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The Economic Benefits of Chlorine Chemistry in Polyurethanes in the United States and Canada

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Contents

Executive summary

Chlorine chemistry is central to the production of most isocyanates, a major component of polyurethane-based products that consumers use every day. By selecting the proper combination of starting materials and processing conditions, these versatile polymers can be produced in various forms such as rigid and flexible foams, surface coatings, adhesives and sealants, elastomers, binders, and fibers. Consumers may be familiar with the use of polyurethanes in products found around the home – including the cushions in furniture and memory foam mattresses, coatings for hardwood floors, and spandex – but may not be familiar with their use in other, less conspicuous applications. These include products such as automotive trim components, adhesives, insulation, and bonding agents in oriented strand board wood products. In the United States and Canada, these industries are quite large, amounting to $7 billion in sales at the wholesale level and much more at the consumer level. This report estimates the benefits of chlorine chemistry in the production of polyurethane-based products by examining the differences in costs and the utility to consumers between chlorine-free substitutes and the chlorine-based products that they currently use.

While chlorine-free chemistries have been commercialized for the production of aliphatic isocyanates for some time, chlorine-free chemistries proposed for the production of aromatic isocyanates have not yet been shown to be commercially viable. Therefore, in the absence of chlorine chemistry, consumers would have to substitute alternative materials for 96% of the polyurethane-based products they currently use. Many alternative materials might be selected as substitutes for polyurethanes in its applications, but consumers prefer the polyurethane-based products because they exhibit the attributes they seek at the required total cost. Furthermore, none of these alternatives can duplicate all of the attributes of polyurethane-containing products, so they would not be perfect substitutes. Additionally, their use would raise costs to consumers because of the need to use materials that have higher life cycle costs or decreased utility. Furthermore, significant amounts of new capital would have to be employed to produce them.

We estimate that the net cost to consumers in the United States and Canada for the substitution of alternative materials for the chlorine-based polyurethanes currently in use would be over $4.6 billion per year, and would require approximately $9.2 billion in new investments. The avoidance of these costs is the economic benefit that chlorine chemistry in the manufacture of isocyanates brings to consumers. Virtually all the chlorine that is used in the manufacture of these products is recovered as hydrogen chloride and sold for reuse, and amounts to only about 9% of total chlorine consumption.

Introduction

Consumers enjoy the benefits of polyurethane-based products every day in a wide variety of consumer and industrial products. Polyurethanes are generally formed when an isocyanate is combined with a polyol in the presence of catalysts and other materials. Polyurethane products can be manufactured with a broad range of properties by altering the proportions and types of the isocyanates and the polyols and by modifying the processing conditions. The major forms of polyurethane products include:

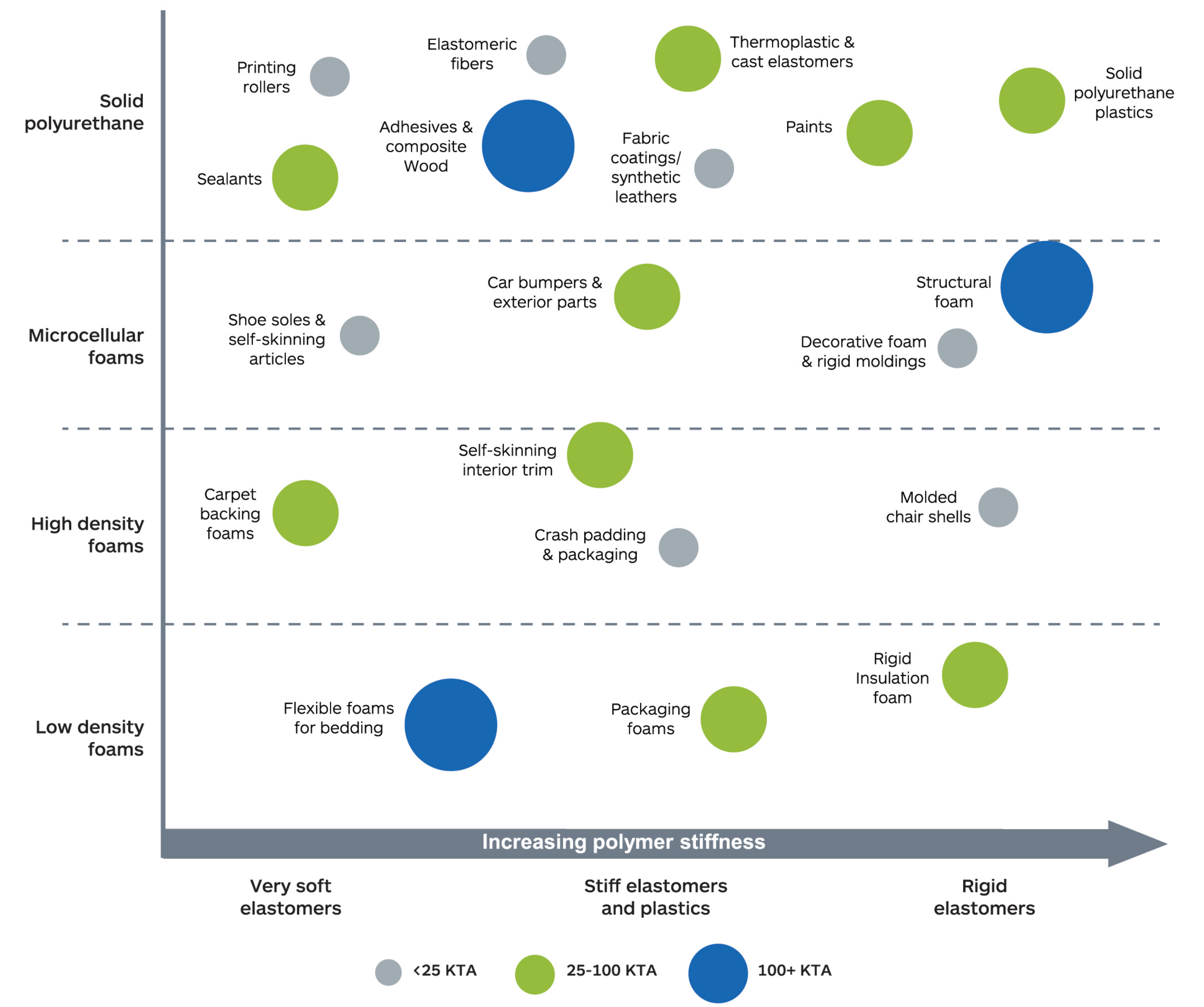
- Flexible foams – used for comfort and versatility in upholstered furniture, bedding, and transportation applications;
- Rigid foams – used for low and high temperature insulation to prevent energy loss in buildings and appliances;
- Surface coatings – used in construction and transportation applications to protect flooring and other exterior or outdoor surfaces;
- Adhesives and sealants – used in construction applications to make moisture-resistant wall, ceiling, and floor panels;
- Fibers – used to make stretch fibers that are stronger than rubber and resistant to aging (often referred to as spandex);
- Elastomers – used for their thermal conductivity and insulating strength as casting resins for wheels, casters, or electronic devices.

The most economically important isocyanates are toluene diisocyanate (TDI) and methylene diphenyl diisocyanate (MDI), both aromatic in their composition. In general, TDI is used in the production of flexible foams and MDI is used in the production of rigid foams and most other products. Many other aliphatic and polymeric isocyanates are produced in smaller volumes, but they are not as widely used as the aromatic isocyanates. The figure below depicts the range of polyurethane products based on their physical properties, with the size of the circles representing the estimated market size in 2014.

Chlorine chemistry is fundamental to the production of polyurethanes because most isocyanates are formed when phosgene is reacted with the appropriate amine, and phosgene is made by reacting chlorine with carbon monoxide. The amine for TDI production is toluene diamine, and the amine for MDI production is aniline. If the polyurethane products made using chlorine chemistry were not available, consumers would have two choices with respect to acquiring substitutes. They could:

- Develop chlorine-free production methods: A number of alternate, chlorine-free routes are technically possible and have been proposed to produce isocyanates, and subsequently polyurethanes. If these processes were developed commercially, consumers could still enjoy the benefits of the polyurethane-based products.
- Use other materials: Consumers could substitute products made from alternate materials such as specialty elastomers, latexes, polymers, or natural materials. These materials may not have the same mix of desirable properties and, as a consequence, consumers may suffer losses in utility from their use. Polyurethanes are typically high performance materials, and substitution could result in lower functional performance.

Polyurethane properties and applications



Source: Adapted by IHS Chemical from the CPI 2014 End-Use Market Survey.

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In the following sections, we describe the properties of the polyurethane-containing materials that make them beneficial to consumers and the issues surrounding the use of substitutes that are not based on chlorine chemistry. The benefits of chlorine chemistry in the production of polyurethane-containing products can be determined from the differences in the costs and the utility to consumers of the chlorine-free substitutes and the chlorine-based ones that they currently use.

Isocyanate consumption and the value of chlorine chemistry

In 2014, consumption of isocyanates in the United States and Canada was approximately 1.4 million metric tons, valued at well over $7 billion.[1] The two primary isocyanates, MDI and TDI, dominate the isocyanate market – together, in 2014, they made up 96% of total isocyanate volume consumption.

MDI is the most widely used diisocyanate in commercial use for a number of reasons. Primarily, it provides excellent performance characteristics when converted into most polyurethane-containing products. MDI-based polyurethanes can be produced in a variety of forms by reactions with various polyester or polyether polyols and using different blowing agents, surfactants, catalysts and/or fire retardants. The products can be in the form of rigid or flexible foams, binders, coatings, adhesives, sealants, and elastomers. A significant amount of MDI is consumed directly as a binder in the manufacture of wood products. These products exhibit durability, versatility, low life cycle costs, and other qualities that make them useful and valuable to consumers.

TDI is consumed primarily in the production of polyurethanes used to form flexible foams and, to a much lesser extent, in surface coatings, adhesives, sealants, and elastomers. Aliphatic isocyanates, which comprise the remaining 4% of consumption, are most often used for products with surface coating applications, but they can also be found in adhesives, sealants, and elastomers.

United States and Canada isocyanate consumption, 2014 (‘000 MT)

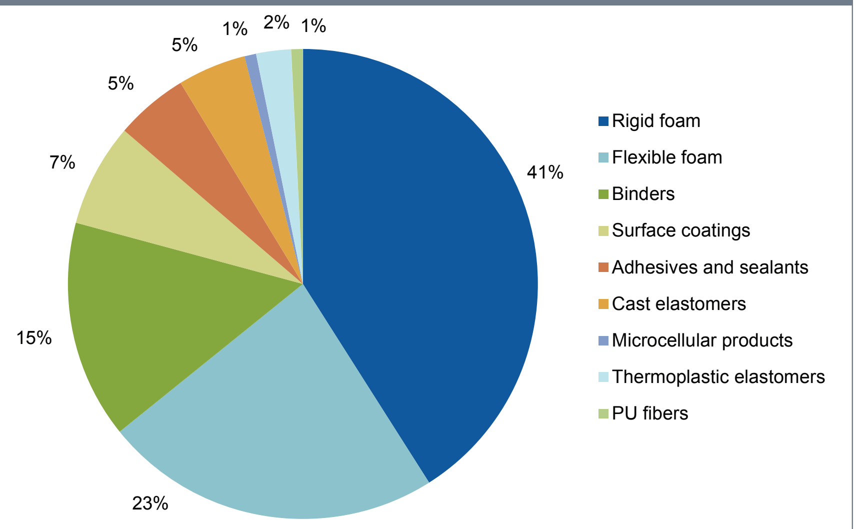
Isocyanate	United States	Canada	Total	Percent
MDI	960	106	1,066	79%
TDI	215	17	232	17%
Alphatic and cycloaliphatic	53	3	56	4%
Total	**1,228**	**126**	**1,354**	**100%**

Source: CEH, Diisocyanates and Polyisocyanates. August 2015. © 2016 IHS

There are currently seven producers of isocyanates in the United States. The four largest are BASF Corporation, Bayer Material Science LLC, known as Covestro since 2015, The Dow Chemical Company, and Huntsman International LLC. These companies account for 99% of US capacity. Only two companies, BASF and Covestro, currently produce TDI. No Canadian company currently produces isocyanates; therefore Canadian consumption comes entirely from imports.

Rigid foams, the largest end-use of polyurethanes, comprise 41% of all isocyanate consumption and flexible foams account for an additional 23%. These uses, together with consumption in binders and surface coatings, account for over 85% of total consumption as shown in the figure.[2] These material forms are then used in a wide variety of applications in both consumer and industrial products.

United States and Canada isocyanates end uses, 2014



Source: CEH, Diisocyanates and Polyisocyanates, August 2015. @ 2016 IHS

1 Henry Chinn with Xu Xu and Masahiro Yoneyama, “Diisocyanates and Polyisocyanates,” Chemical Economics Handbook, August, 2015 and IHS estimates.

2 “Diisocyanates and Polyisocyanates,” op. cit.

Major product applications of isocyanates

Rigid foams	**Flexible foams**
Insulation	Furniture
Roofing	Office chairs
Windows/doors	Bedding/mattresses
Metal Panels	Clothing
Packaging	Headrests/armrests
Freezers and refrigerators	Exterior trim
Air conditioners/water heaters	Packing/packaging
Flotation devices- life jackets, buoys	Carpet underlays
Surface coatings	**Polyurethane cast elastomers**
Paints	Gaskets
Automotive	Shoe soles
Concrete flooring	Tires
Adhesives and sealants	**Microcellular products**
Construction	Auto panels/interior parts
Textile laminates	Bumpers, spoilers
PU fibers	**Thermoplastic elastomers**
Sportswear	Flexible tubing, hose
SpandexTM	Film
Binders	
Binds wood chips into wood products	

Source: CEH, Diisocyanates and Polyisocyanates, August 2015.

Isocyanates in rigid foam manufacturing

More than half of MDI consumption is used to manufacture rigid polyurethane and polyisocyanurate foams. The excellent insulation, mechanical qualities, and strong adhesive characteristics of rigid polyurethanes make them highly desirable for use as insulation in the walls and roofs of commercial and residential buildings. Additionally, rigid foam can be fabricated into self-supporting products, an important property for insulation panels and other construction applications. Nearly 62% of rigid foam is consumed in the construction industry, where the major applications are board and laminate insulation, primarily for commercial construction and to a lesser extent for residential construction.[3]

A related product, polyisocyanurate rigid foam, utilizes MDI in its production. Used predominantly in the construction industry (e.g., insulation for sloped roofs, residential sheathing insulation, and in structural panels), polyiso foam has a higher MDI content than polyurethane foam and has enhanced performance characteristics.

In 2014, the United States and Canadian insulation markets were estimated to be approximately $7.1 billion and $800 million, respectively.[4] In the residential market segment, fiberglass applications hold the largest market share. However, in recent years, sprayed foam insulation has gained on fiberglass's dominant position in insulation, with major inroads made in performance oriented builders, especially high-end custom homes.[5] Compared to conventional fiberglass batting insulation, sprayed foam insulation fills difficult spaces and creates a "tighter house." Spray foam not only fully insulates, but also seals from air and moisture infiltration resulting in more energy efficiency.[6] According to the US Department of Energy, almost half of the energy used in the average American home goes to heating and cooling, while only about 18% goes into heating

3 *Ibid.*

4 Freedonia, "Insulation," 2015 available at http://www.freedoniagroup.com/Insulation.html and IHS Chemical estimates.

5 "Fiberglass and spray foam battle for insulation market share," ProSales, November 9, 2015. Available at http://www.prosalesmagazine.com/products/insulation/fiberglass-and-spray-foam-battle-for-insulation-market-share_o

6 Spray foam education center homeowners guide. Available at http://www.sprayfoam.com/spray-foam-education-center/spray-foam-homeowners-guide/25

water.[7] While the share of energy consumption for heating and cooling has declined in recent years, reducing household energy use still makes a difference in saving consumers money while at the same time reducing generation of greenhouse gases.

Polyurethane-based sprayed or rigid foams are not the only option for these insulation applications. Most alternative low density thermal insulation products, however, must be supported with additional materials and are soft or less resistant to moisture than polyurethane products.[8] Alternative rigid foam or loose fill insulation materials include expandable polystyrene (EPS) and other expanded plastics, fiberglass, mineral (rock and slag) wool, cotton, and recycled cellulose. However, the insulation factor, or R-value, of these alterative materials is typically lower than polyurethane-based products. A lower R-value means that the use of these alternatives results in lower performance insulation properties, and higher energy consumption for both heating and cooling of the building interiors.

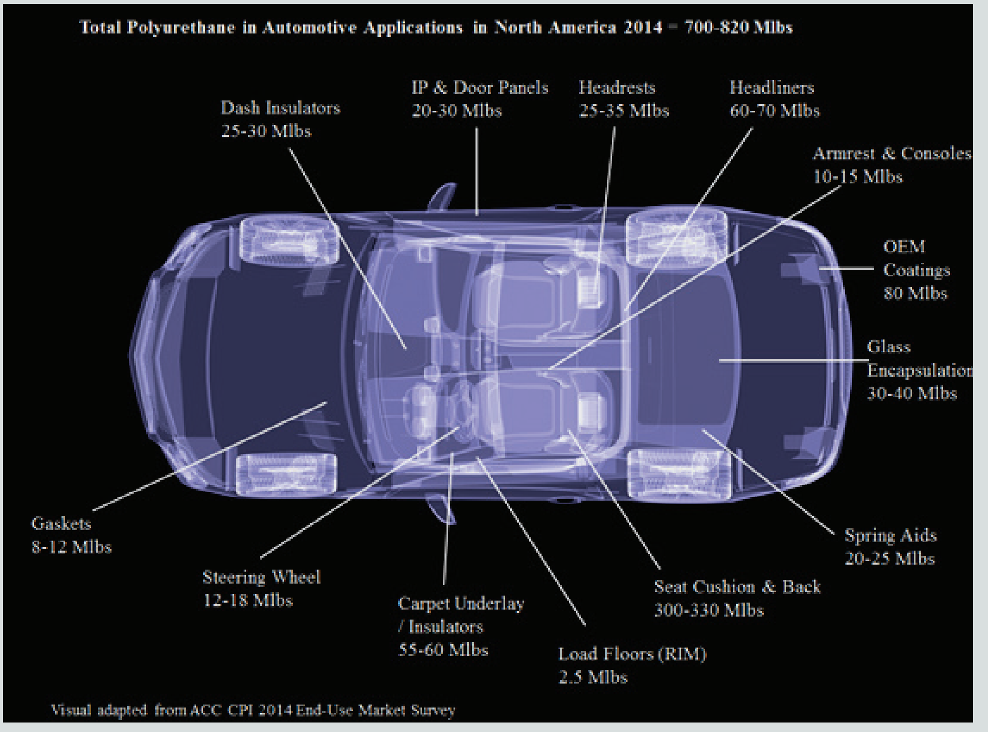
Besides construction, the remaining outlets for rigid MDI foam are in appliances, packaging, and transportation where cushioning and resiliency are important properties. One of the faster growing rigid and semi rigid markets for MDI-based products is the use for sound and energy absorption in automobiles where the polyurethane foams are utilized instead of metal bars for knee bolsters, side-impact absorption beams, and to support instrument panels.[9] See the textbox below for a visual depiction of the use of polyurethanes in automobiles.

7 US Energy Information Administration (EIA), "Residential Energy Consumption Survey (RECS)," 2009. Available at http://www.eia.gov/consumption/residential/index.cfm

8 See "Polyurethane and Polyisocyanurate Foams," ACC Center for the Polyurethanes Industry. Available at http://www.polyurethane.org

9 "Diisocyanates and Polyisocyanates," op. cit.

Polyurethane in automotive applications



The light vehicle industry represents an important sector of the US economy and a major end-use market for plastics. In 2014, the 16.5 million light vehicles sold in the United States and Canada required some 5 billion pounds of plastics and polymer composites valued at $5.8 billion, or $433 in every vehicle. Representing approximately 16% of a vehicle's weight, plastic and composites are essential to a wide range of safety and performance breakthroughs in today's cars, minivans, pickups, and SUVs. Including rubber, coatings, and textiles, an average of 336 pounds of total vehicle weight is from plastics, of which approximately 55 pounds, or 16%, are polyurethane.

Polyurethane is extremely versatile in automotive applications, ranging from seat cushions to engine parts. Although polyurethane manufacturing is based on chlorine chemistry, chlorine is not present in the finished product. Almost all forms of polyurethane are utilized from outside to inside the car:

- Flexible polyurethane foams are used for seat padding, instrument panels, door padding, steering wheel padding, armrests, headrests, carpet underlays, and sun visors.
- Rigid polyurethane foams are used as insulation in trucks carrying semi perishable goods, in travel trailers, in motor homes, and in bumpers to provide energy-absorption.
- Polyurethane elastomers are used in headliners, bumper trims, window frames, steering wheels, truck tailgates and boxes, door skins, fenders, quarter panels, dashboard, door panels, and tires.
- Polyurethane thermoplastics are used in body panels, instrument panels, timing belts, antilock brake system parts, sound-dampening components, and vibration absorption parts.
- Polyurethane adhesives are used as a windshield sealant and in the assembly of body panels; aliphatic polyurethanes are used as the exterior topcoat paint.

Sources: ACC Center for the Polyurethanes Industry 2014 End-Use Market Survey, ACC's Economic & Statistics Department 'Plastics and Polymer Composites in Light Vehicles' 2014, 'Polyurethane Foams' Chemical Economics Handbook.

Isocyanates in flexible foam manufacturing

The manufacture of polyurethane products for various flexible foam applications accounts for 85% of TDI production in the United States and Canada.[10] TDI-based foams normally spring back more easily to their original shape and have a softer feel in applications such as cushions and seats than MDI-based foams or products made from other materials. However, consumer preferences, toxicity concerns, and new design standards have caused some traditional TDI flexible polyurethane foam markets to convert to MDI. MDI usage has increased in the United States as more producers find valuable end-uses in molded flexible foams, as well as high density flexible slabstock foams for transportation and furniture markets. In recent years, approximately 60% of the total isocyanate usage for molded flexible foam is MDI (often in TDI/MDI blends) and 13-14% of total isocyanate usage for flexible slabstock foam is MDI.

One key area consumers have become familiar with is memory foam bedding systems (technically called viscoelastic foams), which is a strong growth segment for MDI usage. In 2014, MDI accounted for around 32% of all diisocyanates used in flexible foam for the bedding market. The special properties of such foams are best demonstrated when they are subjected to load and the influence of body heat. They yield to every contour and distribute the contact pressure from the weight of the body over as large a surface as possible. The market for flexible foams is very large, amounting to nearly $20 billion in upholstered goods and mattresses alone in the United States in 2014.[11]

Products that require flexible foams may be manufactured using materials other than polyurethanes. Some of the substitution possibilities in these markets include products made from short staple polyester fiber, cotton, and latex foam rubber. Short staple polyester fiber and cotton both have poor height recovery. While these materials can be combined with steel springs to improve height recovery, there will still be some utility loss in terms of comfort and durability. Latex foam rubbers, either natural or synthetic, are other possible substitute materials. Latex foam rubbers can surpass flexible polyurethane foams in performance evaluations using ASTM testing standards at a premium cost.[12]

Isocyanates in binders manufacturing

Binders represent the second largest end use of MDI, amounting to about 200,000 metric tons, or 19% of total MDI consumption in 2014. MDI is used both to produce polyurethane products that serve as binders and directly as polymeric MDI (pMDI) to bond wood chips into structural wood products, particularly oriented strand board (OSB), composite panels, and composite lumber. The use of MDI as a binder experienced significant growth in the early 2000s, growing at an average rate of 10% per year. While this market declined during the recession, consumption has rebounded dramatically in recent years. Much of the recent growth is for cellulosic materials for particleboard and medium-density fiberboard (MDF) applications.

In 2014, United States and Canadian plywood and OSB production was approximately 31 billion square feet (on a 3/8" basis), with OSB's share of the market at a dominant 64%. Structural panel consumption finished 2014 at its highest level since late 2007.[13] pMDI forms chemical bonds with the wood, allowing OSB manufacturers to use less resin to achieve the desired performance. Other advantages to using pMDI as a binder include high tolerance for moisture content in wood, low press temperatures, and fast press cycles, which suggest potential energy savings and productivity increases in the manufacturing process.

Substitution possibilities for pMDI in this application include formaldehyde-based resins; vinyl acetate emulsions or epoxy formulations; lignin adhesives; furfuryl alcohol resins; and soy-based adhesives. pMDI has superior mechanical and physical properties in damp conditions, which is why pMDI is often preferred

10 *Ibid.*

11 US Census Bureau Industry Snapshot, NAICS 337910, 337121. Available at http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ASM_2014_31VS101&prodType=table

12 Polyurethane Foam Association, "In-Touch," volume 8, number 1, May 2000, p. 2. Available at http://www.pfa.org/intouch/pdf/v8n1.pdf

13 RISI Structural Panel Dashboard January 2015.

over other competing binder materials. Additionally, certain environmental regulations may favor pMDI over alternative resins.

Isocyanates in coating applications

Polyurethanes used in surface coating applications have different properties depending on which isocyanate is used. Aliphatic isocyanates are normally used to make polyurethane coatings for exterior or outdoor applications because of their outstanding UV and weather resistance properties. [14]Their excellent UV protection properties have led to their use in demanding automotive, exterior exposed metal such as bridges, and concrete floor finish applications. The aromatic polyurethanes (MDI- and TDI-based) oxidize more easily than do aliphatic polyurethanes when exposed to UV light, which makes them prone to degradation and leads to a slight discoloring or yellowing of the product. Aliphatic isocyanates also exhibit good gloss and color retention, making them highly attractive for coatings for the demanding applications in the automotive industry. They can also be used for hardwood floor and machinery finishes. Although aliphatic isocyanates-based polyurethanes provide increased protection, they are more costly to produce then either MDI or TDI-based products. Aromatic coatings are best suited for interior or exterior applications where color retention is not important. MDI is used primarily in two-component polyurethane systems, while TDI is principally used in urethane alkyds, reactive two-component systems, and moisture-curing prepolymer products (all mainly for construction use).

Isocyanates in other applications

The remaining 14% of isocyanate consumption in the United States goes into a wide array of end uses, including coatings, adhesives, sealants, and elastomers in construction, automotive interior and exterior applications, structural metal, footwear, athletic equipment, and spandex products.[15] Alternative materials exist for each of these end uses, and many substitutes are available at lower cost than products based on isocyanates. However, consumers choose polyurethanes because their high performance and durability, and because they would likely experience a utility loss if the alternative material were chosen. For example, acrylic paints can be used for color fastness and UV resistance on indoor and outdoor surfaces, but they are not as durable as polyurethanes for heavy-duty exposure and wear, and so would require more frequent application to preserve the desired appearance.

In summary, products based on isocyanates can be tailored to have a broad range of desirable properties and attributes and they are used widely in consumer and industrial applications. While substitutes that are not based on chlorine chemistry can be found, consumers would experience either losses in utility or increased costs (or both) if they were required to use them in place of the isocyanate-based products they now prefer.

In the following sections we describe the development and use of manufacturing technologies for isocyanates that do not involve chlorine chemistry and the quantification of the benefits that the current technology provides consumers.

Chlorine-free routes for the manufacture of isocyanates

TDI, MDI, and aliphatic isocyanates are all made commercially by reactions between phosgene and an appropriate aromatic or aliphatic amine; aliphatic isocyanates can also be made commercially by a phosgene-free route. Phosgene is made on-site in a simple, single step process by passing purified carbon monoxide and chlorine gas through a bed of highly porous carbon, which acts as a catalyst. Phosgene is then reacted with the appropriate diamine. The subsequent separation and purification of the products of reaction from the polymeric byproducts that are formed is a multi-step, but straightforward process. The hydrogen chloride that is produced as a byproduct of the reaction is recovered and then sold either directly or indirectly in the form

14 Shiwei Guan, “100% Solids Polyurethane and Polyurea Coatings Technology,” Coatings World, March 2003. Available at http://www.madisonchemical.com/madison_resources/downloads/tech_coatingsworld2003.pdf

15 This group of product applications is often referred to as CASE products.

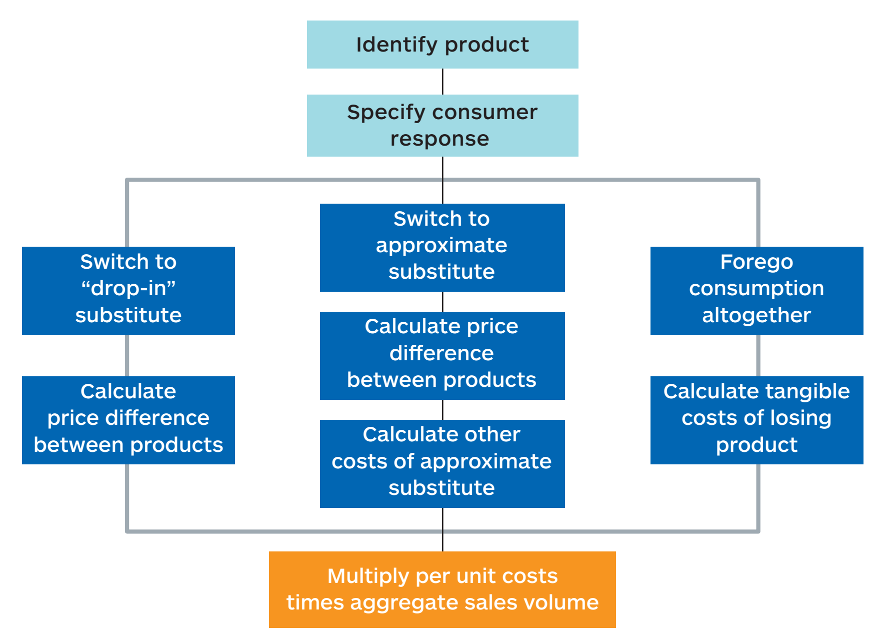
of hydrochloric acid. Numerous attempts have been made to develop non-phosgenation processes to produce aromatic isocyanates, but none have been commercialized due to poor yields and high costs.

For aliphatic isocyanates, technically and economically successful alternatives to the chlorine-based production have been developed. Degussa (formerly Hüls America) has been operating an IPDI plant based on urea since 1996, and BASF operates a hexamethylene diisocyanate (HDI)-IPDI swing plant in Germany using a similar patented phosgene-free process.[16] These routes create bisurea from isophorone diamine, which reacts with alcohol to form biscarbamate and then is cleaved to form IPDI. While raw material costs for these processes may be lower than for chlorine-based ones, they have higher costs of utilities and capital-related fixed costs. More recently in January 2015, Covestro announced the development of a bio-based pentamethylenediisocyanate (PDI), with a 70% content from biomass. Initially the feedstock was a type of corn not intended for human consumption, but the process has been modified to use cellulose or biowaste as raw materials as well.[17] It has been reported that Covestro is expected to begin commercial operations in 2016.[18]

While chlorine-free chemistries have been commercialized for the production of aliphatic isocyanates for some time, chlorine-free chemistries proposed for the production of aromatic isocyanates have not yet been shown to be commercially viable. Therefore, in the absence of chlorine chemistry, consumers would have to substitute alternative materials for 96% of the polyurethane-based products they currently use. The net costs of substituting these alternative materials, which are the economic benefits that chlorine chemistry brings to consumers, are described in the next section.

The economic benefits of chlorine chemistry in polyurethanes

Range of potential consumer responses: Consumer benefits methodology



Source: IHS Energy © 2016 IHS: 60299-5

The benefits of chlorine chemistry to consumers of polyurethanes are determined by the differences in total cost between the products they now enjoy and the substitute materials they would need to use if chlorine-based isocyanates were not available.

Consumers normally select products derived from chlorine-based isocyanates in preference to competing alternatives after consideration of all factors involved in the products' intended uses, not simply the initial product price. This applies to everything from households looking to purchase a comfortable mattress to a business procurement professional selecting a sealant for an automotive windshield. For example, some products may have better physical or mechanical properties than alternatives, have longer service lives, be easier to use directly or to incorporate into other manufactured

16 "Diisocyanates and Polyisocyanates," op. cit.

17 "Bayer MaterialScience develops first coating hardener from biomass." Available at http://www.press.bayer.com/baynews/baynews.nsf/id/Bayer-MaterialScience-develops-first-coating-hardener-from-biomass

18 Ann Thayer, "Greener Routes to Polymers," Chemical & Engineering News, volume 93, issue 4, January 26, 2015. Available at http://cen.acs.org/magazine/93/09304.html

products, have lower maintenance requirements, or provide superior comfort or aesthetics. For the purposes of this analysis, if an alternative to a polyurethane product matched all of these attributes exactly, it would be considered a perfect or "drop in" substitute, and the direct benefit of polyurethane to consumers would simply be the difference in the initial cost of the polyurethane product and the substitute. The difference in the initial price of the products would be due to differences in the costs of the raw materials, plus the costs to convert them into forms the purchaser would actually use. This situation might be approached, for example, if products made from expanded polyethylene or polypropylene (EPE/EPP) or styrene-butadiene rubber (SBR) elastomers were substituted for products made from polyurethane cast elastomers.

Finding perfect substitutes for polyurethane products, or indeed for most products, is usually quite difficult because products made from different materials have different properties and attributes. Therefore, consumers (and procurement specialists) are forced to evaluate all of the properties and attributes of potential substitutes and then decide which among them offers the best overall value given the initial price, expected life, and suitability for the intended use, among other factors. To the extent that a substitute product is deficient in one or more of the properties or attributes, consumers will suffer a loss of utility when employing the substitute. In some cases, the loss of utility is measurable directly, as when a substitute has a shorter service life and must be repurchased more frequently than the polyurethane product. In other cases, it is much more difficult to quantify utility loss. For example, the loss of sleep comfort that occurs when substitutes are used in place of the viscoelastic polyurethane flexible foams in mattresses is very difficult to quantify.

When a polyurethane product is widely used in a particular application, it indicates that products made from other materials are much less desirable – either they have significantly higher costs or their use would involve significant loss of functionality or utility in that application. Identifying substitutes and the costs of substitution in such cases can be quite difficult. When a polyurethane product and products made from other materials have comparable market shares, it is more likely that substitution would be easier, although not necessarily perfect. In these cases, estimating substitution costs can be somewhat easier because there is direct evidence of the total cost differences that drive consumers to choose one product versus another. The total cost differences include not only initial costs, but also replacement and maintenance costs (if applicable), and any losses in utility.

When products made from potential substitute materials that currently do not compete effectively with the polyurethane-based products being evaluated, there is an inadequate history to inform estimates of substitution cost. In these cases, it is necessary to estimate them, considering factors like the cost of the raw materials, the relative amounts of materials that would be required to displace the polyurethane products, the conversion cost to manufacture the product, and the new capital investments that would be required along the entire supply chain. We assume that if new investments are required to produce the substitute material, the required returns on the investments will be passed along to consumers as increases in the price of the substitute materials. This price increase will be passed on to all consumers of the substitute material, not just to those who buy the specific products that are substitutes for polyurethane. Having access to polyurethane-based products eliminates the need to make these additional investments, and thereby provides consumers with derivative benefits in addition to the direct benefits of substitution.

Our estimates of the direct costs of substitution for the various product forms made from chlorine-derived isocyanates are summarized below.

Economic benefits of polyurethanes, 2014

Product form	Isocyanate consumption ('000 MT)	Substitute materials	Consumer benefits ($MM per year)
Rigid foams	554	Fiberglass, EPS; EPE/EPP, polycarbonate structural foam	2,465
Flexible foams	314	SBR and other elastomers, other materials	865
PMDI binders	142	Vinyl acetate emulsions	170
Polyurethane binders	61	SBR and other elastomers	200
Adhesives	73	SBR, other latexes, acrylics	150
Cast elastomers	63	EPP/EPE, SBR and other elastomers	205
Surface coatings	94	Other materials	285
Microcellular products, TPE, and fiber products	53	SBR and other elastomers, EPP/EPE, and other materials	210
Total	**1,354**		**4,550**

Source: IHS

We estimate that the net cost to consumers in the United States and Canada of substituting alternative materials for the chlorine-based polyurethanes currently in use would be $4.6 billion per year, of which $4.1 billion will be borne by US consumers and $0.5 billion by Canadian consumers. Almost half of the costs would arise from the differences between the materials costs of the substitutes and the polyurethanes they would replace, two fifths of the costs would come from the required returns to the new capital that would have to be employed to produce the substitutes, and one tenth of the costs would come from the losses in utility that consumers would experience. Approximately $9.2 billion would have to be invested in new plant and equipment to produce the amounts of substitutes required. Examining this in more detail, we estimate that $8.2 billion in capital spending would be incurred in the US and $1.0 billion in Canada. Avoiding all of these costs is the benefits that the use of chlorine chemistry in the manufacture of isocyanates brings to consumers. In most cases, the potential substitutes shown above are not "drop in" or perfect substitutes since consumers often prefer the polyurethane-containing product, so some loss of utility would be experienced with their use.

Conclusion

Chlorine chemistry is central to the production of most isocyanates, a major component of polyurethane-based products that consumers use every day. By selecting the proper combination of starting materials and processing conditions, manufacturers can produce these versatile polymers in various forms, such as rigid and flexible foams, surface coatings, insulation, adhesives and sealants, elastomers, binders, and fibers. Consumers may be familiar with the use of polyurethanes in products used around the home, such as cushions in furniture and contour-adjusting mattresses, coatings for hardwood floors, and spandex, but may not be familiar with its use in other applications where their exposure is less direct, such as in automotive trim components, adhesives, and as bonding agents in oriented strand board. In the United States and Canada, these industries are quite large, amounting to $7 billion in sales at the wholesale level and much more at the consumer level.

While chlorine-free chemistries have been commercialized for the production of aliphatic isocyanates for some time, chlorine-free chemistries proposed for the production of aromatic isocyanates have not yet been shown to be commercially viable. Therefore, in the absence of chlorine chemistry, consumers would have to substitute alternative materials for 96% of the polyurethane-based products they currently use. Many alternative materials might be selected as substitutes for polyurethanes in its applications, but consumers select the polyurethane-based products because they exhibit the attributes they seek. None of these alternatives can duplicate all of the attributes of polyurethane-containing products; however, so they are not perfect substitutes. Their use would raise costs to consumers because of the need to use materials that have higher life cycle costs or decreased functionality or utility, and significant amounts of new capital would have to be employed to produce them.

We estimate that the net cost to consumers in the United States and Canada for the substitution of alternative materials for the chlorine-based polyurethanes currently in use would be over $4.6 billion per year, and approximately $9.2 billion in new investments would be required. The avoidance of these costs is the benefit that chlorine chemistry in the manufacture of isocyanates brings to consumers. Virtually all the chlorine that is used in the manufacture of these products is recovered as hydrogen chloride and sold for reuse, and amounts to only about 9% of total chlorine consumption.