Chapter 2
A Short History of Research and Development Efforts Leading to the Commercialization of High-Pressure Processing of Food

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Abstract The history of the development and commercialization of high hydrostatic pressure processing of foods includes groups in Japan, Europe, and the United States. This narrative focuses on early research and development commercialization efforts starting in 1984 in the Department of Food Science at the University of Delaware, Newark, Delaware. Research efforts expanded in 1990 as a joint program among the University of Delaware, the Department of Food Science and Technology at Oregon State University, and the US Army Combat Feeding Directorate at the Natick Soldier Research, Development and Engineering Center, Natick, Massachusetts. Activities of an industry-university High Pressure Consortium, managed by Marcia Walker and D. Farkas, at Oregon State University, helped commercialization by providing a focus for research, development, technology transfer, regulatory challenges, and solutions. The plan was to develop the use of high hydrostatic pressure into a profitable, new food processing technology that provided safe, fresh-tasting, convenient foods, with an extended shelf life.

Dr. Edmund Ting at Flow International recognized that breakthroughs in the design of high-pressure vessels and pump intensifiers would be needed. He pioneered unique equipment developments required by the food processing industry and helped clear the way for cost-effective commercial use of high pressure for food preservation.

The commercial use of high hydrostatic pressure for food preservation started in Japan in the late 1980s. Acid products, including yogurt and strawberry jam, were produced. These products resulted from work by a consortium of 25 companies brought together by Professor Rikimaru Hayashi to exploit the potential of high pressure as a nonthermal technology for pasteurizing foods with minimum heat damage.

Independently, Professors Dan Farkas, Dallas Hoover, and Dietrich Knorr initiated studies on the feasibility of high-pressure food processing starting in 1984 at

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the University of Delaware. Workers from the two programs met for the first time in June 1989 at a conference on engineering and food in Cologne, Germany, convened by Professors Walter Spiess and H. Schubert. In 1992 R. Hayashi and C. Balny edited a book (Hayashi and Balny, 1992) covering a joint conference drawing from Japanese and European research work on high-pressure food processing.

A symposium held at the University of Reading, England, on March 28–29, 1994, and the subsequent book, *High Pressure Processing of Foods*, serves as a milestone marking the end of the early history of research and development leading to the wide commercial use of high-pressure food processing. This symposium recognized that: "The scientific basis for the success of the process does involve many disciplines including both chemistry and microbiology. However, its commercial success, as with many food operations, has to be based on an effective integration with the engineering disciplines involved in the design and manufacture of equipment and plant capable of efficiently and safely applying such pressure to both solid and liquid food" (Ledward et al., High Pressure Processing of Foods, Nottingham University Press, Leicestershire Press, UK, 1995).

Keywords High-pressure processing • History • Research and development • Commercialization

2.1 Introduction

The use of high hydrostatic pressure to preserve foods is the first truly new method for food preservation since Nicolas Appert developed the use of heat to preserve foods in sealed glass bottles some 200 years ago. High pressure does not depend on heat, chemicals, reduced water activity, or reduced temperatures to control pathogens or spoilage microbes. Pressures in the range of 200–600 MPa have been found to unfold proteins so that they lose their biological functions as cell wall membranes and enzymes. In contrast to heat, high pressure does not break covalent bonds. High pressure is transferred instantly throughout a package of food independently of size, shape, or composition. These advantages give the food processor an almost ideal method to preserve food without heat and to conserve the product without any loss of original nutrients, flavors, pigments, or functionality.

The benefits of high-pressure food preservation (HPP) were recognized as early as 1894 through the research efforts of Burt Hite at the West Virginia State University Agricultural Experiment Station in Morgantown, West Virginia (Hite et al. 1914). Burt Hite worked with field gun engineers at the Harper's Ferry Arsenal to develop pressure vessels capable of operating at hydrostatic pressures over 680 MPa. His research showed that pressures between 200 and 680 MPa could inactivate yeasts, molds, and spoilage bacteria in foods. However, he was not able to sterilize whole cow's milk to allow room temperature storage. This was Hite's original objective. Hite, and his associates, predicted that fruit juices, in large containers, could be sterilized by high pressure. Work showed that there would be little change in their fresh flavor during room temperature storage.

The work of Hite and his associates did not attract the attention of food processors even when his 1914 paper was cited in W.V. Cruess' *Commercial Fruit and Vegetable Products* first published in 1924. A considerable number of research papers were published over the following years describing the effects of high pressure on microbes, starches, and various proteins including enzymes and enzyme activity (Johnson et al. 1954). However, food processors concluded that the use of high pressure for commercial food processing would be impractical. Pressure vessels, pumps, and instrumentation needed development. Food grade, low gas transmission, and flexible packaging were not available. The availability of frozen foods was increasing and their preservation and packaging technologies were easily adopted. Consumers perceived frozen foods to be close to fresh in quality, nutritional value, and convenience. Frozen foods became a source of convenient meals with the marketing of frozen "TV dinners" through the 1950s.

In this period the demand for polymer plastics drove the development of high-pressure pumps, seals, vessels, tubing, and instrumentation. The 1950s saw the development and increasing demand for jet engine turbine blades. Blades were made by fusing shaped, powdered metal, at high temperatures and pressures, in an argon gas atmosphere. The process required rugged pressure vessels, pumps, and instrumentation. The systems for hot and warm isostatic pressing of powered metal and ceramic parts, in effect, pioneered safe and reliable high-pressure equipment. Pressures in the range of 680 MPa became available in relatively large-volume vessels for routine manufacturing use.

2.2 Early Exploration of High Pressure for Food Processing

Macfarlane (1973) and Bouton et al. (1977), in Australia, published research work on the effect of high pressure, in the range of 140 MPa, on cuts of red meat pre and post rigor mortis. Commercial trials indicated that these pressures could help tenderize cuts of beef. The action of the pressure appeared to be through activation of in vivo proteolytic enzymes in the beef muscle. This was noted by Kennick et al. (1980). D.C. Wilson reported, at the 34th Annual Meeting of the Institute of Food Technologists in 1974, that high pressure could preserve fruits such as apricots packaged in flexible, hermetically sealed pouches.

Sale et al. (1970) published an excellent description of the effects of high pressure on spore survival. Spores of non-proteolytic *Clostridium botulinum* were shown to be extremely resistant to inactivation at pressures approaching 680 MPa. The high-pressure tolerance of bacterial spores indicated that food preservation by high pressure may be limited to pasteurization processes in the absence of hurdles that inhibit the germination and outgrowth of spores in low-acid foods. Foods with a pH value lower than 4.5 would be ideal products for high-pressure commercial sterilization. *Clostridium botulinum* spores in foods with a pH below 4.5 are prevented from producing toxin.

Still, in the early 1980s, a number of technical problems were perceived to prevent the commercial application of HPP to food preservation. These perceptions were strong enough to discourage the application of available, off-the-shelf, commercial high-pressure equipment. In this period consumers were beginning to accept new preservation technologies such as modified atmosphere bagged salads with an extended shelf life. Preservation was achieved by modifying the gas atmosphere composition surrounding the vegetable mix during refrigerated storage and distribution. As more families included two working parents, the demand for convenient fresh-tasting foods strengthened.

2.3 Shifting Consumer Preferences and Perceptions

The food marketing scene in the early 1980s in the United States and in some countries in Europe began to shift in response to consumer demands for fresh-tasting, convenient, and safe refrigerated foods. Frozen foods were providing an increased selection of plated meals. The quality of frozen foods was improving dramatically. Companies were experimenting with cook-chill entrees that were microwave ready from the refrigerator rather than the freezer. Bagged salads were taking over the produce section of the supermarket. Controlled atmosphere packaging was being used to inhibit molds and yeasts in conjunction with reduced water activity. Reduce water activity could control bacterial spore germination and outgrowth. Extended room temperature shelf life of selected fresh-like foods was becoming a reality.

Ionizing radiation for food pasteurization and sterilization was available from the early 1950s as one of the early commercial “cold sterilization” technologies. Ionizing radiation sterilization of drugs and medical devices was embraced by the pharmaceutical, plastics, and packaging industries starting in the 1950s. However, commercial application of this technology for food pasteurization and sterilization was slowed by concerns that ionizing radiation could break covalent bonds. It was thought that the myriad compounds found in foods could form carcinogens or other harmful products during irradiation. Additionally, foods high in sulfur-containing amino acids, such as certain meats and milk, could produce strong off-odors and flavors when irradiated. Negative public perception of the safety of irradiated foods, and the classification of irradiation treatments as chemical additives, effectively blocked the general early acceptance of this technology for food treatment (Baily et al. 1957).

2.4 The Race to Develop Nonthermal Food Preservation Technologies

New technologies for “cold sterilization” of liquid and solid foods were needed to fill the gap left by low consumer interest in ionizing radiation. The race was on to develop viable pasteurization and sterilization technologies that required minimum amounts of heat. These technologies would not depend entirely on heat and could be called minimum-thermal preservation methods. A simple example was the successful use of membranes to remove microbes in beer by filtration. While this technology had been demonstrated in Europe in the nineteenth century using porous ceramic filters, newly developed polymer membranes greatly facilitated expanded commercial applications. Some other nonthermal preservation technologies of interest included pulsed light, pulsed electric fields, and sonic energy. Each of these technologies was found to have advantages and disadvantages when considered for commercial food preservation. For example, particulate foods could not be treated effectively in some cases.

The drawbacks that slowed the commercialization of ionizing radiation for food preservation highlighted the challenges that had to be overcome for a new food preservation technology to be accepted. Acceptance had to be by consumers, food processors, equipment manufactures, and regulatory agencies. Regulatory agencies would need across-the-board assurance of the safety of the food products produced, the processes used, packaging, and equipment.

Equipment manufactures would have to deliver systems that would operate during multiple shifts with very low down time and have ease of maintenance and repair. Equipment would have to have the productivity that would allow both the food processor and the equipment manufacture a reasonable return on their investment. Additionally systems would need low operating costs and would be compatible with environments found in a typical food processing plant.

2.5 Research at the University of Delaware to Meet the Requirements for Successful Commercialization of High-Pressure Food Preservation

In the early 1980s Dallas Hoover, Dietrich Knorr, and Daniel Farkas, faculty members in the newly formed Department of Food Science at the University of Delaware, decided to explore the commercial application of high pressure. A perceived attraction was the availability of cost-effective, off-the-shelf, commercial, warm isostatic pressing equipment. As an example, the lab-scale units manufactured by Autoclave Engineers in Erie, Pennsylvania, were portable, fully instrumented, and very user-friendly. Pressure chamber volumes were large enough to accommodate up to one or more liters of packaged food samples. Despite the findings of Sale and coworkers, that high pressure had little effect on spore inactivation, the incentives for using high pressure, even for pasteurizing foods, appeared to far surpass actual and perceived drawbacks.

Literature research indicated that high pressures, in the range of 340–680 MPa, would not break covalent bonds, but would disrupt hydrogen bonds. The preservation of covalent bonds in biological materials, such as foods, meant that flavors, pigments, and nutritionally important compounds would be conserved when treated with high pressure. The disruption of hydrogen bonds could result in the loss of enzyme and membrane activity of proteins. This loss of activity could result in the death of bacteria, yeast, molds, and parasites.

The effects of high-pressure treatment were instantaneous and uniform throughout a mass of food. Effects were not limited by heat, mass, or momentum transfer. Pressure applied to a 5-g packet would result in the same treatment as a 50-L bulk bag.

The major advantage of high-pressure food treatment, from a regulatory point of view, is that the process does not break covalent bonds. The effects of high-pressure would be similar to freezing or homogenization. Existing microbial safety, processing, labeling, and packaging regulations could apply to high-pressure treated foods. Simply put, the process would be benign and consumer friendly. The consumer could not differentiate treated from untreated products.

The decision to go forward with commercial high-pressure food preservation studies was driven by the favorable factors noted. Research would be needed to place the following essential developments on a sound scientific basis.

- Demonstrate that published research findings indicating that pressures in the range of 200–680 MPa could indeed inactivate six log cycles of bacterial pathogens, spoilage microbes, yeasts, molds, parasites, virus, and insect eggs. Inactivation would need to take place in foods with a range of pH and water activity values and in a wide range of food compositions.
- Determine that package shape and size does not influence inactivation kinetics in various sizes of cylindrical pressure vessels.
- Show that high-pressure processing (HPP) can actually operate at or near room temperature given that compression heating of water can cause significant product temperature increase.
- Demonstrate that foods treated by high pressure for a time sufficient for pasteurization show no change in chemical composition.
- Demonstrate that laboratory and pilot plant size equipment can yield experimental data that can be scaled and applied directly to industrial processes.
- Demonstrate that existing flexible packaging films and laminates can be used to package foods for high-pressure preservation.
- Demonstrate that high-pressure processing systems can be designed to be entirely compatible with existing food processing equipment; processing lines; and plant operating requirements such as ease of installation, cleaning, maintenance, and repair.

Additional process details such as the effect of high pressure on packaging materials; the operation of high-pressure vessels and supporting equipment in a food processing environment; the projected high treatment cost per package; the lack of information on the effects of high pressure on food enzymes; and the batch nature of the process would have to be addressed in subsequent laboratory and pilot plant studies.

2.6 Developing Support for High-Pressure Food Preservation Research, Development, and Technology Transfer

On October 24, 1984, two faculty members from the University of Delaware's Food Science Department in Newark, Delaware, traveled to Autoclave Engineers' headquarters in Erie, Pennsylvania. The objective of the visit was threefold: to discuss the use of Autoclave Engineers' laboratory-/pilot plant-scale cold isostatic pressing equipment for food preservation; to inquire if a unit could be loaned to the Department to conduct feasibility tests; and to convince the management of Autoclave Engineers that if the tests were successful, a lot more high pressure equipment possibly could be sold to the food industry than could ever be sold to the metal working industries. Autoclave Engineers was a leader in the manufacturing of small, reliable, high-pressure vessels and supporting systems. They were also an established supplier of replacement valves, fittings, high-pressure tubing, and accessories for commercial isostatic high-pressure users.

The isostatic press equipment industry is tied closely to the cyclic market for parts requiring fabrication in hot or warm isostatic presses. During good times companies expand and purchased capital equipment. During a recession, orders decrease. The isostatic pressing process itself requires long process cycle times for heating, cooling, and loading and unloading. Equipment may operate six cycles per day. This equates to about 2000 cycles per year. Orders for wear and replacement parts are tied to the number of cycles per year.

During the morning's conversation with company sales and development personal, and after the Autoclave Engineers' people had a good laugh about squeezing tomatoes in one of their presses, the potential for year-round equipment and parts sales to hundreds of potential food processors began to come into focus. The idea of an equipment loan took root based on the potential production tonnages of products such as fruit juices.

The Department of Food Science began work in earnest with the commissioning of a 2-in. inside diameter by 22-in.-long Autoclave Engineers CIP 2-22-60 isostatic press. The high-pressure chamber featured a pin closure and mono-block construction. The complete, self-contained system with pump, intensifier, pressure vessel, pin closure, instrumentation, and controls had a maximum working pressure of 400 MPa. The front and back of the unit are shown in Fig. 2.1. This unit is still in use in the high-pressure research program of Professor Brian E. Farkas. Professor Farkas was the first undergraduate student to use the equipment at the University of Delaware in conjunction with high-pressure research directed by Professor Dietrich Knorr.

As predicted the advantage of the off-the-shelf Autoclave Engineers' system for high-pressure food research was the ease and simplicity of loading, compression, decompression, and unloading samples. The equipment was used, with a minimum of instruction, by undergraduate and graduate students, faculty, and research associates. Sufficient samples could be prepared in the 1-L pressure chamber for sensory tests, long-term storage shelf life tests, and multiple microbial samples. The

Fig. 2.1 Autoclave Engineers CIP 2-22-60 isostatic press at Oregon State University

convenience and simplicity of the system allowed high-pressure research to be undertaken by microbiologists, sensory scientists, nutritionists, food chemists, and food engineers.

2.7 Early Research Observations

In honor of Nicolas Appert, cranberries and orange-cranberry sauce were the first products treated. These were foods first preserved with heat by Appert. Treatment of dry spices showed the resistance of spores to pressure, but more importantly demonstrated the need for high water activity for the efficacy of high pressure as a pasteurization technology. A water activity close to one was needed to optimize the inactivation rates of vegetative bacteria, yeasts, and molds in spices.

One question that was answered in early experiments was the effect of high pressure on different strains of microbial pathogens. Early experiments on the sensitivity of heat-resistant and heat-sensitive *Salmonella* strains showed that reverse results were observed with pressure (Metrick et al. 1989). The heat-resistant strain was sensitive to pressure and the heat-sensitive strain was quite resistant to high-pressure inactivation.

Professor Hoover was able to study the effect of pressure magnitude and holding time on the ability of microbes to recover from sublethal pressure treatments. Storage time, temperature, and enrichment of recovery media were found to play a role in the rate of recovery of microbes exposed to sublethal treatments. The need for storage studies of pressure-treated foods was underlined since products could show no growth just after treatment, but would show growth after one or more weeks of storage (Pandya et al. 1995).

Professor Knorr was able to show that certain compounds, such as chitosan, could increase the rate of microbial inactivation during HPP treatment. He investigated the role of food composition on inactivation rates of microbes during pressure treatment. The "protective effect" of foods was quickly noted since the rate of inactivation of food pathogens and spoilage microbes was found to be less than in buffer solutions (Papineau et al. 1991).

2.8 Building a Scientific Foundation and a Technology Transfer Program for the Commercial Use of High-Pressure Food Preservation

As laboratory research data accumulated showing the favorable effects of high pressure on food quality, shelf life, packaging, and pathways of microbial spoilage, it became clear that several areas of development were needed to facilitate technology transfer and to educate the food processing industry. The unique nature of high-pressure food processing, in contrast to heat processing, would require education of regulatory agencies, equipment suppliers, consumers, and marketers. Needed developments were:

- Knowledge was needed to help regulatory agencies understand the technology and develop regulations for the use of high-pressure processing (HPP) in any desired food processing application.
- Knowledge was needed by HPP equipment makers, in the form of performance specifications, to meet the operating requirements and returns on investments of food processors. Projections were for pressure systems to operate at six cycles per hour during 20-h daily shifts. Production could be 250 days per year. A total of 30,000 cycles per year was projected. This projection was many times the existing use level of available isostatic pressing equipment.
- Knowledge was needed by food processors on the effect of HPP on enzyme activity, package-product interactions, and appropriate packaging materials and package shapes to optimize the fill (volumetric efficiency) of high-pressure vessels. Vessel diameters above 10 in. (250 mm) were favored.
- Knowledge was needed by food processors on how to build and operate efficient high-pressure food processing lines, their staffing, maintenance, and repair needs, space needs, and utility requirements.
- Also needed were HPP pilot-scale food processing lines to allow food processors to prepare sample products for storage studies, home use tests, and consumer focus studies. Processors needed to evaluate the actual pressure, time, and temperature requirements to preserve products prepared under commercial processing conditions using good manufacturing practices. This information would help regulatory agencies write science-based regulations.

2.9 Formation of a High-Pressure Food Processing Consortium

In 1990 Dr. Farkas moved to Oregon State University's Department of Food Science and Technology. The Department had a food processing pilot plant that food processors could use to manufacture small batches of new products for market tests. The decision was made for the Department to sponsor a university-industry-government High Pressure Consortium to help coordinate and facilitate the transfer of research data to interested food processors, equipment makers, regulatory agencies, consumers, marketers, and other researchers. This information also could help to identify operating and regulatory needs that could be made into relevant research projects.

Hayashi (1989) had described the successful use of an industry-university consortium in Japan to help apply HPP research to the development of commercial high-pressure pasteurized products. Consortium meetings in Japan resulted in the publication of three important summaries of ongoing research and development work (Kyoto, San-Ei Publishing Company 1989, 1990, 1991).

The Oregon State University HPP Consortium was based on the successful Fruit Juice Quality Advisory Committee established by Professor Ronald Wrolstad in 1987 in the Food Science and Technology Department. The High Pressure Food Processing Consortium was supported through a small yearly dues contribution from industrial members. Dr. Marcia Walker managed the Consortium and arranged the twice-each-year meetings. The January meeting was held at the Northwest Food Processors Association annual meeting in Portland, Oregon. The June meeting was held in conjunction with the annual Institute of Food Technologists national meeting at various major cities in the United States.

Consortium meetings were open to all personal from companies, government agencies, and universities, from any country in the world. The only requirement for participation was an interest in high-pressure food research, equipment development, government regulations, packaging, microbial safety, spoilage issues, shelf life studies, and related research. Industrial members were not required to make a presentation at each meeting, but were encouraged to ask questions that would highlight needed research. All other participants were encouraged to present summaries of their current research activities. Domestic and international university faculty and students, and government researchers, from around the world, were encouraged to expand on their fields of research. High-pressure equipment suppliers were encouraged to describe the latest developments in their high-pressure food processing systems and any new applications.

The Consortium provided a forum for the then newly created National Center for Food Safety that was established in Chicago as a joint program between the Illinois Institute of Technology and the Food and Drug Administration. The missions of the Center were to help Food and Drug personal develop science-based regulations and to keep FDA workers abreast of rapidly developing new and novel food preservation and processing technologies (Lechowich 1993).

The US Army Natick Laboratories in Natick, Massachusetts, has played a lead role in the development of new food processing technologies in the United States for over 50 years. The Army Quartermaster Corps pioneered the application of ionizing radiation to food preservation starting in the 1950s (Baily et al. 1957).

As research results confirmed the commercial potential for high-pressure food preservation, it was suggested that the Army Food Ration Development Program at Natick be contacted to determine their interest in high-pressure food processing. A seminar “Application of Ultra-High Pressure to Microbial Inactivation” was scheduled for July 28, 1989. Drs. Dallas Hoover and Daniel Farkas were presenters.

Dr. C. Patrick Dunne recognized the potential benefits of fresh-tasting foods with minimal heat damage and suggested a possible joint research and development effort. The food development program at the Natick Labs covered food ration needs from space feeding to assault rations. Single serve and group feeding requirements in arctic, dessert, and jungle feeding situations were included. Soon military-sponsored research on high-pressure food processing joined programs on ionizing radiation, freeze-drying, microwave heating, pulsed electric field pasteurization, and pulsed light treatments. The US Army Natick Combat Feeding Directorate coordinated product, process, and packaging studies. These studies, along with other developments, would result in military and civilian food quality breakthroughs. Commercialization of high-pressure processed foods in the United States would follow.

2.10 High-Pressure Research on Food and Food Components in Europe

High-pressure food processing research spread across Europe. Research support from the European Union and industry resulted in active programs in Germany, France, the United Kingdom, and Italy. Several countries were encouraged to come together to submit joint proposals for funding by the European Union. In this period, Professor Dietrich Knorr accepted a faculty position at the Technical University of Berlin. Professor C.J. Cheftel (1992) carried out high-pressure research on meat preservation. Mark Hendrickx at the Catholic University, Leuven, Belgian, began a lengthy, key study on the effect of high pressure on the activity of food enzymes. Starch and protein denaturation by high pressure was described by Professor K. Heremans (1982). Professor Bernard Tauscher studied the effect of high pressure on vitamins and other nutrients. Professor Margaret Patterson and coworkers (1995) developed an active high-pressure food research program at Queen’s University in Belfast. Much early work is summarized in *High-Pressure and Biotechnology* (1992), edited by C. Balny, R. Hayashi, K. Heremans, and P. Masson, John Libby/INSERM. European and Japanese researchers supplied important research findings on the chemical and biological effects of high pressure in foods and food compounds.

In 1995, *High-Pressure Processing of Foods*, edited by D.A. Ledward, D.E. Johnson, R.G. Earnshaw, and A.P.M. Hasting, was published. The book was based on the proceedings of a symposium held at the University of Reading, in England, March 28–29, 1994. This book served to mark the end of the exploratory phase of research and development on the use of high pressure for food preservation. The book organized basic research on the effect of high pressure on food quality and safety and focused this research on the development needs of the industry. As a result international research and development efforts began to focus on solving equipment and food plant manufacturing problems.

2.11 Development of Dedicated High-Pressure Food Processing Equipment

The rapid expansion of high-pressure food research around the world provided the basic science needed for the commercialization and regulation of the technology. As predicted, in the United States, the minimum chemical changes in foods treated by high pressure resulted in regulations based on existing good manufacturing practices. Food processors were required to demonstrate that HPP-treated foods were safe to consume by insuring a six-log reduction of pathogens likely to inhabit the product. Use-by dates were required to insure the quality and safety of refrigerated and shelf-stable products.

A large amount of research data describing the inactivation kinetics of a wide range of microbes was being generated in laboratories in Europe and the United States. Researchers began comparing the shapes and rates of inactivation curves published by workers using identical microbes, pressures, and time values. At a Nonthermal Processing meeting, several members presented data showing discrepancies in the rate of inactivation of identical microbial samples among reporting laboratories. There was an immediate interest in determining the source of the discrepancies. A group was formed and charged with finding the cause of the discrepancies and proposing methods for their prevention.

The ability to produce accurate inactivation data for pathogens and spoilage microbes using high pressure is fundamental to the commercial success of the technology. Accurate and precise inactivation data is central to regulatory acceptance of a process, to proper equipment design specifications, to HACCP programs, and to the cost and efficiency of the process.

The study group analyzed the variables that could affect the lethality of a high-pressure treatment and concluded that the source of lethality variability rested in the design and operation of the high-pressure chamber and associated equipment used in any lethality study. While high-pressure processing is considered a nonthermal process, when water or high-moisture foods are compressed, there is a parallel increase in sample temperature due to compression heating. A thermocouple located in the center of the sample may show a higher temperature than a thermocouple located in the sample in contact or near the pressure vessel wall. These temperature discrepancies may be transient and may depend on holding time at pressure or on the rate of compression and decompression. High-pressure systems that used oil instead of water could generate perhaps three times the temperature increase over those systems using pure water. Similarly fatty foods would increase in temperature much more than low-fat products.

Dr. V.M. (Bala) Balasubramaniam, Food Engineering faculty member at the National Center for Food Safety and Technology, Illinois Institute of Technology's Moffett campus, undertook the preparation of a protocol that could help researchers produce lethality rate data that did not depend on the type of high-pressure equipment used. This information was a set of guidelines for measuring the lethality of high-pressure treatments (Balasubramaniam et al. 2004). Subsequently Dr. Balasubramaniam proceeded to do basic studies on compression heating rates of foods and food components at various pressure levels (Rasanayagam et al. 2003). After moving to The Ohio State University in 2002, Dr. Balasubramaniam carried out additional studies on heat capacities, thermal conductivities, and other physical properties of foods under pressure (see Chap. 6).

In the mid-1990s, food processors desiring to use high pressure were still hampered by the costs of high-pressure treatment (Demetrakakes 1996). Equipment manufacturers were challenged to design, fabricate, assemble, and install high-pressure food processing equipment that would treat retail size packages of food at costs in the range of five to ten US cents per pound rather than 30 or more cents per pound.

The development of cost-effective, dedicated, high-pressure food processing equipment required a shift in the thinking of the companies' manufacturing pressure vessels, pumps, intensifiers, valves, high-pressure tubing, seals, and instrumentation. While the science was available for designing pressure vessels with cycle lives of well over 100,000 cycles at pressures in the range of 680 MPa, the requirements for the use of water for compression dictated stainless steel liners for these pressure vessels. Pressure relief valves operating 120 times or more per day required special designs to protect the valve from rapid erosion by decompressing water. Erosion and wear were one set of challenges that needed to be overcome. The need for reduced capital costs, cost-effective operation, and ease of maintenance and repair seemed to present an impossible challenge.

Several high-pressure vessel manufactures showed an early interest in the treatment of foods using high pressure. These included Uhde in Germany; ABB Pressure Systems (Quintus) in Sweden; Engineered Pressure Systems, a division of National Forge, in Belgium and the United States; ACB GEC, in France; and Stansted Fluid Power, in the United Kingdom. High-pressure equipment companies in Japan that had manufactured production systems for Japanese food companies did not appear to be interested in developing food processing pressure vessels operating above 400 MPa. Research had established that treatment pressures just under 610 MPa allowed hold times of 3 min to achieve a six-log reduction of most vegetative microbial pathogens and many types of spoilage microbes. Since bringing the treatment vessel to pressure was a function of intensifier horsepower and vessel volume, in principle ten cycles per hour, with a 3-min hold, could be possible. The vessel needed to be loaded, sealed, compressed, held at pressure for 3 min, decompressed, and unloaded in no more than 6 min. A more feasible six cycles per hour appeared to be possible with a 3-min hold at 600 MPa. Dr. Ed Ting, Vice President of Research, at Flow International Corp., in Kent, Washington, observed that without dependable, cost-effective equipment, the commercial development of high-pressure food processing would remain a technical curiosity.

Dr. C.P. Dunne, in 1995, at the Army Combat Feeding Directorate, Natick Labs, proposed funding a design contract. The contract had the objective of challenging the pressure vessel industry to design a high-pressure food processing system that would meet the production needs of both the food processors and equipment suppliers. System goals would be high production rates, ease of integration into existing food processing lines, reliability, ease of maintenance and repair, and low operating costs. A team of pressure vessel experts was assembled to evaluate submitted design proposals. This design competition was a first step in developing an economically feasible high-pressure food processing industry in the United States and later in Europe. Design proposals were submitted by most of the builders of high-pressure processing systems.

The design contract was awarded to Dr. Joseph Kapp of Elmhurst Systems. Elmhurst Systems was a high-pressure-equipment consulting firm. His design proposed the use of multi-wall pressure vessels made from used 155-mm field guns available at the Army Watervliet Arsenal. The gun barrels would be sawed to length and machined to form an outer layer and an inner layer held in compression by shrinking the outer layer on the inner layer. A third inner layer of stainless steel would be inserted in such a manner that the residual compression pressure at its inner surface would be in excess of 680 MPa.

The ASME pressure vessel code, in the United States, required a design that would allow the vessel to leak before breaking if its maximum operating pressure was exceeded or if the inner stainless steel liner wall was damaged through routine use. The strength and thickness of the steel in each layer was specified to achieve a theoretical vessel cycle life well over 100,000 cycles. The design operating pressure was just under 610 MPa. The vessel volume was 30 L, and the inside diameter was in the range of 150 mm (6 in.).

The design proposal showed a pair of 30 L vessels alternately driven by a single pump/intensifier and mounted on frames that would allow each vessel to move from a 45° angle, for automatic gravity driven loading (Fig. 2.2) to the vertical position inside the yoke, for compression, holding, and decompression. Unloading was achieved automatically as the vessel was returned to the 45° angle starting position and the bottom closure was automatically opened. After closing the bottom closure, the vessel was ready to receive water and packages by automatic gravity feed to begin the next cycle.

Two special design features were used to fully automate the system. As the filled vessel tilted toward the vertical position, the top closure plug was automatically placed in the end of the pressure vessel just as the vessel swung inside the yoke. Clearance for the top and bottom closures was achieved by fully inserting them in the vessel.

Fig. 2.2 Prototype Elmhurst Research tilting HPP system showing pressure vessel ready to receive packages from an automated feed chute. After loading, the vessel is moved to the vertical position inside the yoke. A 10-L pilot-scale Elmhurst unit is located in the Department of Food Science of Rutgers University in New Brunswick, NJ

In order to deliver compression water to the vessel through the top closure, the design called for a high-pressure tube to be inserted into a hole drilled through the yoke above the vertically positioned pressure vessel. The high-pressure water line was held in place using a special seal in the top closure. The water delivery tube was held in place during compression, holding, and decompression by the insertion apparatus. After decompression the tube was retracted to allow tilting the pressure vessel for product discharge and reloading.

Elmhurst Systems built a commercial food processing system incorporating the design features described. The pair of vessels remained in commercial operation logging many tens of thousands of cycles.

One major advantage of the Elmhurst design was the movement of the packaged foods through the vessel. This insured that treated product would be handled separately from untreated product. The through flow design is now standard in commercial horizontal units.

Dr. Edmund Ting was Vice President of Research at Flow International Corp. in Kent, Washington. Flow pioneered the use of high-pressure water jets for stone, metal, plastic, and food cutting. He became interested in high-pressure food processing as an expanded market for their high-volume, high-pressure, reliable, rugged, pump/intensifier systems. Under Dr. Ting's direction, with microbial study help from Dr. Errol Raghubeer, Flow was able to develop a semi-continuous high-pressure processor for liquid and semiliquid foods. The system consisted of three 20-L vessels. Each vessel operated on a four-stroke cycle and discharged pasteurized product to an aseptic holding tank. The treated product was filed aseptically in presterilized packages. Results from testing of salsa in a pilot-scale, semicontinuous unit were published by Raghubeer et al. (2000).

In operation untreated product was pumped into the pressure vessel through the intake valve, against a moving free piston, to fill the vessel. High-pressure water was then pumped into the vessel behind the free piston to cause the free piston to compress the product. The product was held at the desired pressure for the necessary time. A discharge valve, leading to the treated product holding tank, was opened, and the treated product was discharged from the vessel by low water pressure on the backside of the free piston. The piston pushed the product through the discharge valve. The pressure vessel was then ready for the next cycle. The fully automated system could achieve over six cycles per hour on all three vessels.

In Europe GCE demonstrated both the feasibility of a semicontinuous system for treating liquids and a horizontal, through flow, high-pressure vessel system for batch treating packaged foods. The horizontal batch system solved two operating problems encountered in the use of existing vertical high-pressure vessel systems in food plant operations. First, the horizontal system removed the need for a high ceiling production area to house large-volume, high-pressure, vertical vessels. Second, high-volume, larger-diameter vessels could be built in longer lengths to meet the package sizes and greater production capacities desired by food marketing people. Horizontal vessels with an internal diameter of 250 mm or larger could be built with the lengths needed to accommodate vessel capacities well over 350 L. Increased production per hour could be achieved, not so much through increased cycle rates per hour but by increased capacity per cycle and increased volumetric efficiency. Larger diameter vessels allowed better packing of desired consumer package shapes. Volumetric efficiencies of 75 % became possible.

Very quickly horizontal, wire wound vessels, 300 L and larger, became the standard for the high-pressure food processing industry. Despite some operating drawbacks, these systems have brought capital and operating costs toward single-digit pennies per package. Flow purchased the Swedish company ABB Pressure Systems and marketed large, horizontal, wire wound food processing systems under the Avure brand. Dr. Raghubeer was able to use these systems to demonstrate the consistent ability of this equipment to pasteurize a wide range of food products. His work helped to achieve acceptance of high-pressure processing by both the Food and Drug Administration and the USDA meat inspection agency in the United States.

The lessons learned from the commercialization of high-pressure food processing in the United States underscore the value of open communications among academic and government research laboratories, regulatory agencies, equipment manufacturers, and food processors and their trade associations. As with the development of heat preservation by Appert in France, military support, in the United States, through the vision of Dr. C. Patrick Dunne, played an important role in moving high-pressure processing technology to successful commercial food processing use.

In 1995 Food Engineering Magazine published an article: “Avomex to Pioneer High Pressure Food Process in the U.S.” The goal of full commercialization had been attained in the United States. The first product was guacamole made from fresh ripe avocados. This refrigerated product with an extended shelf life is still produced by Avomex's successor company Fresherized Foods and several other companies in high volumes. A number of other different high-pressure pasteurized products, including seafood, fruits, and fruit juices and ready-to-eat meat products, are now marketed worldwide with a volume of sales in the United States estimated at over $2 billion annually.

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