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Inorganic and Biomass-Derived Plastics: Viable Economic Alternatives to Petrochemical Plastics?

T. Randall Curlee

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INORGANIC AND BIOMASS-DERIVED PLASTICS: VIABLE ECONOMIC ALTERNATIVES TO PETROCHEMICAL PLASTICS?

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INORGANIC AND BIOMASS-DERIVED PLASTICS: VIABLE ECONOMIC ALTERNATIVES TO PETROCHEMICAL PLASTICS?

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ABSTRACT

This report discusses the economic feasibility of replacing conventional petrochemical-derived plastics with plastics manufactured from inorganic or biomass raw materials. It is argued that the economic feasibility of these new resins will depend on their abilities to (1) provide equivalent material properties at an equal or lower cost than conventional plastics, or (2) provide improved properties in a way such that the marginal benefits of the improved properties outweigh their marginal costs. The potential improved properties of these new resins include engineering materials properties, less environmental degradation associated with disposal, and benefits derived from moving away from intermediate products based on petroleum and natural gas.

Unfortunately, at this time only limited statements can be made about the abilities of these new resins to meet these requirements. In the case of raw materials production, no clear favorite is identified. Current information suggests that oil and natural gas prices will continue to increase, but probably not at the rate experienced during the past one and a half decades. Reserves of inorganic raw materials are large enough that any likely increased demands for those resources for the production of inorganic plastics should have a small effect on inorganic raw material prices. Biomass raw material prices are currently high in relation to oil and natural gas. That gap is, however, expected to decrease as selected agricultural operations are dedicated to fuels and chemicals production. Genetic engineering will also likely result in new or varied species that are more suited to the production of chemical feedstocks. The availability of raw materials does not appear to be a significant problem.

At the intermediate products level, little information is currently available that is relevant to the production of inorganic plastics. Biomass-derived intermediate products, which could substitute for petrochemical feedstocks in the production of conventional plastics, are currently more costly and more contaminated than the same intermediates produced from petroleum and natural gas. Recent studies suggest that, all else being equal, oil and natural gas prices would have to increase by more than 100% before biomass materials would displace any significant percentage of oil and natural gas. In addition, it is generally agreed that if oil and natural gas prices increase sharply, coal -- not biomass -- is the logical alternative raw material. Revolutionary technologies,

such as those based on microorganisms, may, however, greatly reduce the cost of biomass conversion.

Little specific information is available on the likely costs of inorganic and biomass-derived resins that are in the development stage. It is, however, generally accepted that without major technological advances, the prices of inorganic and biomass-derived plastics will be significantly higher than the current or forecasted prices of petrochemical-derived plastics. Prices of the few biomass-derived resins currently being marketed are about double the prices of the conventional resins with which those new resins must compete.

If inorganic and biomass-derived plastics are to become competitive with conventional plastics, the cost differences between the resin types will have to narrow. Alternatively, the special properties of the new resins will have to prove to be quite valuable. The non-flammability characteristics of inorganic plastics may prove particularly valuable in sectors with rapidly growing plastics consumption, such as construction. The biodegradability characteristics of many biomass-derived plastics may prove valuable in the packaging area. An estimation of the specific benefits of the special characteristics offered by inorganic and biomass-derived plastics must, however, be done for each characteristic and each end product and must await further research.

An added problem for inorganic and biomass-derived plastics concerns barriers to market entry. Even if either of the above necessary conditions for economic feasibility holds, the market penetration of the new resins awaits stiff competition from an entrenched petrochemical and resin industry. It has been argued that the production of some of the main resin feedstocks, e.g. ethylene, is essentially a by-product of the refining industry. The prices of resin feedstocks could therefore come down sharply in response to threatened competition. Adopters of the new technology will face significant technological, market, and regulatory uncertainties.

In addition, the arguments for inorganic and biomass-derived plastics on the basis of reducing environmental degradation are at this time somewhat tenuous. And, in general, the arguments for the development and use of these new resin on the basis of saving petroleum and natural gas have been overstated. The main arguments for a stronger role for the public sector to encourage the transition away from conventional plastics are therefore less than convincing. There are, nevertheless, movements at the national, state, and local levels that will directly or indirectly limit the use of conventional plastics and encourage the transition to alternative materials.

The overall feasibility of replacing conventional plastics with ones based on inorganic or biomass materials will turn on numerous economic, technological, and institutional factors. It will also turn on the public sector's evaluation of the need to move away from plastics based on petrochemicals.

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1. INTRODUCTION

There is currently significant interest in developing and using new plastics that are made from raw materials other than petroleum and natural gas. Inorganic and biomass-derived polymers are receiving the most attention. The vast majority of this work has appropriately focused on the technological problems that must be overcome before these new polymers become viable alternatives to conventional plastics. And while progress has been slow on the technological front, recent developments are encouraging.

Little work has, however, been done to assess the economic and institutional viability of these new polymers. Some suggest that inorganic and biomass-derived plastics will replace most or a significant proportion of petrochemical-derived plastics in the coming one to two decades. Others suggest that even if the current R&D activities in this area are successful, the economic and institutional realities are such that biomass and inorganic plastics will only be applicable to certain specialty markets and cannot be expected to displace a large percentage of conventional plastics. The primary purpose of this report is to address this controversy.

The increased interest in biomass and inorganic plastics has arguably resulted from three important trends. The first is our general concern about oil prices and oil import vulnerability. The production and use of plastics in the United States have more than quadrupled during the past two decades. Further, my projections indicate that U.S. plastics production will increase from about 45 billion pounds in 1984 to about 64 billion pounds in 1995 (Curlee 1986). Given that plastics are manufactured primarily from oil and natural gas, plastic manufacturers and consumers of plastic products are concerned that prices of plastics will be subject to the whims of the international oil market. In addition, the public sector is concerned that increased demands for plastics will push the price of oil higher and in general make our oil vulnerability problem more severe. A movement away from oil and natural gas and toward biomass and inorganics is seen as a way to help insulate plastic markets from the price volatility of the oil market and at the same time decrease the probability of oil market disturbances by reducing the demand for oil.

The second trend is derived from our growing concern about environmental issues and how conventional plastics may contribute to environmental degradation. The EPA reports that on a weight basis plastics accounted for about 7.2% of the typical U.S. municipal waste stream (MWS) in 1984 and are projected to increase to about 9.8% by the year 2000. On a volume basis the percentage numbers are double to triple the above weight estimates. Conventional plastics are widely perceived to be problematic when disposed of by either landfill or incineration and have been the target of both state and federal regulators. A movement away from conventional plastics toward biomass and inorganic plastics is seen as a way to avoid the potential harmful effects of incinerating or landfilling petrochemical-derived plastics, or at minimum to avoid further regulatory intervention.

The third trend concerns the drive to improve the physical and chemical properties of plastics. Plastics are increasingly viewed as viable alternatives to metals, alloys, ceramics, wood, paper, and other widely used materials. As will be discussed below, the successful development of biomass and inorganic plastics will offer physical and chemical properties that may allow plastics to be used in new applications and improve the performance of plastics in current applications.

The validity of each of the above arguments for the development and use of plastics based on biomass or inorganic materials will be addressed more fully in the following sections. It is important to point out at this juncture, however, that the economic and institutional viability of these new polymers as replacements for conventional plastics cannot be divorced from how the new polymers address these trends. In order for inorganic and biomass-based plastics to become economically viable, one of two sets of criteria must be met: (1) the new plastics must be able to provide the same material characteristics at equal or lower cost than those provided by currently used plastics, or (2) if the new plastics are more costly than currently used plastics, the additional cost must be less than the additional benefits the new polymers provide in terms of meeting the key trends that have encouraged the development of these new materials -- i.e., material properties, environmental degradation, and/or oil use and vulnerability.

The following section of this report focuses on the key technical issues that face the successful development and use of inorganic and biomass-derived plastics. More specifically, the second section addresses the general material properties of conventional, inorganic, and biomass-derived plastics and examines the arguments concerning the effects of each plastic type on the environment. Section III focuses on the economic and institutional barriers that must be overcome before inorganic and biomass-derived plastics can replace a significant percentage of conventional plastics. Also addressed in Section III are the arguments that suggest that inorganic and biomass-derived plastics should be developed in response to future oil prices and oil vulnerability. Conclusions are summarized in Section IV.

2. TECHNOLOGICAL ISSUES

2.1 INTRODUCTION

A detailed discussion of the physical and chemical properties of organic and inorganic polymers is beyond the scope of this report. One must, however, have a general understanding of the technological incentives and barriers facing the development of inorganic and biomass-derived plastics before the economic and institutional viability of these new plastics can be discussed. Economic and institutional viability are inextricably linked with technological viability in ways that are not always obvious. The purpose of this section is therefore to present a relatively non-technical discussion of the technological issues facing the development and use of inorganic and biomass-derived plastics.

There are three major focuses of this section. The first is on what we mean by inorganic and biomass-derived plastics. As will become obvious, the definitions of these new polymers differ depending on the source. The second focus is on the general physical and chemical characteristics of petrochemical, inorganic, and biomass-derived plastics and on the technical problems that face the production and use of each type of polymer. The third focus is on the likely environmental effects of the three plastic types. The somewhat limited information that is currently available on the potential environmental impacts is summarized. This section therefore addresses two of the major trends that are driving the development and use of plastics based on raw materials other than oil and natural gas -- i.e., the drive for new and better material properties and the increased concern about the role of plastics in environmental degradation.

2.2 INORGANIC AND BIOMASS-DERIVED PLASTICS DEFINED

The definition of inorganic and biomass-derived plastics depends on the source. The definition of inorganic plastics is most problematic. Currell (1985) defines inorganic polymers as including all materials with an inorganic macromolecular backbone structure. Zeldin (1976) defines an inorganic polymer as any high molecular weight substance containing repeating metallic and/or non-metallic elements in the backbone structure. Ray (1978) states that "inorganic polymer" has often implied any macromolecule that does not have a backbone of carbon atoms. The above definitions lead, however, to a very broad definition of inorganic polymer -- one that includes substances such as diamonds, graphite, glasses, ceramics, and even concrete. Ray goes on to point out that a more meaningful definition for inorganic polymer may be all linear macromolecules with at least two different elements, one of which can be carbon, and which are linked together by covalent bonds. Ray's definition includes polymers that retain at least some of their characteristic properties of macromolecules both in solution and in the molten state. This definition puts inorganic polymers in the same general classification as conventional petrochemical-derived plastics. Ray's definition includes polymers based on elements such as sulphur, boron, aluminum, silicon, tin, phosphorus, and the transition elements.

The definition of biomass-derived plastics is less problematic. A typical definition is given by Chum. Chum (1987) defines biobased materials as all polymeric materials derived from renewable resources by chemical/mechanical methods or renewable materials produced in biological processes.

For the purposes of this report, however, none of the above definitions are particularly helpful. A more appropriate definition for this report is focused on the applications of the polymer rather than the polymer's physical and chemical properties. For our purposes it is sufficient to define inorganic and biomass-derived plastics as all polymers that are predominately manufactured from inorganic or biomass materials and which are potential substitutes for petrochemical plastics in the applications in which those petrochemical plastics are currently used. By adopting this definition, we do not consider inorganic or biomass-derived plastics that have general or specialty applications not currently served by conventional petrochemical plastics.

2.3 TECHNOLOGICAL CONSIDERATIONS

2.3.1 Introduction

Plastics have been produced and used in the United States since the 1860s when John Wesley Hyatt developed cellulose nitrate and used the material in the production of billiard balls and eye-glass frames. The period 1930-1940 saw the development of today's major thermoplastic materials, such as polystyrene, low-density polyethylene, and polyvinyl chloride.

It is interesting to note that the first plastics were produced predominately from biomass materials and coal. Coal has been used, for example, in the production of polyvinyl chloride, polyvinyl acetate, polystyrene, and polyamides. Agricultural products have also been used in a variety of plastics. For example, ethanol has been converted into ethylene, which has in turn been used to produce ethyl cellulose, polyethylene, and polystyrene. Other agricultural products, such as oat hulls, wood, corn, soya beans, and oil seeds, have also been used to produce a variety of plastic resins. In addition, inorganic materials, such as brine, limestone, silica, and boric acid have historically been used in combination with organic materials to produce widely used polymers. These inorganic materials have been employed either as fillers or in small amounts for catalytic and other purposes.

Gradually, plastics manufactured from coal and agricultural materials were replaced by petroleum and natural gas as the U.S. chemical industry became more dependent on those raw materials. Petroleum and natural gas and the processes that developed around those raw materials offered a more homogeneous and less contaminated product. Today the U.S. chemical industry depends on natural gas for about 27% of its raw materials, with petroleum accounting for essentially all of the remainder. Coal contributes less that 0.1% of chemical feedstocks (International Research and Technology Corporation, 1974).

The major chemical feedstocks entering into the production of plastics are ethylene, propylene, and benzene. In 1985 ethylene accounted for about 46% of total U.S. resin production (21,940 million pounds), propylene about 16% (7,675 million pounds), and benzene also about 16% (7,495 million pounds). [The Society of the Plastics Industry (1986) provides more detailed information on the quantities of precursors used for the production of various plastic resins.][1]

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[1]The production of plastics is complicated and involves numerous steps. Hydrocarbon Processing (1988, pages 59-90) provides a straightforward guide to the production of various polymers and other chemicals.

2.3.2 Properties of Conventional Plastics

During the past 40 years, petrochemical-derived plastics have partially replaced many traditional materials, such as wood, glass, steel, aluminum, stone, and agricultural materials, such as wool and cotton. In addition to often being less costly than the materials they replace, the increased use of plastics has been based on weight reduction, resistance to corrosion, ease of fabrication, electrical insulating properties, and superior engineering performance.

However, while conventional plastics have general properties that make them attractive for many applications, they also have disadvantages. These disadvantages include thermoplastics' relatively low resistance to melting at moderate temperatures, flammability, and a lack of resistance to certain organic solvents. Many conventional polymers are also found to distort when subjected to periods of prolonged stress. Although R&D is continually producing petrochemical-derived plastics that perform better with respect to these problem areas -- e.g., additives have improved heat resistance, reduced flammability, and improved strength and toughness -- these general problems are not expected to be completely eliminated.[2]

2.3.3 Properties of Inorganic Plastics

The inabilities of conventional plastics in terms of their thermal stability and oxidation resistance, encouraged the development of new, non-metallic polymers that could retain their mechanical and electrical

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[2]The physical and chemical properties of the currently used resins vary widely. For more information on these specific properties, see Chapter 2 and Appendix A of my recent book (Curlee, 1986b).

properties at higher temperatures than organic plastics, while maintaining the attractive features of conventional plastics. Ray (1978) reports that the rapid growth in the aerospace industry following the Second World War created an urgent demand for such materials. Attempts were made to synthesize long-chain polymers from inorganic elements in a structural pattern similar to those of the most useful organic polymers. The main focus of the work has been on elements such as boron, aluminum, silicon, and phosphorus. Unfortunately, this approach has produced few inorganic polymers that exploit the special characteristics of inorganics, while maintaining the desirable properties of organic polymers.

The major success has been with polymers based on silicon. The first polysiloxanes became available commercially following the Second World War and are now used widely. However, in relative terms the production of all silicone thermosets in the U.S. remains small. About 16 million pounds were produced in 1984, as compared to the total 1984 U.S. production of all plastic resins of 46,336 million pounds (Society of the Plastics Industry, 1986). Silicones are currently used in polishes and paints, dental and medical materials, textile treatments, sealants, resins for electrical insulation, and as spray lubricants.

Another example of an inorganic plastic that has met some success is plastic sulphur. Sulfur has been used in thermoplastic cement, which has shown good mechanical properties and good chemical resistance to acids and oils. Magill (1987) reports that a new class of inorganic plastics based on phosphorus, the polyphosphazenes, are also receiving a lot of attention. Magill claims these new polymers have the potential to be more useful than the polysiloxanes. There properties can be varied at will via side group substitution to obtain polymers that are crystalline, elastomeric, or foams.

The current inorganic plastics, like organic plastics, differ significantly depending on the specific polymer. In general, however, when compared to most organic polymers, inorganic polymers are stronger, harder, more brittle, and usually insoluble. Further, with few exceptions, they do not burn, and they melt or soften only at very high temperatures.[3]

What future developments can be expected? Ray (1978) states that "...to the end of the present century we are likely to see a dramatic, though gradual, movement away from many of the organic polymers that we have grown accustomed to using, towards a new generation of materials that will be largely or even entirely inorganic." (page 155). Ray goes on the say that "The first step towards the eventual replacement of plastics by inorganic materials is likely to be the development of composite materials containing very much higher proportions of inorganic fillers than at present can be incorporated into thermoplastics." (page 157). According to the author, such materials could be virtually non-inflammable. "Entirely new methods of processing will have to be developed for polymeric materials that are wholly inorganic." (page 159).

Allcock (1987) reports that fundamental work is needed to synthesize new inorganic polymers. "In the present context, 'synthesis' means the assembly of new macromolecules by the use of a wide range of chemical

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[3]For more detailed information on the characteristics of inorganic polymers, see, for example, Ray (1978), Allcock (1987), Magill (1987), Gerber and McInerney (1979), and Holliday (1970).

techniques.... (O)nly a few inorganic backbone polymers have been synthesized and developed to the point where their properties can be evaluated. Thus, the critical need for the growth of this field is the development of new synthesis methods that will allow the preparation of linear polymers based on backbone systems, such as B-N, Al-O, Al-N, S-N, and metal-oxygen. Unless this problem can be solved, the future of inorganic polymers will be restricted mainly to the development of existing systems." (pages 53-54).

2.3.4 Properties of Biomass-Based Plastics

When discussing biomass-based plastics as substitutes for conventional petrochemical plastics, a distinction must be made between two types of substitution. The first can be termed direct substitution, which refers to the substitution of biomass-derived intermediate chemical feedstocks for petrochemical-based intermediate feedstocks. An example is the production of polyethylene in which ethylene produced from ethanol is substituted for ethylene produced from petroleum. For this first type of substitution, the physical properties of the biomass-derived plastics are identical to the properties of the same resins produced from petrochemicals. The second type of substitution can be called indirect substitution and refers to the substitution of new plastics manufactured from biomass materials for plastics currently made from petrochemicals.

The conversion of biomass into basic chemicals has been the subject of numerous reports.[4] Approaches too numerous to address in this report

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[4]See, for example, King, Cleveland, and Streatfeild,(1978); Shultz and Morgan (1984); Scott (1987); Donaldson and Culberson (1983); Weisz and Marshall (1980); Szmant (1986); Scheithauer and Dripchak (1988); Wright (1987); and Lipinsky (1981).

have been explored to produce several basic chemical feedstocks that could feed directly into the production of plastics. For example, starchy biomass can be converted into glucose, glucose to ethanol, and finally ethanol to ethylene. Unfortunately, according to Lipinsky (1981), about three pounds of starch are consumed for every pound of ethylene produced, and each stage of the process is more complicated than cracking natural gas liquids into ethylene. "Some research personnel are suggesting accelerated development of organic chemicals based on synthesis gas (made from biomass materials), so that synthesis gas can replace ethylene as the primary building block for organic chemicals. Another route to a wide variety of organic chemicals is to employ acetylene as the building block. Acetylene can be produced from biomass by the production of charcoal, employing the charcoal to produce calcium carbide." (King, Cleveland, and Streatfield, 1978, page 295). Although methanol is currently produced from natural gas, it was originally produced from the destructive distillation of wood. Acetone and acetic acid can also be produced by the same procedure.

The bottom line is that there is currently a great deal of technological flexibility to substitute biomass materials for oil and natural gas as feedstocks to basic chemical production. Biomass materials are not currently used for this purpose because it is more costly to do so. There are also more problems with product contamination when biomass materials are used. The major technological problem in this area is not, therefore, to develop processes by which biomass can be converted to chemicals. The challenge is to produce new technologies that can accomplish the conversion at a cost competitive with oil and natural gas. Improved technologies, such as biocatalysis, are promising. An alternative challenge is to engineer the biomass feedstock itself so that it is more suited to the current technologies available for conversion to chemicals. The selection of species and optimization of composition through breeding and other genetic methods could alter the composition and availability to make biomass more acceptable as a chemical feedstock.

The properties of current and envisioned biomass-derived plastics that substitute in an indirect way are summarized in Chum (1987). Like petrochemical and inorganic plastics, the characteristics of the biomass-derived plastics vary significantly depending on the resin. For example, some polymers are based on the lignin portion of the biomass. According to Chum, lignin plastics are "glassy in character, and therefore are brittle, rigid, have high modulus, low-impact strength, low strain, and low-energy dissipative properties. The most common application in which lignins can be used is in replacement of phenols in phenol-formaldehyde thermosetting resins. Brittleness and slow reactivity of lignins compared to phenols have caused their use to be confined to that of a filler, though there is current activity toward improving the properties of the lignins." (page 229). Other work focuses on the production of plastics from the starch in biomass. "Examples of successful materials made from starch include bags that are used in hospitals ... to contain contaminated clothes. In washing, the bags dissolve away, leaving the clothes behind. Biodegradability is a very important property of starch-derived materials." (Chum, 1987, page 242).

Plastics containing starch, such as the product ECOSTAR, have been commercialized successfully in Europe, where the use of degradable plastic grocery bags is in some cases mandatory. The negative properties of products such as ECOSTAR include degradation above about 230 degrees C, less resistance to water penetration, less break strength, and translucency.

Other work is being done at Purdue University to utilize various components of the corn plant in the production of plastics. "'Plasticization' of the nonstrarch portion of the corn plant (corn stalks, corn fiber products, etc.) by graft polymerization creates interpenetrating networks that would allow its use in inexpensive, lightweight structural and engineering plastics, including composites and fiber-reinforced thermoplastics" (Chum, 1987, page 243). These biomass-derived materials could be used for many applications currently served by conventional plastics, including packaging, appliances, auto parts, housewares, furnishings, and so forth.

Although many of the first thermoplastics were produced from cellulose, their markets were eroded as more sophisticated and lower-cost petrochemical polymers arose and competed. Biomass-derived polymers that would be competitive in a materials sense with existing petrochemical plastics are only in the development stage. However, with the exception of biodegradability, these new biomass-derived plastics do not promise to be superior to conventional plastics in terms of their material properties.

2.4 POLYMER TYPE AND POTENTIAL ENVIRONMENTAL DEGRADATION

2.4.1 Conventional Plastics

There is currently a great deal of controversy about the environmental effects of plastics when landfilled or incinerated. A detailed discussion of the various arguments is given in my recent book (Curlee, 1986b, Chapters 2 and 7).

There are two schools of thought about plastics in landfills. One school argues that plastics are not acceptable in landfills because they do not degrade. Some argue that because plastics do not degrade and do not compact easily, they allow leaching of potentially toxic substances by facilitating the flow of water to those substances. Others argue that when plastics are not distributed evenly in landfills, they result in "spongy" areas once the landfill is completed, thus limiting the potential uses of the landfill following closing. Yet others argue that plastics are not acceptable simply because they are bulky and require a significant amount of space in the landfill. According to recent data from the EPA, plastics account for 7.2% of the weight of the typical U.S. municipal waste stream. However, on a volume basis, the percentage doubles to 14.4%. Further, EPA projects that by the year 2000 plastics will account for 9.8% of the weight of MSW, or 19.6% of the volume.

The problem of plastics in landfills is exacerbated by the growing concern about landfill capacity and cost. The EPA projects that 50% of all major U.S. cities will exhaust their current landfill capacities by 1990. And in some states landfill capacity is not being increased because of political or other reasons. For example, New York state has closed 18 landfill sites in the past year and has not opened any new ones. The public is not supportive of developing new landfills and uncertainties about environmental regulations are high. The March 1988 issue of Waste Age magazine reports that in 1987 the average tipping fee at sanitary landfills in the U.S. was $20.36 per ton, up 51.6% in nominal terms from 1986. Cost increases have been most severe in the northeast region of the country, where land is more scarce. In the northeast region the cost of landfill increased from $20.59 per ton in 1986 to $39.23 per ton in 1987. The U.S. currently generates about 150 million tons of municipal waste per year, or nearly 3.5 pounds per person per day.

The other school of thought about plastics in landfills argues that plastics are actually advantageous because of their non-biodegradability. Because plastics do not degrade, at least rapidly, they do not contribute to either liquid or gaseous toxic substances.[5] In addition, when plastics are distributed evenly with other waste materials, the plastics tend to provide structural stability to the landfill site after it is closed. As other wastes degrade, plastics are claimed to support the soil above the waste level.

More controversy exists about the environmental effects of plastics when incinerated. Again there are two schools of thought. Some plastics, especially PVC, can produce significant levels of hydrogen chloride. About one half of the weight of PVC is composed of hydrogen and chloride, which combine during burning to form hydrogen chloride. The hydrogen chloride then reacts with water to form hydrochloric acid.

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[5]Note that some have suggested that plastics when subjected to thermal stress, such as is found in landfills, can produce toxic gases.

A recent European study concluded that 24%-50% of the emissions of HCl from incineration can be attributed to PVC combustion. One school of thought argues therefore that plastics are not acceptable for incineration on the basis of their contribution to acid rain.

Probably the most concern has, however, been raised about the production of furans and dioxins, which are known carcinogens. Several reports have suggested that there may be a link between the burning of plastics and the production of furans and dioxins. This claim has, however, been discredited by a recent study sponsored by the state of New York. [See New York State Energy Research and Development Authority (1987) or Visalli (1987).] In that study, no link was found between the burning of PVC or any other plastic and the production of dioxins or furans. Variations in combustion efficiency were found to correlate highly with changes in dioxin and furan emissions.[6]

Yet another concern has been raised by Dr. Richard Magee of the New Jersey Institute of Technology. In a recent presentation at the RecyclingPlas III conference sponsored by the Plastics Institute of America, Magee suggested that there could be a link between metals emissions and the burning of plastics. Plastics may contribute to the formation of particulates to which metals attach and then escape from the stacks. Magee went on to say that currently there is no data to confirm or deny this suspicion.

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[6]It is interesting to note that no nationwide standards exist for dioxins emissions from waste-to-energy facilities in the United States. In 1986 Sweden became the first country to issue specific dioxin regulations.

The other school of thought concerning plastics in incineration argues that plastics are of no great concern if current emission-control technologies are used properly. In fact, the incineration of plastics may be advantageous because of the high Btu contents of most plastics--roughly equivalent to coal on a per pound basis. The high heat produced by burning plastics helps to incinerate other materials not so easily burned. Other arguments have been made to defend plastic incineration. For example, Graff (1988) reports that recent tests in Canada show that scrubbing technology can remove 99.9% of dioxins from stack gases. Others argue that technology is readily available to control HCl emissions. Yet others argue that the potential environmental effects of municipal solid waste (MSW) incineration have been given more attention than they deserve. Magee (1988) argued that the overall air pollution effects of current and planned waste incinerators are trivial when compared to the effects of large-scale polluters, such as coal-fired electricity generation plants. According to Magee, only 0.2% of total air emissions currently come from solid waste incinerators in the United States.

Note that the U.S. currently landfills about 90% of its solid waste. About 5% is incinerated, and the remaining 5% is recycled. Some have speculated that as much as 40% of U.S. MSW will be processed by incineration with heat recovery by the year 2000.

2.4.2 <u>Inorganic Plastics</u>

There is currently little information to suggest the potential environmental effects of disposing of inorganic plastics. Questions may be raised about the incineration of polymers that have backbones that contain metals. There would appear to be few problems with the disposal of inorganic plastics by landfill. However, a thorough assessment of the environmental effects of disposing of inorganic plastics awaits future scientific research.

2.4.3 Biomass-Derived Plastics

The environmental impacts of biomass-derived plastics that substitute for conventional plastics in a direct way -- i.e., by substituting for basic chemicals that are used in the production of conventional plastics -- will be the same as current petrochemical-derived plastics. Questions can, of course, be raised about the environmental effects of producing the basic chemicals from biomass or from oil and natural gas.

The main argument with respect to biomass-derived plastics would appear to be the potential biodegradability of those resins. The issue of biodegradable plastics and environmental degradation is currently receiving a lot of attention. Biodegradables consist of two basic types -- polymers that are completely digestible by bacteria (used for some medical purposes such as soluble stitches for surgery) and polymers that contain additives that are digestible and which leave a relatively weak polymer that degrades over time. Both types of plastic can be produced at the present time. Chum (1987) reports that the cheapest ones are about twice as expensive as polyethylene, which is often used to manufacture films for packaging.

One biodegradable plastic being developed at Purdue is a marriage of cellulose, starch, and petroleum-based polymers. A blend has been developed that behaves much like ordinary expanded polystyrene, but is

20% to 30% starch by weight and is susceptible to decomposition by soil bacteria. Other biodegradable polymers are being developed by ICI Americas for use in bottles for the European market.[7] In addition, a new two-year study was begun recently by the Polymer Processing Institute of Hoboken, New Jersey to develop biodegradable materials that can be used for marine products, such as fishing traps and pots, which are currently manufactured from conventional plastics. The recently passed United States-Japan Fishery Agreement Approval Act of 1987 places severe limitations on the disposal of plastics at sea. Finally, a study is currently underway at Battelle Memorial Institute in association with A.G. Van Stok and Associates to study the biodegradability of various plastic wastes.

Some argue that biodegradable plastics based on biomass materials are the solution to "the plastics problem." Others argue that biodegradables will have only limited applications and could have detrimental effects if used in some applications. Wehrenberg (1981) claims that biomass-derived thermoplastics, such as lactic acid polymers, are environmentally compatible since they degrade back to natural monomers such as lactic acid and glycolic acid. The author also concludes that such polymers pose no environmental problems when incinerated. The environmental implications of degradables that use, for example, starch in combination with conventional resins, are more

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[7]Plastics can also be made to degrade by direct sunlight. Photodegradable six-pack beverage rings are currently being produced by Dow Chemical, DuPont, and Union Carbide. Currently, eleven states require that six-pack rings be degradable. Recently passed federal legislation requires that all six-pack rings used in the U.S. be made from degradable materials by 1990.

questionable. Although it is generally suggested that biodegradable plastics will pose no environmental problems in landfills or when incinerated, a final verdict on the issue would appear to await additional study.

Opponents of biodegradables argue that the products of degradation are not understood well. They further argue that the use of biodegradables will severely limit the possibilities for recycling conventional plastic wastes. Processes currently being marketed to recycle commingled thermoplastics into bulky products that compete with wood and concrete, such as the ET-1 from Belgium or the Superwood process from Ireland, could not use plastic waste that contains biodegradable resins. The use of biodegradables in applications such as packaging may therefore limit the recyclability of conventional plastics in those waste streams.

3. ECONOMIC AND INSTITUTIONAL ISSUES

3.1 INTRODUCTION

This section focuses on the economic and institutional factors that will influence the viability of inorganic and biomass-based plastics as substitutes for conventional plastics. It is appropriate to point out at the beginning of this section that sufficient information does not currently exist to allow any definitive statements to be made about the future economic viability of these alternative polymers. Those statements await further data and research. The question of economic viability can, however, be disected into its component parts and work can begin to "fill in the blanks."

Recall from the first section of this report that in order for inorganic and biomass-derived plastics to be viable economic alternatives to conventional plastics one of two conditions must hold: (1) the alternative plastics must either provide the same material characteristics at a cost equivalent to or lower than currently available petrochemical plastics, or (2) the marginal benefits of the new polymers -- in terms of engineering material properties, environmental effects, and reduced oil vulnerability -- must exceed the marginal costs of those new polymers. The potential differences in material properties and environmental effects have thus far been discussed, and the various arguments have been found to be somewhat tenuous.

In this section we focus on the information that is currently available on the cost of the different resins and on the arguments that promote alternative plastics on the basis of oil vulnerability. For the most part, there is no speculation in this section on the specific marginal benefits that these new polymers may provide. An evaluation of those specific economic benefits is a very detailed empirical problem and is beyond the scope of this preliminary report. Rather, this section focuses on information that may suggest where different polymer types have a relative cost advantage and on the general benefits that these alternative polymers may provide. Also discussed are what we may call "institutional factors" that may impede the market acceptance of these new plastics.

The arguments are presented in two main subsections. The first focuses on the economic and institutional factors that are considered by the private sector in its decisions about which plastics to manufacture and use. The second subsection focuses on the perspective of the public sector and its decision to promote inorganic and biomass-derived plastics, promote petrochemical plastics, or remain neutral on the issue.

3.2 THE PRIVATE SECTOR

A useful place to begin our discussion of the economic and institutional incentives and barriers facing the private sector in its decision about alternative polymer types is to identify the various steps involved in the production and use of plastics. While reliable information is not currently available on what specific new plastics made from biomass and inorganics may cost, information is available on the cost and availability of raw materials and intermediate products. Also available is information on the cost of current resins and the use of current resins in different applications. By discussing the question of economic and institutional viability in terms of the various steps in the production and use of plastics, the relative advantages of inorganic and biomass-derived plastics can be examined.

Figure 1 depicts the various steps in the production and use of plastics. To the extent that information is currently available, the raw-materials, intermediate-products, resin-production, and consumer-usage steps are discussed in the following subsections with respect to petrochemical, inorganic, and biomass-derived plastics. Sufficient information does not currently exist to compare the relative advantages of the different plastic types at the remaining production steps.

3.2.1 Raw Materials

3.2.1.1 Petrochemical Plastics

As stated above, conventional plastics are manufactured almost entirely from crude oil and natural gas. The availability and future cost of these natural resources are therefore important to the future viability of conventional plastics.

Cohn and Curlee (1987) provide estimates of the petroleum that has historically been consumed in the production of petrochemicals and plastics. That report cites estimates from Cosslett (1986) that indicate that the United States consumes about 7% of its petroleum consumption in the production of organic chemicals. This includes the petroleum used for both energy and raw material purposes. The Cohn and Curlee report also provides estimates of the petroleum that is used in the production of all plastic resins. Aggregating up from estimates of the energy requirements for the production of specific resins and given estimates of U.S. production of each resin, it was estimated that approximately 343.7 millions of barrels of oil equivalent (BOE) were consumed in the

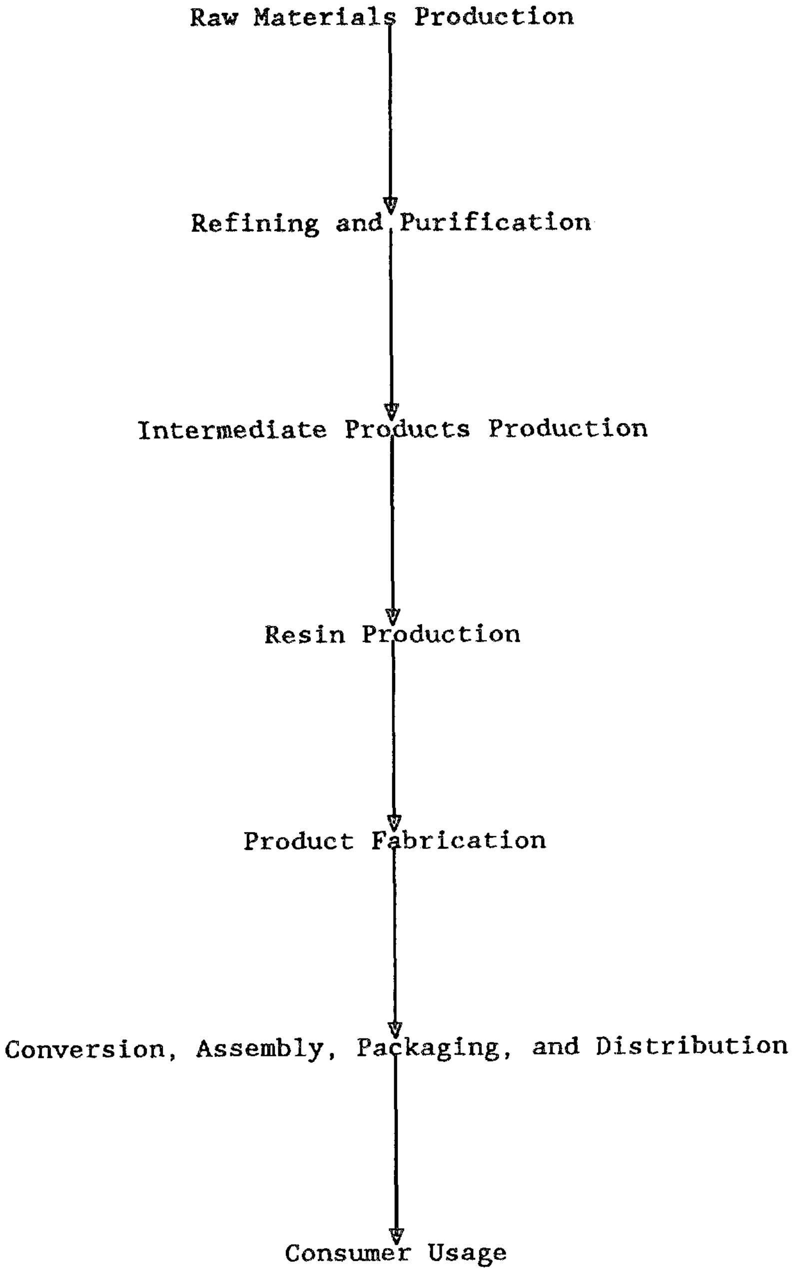

Fig. 1. Steps in the production and use of plastics

production of all petrochemical-derived plastic resins in the U.S. in 1985. This represents about 6.5% of all U.S. petroleum consumption for that year. (Note that there are significant process energy inputs required for the conversion of basic chemicals to final resins.)

A slightly larger percentage of natural gas is consumed in the production of chemicals. The American Gas Association reports that the chemicals and allied products sector consumed 1,568 billion cubic feet of the 6,486 billion cubic feet consumed in the industrial sector in 1978, or about 24% of the total. Total natural gas consumption in the U.S. in 1978 was about 19,627 billion cubic feet according to the Energy Information Administration, implying that about 8.0% of total U.S. consumption of natural gas was for the production of chemicals and allied products. No estimates of the quantity of natural gas used in the production of conventional plastics have been identified. Therefore, while the percentage of oil and natural gas used for chemicals and plastics production in the U.S. is not insignificant, neither is it extremely large.

Concerns about the availability of crude oil, and to a much lesser extent natural gas, have been largely exagerated. In previous publications [Curlee (1983), Curlee (1984a), Curlee (1984b) and Curlee, Turhollow, and Das (1988)] I have argued that the availability of crude oil has not historically been a severe problem, even during the oil disruptions of the past one and a half decades. During the 1973-74 disturbance, non-communist production fell at its maximum only about 9.5%. During the Iranian Revolution and the start of the Iran-Iraq War, free-world production fell a maximum of only 4 to 5%. And in all three cases the durations of the production reductions were only about 2 to 4 months. Producers of chemicals and resins have historically been able to obtain sufficient quantities of raw materials; and short of a total shutdown of the Persian Gulf region, availability of oil and natural gas for the production of plastics should not be a severe problem.

While availability of oil and natural gas is not a key concern, the prices of those raw materials are subject to significant uncertainty. Saudi Arabian light crude increased in price from $2.10 to $9.60 per barrel form January 1973 to January 1974. The spot price for the same crude escalated from $18.49 to $36.00 per barrel from January 1979 to October 1980. And while nominal oil prices have reversed direction in recent years, there remains the more than trivial probability that real oil prices will escalate further in future years. However, as I have argued elsewhere [Curlee (1985a), and Curlee and Reister (draft)], the probability that oil prices will escalate drastically and remain at that high price is less than in previous years. Short to medium-term price spikes are more likely during the next one to two decades than are sharply higher long-term prices. Such long-term price increases would not appear to be in the overall interest of the major oil producing countries. In the opinion of the author, the oil price forecasts given in Curlee (1985a) remain relevant today. In real terms, the price of crude oil is expected to remain about constant throughout the remainder of this decade. For the two decades following 1990, the price of oil is expected to increase by about 2% per year in real terms, i.e., when adjusted for inflation.

Another way of examining the importance of oil and natural gas prices to producers of plastic resins is to estimate the contribution that energy inputs make to the price of plastics. Gaines and Shen (1980) provide estimates of the energy inputs (for material and energy purposes) required to produce various resins. The estimates range for some commonly used polymers from a low of 31,000 Btus/pound for olefins to a high of 90,400 Btus/pound for nylon. Polyester is in the mid-range at about 48,700 Btus/pound. As an example, consider the cost of energy incorporated in one pound of polyester, and for simplicity assume that all energy inputs are from natural gas. Given that natural gas has an average energy content of about 1,000 Btus/cubic foot, approximately 48.7 cubic feet of natural gas would be required to make one pound of polyester. In 1986 the Energy Information Administration reported that the cost of delivered natural gas to industrial users was an average $3.23 per thousand cubic feet. Thus, given our simplifying assumptions, one pound of polyester contains about 15.7 cents of energy inputs per pound. The average price of bottle-grade polyester (PET) in 1986 was 54.13 cents per pound according to Modern Plastics. Therefore, our rough "back of the envelope" calculation suggests that about 29% of the current price of polyester can be attributed to the cost of energy. Doing the same type of calculation for LDPE, we find that about 11.3 cents of energy is contained in one pound of LDPE. Given that the average price of LDPE was about 29.63 cents per pound in 1986, about 38.1% of the price of LDPE can be attributed to energy inputs.

3.2.1.2 Inorganic Plastics

Recall from Section II of this report that research is currently being conducted to produce inorganic polymers from a variety of inorganic elements. This subsection focuses on the availability and prices of borates, phosphorus, silicon, and sulfur. Table 1 gives information from Cohn and Curlee (1987) on the U.S. and world production of the above mentioned materials in 1984.

Table 2 gives information from Cohn and Curlee (1987) on the reserves of selected minerals in 1984. Table 3 gives information on the reserves-to-yearly-production ratios for the selected minerals. Note that the reserves-to-yearly-production ratios for all the minerals examined are quite large -- both for the U.S. and world markets. Availability of raw materials for inorganic polymers does not appear to be a problem.

Price information on these various minerals is available from the Minerals Yearbook published by the Bureau of Mines. The price of ferrosilicon has remained quite stable in recent years at about 42 to 43 cents per pound. The price of elemental sulfur decreased slightly from about $111 per metric ton in 1981 to about $106 per ton in 1985. The price of phosphate rock has also remained flat during recent years. In 1982 the price of 75% bone-phosphate-of-lime-content phosphate rock was $34 per metric ton; the price remained unchanged in 1985. Whether or not future prices of these raw materials would increase sharply in response to additional demands on those resources for inorganic polymers is a complicated econometric question and is difficult to comment on at this

Table 1. Production of selected minerals: 1984
(in millions of short tons)

Mineral	U.S.	Non-U.S.	World
Borates (B_2O_3)	0.658	0.442	1.110
Phosphate Rock	50.835	100.528	151.363
Elemental Phosphorus	1.05	2.07	3.12
Silicon Metal	0.183	0.640	0.823
Sulfur	12.798	57.870	70.669

Source: Cohn and Curlee (1987)

Table 2. Reserves of selected minerals: 1984
(in millions of short tons)

Mineral	U.S.	Non-U.S.	World
Borates (B_2O_3)	230.0	450.0	680.0
Phosphate Rock	6,283.0	37,808.9	44,091.9
Silicon	(Ample reserve base -- all countries)		
Sulfur	192.9	2,342.4	2,535.3

Source: Cohn and Curlee (1987)

Table 3. Reserves-to-yearly-production ratios for selected minerals: 1984

Mineral	U.S.	Non-U.S.	World
Borates	349.5	1,018.1	618.2
Phosphate Roack	123.6	376.1	291.3
Silicon	(Ample reserve base all countries)		
Sulfur	15.1	40.5	35.9

Source: Cohn and Curlee (1987)

time. The large reserve-to-production ratios would, however, suggest that the price response would not be great.[8]

3.2.1.3 Biomass-Derived Plastics

As is the case with inorganic plastics, biomass-derived plastics are currently being developed that could utilize numerous biomass raw materials. Processes based on wood, grains, and agricultural residues either currently exist or are in the development stage. Rather than focusing on a particular crop, (for example, corn is often mentioned as a raw material) this subsection focuses on the results of previous studies that give general forecasts of bioresources availability in future years.

Scholl, Salo, and Henry (1980) give projections of the potential annual availability of several bioresources for fuels and chemicals in the year 1995. Those projections were based on information from various sources and are presented in Table 4. According to the authors, these potential resources are the materials that remain after existing demands for food, feed, forest products, and internally consumed fuel have been satisfied. The estimated availabilities of some grains and sugar are said to be least reliable since annual production and consumption for conventional purposes can vary widely. The authors further note that the residues reported are currently returned to the soil. If they were

[8]Some have raised questions about the energy that is required to produce elemental phosphorus, silicon, and sulfur. Cohn and Curlee (1987) examined this question and reported the following energy input estimates: Elemental phosphorus requires about 7,000 Kwhs of electricity for each short ton produced, elemental silicon requires about 11,800 kWhs per short ton, and sulfur about 7.3×10^6 Btus.

Table 4. Potential annual availability of bioresources for fuels and chemicals in 1995

	Million Dry Tons	1995 %
WOOD:		
Surplus Growth	26	
Forest Residues	131	
Mortality	98	
Noncommercial	0	
Mill Residues	3	
Other	51	
TOTAL WOOD	309	38
GRAINS:		
Corn	0	
Wheat	0	
Soybeans	14	
Sorghum	0	
Other	11	
TOTAL GRAINS	25	3
AGRICULTURAL RESIDUES:		
High Moisture	150	
Low Moisture	260	
Trash/Hulls	8	
Manures	65	
TOTAL AGRICULTURAL RESIDUES	483	58
MISCELLANEOUS	6	1
TOTAL RESOURCES	823	100

Source: Scholl, Salo, and Henry (1980)

removed for fuel or chemical purposes, it would be necessary to increase the use of fertilizers.

Scholl, Salo, and Henry (1980) report that in the midterm (1995-2025), silvicultural or large-scale agricultural biomass farms could produce biomass exclusively for energy and chemical feedstocks. Table 5 presents information by geographical region on the potential biomass that could be produced from silvicultural farms in the 1995-2025 time frame. It was assumed that 10%, or about 325 million acres of the forest, pasture and range, and forage cropland could be devoted to silvicultural farms. Two levels of productivity were used in the projections--today's productivity of about 8 dry tons per acre and 16 dry tons per acre, which reflects anticipated productivity improvements in the next century.

Tables 6 and 7 are taken from Wright (1987). Table 6 gives information on the growth and production of underutilized wood resources in the United States. Table 7 gives estimates of the availability of U.S. agricultural residues. Note that while the estimates differ significantly depending on the source, all the estimates are quite large.

As reported earlier, corn has been the focus of much attention, partially because of the large surplus of this crop in the United States. Chum reports that the total production of corn in the U.S. in 1986-87 was about 13 billion bushels, of which she labels 5.7 billion bushels as surplus.[9] According to Chum, this surplus represents 227 billion pounds

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[9]The U.S. Department of Agriculture (1988) reports that in the crop year 1986-87, 8.2 billion bushels of corn were produced in the U.S., and total supply--i.e., beginning stocks plus production--was 12.3 billion bushels. Ending stocks were 4.9 billion bushels.

Table 5. Estimated availability of biomass from silvicultural energy farms (1995-2025)

Regions	Million Dry Tons/Year Given Current Productivity	Million Dry Tons/Year Given Anticipated Productivity in Next Century
Northeast	19.0	33.0
Southeast	53.0	95.4
Appalachian	35.2	66.0
Lake States	27.0	54.0
Corn Belt	35.2	66.0
Delta States	38.0	68.4
Northern Plains	6.3	12.6
Southern Plains	41.4	73.6
Mountain	0	0
Pacific	7.0	14.0
TOTAL US	262.1	488.0

Source: Scholl, Salo, and Henry (1980)

Table 6: Growth and production of underutilized traditional wood resources in the United States (millions of dry tons/year)

Study	Wastes Total	Wastes Collectible	Excess Production Total	Excess Production Collectible
Young et al., (1986)		100		
Jefferies (1983)	384	175	418	201
Ng et al., (1983)	230	171	451	270
Ferchak and Pye (1981)		279	3007	1002
OTA (1980)	84		679-1807	309-617
Humphrey et al., (1977)	61			
Soc. Am. Foresters (1979)			1240	
Average	190	181	1271	484

Source: Wright (1987)

Table 7. Estimates of agricultural residue availability

Study	(millions dry tons/year) Total	Collectible
Young et al., 1986		401
Jeffries 1983	386	
Ng et al., 1983	811	318
Goldstein 1981	356	
OTA 1980	420	83
Vergara and Pimentel 1979	474	
Humphrey et al., 1977	401	
Tyner and Bottum 1979	—	52
Average	456	213

Source: Wright (1987)

of starch. Recall that the total production of all petrochemical plastics in 1985 was about 48 billion pounds.

The estimates of the quantities of biomass that are potentially available for fuel and chemicals production are very large. The question concerning biomass raw materials is therefore more one of cost than of potential production. Table 8 presents information from Scholl, Salo, and Henry (1980) on the estimated costs of different biomass sources in 1995. Note that the costs vary from a low of $16 per ton for trash/hull residues to $133 per ton for cane and beets. These cost estimates include production and collection cost and a transportation cost for an average distance of about 40 miles from the point of utilization.

Scholl, Salo, and Henry (1980) report that the expected cost of biomass from silvicultural energy farms is between $20 and $30 per dry ton in 1995 (1977 dollars). Wright (1987) gives cost estimates for various herbaceous energy crops given state-of-the-art production methods. Those costs range from $38.30 per dry ton for subtropics napier grass to $55.87 per dry ton for Piedmont switch-grass.

3.2.2 Refining and Intermediate Products

The above subsection gives limited information on the availabilities and costs of the main raw materials that are or would be utilized in the production of petrochemical, inorganic, and biomass-derived plastics. In general, it was concluded that availability of raw materials is not a significant problem for any of the three plastics considered. The limiting factor will be raw material costs. We further concluded that the real prices of oil and natural gas will increase in future years. The price escalations should not, however, be as severe as observed

Table 8. Estimated cost of bioresources in 1995 (1977 Dollars)

Resource	$/Dry Ton
WOOD:	
Eastern U.S.	10-15
Western U.S.	20-67
GRAINS:	89-123
SUGARS:	
Cane and Beets	94-133
Sweet Sorghum	43-50
AGRICULTURAL RESIDUES:	
High/Low Moisture	34-40
Trash/Hull	16

Source: Scholl, Salo, and Henry (1980)

during the past decade and a half. The nominal prices of inorganic raw materials have been fairly stable in the last few years; and given the large inorganic resource base, prices are not likely to increase drastically in response to increased demand for inorganic plastics. The nominal prices of organic raw materials may decrease slightly in coming years as the technologies to grow those raw materials improve.

In this subsection we focus on the cost of converting raw materials into intermediate products that could be used in the production of plastics. For the most part, this discussion focuses on the refining and conversion of biomass materials into basic chemicals that could substitute for petrochemical-derived chemicals in the production of conventional plastics. We do not focus on inorganic intermediate products because the processes to be used are not well defined at this time. No information was identified that would suggest the cost of transforming basic inorganic feedstocks into intermediate products that would in turn be converted into final inorganic plastics.

3.2.2.1 Petrochemicals

Table 9 gives information from Modern Plastics on the prices of several intermediate petrochemicals used in the production of commonly used plastics. Also given is price information on crude oil. Note that the nominal prices for most basic chemicals have remained relatively flat over the 1984-1987 time frame, despite significant reductions in the price of oil.

The April 1988 issue of Hydrocarbon Processing gives U.S. intermediate product price forecasts through the end of the century. Table 10 summarizes the findings of the base case of the study. Between

Table 9. Nominal prices of selected polymer feedstocks and crude oil
(cents per pound, largest bulk basis)

Year	Quarter	Ethylene	Propylene	Styrene	Benzene	Vinyl Chloride	Oil
1984	3	18.7	19.0	28.0	18.0	18.0	9.7
	4	17.7	18.5	26.0	17.3	18.0	9.7
1985	1	16.0	18.0	24.0	16.5	18.0	9.3
	2	15.5	17.5	26.0	19.0	18.0	9.3
	3	15.0	17.0	25.5	20.0	16.5	9.3
	4	15.5	17.0	23.5	16.5	16.5	9.1
1986	1	18.3	16.5	23.0	13.4	17.8	6.3
	2	14.5	12.5	19.0	11.6	16.5	5.0
	3	14.0	11.0	17.0	11.0	15.5	4.1
	4	14.5	10.5	23.0	11.6	15.5	4.7
1987	1	15.0	11.0	30.0	17.0	16.5	5.5
	2	14.5	15.0	42.0	13.0	17.0	6.1
	3	15.0	18.0	38.0	13.0	19.0	6.0
	4	18.0	20.0	40.0	13.0	20.0	5.9

Source: Modern Plastics, January 1988, page 9.

Table 10. U.S. nominal price forecasts for selected chemicals (compound rates of growth, 1986-2000)

Chemical Feedstock	% Growth
Ethylene	6.3
Propylene	8.9
Butadiene	5.8
Benzene	8.7
Styrene	6.9

Source: Hydrocarbon Processing, April 1988, page 15.

now and the year 2000, prices of polymer feedstocks are projected to increase in nominal terms by about 5.8% to 8.9%, depending on the specific chemical.

Future prices of petrochemicals will, of course, depend on numerous factors, prices of oil and natural gas and technological advances being only two. Anderson, Johnson, and Mowry (1985) report that the cost of producing basic aromatic commodities is about 80% feedstock related. Hydrocarbon Processing (April 1988, page 13) reports that a recent study by Probe Economics forecasts that U.S. exports of basic petrochemicals will decrease as production capacity is increased in the oil producing countries, and the "export oriented countries" of the Far East and South America. Hydrocarbon Processing goes on to state that "The ready availability of chemicals produced offshore will depress U.S. prices to levels below capacity replacement values. Ethylene derivatives, such as styrene, ethanol and ethylene glycol, will be starved for domestic ethylene feedstock. PVC plants may relocate to ports of entry to improve access to imported EDC and VCM." (April 1988, page 15).

A discussion of the technological advances that are likely in the petrochemicals industry is beyond the scope of this report. It is important to point out, however, that technological advances are constantly being made that may reduce the real cost of producing a given product from a given raw material, all else being equal. Work to improve the engineering efficiency of catalysts is receiving significant attention. [Hadder (1988) reviews numerous technological areas that are prime candidates for improvements in the near to intermediate term.]

Advances in inorganic and biomass-derived intermediates must therefore compete with a petrochemicals industry that is constantly advancing.

3.2.2.2. Biomass-Derived Intermediates

Several studies have focused on the economic feasibility of using biomass materials to manufacture basic chemicals and fuels. This subsection focuses on the results of those studies, particularly with respect to the basic chemicals that might substitute directly for petrochemicals in polymer production.

Most of the studies have focused on the production of ethanol from various parts of the biomass stream. Ethanol has four major applications: the production of alcoholic beverages, for use as a fuel extender, for use as an intermediate chemical, and for use as a feedstock to produce other chemicals. The focus of this section is on its use as a feedstock for other chemicals. When used as a chemical feedstock, ethanol can be converted into ethylene, which can become a feedstock for various conventional plastics -- e.g., PVC, polyethylenes, and styrenics. Ethanol can also be converted into other intermediates that lead to polyesters, polyvinyl acetates, and cellulose acetates. Thomas (1985) reports that about 1.7 pounds of ethanol are required to manufacture 1 pound of ethylene.

Hacking (1986) reports that the cost of ethanol production from corn in the United States using current state-of-the-art technology is between $1.40 and $1.51 per gallon, depending on the size of the operation. Busche (1986) estimates the U.S. cost of ethanol production using state-of-the-art continuous fermentation is about $1.19 per gallon. Wright (1987) gives several estimates of the cost of producing ethanol from the lignocellulose portion of biomass. Those estimates range from a low of $1.14 per gallon to a high of $1.68 per gallon, given state-of-the-art applications of the different basic technologies.

A more thorough assessment of the potential for biomass as a chemical feedstock has been done by Donaldson and Culberson (1983). That study was based on (1) a Delphi study with 50 recognized authorities to identify key technical issues relevant to producing chemicals from biomass and (2) a linear programming (LP) model of commodity chemical production from renewable resources, coal, and gas and petroleum-derived resources. The LP model considered numerous biomass sources, including corn, corn stover, kelp, marine algae, lignin from the kraft process, sugar beets, sugar cane, sweet sorghum, wheat straw, and wood. The production of some 25 basic chemical were modeled. All input prices and technology specifications were for the state-of-the-art at the time of the study. Base-case raw material availabilities and prices are given in Table 11. In the base case, the authors constrained the LP model to produce the quantity of basic chemicals produced in 1979 and found that, given the depicted technologies and relevant prices, biomass raw materials are dominated by petroleum, natural gas, and coal. None of the biomass resources considered were used for chemical production. Summary results from the base-case analysis are given in Table 12. The authors then considered the case where petroleum and natural gas costs are increased by 100% as compared to the base case. In this case, ethanol from sugar beets, sugar cane, and sweet sorghum enters the optimal solution. Summary results from this alternative case are given in Table 13.

Table 11. Prices and availabilities of raw materials in the Donaldson-Culberson report--base case

Primary Raw Material	Quantity Available (10^3 tons)	Price ($/tons)
Aquatic biomass	40,600	110
n-Butane	1,500	260
Coal	99,999	36
Corn	16,400	120
Corn stover	83,300	45
Feedlot wastes	14,000	6.3
Kelp	33,100	
Lignin, Kraft	19,000	41
Marine algae	33,100	70
Molasses	4,880	34
Municipal solid waste	9,080	0
	38,100	4.4
	62,600	8.8
Naphtha, coal	99,999	47
Naphtha, petroleum	99,999	32
Natural gas (methane)	99,999	15
Refinery gas	99,999	22
Sewage sludge	99,999	0
Sugar beets	17,000	32
Sugar cane	20,500	25
Sulfite black liquor	370	0
Sulfite waste liquor	60,800	0
Sweet sorghum	52,900	20
Wheat straw	31,200	46
Wood	33,700	22
	10,600	33
	36,000	44

Source: Donaldson and Culberson (1983) page 17.

Table 12. Donaldson-Culberson base-case solution: chemical production and raw material utilization

Primary Product	Relative to 1979 Production	Primary Raw Material	Quantity Utilized (10^3 t)
Acetaldehyde	1.0	Aquatic biomass	
Acetic acid	1.0	*n*-Butane	1,500
Acetone	1.0	Coal	6,958
Ammonia	1.0	Corn	
Benzene	1.0	Corn stover	
Butadiene	1.0	Feed lot wastes	
n-Butanol	1.0	Kelp	
Cyclohexane	1.0	Lignin, Kraft	
Cyclohexanone	1.0	Marine algae	
Ethanol	6.0	Molasses	
Ethylbenzene	1.0	Multiple solid	
Ethylene	1.0	wastes	
Ethylene glycol	1.0	Naphtha, coal	
Ethylene oxide	1.0	Naphtha, petroleum	64,556
Formaldehyde	1.0	Natural gas	15,459
Glycerol	1.0	(methane	
Methanol	1.0	Refinery gas	1,043
Methyl ethyl ketone	1.0	Sewage sludge	
Phenol	1.0	Sugar Beets	
Phthalic anhydride	1.0	Sugar cane	
Isopropanol	1.0	Sulfite black liquor	
Propylene	1.1	Sulfite waste liquor	
Propylene oxide	1.0	Sweet sorghum	
Urea	1.0	Wheat straw	
p-Xylene	1.0	Wood	

Source: Donaldson and Culberson (1983) page 23.

Table 13. Donaldson-Culberson 100% petroleum and NG price increase case: chemical production and raw material utilization

Primary Product	Relative to 1979 Production	Primary Raw Material	Quantity Utilized (10^3 t)
Acetaldehyde	1.0	Aquatic biomass	
Acetic acid	1.0	*n*-Butane	1,5000
Acetone	1.0	Coal	139,746
Ammonia	1.0	Corn	
Benzene	1.0	Corn stover	
Butadiene	1.0	Feed lot wastes	
n-Butanol	10.8	Kelp	
Cyclohexane	1.0	Lignin, Kraft	
Cyclohexanone	1.0	Marine algae	
Ethanol	10.3	Molasses	
Ethylbenzene	1.0	Multiple solid	
Ethylene	1.0	wastes	
Ethylene glycol	1.0	Naphtha, coal	21,562
Ethylene oxide	1.0	Naphtha, petroleum	
Formaldehyde	1.0	Natural gas	14,139
Glycerol	1.0	(methane	
Methanol	1.0	Refinery gas	2.670
Methyl ethyl ketone	1.0	Sewage sludge	
Phenol	1.0	Sugar Beets	17,000
Phthalic anhydride	1.0	Sugar cane	14,750
Isopropanol	1.0	Sulfite black liquor	
Propylene	1.0	Sulfite waste liquor	
Propylene oxide	1.0	Sweet sorghum	11,080
Urea	1.0	Wheat straw	
p-Xylene	1.0	Wood	

Source: Donaldson and Culberson (1983) page 29.

The overall results from the Delphi study and the LP model used in the Donaldson and Culberson report indicate that "...in the absence of gas and petroleum, coal undoubtedly would be a major source of chemicals first, followed by biomass. The most attractive biomass resources are wood, agricultural residues, and sugar and starch crops." (page 1). The authors go on to conclude that "A reasonable approximation to our current product slate could be produced from renewable resources without the use of petroleum, gas, or coal as feedstocks. The primary resource would be wood. Such an industry would be highly unprofitable, however, because revenues from sales would recover only 35% of the costs at current market prices." (page 57).

The basic conclusions reached by Donaldson and Culberson about the preference of coal over biomass is reiterated by other authors. For example, Parker (1978) concludes that "...ethanol, via fermentation of biomass, is sufficiently close to being competitive (with petrochemicals) that considerable debate regarding its potential is in progress" (page 295). Parker goes on to conclude, however, that coal will be first in line to replace petroleum, not biomass. Parker also concludes that "It can be expected that petroleum and natural gas will be available for conversion to petrochemicals for a longer time span than they can be employed for just their fuel value. This situation will result in ethylene and petroleum based aromatic chemicals remaining very significant factors in the organic chemical industry into the twenty-first century." (page 297). Other authors share the pessimistic view about the use of biomass for chemicals. A 1980 World Bank report concludes that "Among the technologies currently available, ethylene production from biomass ethanol is unlikely to be competitive with petroleum derived ethylene until the crude price of oil reaches $40-45 per barrel (assuming an economic cost of sugar-cane at $10-12 per ton)." (page 45). Weisz and Marshall (1980) conclude that "The cost of net fuel producible from biomass is unlikely to dip below the cost of synthetic fuel from coal (or from oil shale) in the future, barring unforeseen breakthroughs in agronomy and conversion technology..." (page 102).

Work is, of course, being done to improve the technology and reduce the cost of converting biomass materials to chemicals. Wright (1986) states that further developments of enzymatic hydrolysis may lead to an ethanol cost of less than $1.00 per gallon. Other work is being done on the production of chemicals using biocatalysis. [See Goldstein (1986).] At this time, the future for biomass-derived intermediate chemicals as replacements for petrochemicals does not look particularly promising without a major technological breakthrough.

3.2.3 <u>Resin Production</u>

Very little information is currently available about the cost of producing new inorganic and biomass-derived plastics that could potentially replace petrochemical plastics. The available degradable, biomass-derived plastics, such as ECOSTAR mentioned earlier, currently cost about twice as much as the resins they would replace. [Chum (1987) reports that ECOSTAR costs about 68 cents per pound, while polyethylene costs only 34 cents per pound.] For the most part these new plastics are in the development stage or are only ideas for further research.

Information is, however, available on current and projected prices for conventional plastics. These prices suggest the prices at which inorganic and biomass-derived plastics must compete. Table 14 gives information from Modern Plastics on the historical prices of several major resins.

Table 15 gives U.S. price increase projections for selected resins for the rest of this century. The information, reported in the April issue of Hydrocarbon Processing, indicates that the major resins will increase in nominal price by about 6% to 7% per year, depending on the resin.

3.2.4 Consumer Usage

Up to this point the discussion has focused on the potential competitiveness of inorganic and biomass-derived plastics as substitutes for conventional plastics at the raw materials, intermediate products, and resin levels. In this subsection the focus is on how these new plastics may compete in the production and use of products for specific consumer applications. More specifically, the discussion includes where plastics are currently being used, how the use of plastics is projected to change in those specific applications, and how the specific properties of inorganic and biomass-derived plastics may encourage the use of these new resins in specific product categories.

In my recent book [Curlee (1986b)], projections are given of the use of plastics in several consumer applications. Figures 2, 3, and 4 summarize those projections. Total U.S. resin production is projected to increase from its estimated 1984 level of about 45 billion pounds to about 64 billion pounds in 1995. The two largest uses of plastic resins are projected to be for packaging and building and construction

Table 14. Market-price history for basic grades of volume thermoplastics[a]

	Market price, ¢/lb., largest bulk basis, in given business quarter													
	1984		1985				1986				1987			
Polymer or feedstock[b]	3	4	1	2	3	4	1	2	3	4	1	2	3	4
LDPE, line	33.0	30.0	27.5	26.5	29.0	30.0	34.0	29.0	27.0	28.5	27.5	30.5	35.0	38.0
HDPE, blow molding	34.7	32.3	33.0	31.0	31.0	31.0	31.0	30.0	29.0	32.0	30.0	30.5	34.0	39.0
Ethylene	**18.7**	**17.7**	**16.0**	**15.5**	**15.0**	**15.5**	**18.3**	**14.5**	**14.0**	**14.5**	**15.0**	**14.5**	**15.0**	**18.0**
Polypropylene														
homopolymer modeling	36.7	35.0	36.0	36.0	36.0	36.0	35.0	33.0	32.0	34.0	36.0	38.0	40.0	44.0
Propylene, polymer grade	**19.0**	**18.5**	**18.0**	**17.5**	**17.0**	**17.0**	**16.5**	**12.5**	**11.0**	**10.5**	**11.0**	**15.0**	**18.0**	**20.0**
Polystyrene														
crystal molding	38.0	37.0	33.5	33.5	35.5	34.0	35.0	29.0	33.0	35.0	37.5	51.0	52.0	53.0
Styrene[c]	**28.0**	**26.0**	**24.0**	**26.0**	**25.5**	**23.5**	**23.0**	**19.0**	**17.0**	**23.0**	**30.0**	**42.0**	**38.0**	**40.0**
Benzene[d]	**18.0**	**17.3**	**16.5**	**19.0**	**20.0**	**16.5**	**13.4**	**11.6**	**11.0**	**11.6**	**17.0**	**31.0**	**13.0**	**13.0**
PVC, pipe-grade	29.0	24.0	30.0	29.0	27.0	27.0	30.0	27.0	27.5	29.0	31.0	33.0	34.0	37.0
Vinyl chloride[e]	**18.0**	**18.0**	**18.0**	**18.0**	**16.5**	**16.5**	**17.8**	**16.5**	**15.5**	**15.5**	**16.5**	**17.0**	**19.0**	**20.0**
PET, bottle-grade[f]	57.5	58.0	56.0	57.0	56.5	55.0	54.0	53.5	54.0	55.0	55.0	57.0	57.0	57.0
Crude oil[g]	9.7	9.7	9.3	9.3	9.3	9.1	6.3	5.0	4.1	4.7	5.5	6.1	6.0	5.9

[a] These are not spot prices but contract or prevailing selling prices that incorporate discounts, allowances, or rollbacks from current list. Each figure is thought to represent the level which many transactions occurred in a given business quarter, but it is not necessarily the precise average or median figure within the full range of market prices reported at the time. Resin figures are for natural grades in hopper cars.

b Rule-of-thumb is that one pound of monomer yields one pound of polymer, but ratios actually vary from 1:1 to 1:2.1 depending on polymer.

[c] One pound of styrene monomer is yielded by 0.86 lb. of benzene and 0.3 lb. of ethylene.

[d] Benzene prices conventionally are given in $/gallon. There are 7.32 lb. to the gallon.

[e] One pound of vinyl chloride monomer is yielded by 0.46 lb. of ethylene and 0.54 lb. of chlorine.

[f] Clear, 80-1.V resin grade.

[g] Figures, presented as guidelines, represent contract prices for Saudi marker crude through the second quarter, 1985, and thereafter the average monthly netback at Rotterdam for the benchmark crude. Oil prices are conventionally given in $ per lb. There are 300 lb. in a barrel of Saudi marker crude.

Source: Modern Plastics, January 1988, page 9.

Table 15. U.S. price forecasts for selected resins
(nominal compound rates of growth, 1986-2000)

Thermoplastic Resin	Projected % price increase
Low Density Polyethylene	6.6
High Density Polyethylene	6.5
Polypropylene	6.0
Polystyrene	6.2
PVC	7.0

Source: Hydrocarbon Processing, April 1988, page 15.

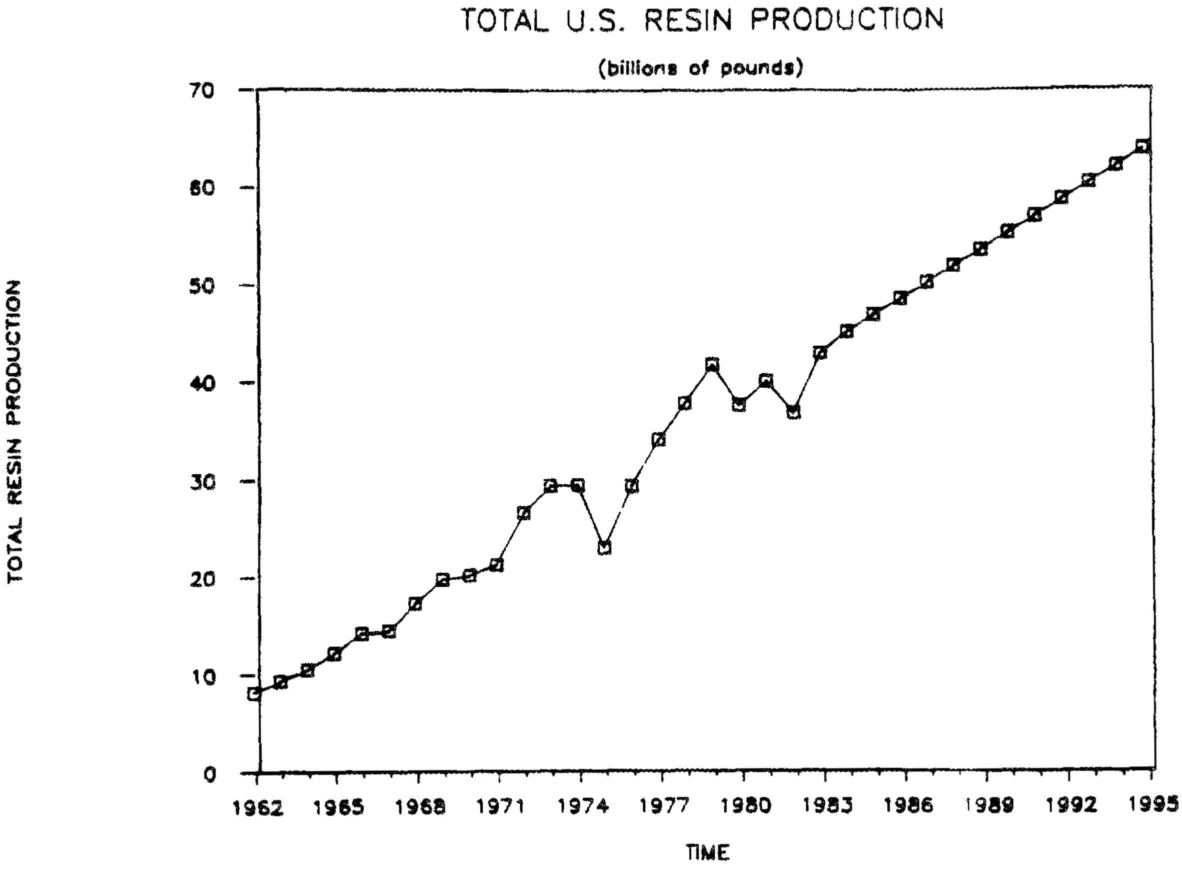

Fig. 2

Source: Curlee (1987)

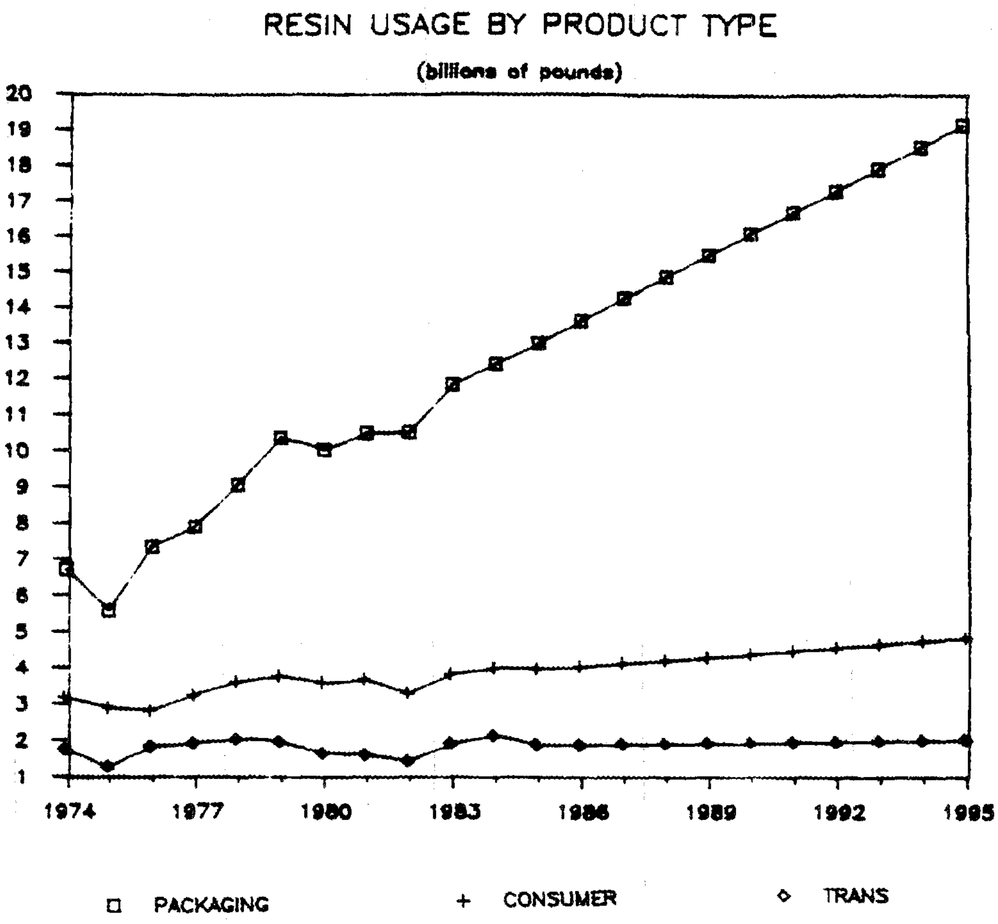

Fig. 3

Source: Curlee (1987)

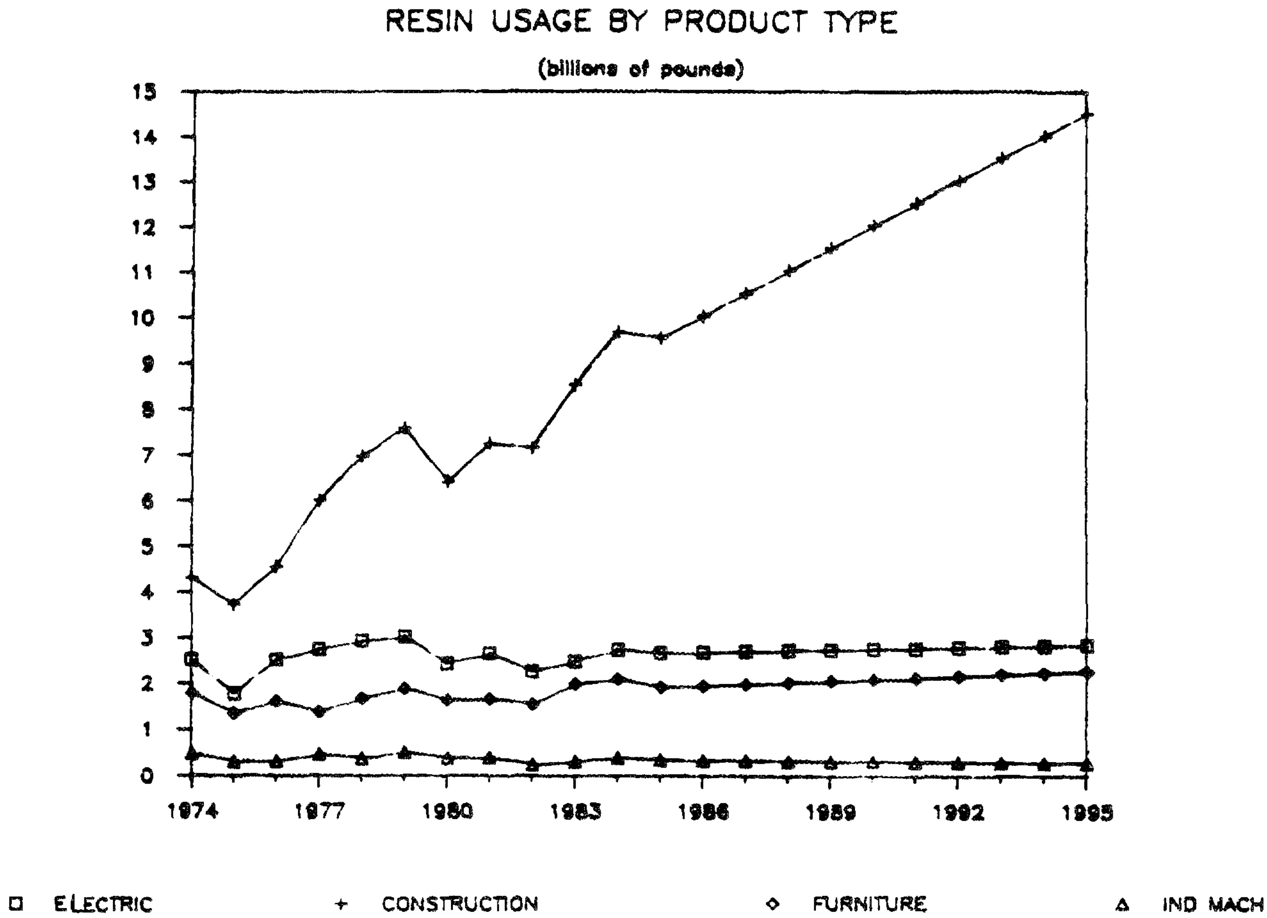

Fig. 4

Source: Curlee (1987)

materials. The use of plastics for packaging increased from 6.7 billion pounds in 1974 to 12.4 billion pounds in 1984. Projections indicate that plastics in packaging will increase to 19.1 billion pounds in 1995. Plastics consumption in the building and construction sector increased from 4.3 billion pounds in 1974 to 9.7 billion pounds in 1984. The use of plastics in the building and construction sector is projected to increase to 14.5 billion pounds in 1995. The third largest product sector is consumer and institutional goods. This sector is, however, not expected to experience the growth in plastics consumption that is expected in the packaging and building and construction sectors.

The April 1988 issue of Hydrocarbon Processing reports the findings of another study to project future thermoplastic consumption. The results of that study are summarized in Table 16. The projections, summarized from a study by Freedonia Group, Cleveland, Ohio and entitled Thermoplastics to 2000, suggest that total U.S. plastics consumption will increase to 60.5 billion pounds by 1992 and to 80.0 billion pounds by 2000. The Freedonia Group report agrees with my assessment that the use of plastics in packaging and construction will grow most rapidly. The use of thermoplastics in packaging (about 99% of the total plastics used for that sector according to my projections) is projected to increase to 18.8 billion pounds in 1992 and to 26.0 billion pounds in 2000. The use of thermoplastics in construction (about 79% of the total plastics for that sector according to my projections) is projected to increase to 9.3 billion pounds in 1992 and to 12.2 billion pounds in 2000.

The important point to make with respect to these projections concerns the advantage that inorganic and biomass-derived plastics may

Table 16. Projected consumption of selected thermoplastics by type and demand sector

Item Thermoplastic	1977	1987	1992	2000
Thermoplastics demand by resin type	**23,880**	**40,206**	**49,600**	**66,100**
Polyolefins	11,354	20,568	25,700	34,350
Polyvinyl chloride	5,061	7,607	9,200	12,200
Polystyrene	3,264	4,747	5,600	7,000
Engineered plastics	637	1,364	1,900	3,050
Other thermoplastics	3,564	5,920	7,200	9,500
Thermoplastics demand by market	**23,880**	**40,206**	**49,600**	**66,100**
Packaging	7,527	14,795	18,836	26,037
Construction	4,750	7,693	9,303	12,238
Household	2,811	4,011	4,619	5,664
Consumer	2,504	3,283	3,815	4,726
Industrial	1,287	2,327	2,837	3,544
Transportation	1,224	1,202	1,494	2,058
Agriculture	550	649	760	920
Other markets	3,227	6,246	7,936	10,913
% Thermoplastics	79.6	81.8	82.0	82.6
Total Plastics demand	29,997	49,146	60,500	80,000

Source: Hydrocarbon Processing (April 1988), page 17 have relative to petrochemical plastics in these different applications. Recall that one of the major advantages of biomass-derived plastics is their potential biodegradability. This material characteristic will be most important in products that cannot easily be diverted from the municipal waste stream, such as packaging and consumer and institutional goods. Given that the use of plastics in packaging is expected to increase sharply in coming years, the potential use of biomass-derived plastics for biodegradability purposes is large in absolute terms, even if only a small percentage of the total packaging market is filled by these new resins.

A similar point can be made with respect to plastics made from inorganic materials. A key limitation to the additional use of plastics in the building and construction sector concerns the combustibility of conventional plastics and the harmful pollutants given off during their burning. Plastics manufactured from inorganic materials would not be subject to this criticism and therefore may be attractive to the rapidly growing building and construction sector. Whether the improved material properties outweigh the expected additional costs of these new resins remains an empirical question.

3.2.5 Additional Points Relevant to the Private Sector's Adoption of Inorganic and Biomass-Derived Plastics

As is obvious by now, an assessment of the economic viability of inorganic and biomass-derived plastics as substitutes for conventional plastics must consider numerous factors. Economic viability is not simply a question of, for example, oil prices or improved material properties. Due to the complexity of the problem we cannot, unfortunately, at this time make any definitive statements about the overall economic viability of these new resins.

The evidence thus far presented does, however, suggest that inorganic and biomass-derived plastics are not currently viable economic alternatives to conventional plastics in those applications for which plastics are used predominantly. In order for these new resins to become viable economic alternatives, one or more of the following conditions will have to be satisfied: (1) Significant changes will have to occur in the relative prices of inputs for the different resin types -- i.e., raw materials, capital, labor, and energy. (2) Major advancements will have to be made in the technologies applied to one or more steps in the production process -- i.e., raw materials, intermediate products, resin production, and fabrication. (3) Changes will have to occur at the consumer level such that the special properties of inorganic and biomass-derived plastics will cater specifically to those demand variations.[10] Or (4) regulatory changes will be required to encourage the private sector to switch to these new resins, irrespective of their costs. The fourth point is the subject of the next subsection.

Note that while it is necessary that one or more of the above conditions be met before inorganic and biomass-derived plastics become attractive to the private sector, meeting these conditions does not necessarily imply that the private sector will move to these new resins.

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[10]The fact that technologies are changing to produce and use other materials for similar purposes cannot be ignored. Inorganic and biomass-derived plastics must compete with, for example, ceramics, metals, alloys, and composites; and the technologies associated with these materials are also changing rapidly. For a summary of these changes see, for example, Curlee (1988).

Problems in the form of what we may call institutional constraints may persist. These problems may take various forms.

The first, and potentially one of the most severe problems facing the market penetration of plastics based on inorganics and biomass, is the potential for what may be termed "price squeezing" by the producers of conventional resin feedstocks. By price squeezing we mean the reduction of resin feedstock prices by feedstock manufacturers to levels possibly below marginal cost. Referring to the petroleum-natural gas chemical industry, Thomas (1985) observes that "One important advantage that these companies possess and should never be underestimated is a flexible marketing structure. This is based on the consideration that the primary products derived from crude oil are fuel oil and petrol. Ethylene-, propylene-, and butane-related products are essentially by-products whose output is determined by the throughput and process conditions of the refinery. This permits the companies to be flexible in the production of particular chemicals and to apportion costs and charge prices to their various products in a way that would protect any threatened product while optimizing overall profitability from their operations" (page 104). This problem may be particularly severe for biomass-derived plastics that substitute in a direct way -- i.e., substituting for basic resin feedstocks.

Questions have also been raised about the degree to which the established petrochemicals industry would embrace new plastic technologies, irrespective of their potential cost advantages. The current petrochemical industry has a high capital intensity and a vast and sophisticated worldwide network of production, marketing, and research facilities. This physical and institutional framework is not altered easily or at low cost. It cannot, therefore, be expect that the current petrochemicals industry would embrace new and revolutionary technologies very quickly, even if those technologies are shown to be less costly.

The severity of this problem is lessened by the fact that the current plastics and petrochemicals industries are not highly concentrated. The U.S. Census reports that the 1982 4-firm concentration ratio for the "plastics and chemical resins" industry was 22; the 8-firm ratio was 38; and the 20-firm ratio was 64. In the "industrial organic chemicals" industry, the 4-firm ratio in 1982 was 36; the 8-firm ratio was 52; and the 20-firm ratio was 73.[11]

This potential problem is also lessened in that the acceptance and market penetration of new technologies based on inorganics and biomass do not necessarily depend on the current petrochemicals industry. It is likely that the new technologies will be sufficiently different from the current technologies so that there will be no great advantage in terms of skills or capital investments that will be held by the existing petrochemical industry. New industries could evolve to promote new inorganic or biomass-derived plastics. Existing industries, such as the paper and pulp industry, may be particularly suited to the manufacture of

[11]An industry concentration ratio indicates the percentage of industry sales that are accounted for by the largest 4, 8, 20, etc. firms in that industry. Some have argued that higher concentration ratios may create market power that in turn makes market entry by new firms or competing products more difficult.

biomass-derived plastics.[12] One should not underestimate, however, the difficulties and time involved in forming markets for new materials that are substitutes for materials manufactured in well established markets.

A more generic set of potential problems has to do with the risks or uncertainties that firms will face when adopting new technologies to manufacture and use inorganic and biomass-derived plastics. These uncertainties can be placed into three categories -- technological, market, and regulatory -- and can result in a risk averse firm not adopting a new technology or material even when that technology or material is expected to result in cost savings.[13] Technological uncertainties exist because most new resins are untested or in the development stage. Information about technical parameters and production costs associated with a particular technology are not generally available. Further, the material properties are in many cases not understood well.

Market uncertainties arise from a variety of sources. Uncertainties may exist about the availability of raw materials and the prices of those materials. This may be particularly true in the case of biomass. Uncertainties may exist about the formation of distribution channels for

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[12]An example of this movement is the recent entry of Archer-Daniels-Midland Company (ADM), a major corn starch producer, into the biodegradable plastics market. ADM recently acquired the rights to a British process to imbed polyethylene film with corn starch to produce plastic bags that when disposed of will break down into a fine dust.

[13]Note that risk averse firms prefer certain as compared to uncertain outcomes and will be willing to pay a risk premium to insure that certainty. Depending on the level of uncertainty and the level of risk aversion, the firm may select the more certain but higher cost technology (in essence the firm pays a risk premium) rather than the less certain but lower expected cost technology.

resins and final products. Uncertainties may also exist about consumer acceptance of these new resins. Finally, and probably most severe are regulatory uncertainties. Often regulatory uncertainties compound the other forms of uncertainty. And, unfortunately, legislation and regulations are difficult to predict. A discussion of the motives for government involvement in this issue and a review of current regulatory actions that may affect the economic viability of new inorganic and biomass-derived plastics is the subject of the next subsection.

3.3 THE PUBLIC SECTOR

3.3.1 Introduction

A strong argument can be made that the main impetus for R&D in the area of inorganic and biomass-derived plastics has resulted from government regulations or the threat of regulations with respect to the production and use of conventional plastics and crude oil. Further movements to replace conventional plastics will most certainly depend on the incentives and disincentives that result from public sector actions. This subsection therefore moves away from the firm's or the individual's decision to adopt inorganic or biomass-derived plastics and focuses on the potential role to be played by the public sector or government. More specifically, the section discusses on conceptual and empirical grounds the arguments that would defend public sector actions to encourage movements away from conventional plastics and toward inorganic and biomass-derived plastic. Also discussed are recent regulatory actions at the national, state, and local levels that directly or indirectly affect the overall viability of inorganic and biomass-derived plastics.

3.3.2 Why Public Sector Involvement?

Economic theory suggests that in the absence of some kind of market failure, a competitive market allocation of resources will maximize economic efficiency. Economic efficiency has to do with obtaining the greatest value of real output for a given input cost, or alternatively achieving a given value of real output at minimum input cost. Unless some form of market failure can be shown to exist, the public sector's involvement will result in a less efficient allocation of overall resources.

Market failures can take various forms. In the case of the public sector's involvement to encourage the transition away from the use of conventional plastics, market externalities are most relevant. Externalities have to do with costs or benefits that result from the production, use, or disposal of a good, but that are not borne by the parties making the economic transaction. Because these costs or benefits are not a relevant considerations of the buyer or seller of the good, they are not included in the purchase price. When externalities can be shown to exist, government intervention to in effect correct the market prices will result in a more efficient overall allocation of resources. With respect to the question at hand, two particular externalities are relevant -- (1) potential environmental degradation associated with conventional plastics, and (2) externalities associated with the production and use of oil.

The question of environmental degradation and the use of petrochemical, inorganic, or biomass-derived plastics is discussed in Section 2.4 of this report. Recall that at this point in time we cannot make definitive statements about the environmental damage that is currently being caused by the production, use, and disposal of conventional plastics or the potential reduction in that environmental damage that could be attributed to a switch to inorganic or biomass-derived plastics. Arguments for government intervention on the basis of reducing environmental degradation are therefore somewhat tenuous.

The question of oil vulnerability and the potential benefits that might result from moving away from petrochemical plastics has been discussed in Section 3.2 of this report. Recall that the arguments based on oil availability and price have for the most part been overstated. First, as I have discussed elsewhere [Curlee and Wright (1988)], the problem of oil vulnerability is not so much a question of availability as it is a question of oil prices. Second, long-term oil prices during the next two decades are not expected to be subject to the severe long-term price increases that have occurred during the past one and a half decades. Oil vulnerability will most likely take the form of short-term to intermediate-term price spikes. In any case, current estimates indicate that oil prices would have to about double before any significant quantity of petrochemical-based plastics would be replaced on the basis of cost minimization.

A further point is relevant. If the goal of switching to inorganic and biomass-derived plastics is to reduce our domestic consumption of petroleum, it would appear that other opportunities are available to conserved more petroleum at far lower costs. For example, ethanol produced from biomass can simply be used as a fuel instead of a chemical feedstocks. Oil is conserved in either case; however, the conversion to ethanol fuel (which is already occurring) would appear to be easier and less costly than the conversion to biomass-derived chemical feedstocks. Ethanol for fuel could accommodate much higher levels of contamination than could be tolerated in ethanol for further chemicals production.

3.3.3 Possible Government Actions

Although the arguments for government actions to encourage the switch from petrochemical plastics to inorganic and biomass-derived plastics remain somewhat unsettled at this time, government actions may be called for. Such actions could take various forms that would either make the use of conventional plastics more expensive or reduce the cost of the alternative resins.

Taxes could be imposed on the production and use of conventional plastics to reflect the potential external environmental cost associated with the use of those resins. In applications where the use of conventional plastics is concluded to be unacceptable, outright bans could be imposed. Alternatively, the use of alternative plastics could be subsidized directly or indirectly. The subsidies could range from R&D funding assistance to tax credits to firms manufacturing or using the new plastics.

The potential problems posed by oil vulnerability are best addressed by imposing a tariff or tax on imported oil. Such a tariff or tax would reflect the externalities associated with the importation and use of vulnerable petroleum. Further, the tariff or tax would put all domestic users of petroleum on an "equal footing," thus allowing the market mechanism to determine which of the current uses of petroleum would be reduced. As stated above, reducing the quantity of petroleum used for resin manufacture is not necessarily the least costly means of reducing oil consumption.

3.3.4 Recent Public Sector Regulatory and Legislative Actions

Various actions are being taken at the national, state, and local levels that will have a direct or indirect effect on the decision to replace conventional plastics with other materials. At the national level at least three legislative initiatives are relevant -- the Clean Air Act, the Resource Conservation and Recovery Act (RCRA), and the United States-Japan Fishery Agreement Approval Act. The reauthorization of the Clean Air Act, currently being debated in Congress, could have significant indirect implications for both the production and disposal of plastics. A recent article in Chemical Engineering argues that the current House and Senate bills to reauthorize the act will place severe economic pressure on the domestic chemical process industries because of more stringent measures. The new legislation if passed could impose additional costs of $11-18 billion on the domestic industry. A revised Clean Air Act could also increase the cost of disposing of conventional plastics if incineration regulations become more stringent, thus promoting the use of degradable or inorganic plastics.

RCRA is also due for reauthorization this calendar year. Subtitle D of RCRA regulates landfills and waste incineration. As is the case with the Clean Air Act, a more stringent RCRA could make the disposal of conventional plastics more expensive. There is some speculation that the reauthorized RCRA may also contain waste minimization provisions that could impact on the use of conventional resins in large-volume uses such as packaging.

The United State-Japan Fishery Act will eventually prohibit the dumping of all non-degradable plastics at sea. This will have obvious implications for biomass-derived plastics that are biodegradable.

Actions at the state and local levels are increasing rapidly to encourage recycling of plastics or to place bans on the use of certain resins for selected uses. For example, legislation was introduced recently in the New York state legislature to ban polystyrene foam and PVC packaging. Eleven states currently have bottle deposit bills that encourage the recycling of PET beverage bottles. Eleven states now ban non-biodegradable plastic yokes on six-packs of beverage containers. Oregon is debating a banning of non-biodegradable plastic grocery bags and diaper linings. Suffolk county (Long Island, New York) recently banned food stores and fast food restaurants from using plastic bags and containers. These state and local actions follow similar actions in Europe. For example, Italy recently decreed that all plastics used for nondurable goods must be made degradable by 1989.

4. CONCLUSIONS

Will inorganic and biomass-derived plastics replace a significant fraction of petrochemical plastics during the coming one to two decades? Unfortunately, the information required for a definitive assessment of this question is not currently available. This report has, however, examined in a conceptual sense what must happen before inorganic and biomass-derived plastics become viable economic alternatives. This report has also examined the limited empirical information that is currently available which suggests the relative advantages held by the different resin types.

Conceptually, the problem for inorganic and biomass-derived plastics can be stated quite simply. The economic viability of these new resins will depend on their abilities to (1) provide equivalent material properties at an equal or lower cost than conventional plastics, or (2) provide improved properties in a way such that the marginal benefits of the improved properties outweigh their marginal costs. The potential improved properties of these new resins include engineering materials properties, less environmental degradation associated with disposal, and benefits derived from moving away from intermediate products based on petroleum and natural gas.

Empirically, only limited statements can be made at this time about the abilities of these new resins to meet these requirements. A focus on the cost of raw materials production indicates no clear favorite. Current information suggests that oil and natural gas prices will continue to increase, but probably not at the rate experienced during the past one and a half decades. Reserves of inorganic raw materials are large enough that any likely increased demands on those resources for the production of inorganic plastics should have a small effect on inorganic material prices. Biomass material prices are currently high in relation to oil and natural gas. That gap is, however, expected to decrease as selected agriculture operations are dedicated to fuels and chemicals production. Genetic engineering will also likely result in new or varied species that are more suited to the production of chemical feedstocks. In none of the cases does the availability of raw materials appear to be a significant problem.

At the intermediate products level, little information is currently available relevant to the production of inorganic plastics. Biomass-derived intermediate products are not currently competitive with the same intermediates produced from petroleum and natural gas. Recent studies suggest that, all else being equal, oil and natural gas prices would have to increase by more than 100% before biomass materials would displace any significant percentage of oil and natural gas. In addition, it is generally agreed that if oil and natural gas prices increase sharply, coal -- not biomass -- is the logical alternative raw material. Revolutionary technologies, such as those based on microorganisms, may, however, greatly reduce the cost of biomass conversion.

Little specific information is available on the likely costs of inorganic and biomass-derived resins. It is, however, generally accepted that without major technological advances, the prices of inorganic and biomass-derived plastics will be significantly higher than the current or forecasted prices of petrochemical-derived plastics. Prices of the few biomass-derived resins currently being marketed are about double the prices of conventional resins with which those new resins must compete.

If inorganic and biomass-derived plastics are to become competitive with conventional plastics, the cost differences between the resin types will have to narrow. Alternatively, the special properties of the new resins will have to prove to be quite valuable. The special properties may be valuable directly to the users of the resins, or, alternatively, the properties may be judged to be of significant value to society as a whole. Engineering material properties fall within the first category. Properties associated with environmental degradation and oil use fall within the second category. The non-flammability characteristics of inorganic plastics may prove particularly valuable in sectors with rapidly growing plastics consumption, such as construction. The biodegradability characteristics of many biomass-derived plastics may prove valuable in the packaging area. An estimation of the specific benefits of the special characteristics offered by inorganic and biomass-derived plastics must, however, be done for each characteristic and each end product and must await further research.

An added problem for inorganic and biomass-derived plastics concerns barriers to market entry. Even if either of the above mentioned necessary conditions for economic feasibility holds, the market penetration of the new resins awaits stiff competition from entrenched petrochemical and resin industries. It has been argued that the production of some of the main resin feedstocks, e.g. ethylene, is essentially a by-product of the refining industry. The prices of resin feedstocks could therefore come down sharply in response to threatened competition. Adopters of the new technology will face significant technological, market, and regulatory uncertainties.

In addition, the arguments for inorganic and biomass-derived plastics on the basis of reducing environmental degradation are at this time somewhat tenuous. And, in general, the arguments for the development and use of these new resins on the basis of saving petroleum and natural gas have been overstated. The main arguments for a stronger role for the public sector to encourage the transition away from conventional plastics are therefore less than convincing. There are, nevertheless, movements at the national, state, and local levels that will directly or indirectly limit the use of conventional plastics and encourage the transition to alternative materials.

The overall feasibility of replacing conventional plastics with ones based on inorganic or biomass materials will turn on numerous economic, technological, institutional factors. It will also turn on the public sector's evaluation of the need to move away from plastics based on petrochemicals. Unfortunately, at the present time there is not sufficient evidence to argue definitively for any specific outcome.

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