Food Science and Technology International
http://fst.sagepub.com/

High-pressure Food Processing

V.M. Balasubramaniam and D. Farkas

Food Science and Technology International 2008 14: 413
DOI: 10.1177/1082013208098812

The online version of this article can be found at:
http://fst.sagepub.com/content/14/5/413

Published by:
SAGE
http://www.sagepublications.com

On behalf of:
CSIC

Consejo Superior de Investigaciones Científicas (Spanish Council for Scientific Research)

Additional services and information for *Food Science and Technology International* can be found at:

Email Alerts: http://fst.sagepub.com/cgi/alerts

Subscriptions: http://fst.sagepub.com/subscriptions

Reprints: http://www.sagepub.com/journalsReprints.nav

Permissions: http://www.sagepub.com/journalsPermissions.nav

Citations: http://fst.sagepub.com/content/14/5/413.refs.html

>> Version of Record - Jan 16, 2009

What is This?

Downloaded from fst.sagepub.com at CIDADE UNIVERSITARIA on September 24, 2014

High-pressure Food Processing

V.M. Balasubramaniam[1],* and D. Farkas[2]

[1]*Department of Food Science and Technology, The Ohio State University*
Columbus, OH 43210-1007, USA
[2]*Deptartment of Food Science and Technology, Oregon State University, Corvallis, OR 97331-6602 USA*

High pressure processing (HPP) of foods offers a commercially viable and practical alternative to heat processing by allowing food processors to pasteurize foods at or near room temperature. Pressure in combination with moderate temperature also seems to be a promising approach for producing shelf-stable foods. This paper outlines research needs for further advancement of high pressure processing technology. Kinetic models are needed for describing bacterial inactivation under combined pressure-thermal conditions and for microbial process evaluation. Further, identification of suitable surrogate organisms are needed for use as indicator organisms and for process validation studies. More research is needed to evaluate process uniformity at elevated pressure-thermal conditions to facilitate successful introduction of low-acid shelf-stable foods. Combinations of non-thermal technologies with high pressure could reduce the severity of the process pressure requirement. Likewise, processing equipment requires improvements in reliability and line-speed to compete with heat pasteurization lines. More studies are also needed to document the changes in animal and vegetable tissue and nutrient content during pressure processing, from types of packaging, and from storage.

Key Words: high pressure processing, process uniformity, microbial safety, pasteurization, sterilization

INTRODUCTION

Thermal processing is a primary method for food pasteurization and sterilization. However, the application of heat impairs food quality. As an alternative to thermal processing, high-pressure processing (HPP) uses elevated pressures, with or without the addition of heat, to achieve microbial inactivation or to alter the food attributes. Because HPP does not break covalent bonds, it can retain food quality and natural freshness while extending microbiological shelf-life. The process is also commonly referred to as high hydrostatic pressure (HHP) processing and ultra high-pressure (UHP) processing.

High-pressure processing has been a topic of interest for several reasons. For one, the technology has been quoted as being one of the best innovations in food processing in fifty years (Dunne, 2005). It gives food processors the opportunity to process foods with cleaner ingredients and fewer additives. HPP is effective on a wide variety of foods, such as fruits, juices, vegetables, seafood, sauces, and ready-to-eat meats. During the last decade, the technology has been used by the food industry as an intervention technology for killing *Escherichia coli, Salmonella, Listeria, and Vibrio* pathogens in food products without additional heat processing. The US Department of Defense and NASA are interested in high-pressure processing for preservation of high-quality, shelf-stable low-acid foods. Beyond the food industry, high-pressure technology could lead to processing of biological pharmaceutical products and specialized intravenous solutions, or lead to development of a human vaccine from pressure-inactivated viruses serving as antigens for inoculation. The objective of this chapter is to summarize the status of HPP technology in the processing of foods and to identify key research needs.

State-of-Art of the Technology

Several papers summarize the advantages and limitations of high-pressure processing of foods (Cheftel, 1995; Thakur and Nelson, 1998; Smelt, 1998; Tewari et al., 1999; IFT, 2000; Otero and Sanz, 2000; Hugas et al., 2002; Matser et al., 2004; Black et al., 2007; Rastogi et al., 2007). The following discussion briefly summarizes the current state-of-the-art of the technology, and its advantages and limitations.

**To whom correspondence should be sent (e-mail: balasubramaniam.1@osu.edu).*
Received 3 March 2008; revised 8 August 2008.

Food Sci Tech Int 2008;14(5):0413–418
© SAGE Publications 2008
Los Angeles, London, New Delhi and Singapore
ISSN: 1082-0132
DOI: 10.1177/1082013208098812

Downloaded from fst.sagepub.com at CIDADE UNIVERSITARIA on September 24, 2014

High-pressure processing begins by packaging untreated products in flexible containers followed by loading them into a high-pressure chamber filled with water to exert the pressure. The vessel is sealed and pressure applied by forcing additional water into the sealed vessel until the desired processing pressure is reached. The pressure is held for a specific time and then released, after which the processed products are removed and stored. Pasteurization treatments use pressures in the range of 600 MPa for several minutes at ambient temperatures.

HPP can be used to process both liquid and solid foods in batch equipment, and liquid foods in semi-continuous equipment. Commercial scale high-pressure processing systems cost somewhere between $500,000 and $2.5 million dollars, depending on the equipment capacity and extent of automation. As a new processing technology, with a limited market, pressure-processed products may cost 3–10 cents per pound more to produce than thermally processed products. With two or more pressure vessels operating under typical food processing conditions, a throughput of approximately 20 million pounds per year is achievable.

Over the last decade, significant progress has been made in high-pressure pasteurization of foods, and a number of commercial products have been introduced into the market. High-pressure pasteurization treatments inactivate pathogenic and spoilage bacteria, yeasts, and molds, but have limited effectiveness against spores and enzymes (IFT, 2000). Examples of high-pressure pasteurized products available commercially in the United States include: smoothies, guacamole, ready-meal components, oysters, ham, fruit juices, and salsa (Matser et al., 2004; Dunne, 2005; Clark, 2006).

High-pressure sterilization is a pressure-accelerated thermal process that requires a combination of elevated pressures (up to 800 MPa) and temperatures (90–120 °C) to produce shelf-stable foods that are free of harmful bacterial spores, spoilage spores, and enzymes (Sizer et al., 2002; Matser et al., 2004). Pressure-accelerated, thermally-processed, shelf-stable products such as low-acid soups are not commercially available yet. Obtaining such products is a topic of current research.

RESEARCH NEEDS

The following research needs and priorities have been identified on high-pressure processing.

Microbial Efficacy

High-pressure treatments, in general, are effective in inactivating most pathogenic and spoilage vegetative microorganisms at pressures between 200 and 600 MPa over a milder range of process temperatures. It should be noted that pressure resistance of vegetative microorganisms can peak at ambient temperatures, and may decline at higher or lower temperatures. The extent of inactivation also depends on the type of microorganism, food composition, pH, and water activity. Gram-positive organisms are more resistant than gram negatives. Significant variations in pressure resistances can be seen among strains (Cheftel, 1995). Pressure will also sublethally stress or injure bacteria. Therefore, care should be taken to use nonselective microbiological media to allow detection of all viable organisms of concern during post treatment storage at several temperatures between 4 °C and 30 °C.

Similarly, most yeasts are inactivated by exposure to 300–400 MPa at 25 °C within a few minutes. However, yeast ascospores may require treatment at higher pressures. Pressure inactivation of molds appears to be similar to yeast inactivation. Yet, additional studies on molds of interest in food preservation are needed.

Among viruses, the high degree of structural diversity is reflected in their wide range of pressure resistances (Smelt, 1998). For example, human viruses appear more pressure-sensitive than the tobacco mosaic viruses. Overall, these results suggest that most human viruses could be eliminated by pressure treatments designed to eliminate bacteria of concern. However, this requires further study before such broad range conclusions can be drawn (Farkas and Hoover, 2000).

Studies on the efficacy of HPP on spore inactivation have shown that bacterial spore inactivation requires a combination of elevated pressures and moderate temperatures. So far, only a limited number of *Clostridium botulinum* strains have been tested. Nonproteolytic type B spores appear to be the most pressure-resistant spore-forming pathogens found to date (Sizer et al., 2002).

More research is needed to characterize the combined pressure–thermal resistance of pathogenic and spoilage microorganisms. It is important to evaluate the influence of the food matrix, pH, and water activity on these microorganisms and to identify surrogates that can be used to estimate the effectiveness of high-pressure sterilization or pasteurization during commercial processing. It is further desirable to develop non-microbial, enzyme-based markers that can serve as process indicators.

More studies are needed to minimize tailing, which is often observed in semi-log plots of bacterial inactivation after pressure treatment (Tay et al., 2003). For example, HPP effectiveness may be enhanced by using antimicrobial compounds such as bacteriocins to reduce the severity of HPP processing and to eliminate tailing.

Databases containing kinetic model parameters for various target pathogenic and spoilage microbes

Downloaded from fst.sagepub.com at CIDADE UNIVERSITARIA on September 24, 2014

are needed. Such databases would use defined pressure–thermal conditions and would be useful for the evaluation of various critical process parameters. It appears that nonlinear models best describe the combined pressure–thermal inactivation kinetics of various microorganisms, compared to traditional first order linear models (Peleg and Cole, 1998).

Kinetic models can also be used in the development of HACCP plans and process validation studies (IFT, 2000). Hence, it is of utmost importance to investigate the influence of pressure on reducing microbial populations using the proper experimental design. This includes a statistically valid collection of data taken at different pressure–thermal conditions using realistic foods, so that kinetic parameters are quantified. Researchers must properly document the equipment, process conditions, and microbial techniques (Balasubramaniam et al., 2004).

Additionally, molecular level mechanistic studies are essential to strengthen understanding of the fate of microorganisms under pressure and combined pressure–thermal conditions. Especially needed are more studies on spore physiology and insights on the pressure–temperature conditions affecting spore germination and inactivation. The extent and mechanisms of bacterial injury during high-pressure pasteurization and sterilization merit further investigation. Studies are also needed to evaluate the efficacy of pressure treatment and mechanisms for inactivating various food toxins.

Process Uniformity

One of the unique advantages of HPP technology is its ability to provide a uniform temperature increase in treated samples at a rate limited only by the rate of pressure increase. The rate of compression is set by the size of the pump, the volume of the pressure vessel, compression media, and desired final pressure. The temperature increase during treatment is attributed to heat of compression resulting from the mechanical compression of the food and compression media (Rasanayagam et al., 2003). Uniform compression heating and expansion cooling on decompression helps to reduce the severity of thermal effects encountered with conventional processing techniques. Knowledge about both temperature and pressure histories is important for evaluating process uniformity during high pressure assisted thermal processing (Ting et al., 2002).

Engineers generally accept that pressure is transmitted uniformly and quasi-instantaneously throughout the sample volume. Therefore, if one considers pressure effects alone at ambient temperatures (e.g., in the case of high-pressure pasteurization), no significant issues arise in process nonuniformity. On the other hand, at the elevated pressure–thermal conditions required for food sterilization, thermal effects due to compression heating of materials cannot be ignored. Due to possible differences in compression heating of lipids, water, proteins, and carbohydrates, the temperature of a product processed inside a pressure chamber can change as a result of heat exchange to or from the pressure-transmitting fluid and individual food components. It is necessary to insulate the pressure-transmitting fluid and food packages from the walls of the pressure vessel if the walls are at a lower temperature than the desired process temperature.

The temperature gradient within different regions of the processed volume could result in pronounced nonuniform process lethality with respect to microbial inactivation. With proper insulation or vessel wall temperature adjustment, the resulting temperature distribution within a pressure chamber should only depend on the thermophysical properties of food and pressure transmitting fluid.

After the pioneering work of Bridgman, the properties of water under pressure were well documented. Data are available from the International Association for the Properties of Water and Steam (IAPWS). A software implementation of IAPWS work can be obtained from the US National Institute of Standards and Technology (NIST). Most high-moisture foods are assumed to have thermophysical properties similar to water at the pressures and temperatures used in HPP. This assumption is made due to a lack of information on the properties of food materials (e.g., thermal conductivity, specific heat, etc.) under pressure. Reliable data on pressure–temperature effects on physical transport and thermodynamic properties of food materials are not readily available, and therefore, more research is needed in this area. Further, reliable mathematical models are needed for process validation and optimization. It would be useful to have sensors and/or approaches that can be used to evaluate combined pressure–thermal effects. Reliable instruments for monitoring pH of the test samples under pressure are needed.

High Pressure in Combination with Thermal and Other Nonthermal Technologies

Combining HPP with additional hurdles and other milder process treatments may help reduce process costs and allow wider industrial adaptation of HPP. Because the cost of high-pressure equipment exponentially increases with pressure beyond 600 MPa, significant reductions in process pressure requirements are highly desirable. Researchers have proposed various approaches for reducing process severity and cost during high-pressure pasteurization and sterilization. The application of pressure in combination with gases, such as carbon dioxide or argon, has been proposed for continuous juice pasteurization. Further possibilities may include combining pressure treatment with

Downloaded from fst.sagepub.com at CIDADE UNIVERSITARIA on September 24, 2014

processes such as mild heat, and other nonthermal preservation methods such as irradiation, pulsed electric field processing, and ultrasound. Antimicrobial preservatives such as nisin, pediocin, and chitosans have been proposed to reduce process severity. Depending on the nature and practical limitations of processes being combined, either sequential or simultaneous treatment may be possible. Systematic studies documenting the potential synergistic (or antagonistic) effects of pressure, temperature and other combination processes and their respective kinetics of microbial and enzyme inactivation are very limited, and more such studies are needed.

Equipment Reliability and Line Speed

The US food industry has gained about 15 years of experience with commercial scale high-pressure equipment, with the introduction of high-pressure pasteurization systems in the 1990s. More research is needed to improve reliability of HPP systems. Guidelines and operating standards should be developed in such areas as operator safety, equipment installation, and maintenance standards. Most of the commercial systems marketed to date are batch. However, semi-continuous equipment is available for liquid foods. Improved commercial systems need to be developed that can support line speeds competitive with traditional heat pasteurizer lines.

Food Structure and Functionality

Functional properties of food constituents such as native proteins and carbohydrate polymers can be influenced by pressure treatment. For example, hydration, molecular interaction, and surface characteristics of proteins are affected by pressure treatment (Hayakawa et al., 1996). High-pressure processing can influence protein confirmation and lead to protein unfolding, aggregation, or gelation. More research is needed to understand the effects of high pressure on the unfolding mechanisms of proteins in water and foods as a function of temperature, pH, water activity, and composition.

Similarly, pressure treatment can influence the gelatinization of starch compounds. The pressure effect on proteins and carbohydrates can be significantly different from thermal effects. For example, at room temperature, egg gels can be formed using pressure alone. Depending on the pressure–thermal conditions used, the characteristics (e.g., hardness and elastic modulus) of the pressure treated gel can be significantly different from thermally formed gels. Similar differences are also possible between pressure and thermally gelatinized starch. Thus, pressure treatment could be used to create novel food products with unique structures, textures, or tastes. It may be possible to obtain analogue products with minimal effects on flavor, color, and nutritional value, without significant thermal degradation. More research is needed to understand the molecular basis of pressure–thermal effects on proteins and carbohydrates. This information can be used to improve food structure and functionality and to identify optimal process conditions for development of novel food products.

Solid foods such as fresh fruits, vegetables, and meats often lose cellular fluid during HPP treatment, possibly due to cell rupture or denaturation of raw meat proteins. Physical changes in animal and vegetable tissue as a result of HPP merit further investigation. The impact of HPP on various package materials and product shelf life is also worth further attention. Industrial application will be helped by identifying ways to minimize such harmful storage effects. More research is needed on the effect of HPP on nutrients and bioavailability of nutrients. Further, documenting consumer acceptability of these novel products is advised before successful introduction into the commercial market.

CRITERIA FOR ESTABLISHMENT OF RESEARCH PRIORITIES

High-pressure processing holds significant promise in the delivery of fresh tasting foods to consumers. With safety as the basic governing principle, certain research priorities can be determined based on commercialization impact and the breadth of benefit across industry. Long-term viability of the country's food industry depends on a strongly trained workforce. Therefore, universities receiving funds should be encouraged to support graduate and undergraduate education in HPP. Interaction between academic researchers with industry and government agencies should be further encouraged, especially the establishment of integrated research, teaching, and outreach activities that include multi-institutional collaborative efforts.

Support from Public Research Funds

Public research funds should be directed towards basic and applied research questions that can aid the entire food industry in overcoming key technological hurdles. This may include research on process characterization, chemical changes (protein unfolding) during processing and storage, molecular understanding of microbial resistance, and identification of pressure-resistant surrogate organisms. These research findings can benefit the food industry as a whole, not just a select list of companies. With US state-level budget cuts ongoing, another major priority is the maintenance and strengthening of pilot plant equipment infrastructure and capabilities of state land grant Institutions.

Downloaded from fst.sagepub.com at CIDADE UNIVERSITARIA on September 24, 2014

Table 1. Selected examples of centers of excellence in high pressure processing research.

Organization	Participating organization	Web address
Center for Advanced Processing and Packaging Studies (CAPPS)	Ohio State University, North Carolina State University, University of California Davis, US Army Natick, and food industry	http://www.fst.ohio-state.edu/capps/mission. html http://grad.fst.ohio-state.edu/hpp/
Center for Nonthermal Processing of Foods	Washington State University and food industry	http://c100.bsyse.wsu.edu/barbosa/cnpf/
National Center for Food Safety and Technology	Illinois Institute of Technology, Food and Drug Administration, and food industry	http://www.ncfst.iit.edu/
Oregon State University	Oregon State University and food industry	http://osuseafoodlab.oregonstate.edu/
High pressure processing laboratory at Virginia Tech	Virginia Tech and food industry	http://www.hpp.vt.edu/

Availability of such testing facilities at various state-level laboratories can facilitate wider adaptation of the new technology by small and medium-scale companies.

Innovative Ideas for Establishment of Partnerships

Industry, academia and government recommended a multi-disciplinary approach involving university-industry-government collaboration to address various research needs identified above. For example, the Defense Logistics Agency (DLA), through their combat ration network (CORANET) technology implementation program, funded a feasibility study to produce shelf-stable high-pressure processed egg products, as a collaborative effort between Washington State University, Ohio State University, and Illinois Institute of Technology. This team also partnered with different industrial entities (Michael Foods, Wornick Foods, Avure Technologies) and government organizations (US Army Natick soldier systems and Defense Logistics Agency). US Army Natick, in collaboration with the food industry, also formed an industrial consortium to investigate the feasibility of using pressure technology for producing low-acid shelf-stable foods. Furthermore, a number of university-based organizations (Table 1) have been successful in bringing industry and government researchers together to evaluate the safety assessments of advanced food processing technologies, including high-pressure processing.

As pointed out, the above collaborative model has some potential pitfalls. In the absence of significant funding and coordination, the research time horizon may be considerably longer than the time over which commercial processors are willing to commit resources. Some industrial members may wish to keep some research findings proprietary. The scientific information learned may not be disseminated to the rest of the world in the form of peer-reviewed publications or public domain literature, possibly due to lack of consensus among the participating commercial entities. Hence, emphasis should be placed on information dissemination in the form of peer-reviewed publications and short courses. However, the benefits overweigh the limitations. Three-way collaborative efforts provide the opportunity for industrial infusion of capital into commercially relevant research projects that address some of the common food safety and technology questions, which cannot be tackled by one single entity. Further, universities can play a crucial role in providing much needed multi-disciplinary scientific expertise, and can assist industry and government agencies in training the next-generation workforce.

ACKNOWLEDGEMENT

References to commercial products or trade names are made with the understanding that no endorsement or discrimination by The Ohio State University is implied.

REFERENCES

Balasubramaniam V.M., Ting E.Y., Stewart C.M. and Robbins J.A. (2004). Recommended guidelines on laboratory practices for conducting high-pressure experiments. *Innovative Food Science & Emerging Technologies* **5**: 299–306.

Black E.P., Setlow P., Hocking A.D., Stewart C.M., Kelly A.L. and Hoover D.G. (2007). Response of spores to high-pressure processing. *Comprehensive Reviews in Food Science and Food Safety*, **6**(4): 103–119.

Cheftel J.C. (1995). Review: high pressure, microbial inactivation, and food preservation. *Food Science and Technology International* **1**: 75–90.

Clark J.P. (2006). High-pressure processing research continues. *Food Technology*, **60**(2): 63–65.

Downloaded from fst.sagepub.com at CIDADE UNIVERSITARIA on September 24, 2014

Dunne C.P. (2005). Killing pathogens: high-pressure processing keeps food safe. Available at http://www.military.com/soldiertech/0,14632, Soldiertech_Squeeze,00.html (accessed 15 September 2006).

Farkas D. and Hoover D. (2000). High pressure processing: kinetics of microbial iactivation for alternative food processing technologies. *Journal of Food Science* (Supplement): **65**: 47–64.

Hayakawa I., Linko Y.-Y. and Linko P. (1996). Mechanism of high pressure denaturation of proteins. *Lebensmittel-Wissenschaft und-Technologie* **29**: 756–762.

Hugas M., Garriga M. and Monfort J.M. (2002). New mild technologies in meat processing: high pressure as a model technology. *Meat Science* **62**(3): 359–371.

Institute of Food Technologists (2000). Kinetics of microbial inactivation for alternative food processing technologies. *Journal of Food Science* (Supplement) **65**: 1–64.

Matser A.M., Krebbers B., Berg R.W. and Bartels P.V. (2004). Advantages of high pressure sterilisation on quality of food products. *Trends in Food Science and Technology* **15**(2): 79–85.

Otero L. and Sanz P.D. (2000). Modelling heat transfer in high pressure food processing: a review. *Innovative Food Science and Emerging Technologies* **4**: 121–134.

Peleg M. and Cole M.B. (1998). Reinterpretation of microbial survival curves. *Critical Reviews in Food Science and Nutrition* **38**: 353–380.

Rasanayagam V., Balasubramaniam V.M., Ting E., Sizer C., Bush C. and Anderson C. (2003). Compression heating of selected fatty food materials during high-pressure processing. *Journal of Food Science* **68**(1): 254–259.

Rastogi, N.K., Raghavarao K.S.M.S., Balasubramaniam V.M., Niranjan K. and Knorr D. (2007). Opportunities and challenges in high pressure processing of foods. *Critical Reviews in Food Science and Nutrition*, **47**(1): 69–112.

Sizer C.E., Balasubramaniam V.M. and Ting E. (2002). Validating high pressure processes for low-acid foods. *Food Technology* **56**(2): 36–42.

Smelt J.P.P.M. (1998). Recent advances in the microbiology of high pressure processing. *Trends in Food Science and Technology* **9**: 152–158.

Tay A., Shellhammer T.H., Yousef A.E. and Chism G.W. (2003). Pressure death and tailing behavior of *Listeria monocytogenes* strains having different barotolerances. *Journal of Food Protection* **66**(11): 2057–2061.

Tewari G., Jayas D.S. and Holley R.A. (1999). High pressure processing of foods: an overview. *Science des Aliments* **19**: 619–661.

Thakur B.R. and Nelson P.E. (1998). High pressure processing and preservation of foods. *Food Reviews International* **14**(4): 427–447.

Ting E., Balasubramaniam V.M. and Raghubeer E. (2002). Determining thermal effects in high pressure processing. *Food Technology* **56**(2): 31–35.

Downloaded from fst.sagepub.com at CIDADE UNIVERSITARIA on September 24, 2014