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Guidance for Industry

Acrylamide in Foods

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Office of Food Safety, HFS-300
Center for Food Safety and Applied Nutrition
Food and Drug Administration
5001 Campus Drive
College Park, MD 20740
(Tel) 240-402-1700
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U.S. Department of Health and Human Services
Food and Drug Administration
Center for Food Safety and Applied Nutrition

March 2016

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Guidance for Industry¹ Acrylamide in Foods

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I. Introduction

This guidance provides information to help growers, manufacturers, and food service operators reduce acrylamide levels in certain foods. Acrylamide is a chemical that can form in some foods during certain types of high-temperature cooking. Reducing acrylamide levels in foods may mitigate potential human health risks from exposure to acrylamide. This guidance is intended to suggest a range of possible approaches to reducing acrylamide levels and not to identify specific recommended approaches. This guidance also does not identify any specific maximum recommended level or action level for acrylamide. The Food and Drug Administration (FDA or “we”) will update this guidance as needed to reflect new developments in the field of acrylamide reduction.

FDA’s guidance documents, including this guidance, do not establish legally enforceable responsibilities. Instead, guidances describe our current thinking on a topic and should be viewed only as recommendations, unless specific regulatory or statutory requirements are cited. The use of the word *should* in FDA guidances means that something is suggested or recommended, but not required.

II. Background

In 2002, scientists announced the discovery of the chemical acrylamide in a variety of heated foods (Ref. 1). Further research determined that acrylamide forms in some foods during certain types of high-temperature cooking (Refs. 2-3). Acrylamide in food is a concern because it can cause cancer in laboratory animals at high doses, and is “reasonably anticipated to be a human carcinogen” (Ref. 4)². In 2010, an international evaluation of

¹ This guidance has been prepared by the Division of Plant Products and Beverages, Office of Food Safety, in the Center for Food Safety and Applied Nutrition at the U.S. Food and Drug Administration.

² The complete quotation is “Acrylamide is *reasonably anticipated to be a human carcinogen* based on sufficient evidence of carcinogenicity from studies in experimental animals” (Ref. 4). The NTP classifies a

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acrylamide by the WHO/FAO Joint Expert Committee on Food Additives (JECFA) (Ref. 5) concluded that acrylamide may be “a human health concern.”³ JECFA’s work was based in part on studies conducted by the FDA National Center for Toxicological Research for the National Toxicology Program (Ref. 6).

Acrylamide forms in foods from a chemical reaction between asparagine, an amino acid, and reducing sugars such as glucose and fructose. This reaction is part of the Maillard reaction, which leads to color, flavor, and aroma changes in cooked foods (Refs. 2-3, 7). Acrylamide formation usually occurs at elevated temperatures used when frying or baking (above 120 °C (248 °F)) and in low moisture conditions, although acrylamide has also been identified in some fruit and vegetable products heated at lower temperatures or higher moisture conditions (Refs. 8-11). Also, acrylamide formation occurs primarily in plant-based foods, notably potato products such as french fries and potato chips; cereal- grain-based foods such as cookies, crackers, breakfast cereals, and toasted bread; and coffee. Acrylamide is also found in cigarette smoke and is produced industrially for use in products such as plastics, grouts, water treatment products, and cosmetics.

Since the discovery of acrylamide in food, the international research community has explored numerous strategies for reducing acrylamide in food products. This work is summarized in the scientific literature (Refs. 12-29), as well as in guidance materials prepared by industry, other governments, and international organizations. Notable guidance materials include the “Acrylamide Toolbox” produced by FoodDrinkEurope (Ref. 30) and the Codex Alimentarius “Code of Practice for the Reduction of Acrylamide in Foods” (Ref. 31). Other guidance documents include FoodDrinkEurope Toolbox brochures on selected foods for small- and medium-sized businesses (Refs. 32-36), reviews of acrylamide mitigation produced by the Association of the Chocolate, Biscuits, and Confectionary Industries of the European Union (CAOBISCO) (Refs. 37-38), and “Guidelines to Authorities and Consumer Organisations on Home Cooking and Consumption” and “Manual on Strategies to Food Industries, Restaurants, etc., to Minimize Acrylamide Formation” produced by the Heat-Generated Food Toxicants: Identification, Characterization and Risk Minimisation (HEATOX) Project (Refs. 39-40). FDA has also published advice for consumers on its website (Ref. 41). This guidance document for industry draws on such publications, and FDA encourages manufacturers to review all resources when considering their approach to reducing acrylamide levels in their products.

To obtain additional information, particularly information relevant to the United States, FDA published a notice in the Federal Register in August 2009 (74 FR 43134) requesting information on practices that manufacturers have used to reduce acrylamide in food and the reductions they have been able to achieve in acrylamide levels.

substance as “reasonably anticipated to be a human carcinogen” if, in relevant part, “there is sufficient evidence of carcinogenicity from studies in experimental animals, which indicates there is an increased incidence of malignant and/or a combination of malignant and benign tumors (1) in multiple species or at multiple tissue sites, or (2) by multiple routes of exposure, or (3) to an unusual degree with regard to incidence, site, or type of tumor, or age at onset” (Ref. 4).

³ The complete quotation is “The Committee considered that for a compound that is both genotoxic and carcinogenic, these [margins of exposure] indicate a human health concern” (Ref. 5).

III. Discussion

A. General comments

This guidance suggests a range of possible approaches to acrylamide reduction. It is not intended to identify specific recommended approaches. Acrylamide reduction is an area of ongoing research, and some approaches discussed may still be at a research stage, rather than in general use. We recommend that manufacturers evaluate approaches that may be relevant to their particular processes and consider adopting approaches, if feasible, that reduce acrylamide levels in their products. When evaluating approaches, it is important to consider the impact on overall chemical and microbiological safety, nutritional quality, and organoleptic properties (Ref. 31).

Factors affecting acrylamide formation are present at various stages from farm to table, so this guidance is for growers, manufacturers, and food service operators. Sections B, C, and D of the guidance cover raw materials, processing practices, and ingredients affecting potato-based foods, cereal-based foods, and coffee, respectively. Section E provides suggested preparation and cooking instructions on packaged frozen french fries. Finally, Section F informs food service operations of techniques for preparing potato-based and cereal-based foods.

FDA is not suggesting maximum recommended levels for acrylamide in various products at this time. We recommend that manufacturers be aware of acrylamide levels in their products, because knowledge of acrylamide levels is essential for determining the effectiveness of acrylamide reduction techniques. The predominant analytical methods for acrylamide determination are liquid chromatography/tandem mass spectrometry (LC/MS-MS) and gas chromatography/mass spectrometry (GC/MS) (Ref. 42). LC/MS-MS and GC/MS methods, though highly sensitive, are expensive and time-consuming. Also, because acrylamide can vary significantly between identically prepared products, extensive sampling may be required to detect the effects of process changes (Refs. 43-44). One approach to reducing analytical testing (e.g., by LC/MS-MS and GC/MS) is to identify a characteristic that can be monitored as a proxy for acrylamide, such as color or moisture, and calibrate variation in this characteristic to analytically determined acrylamide levels. To be effective, such analysis may have to be performed on a product by product basis. Methods other than LC/MS-MS and GC/MS, such as immunoassays (Refs. 45-49), also have been proposed. FDA has monitored acrylamide levels in foods in the U.S. (Refs. 10-11) and conducted exposure assessments of U.S. consumers (Ref. 50). FDA will continue to monitor acrylamide levels in food to determine, in part, if reductions in acrylamide occur over time.

B. Potato-based foods

i. Raw materials

In potatoes, reducing sugars are present in excess compared with asparagine, and reducing sugar levels are the important factors driving acrylamide formation. Careful control of

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reducing sugar levels can reduce acrylamide formation in finished potato products such as french fries and potato chips. Among the factors that affect reducing sugar levels are potato variety, growing and harvesting practices, maturity, handling, and storage conditions (including temperature and control of sprouting).

Varieties. French fry and potato chip producers have traditionally selected potatoes that are low in reducing sugars to minimize browning. Chipping potatoes (for potato chips) typically have the lowest sugar levels, followed by potatoes for french fry processing, and fresh market potatoes (Ref. 51). Selecting potato varieties that are as low as possible in reducing sugars may help reduce acrylamide, while still retaining desirable product qualities. Some members of the Snack Foods Association (SFA) recommend against using Russet varieties for producing potato chips because of high reducing sugar levels (Ref. 44).

Typically, manufacturers use different potato varieties throughout the year, depending on whether the potatoes are coming from fresh crops or from storage. The most suitable variety may vary by region and by season. Large manufacturers may be able to specify suitable varieties or grow their own varieties through contracts. Smaller manufacturers may be able to consult with local extension services to identify low-reducing-sugar potato varieties available in their region at different times of the year, or request their suppliers to provide low-reducing-sugar varieties, when possible.

New potato varieties with lower reducing sugar content and greater resistance to cold-induced sweetening are in development, as are cultivars with lower levels of asparagine (Refs. 30, 52, 53). Both conventional breeding (e.g., crossing commercial potato varieties with wild varieties) and biotechnology have shown promise in reducing acrylamide levels. Six new bioengineered potato varieties with lower asparagine and/or reducing sugar levels and lower acrylamide formation potential have completed FDA's final biotechnology consultation process (Ref. 54). Development and commercialization of new potato varieties is a lengthy process, but may ultimately provide the most effective solution for acrylamide reduction. As new potato varieties come on the market, consider adopting varieties that offer the potential to reduce acrylamide levels.

Summary: Selecting potato varieties that are low in acrylamide precursors, keeping in mind seasonal variation, may help reduce acrylamide.

Growing and harvesting practices. Immature potato tubers have higher reducing sugar levels (Refs. 20, 43-44), and use of mature tubers has been associated with lower acrylamide levels in cooked potatoes (Ref. 55). Growers can optimize potato maturity at time of harvest by controlling planting time and input management (Ref. 44). There is some evidence that increasing fertilization with potassium or avoiding excessive fertilization with nitrogen can hasten maturation and result in lower sugar levels at harvest or after harvest (Refs. 20, 29). Some data suggest that use of earlier maturing varieties, selecting growing sites where harvests can be delayed, and maintaining continued irrigation to avoid growth interruptions may also assist in managing maturity (Ref. 20). An optimal maximum sucrose level of 1.5 mg/g at harvest has been recommended by some as an indicator of maturity in chipping potatoes intended for storage (Refs. 20, 56), although the optimal sucrose level depends on the product and the process (Ref. 57). After harvest, manufacturers should avoid immature

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tubers by selecting, sorting, or grading potatoes before processing (Ref. 31).

Summary: Optimizing potato maturity by controlling planting time, harvest time, and input management, and by removing immature tubers before processing, may help reduce acrylamide.

Defects and bruising. Both potato defects and bruising of potatoes during harvesting and handling can be associated with increased levels of acrylamide in products (Ref. 44). Avoiding handling potatoes with excessive roughness, avoiding bruising potatoes, and sorting out or carefully trimming potatoes with defects may help reduce acrylamide.

Summary: Avoiding handling potatoes with excessive roughness, avoiding bruising potatoes, and sorting out or carefully trimming potatoes with defects may help reduce acrylamide.

Cold temperatures during harvest, transport, delivery, and storage. Potatoes exposed to sustained cold temperatures can undergo “cold sweetening,” i.e., develop higher levels of reducing sugars in response to cold. Temperature, among other factors, can be considered when determining harvest times (Ref. 58). Avoiding sustained cold temperatures during transport and delivery for processing or storage could reduce acrylamide (e.g., avoid leaving potato deliveries outside in freezing conditions) (Ref. 31).

Potatoes are stored through the fall, winter, and spring to provide a steady source of potatoes for processing throughout the year. Storage is typically in temperature- controlled, humidity-controlled, ventilated storage facilities. Trade associations recommend temperatures greater than 43 °F for long-term storage of potatoes used for potato chips or for french fries (Refs. 30, 44). Some guidelines recommend higher temperatures (e.g., near 50 °F or greater for chipping potatoes (Refs. 51, 59) or 47-50 °F for french fry processing (Ref. 51)).

Summary: Avoiding cold temperatures during harvest, transport, delivery, and storage may help reduce acrylamide.

Storage and Sprouting. Potatoes in long-term storage will begin to sprout after a dormant period if sprout production is not suppressed, e.g., by use of chemicals or controlled temperature storage. Sprouting can lead to conversion of stored starch to sugars (Ref. 43), increasing potential for acrylamide formation and excessive browning in cooked products. Therefore, some guidelines recommend the use of sprout suppressants, following good agricultural practices (Ref. 30).

Insufficient storage ventilation leading to oxygen starvation of potatoes has also been associated with increased sugar levels (Ref. 51). Potential causes of insufficient oxygen availability include infrequent operation of the ventilation system or excess dirt on potatoes (Ref. 51).

Summary: Managing storage conditions to control sprouting and provide ventilation may help reduce acrylamide.

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Reconditioning. Potatoes that have higher reducing sugar levels due to exposure to cold temperatures during storage may be reconditioned at warmer temperatures (e.g., at temperatures around 60 °F (Ref. 60) or at ambient temperatures (Ref. 30)) to encourage the conversion of reducing sugars back into complex carbohydrates. Sprouting may be avoided by using reconditioned potatoes relatively soon after reconditioning (Ref. 60). Acrylamide could be reduced by avoiding using potatoes that have been in storage for prolonged periods after which cold sweetening may be difficult to reverse (Refs. 20, 44), although some potato varieties can remain in storage longer than others without development of reducing sugars (Ref. 57). Monitoring reconditioning by measuring reducing sugar levels or conducting fry tests may also help reduce acrylamide (see below).

Summary: Monitoring reconditioning results and avoiding reconditioning potatoes stored for prolonged periods may help reduce acrylamide.

Screening incoming potatoes. Reducing sugar levels can be assessed in incoming potatoes by sugar measurements or fry tests. Fry tests, a method used on French fries, typically consist of frying freshly cut potato strips for 3 minutes at approximately 360 °F (182 °C), and comparing the fried strips to the “USDA Color Standards for Frozen French Fried Potatoes,” based on such factors as overall color and brightness, sugar ends, and sugar tips (Refs. 43, 61). Manufacturers may find it helpful to use a colorimeter. Checking color after test strips have been blanched, par-fried, and final fried may also be useful, since this treatment more closely mirrors the typical fry production process (Ref. 61). Darker fry test results or high reducing sugar levels correlate with finished products that will brown too strongly and have higher acrylamide levels.

U.S. producers of frozen french fries and sliced potato chips have not recommended a target reducing sugar level for incoming potatoes (Refs. 43-44). According to the Frozen Potato Products Institute (FPPI), french fry manufacturers typically establish grower incentives to provide potatoes with as low a reducing sugar level as feasible, rather than specifying levels (Ref. 43). Incoming potatoes with undesirably high sugar levels can also be subjected to additional treatments, such as reconditioning and blanching, to reduce sugar levels before high temperature cooking processes (Ref. 31).

The Acrylamide Toolbox recommends selecting potato varieties with low reducing sugars that are suitable for the product type (Ref. 30). However, for color control, the University of Idaho has recommended that glucose levels be less than 0.35 mg/g (0.035 percent) fresh tuber weight for chipping potatoes and less than 1.2 mg/g (0.12 percent) for french fries (Ref. 51) (glucose numbers can be doubled to approximate total reducing sugar levels (Ref. 43)).

Summary: Assessing reducing sugar levels in incoming potatoes, identifying target levels for incoming potatoes, or using treatments to reduce sugar levels may help reduce acrylamide.

Table 1: Summary for POTATOES: Raw materials

- **Selecting potato varieties that are low in acrylamide precursors, keeping in mind seasonal variation, may help reduce acrylamide.**
- **Optimizing potato maturity by controlling planting time, harvest time, and input management, and by removing immature tubers before processing, may help reduce acrylamide.**
- **Avoiding handling potatoes with excessive roughness, avoiding bruising potatoes, and sorting out or carefully trimming potatoes with defects may help reduce acrylamide.**
- **Avoiding cold temperatures during harvest, transport, delivery, and storage may help reduce acrylamide.**
- **Managing storage conditions to control sprouting and provide ventilation may help reduce acrylamide.**
- **Monitoring reconditioning results and avoiding reconditioning potatoes stored for prolonged periods may help reduce acrylamide.**
- **Assessing reducing sugar levels in incoming potatoes, identifying target levels for incoming potatoes, or using treatments to reduce sugar levels may help reduce acrylamide.**

ii. Processing and ingredients

This section reviews the processing of french fries, sliced potato chips, fabricated potato chips, and other fabricated potato snacks.

a. *French fries.* In the U.S., french fries supplied to foodservice establishments and packaged for direct sale to consumers are typically frozen, par-fried french fries. A standard production process for frozen, par-fried french fries consists of peeling, washing, sorting for size and defects, cutting or slicing, blanching, dipping or coating (e.g., in a dextrose solution), drying, and par-frying. The par-fried products are intended to be cooked to completion in a food-service establishment or in the consumer's home. Levels of acrylamide are low in the par-fried fries, but increase significantly in the final cooked product. Final cooking conditions are the major factor in determining final acrylamide levels, but changes in processing by frozen french fry manufacturers can also affect acrylamide levels in the final product (Ref. 43).

Sorting. See the discussion on choosing potato varieties and screening potatoes in Section III.B.i.

Cutting. Acrylamide formation is typically higher in the surface layer or crust of foods than in the inside; therefore, decreasing product surface area relative to volume may decrease acrylamide in cooked french fries. For frozen french fries, cutting thicker strips or shapes with lower surface area may reduce acrylamide (Refs. 31, 62). Cutting potato rings that avoid inner core material may also lower acrylamide compared to straight cut fries (Ref. 63).

Smaller or thinner potato pieces have a greater surface area to volume ratio than larger

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pieces, and produce more acrylamide on a volume basis (Refs. 29, 30-31). Screening to remove nubbins (short strips) and slivers (thin strips) may reduce acrylamide. Optimization of cutting practices may be useful in limiting production of small fragments (Ref. 64).

Summary: Cutting fries in shapes with lower surface area to volume ratio and screening out small fragments may help reduce acrylamide.

Blanching. Manufacturers of frozen french fries routinely blanch raw potato strips in hot water or steam before par-frying. Blanching can provide more uniform color after frying, inactivate enzymes, and form a layer of gelatinized starch that limits oil absorption and improves fry texture (Refs. 65-66). Blanching also removes reducing sugars and asparagine from the potato surface, decreasing acrylamide in fries (Ref. 30). Modifications to blanching processes, such as changes in time and temperature, may help reduce acrylamide, although such modifications may affect product quality. For example, one research study found that shorter blanching times at high temperatures were more effective at acrylamide reduction than longer low-temperature blanches (Ref. 65).

Summary: Changing blanching practices may help reduce acrylamide, although such changes may affect product quality.

Dips and coatings. For foodservice fries, blanching may be followed by dipping in a dextrose solution to replace sugars removed during blanching and provide uniform coloration (Ref. 43). Initial recommendations called for avoiding the use of sugar solutions as a browning agent or a coating (Ref. 31). However, french fries produced by blanching and dipping in a dextrose solution may show less variability in acrylamide levels and reduced acrylamide compared with fries that rely on naturally present sugars for color, flavor, and aroma development (Ref. 67). With less variability, manufacturers may find it easier to identify treatments that are effective in mitigating acrylamide in industrial processes (Ref. 67). Dipping with fructose should be avoided (Ref. 68).

Summary: Using sugar dips to reduce variability may help reduce acrylamide, but using reducing sugars such as fructose in dips may increase acrylamide.

One approach used by manufacturers to reduce acrylamide formation in oven-baked frozen french fries is to add a food-grade coloring agent such as annatto (Refs. 30, 43). The darker color may improve product appearance and discourage over-baking by the consumer, which can increase acrylamide levels.

Summary: Using alternative coloration methods may help reduce acrylamide by discouraging over-baking.

Addition of sodium acid pyrophosphate (SAPP) during blanching (Ref. 31) or in a dip after blanching (Ref. 30) is standard industry practice to prevent darkening of uncooked potato fry strips (Ref. 30). Treatment with SAPP also reduces acrylamide (Ref. 30), presumably by acidifying the surface of potatoes (Refs. 30, 31, 69). However, SAPP may cause off flavors at levels higher than current industry usage (Ref. 43). Current

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industry usage is approximately 0.5 to 1.0 percent SAPP (Ref. 70).

Some french fries are dipped before frying in batter coatings containing flours, starches, hydrocolloids, or other ingredients to improve texture, flavor, structure, and heat retention (Refs. 71-72). Some batters may reduce acrylamide formation (Ref. 73), but Codex (Ref. 31) recommends examining batter ingredients to ensure there are no ingredients that can increase acrylamide formation in final fried products.

Summary: Using SAPP may help reduce acrylamide, as may evaluating other dip or batter ingredients to determine if they contribute to acrylamide formation during frying.

Table 2: Summary for POTATOES: Processing french fries

- **Cutting fries in shapes with lower surface area to volume ratio and screening out small fragments may help reduce acrylamide.**
- **Changing blanching practices may help reduce acrylamide, although such changes may affect product quality.**
- **Using sugar dips to reduce variability may help reduce acrylamide, but using reducing sugars such as fructose in dips may increase acrylamide.**
- **Using alternative coloration methods may help reduce acrylamide by discouraging over-baking.**
- **Using SAPP may help reduce acrylamide, as may evaluating other dip or batter ingredients to determine if they contribute to acrylamide formation during frying.**

Other considerations

The following section summarizes information on possible acrylamide reduction techniques for french fries that have produced ambiguous results, and therefore may have not been successfully implemented on an industrial scale.

*Treatment with cations*⁴. Treatment of potato strips (french fries) with calcium salts or sodium chloride before frying decreased acrylamide significantly in laboratory studies (Refs. 30, 74-75), but treatment with calcium lactate gave poor results on an industrial scale (Ref. 30). Calcium use may cause hard texture and off tastes in fries, and may not be compatible with SAPP use (Ref. 30). Manufacturers may be reluctant to add sodium for nutritional reasons.

*Treatment with acidulants*⁵. Acidulants (acetic acid, ascorbic acid, citric acid, monosodium citrate, sodium citrate, lactic acid, lactic acid bacteria) effectively suppress acrylamide formation in laboratory model systems and in fried potato products, including french fries (Refs. 13, 18, 30, 43, 69, 76-79). However, they can also cause a sour or tart taste (Refs. 18, 30, 43), suppress development of other flavors (Ref. 30), and potentially cause corrosive

⁴ A positively charged ion such as calcium (Ca^{+2}), magnesium (Mg^{+2}), or sodium (Na^{+}).

⁵ Acidulants are chemicals that are added to food to increase acidity.

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effects on production equipment (Ref. 30). In a manufacturing trial, treatment with citric acid and acetic acid did not provide additional acrylamide reduction compared with standard practices (Ref. 30).

Treatment with amino acids. Amino acids⁶ (e.g., glycine, lysine, cysteine, taurine) reduced acrylamide in potato model systems (Ref. 18) and in potato pieces (Ref. 80) and potato slices (Refs. 69, 81) in laboratory studies. However, glycine reportedly caused excessive browning and bitter flavor in finished potato products (Ref. 43) and was ineffective when tested on french fries in laboratory studies (Ref. 30). The amino acid cysteine reportedly caused unpleasant odors in potato model systems (Refs. 18, 82-83).

Treatment with asparaginase. Asparaginase is an enzyme that breaks down asparagine to aspartic acid and ammonia, preventing asparagine from reacting with sugars to form acrylamide. Four asparaginase preparations with different pH and temperature optima have undergone the GRAS notification process in the U.S., and are currently available for commercial use in foods (Refs. 84-89). Some success has been reported with asparaginase treatment in french fries and other cooked potato products in laboratory trials and pilot plant studies (Refs. 18, 85, 90). The effectiveness of asparaginase in reducing acrylamide in the finished product has been shown to increase when the raw material is blanched prior to enzyme application (Refs. 28, 85). However, the 2013 edition of the Acrylamide Toolbox reported that asparaginase produced inconsistent reductions in acrylamide in industrial trials of frozen parfried french fries and depended on conditions when the enzyme was applied (Ref. 30). Asparaginase was effective in reducing acrylamide in finished products when used on non-parfried blanched, chilled potato strips, as the longer contact time between the enzyme and asparagine resulted in asparagine depletion (Ref. 30). Potential barriers identified by industry to the use of asparaginase in french fry production include costs of the enzyme and adaptation of manufacturing lines (Ref. 43); effects on flavor resulting from asparagine depletion (Ref. 43); different optimal temperatures and pH for asparaginase activity and other processes, e.g., SAPP treatment (Refs. 30, 43); and the potential for microbial growth in solutions held at temperatures optimal for asparaginase (Ref. 43).

Other ingredients. Some studies have identified a number of other ingredients that reduced acrylamide formation in laboratory studies in french fries or other potato products, including plant extracts (Refs. 91-92), hydrocolloids (Ref. 73), vitamins (Ref. 93), antioxidants, and spices (Ref. 18). The efficacy of these compounds in finished food products is not clear (Ref. 18). For new ingredients, it is important to consider such factors as impact on moisture content (Ref. 44), sensorial quality, nutritional quality, regulatory status, and potential formation of byproducts.

b. Sliced potato chips. A typical production process for sliced potato chips consists of peeling, washing (and/or blanching), slicing, frying, sorting, seasoning, and packaging.

Peeling. Abrasive peeling is typically used in the potato chip industry. Peeling chipping potatoes more than what is typical for chip preparation can decrease acrylamide levels in the finished chips because reducing sugar levels may be higher near the peel (Refs. 30, 44).

⁶ Amino acids are molecules that combine to form proteins.

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Trials of hot steam peeling as an alternative to abrasive peeling indicate that it may increase acrylamide levels in potato chips (Ref. 44), depending on potato variety and season (Refs. 30, 57).

Summary: Increasing peel removal may help reduce acrylamide.

Sorting. See the discussion on choosing potato varieties and screening potatoes in Section III.B.i.

Washing/Soaking/Blanching. Potato slices typically are washed in ambient temperature water before frying (Ref. 94), or they may be blanched optionally (Ref. 95). Water can extract acrylamide precursors from potatoes, thereby decreasing acrylamide production in fried slices. Prolonged soaking and higher temperature conditions lead to greater extraction of acrylamide precursors and decreased production of acrylamide (Refs. 18, 65). However, excessive soaking can affect organoleptic qualities (e.g., taste, mouth feel). Some members of the SFA concluded that washing potato slices with warm water reduces acrylamide levels to a modest extent, but also significantly affects quality and operating costs (Ref. 44), while the Acrylamide Toolbox (Ref. 30) concluded that washing has had variable success in chips in laboratory and pilot trials, but that blanching is not a desirable mitigation technique because it leads to loss of flavor, loss of texture, and increased oil uptake.

Summary: Washing or soaking potato chips before frying may help reduce acrylamide, but may cause unacceptable changes to some chips.

Slicing. Decreasing the slice thickness of potato chips may reduce their acrylamide content. The observed effect is opposite that seen for french fries (where thicker slices have lower acrylamide), due to the low moisture and fry temperature profile of finished potato chips. Thinner slices may require less thermal input to remove moisture from the finished chip than thicker slices, thereby reducing the level of acrylamide formed (Refs. 30, 57).

Summary: Cutting thinner potato chip slices may help reduce acrylamide.

Thermal input. Higher temperatures and longer cooking times can increase acrylamide formation in potato chips. In particular, acrylamide formation increases at the end of the frying process, as moisture content falls, e.g., below 3 percent (Refs. 27, 94).

One approach to decreasing thermal input is to decrease frying temperatures, while increasing the amount of time chips are in the fryers (Ref. 44). Some U.S. potato chip manufacturers have adopted recommendations (Ref. 18) to set fryer temperatures to 175 °C (347 °F) or below, depending on the product and the frying system (Ref. 44). Resulting chips have higher moisture levels and lighter color than previous chips (Ref. 44). Frying at lower temperatures (e.g., below 170 °C (338 °F)) may cause higher fat uptake and affect crispness (Refs. 18, 44).

Moisture levels in finished products are an important consideration (Refs. 18, 30, 44). Targeting higher moisture endpoints in sliced potato chips (1.3 to 1.5 percent, depending on

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the product) can result in reduced acrylamide (Ref. 44). Moisture levels that are higher (e.g., greater than 1.5 %) may affect flavor, texture, and shelf life (Refs. 30, 44), though some of these effects may be offset by other changes, such as in packaging. When evaluating proposed mitigation techniques, it is important to consider the moisture level of finished products (Refs. 18, 44). In some cases, mitigation techniques may appear to lower acrylamide, while actually raising product moisture to an unacceptable level (e.g., one that increases the rate at which products will become stale) (Refs. 44, 94).

Summary: Decreasing frying temperatures to 175 °C (347 °F) or below and targeting higher moisture endpoints may help reduce acrylamide, but it is important to determine if moisture endpoints provide acceptable product quality.

Flash frying⁷ with rapid cooling and vacuum frying⁸ may be useful approaches for reducing acrylamide levels for some manufacturers (Ref. 30). Vacuum frying may reduce acrylamide formation significantly without significant changes in organoleptic properties (Ref. 18). However, FoodDrinkEurope reports that vacuum frying may not provide the desired product attributes, and may have limited throughput capacity (Ref. 30).

It also may be helpful to use a multi-stage cooking process, in which higher temperatures are applied initially, followed by lower temperatures (e.g., below 120 °C / 250 °F (Ref. 94)) near the end of the cooking process when moisture levels are lower and the products are more susceptible to acrylamide formation. The lower temperatures may be applied in this second stage using oven-drying (Refs. 94, 96) or vacuum frying (Ref. 94).

Similarly, lower temperatures may occur in batch frying when making kettle chips (Refs. 44, 57). Some members of SFA report that changing the thermal input (e.g., time and temperature) during batch frying of kettle chips may be the most effective way to reduce acrylamide, specifically, by lowering the initial temperature from 310 °F (+/- 5 °F) to 295 °F (+/- 5 °F) (i.e., from 154 °C to 146 °C), lowering drop temperature to 250 °F (121 °C) after 3 minutes, and lowering the exit temperature at the end of the batch process by a comparable amount (Ref. 44).

Summary: Using lower temperatures during final cooking stages and using techniques like flash frying, vacuum frying, or batch frying may help reduce acrylamide.

Color and sorting. Optical sorting of finished chips can remove browned chips, burned chips, and chips made from bruised or defective potatoes (Refs. 30, 31, 44). All of these defects can indicate chips that have higher acrylamide levels (Ref. 44). Generally, finished chips should be a light golden color or a golden yellow color (Refs. 30, 44). One manufacturer reported using Hunter color measurement for fabricated potato chips, with a target “L” value of 59 to 68 and an “a” value of 3 to 6 (Ref. 44).⁹ It is important to correlate measured levels of acrylamide in chips with finished product color to have a rough indicator of acrylamide levels. To be useful, such correlations may have to be established for

⁷ Frying at high temperatures for short periods of time.

⁸ Frying under reduced atmospheric pressure to allow use of a lower oil temperature.

⁹ On the Hunter L, a,b color scale, “L” is an indicator of lightness of color and “a” is an indicator of position of the color on a red-green color axis (<http://www.hunterlab.com/pdf/color.pdf>).

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individual potato varieties and individual products.

Summary: Sorting by color may help reduce acrylamide, by providing a useful indicator of acrylamide levels, especially if correlated with measured levels of acrylamide in specific products.

Table 3: Summary for POTATOES: Processing sliced potato chips

- **Increasing peel removal may help reduce acrylamide.**
- **Washing or soaking potato chips before frying may help reduce acrylamide, but may cause unacceptable changes to the chips.**
- **Cutting thinner potato chip slices may help reduce acrylamide.**
- **Decreasing frying temperatures to 175 °C (347 °F) or below and targeting higher moisture endpoints may help reduce acrylamide, but it is important to determine if moisture endpoints provide acceptable product quality.**
- **Using lower temperatures during final cooking stages and using techniques like flash frying, vacuum frying, or batch frying may help reduce acrylamide.**
- **Sorting by color may help reduce acrylamide, by providing a useful indicator of acrylamide levels, especially if correlated with measured levels of acrylamide in specific products.**

Other considerations

The following section summarizes information on proposed acrylamide reduction techniques for sliced potato chips that have produced ambiguous results, and therefore may have not been successfully implemented on an industrial scale.

Treatment with cations. There are conflicting reports on the effectiveness of cations in potato chips. In laboratory trials, treatment with calcium chloride or calcium lactate decreased acrylamide in potato chips (Refs. 18, 69); however, the SFA (Ref. 44) reported that calcium chloride treatment was not effective or negatively affected potato chip quality. On the other hand, the Acrylamide Toolbox (Ref. 30) reported that calcium-treated chips had acceptable sensory quality compared with non-treated chips, but noted that sensory quality must be confirmed in treated chips with the same moisture content as non-treated chips, particularly since calcium treatment has been linked to brittleness and off flavors previously (Ref. 30). Sodium chloride also reduced acrylamide levels in laboratory trials (Ref. 97). A potential concern with sodium chloride treatment is increased sodium intake, although the amount of sodium needed to affect acrylamide may be less than is normally present in salted chips at retail (Ref. 69).

Treatment with acidulants. In laboratory trials, treatment with acidulants decreased acrylamide levels in sliced potato chips (Refs. 69, 78). According to the SFA (Ref. 44), treatment of sliced potato chips with the acidulants phosphoric acid and citric acid was not effective or negatively affected chip quality. However, others have reported that acrylamide reductions can occur at acid concentrations that provide good sensory quality (Ref. 69). Combinations of acidulants and amino acids (Ref. 69) have also been reported to be

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effective at reducing acrylamide in potato chips. Sensory effects may be variable depending on the product (Ref. 30).

Treatment with amino acids. In laboratory trials, treatment of potato slices with certain amino acids (glycine, glutamine) in a blanching step decreased acrylamide levels in potato chips (Refs. 69, 98). Combined treatment with glycine and citric acid was also reported to have additive effects in reducing acrylamide in a potato cake model (Refs. 30, 77). However, the SFA (Ref. 44) reported that several manufacturers testing L-cysteine and other amino acids found that they did not have a significant effect on acrylamide in sliced potato chips when tested on an industrial scale.

Treatment with asparaginase. Asparaginase cannot readily pass through cell walls of freshly cut potato slices. Weakening of cell walls by soaking and pre-treatments including blanching, application of acidulants, and ultrasound may allow asparaginase to diffuse into potato slices and deplete acrylamide precursors (asparagine and reducing sugars), but such treatments can also damage the integrity of potato slices and affect chip flavor and texture (e.g., Ref. 30). Furthermore, the SFA reported that sonication¹⁰ and pulse vacuum infusion¹¹ did not increase the efficacy of asparaginase treatment (Ref. 44). Treatment with asparaginase in industrial settings has been ineffective and it is not a recommended mitigation option for sliced potato chips (Refs. 30, 44).

Other ingredients. Antioxidants also have been reported to decrease acrylamide in potato chips in some laboratory trials (Refs. 18, 91), but the effect of antioxidants on acrylamide in laboratory trials has been inconsistent (Ref. 99). Antioxidants are not addressed by the Acrylamide Toolbox or the SFA. For all ingredients, it is important to consider such factors as impact on moisture content, sensorial quality, nutritional quality, regulatory status, and potential formation of byproducts.

c. Fabricated potato chips and other fabricated potato snacks

A typical production process for fabricated¹² potato chips consists of preparation of a dehydrated potato product such as potato flakes or granules, mixing with water and other ingredients to form dough, sheeting the dough, cutting, cooking (frying or baking), sorting, seasoning, and packaging. For extruded¹³ snacks, an extrusion step, with cutting and forming operations, follows dough formation. Some considerations for sliced potato chips (see Section III.B.ii.b) also apply to fabricated potato chips or other potato-based snacks. In addition, the following specific information may prove useful.

Potato flakes. Potato flakes are typically made with industry reject or table stock potatoes that have high levels of reducing sugar (greater than 2.0 percent) (Ref. 44). As a result, potato flakes tend to be high in reducing sugars, posing mitigation challenges (Ref. 44).

¹⁰ Using sound waves to disrupt potato cell walls and allow asparaginase to enter cells.

¹¹ Using vacuum pulses to infuse substances (e.g., asparaginase) through potato cell walls.

¹² Fabricated products are made from dried potato products (e.g., flakes), rather than fresh potatoes.

¹³ Extruded snacks are produced by cooking, pressurizing, and forcing a dough through a die to form a unique shape.

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Changes in flake purchasing patterns may help with acrylamide management. The U.S. snack industry reports that reducing sugar levels in incoming flakes can range from 0.2 percent to 2.5 percent, and can vary widely between different shipments (Ref. 44). One option for some snack food manufacturers may be to specify a maximum level of acceptable reducing sugars in incoming flakes. Potato flake supplies bought early in the processing season may have lower levels of reducing sugars (Ref. 100). Also, blending flakes from different sources may help reduce variability in sugar levels (Ref. 100).

Changes in flake production also may yield flakes with lower reducing sugar levels. Where possible, lower sugar potatoes should be used, but this may not be consistently feasible, given current source potatoes (Ref. 44). Flakes made from fully peeled potatoes may have less acrylamide-forming potential than unpeeled or partially peeled potatoes (Ref. 101). Treatment with acids or calcium chloride during flake production also may lower acrylamide-forming potential (Refs. 44, 101). The SFA (Ref. 44) reported lower acrylamide content in baked potato snacks and fried and baked potato crisps made from calcium-treated flakes, with calcium chloride proving more effective than calcium lactate (Ref. 44). Acidifying blanch water for potato flake production to pH 4.0 – 6.5 also reduced acrylamide in potato-flake based products by more than 30 percent (Refs. 44, 101). Problems with cooking and drying arose when the pH fell below 4.0, or calcium levels were too high (Ref. 41). Some SFA members also reported success combining asparaginase treatment with calcium salts during flake production (Ref. 44). Similarly, an asparaginase manufacturer reported a 60 percent reduction in acrylamide in an industrial snack production trial using asparaginase-treated potato granules (Ref. 84).

Summary: Selecting potato flakes with lower levels of reducing sugars may help reduce acrylamide. Lower reducing sugar levels may be found by specifying maximum sugar levels, buying early in the processing season, or by mixing flakes from different sources. Flakes treated with acidulants, calcium, or asparaginase during flake production may also produce flake-based products with lower acrylamide.

Other dough components. Partial substitution of potato flakes or granules with ingredients with lower reducing sugar or asparagine levels (e.g., potato starch or rice) may reduce acrylamide formation in fabricated potato snacks (Refs. 14, 31). Adding fewer reducing sugars to the dough (i.e., for flavor) can reduce acrylamide approximately 10 percent (Ref. 44).

Summary: Partially substituting potato flakes with other ingredients may help reduce acrylamide in fabricated potato products.

Treatment with calcium salts. Addition of calcium salts to doughs is effective in reducing acrylamide in fabricated potato snacks (Ref. 30). Reductions in acrylamide of 30 to 40 percent in various potato-based snacks and fabricated potato chips have been reported (Refs. 30, 44, 102). Calcium addition may be more effective at an acidic pH (Ref. 102). Potential problems, particularly when calcium is in excess, include off flavors and changes in texture and color (Refs. 30, 102).

Summary: Adding calcium salts to potato doughs may help reduce acrylamide in

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fabricated potato products.

Treatment with acidulants. Citric acid and ascorbic acid have been used successfully to reduce acrylamide in some fabricated potato products, with no effect on taste (Refs. 30, 44, 78). In trials, the impact of citric acid on taste was seen to be product dependent, with no effect on some products, but off flavors in others (Ref. 30). As noted above, addition of low levels of acids may improve the efficacy of calcium chloride treatment of fabricated products (Refs. 30, 102).

Summary: Adding acidulants to potato doughs may help reduce acrylamide in fabricated potato products.

Asparaginase. Initial reports indicated that asparaginase might not be useful for fabricated potato dough products because too much asparaginase was required and resulted in significant off flavors and odors from aspartic acid and ammonia byproducts (Refs. 31, 44). More recent results indicate that the enzyme can be beneficial for some products, depending on recipe and production process (Refs. 30, 84).

Summary: Adding asparaginase to potato doughs may help reduce acrylamide in some fabricated potato products.

Thermal input. For general information, see Section III.B.ii.b above. This section provides additional information on fabricated potato products. One trade association reported that changing thermal input (e.g., time, temperature) may be the most effective way for small manufacturers of fabricated potato chips to mitigate acrylamide (Ref. 44). Ideal temperature may vary with incoming potato flake sugar content (Refs. 44, 57). This trade association also reported that decreasing oven temperature during drying to 123 °C (235 °F) while increasing the drying dwell time reduced acrylamide formation in fabricated potato products (Ref. 44).

As with sliced potato chips, multistage cooking processes may be helpful in reducing acrylamide levels. Reductions in acrylamide were reported for fabricated potato chips prepared by baking or frying in two stages, when the second stage temperature was held below 120 °C (248 °F) (Refs. 94, 103). In addition, acrylamide can be reduced for fabricated chips by setting higher moisture endpoints (Ref. 44). Trade association member companies have suggested moisture levels ranging from 1.65 to 2.2 percent for fabricated chips (Ref. 44).

Summary: Decreasing cooking temperatures, using lower final temperatures in multistage processes, and using higher moisture endpoints may help reduce acrylamide in fabricated potato chips.

Color and sorting. See section III.B.ii.b.

Table 4: Summary for POTATOES: Processing fabricated potato chips and other fabricated potato snacks

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- **Selecting potato flakes with lower levels of reducing sugars may help reduce acrylamide. Lower reducing sugar levels may be found by specifying maximum sugar levels, buying early in the processing season, or by mixing flakes from different sources. Flakes treated with acidulants, calcium, or asparaginase during flake production may also produce flake-based products with lower acrylamide.**
- **Partially substituting potato flakes with other ingredients may help reduce acrylamide in fabricated potato products.**
- **Adding calcium salts to potato doughs may help reduce acrylamide in fabricated potato products.**
- **Adding acidulants to potato doughs may help reduce acrylamide in fabricated potato products.**
- **Adding asparaginase to potato doughs may help reduce acrylamide in some fabricated potato products.**
- **Decreasing cooking temperatures, using lower final temperatures in multistage processes, and using higher moisture endpoints may help reduce acrylamide in fabricated potato chips.**

Other considerations

The following section summarizes information on proposed acrylamide reduction techniques for fabricated potato chips and other fabricated potato snacks that have produced ambiguous results, and therefore may have not been successfully implemented on an industrial scale.

Amino acids. Addition of amino acids (e.g., glycine, lysine, and cysteine) shows promise for acrylamide reduction in fabricated potato products, based on laboratory and pilot trials (Refs. 30, 102, 104). However, effects on color, taste, and texture from amino acids may be a concern if amino acid levels are too high (Ref. 30).

C. Cereal-based foods

Cereal-based foods include foods such as bread, crackers, and breakfast cereals that are cooked from cereal crops such as wheat and corn. Section C reviews information on raw materials and processing approaches that may reduce acrylamide in cereal-based foods.

i. Raw materials

In cereals such as wheat, asparagine is present in excess compared with reducing sugars. Therefore, the concentration of asparagine, not reducing sugars, is the important factor driving acrylamide formation in cereal-based foods (Refs. 20, 30). Cereal grain type, grain variety, and growing conditions are some of the factors that affect asparagine levels.

Cereal type, cereal variety, and mineral nutrient level. Asparagine levels vary between cereal types, between varieties, and depending on growing year and location. This

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variability can significantly impact acrylamide levels in bakery products (Refs. 13, 17, 20, 30). Comparing free asparagine levels in different cereal crops, rye has the highest free asparagine content, followed by wheat, corn and oats, and then rice (Ref. 20). Whole grain products (e.g., whole wheat) have higher asparagine concentrations than refined grains, and produce more acrylamide in finished products (Refs. 20, 30).

Mineral nutrient level is one factor affecting asparagine levels in wheat. Sulfur deficiency can lead to greater asparagine formation, demonstrating the need to maintain sufficient soil sulfur levels (Refs. 16, 19-20, 30). Based on studies in the United Kingdom, a minimum of 15 kg sulfur/hectare¹⁴ was recommended for wheat production, along with sufficient phosphate and potassium (Ref. 16). Sulfur deficiency in only part of a total area under production (e.g., unfertilized field margins) could potentially cause spikes in asparagine levels in certain batches of wheat (Ref. 16). Excessive nitrogen fertilization may increase levels of asparagine in cereal crops (Refs. 13, 20).

Where possible, using wheat varieties low in asparagine, using wheat grown on sites that have shown reduced potential for asparagine accumulation in the past, and using wheat grown with adequate soil sulfate and without excessive nitrogen fertilization (Refs. 13, 20, 30) may help reduce acrylamide formation in cereal products. For the future, development of wheat varieties with low asparagine content under different growth conditions is a promising approach (Ref. 30).

Summary: Using wheat varieties that are lower in asparagine and using wheat grown with adequate soil sulfate and without excessive nitrogen fertilization may help reduce acrylamide in cereal-based foods.

Substitution. Partial substitution of low-asparagine cereals for high-asparagine cereals (e.g., rice for wheat) may allow reductions in acrylamide, while still maintaining desirable product characteristics (Refs. 14, 17, 30, 31). Reducing whole grain content may also reduce acrylamide (Refs. 20, 30-31), but FDA does not recommend this approach given the benefits of whole grains (Refs. 20, 105).

Summary: Partially substituting low-asparagine cereal grains for high-asparagine cereal grains may help reduce acrylamide in cereal-based foods.

Table 5: Summary for CEREAL-BASED FOODS: Raw materials

- **Using wheat varieties that are lower in asparagine and using wheat grown with adequate soil sulfate and without excessive nitrogen fertilization may help reduce acrylamide in cereal-based foods.**
- **Partially substituting low-asparagine cereal grains for high-asparagine cereal grains may help reduce acrylamide in cereal-based foods.**

¹⁴ Approximately 13.4 pounds/acre.

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ii. Processing and ingredients

This section provides information for different types of cereal-based foods, separated by type of processing intervention, rather than product category.

Leavening. The leavening agent ammonium bicarbonate increases acrylamide in baked goods containing reducing sugars by promoting the formation of reactive carbonyl sugar fragments (Ref. 106). Replacement of ammonium bicarbonate in baked goods such as cookies and crackers with alternative leavening agents is a successful, industrially proven mitigation technique (Refs. 17, 30, 37-38, 44, 107). According to the SFA, replacement of ammonium bicarbonate is one of the most effective mitigation techniques in cookies for smaller member companies, due to reasonable costs and limited impact on quality (Ref. 44). Alternative leavening agents include sodium bicarbonate and acidulants; sodium bicarbonate plus SAPP and organic acids; and potassium bicarbonate with potassium bitartrate (Refs. 17, 31, 108-109).

Proposals to substitute sodium bicarbonate for ammonium bicarbonate have raised concerns about the potential for increased sodium exposure (Refs. 20, 30, 31). To minimize increases in sodium intake from using sodium bicarbonate, it is important to consider whether less sodium can be added elsewhere in the baking process, e.g., as an ingredient (Ref. 20). Also, calcium and potassium-based leavening agents may be acceptable alternatives to sodium and ammonium-based leavening agents in some products (Ref. 108). Compared with ammonium bicarbonate, alternative leavening agents may have unwanted effects on taste and texture, and cause decreased browning, more limited leavening, and slower gas generation in baked goods (Refs. 17, 20, 31, 110). However, quality effects may be very limited or acceptable (e.g., Ref. 107) and other changes may address some quality issues; e.g., adding organic acids to address alkaline taste or adding amino acids to increase browning (Ref. 106).

Summary: Replacing ammonium bicarbonate in cookies and crackers with alternative leavening agents, while avoiding overall increases in sodium levels, may help reduce acrylamide.

Sugars. Replacement or avoidance of reducing sugars has proved to be a successful strategy for acrylamide mitigation in cookies, crackers, and other baked goods (Refs. 20, 30, 37-38). Replacement of reducing sugars with sucrose is particularly effective in sweet baked goods where browning is not critical (Ref. 31). The following suggestions and comments apply to use of sugars in baked cereal-based foods:

- Where possible, replace reducing sugars (e.g., glucose, fruit purees, inverted sugar, corn syrup, fructose, honey) with nonreducing sugars (e.g., sucrose or trehalose) (Refs. 13, 17, 20, 31, 106-107, 111-112).
- For recipes that require reducing sugar, substitute glucose for fructose where possible. For products using corn syrup, choose syrup with low fructose content (Refs. 30-31).
- Replacement of reducing sugars (or replacement of fructose with glucose) may be most effective in products that contain ammonium bicarbonate (Refs. 20, 30, 106).

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- Replacement of reducing sugars may cause a lighter colored product or interfere with flavor formation for some products (e.g., gingerbread), but not have a significant effect or unacceptable effect on other products (Refs. 20, 30, 38, 106).
- For breakfast cereals, avoid adding reducing sugars (including fruit syrups and honey) to cereals before high-temperature cooking (toasting) steps (Refs. 30-31). Reducing sugars applied as coatings after cooking do not influence acrylamide levels (Refs. 30-31).
- Decreasing molasses use in cookies may reduce acrylamide formation (Ref. 44).

Summary: Replacing reducing sugars with nonreducing sugars, using reducing sugars with lower fructose content, and only adding sugar coatings to breakfast cereals after toasting steps may help reduce acrylamide.

Asparaginase. Asparaginase treatment is one of the most effective practices adopted by manufacturers for cereal goods, with multiple products commercialized (Refs. 20, 30, 38, 44). Acrylamide reductions of approximately 35 to 90 percent have been reported for asparaginase treatment of various cereal-dough-based products in commercial or trial use, such as tortilla chips, corn chips, pretzels, crackers, crispbread, cakes, cookies (including gingerbread), honey cakes, and hydrolyzed ready-to-eat cereal products (Refs. 20, 30, 44, 95, 111). A major advantage of asparaginase is its limited effect on product characteristics or organoleptic properties, as might occur with recipe or process changes (Ref. 20).

The primary factors affecting successful use of asparaginase in cereal-based products are enzyme dose, asparaginase-dough contact time, and dough water content (Refs. 30, 38, 44, 95). The enzyme can be added in a granular form to dry ingredients (e.g., in crackers or pretzels) or as a liquid (e.g., in tortilla chips and corn chips). While some modifications to manufacturing lines may be necessary, e.g., to increase holding time in the presence of asparaginase, dry addition typically requires only minimal process changes (Refs. 20, 44, 95). Asparaginase effectiveness is greater in high moisture doughs compared with low moisture doughs (such as ginger cookies) (Refs. 30, 38, 95). Also, asparaginase is not effective for breakfast cereals that have low moisture content or that are based on coarsely ground flours and chopped grains, because of limited penetration of asparaginase into the product (Ref. 30). In addition, some ready-to-eat cereal production processes involve preconditioning that can deactivate asparaginase (Ref. 57).

Chlorine content and pH also affect asparaginase activity. Water containing chlorine or chlorine derivatives (e.g., public drinking water) may reduce asparaginase activity in cereal-dough-based products (Ref. 44). Laboratory testing of asparaginase revealed that an asparaginase enzyme (Novozymes, derived from *A. oryzae*) was most active at neutral pH, and that for most bakery products, asparaginase could be used at dough pH (Ref. 95). For masa¹⁵ preparation, the SFA reported that higher lime content could potentially raise dough pH and reduce asparaginase activity (Ref. 44).

Summary: Using asparaginase treatment may help reduce acrylamide in cereal-based foods, but dose, contact time, dough water content, pH, and water chlorination are

¹⁵ Masa is a corn-based dough used to make tortillas and tortilla chips.

important considerations.

Treatment with cations. For breads, fortification of flour¹⁶ with 0.3 to 1 percent calcium carbonate or calcium chloride reduced acrylamide levels compared with unfortified bread (Refs. 30, 110, 113). Magnesium fortification at equivalent levels reduced acrylamide formation in bread to a lesser degree (Refs. 30, 110, 113). Because acrylamide in bread forms primarily in crusts, applying calcium directly to dough surfaces, e.g., in releasing agents or on loaf tops, may be a useful approach (Refs. 30, 110). Sodium chloride may also reduce acrylamide in breads, but Claus et al. (Ref. 114) reported that the optimal concentration of sodium chloride for acrylamide minimization is 1 to 2 percent and is routinely used in industrial bread production. Calcium propionate should be avoided for acrylamide reduction as it caused a greater than 90 percent increase in acrylamide levels in bread (Ref. 30).

For breakfast cereals, many cereals are already fortified with calcium. Manufacturers may want to consider calcium addition for non-fortified cereals (Ref. 30). Sodium chloride also may mitigate acrylamide in breakfast cereals (Ref. 115), but avoidance of excess dietary sodium also should be considered.

For crackers (including crispbreads) and cookies (including gingerbread), calcium and magnesium supplementation showed potential to reduce acrylamide in laboratory trials (Refs. 110, 113), but product quality has been poor (Refs. 30, 110). Also, in laboratory trials, calcium propionate (at 0.35 to 0.75 percent) accentuated acrylamide formation in cracker and cookie doughs (Ref. 110).

Summary: Using calcium supplementation may help reduce acrylamide in non-calcium-fortified breads or breakfast cereals, but the addition of calcium propionate may increase acrylamide levels.

Yeast fermentation. Because yeast use asparagine during growth, some data indicate that yeast fermentation is associated with lower asparagine levels in doughs and lower acrylamide levels in baked cereal goods such as crispbreads (Refs. 17, 30, 111). Longer fermentation time may be a useful strategy to reduce acrylamide formation in breads, crispbreads, and crackers (Refs. 12, 17, 30, 111), although extended fermentation also may have unwanted effects, such as weakened gluten and flatter breads (Ref. 12). As an alternative to longer fermentation, greater quantities of low-gassing yeast can be used to increase asparagine consumption while keeping gas levels constant (Refs. 17, 30, 110). A modified form of yeast that has increased rates of asparagine consumption has undergone the GRAS notification process in the U.S (Ref. 116). It is important to keep in mind that recipe or process changes that affect yeast adversely (e.g., excess sodium chloride) also may affect final acrylamide levels (Refs. 12, 113).

Summary: Using yeast fermentation and changing fermentation conditions may help reduce acrylamide in cereal-based foods.

¹⁶ In the U.S., “enriched flour” may contain 960 mg calcium/lb flour (21CFR137.165), or approximately 0.2 percent calcium or 0.5 percent calcium carbonate.

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Thermal input. Modifications to baking time and temperature can result in lower acrylamide levels in baked goods, breakfast cereals, crispbreads, and other cereal-based foods (Refs. 20, 30, 117). Products can be baked at lower temperatures for longer periods of time (Refs. 12, 17, 30, 117-118). Another approach is to lower baking temperatures during the final stages of cooking when moisture levels are low and acrylamide formation is more likely (Refs. 17, 31, 113). Likewise, it may be possible to increase temperatures earlier in the baking process when higher moisture levels should prevent acrylamide formation (Ref. 31). Potential disadvantages of temperature reductions include slower production lines, lighter color (Refs. 20, 30), shorter shelf life with higher moisture products, and the need for recipe changes (Refs. 17, 30). For breads, convection ovens may give higher acrylamide levels than deck ovens, due to more intense drying of the crust (Ref. 12), while steam baking or baking with lidded pans reduced acrylamide levels compared with other baking techniques (Ref. 30). Alternative baking technologies, such as infrared radiation and air impingement, also can reduce acrylamide levels (Refs. 30, 111), but these technologies may not be in widespread use in the U.S. (Ref. 111).

Summary: Lowering thermal input through modifying baking times and temperatures and considering alternative baking technologies may help reduce acrylamide in cereal-based foods.

Color. For many cereal-based foods (e.g., breads), darker color can be a useful indicator of acrylamide levels, with a darker color being associated with higher acrylamide levels (Refs. 17, 30); however, in a few products, such as some breakfast cereals, darker color may be associated with less acrylamide (Refs. 24-25). Color may be a useful monitor of acrylamide levels during production or when investigating the effects of different baking conditions, but the correlation between color and acrylamide may have to be determined on a product by product basis.

Summary: Monitoring production by using color as an indicator of acrylamide may help reduce acrylamide, but the correlation between color and acrylamide may have to be determined on a product by product basis.

Moisture. For some cereal-based foods (e.g., crispbreads), setting a higher finished moisture level may be a useful strategy for controlling acrylamide (Refs. 30, 37-38). However, too high a moisture level may impact product shelf life or flavor (Refs. 30, 44). Monitoring moisture levels in finished products may also be a good indicator of acrylamide levels in a product with standardized moisture levels (Ref. 30).

Summary: Setting a higher moisture endpoint may help reduce acrylamide in cereal-based foods, and monitoring moisture levels in finished products may be useful as an indirect indicator of acrylamide levels.

Table 6: Summary for CEREAL-BASED FOODS: Processing and ingredients

- **Replacing ammonium bicarbonate in cookies and crackers with alternative leavening agents, while avoiding overall increases in sodium levels, may help reduce acrylamide.**
- **Replacing reducing sugars with nonreducing sugars, using reducing sugars with lower fructose content, and only adding sugar coatings to breakfast cereals after toasting steps may help reduce acrylamide.**
- **Using asparaginase treatment may help reduce acrylamide in cereal-based foods, but dose, contact time, dough water content, pH, and water chlorination are important considerations.**
- **Using calcium supplementation may help reduce acrylamide in non-calcium-fortified breads or breakfast cereals, but the addition of calcium propionate may increase acrylamide levels.**
- **Using yeast fermentation and changing fermentation conditions may help reduce acrylamide in cereal-based foods.**
- **Lowering thermal input through modifying baking times and temperatures and considering alternative baking technologies may help reduce acrylamide in cereal-based foods.**
- **Monitoring production by using color as an indicator of acrylamide may help reduce acrylamide, but the correlation between color and acrylamide may have to be determined on a product by product basis.**
- **Setting a higher moisture endpoint may help reduce acrylamide in cereal-based foods, and monitoring moisture levels in finished products may be useful as an indirect indicator of acrylamide levels.**

Other considerations

The following section summarizes information on proposed acrylamide reduction techniques for cereal-based foods that have produced ambiguous results, and therefore may have not been successfully demonstrated on an industrial scale.

Treatment with amino acids. For breads, addition of various amino acids (e.g., cysteine, glycine) to doughs has been shown in laboratory and pilot plant trials to reduce acrylamide formation in various types of bread (Refs. 12, 30, 98, 114, 119). However, excess cysteine in doughs can negatively affect bread structure and flavor. Glycine also may mitigate acrylamide when added to bread dough or applied as a spray to the surface of the dough prior to baking (Refs. 12, 30, 110, 111, 119). However, glycine in large amounts may reduce fermentation (Ref. 30). Also, a glycine spray needed repeated applications and reduced acrylamide levels only about 15 percent (Ref. 30).

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For breakfast cereals, glycine reduced acrylamide formation (e.g., 50-75 percent) in wheat flake cereals in pilot trials, but also caused excessively dark colors and bitter taste (Refs. 17, 30). Producing acceptable flakes required radical changes in the toasting operation (Ref. 17). According to FoodDrinkEurope (Ref. 30), researchers have not been able to mitigate glycine's effects on color and taste, while also meeting requirements for moisture, texture, and shelf life. Added proline and lysine also caused unacceptably bitter flavors (Ref. 30).

For cookies, crackers, and crispbreads, amino acids (e.g., glycine) were successful in reducing acrylamide levels in experimental trials (e.g., approximately 15 percent in savory biscuits to 80 percent in crispbread) (Refs. 30, 113), but poor product color and quality typically resulted (Ref. 30).

Treatment with acidulants. Acidulants such as citric acid reduce acrylamide levels in cereal dough-based products through their interference with the Maillard reaction¹⁷ (Refs. 8, 17, 30, 78, 110). A manufacturer of citric acid products stated that it achieved acrylamide reductions of over 60 percent in breakfast cereals in industrial trials, from 30 to 70 percent in cookies and crispbreads in laboratory trials, and up to 90 percent in gingerbread in industrial trials, without effects on taste (Ref. 78). However, other sources report significant impacts in baked goods for acidulants, including sour taste, lessened browning, and a limited practical pH range for doughs (Refs. 17, 30, 113). Another concern is that lowering dough pH may favor the formation of the undesirable chemical byproduct 3-monochloropropanediol (3-MCPD) (Refs. 17, 30, 110, 113). Spraying dough surfaces with acidulants, rather than incorporating acidulants in dough, may avoid some side effects (Refs. 17, 78).

Dough holding time. Higher acrylamide formation was reported in "aged" (up to 3 hours) sweet cookie dough (Ref. 110), leading to recommendations to avoid letting doughs age (Refs. 30, 110). However, a trade organization reported that this approach was not supported by further evidence (Ref. 38).

Rework. Initial research suggested that eliminating use of rework dough¹⁸ could lower acrylamide levels in certain baked goods (Ref. 30). These results have not been born out in manufacturing settings (Refs. 30, 38). More recent information suggests that in doughs with asparaginase, use of rework may reduce acrylamide by providing additional time for the enzyme to react (Ref. 57). Manufacturers may wish to investigate individual products to determine if rework affects acrylamide levels.

D. Other foods

Coffee. Coffee is a significant source of acrylamide exposure for adults. Limited

¹⁷ The Maillard reaction is a non-enzymatic reaction between sugars and proteins that occurs upon heating and that produces browning of some foods. See <http://www.merriam-webster.com/dictionary/maillard%20reaction>.

¹⁸ For purposes of this guidance, the term "rework dough" refers to dough that is left over from preparing dough for manufacturing (such as trimmings left from cutting cookies on a baking sheet) and then is fed into the manufacturing process again.

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information is available on factors known to affect acrylamide concentrations in coffee.

Robusta beans have somewhat higher acrylamide levels than arabica beans. Dark roast coffee has less acrylamide than light roast coffee (since acrylamide formed early in roasting is destroyed later in the roasting process). Acrylamide levels in roasted coffee decline during long-term storage. Also, different preparation methods (e.g., espresso versus filter brewed) result in different levels of acrylamide in coffee as consumed (Refs. 15, 30-31, 120).

A number of mitigation methods have been suggested for coffee, such as steam roasting, vacuum roasting and asparaginase treatment (Refs. 15, 121-122), but FDA is not aware of any proven mitigation measures. In more recent laboratory and pilot trials, treatment of green coffee beans with asparaginase resulted in lower acrylamide levels (5-45 percent) after roasting compared with untreated roasted beans, but coffee taste was significantly and negatively affected (Ref. 30). A viable commercial process is not yet available (Ref. 30).

E. Preparation and cooking instructions on packaged frozen french fries¹⁹

For french fries, the recommended maximum cooking temperature for frying is 345-350 °F/approximately 170-175 °C (Refs. 30, 43). Providing appropriate cooking instructions on frozen french fry packages may help reduce acrylamide formation safely during final preparation by consumers and food service operators. Examples of such instructions (which may not be applicable to all products) are:

- Cook to a light golden color. Avoid browning fries.
- Avoid overcooking or undercooking.
- Avoid cooking in a toaster oven to prevent overcooking.
- Reduce cooking time when cooking small amounts.

Summary: Providing appropriate cooking instructions on frozen french fry packages to guide final preparation by consumers and food service operators may help reduce acrylamide.

F. Information for food service operations²⁰

Educating food service workers on the following techniques may help food service operations reduce acrylamide when frying potatoes, such as french fries:

- Following manufacturer directions regarding frying oil temperature. The recommended maximum oil temperature to avoid acrylamide formation is 345-350 °F (170-175 °C).
- Cooking fries to a light yellow or golden yellow color.
- If choosing to start with frozen product, cooking fries from the frozen state, not

¹⁹ This section draws on the following sources: Refs. 30-31, 41, 43.

²⁰ This section draws on the following sources: Refs. 30-31, 41, 43, 123.

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pre-thawing for quicker cooking. Cooking frozen fries from the frozen state, as recommended by manufacturers, reduces increased oil absorption at lower cooking temperatures.

- Screening out fines (very small pieces) after frying.
- Avoiding overcrowding fryers, which can cause oil temperature drops followed by temperature surges. High temperatures are more likely to produce acrylamide.
- Removing fried products promptly from the fryer, or using automated fry removal equipment.
- Calibrating fryers regularly to ensure that fryer temperatures are adequately controlled.
- Changing older (overused) oil promptly. Fries prepared in overused oils can appear darker than fries produced in fresh oil, making it difficult to check fry color.
- Selecting fry varieties (e.g., potato variety, fry cut) that form less acrylamide when frying.

Summary: Educating food service workers to follow proper frying techniques for french fries may help reduce acrylamide.

The following techniques may help food service operations reduce acrylamide in foods made from fresh potatoes. Some of these techniques are similar to those covered in Section B:

- Selecting potato varieties for frying or roasting that produce lower levels of acrylamide, e.g., potatoes with lower reducing sugar levels. Potential sources of information on acrylamide formation/reducing sugar levels include distributors, extension agencies, and trade associations. Sweet potatoes can also form acrylamide.
- Following proper procedures for handling fresh potatoes and requesting that suppliers do the same. Proper handling is especially important for potatoes that will be fried or roasted. Examples of such practices (from Section B) include not handling potatoes roughly, storing potatoes in a cool, dark place, and not refrigerating potatoes or storing them in freezing conditions.
- Soaking raw potato slices in water for 15-30 minutes before frying or roasting to lower sugar levels before cooking, but drying pieces before frying.
- Cutting thicker strips or larger pieces of potatoes when frying and roasting and removing very small pieces (fines) from fryers. Smaller potato pieces are more likely to have higher acrylamide levels after frying.
- Frying fresh-cut french fries or roasted potatoes to a light yellow or golden yellow color.

Summary: Selecting potato varieties that are low in reducing sugars for frying or roasting, properly handling and storing potatoes, and using certain cooking practices for foods made from potatoes may help reduce acrylamide in potato-based foods.

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The following techniques may help food service operations reduce acrylamide in cereal-based foods:

- Using color as an endpoint when preparing baked goods, such as baking and toasting breads and other baked goods to a light brown, not a dark brown color. In general, lighter-colored bread crusts and lighter-colored cookies will have lower acrylamide levels than darker versions of the same breads or cookies.
- Overly dry or crusty cereal-based foods (such as baked goods) are also likely to have higher levels of acrylamide, so cooking to a moister endpoint may also help control acrylamide levels.

Summary: Baking and toasting breads and other baked goods to a light brown, not a dark brown color; and avoiding overly dry or crusty products may help reduce acrylamide in cereal-based foods.

Table 7: Summary for PACKAGED FROZEN FRENCH FRIES AND FOOD SERVICE OPERATIONS

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| <ul style="list-style-type: none">• Providing appropriate cooking instructions on frozen french fry packages to guide final preparation by consumers and food service operators may help reduce acrylamide.• Educating food service workers to follow proper frying techniques for french fries may help reduce acrylamide.• Selecting potato varieties that are low in reducing sugars for frying or roasting, properly handling and storing potatoes, and using certain cooking practices for foods made from potatoes may help reduce acrylamide in potato-based foods.• Baking and toasting breads and other baked goods to a light brown, not a dark brown color; and avoiding overly dry or crusty products may help reduce acrylamide in cereal-based foods. |
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IV. References

We have placed the following references on display in the Division of Dockets Management, Food and Drug Administration, 5630 Fishers Lane, rm. 1061, Rockville, MD 20852. You may see them at that location between 9 a.m. and 4 p.m., Monday through Friday. As of September 25, 2015, FDA had verified the Web site address for the references it makes available as hyperlinks from the Internet copy of this guidance, but FDA is not responsible for any subsequent changes to Non-FDA Web site references after September 25, 2015.

Any references in this guidance to patents or patent applications are not intended to imply any manner of FDA support, favor, or endorsement.

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