A 100-Year Review: A century of dairy processing advancements— Pasteurization, cleaning and sanitation, and sanitary equipment design¹

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ABSTRACT

Over the past century, advancements within the mainstream dairy foods processing industry have acted in complement with other dairy-affiliated industries to produce a human food that has few rivals with regard to safety, nutrition, and sustainability. These advancements, such as milk pasteurization, may appear commonplace in the context of a modern dairy processing plant, but some consideration of how these advancements came into being serve as a basis for considering what advancements will come to bear on the next century of processing advancements. In the year 1917, depending on where one resided, most milk was presented to the consumer through privately owned dairy animals, small local or regional dairy farms, or small urban commercial dairies with minimal, or at best nascent, processing capabilities. In 1917, much of the retail milk in the United States was packaged and sold in returnable quart-sized clear glass bottles fitted with caps of various design and composition. Some reports suggest that the cost of that quart of milk was approximately 9 cents—an estimated \$2.00 in 2017 US dollars. Comparing that 1917 quart of milk to a quart of milk in 2017 suggests several differences in microbiological, compositional, and nutritional value as well as flavor characteristics. Although a more comprehensive timeline of significant processing advancements is noted in the Appendix Table A1 to this paper, we have selected 3 advancements to highlight; namely, the development of milk pasteurization, cleaning and sanitizing technologies, and sanitary specifications for processing equipment. Finally, we provide some insights into the future of milk processing and suggest areas where technological advancements may need continued or strengthened attention and development as a means of securing milk as a food of high safety and value for the next century to come.

Key words: milk processing, pasteurization, 100-year review, sanitation, food safety

A CENTURY OF MILK PROCESSING ADVANCEMENTS

One of the first dairy histories, written in 1899, stated, “No branch of agriculture has made greater progress than dairying during the nineteenth century... It is now regarded as among the most progressive and highly developed forms of farming in the United States” (Alvord, 1899). If the author had foreseen the revolutionary advances occurring in the next hundred years, he likely would have reiterated this sentiment.

One hundred years ago, in 1917, most of the world was enmeshed in the throes of World War I. Expansion of railroads and the beginning of farm to city migration was changing the landscape of the United States and Europe. Cities such as New York, Boston, Philadelphia, Chicago, and London were growing at rapid rates. Dairy processing, especially that of raw fluid milk, was at a turning point. By 1917, pasteurization was beginning to gain acceptance as a means of preserving milk and controlling milk-borne disease. In Denmark and Sweden, commercial pasteurization of milk was common as early as the mid-1880s, due in part to the early recognition by Danish butter makers of its merits (Herrington, 1948b; Westhoff, 1978). However, cities in the United States were much slower to openly embrace pasteurization techniques, despite evidence of some commercial pasteurization occurring covertly as early as the late-1890s (Herrington, 1948b).

In 1902, only 5% of the milk supply of New York City was heat treated, but by 1914, this number had risen to 88% (Jordan, 1913; Ayers, 1916). However, it would take several more years for pasteurization to become commonplace in smaller cities. Herrington cited the percentage of US cities pasteurizing at least half of their milk supply in 1915 at 77.8% for populations >500,000, 30% for 100,000–500,000, 16.7% for 25,000–50,000, and 6% for 10,000–25,000. These proportions would rise over the next few years to 100, 91.9, 80, and 45.7%, respectively, in 1924 (Herrington, 1948b).

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The automation of cream separation, bottle washing, filling, and capping marked the beginning of the modern industrialization of milk processing. The first automatic bottle machine was patented in 1907, and power cappers and fillers began to be used commercially starting in 1913 (Henderson, 1971b). Mechanical bottle washers were first introduced in 1895, and then improved with soaker-type bottle washers in 1906 (Henderson, 1971b). Industrialization of these dairy processes brought the establishment of milk food safety and sanitation standards. At the same time, better cleaning agents became available and widely used. Chlorine-type bleach began to be used for sanitizing equipment surfaces in 1912 (Henderson, 1971b).

Additionally, agriculture research had been on the rise since the late 1800s with governmental establishment of agriculture colleges and research institutions throughout Europe and the United States. Furthermore, cities across Europe and the United States were beginning to pass laws mandating some form of pasteurization or pasteurization standards as the link between fluid milk and some disease or illnesses began to be recognized. By 1898, pasteurization of all bottled milk was made compulsory in Denmark (Herrington, 1948b). In the United States, Chicago was the first major city to pass a mandatory milk pasteurization law in 1909, whereas New York was one of the last, in 1933 (Selitzer, 1976).

Research from the late 19th century by the celebrated German physician and microbiologist Robert H. Koch and others had linked the health of the cow to the transmission via fluid milk of certain diseases, including tuberculosis, diphtheria, typhoid fever, scarlet fever, anthrax, cholera, and foot and mouth disease (Freeman, 1896a,b; Calm and Shinert, 1899; Henderson, 1971d; Westhoff, 1978). Further advocacy work by Henry Koplix and Nathan Straus, Charles E. North, William D. Hoard (Hoard, 1918) and others (Selitzer, 1976; Westhoff, 1978) highlighted the role of milk spoilage and unsafe milk on increased fatality, especially in children, directly contributing to the creation and adoption of some food safety laws regarding pasteurization.

Although the concept of milk pasteurization was accepted and commercial pasteurization common by 1917, acceptable pasteurization standards had yet to be generally agreed upon (Appendix Table A1). The methods, temperatures, and timings for pasteurization were extremely varied. The first pasteurization in the United States was a type of early flash pasteurization, where continuous flow of milk was heated at around 71.1°C (160°F) for 30 to 60 s and then rapidly cooled (Westhoff, 1978). However, proper control of this process was not possible at the time due to the lack of automatic heat regulators and other technology to

control the temperature and times (Selitzer, 1976). Additionally, when pasteurization was first introduced, the lactic acid-producing bacteria were essentially destroyed, allowing thermophilic bacteria to proliferate, resulting in the milk displaying a more proteolytic form of spoilage rather than acid development during storage (Herrington, 1948b). Because of these problems, initial attempts at flash pasteurization were quickly condemned by public health officials (Selitzer, 1976).

Another early method used widely during the first decades of the 1900s was the in-bottle method, where bottled milk was heated at 62.8°C (145°F) for 20 to 30 min (Westhoff, 1978). The in-bottle method received support because it eliminated contamination post-pasteurization; however, it was not as favored commercially. A less common method also used was the bottling hot method, where milk was heated at 62.8°C (145°F) for 20 to 30 min and then filled into pre-steamed bottles (Westhoff, 1978).

However, by 1917, the most common and accepted method of pasteurization was the holding method, although there was still significant in-bottle pasteurization (Westhoff, 1978). With the holding method, milk was heated in vats at 60 to 65.6°C (140–150°F) for 30 min. Commercial holder apparatuses became available around 1907 in the United States, but due to their prohibitive cost, other smaller regenerative heaters and pasteurizers were also developed simultaneously (Hall, 1976; Selitzer, 1976). In 1908, the double-tube regenerative holder, in which outgoing milk helped heat incoming raw milk to reduce heating and cooling costs, was introduced and was widely used in milk plants in France, Denmark, Italy, and other countries (Henderson, 1971e). In 1911, the coil vat was first used as a batch milk processor; and around 1913, the barrel heater was introduced (Selitzer, 1976).

The groundwork for official standards of milk pasteurization was also being determined during this time. Between 1890 and 1927, at least 31 different time/temperature combinations were recommended for adequate pasteurization, with the most common being 142°F (61.1°C) or 145°F (62.8°C) for 30 min (North, 1925; Westhoff, 1978). Additionally, inadequately pasteurized milk could result from variations in temperature, holding time, and flow rate simply due to the technology of the equipment at the time. Early work supported a low-temperature holding method and recommended 60°C for 20 min (Rosenau, 1909). In 1911, the National Committee on Milk Standards in the United States recommended 62.8°C (145°F) for 30 min (North, 1925; Westhoff, 1978) but this standard was still not consistently accepted. In 1913, other studies investigated the types of bacteria in raw milk and in same milk pasteurized at different temperatures (Ayers and Johnson,

1913; Henderson, 1971c). Further studies and set standards were needed and would come in the next decade.

Beyond safety standards, Stephen M. Babcock's milkfat tests in 1890 were the first steps toward establishing dairy industry standards for the composition and quality of the raw milk product itself. Milk was often watered down—purposely or inadvertently—before this time, and the Babcock test provided a way to check the milkfat content. By 1900, many cities had begun to establish minimum standards of milkfat for fluid milk (Selitzer, 1976). Additionally, the Mojonnier test for fat and total solids was introduced in 1915 (Hall, 1976).

The rise of mechanical refrigeration and insulated or refrigerated milk train cars, in addition to the first use of tank trucks for transporting milk, facilitated the further transportation and longer storage of fluid milk than ever before. In 1914, glass-lined motor tank trucks were introduced by the Pfaudler Company for transporting milk in bulk (Hall, 1976). With the switch to bulk trucks, the milk hauler pumped milk directly from farmer's refrigerated bulk tank into the bulk truck and then drove to the factory, where the milk was pumped into holding tanks. This process discontinued the need for milk cans and their subsequent cleanings, thereby eliminating another major point of contamination. Electricity in businesses and homes throughout the 1920s and 1930s would change this even further. In 1922, there were about 13 railroad tank cars in the entire United States; by 1947, 40 tank cars were used for transporting milk to Chicago alone (Henderson, 1971a). Handling and conveyance of milk was also done using galvanized steel or iron cans. Not only were these cans especially heavy when filled with milk, but they were susceptible to rusting and milk contamination. These advancements also affected the location and size of the local dairies, as farmers, producers, and distributors began to shift to larger, more centralized processing operations. Associated dairying or co-operatives began to become common to allow the smallest farmers or producers to continue to sell and trade.

The trade and transport of butter and cheeses had been established in Europe since the Middle Ages, as river trade moved products from country to city and city to city. However, these same advancements that improved fluid milk around the turn of the 20th century also improved the longevity and trade of other milk products.

Ice cream has its roots in the water ices and milk ices of Asia, which were brought back to Europe in the 13th century by Marco Polo and spread across Europe over the next several hundred years (Turnbow and Raffetto, 1928; Arbuckle, 1986). Cream or butter ices were served by courts and royalty in the 18th century and made their way to the United States with early

English colonists in the late 1700s (Turnbow and Raffetto, 1928; Arbuckle, 1986). The first wholesale ice cream industry in the United States was established in Baltimore, Maryland, in 1851 by Jacob Fussell, with early plants in St. Louis, New York, Washington, Chicago, and Cincinnati (Arbuckle, 1986). Development of condensed and dry milk, introduction of the brine freezer, pasteurization, homogenization, the Mojonnier milk tester, ice cream overrun tester, direct-expansion batch-type ice cream freezer, and improvements in processing equipment would have a major impact on the availability and quality of ice cream products (Turnbow and Raffetto, 1928; Hall, 1976; Arbuckle, 1986). However, the introduction of the ice cream cone at the 1904 World's Fair in St. Louis is thought to have significantly increased the popularity and production of ice cream (Turnbow and Raffetto, 1928; Herrington, 1948a). Regardless, by 1917, ice cream was a common and popular treat, whose availability and production would only be increased in coming years by technology and ease of improvements in production and availability of mechanical refrigeration. The US government did not provide ice cream production figures until 1909, but production increased from 80 million gallons in 1909 to 219 million gallons in 1917 (Turnbow and Raffetto, 1928). By 1942, the country's ice cream production had reached 462 million gallons per year (Herrington, 1948a). Production data in the United States place 2016 ice cream production on the order of 918 million gallons across all classes, such as low and nonfat (USDA-NASS, 2017).

MILK PRODUCT PASTEURIZATION

In 1912, Dr. Charles E. North firmly stated to the Convention of International Milk Drinkers, "I believe the milk problem, as a problem, is being rapidly settled. I think that the establishment of a uniform standard by our public health authorities will be a tremendous step. The adoption of sanitary measures and pasteurization by you will be the other great step. When these two things are done, the milk problem will be extinct . . . The milk of the future and the milk that you sell will be clean, first, and secondly, it will be pasteurized, and I doubt whether there will be necessary very many classes or grades of milk. We will find that one grade and one class is the satisfactory milk, and it will be both clean milk and pasteurized milk, produced economically and at a reasonable price" (North, 1912; Selitzer, 1976).

By 1917, the merits of pasteurization were readily accepted, but acceptable standards and the enforcement of those standards in commercial practice were still to come. These improvements in pasteurization and standards for pasteurization would greatly affect the milk

industry from 1917 to today. From 1915 to 1924, the US Public Health Service (PHS) reported an increase in pasteurization of milk sold in cities with populations >10,000 from 6 to 45.7% (Henderson, 1971e). By 1947, the PHS reported that 90% of the milk sold in cities with populations >10,000 was pasteurized (Henderson, 1971e).

In 1917, the most common method of pasteurization was probably the holding method and it would continue to be so into the 1930s and early 1940s (Selitzer, 1976; Westhoff, 1978), due in part to the simplicity of the system and reduced cost relative to continuous pasteurizers. In 1920, the American Public Health Association Committee on Milk Supply reported that none of the ~4,200 pasteurization plants in United States afforded full protection against ineffective pasteurization (Appendix Table A1; Anonymous, 1920; Westhoff, 1978). In response to this and the lingering questions on proper pasteurization standards, Henry North and the Borden Company, along with over 20 invited experts, set up a series of 4 experiments in an Endicott, New York, milk plant in 1922–1923 (Heulings, 1925; North, 1925; Westhoff, 1978). In the experiments, which would come to be known as “the Endicott experiments,” milk was inoculated with various pathogenic cultures, including *Mycobacterium tuberculosis*, to test effectiveness of different time/temperature combinations (Moore et al., 1925; Park et al., 1925). Additionally, common machinery was examined and found to have defects with inadequate temperature control, vat manufacturing defects, leaking valves, and imprecise timing, leading to the conclusion that pasteurization plants needed better engineering and equipment controls (Moore et al., 1925; Park et al., 1925). Additional studies in 1933 by Thurston and Olson would compare types of bacteria in high-grade raw and pasteurized milk (Thurston and Olson, 1933; Henderson, 1971c); interestingly, the former work found an increased level of acid-forming bacteria following pasteurization in contrast to subsequent work, noted below.

Advancing technology continued to improve the pasteurization process as well. Pasteurization equipment in 1917 consisted of a heater, a vat or pocket-type holder, and a cooler (North, 1925). Improving on the double-tube regenerative holder of the 1910s, regenerative plate heat exchangers were first introduced in 1923 (Henderson, 1971e; Hall, 1976). Another key advance to the dairy industry was the introduction of mechanical refrigeration and the 1934 discovery of the compression cycle, providing huge improvements over the use by early milk plants of surface coolers kept cold with just ice or well water (Henderson, 1971b). The vacuum pasteurization method was improved for commercial use by 1946 (Hall, 1976). These and other improvements

in the technology and automation of pasteurization in the coming years would greatly affect the production of the industry—fluid milk operations in 1925 produced only 28 gallons of pasteurized product per man-hour; this rose to 40 gallons in 1945, and to 180 gallons per man-hour in 1965 (Hall, 1976). Part of this increase can be attributed to the shift from batch pasteurization to continuous pasteurization that the improved technology allowed.

In 1924, the first PHS pasteurization ordinance was published, requiring 142°F (61.6°C) for 30 min (Hall, 1976; Westhoff, 1978). By 1935, Canada and some parts of the United States required pasteurization at 140 to 145°F for 30 min, whereas in Great Britain milk was to be pasteurized at 145 to 150°F for 30 min and immediately cooled to 55°F (Kay and Graham, 1935). In 1950, a study suggested a possible link between a Q-fever outbreak in southern California with raw milk infected with *Coxiella burnetii* (Bell et al., 1950). Although this was later established to not be the case (Krumbiegel and Wisniewski, 1970), it led the PHS to establish a research project to study the thermal resistance of *C. burnetii* and subsequently increase pasteurization recommendations to 145°F (62.8°C) for 30 min (Westhoff, 1978).

Quality control standards for pasteurization also improved in the early 1930s with the discovery of the alkaline phosphatase test. Since the turn of the century, quality control of pasteurization or pasteurization machinery had been limited to time-intensive bacterial counts or the rudimentary methylene blue test, in which the color-changing reduction of methylene blue was used as an indicator of the bacterial content of milk (Clark et al., 1925; Lewis and Deeth, 2009). Kay and Graham, however, found that the phosphatase enzyme was denatured under proper pasteurization techniques and could be checked by 2 simple tests (Graham and Kay, 1933; Kay and Graham, 1933, 1935). Conditions required to denature the enzyme are slightly more severe than those required for inactivation of *Mycobacterium tuberculosis* (Lewis, 1994). If these conditions are not met and active phosphatase is still present under alkaline conditions, phenol will be released, which is determined colorimetrically (Rankin et al., 2010).

Alkaline phosphatase has been used since then as an index for adequate pasteurization of milk, with improvements in analytical equipment technology to further allow its measurement with more precision (Lewis, 1994).

It should be noted that acceptance of homogenization in the 1930s also benefited pasteurization. As one editorial noted in 1925, pasteurization was not only a matter of public safety to the fluid milk customer. Varying pasteurization methods increased or decreased

the apparent volume of cream above or below that of untreated milk, affecting the visible cream layer (but not the actual milkfat content), which was the major trait by which quality milk was judged by the consumer at that time (Anonymous, 1925).

The introduction of the “electropure process” of pasteurization using ohmic heat in 1919 created new interest in the concept of flash pasteurization (Selitzer, 1976). By 1923, an early high-temperature, short-time (HTST) pasteurizer was developed, but HTST was not common for another 10 to 20 yr (Hall, 1976). Additionally, initial efforts at flash pasteurization were slow and expensive due to amount of ice required for cooling (Henderson, 1971b). Together with the introduction of the electric motor in 1919 (Selitzer, 1976) and improvements in refrigeration technology, HTST continuous processes developed between 1920 and 1927 (Lewis and Deeth, 2009).

The commercial introduction of regenerative plate heat exchangers in the 1930s allowed for further development of HTST methods (Westhoff, 1978). Fool-proof controls and better equipment were necessary to overcome the problems of early attempts at HTST and the attempts of the 1920s (Selitzer, 1976). Expectedly, there was strong reluctance from public health officials due to past problems, but acceptance came with improvements in controls and development of equipment, such as leak-proof valves and reliable controls and regulators (Selitzer, 1976; Westhoff, 1978). By 1938, HTST systems included sophisticated controls and diversion valves (Hall, 1976), significant developments that affected the high production rate of pasteurization (Hall, 1976).

In 1933, the US PHS Milk Ordinance code included HTST standards for first time, with a recommendation of 161°F (71.7°C) for 15 s, due to creaming of milk and thermal destruction of microorganisms (Westhoff, 1978). Later research concluded that 160°F (71.1°C) for 15 s resulted in destruction of tested pathogens (Workman, 1941; Westhoff, 1978). By the 1950s, HTST pasteurizers were widely used (Hall, 1976), with 75% of pasteurized fluid milk in the UK being HTST pasteurized (Lewis and Deeth, 2009).

Pasteurization at higher temperatures, referred to early on as “quick time” pasteurization, was being explored as well (Dahlburg et al., 1941; Westhoff, 1978). In 1921, Jonas Nielson first sterilized milk using a process that would be known as ultra-high-temperature (UHT) pasteurization (Hall, 1976). In 1927, a steam injection system was patented by Grinrod that heated milk to 110°C, held it for 1 to 2 min, and then cooled the milk using an expansion chamber by removing the condensed steam (Hostettler, 1981). The coming years brought improvements in the steam injection process,

with temperatures near 150°C and holding times as short as 30 s (Westhoff, 1978; Hostettler, 1981). At the same time as conventional HTST systems (plate exchangers and indirect heaters) were being used at temperatures above those recommended for HTST pasteurization to reduce bacterial load and increase shelf life, these direct heating methods (steam injection or steam infusion) were being developed and tested for use at high temperatures (Westhoff, 1978).

Research by the National Institute for Research in Dairying in the 1970s comparing indirect heater (plate heat exchanger) and direct heater (steam injection) systems found that the direct heating system had to be operated 3 to 4°C higher than the indirect system to produce equal sporicidal effects (Franklin et al., 1970; Westhoff, 1978). However, differences in vitamin and nutritional value of the processed milk by indirect or direct system were reported as negligible (Burton et al., 1970; Westhoff, 1978).

In 1958, UHT was used commercially first for ice cream mix, and then later for fluid milk (Hall, 1976). In 1966, heat treatment providing a sterile concentrated milk was first commercially marketed (Hall, 1976). In 1969, UHT pasteurization standards were first published (Hall, 1976); UHT processes can be either pasteurization or sterilization, depending on the time/temperature combination (Westhoff, 1978). The UHT process is defined by the International Dairy Federation as 130°C continuous flow and hold for >1 s (Westhoff, 1978). However, in many European nations, UHT refers to a time/temperature combination that renders the product commercially sterile (Westhoff, 1978).

More recent pasteurization standards are as follows. According to Westhoff (1978), vat or batch standards were 145°F (62.8°C) for 30 min for fluid milk, 150°F (65.6°C) for 30 min for cream, and 155°F (68.3°C) for 30 min for ice cream mix; HTST pasteurization standards were 161°F (71.7°C) for 15 s for milk, 166°F (74.4°C) for 15 s for cream, and 175°F (79.4°C) for 25 s for ice cream mix; various time and temperature standards for UHT processing of milk were also published, such as 191°F (88.3°C) for 1 s, 194°F (90°C) for 0.5 s. In 1989, the UK Milk Special Designation Regulations required that pasteurized milk be retained at a temperature of 62.8°C to 65.6°C for at least 30 min and immediately cooled to <10°C; retained at a temperature of >71.7°C (<78.1°C in Scotland) for at least 15 s and be immediately cooled to <10°C (or <6°C in Scotland); or retained at such a temperature for such a period as may be specified by the licensing authority, with the approval of the minister (Lewis, 1994). In Great Britain in 2003, 92.9% of heat-treated milk for drinking was pasteurized, 1.4% was sterilized in container, and 5.7% was UHT treated. In Australia, 91.9, 0, and 8.1% of milk was pasteurized,

sterilized in container, and UHT treated, respectively (Lewis and Deeth, 2009).

CLEANING AND SANITIZING

Initial efforts at modern sanitation of the milk industry began with the invention of the glass milk bottle and its caps. Further innovation brought power cappers, bottle fillers, and mechanical bottle washers. By 1917, the first steps toward cleaning and sanitation processes were taken. However, it was not until the industrialization and automation of the dairy industry in the middle of the 20th century that standards were applied to cleaning and sanitation, which set the stage for the processes and standards still used today.

Further sanitation was afforded by continuous automatic can washers in 1919, the first use of stainless steel in commercial dairy equipment in 1925, use of the first welded stainless steel bulk tanker in 1927, and the introduction of sanitary-type pumps for dairy products in 1934 (Hall, 1976). Introduction of better detergents and cleansers also advanced the role of sanitation in the dairy industry. Soap, caustic soda, and soda ash were the standard cleaning agents of the early 1900s, with calcium hypochlorite as the available sterilizer (Cole, 1955). The 25-year period following 1917 saw the introduction of a variety of detergents, cleansers, and other cleaning agents that were essential precursors to the huge developments in dairy sanitation that would come about from the mid to late 1940s. This period brought the introduction of trisodium phosphate (early 1920s), metasilicate (late 1920s), chlorinated phosphates and acid-type cleaners (early 1930s), anionic wetting agents (1935), EDTA and gluconates (late 1930s; Cole, 1955), and the introduction of quaternary ammonia compounds as cleaners in 1939 (Hall, 1976) and hexametaphosphate in milking units (Babel, 1955).

However, it was the development of cleaning-in-place (CIP) technology that revolutionized sanitation pro-

cesses in the dairy industry. Cleaning-in-place technology had its beginnings in the metal shortages of World War II. Standard materials for dairy piping systems—tinned-copper or stainless steel tubing—were scarce in the United States, leading to the incorporation of heat-resistant borosilicate glass fixtures and piping as early as 1941 (Hucker and Thomas, 1943; Thom, 1949; Fleischman et al., 1950). Borosilicate glass piping had been selectively used in other areas of the food industry since 1926 when it was developed by Corning (Funke and Blizard, 1944, Fleischman et al., 1950). Because this glass tubing was fragile, CIP design and operations were initially attempted to reduce breakage from repeated disassembly. An early field test showed that glass tubing could be effectively cleaned and sterilized in place (Hucker and Thomas, 1943). Additionally, Hucker and Thomas, (1943) showed that the bacterial count of fluid milk did not increase after passage through the glass tubing, which was later confirmed (Fleischman et al., 1950; Kaufmann et al., 1955). As labor was also scarce during World War II, the less labor intensive CIP processes were advantageous to dairy plants and industry from a personnel standpoint.

Reports of successful use of glass tubing in dairies in New York State with CIP methods were reported as early as 1943 (Hucker and Thomas, 1943; Funke and Blizard, 1944). Thom reported that by 1949, glass piping and CIP methods were in place in more than 20 dairies (Figure 1), saving costly clean-up time (Thom, 1949). Many of these early attempts not only proved successful but were found to be easier to avoid contamination than with metal piping that was continually disassembled and reassembled.

These first attempts at permanent piping were generally implemented to move raw milk in the plants, both because of the typical long length of these pipes and the belief that these were the safest experimental lines because the milk would still be subjected to pasteurization (Thom, 1949). Approval by local city and state

Figure 1. A 1970s-era Pyrex milk pipeline showing metal (probably chrome-plated) connection fittings. Image courtesy of D. M. Chance, Pioneer Acres, Galena, MD.

health departments of these CIP methods was also reported, although some agencies demanded that an experimental raw milk line be tested and validated before approval was granted (Thom, 1949). As steel became available again at the close of World War II, stainless steel pipes of a specific grit finish were also shown to be able to be cleaned-in-place properly (Abele, 1955).

Initial CIP methods varied but were generally as follows: flush system of residue, clean valves and caps and manually cleaned parts, set up return lines to recirculate, wash by recirculating acid or alkaline detergents, rinse and cool the system, drain completely, reassemble for processing, and sanitize with hot water or chemical sanitizers (Seiberling, 1955a). One early protocol called for a 10-min water rinse, >15-min circulation of 110°F 0.6% alkaline cleanser with 4.0% wetting agent (with brush periodically), 110°F water rinse, and a sterilizing 190°F water rinse followed with a 100-ppm chlorine rinse immediately before use (Hucker and Thomas, 1943). Metal fittings were disassembled periodically for cleaning and then cleaned again after reassembly (Hucker and Thomas, 1943). Another early recommendation called for a cold water flush, a small sponge or ball brush forced through the lines with cold water, another cold water flush, 15- to 60-min circulation of 135 to 165°F detergent cleaning solution (0.25–1.0%), another small sponge or ball brush forced through the lines with water, disassembly and cleaning of the pumps and valves, reassembly, and a final warm water rinse with subsequent sterilization with >100 ppm of chlorine and 160 to 180°F water rinse (Thom, 1949). Double lines were especially recommended to allow for recirculation of solutions, saving cleaning solution, water, labor, and money (Thom, 1949). Within this same era, the *Journal of Dairy Science* published a review of sanitation methods for dairy plants (Kaufmann, 1956).

Early work also established the deleterious effects of reactive sanitizing agents on dairy product quality, such as the residual effects of quaternary ammonia on lactic acid bacteria growth (Miller and Elliker, 1951) and halogen residuals on off-flavors (Jensen et al., 1963; Hekmati and Bradley, 1979) and color (Toba et al., 1980) in milk. Theoretical or preliminary setups for automation of CIP began in 1953 (Seiberling, 1954, 1955a,b); however, the key to CIP automation was the development of an automated valve that could be cleaned in place (Harper, 2010). Seiberling and Harper (1957b) developed the automated air-operated valve and confirmed its ability to be cleaned in place using radioactive Ca^{45} , followed by a trial of the automated CIP system using these valves in an Ohio dairy plant in 1956. That same year, use of spray ball devices was also reported (Seiberling and Harper, 1957a). A few years later, the first commercial evaluation of total process/

CIP automation occurred (Bonem, 1960), followed by the introduction of CIP cleanable clarifiers in 1962 (Hall, 1976). At this time, these systems were no longer simple pipelines left in place but engineered systems that required specialized labor and forethought. Development of CIP technology involved close attention to pipework design, valve configurations, spraying devices, chemical systems, and automatic operations (Kirkland, 1994).

By the late 1960s, the CIP technology introduced and developed by the dairy industry began to be adopted for use in other food and beverage industries, and by the late 1970s, the pharmaceutical industries also began introducing automated CIP methods. This CIP technology and practices have revolutionized not only the dairy industries, but food and pharmaceutical production in general.

As the 20th century was ending, issues such as emerging pathogens and unique processing soils, such as milk burnt onto heat transfer surfaces, came to bear on the industry and the processing plants. The bacterium *Listeria monocytogenes* (still regarded as a most significant pathogen), other pathogens, and spoilage bacteria (Witter, 1961), as well as the means to control and prevent their presence in finished dairy foods, became of particular concern (Cousin and Marth, 1977; Vasavada, 1988). In parallel with control and prevention measures and the adoption of more sophisticated processing equipment, extended run times, and novel heat exchange devices, the issue of biofilm formation and removal came to bear on the industry (Wong, 1998; Anand and Singh, 2013) with renewed vigor for the adoption of rigorous CIP designs (Alvarez et al., 2010).

SANITARY DESIGN SPECIFICATIONS

It seems appropriate that a publication in the first year of the *Journal of Dairy Science* began with an effort to continue to refine the questions of milk quality (Harding et al., 1917). In part, that definition and our efforts to improve the quality of milk products reside in the establishment of official industry-wide sanitary standards for milk handling and processing equipment. These standards were formally set into motion in 1933, when the International Association of Milk Inspectors formed a committee to establish standards in an effort to combat bad sanitation practices. The resulting sanitary standards for milk piping and thermometer fittings were published in 1938 in collaboration with a committee of the International Milk Dealers Association (Abele, 1955). However, the demands of World War II on the industry put developments on hold for several years. In 1944, the International Association of Milk and Food Sanitarians (IAMFS), and United

States Public Health Services Milk and Food Sanitation section were invited by the newly organized Sanitary Standards Subcommittee of the Dairy Industry Committee (DIC) to form a collaboration to formulate what would become known as “3-A” sanitary standards of dairy equipment and processing for the dairy industry (Abele, 1955). The designation of “3-A” is derived from the 3 groups that collaborated to develop these standards (Appendix Table A1). Under these organizations, 3 major dairy industry sectors were represented, meaning that these new standards would be widely adopted by all dairy industries, not just the fluid milk dairy industry.

These sanitary standards and accepted practices not only established theoretical sanitary methods and how equipment should be properly cleaned, but also how and of what materials processing equipment should be constructed for easier cleaning and proper maintenance (Abele, 1955). By 1955, 3-A standards had been established for 2 sanitary procedures and 14 pieces of equipment, with 8 more equipment pieces in the process of being formulated (Abele, 1955).

The 3-A Sanitary Standards and 3-A Accepted Practices for CIP were first published in 1953 (International Association of Milk and Food Sanitarians, 1953). Standards for different cleaning methods were not set, as various methods had been shown to be effective. However, it was established that piping should be made of 18–8 stainless steel or glass piping with fittings of 18–8 stainless steel or glass and 120 grit finish for steel piping or fittings. Gaskets needed to be made of smooth, nontoxic, low absorbent material, and both gaskets and fittings had to be flush with interior of piping (International Association of Milk and Food Sanitarians, 1953). The move toward set dairy standards was seen both in the United States and Europe, as what were once local initiatives regarding the hygienic quality and composition of liquid milk resulted in local, regional, and then national standards (DeKok, 1986).

Further research in the 1950s brought additional improvements to CIP design and sanitation in general, especially with regard to metal welds (Havighorst, 1951), fittings, and adaptors attaching the CIP metal or glass pipes together, changing the way these parts were constructed to allow them to be cleaned in place as well. These innovations also allowed the process of CIP to be automated, truly changing the dairy industry and allowing for a higher quality and quantity product with much less labor, saving money for both the producer and consumer.

Examples of current design specifications used in application to the broad dairy manufacturing industry include those set forth by 3-A (<http://www.3-a.org/>) and NSF International (<http://www.nsf.org/>) in the United

States as well as like-minded specifications from other countries or regions such as those published by the European Hygienic Equipment Design Group (EHEDG). As the supply of dairy foods continues to grow in global trade, the need to ensure the safety and quality of such foods increases. A critical component of ensuring safety and quality standards is to adopt and enforce compliance with these existing specifications and to consider a means of creating a unified set of specifications for the global marketplace.

THE NEXT CENTURY OF MILK PROCESSING

With a large number of skilled scientists, manufacturers, and regulators applying significant attention to the processing of milk products for well over the past century, we could argue that the dairy processing industry is mature to the point that most major problems facing the milk industry have already been overcome and that most major advancements have been achieved. Coupled with the high degree of regulatory scrutiny and structure both imposed by governments and now more commonly by the industry and through litigation actions, we might question whether major advancements are positioned on the horizon or are even needed for a healthy future of diverse, safe dairy foods processing industry. Although this pattern of investment and research has been, to date, a model of wise stewardship of this industry, future challenges will require increased standards of investment and research based on what we foresee will become the challenges of the next century of dairy manufacturing. We propose and describe 3 challenges ahead of potential significance that seem to be gaining increased momentum and require our attention and technological investment: (1) verifiable documentation of practices to control milk product safety, (2) improved environmental footprint, and (3) the presence of non-animal-derived food products.

The first issue is the growing requirements and technologies to document that all required processing parameters significant to food safety have been controlled and that the achievement of those controls has been adequately documented. For example, the fundamental definition of milk “pasteurization” as presented in the US Pasteurized Milk Ordinance (PMO; Anonymous, 2015) is a prime example wherein processing criteria have been accepted and published, yet some criteria exist without a clear means of documenting that they have been met; the PMO reads

The terms “pasteurization,” “pasteurized” and similar terms shall mean the process of heating every particle of milk or milk product, in properly designed and operated equipment, to one (1) of

the temperatures given in the following chart and held continuously at or above that temperature for at least the corresponding specified time.

The chart referenced in this definition provides time and temperature minima for the heat processing of different liquid milk streams (e.g., 72°C, 15 s for fluid milk). This most fundamental definition of milk pasteurization contains 5 criteria required to achieve food safety; the achievement and adequate documentation of all of these criteria becomes more complicated and increasingly important in our litigious society. The 5 main control criteria in this PMO definition of milk pasteurization, slightly reworded for clarity, are as follows: (1) every particle of milk must be heated in accordance with the time and temperature criteria, (2) the equipment must be properly designed, (3) the equipment must be properly operated, (4) a temperature standard must be met, and (5) a holding time standard must be met in complement to the temperature. The temperature standard criterion (4) is readily met and documented through the proper function and operation of the safety thermal limit recorder and the generation of a temperature chart. The achievement of and documentation for the other 4 criteria are less structured. For instance, the time criterion (5) for a continuous pasteurizer is not actually recorded outside of the regulatory timing and sealing event—an event that may occur as infrequently as annually. Minimally, a plant should visually inspect and record that all regulatory seals are in place each day as one means of verifying the time criterion is being met. We invite all readers to consider what documentation a manufacturing plant may be asked to produce to authoritatively verify that each of these criteria was met using either vat or continuous pasteurization for a particular lot of finished product, especially in a scenario where product safety may be suspect and under the scrutiny of litigation. This example of compliance with and documentation of the criteria of milk pasteurization is one of a multitude of food safety-related processes that, in the future, will most likely require an increased means of not only improved compliance in design and intention, but a defensible means of documenting that compliance has been achieved.

The second potential future development of the next century will involve increased scrutiny on and development of technologies to reduce the environmental footprint of milk processing (von Keyserlingk et al., 2013). Current designs around the provision of food for the growing global population find that milk and dairy products provide a significant and nutritionally valuable food through bioconversion of material that is mostly inedible to humans into a material with few

nutritional rivals. However, all modern industries engaged in the production of food will continue to need to develop technologies in response to pressures from ever-tightening resources and unsustainable environmental footprints. Beginning in approximately 2015, the US National Science Foundation determined to invest in the development of such technologies through a specific funding stream titled, “Innovations at the Nexus of Food, Energy and Water (FEW) Systems,” wherein research is funded to advance our understanding of the FEW nexus, develop real-time interfaces to understand and support decision making of FEW systems, create innovations to FEW problems, and to develop a workforce with increased literacy on FEW systems. Given the large size and capacities of the dairy manufacturing industry based on available metrics significant to this subject (Milani et al., 2011; Tomasula et al., 2013; Vergé et al., 2013), technological advancements may address such issues as water processing and recovery, waste stream control, heat transfer efficiencies, disposition of cleaning and sanitizing chemistries and their disposition, and resources involved in packaging. A short list of possible other technologies that we will might further develop or that may be more readily adopted in the future include such advancements as (1) electrochemically activated chemistry, wherein caustic and chlorine sanitizer are created from the electrochemical treatment of relatively innocuous NaCl salt solutions, thus reducing the shipping and storage needs for hazardous NaOH and chlorine sanitizers (Aider et al., 2012); (2) product vessels with properly designed anti-vortex devices (Figure 2) to reduce the volume of water, chemicals, and energy required in CIP circuits, while improving the cleaning performance (Chen et al., 2007); (3) liquid ring pumps that can effect dramatic reductions in water, chemical, energy, and cleaning time while also reducing pump wear and maintenance (Nash, 1914); (4) pulsed-flow CIP to reduce the water volume, chemical, and energy consumption in the line CIP circuits (Augustin and Bohnet, 2001); and (5) non-thermal means of pasteurization, such as membrane separation/filtration or radiation-based treatments, with potential energy savings, reduced fouling, and increases in product functionality (Datta and Tomasula, 2015). The future will include increased scrutiny on our industry and will contain more detailed, comprehensive information describing the FEW nexus of dairy production and manufacturing. The dairy industry would be wise to continue to make strong investments to advance processing technologies capable of meeting and exceeding the future demands in this realm.

We suggest that a final future-facing issue resides with the potentially malleable definition of milk itself. For instance, as written in the US Code of Federal

Figure 2. Image of the outlet of a milk storage vessel fitted without (A) and with (B) a vortex-preventing device. Such devices can dramatically improve the efficiency and efficacy of clean-in-place (CIP) operations and increase the operational life of critical operating devices such as pumps, meters, and valves.

Regulations (21CFR101.110), the definition of milk is published as follows:

“Milk is the lacteal secretion, practically free from colostrum, obtained by the complete milking of one or more healthy cows.”

whereas regulations [ATCP 65.01(36); https://docs.legis.wisconsin.gov/code/admin_code/atcp/055/65] currently in force within the dairy-rich state of Wisconsin define milk as follows:

“‘Milk’ means the normal lacteal secretion, practically free of colostrum, obtained by the complete milking of one or more healthy milking animals.”

The main differences in the Wisconsin regulations include the term “normal” to exclude a variety of “abnormal” or unhealthful states of milk and the term “milking animals,” creating a legal broadening for milk from non-bovine species. In public practice, however, the definition of “milk” is becoming dramatically broader and broadening with continued implications for the traditional milking animal industry. The soy, almond, cashew, rice, oat, flax, and other non-animal industries apply various technologies to design foods based on the strengths of animal milk products such as nutrition, taste, and functionality but with value-added benefits such as nutrient enrichment, calorie density, and allergen- and lactose-free status. Markets for plant-based milks or milk alternatives are reported to exceed \$10 billion by the year 2019 and currently exhibit double-digit growth (Anonymous, 2016). Efforts have been underway to clarify the use of the term “milk” for labeling purposes, given the highly regulated US definition of milk and the need to ensure that consumers are not being misled. Regardless of how the term “milk” will

be applied, plant-based beverage industries are making strong investments in their abilities to compete with animal-based milk, and our industry would be wise to continue making technology-based investments. Improvements in flavor, digestibility (Tunick et al., 2016), shelf life (Caplan and Barbano, 2013), an increase in the variety and application of milk-derived ingredients, and the development of novel dairy products are a few of many areas that will need continued attention for dairy-based milk products.

We suggest that these 3 technological issues—process verification, improved environmental footprint, and responses to the presence of milk alternatives—represent a few of a multitude of areas we will face as an industry in the next century. We are hopeful that the model of the past century of success, built on the combined effort of industry, regulatory, and research stakeholders, will be sustained through the next century of processing technology advancements and will provide the dairy industry with the technological advancements and educated individuals to ensure that this historically important human food remains as viable in the century ahead as it was a century ago. We anticipate a captivating summary of these advancements at the bicentennial mark of the *Journal of Dairy Science*.

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APPENDIX

Table A1. Early milestones in the history of the past century of milk processing

Date	Milestone	Reference
1919	Homogenized milk sold in Connecticut.	Trout, 1963
1920	American Public Health Association Committee on Milk Supply declares that none of the 4,200 milk-processing plants in the United States offer full protection against inadequate pasteurization.	Anonymous, 1920
1921	First sterilized milk is produced by Jonas Nielson using a forerunner of the UHT process.	Hall, 1976
1922–1923	Endicott experiments are initiated, providing a definitive standard of heat treatment for milk pasteurization.	Heulings, 1925; North, 1925
1924	First US pasteurization ordinance is published.	Hall, 1976; Westhoff, 1978
1925	Stainless steel is first used in commercial dairy equipment.	Hall, 1976
1928	Regenerative plate heat exchangers are introduced. High temperature, short time (HTST) pasteurizer is first developed.	Westhoff, 1978
1933	US Pasteurized Milk Ordinance includes HTST standards.	Westhoff, 1978
1933	First papers are published describing alkaline phosphatase testing as a means of validating the milk pasteurization process.	Graham and Kay, 1933; Kay and Graham, 1933, 1935
1934	Cyclical refrigeration is introduced.	
1934	Sanitary style pumps are introduced for dairy processing.	Hall, 1976
1930s	Homogenization begins to gain application to prevent creaming of fluid milk products and to allow milk thermal treatments to be more uniformly applied.	Selitzer, 1976
1944	The initial structure of 3-A, as in 3-A sanitary specification standards, is put into place.	Abele, 1955
1950	<i>Coxiella burnetii</i> is implicated as the causative agent in raw milk Q-fever outbreak; US Public Health Service initiates research that results in increase of pasteurization temperature.	Bell et al., 1950
1953	Designs for automated clean-in-place (CIP) systems are initiated.	Seiberling, 1954, 1955a,b
1958	First UHT system is installed for commercial operation.	Hall, 1976