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Can coatings for foods and beverages: issues and options

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Abstract: Canned foods and beverages constitute a major part of the global food supply. Consumers expect canned foods and beverages to maintain their flavour, texture and colour and be free of illness-causing pathogens. This is generally accomplished by coating can interiors with protective resins. With recent calls for the removal of commonly used epoxy resins, an understanding of the availability, technological feasibility and health profiles of alternative coating options is needed. Some of this information is publicly available but more research and dialogue are needed in order to make informed decisions about coating alternatives' technological feasibility, risks and benefits.

Keywords: can manufacture; resins; can coating; epoxy resin; BPA; bisphenol A; canned foods; canned beverages; options; alternative can coatings; risks; benefits; environmental policy; risk management.

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1 Introduction

Canning – the sealing of foods and beverages in an airtight container with heating to destroy pathogens and inactivate enzymes – is thought to have originated in the early

1800s in response to the French government's call for a way to preserve foods for Napoleon's armed forces (Jackson, 1979). Tinplate (tin-coated iron) cans appeared in the USA in the 1820s and were handmade in advance of crop harvesting season (Ellis, 1979; Robertson, 2006). The first aluminium cans were marketed in the USA in 1958 (Hosford and Duncan, 1994). Currently, canning of foods and beverages in tin-plated steel or aluminium is a workhorse of food preservation and storage because of its relatively low material cost, the speed of production (a relatively small facility can produce 2–3 million cans per day) and durability of the container. Canning is also popular because properly canned foods maintain their taste, texture and colour (Jackson, 1979) and provide food security, i.e. because of the long shelf life of canned foodstuffs, one bad crop year does not result in food shortages. Hermetically sealed cans also keep out insects or other substances that can cause food spoilage, prevent changes in moisture content of the food and protect against food changes due to exposure to light (Ellis, 1979).

The engineering and manufacturing of lightweight cans that maintain structural integrity is a complex process. Technology of can-making is intertwined with the chemistry of can coatings, which are used to protect foods and beverages from the metal surface (preventing degradation of taste) and the metal surface from the foodstuffs (to protect the metal integrity and reduce the risk of food-borne illness and death).

Cans are coated with resins, the components of a liquid that can set into a hard enamel-like finish (Wikipedia, 2012). Natural resins, called oleoresins, are derived from various plants. Synthetic resins solidify in a manner similar to plant resins but are liquid monomers of plastics that cure irreversibly (Wikipedia, 2012). Recent attention has focused on one synthetic resin – epoxy resin – that is commonly used to coat the interior of food and beverage cans, because its foundational building block is bisphenol A (BPA). Widespread human exposure to BPA as well as BPA's potential health effects have been the subject of intense scientific and public scrutiny and debate. Urinary BPA measurements from the National Health and Nutrition Examination Survey have revealed widespread human exposure to BPA (Calafat et al., 2008). BPA has been measured in canned food products (Cao et al., 2010); Carwile et al. (2011) reported a marked increase in urinary BPA levels in students who consumed canned soup for five consecutive days. LaKind and Naiman (2011) found a statistically significant association between urinary BPA levels and soda consumption in the US population. There have been calls for phasing out epoxy resins and requiring the use of alternative can-coating resins.

Unfortunately, there have been many instances where the ban or voluntary removal of a chemical from the market or a specific product has resulted in the use of an alternative chemical with ensuing negative consequences (LaKind and Birnbaum, 2010). Canned foodstuffs are currently an integral part of the international food supply, and the development of alternative can coatings requires a paradigm for making considered choices about such alternatives and avoiding decision-making that will negatively impact public health and safety (LaKind and Birnbaum, 2010). Competing pressures are placed on can manufacturers and all must be balanced when considering changes in can-making technology. First and foremost, cans must protect food and beverages under severe conditions, maintain an airtight seal even under high pressure and prevent changes to food taste, odour, appearance and texture (Page, 2010). They must also be interchangeable to meet the needs of multiple food manufacturers, be resistant to damage during handling, be available at competitive cost (necessitating high-speed production and light weights) and have minimal environmental and health impact (Page, 2010). Ideally, a process or formulation change made to enhance one of these features should not adversely impact another. The US Food and Drug Administration (US FDA) has stated that it will "support changes in food can linings and manufacturing to replace BPA or minimize BPA levels where the changes can be accomplished while still protecting food safety and quality…Reliable can lining materials are a critical factor in ensuring the quality of heat processed foods" (USFDA, 2010a). However, there is minimal readily available information on can coating options and comparisons of those options to inform such evaluations. In this paper, information is provided to introduce the reader to the complexities associated with selection of coating alternatives, the data gaps and need for additional research.

The US Environmental Protection Agency (EPA) Design for the Environment (DfE) programme has developed a process for evaluating chemical alternatives. DfE considers product manufacture, use and disposal with the goal of using of safer chemicals that maintain the desired functionality (Lavoie et al., 2010) while minimising the likelihood of unintended negative consequences. The DfE programme evaluates, among other factors, whether alternatives are commercially available, technologically feasible, the same or better value in cost and performance, have an improved health and environmental profile, and have the potential for lasting change (i.e. the alternative is not likely to be targeted for restrictions shortly after its selection) (Lavoie et al., 2010). In this paper, an overview of can fundamentals is given in Section 2, followed by description of selected DfE factors used here as an organising framework to evaluate can coating alternatives – specifically, technological feasibility and performance characteristics and potential for lasting change (Section 3). Next, commercially available can coating categories are qualitatively ranked (Section 4) using information drawn from the literature, textbooks on resins and from interviews with coating chemists. Issues related to difficulties in developing comparative health profiles and in creating *de novo* can coatings are described in Section 5.

2 What is a can and why is it coated?

While a can may appear to be a simple device, the required engineering precision has been likened to that needed for production of aircraft wings and space vehicles (Hosford and Duncan, 1994). Today's cans are manufactured to be as lightweight as possible (to conserve materials and energy required for shipping) while maintaining structural integrity. Over the last 40 years, advances in can manufacturing engineering have been made in concert with the availability of synthetic resins with properties that differ from those of natural resins. Any discussion of options for can coating materials must therefore begin with a description of how cans themselves are made. Following is a synopsis; for a more detailed description see Page (2010).

2.1 The can

Cans for human foods and beverages are made of aluminium or steel from either two or three metal pieces (with Cu, Mn, Mg, Zn, Si, Cr, Fe and Ti commonly added as alloying elements to aluminium) (Robertson, 2006). Two-piece cans are formed by punching a metal disk into a shallow cup ('drawing'). For taller cans, more than one drawing step is needed and can be followed by stretching or ironing the metal ('drawn and wall-ironed') (Oldring and Nehring, 2007). The lid, made from a separate piece of metal, is attached after the can is filled.

Three-piece cans are made from coated steel (but left uncoated at the site of welding) that is rolled into a cylinder and then welded at the seam, which is protected by an additional side strip of enamel (Robertson, 2006). Next, the bottom is attached, the can is filled and finally the lid is added (Oldring and Nehring, 2007). Ninety-nine percent of metal cans have at least one double seam attaching the end to the can (Theobald and Winder, 2006).

2.2 The filling

Most foods and many beverages are sterilised after placement in the can (Pflug and Esselen, 1979). Cans are filled with foods or beverages that are near boiling for sterilisation (Ellis, 1979) or filled and then heated for pasteurisation. In general, beer and certain beverages undergo a 20–30 min pasteurisation cycle at 140–160 ºF and foods are often cooked in the can at a minimum of 250 ºF and 15 psi steam pressure for up to 90 min (USEPA, 2002).

2.3 The coating

Iron and steel cans were originally coated with tinplate, leading to the misnomer 'tin can' (Ellis, 1979; Brody and Marsh, 1997). Today's steel cans used for light-coloured fruits and fruit juices still employ a tin coating without an additional organic coating; the oxidation of the tin rather than oxidative degradation of the food helps prevent fruit darkening and flavour changes during storage (Blunden and Wallace, 2003).

In cans without organic coatings, tin dissolution provides electrochemical protection to the steel's iron (Coles and Kirwan, 2011). For most foods and beverages, however, contact with tin results in tin corrosion, leading to food contact with the underlying steel. The food or beverage then attacks the steel leading to pitting corrosion and can also result in hydrogen production, can swelling and potential can damage (Ellis, 1979).

In aluminium cans, a thin Al_2O_3 film forms with exposure to air or water (Oldring and Nehring, 2007). While this coating is non-flaking and resistant to chemical dissolution, its solubility increases at both low and high pH and with high NaCl concentrations (Oldring and Nehring, 2007). Once the can is sealed, regeneration of the coating depends on the presence of oxygen in the can, which in general is limited (Ellis, 1979). Without the oxide layer, corrosion of the aluminium occurs. Thus, without an organic coating, aluminium can shelf life is inadequate (Ellis, 1979).

So for both steel and aluminium cans, an additional organic coating is needed. Early organic can coatings were made from china wood oil and natural resins (Ellis, 1979). Synthetic resins, developed beginning in the 1940s, provided more flexibility in meeting technological requirements for high-speed manufacturing and for contact with varying foods and drinks (Ellis, 1979). With most three-piece and two-piece drawn-and-redrawn food and beverage cans, the coating is applied to the metal prior to can fabrication and then cured either by heat or ultraviolet radiation (USEPA, 2002; Robertson, 2006); coating is applied after fabrication for drawn and ironed cans. During the curing process, most currently used resins react with cross-linking agents to form a three-dimensional cross-linked network that provides the corrosion resistance and flexibility of the film

(Oldring and Nehring, 2007). This coating acts not only as a sealant but also as a lubricant, without which the high-speed can fabrication process (line speeds of hundreds of cans per minute) would produce rapid wearing of the can-making equipment. After can fabrication, additional coatings may be applied and heat-cured to ensure that any flaws in the metal are completely covered (USEPA, 2002).

During can manufacture, the metal is subjected to stresses including those that alter the cylindrical can shape (e.g. flanging for attachment of can ends) and ones that increase the axial and panel strength of the can (e.g. beading which produces the ridges encircling the can) (Brody and Marsh, 1997; USEPA, 2002). In addition, the neck of the cylinder is thinned to decrease the size of the lid (Robertson, 2006) and the can headspace. Coatings applied prior to manufacture must be able to withstand these processes. Even for can types that permit coating application after can formation, the coating must still withstand further deformations required to finish the can production (Oldring and Nehring, 2007).

Coatings must provide can integrity and preserve food flavour and appearance in order to be acceptable to can manufacturers, food manufacturers and consumers.

Can integrity: The key function of the coating is to ensure that the food or beverage does not corrode the metal, allowing for entry of microbes. Due to consumer expectation of long shelf life, coatings must be formulated to protect the consumer against microbial food sickness for many years. The coating should be tough enough to protect the can's integrity if it is bent or dinged. Can coatings must survive can manufacture and ambient and food processing conditions (e.g. physical handling, temperature changes) without degradation or peeling off the metal substrate (Page, 2010).

Taste and odour: Interactions between foods and beverages and the can metal may alter the product's taste, rendering it unpalatable to the consumer. For example, a poorly coated steel beer can results in beer–metal interaction, giving the beer a metallic flavour (Robertson, 2006). While organoleptic issues may seem secondary, off-flavours can gives the consumer a sense of feeling sick, and can affect the entire supply chain from the supermarket to the packaging suppliers (Huber et al., 2002). In Europe, food contact materials cannot transfer to food in an amount that causes either organoleptic issues or 'unacceptable compositional change of the food' with violations resulting in penalties, fines and risk of legal liability (Huber et al., 2002).

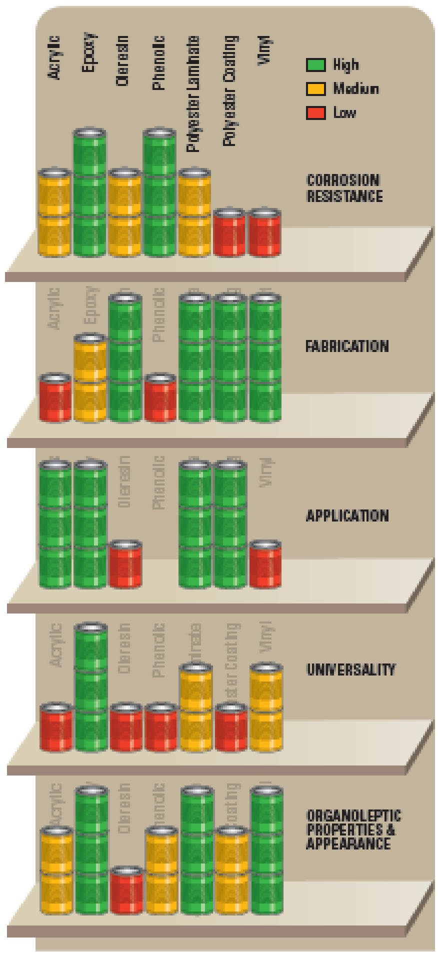
Appearance: Coatings are applied to improve the visual appearance of both the can and the product (Ellis, 1979). Coatings are also used to prevent interaction between sulphur compounds in the foods and beverages (from proteins, preservatives or pesticide residues) and the metal substrate, leading to formation of iron sulphide or tin sulphide staining, which is objectionable to consumers (Robertson, 2006). In addition, aluminium beer can coatings protect the beer from low levels of Al that produce unacceptable cloudiness (Robertson, 2006).

3 Commercially available resin types: a framework for comparison

Several can coating resin types are commercially available, including oleo-resinous compounds (natural oil-based coatings derived from fossil gums) and synthetic resins (acrylic, epoxy, phenolic, polyester and vinyl resins). Each resin can be produced from multiple starting materials (natural substances or monomers) and the final polymer is typically blended to achieve the desired attributes suited for each can/filling combination. Resin blends are identified by their hyphenated name (e.g. epoxy-amino), with the second resin ranging in concentration from a few percent up to 50%. Other agents are often added to create desired properties (e.g. coatings are made white with a dispersion of TiO_2; releasing agents are added to coatings to enhance removal of meats and fish from cans; Ellis, 1979).

In this evaluation, the following properties of commercially available can coating resins are compared (Figure 1): technological feasibility (corrosion resistance, fabrication, application and universality), and consumer acceptance (organoleptic properties and appearance). Comparison of the health profile of the resins will ultimately be a critical component of a complete evaluation, but for reasons described in Section 5, a comparative health profile is not included here.

Figure 1 Qualitative rankings (high – green, medium – yellow, low – red) of major resin types in terms of technologic feasibility and consumer acceptance (see online version for colours)



Sources: Image concept: Joshua Naiman; design: Jeff Aiken Creative Direction LLC)

3.1 Technological feasibility

Four overarching concepts must be considered when comparing technological feasibility of resin types: corrosion resistance, fabrication, application and universality.

Corrosion resistance (CR): Coating resistance to corrosion is critical for food safety. A coating's effectiveness is related to its impermeability to gases, liquids and ions (Robertson, 2006). Each food and beverage has an inherent intensity and type of corrosiveness, as do processing and storage environments (Robertson, 2006). Corrosion resistance is evaluated by can manufacturers using pack tests: coated cans are filled with the product and kept for periods of time equal to and exceeding the expected shelf life of the product (Page, 2010). Over the course of the shelf-life time period, successive cans are opened and examined for coating removal and presence of corrosion as well as changes in appearance and flavour of food or beverage and changes in appearance to the can such as staining (Page, 2010). Because expected shelf life can exceed two years, pack tests times are lengthy. Methods for accelerating shelf-life testing such as increasing the storage temperature have been used (Page, 2010) but problems with accelerated tests have been reported (Mizrahi, 2000). Coatings are also evaluated with an abuse test, in which a coated can is filled with an aggressive product, sealed, damaged near the seam and then exposed to a bath of water containing pathogens; if the coating is not sufficiently durable, pathogens will enter the can and cause the can to blow (Page, 2010). The aggressiveness of foods and beverages is characterised based on experience with how these products interact with a given can coating formulation. Aggressiveness is important because a product that attacks the coating and reaches the metal substrate enables the onset of corrosion. For example, celery, rhubarb and tomato concentrate are generally considered aggressive, whereas apricots and beans are low-aggressive foods (Szefer and Nriagu, 2007; Coles and Kirwan, 2011).

Fabrication (F): Fabrication is the mechanical process of can formation. Coatings must withstand fabrication without fracturing or flaking via a combination of flexibility and toughness, defined by Koleske (2000) as:

> Flexibility is the ability of a coating to be bent or flexed in forming operations without cracking, losing adhesion, or failing in some other manner. Toughness is the ability of a coating to withstand large stress forces imposed over a short time without cracking, rupturing, shattering, or tearing.

Application (A): A resin with good application properties is easy to use and adheres strongly to the metal substrate. If the bond between the coating and the metal substrate is compromised due to poor adhesion, the coating can lift off the can interior causing anodic reactions between the food/beverage and the metal, leading to can failure (Robertson, 2006).

Universality (U): Foods and beverages have a wide range of chemical characteristics that influence their corrosivity and contain many compounds that accelerate corrosion (e.g. O_2, anthocyanin pigments, synthetic colouring, nitrates, sulphur compounds, trimethylamines) (Robertson, 2006). It is economically advantageous to manufacture a multi-purpose can type appropriate for as many foods and beverages as possible. A resin that functions well with a wide range of food and beverage types has high universality.

3.2 Consumer acceptance

A coating that does not adversely impact the organoleptic properties or appearance of the food or beverage will have higher consumer acceptance (CA).

4 How do the major classes of commercially available resins stack up?

Each major resin type is discussed below in terms of technologic feasibility and consumer acceptance and qualitatively ranked for each factor (high – green, medium – yellow, low – red; see Figure 1). The rankings are designated below by the factor abbreviation (e.g. CR = corrosion resistance) and the rank (e.g. CR:low).

Acrylic: For non-food applications, acrylics are highly corrosion-resistant (Brendley and Haag, 1973); however, for food contact, acrylics can only be derived from FDA-approved monomers that provide less corrosion resistance (CR:medium). Acrylics are too brittle to withstand can fabrication, especially the process for drawn cans (F:low). Acrylics are easily applied as a spray (A:high). The predominant monomer used for the production of acrylic resins is ethylacrylate, which has an extremely low threshold for odour detection (2×10^{-4} parts per million) (Fazzalarai, 1978). Thus, acrylic resins are used principally for external can coatings (U:low for internal can coatings). Acrylic resins retain their colour, but another of the major starting monomers (styrene) imparts flavours in some foods (Robertson, 2006) and as noted above ethylacrylate has a low odour threshold (CA:medium).

Epoxy: The use of epoxy coatings in can manufacturing began in the 1950s. The resins are produced by condensation of epichlorohydrin and bisphenol A, yielding bisphenol A diglycidyl ethers (Robertson, 2006). Compared to the oleoresins that preceded the use of epoxies, epoxy resins provided substantially greater flexibility. At present, epoxy-based resins are the most widely used polymers for coating aluminium and steel cans. The North American Metal Packaging Alliance (NAMPA) has estimated that 95% of food contact can coatings are epoxy type. Only a very small percentage of epoxy resins do not use BPA as the starting monomer (< 0.1% of epoxy resins are based on bisphenol F and are used only as thermal stabilisers for polyvinyl chloride [PVC] vinyls).

Epoxy-based resins are strong and flexible and have excellent chemical resistance (Robertson, 2006; NRCC, 1966) (CR:high). Epoxies are compatible with more food and beverage types than other currently available resins (U:high). They adhere well to metal substrates and are thus used as a base coat for acrylic and vinyl coatings (Robertson, 2006) (A:high). Despite the excellent mechanical properties of epoxy resins (Robertson, 2006; NRCC, 1966), when used alone (i.e. unblended) they fail during fabrication of drawn-and-redrawn two-piece food cans (F:medium). Epoxy resins do not impart flavour to foods (Barrett et al., 2005) and many epoxy resins are non-yellowing, retaining their appearance (CA:high).

Oleoresins: Oleoresins are derived from fusing natural gums and rosins and then blending them with drying oils (e.g. linseed or tung oil) (Robertson, 2006). Prior to 1965, oleoresins were the only coatings used in cans but they fell out of favour decades ago and had limited uses (Oldring and Nehring, 2007) until recently when the controversy over epoxy resins resulted in increased use. Oleoresins are used primarily for fruit drinks, fruits and vegetables (Robertson, 2006).

Oleoresins have an open micellar structure making them prone to corrosion (Robertson, 2006) (CR:medium). They are able to withstand the fabrication process (F:high) but adhere poorly to the metal substrate and require long curing times (10–15 min) that are not well-suited to modern high-speed can manufacturing (A:low). Because of poor corrosion resistance, oleoresin use is limited to non-aggressive foods (e.g. dried beans) and cannot be used in drawn-redrawn cans (Robertson, 2006) (U:low). The micellar structure also results in staining problems with sulphur-containing foods unless the oleoresin is combined with zinc oxide (Robertson, 2006). Oleoresins do not retain colour, and tend to impart taste to foods (Robertson, 2006; Oldring and Nehring, 2007) (CA:low).

Phenolic: Phenolic resins are produced by the condensation of one or more phenols with one or more aldehydes (Oldring and Nehring, 2007). They are highly corrosion-resistant (CR:high), but have limited uses due to their poor flexibility (U:low) (Oldring and Nehring, 2007). Their brittleness makes them ill-suited for high-speed fabrication processes (F:low). Phenolics are often used as a cross-linker in blends with other resins to improve resistance to sulphur staining (for example, with meats and fish) and enhance corrosion resistance for very aggressive foods (Oldring and Nehring, 2007), but their percentage in blends is low and application properties cannot be ranked. They impart flavour and odour to some foods (Robertson, 2006) (CA:medium).

Polyester: Polyester resins are produced by condensing an acid with one or more alcohols or epoxides (Robertson, 2006) followed by copolymerisation with one or more cross-linking agents (USFDA, 2010b). Polyester resins fail with aggressive or acidic foods (Oldring and Nehring, 2007) due to hydrolytic attack of the ester bond under low pH conditions (CR:low). Polyester resins range from extremely hard to extremely flexible (Parkyn et al., 1967) depending on the resins with which they are blended (Oldring and Nehring, 2007). Flexible polyester resins excel at withstanding the fabrication process (F:high) and are easy to apply (A:high). However, due to their poor corrosion resistance, they have limited use (U:low). Polyester does not impart taste or odour to foods and beverages (Stoye and Freitag, 1998) but does have ‘scalping’ properties, i.e. it absorbs flavours from a small number of foods and beverages (CA:medium).

It has been suggested that polyester resin could serve as a safer alternative to epoxy coatings based on its ‘successful’ use for can interiors in Japan since the 1990s (Breast Cancer Fund, 2010). A distinction must be made, however, between polyester coatings and the polyester material used in Japan (Hanlon et al., 1998), which is actually the laminate material polyethylene terephthalate (PET), a polyester produced by reacting ethylene glycol with dimethyl terephthalate (Robertson, 2006). In laminate application, PET film is laid over a metal-coating adhesive which is sometimes BPA-based. After the film is applied, the metal is formed into a can with the PET film stretching to the can’s shape. These cans are used in Japan for beverage cans and vending machine hot teas and coffees and in North America for canned salmon, a non-aggressive food. Its greater thickness gives PET laminate improved corrosion resistance compared to polyester resin

(CR:medium). Laminate coatings are compatible with two-piece drawn can technology and some three-piece beverage cans where the seam is sealed with adhesive (F:high). However, laminates cannot be used for welded three-piece cans because welding the seam (with temperatures exceeding 400º F) chars and destroys the laminate (U:medium). Laminates are readily applied (A:high) and have similar taste and odour properties as polyester resin, but PET has low flavour-absorbing characteristics (Turner, 2001) (CA:high).

Vinyl: Vinyl resins are often blended with alkyd, epoxy and phenolic resins to improve their performance (Robertson, 2006). Unblended vinyl resin is not corrosion resistant (CR:low) but is flexible (Robertson, 2006) and readily withstands can fabrication (F:high). With one exception described below, vinyl resins are not applied directly to the metal substrate but are instead applied over an underlying epoxy coating (a two-coat system). Without the underlying coat, they adhere poorly to the metal substrate (A:low). In addition, they are unable to withstand the retorting process with many food types and are mostly used with cans that are hot-filled for high acid foods (U:medium). Vinyl resins do not impart taste to foods or beverages (Barrett et al., 2005; Robertson, 2006) (CA:high).

Vinyl organosol coatings – the white or buff-coloured coatings found in some two-piece food cans (e.g. canned fish) – can be used without a two-coat system. Organosol is a dispersion of high molecular weight PVC resin in a hydrocarbon solvent, which when combined with other resins such as epoxy yield a coating with improved chemical resistance, thermal stability, and adhesion (Robertson, 2006).

5 Is there a ‘best’ coating for cans?

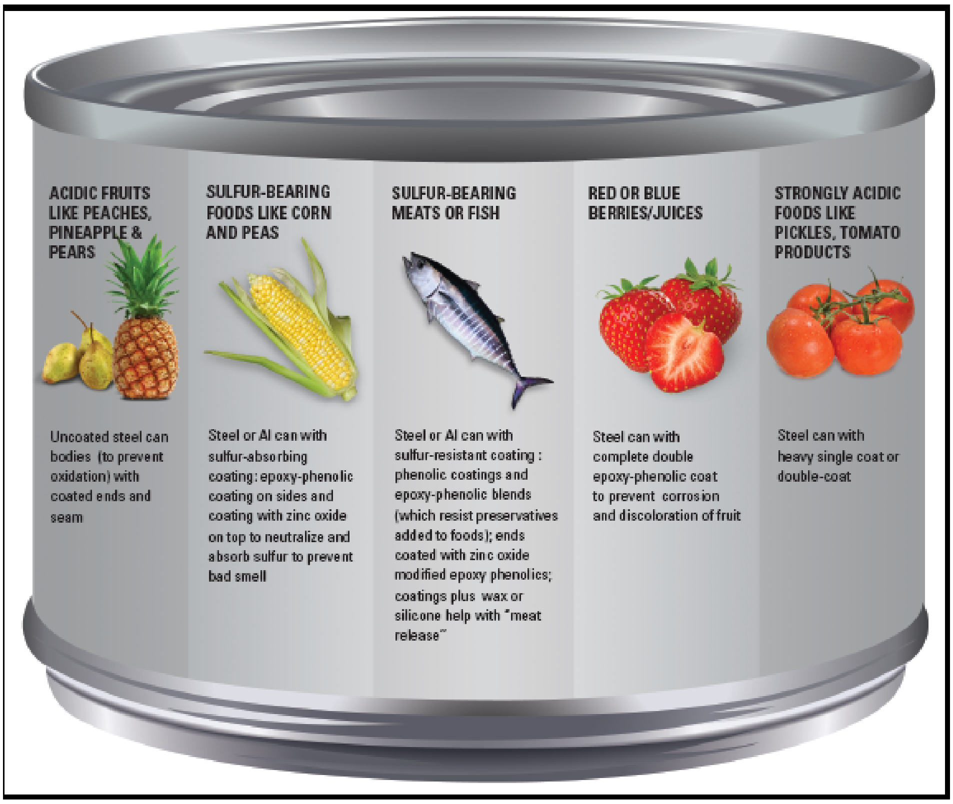
As we no longer live in a world where people rely on local, seasonal foods for year-round consumption, some form of packaging that maintains food quality and safety with a long shelf life is required. Plastic and glass are options, although even lids on glass packaging use polymeric coatings (Petersen and Jensen, 2010). It has been estimated that 70–80% of foods are packaged in materials made of polymers (Sheftel, 2000). Given the importance of canned foods and beverages to the international food supply for food safety, long-term food storage, and cost effectiveness, it is likely that canned foods and beverages will be with us for many years. For almost all foods and beverages, uncoated cans are not an option as the risk of can leakage and related food poisoning is too great.

The qualitative rankings derived in this exercise indicate that no one type of resin has all of the desired attributes (Figure 1). It is hoped that these rankings will be buttressed by new information as it becomes available. In the meantime, what about new coating formulations? Each new food/beverage/coating/processing combination must be tested to ensure that it can withstand fabrication and processing and also be tested using real-world simulations to determine the effect of shelf life on product quality, nutritional value and flavour (Robertson, 2006). For example, biobased, BPA-free epoxy coatings are under development but will require additional research to improve thermomechanical properties (C&EN News, 2011). With any new coating/product combination, failure mechanisms are not fully understood until chemical interactions between food and coating are tested.

The formulation must also undergo migration and toxicity testing to obtain approval for use by the FDA. Development of a new coating typically takes 1–3 years, the testing period lasts for an additional 2–3 years, and up to two years are needed for commercialisation. If entirely new types of resins are introduced, can-making technology will need to evolve as can manufacturing and can-coating technologies are intertwined.

As is clear from this overview of can coatings, no single commercially available resin type is suitable for all foods and beverages. In fact, resins are typically blended to maximise each attribute according to specific food and beverage properties (Figure 2). Calls for replacing a commonly used resin type approved for food contact raise an important question that adds another layer on top of the technological complexities: what is the best process for determining whether a new resin or resin blend is safe for food contact use?

Figure 2 Can coating complexities (Robertson, 2006; Oldring and Nehring, 2007): No single resin is compatible with all food types (see online version for colours)



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EPA has noted the importance of an improved health profile when evaluating chemical alternatives (Lavoie et al., 2010). However, conducting a comparative health evaluation for can coatings is extremely complicated due to the large numbers of monomers, polymers and copolymers approved for food contact. One cannot simply evaluate the final polymer as it may be formulated from more than one monomer or natural substance. In addition, a specific resin type may be used in a copolymer formulation. Finally, coating formulations include additives such as plasticisers, antioxidants, catalysts, stabilisers, hardeners, and pigments (Sheftel, 2000). Should the health profile be based on the monomer(s) used to develop the polymer or on the final formulation? The European Union Commission lists approximately 3000 components that have the potential to migrate into foods and beverages (Sheftel, 2000) and according to NAMPA, the can-manufacturing industry supports over 1700 can coating specifications. Thus, health profiles would need to be developed for hundreds or perhaps thousands of chemicals or mixtures.

While development of comparative health profiles for all possible monomers or coating formulations is outside the scope of this review, it is worth summarising how human health risks from exposure to can coatings are currently assessed in the USA. Polymeric ingredients with the potential to migrate into foods and beverages are regulated as indirect food additives under Parts 175–179 (Volume 21) of the Code of Federal Regulations and industry must demonstrate that the ingredients are safe for intended uses (Sheftel, 2000). For each polymer, a determination must be made regarding migration potential of the main components of the polymers. Depending on the amount of migration, an estimate is made of the expected amount of human daily intake. This in turn determines the type and amount of toxicity testing required (Petersen et al., 2008). Components with acceptable toxicity testing may be used in formulations for food contact. This current approach has been unsatisfactory to those who believe that risks associated with the monomer BPA have not been fully assessed and that cans coated with epoxy resins are harmful to human health. The DfE (Lavoie et al., 2010) approach utilises hazard assessment rather than a risk-based approach (which incorporates extent of human exposure); the assumption in the DfE process is that for the chemical alternatives with same functional use and application, human exposures are roughly equivalent. However, migration potential (i.e. exposure) may vary considerably according to the extent of migration of the monomer in a specific product so any comparative assessment would need to consider this aspect of coating formulations.

All coatings, whether derived from natural or synthetic chemicals, contain constituents that may migrate into foods and beverages. Given the complexity and length of time required to develop and test new coating formulations that possess the appropriate and necessary characteristics (technological feasibility and consumer acceptance), a consistent, systematic and lasting approach towards evaluation of human exposures to can coatings and potential associated health risks is needed to encourage new formulation development.

While this review focused on important technological aspects of the most commonly used can coatings for foods and beverages and noted the complexities associated with developing comparative health profiles, there are also several other aspects of can coatings that warrant evaluation (Table 1). Research and open dialogue on all of these issues are needed in order to ensure that foods and beverages packaged in cans will be safe over the desired shelf life of the product and that newly developed alternatives have the potential for lasting change. It is hoped that the information provided here will inform discussions among policy-makers, scientists and others and prompt additional needed dialogue and research.

Table 1 Comparisons of technological aspects of the more commonly used can coating types. Additional aspects of can coatings – chemical, technological, toxicological, policy-related – that warrant in-depth assessments are shown here. References to introduce the reader to these topics are provided

Topic	*Reference*
Chemical	
Chemicals such as solvents, pigments and cross-linking agents in can-coating formulations	Brody and Marsh (1997)
Evaluations of both parent compounds and transformation products in coating formulations	Petersen et al. (2008)
Chemicals used in coatings for seals, lids and caps	Theobald and Winder (2006); Gavin and Weddig (1995)
Technological	
Variations in coating formulations necessary for different cooking and retorting processes	Gavin and Wedding (1995)
Toxicological	
Other coating chemicals that have been the focus of environmental concern (e.g. BADGE)	Cao et al. (2009)
Consumer exposures (migration)/risks from coating compounds	Crosby (1981)
Toxicological evaluations and comparisons of mixtures in a wide array of formulations	Cassee et al. (1998)
Policy	
Risk assessment versus precautionary principle in developing new can coatings	Kriebel et al. (2001); Glickman and Gough (1990)
Differences in international policies and recommendations	EFSA (2011); Le Point (2011)

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References

Barrett, D.M., Somogyi, L.P. and Ramaswamy, H.S. (Eds) (2005) *Processing Fruits: Science and Technology*, CRC Press, Boca Raton, FL.

Blunden, S. and Wallace, T. (2003) 'Tin in canned food: a review and understanding of occurrence and effect', *Food and Chemical Toxicology*, Vol. 41, pp.1651–1662.

Breast Cancer Fund (2010) *Safer Alternatives to Bisphenol A (BPA)*. Available online at: http://www.calwic.org/storage/documents/state/2010/bpa_alternatives.pdf (accessed on 3 February 2012).

Brendley, W.H. and Haag, T.H. (1973) 'Physical characterization of water dispersed and soluble acrylic polymers', in Gardon, J.L. and Prane, J.W. (Eds): *Nonpolluting Coating and Coating Processes*, Plenum Press, New York, pp.5–24.

Brody, A.L. and Marsh, K.S. (1997) *The Wiley Encyclopedia of Packaging Technology*, 2nd ed., John Wiley & Sons, Inc., New York.

Calafat, A.M., Ye, X., Wong, L.Y., Reidy, J.A. and Needham, L.L. (2008) 'Exposure of the U.S. population to bisphenol A and 4-tertiary-octylphenol: 2003–2004', *Environmental Health Perspectives*, Vol. 116, No. 1, pp.39–44.

Cao, X.L., Corriveau, J. and Popovic, S. (2010) 'Bisphenol A in canned food products from Canadian markets', *Journal of Food Protection*, Vol. 73, No. 6, pp.1085–1089.

Cao, X.L., Dufresne, G., Clement, G., Bélisle, S., Robichaud, A. and Beraldin, F. (2009) 'Levels of bisphenol A diglycidyl ether (BADGE) and bisphenol F diglycidyl ether (BFDGE) in canned liquid infant formula products in Canada and dietary intake estimates', *Journal of AOAC International*, Vol. 92, No. 6, pp.1780–1789.

Carwile, J.L., Ye, X., Zhou, X., Calafat, A.M. and Michels, K.B. (2011) 'Canned soup consumption and urinary bisphenol A: a randomized crossover trial', *JAMA*, Vol. 306, No. 20, pp.2218–2220.

Cassee, F.R., Groten, J.P., van Bladeren, P.J. and Feron, V.J. (1998) 'Toxicological evaluation and risk assessment of chemical mixtures', *Critical Reviews in Toxicology*, Vol. 28, No. 1, pp.73–101.

C&EN News (2011) Biobased BPA-free epoxies, *C&EN News*, 5 September, p.54.

Coles, R. and Kirwan, M.J. (Eds) (2011) *Food and Beverage Packaging Technology*, 2nd ed., John Wiley and Sons Ltd, UK.

Crosby, N.T. (1981) *Food Packaging Materials: Aspects of Analysis and Migration of Contaminants*, Applied Science Publishers, Essex, England.

EFSA (European Food Safety Authority) (2011) *Bisphenol A*. Available online at: http://www.efsa.europa.eu/en/topics/topic/bisphenol.htm (accessed on 3 February 2012).

Ellis, R.F. (1979) 'Rigid metal containers', in Jackson, J.M. and Shinn, B.M. (Eds): *Fundamentals of Food Canning Technology*, AVI Publishing Company, Westport, CT, pp.95–122.

Fazzalarai, F.A. (Ed.) (1978) *Compilation of Odor and Taste Threshold Values Data*, American Society for Testing and Materials, DS 48A, ASTM, Baltimore, MD.

Gavin, A. and Weddig, L.M. (Eds) (1995) *Canned Foods: Principles of Thermal Process Control, Acidification and Container Closure Evaluation*, The Food Processors Institute, Washington, DC.

Glickman, T.S. and Gough, M. (1990) *Readings in Risk*, Resources for the Future, USA.

Hanlon, J., Kelsey, R. and Forcinio, H. (1998) *Handbook of Package Engineering*, 3rd ed., Technomic Publishing Company, Inc., Lancaster, PA.

Hosford, W.F. and Duncan, J.L. (1994, September) 'The aluminum beverage can', *Scientific American*, pp.48–53.

Huber, M., Ruiz, J. and Chastellain, F. (2002) 'Off-flavour release from packaging materials and its prevention: a foods company's approach', *Food Additives & Contaminants*, Vol. 19, pp.221–228.

Jackson, J.M. (1979) 'Development of the canning industry', in Jackson, J.M. and Shinn, B.M. (Eds): *Fundamentals of Food Canning Technology*, AVI Publishing Company, Westport, CT, pp.1–9.

Koleske, J.V. (2000) *Mechanical Properties of Solid Coatings*, Wiley, Charleston, USA. Available online at: http://www.wiley.com/legacy/wileychi/eac/pdf/A0608-W.PDF (accessed on 3 February 2012).

Kriebel, D., Tickner, J., Epstein, P., Lemons, J., Levins, R., Loechler, E.L., Quinn, M., Rudel, R., Schettler, T. and Stoto, M. (2001) 'The precautionary principle in environmental science', *Environmental Health Perspectives*, Vol. 109, No. 9, pp.871–876.

LaKind, J.S. and Birnbaum, L.S. (2010) 'Out of the frying pan and out of the fire: the indispensable role of exposure science in avoiding risks from replacement chemicals', *Journal of Exposure Science and Environmental Epidemiology*, Vol. 20, No. 2, pp.115–116.

LaKind, J.S. and Naiman, D.Q. (2011) 'Daily intake of bisphenol A (BPA) and potential sources of exposure – 2005–2006 NHANES', *Journal of Exposure Science and Environmental Epidemiology*, Vol. 21, pp.272–279.

Lavoie, E.T., Heine, L.G., Holder, H., Rossi, M.S., Lee, R.E., Connor, E.A., Vrabel, M.A., Difiore, D.M. and Davies, C.L. (2010) 'Chemical alternatives assessment: enabling substitution to safer chemicals', *Environmental Science & Technology*, Vol. 44, No. 24, pp.9244–9249.

Le Point. fr (2011) *L'Assemblée unanime interdit les contenants alimentaires avec du bisphénol A*. Available online at: http://www.lepoint.fr/politique/l-assemblee-unanime-interdit-les-contenants-alimentaires-avec-du-bisphenol-a-12-10-2011-1383798_20.php (accessed on 3 February 2012).

Mizrahi, S. (2000) 'Accelerated shelf-life tests', in Kilcast, D. and Subramaniam, P. (Eds): *The Stability and Shelf-life of Food*, Woodhead Publishing Limited, Cornwall, England, pp.107–128.

NRCC (National Research Council Canada) (1966) *CBD-79. New Organic Coatings*, Canadian Building Digests. Available online at: http://www.nrc-cnrc.gc.ca/eng/ibp/irc/cbd/building-digest-79.html (accessed on 3 February 2012).

Oldring, P.K.T. and Nehring, U. (2007) 'Metal packaging for foodstuffs', *Packaging Materials*, ILSI (International Life Sciences Institute), Belgium, pp.1–40.

Page, B. (2010) *Metal Packaging*, 2nd ed., Pira International Ltd., Surry, UK.

Parkyn, B., Lamb, F. and Clifton, B.V. (1967) *Polyesters, Volume 2. Unsaturated Polyesters and Polyester Plasticizers*, American Elsevier Publishing Company, New York.

Petersen, J.H. and Jensen, L.K. (2010) 'Phthalates and food-contact materials: enforcing the 2008 European Union plastics legislation', *Food Additives & Contaminants: Part A: Chemistry, Analysis, Control, Exposure & Risk Assessment*, Vol. 27, No. 11, pp.1608–1616.

Petersen, H., Biereichel, A., Burseg, K., Simat, T.J. and Steinhart, H. (2008) 'Bisphenol A diglycidyl ether (BADGE) migrating from packaging material 'disappears' in food: reaction with food components', *Food Additives & Contaminants: Part A: Chemistry, Analysis, Control, Exposure & Risk Assessment*, Vol. 25, No. 7, pp.911–920.

Pflug, I.J. and Esselen, W.B. (1979) 'Heat sterilization', in Jackson, J.M. and Shinn, B.M. (Eds): *Fundamentals of Food Canning Technology*, AVI Publishing Company, Westport, CT, pp.10–94.

Robertson, G.L. (2006) *Food Packaging: Principles and Practice*, Taylor & Francis, Boca Raton, FL.

Sheftel, V.O. (2000) *Indirect Food Additives and Polymers: Migration and Toxicology*, Lewis Publishers, Boca Raton, FL.

Stoye, D. and Freitag, W. (Eds) (1998) *Paints, Coatings and Solvents*, 2nd ed., Wiley-VCH, Germany.

Szefer, P. and Nriagu, J.O. (Eds) (2007) *Food and Beverage Packaging Technology; Mineral Components in Foods*, CRC Press, Boca Raton, FL.

Theobald, N. and Winder, B. (Eds) (2006) *Packaging Closures and Sealing Systems*, Blackwell Publishing Ltd., UK.

Turner, T.A. (2001) *Canmaking for Can Fillers*, Sheffield Academic Press Ltd., England.

USEPA (US Environmental Protection Agency) (2002, November) *National Emission Standards for Hazardous Air Pollutants (NESHAP) for Source Category: Surface Coating of Metal Cans: Background Information for Proposed Standards EPA-453/R-02-008*, Office of Air Quality Planning and Standards, Emission Standards Division Research Triangle Park, North Carolina. Available online at: http://nepis.epa.gov/Adobe/PDF/P1008FRH.PDF (accessed on 3 February 2012).

USFDA (US Food and Drug Administration) (2002) *Guidance for Industry: Preparation of Food Contact Notifications for Food Contact Substances: Toxicology Recommendations*. Available online at: http://www.fda.gov/Food/GuidanceComplianceRegulatoryInformation/GuidanceDocuments/FoodIngredientsandPackaging/ucm081825.htm#iva (accessed on 3 February 2012).

USFDA (US Food and Drug Administration) (2010a) *Update on Bisphenol A: Use in Food Contact Applications*. Available online at: http://www.fda.gov/newsevents/publichealthfocus/ucm197739.htm (accessed on 3 February 2012).

USFDA (US Food and Drug Administration) (2010b) *Code of Federal Regulations Title 21*, Department of Health and Human Services, Subchapter B – Food for Human Consumption. Available online at: http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=177.2420 (accessed on 3 February 2012).

Wikipedia (2012) *Resin*. Available online at: http://en.wikipedia.org/wiki/Resin (accessed on 3 February 2012).