P.

The only source of methoxyl groups in the insoluble model is from the attached lignin model (two methoxyls per dimer). The Zeisel methoxyl determination has proven to be reliable for a variety of insoluble substrates;^{27,28} values are generally very reproducible in the range of methoxyl content expected for insoluble model 11Tr-P.²⁹

Methoxyl content analyses were performed in triplicate on 11Tr-P to give values of 2.67, 2.67%, and 2.79% for an average of 2.71% methoxyl. This methoxyl content corresponds to a loading of 0.436 millimoles of dimer per gram of polymer product. Although this value is slightly higher than the value determined by weight difference, it is considered a more reliable estimate of loading, since the sources of error in the gravimetric analysis (i.e., mechanical losses) would give a lower than actual value.

Additionally, the general degree of loading was confirmed by weight differences of a sample of 11Tr-P before and after an acid treatment (ca. 0.38-0.44 mmol/g of material could be hydrolyzed off the polymer using TFAA). Also, in a separate experiment,³⁰ a sample of 11Tr-P was treated with diazomethane to methylate the phenol of the attached dimer. The methoxyl content of the diazomethane treated product (with three methoxyls per dimer) was found to be 4.33%, which compares favorably to the theoretical value of 4.06%, based on the original

methoxy analysis. Excess methoxyl content of the diazomethane treated 11Tr-P may be due to the methylation of phenolic contaminants which are part of the original polystyrene 31-P.

Nevertheless, the loading value of 0.436 millimoles per gram was used for calculating stoichiometric quantities used for the subsequent degradation studies. This loading represents a 61.5% conversion of trityl chloride groups (to trityl ethers) and corresponds to 1 model dimer per ca. 14 polystyrene aryl rings.

How can it be shown that the dimer loaded on 11Tr-P is covalently bonded and not just adsorbed? It seems unlikely that even a strongly adsorbed substrate would remain on the polystyrene following the extensive soxhlet extraction purification procedures which follow the attachment reaction (see Experimental). However, a control experiment was designed to further rule out adsorption as a possibility. A portion of the polymer-bound trityl alcohol (which does not have a reasonable mechanism with which to form a covalent bond with a primary alcohol substrate) was stirred with an excess of compound 11, in a manner analogous to the preparation of 11Tr-P. After the workup/purification procedure, the polymer beads were dried in vacuo to a constant weight; the weight of the resultant beads showed no weight gain, confirming that the lignin dimer of 11Tr-P is not adsorbed but, rather, covalently bound.

In a related experiment, a portion of 11Tr-P was subjected to an exhaustive methylation (using dimethyl sulfate) in an effort to make any adsorbed material more extractable. No material detectable by gas chromatography was extractable from the dimethyl sulfate treated beads, again confirming that the lignin dimer of 11Tr-P is covalently bound.

Homogeneous Degradations

Preliminary Degradations at 135°C

Preliminary homogeneous degradations of compounds 11 and 11Tr were performed in an effort to understand any peculiar behavior of these lignin models. Yields of guaiacol from the 135°C kraftlike degradations of 11 and 11Tr are shown in Table 4. It should be noted that 11Tr required the addition of *p*-dioxane (28.5%) to maintain soluble conditions during the reactions.

Table 4. Relative yields of guaiacol from the 135°C kraftlike degradations of compound 11 (in an aqueous system) and compound 11Tr (in an aqueous/28.5% *p*-dioxane system).

Time, min	11 (in H ₂ O) % Guaiacol	11Tr (in H ₂ O/ <i>p</i> -dioxane) % Guaiacol
7.5	0	0
15	0	0
30	0	4.6
60	3.4	17.8
120	5.9	37.9

The dramatic difference in the rate of guaiacol production suggests that the reactions of 11 and 11Tr must have unique mechanistic features. Examination of the methylated reaction extracts from the degradation of 11 shows the presence of the methylated analog of structure 37 (Fig. 2). Apparently, the primary alcohol acted as a "built-in" quinonemethide captor; Fig. 2 illustrates how the ionized primary alcohol could attack the quinonemethide, 11-QM, and form a six-membered ring (as it rearomatizes the system).³² This cyclization thus interferes with the typical kraft-system fragmentation reactions.

The above-mentioned behavior was not observed during the reactions of 11Tr; presumably, fragmentation reactions proceed without competing cyclizations,

giving further evidence for the stability of soluble trityl ethers under the chosen conditions. Similarly, cyclization should be unlikely with the insoluble model, 11Tr-P, since the propyl alcohol handle is blocked by the attachment to the polymer. Clearly, compound 11Tr constitutes a more appropriate control with which to compare the behavior of the insoluble model.

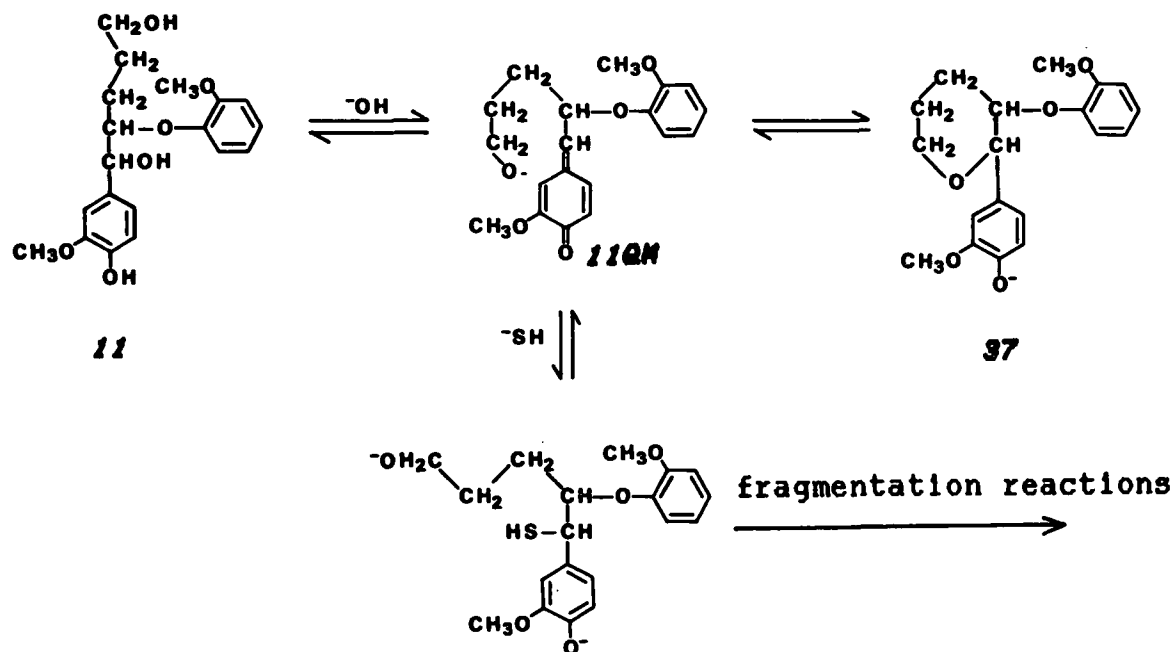


Figure 2. Cyclization reactions occurring during the kraftlike degradation of compound 11.

Homogeneous Degradations at 150°C

Kraftlike degradations were performed on both compounds 11 and 11Tr at 150°C, in both aqueous and aqueous/28.5% *p*-dioxane media. The percentage of *p*-dioxane used was arbitrary and convenient (1.0 in a total of 3.5 mL); compound 11Tr may indeed be soluble at a lower level of *p*-dioxane addition, at 150°C. Figure 3 shows the relative yields of guaiacol in each of these systems.

As was mentioned earlier, 11Tr is not soluble in an aqueous reaction system at room temperature. Nevertheless, the degradation of 11Tr was performed in the

water-only system to determine whether or not 11Tr is soluble at 150°C. The relatively low production of guaiacol suggests that 11Tr is sparingly soluble in the aqueous system even at 150°C.

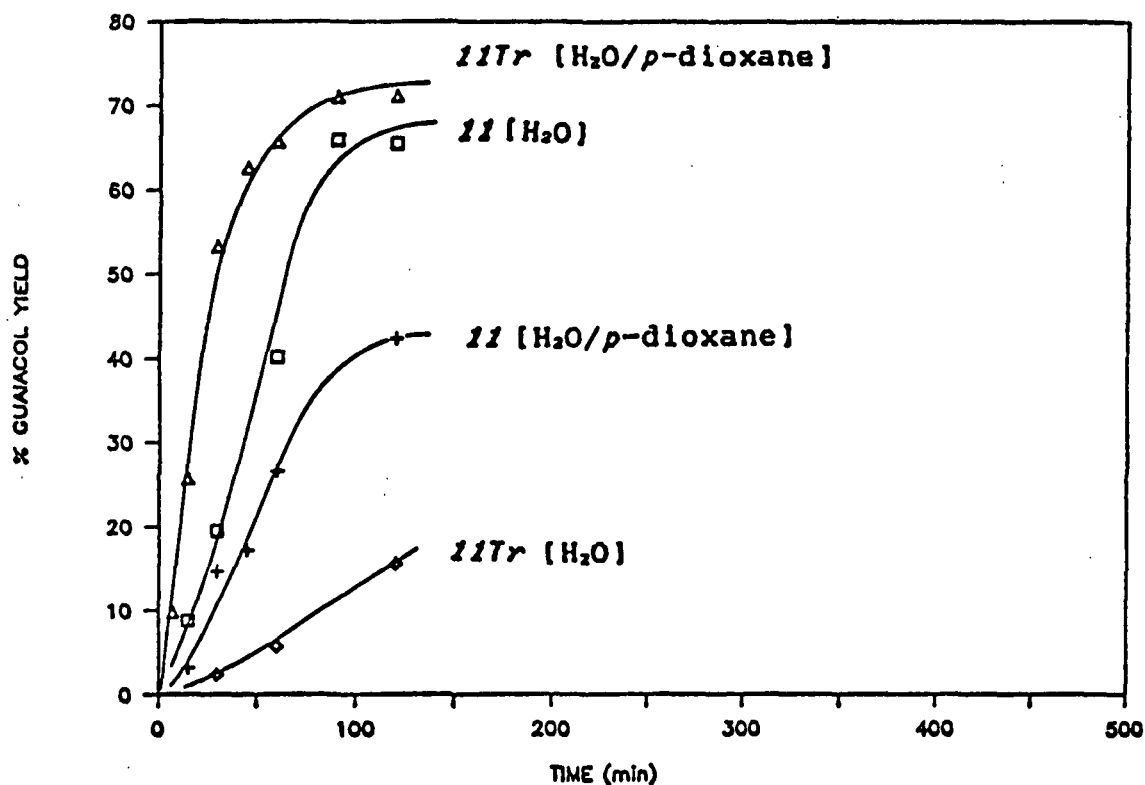


Figure 3. The relative yield of guaiacol from the kraftlike degradation of compounds 11 and 11Tr in both water and water/28.5% *p*-dioxane.

As Fig. 3 illustrates, the yields of guaiacol from the reaction of 11Tr in the aqueous/*p*-dioxane medium level off at ca. 71% after 90 minutes. Direct comparison of the guaiacol yield from 11 and 11Tr in the water/*p*-dioxane medium suggests that the cyclization process described previously (Fig. 2) is responsible for the depressed yields of guaiacol from 11.

Compound 11 fragments faster in the water-only medium than in the water/*p*-dioxane system. However, this observation does not suggest that the cyclization reaction (Fig. 2) did not occur in the aqueous medium - cyclization product

37 was observed in reaction extracts from both the water and water/p-dioxane reactions of 11. Rather, p-dioxane has been observed to depress the fragmentation of other β -aryl ether model compounds,³³ and is presumably slowing the production of guaiacol in this instance. Similarly, we can speculate that the rate of guaiacol production from 11Tr would have increased if the percentage of p-dioxane had been decreased (as long as solubility was maintained).

In addition, kraftlike degradations were performed with compound 11Tr in a water/28.5% DMSO system. The rate of guaiacol production from 11Tr in the DMSO system parallels the production in the p-dioxane system for the first 60 minutes (Table 5), after which the overall yield of guaiacol diminishes. A tentative explanation is that the loss of guaiacol at the later times is due to DMSO-promoted polymerization.

Table 5. Relative yields of guaiacol from the 150°C kraftlike degradations of compounds 11 and 11Tr in aqueous or aqueous/28.5% cosolvent systems.

Time, min	Compound 11		Compound 11Tr		
	H ₂ O	H ₂ O/ <u>p</u> -dioxane	H ₂ O	H ₂ O/ <u>p</u> -dioxane	H ₂ O/DMSO
	% Guaiacol		% Guaiacol		
7.5	--	--	--	9.8	13.1
15	8.8	3.2	--	25.7	29.7
30	19.5	14.7	2.4	53.3	48.2
45	--	17.2	--	62.6	57.4
60	40.2	26.6	5.7	71.0	41.2
90	65.5	42.4	--	71.2	26.7
120	--	--	15.6	--	5.1

Heterogeneous Reactions at 150°C

As previously mentioned, soluble model 11Tr was considered an appropriate control with which to compare the fragmentation behavior of the insoluble model. Fragmentation of 11Tr yielded guaiacol in a straightforward manner in the water/p-dioxane system. We therefore anticipated that the most meaningful comparison between the soluble and insoluble models would be with this cosolvent system.

Heterogeneous model 11Tr-P was reacted in both water-only and water/p-dioxane under kraftlike conditions. Figure 4 depicts the production of guaiacol from each of these systems, relative to the yield of guaiacol from 11Tr. The rate of guaiacol production from the insoluble model 11Tr-P in the p-dioxane system is unusually slow, ca. 9% after 8 hours. In contrast, the guaiacol yield from 11Tr-P in the water system was ca. 60% after 8 hours.

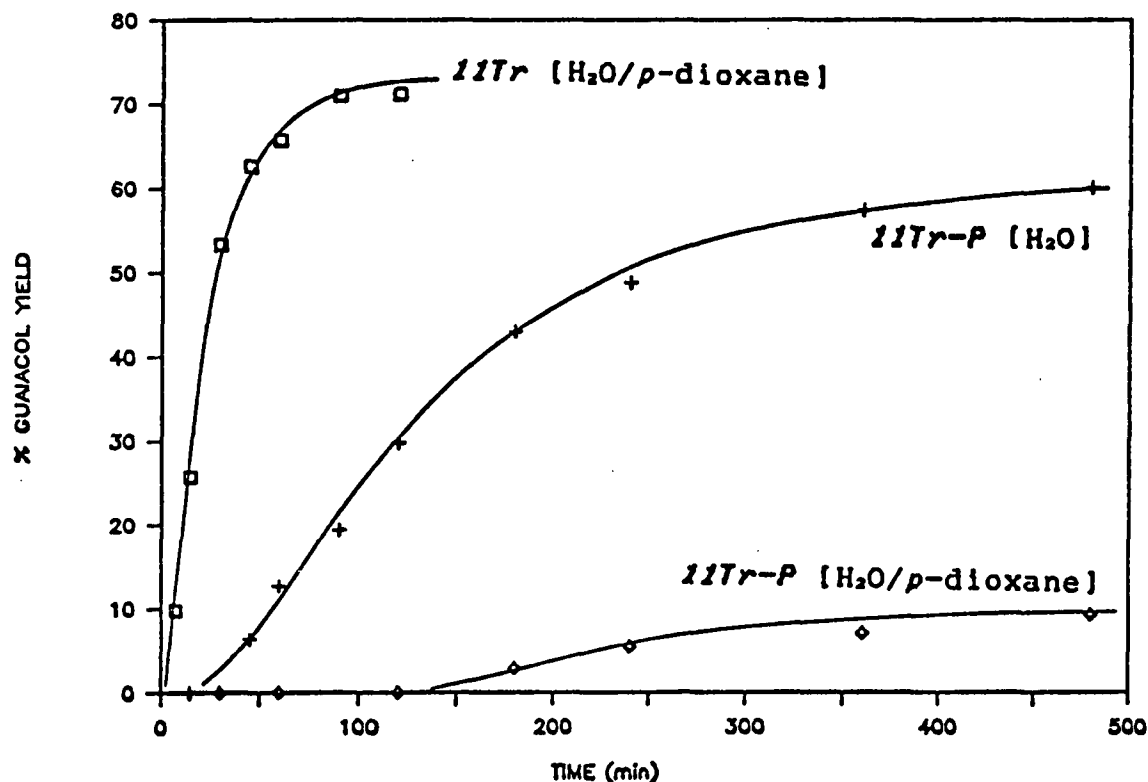


Figure 4. The relative yield of guaiacol from the kraftlike degradation of insoluble model 11Tr-P in aqueous and aqueous/p-dioxane systems.

The dramatic effect of p-dioxane on the production of guaiacol was unexpected; possible explanations include phase separation of the reaction medium and/or collapse of the macroreticular network. Phase separation of p-dioxane/ aqueous NaOH mixtures has been observed at high temperatures (90 to 170°C) by Obst.³⁴ If phase separation has occurred during the reactions of 11Tr-P and the organic layer has penetrated and "surrounds" the polymer, then the access of hydroxide and hydrosulfide to the reaction sites would be limited.

Moreover, while macroreticular polystyrenes are generally considered "non-swelling,"¹⁶ functionalized Amberlite XE-305 has been shown to swell moderately in p-dioxane.³⁵ The presence of p-dioxane in the kraftlike reactions could have swelled the polymer backbone of 11Tr-P and caused the macroreticular network to collapse. In this instance, the availability of the reactive sites would be restricted.

Would another cosolvent have a similar effect on the behavior of 11Tr-P? The insoluble model was reacted in a water/DMSO kraftlike system; Fig. 5 shows the production of guaiacol from soluble model 11Tr and insoluble model 11Tr-P in the DMSO. Again, the addition of a cosolvent has drastically depressed the yield of guaiacol. (Table 6 shows the complete tabulated data from reactions of 11Tr-P.)

Interpretation of Data from Insoluble Model 11Tr-P

The unexpected behavior of the insoluble model in water/cosolvent systems makes comparisons to the analogous soluble systems difficult. A logical approach would be to synthesize a derivative of 11 which would be soluble in an aqueous reaction medium, yet would prevent the competing cyclization reaction (Fig. 2). A likely candidate would be 11, monomethylated at the primary hydroxyl (11Me). The aqueous kraftlike reactions of 11Me could then be appropriately compared with the reactions of insoluble model 11Tr-P.

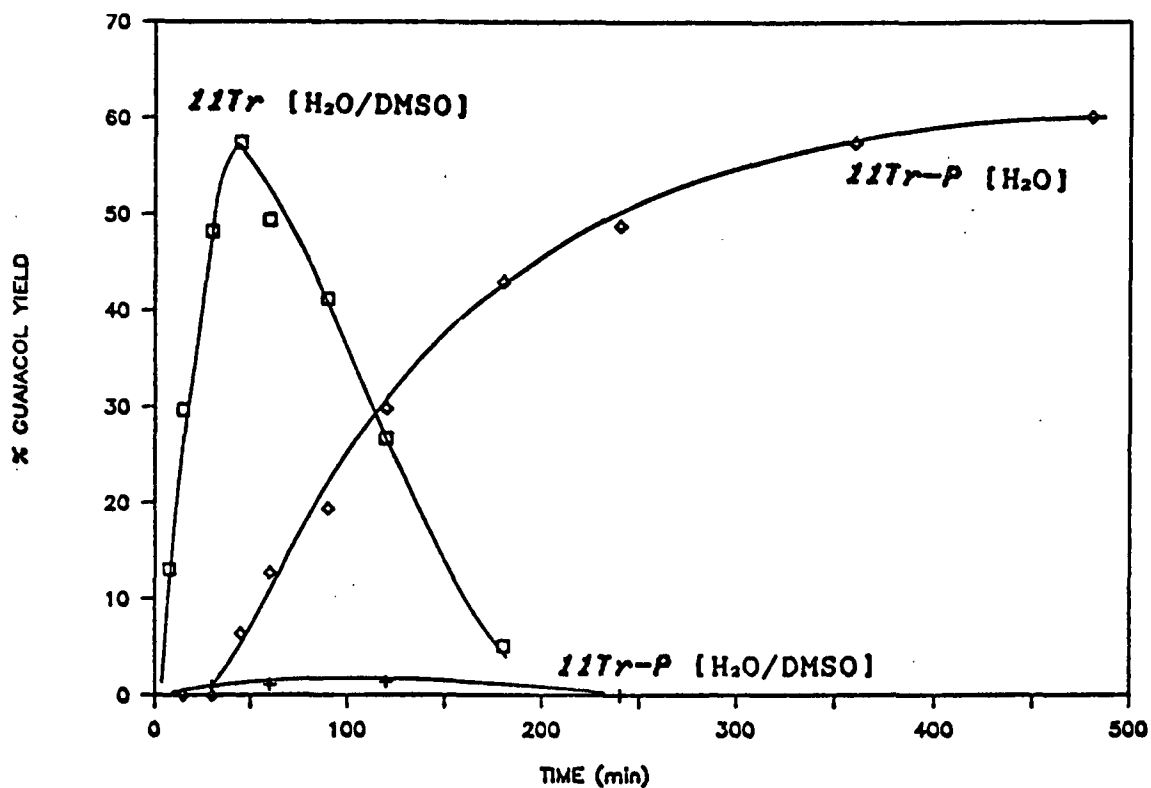


Figure 5. The relative yield of guaiacol from the kraftlike degradations of insoluble model 11Tr-P in aqueous and aqueous/28.5% DMSO reaction systems.

Table 6. Relative yield of guaiacol from the 150°C kraftlike degradations of insoluble model 11Tr-P in aqueous and aqueous/28.5% cosolvent reaction systems.

Time, min	Insoluble Model 11Tr-P		
	H ₂ O	H ₂ O/p-dioxane	H ₂ O/DMSO
	% Guaiacol		
15	0	--	--
30	0	0	--
45	6.4	--	--
60	12.7	0	1.1
90	19.4	--	--
120	29.8	0	1.4
180	43.0	2.9	--
240	48.8	5.5	0
360	57.4	7.1	--
480	60.1	9.3	--

However, even if a more appropriate soluble model (11Me) was prepared and studied, the interpretation of the guaiacol production from 11Tr-P is further complicated by observations that polymer-bound trityl ethers are not as alkali-stable as their soluble counterparts; cyclized product 37, which could only be present after trityl ether cleavage, was observed by GC/MS in extracts from the reactions of 11Tr-P. [Also, the alkaline lability of the trityl ether in the polymer-bound monomer 27Tr-P was previously detailed (Table 3).] The guaiacol production from the reaction of 11Tr-P is, therefore, from a combination of heterogeneous and homogeneous reactions.

A rough estimate of the maximum amount of guaiacol possible from soluble reactions of liberated 11 was calculated from the integrated rate expressions for consecutive, first-order, irreversible reactions.³⁶ The insoluble reaction which yields guaiacol was excluded from the calculation. The rate constant for the trityl cleavage reaction was estimated from the data from reactions of polymer-bound monomer 27Tr-P, and the rate constant for the soluble fragmentation reaction was derived from the data of the degradation of 11 in the aqueous kraftlike system (Table 5). Figure 6 shows the estimate for guaiacol production from soluble reactions and the difference between this estimate and the total yield of guaiacol from the degradation 11Tr-P.

Clearly, the relative alkaline lability of the polymer-bound trityl ether limits the utility of the insoluble model for quantitative studies. Nevertheless, the general design of the insoluble model appears sound. The techniques developed herein could be extended to exploit the unique characteristics of compound 11. An insoluble model based on a more stable polymer attachment, such as a polymer-bound benzyl ether,¹ could be prepared from 11, or from a version of

11 which has the phenol and secondary hydroxyl blocked with a removable protecting group.

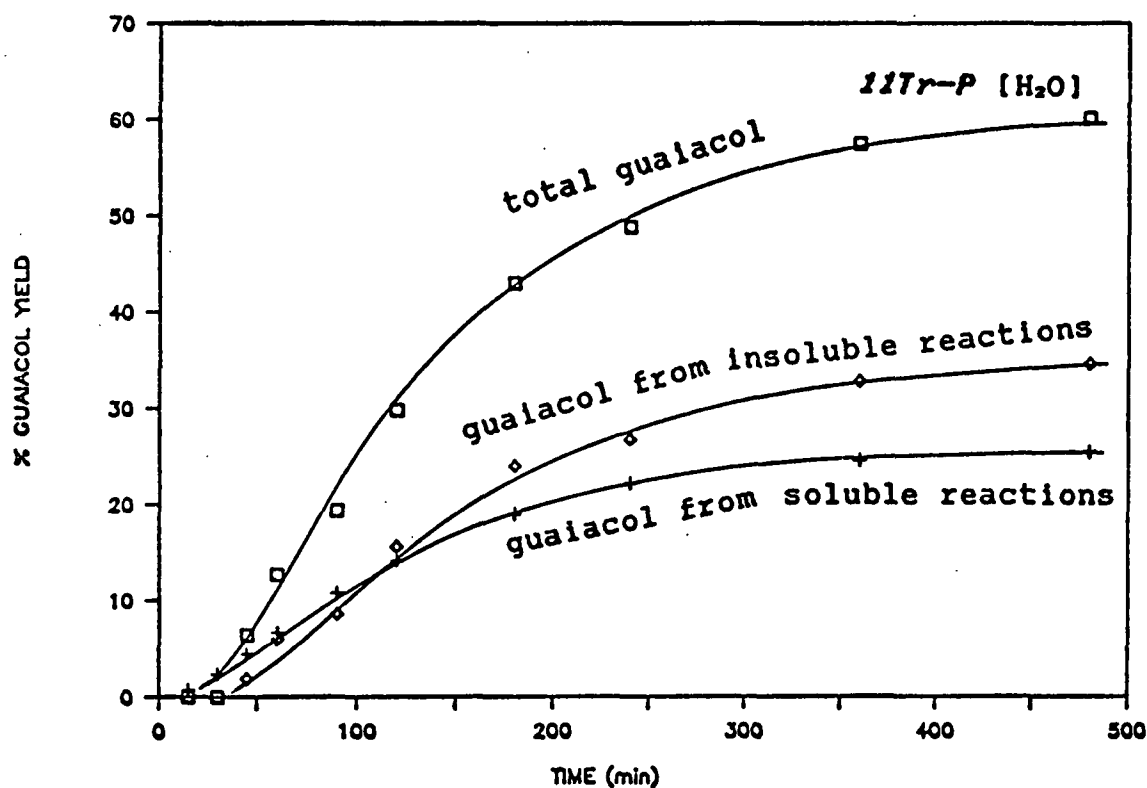


Figure 6. An estimate of the amount of guaiacol from soluble and insoluble reactions compared to the total yield of guaiacol from the kraftlike reactions of 11Tr-P.

SUMMARY

Unique lignin model dimer 11 has been shown to be an interesting and useful compound with which to study alkaline delignification. Compound 11 and its soluble tritylated analog 11Tr have been studied under 150°C kraftlike conditions and shown to have unique mechanistic features.

Compound 11Tr degraded to give guaiacol in a manner similar to other β -aryl ether models; the tritylated propyl alcohol handle did not interfere with ordinary fragmentation reactions. However, the nontritylated 11 undergoes cyclization

reactions which compete with fragmentation reactions. The nonderivatized propyl alcohol handle of 11 cyclizes by capturing quinonemethides and, in a different study, the handle of 11 has been exploited as an internal mechanistic probe in an attempt to differentiate between ionic and electron-transfer reaction mechanisms.³²

The polymer-bound trityl ether analog of 11, namely 11Tr-P, was prepared and studied as an insoluble lignin model under kraftlike conditions. In aqueous kraftlike media, 11Tr-P gave reasonable yields of guaiacol. However, the addition of cosolvents, *p*-dioxane or DMSO at a level of 28.5%, drastically depressed the yield of guaiacol from 11Tr-P. The influence of cosolvents is postulated to be due to physical effects such as solvent phase separation or collapse of the porous polymer network. A direct comparison of the cosolvent reactions of 11Tr-P to the soluble reactions of 11Tr (which required cosolvent to maintain solubility) may not, therefore, be appropriate.

In addition, polymer-bound trityl ether groups were found to be not as stable as their soluble analogs. The production of guaiacol from the reactions of 11Tr-P is, therefore, from both soluble and insoluble reactions. Data generated from this study have provided only an estimate of the quantity of guaiacol produced from the insoluble reaction.

EXPERIMENTAL

General Information

The specific instrumentation used, the performance of elemental analyses, and the reagents and solvents used have been previously detailed.²⁰

Amberlite XE-305 (macroreticular polystyrene) was purchased from Poly-sciences, Inc., Warrington, Pennsylvania, as manufactured by Rohm and Haas Co.,

Philadelphia, Pennsylvania. The methoxyl analyses of the insoluble model was performed by Mr. David Hogan of Chem-Lig International, Inc., Schofield, Wisconsin.

Simulated Kraft Pulping Reactions

The kraftlike degradations of both the hetero- and homogeneous lignin models were performed in 4 mL stainless steel pressure vessels (bombs). All pure solvents and solvent mixtures were deoxygenated before use. The bombs were loaded under dry N₂ with the following quantities: 0.015 mmol of soluble or insoluble lignin model, 20 equiv of NaOH and 5 equiv Na₂S, and a total volume of 3.5 mL. For the insoluble model case, 34.4 mg of material (which contained 0.436 mmol of attached model dimer per gram of polymer beads) was weighed directly into each bomb; these individual portions of beads were vacuum desiccated overnight and then the other reaction components were pipetted into the bombs. The soluble lignin models were dissolved in aqueous NaOH or cosolvent (p-dioxane or DMSO) and pipetted into the bombs.

After the contents were loaded, the bombs were sealed, prewarmed at 60°C for 30 min, and then tumbled in an oil-bath, at 135 or 150°C, for the desired reaction times. The production of guaiacol was quantitatively analyzed using a methylation/GC technique, with p-isopropylphenol as internal standard (IS), as described below.

Guaiacol Methylation/Analysis²⁶

Dimethylsulfate (1 mL, 100-350 equiv/model) was added to the model degradation solution/IS mixture, and the solution was stirred rapidly for 15 min in a loosely stoppered 25 mL Erlenmeyer flask. Concentrated ammonium hydroxide (4.5 mL) was added to quench the excess dimethyl sulfate, and the solution was

stirred for another 15 min. Chloroform (2 mL) was added, and the solution was stirred vigorously for 2 min, after which the CHCl_3 phase was removed with a disposable pipette, dried (Na_2SO_4) and analyzed by GC.

The identical procedure was carried out with the insoluble model degradation reaction mixtures; the entire bomb contents (beads included) were subjected to the dimethyl sulfate, the final CHCl_3 extraction, in these cases, was stirred for 5 min.

Analyses of the methylated guaiacol/*p*-isopropylphenol mixtures were performed on a Hewlett Packard gas chromatograph using a 6 ft, 1/4 inch glass column packed with 3% silicone OV-1 on 100/120 chromosorb W-HP. The following temperature program was used: 65° (2 min), then 20/min to 80° (3 min), and then 30°/min to 285°C (4 min).

Purification of Amberlite XE-305 Resin (31-P)²⁰

Approximately 100 g of Amberlite XE-305 was gently mechanically stirred for ca. 1 hr in 1500 mL of each of the following solvents (respectively) at or near reflux: benzene, methanol, DMF, *p*-dioxane/2N NaOH (1:1, v/v), *p*-dioxane/2N HCl (1:1, v/v), methanol, and benzene. After each heating/stirring period, the resin was filtered (using a gas dispersion tube and vacuum) and washed thoroughly with ca. 500 mL of the subsequent solvent. Thereafter, the resin was washed with ca. 500 mL each of room temperature methanol and CH_2Cl_2 , transferred to a large cellulose thimble, and Soxhlet extracted with Et_2O and with hexane for 8-10 hr in each case. (This final Soxhlet extraction sequence was used with all polymer products.) Finally, the resin was dried in vacuo at 100°C for several days until a constant weight was achieved. (Table 2 includes elemental analyses of the polymer preparations.)

Brominated Amberlite XE-305 (32-P)²³

To a suspension of 25.1 g 31-P in 360 mL of CCl_4 was added 0.94 g of thallic acetate sesquihydrate. This mixture was stirred in the dark for 30 min, at which time 8.05 g of bromine (freshly distilled) in 20 mL CCl_4 was added over 15 min. The reaction was gently stirred at room temperature for 1 hr and at reflux for 1.5 hr, after which the mixture had lost all color due to free bromine. The mixture was cooled and filtered; the collected resin was rinsed and filtered with 200 mL of the following solvents: CCl_4 , acetone, acetone/water (2:1), acetone, benzene, hot methanol, and methanol. The resin was Soxhlet extracted with Et_2O and hexane, collected, and dried in vacuo at 80°C to give 28.8 g of polymer 32-P.

Lithiated Amberlite XE-305 (33-P)

A portion of the brominated resin, 23.7 g (43.5 mmol Br) of 32-P, was suspended in 300 mL of dry benzene under a N_2 atmosphere (the N_2 was scrubbed dry and oxygen-free with an OXICLEAR gas purifier). While maintaining anhydrous conditions, 82 mL (131 mmol) of 1.6M n-butyllithium in hexane was added to the reaction mixture, after which the mixture was refluxed for 2 hr. The resin was filtered (using a gas dispersion tube with positive N_2 pressure), rinsed and filtered with dry THF, and the lithiated resin 33-P was suspended in 200 mL dry THF in preparation for the subsequent reaction.

Polymer-bound Trityl Alcohol (35-P)

Benzophenone, 19.8 g (2.5 equiv, relative to the expected Li content of 33-P) was dissolved in 125 mL of dry THF. This solution was added, over 5 min, to the stirring mixture of 33-P, as described above. The mixture was stirred for 2 hr at room temperature and filtered; the resulting resin was then rinsed

and filtered with 2 x 100 mL of the following solvents: THF, Et₂O, THF/water (2:1), water, THF, benzene, and hot methanol. The resin was Soxhlet extracted with Et₂O and hexane, and dried in vacuo at 100°C to give a cream-colored resin 35-P.

Polymer-bound Trityl Chloride (36-P)

Approximately 27 g of 35-P from above, was suspended in 350 mL of dry benzene and 63.7 g (0.82 mmol) of acetyl chloride was added. The reaction mixture was gently stirred at reflux under dry N₂ for 19 hr, after which it was allowed to cool. The resin was collected by filtration and rinsed and filtered with the following solvents: 3 x 75 mL benzene, 3 x 75 mL CH₂Cl₂, and 3 x 75 mL low boiling pet-ether. The resin was Soxhlet extracted with Et₂O and hexane, and dried in vacuo at 100°C to give 25.1 g of 36-P.

3-(3-Methoxy-4-hydroxyphenyl)-1-(polystyryltrityloxy)propane (27Tr-P)

Polymer-bound trityl chloride (36-P), 4.6334 g (4.21 mmol chlorine content), was gently stirred (with a small magnetic stir-bar) in 60 mL dry pyridine (under N₂) and 2.50 g (3 equiv) of 3-(3-methoxy-4-hydroxyphenyl)-1-propanol (27) was added. The mixture was stirred for 5 days after which the polymer was washed successively with dry pyridine and dry Et₂O. The beads were placed in a cellulose thimble and Soxhlet extracted for 12 hr with Et₂O and hexane. The resultant beads were dried in vacuo at 40°C until a constant weight of 4.8118 g was achieved. The amount of material loaded, 0.2233 g, was calculated from the following equation:

$$[\text{model loaded (g)}] = \frac{[\text{weight gain of polymer product}]}{1 - \frac{[\text{MW of HCl}]}{[(\text{MW of model}) - 1.008]}}$$

The loading level, determined from this gravimetric analysis, was calculated to be 0.256 mmol/g. The quantity of compound 27 which could be liberated from 27Tr-P upon acid hydrolysis (as measured by GC) corresponds to 102% of the above-mentioned loading.

2-(2-Methoxyphenoxy)-1-(3-methoxy-4-hydroxy)-5-(polystyryltrityloxy)-1-pentanol (11Tr-P)

Into 50 mL of dry pyridine and 25 mL dry benzene was suspended 3.9121 g (3.55 mmol chlorine content) of 36-P. To this was added 7.10 g (20.4 mmol) of compound 11 and the reaction mixture was gently stirred (with a small magnetic stir-bar) at 45-50°C for 6 days. The beads were transferred to a glass thimble, filtered, and rinsed with fresh dry pyridine and benzene. The beads were then Soxhlet extracted with Et₂O and hexane (for 10-12 hr with each solvent), and the beads were dried in vacuo at 45°C to a constant weight of 4.4756 g. The amount of 11 loaded on 11Tr-P was calculated (based on the gravimetric analysis) to be 0.630 g, which corresponds to 0.405 mmol/g. A more reliable estimate of loading, 0.436 mmol/g, was derived from methoxyl analyses, and used when calculating stoichiometries for the degradation studies.

Acid Hydrolysis of Polymer-bound Models; General Procedure

Approximately 50-150 mg of insoluble model was suspended in 2 mL CH₂Cl₂ in a 60 mL separatory funnel (which had a plug of glass wool compressed into place just above the stopcock). To this suspension was added 0.5 mL of trifluoroacetic acid (TFAA) and the mixture was periodically swirled over 15 min. The mixture was then drained into another separatory funnel which contained an excess of saturated aqueous K₂CO₃; the K₂CO₃ neutralized excess TFAA and hydrolyzed any trifluoroacetates which may have formed.³¹ The overall process was repeated 2x or 3x with the polymer beads, after which the resultant CH₂Cl₂ layer was separated and its contents analyzed by GC or GC/MS.

Identification of Cyclized Product 37

The methylated extracts from the kraftlike reactions of compound 11 were subjected to GC/MS analysis. Gas chromatographic separation was achieved on a Hewlett-Packard 5840A GC using a 6 ft, 1/4-inch glass column packed with 3% silicone OV-17 on 100/120 chromosorb W-HP (100-300°C at 10°/min); the methylated analog of 37 was eluted at ca. 19.7 min: MS m/e (%) 344 (34.7, M⁺), 221 (100.0), 151 (47.7), 220 (27.8), and 165 (15.5). An authentic sample of 37 (nonmethylated and methylated) was available from a separate study; GC/MS comparisons were identical.

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CONCLUSIONS AND SUGGESTED FUTURE WORK

The preparation and characterization of an insoluble/heterogeneous lignin model has been accomplished. Comprising the insoluble model was a basic reactive unit of lignin, a β -aryl ether, attached to a polystyrene matrix by means of a polymer-bound triphenylmethyl (trityl) ether. The prerequisite polymer-bound trityl chloride was prepared by following proven synthetic techniques.

The point of model-to-polymer attachment was a propyl alcohol handle which had been incorporated into a lignin dimer structure. Three potentially useful lignin dimers with propyl alcohol handles were synthesized during the course of the thesis (Fig. 1), although only one (compound III) was employed to produce a heterogeneous model. The modification of existing procedures and the development of new synthetic schemes, in order to prepare such models, proved to be the most formidable task in the course of the preparation of an insoluble model.

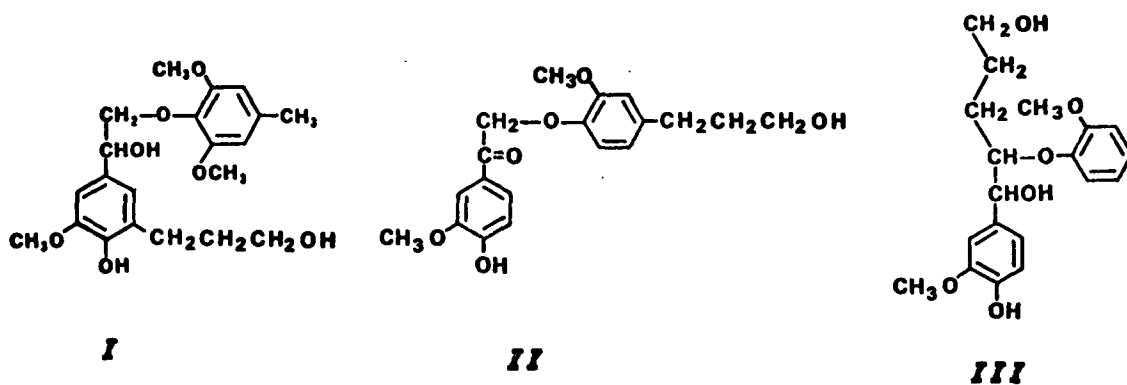


Figure 1. Three lignin model dimers prepared during the course of the thesis.

Two of the three synthetic schemes developed herein (to give compounds II and III) are generic techniques by which a propyl alcohol handle can be introduced to a variety of lignin models. Compound I resisted tritylation, but may

still prove useful if the structure can be modified to allow derivatization at the handle.¹

Compound III, on the other hand, had desirable properties and was successfully supported via a polymer-bound trityl ether to a macroreticular polystyrene to produce a heterogeneous lignin model. Also, unusual behavior of III was observed under kraftlike conditions, which may make the compound useful in studies designed to differentiate between ionic and electron transfer mechanisms.²

The synthesis of compound I, although it does not add a handle to an already prepared dimer, is a straightforward method to prepare a lignin model with a handle. Certainly, I could be used as a basis for a polymer-bound model.

Preliminary reactions of the insoluble model, based on III, gave moderate yields of guaiacol, a fragmentation product; the yields were dramatically depressed upon the addition of cosolvents. The cosolvent effect complicated the interpretation of results from the insoluble model and, for future work in this area, the use of cosolvents is not recommended.

The polymer trityl ether attachment was not as stable to kraftlike conditions as its soluble analog. A portion of the guaiacol production from the reactions of the insoluble model are from the soluble reactions of liberated III.

The alkaline lability of the polymer-bound trityl ether limits the potential usefulness of the particular insoluble model developed herein. Nevertheless, the general design - a polymer-bound protecting group linked with a specific functional group handle - appears sound. Moreover, the particular insoluble model (based on III) could be used to study lignin reactions in other systems under which the polymer linkage would be stable.

The unique characteristics of compound III should still prove useful for the preparation of another insoluble model based on a more stable attachment, such as a polymer-bound benzyl ether (Fig. 2).³ Tritylated III could have the remaining hydroxyls blocked with a derivative that is stable over the entire pH range, such as a β -(trimethylsilyl)ethoxymethyl (SEM) ether.⁴ Acid hydrolysis of the trityl ether would leave the propyl alcohol handle as the only free hydroxyl which could be attached to a polymer by means of a chloro- or iodo-methylated polystyrene.^{5,3} The functionalized polymer no longer requires selectivity for a primary hydroxyl. The SEM ethers can be readily removed by fluoride ion, giving an alternative insoluble lignin model.

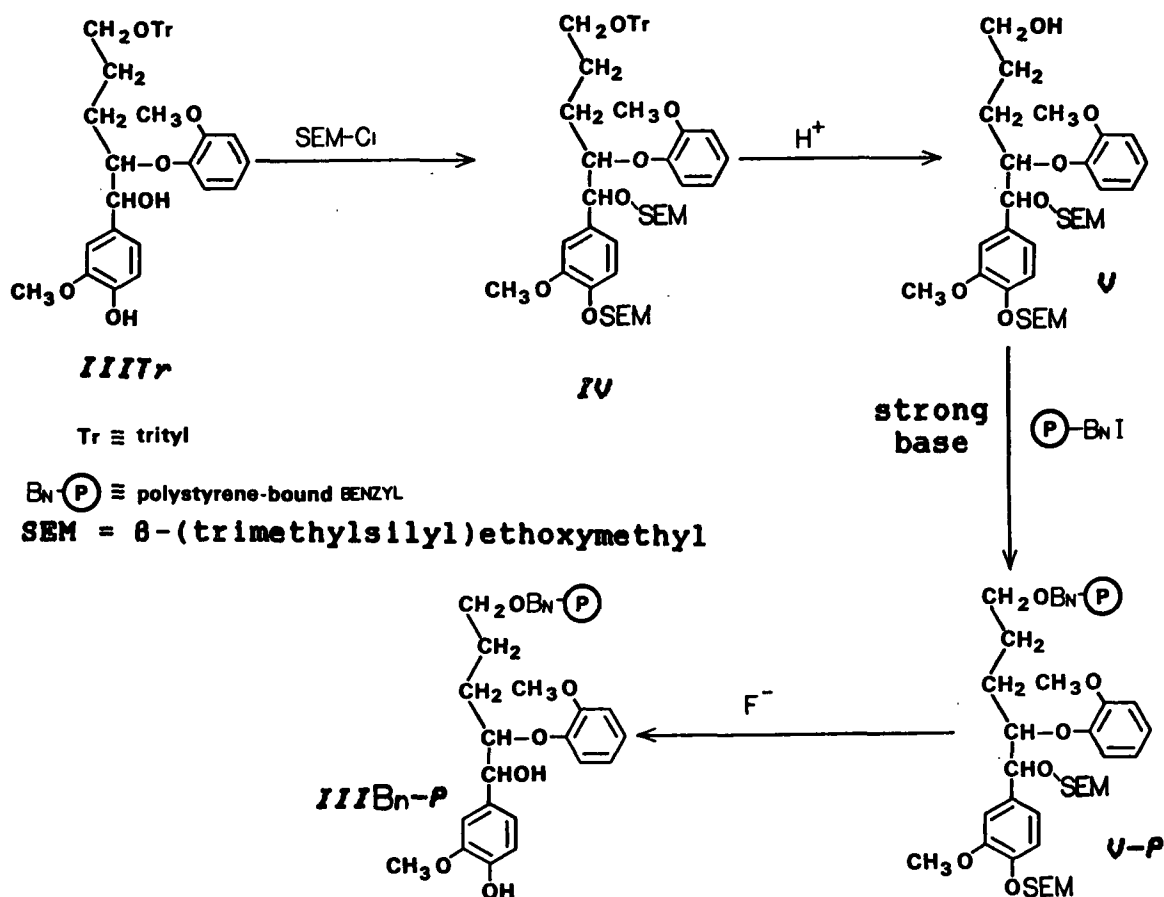


Figure 2. Possible synthetic route to an insoluble lignin model based on a polymer-bound benzyl ether linkage to compound III.

Finally, the insoluble model developed herein may be considered as a prototype; the basic design should allow for the production of other heterogeneous models with varying characteristics. The convenient form of the insoluble model (polymer beads) adds to their potential versatility; polymer-supported models can be studied under either batch or continuous (continual fresh reagent) experimental conditions. Heterogeneous models, just by virtue of their insolubility, incorporate characteristics of reactions occurring at solid-liquid interfaces and as such should provide the lignin chemist with an additional tool to study the reactions of lignin.

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ACKNOWLEDGMENTS

First and foremost, I would like to extend a special thanks to Dr. D. R. Dimmel, who has served as my advisor and the chairman of the Thesis Advisory Committee; Don tends to bring out the best in his students, and I am thankful that our paths have crossed.

I would also like to express appreciation for the guidance provided by the remaining members of the Advisory Committee, Drs. T. M. McDonough, L. R. Schroeder, and H. T. Cullinan, Jr.

Sincere appreciation also goes out to other faculty, staff members, and fellow students who provided assistance and friendship. Special thanks go to staff members Lois Schuller, and Glen Yates and Leroy Borchardt of Analytical Services.

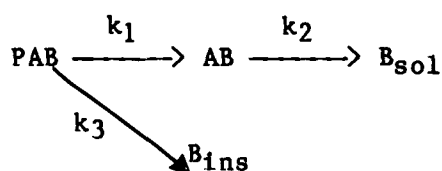
The financial support provided by The Institute of Paper Chemistry is gratefully acknowledged.

Finally, I would like to thank my wife, Kristine, for her continuing patience and encouragement and, especially, for her love and understanding.

APPENDIX I

ESTIMATE OF GUAIACOL PRODUCTION FROM SOLUBLE REACTIONS, DURING THE REACTIONS OF THE HETEROGENEOUS MODELS

As mentioned in the results and discussion of Article II, the polymer-bound trityl ether attachment was observed to be cleaving during the reactions of the polymer-bound dimer. The observed guaiacol production from the insoluble model is, therefore, from both soluble and insoluble reactions, as shown below:



where, PAB = insoluble model dimer

AB = liberated dimer (after trityl ether cleavage)

B_{sol} = guaiacol yield from liberated AB

B_{ins} = guaiacol yield, from direct fragmentation of PAB.

In order to derive a rough estimate of the maximum guaiacol production from soluble reactions, the insoluble k_3 reaction was ignored, and B_{sol} was calculated from the integrated rate expressions for consecutive, first-order, irreversible reactions as shown:

$$\begin{aligned} \text{PAB}_t &= \text{PAB}_0 \exp -k_1 t \\ \text{AB}_t &= \cancel{\text{AB}_0 \exp -k_2 t} + \frac{k_1}{k_2 - k_1} \text{PAB}_0 (\exp -k_1 t - \exp -k_2 t) \\ \text{B}_{\text{sol},t} &= \text{PAB}_0 [1 - \exp -k_1 t - \frac{k_1}{k_2 - k_1} (\exp -k_1 t - \exp -k_2 t)] \\ &\quad + \cancel{\text{AB}_0 (1 - \exp -k_2 t)} + \cancel{\text{B}_{\text{sol},0}} \end{aligned}$$

The rate constant k_1 was derived from the trityl cleavage data for the polymer-bound monomer (27Tr-P, Table 3, Article II). The natural log (ln) of the polymer-bound monomer concentration was plotted vs. time. (The available concentration of polymer-bound monomer was assumed to be 26% of the actual amount of monomer loading, since there was no cleavage after ca. 26% yield of monomer.) The slope of the above line is $k_1 = -0.035 \text{ min}^{-1}$ [correlation coefficient = 0.99 (Texas Instrument TI-55III calculator program)].

The rate constant k_2 was derived from the guaiacol production data from the degradation of the nonderivatized dimer (compound 11, Table 5, Article II) in the water system. The ln of the concentration of 11 was plotted vs. time; the slope of the line was $k_2 = -0.009 \text{ min}^{-1}$ (correlation coefficient = 0.99).

Employing the above rate constants, and assuming that the maximum portion of polymer-bound trityl ethers that can be cleaved in alkali is ca. 26%, we calculated an estimate of guaiacol production from liberated dimer (AB = 11) at various reaction times. Below is a sample calculation for 90 minutes.

$$B_{\text{sol},t} = PAB_0[1 - \exp(-k_1 t) - \frac{k_1}{k_2 - k_1}(\exp(-k_1 t) - \exp(-k_2 t))]$$

$$\begin{aligned} B_{\text{sol}}(@90 \text{ min}) &= 0.26[1 - 0.428 - (-1.35)(0.0428 - 0.445)] \\ &= 0.108 \approx 10.8\% \text{ guaiacol from soluble reactions} \end{aligned}$$

APPENDIX II

ACIDIC CLEAVAGE OF POSTDEGRADATION, POLYMER-BOUND PRODUCTS

In order to more completely describe the chemistry of the polymer-bound lignin dimer, it was intended to analyze the molecules remaining on the polymer after the kraftlike degradations. The acid hydrolysis procedure previously described (Article II, Experimental) was repeated with samples of post-degradation polymer-bound lignin model dimer.

The acid hydrolysis procedure employed a large excess of trifluoroacetic acid; it was not optimized as to cleave remaining polymer-bound products without inducing acid rearrangements or degradations. The only product identified by GC/MS, to date, (from the acid treatment of postdegradation insoluble model samples) was cyclization product 37 (Fig. 2, Article II). In this instance, structure 37 was no doubt derived from acid cleaved polymer-bound starting material (compound 11, Article II, Fig. 1). Acidic conditions can also lead to this cyclization product from liberated 11.

