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Food safety: new concepts for the new millennium ☆

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Abstract

Current market trends for high quality, fresh, convenient foods, plus improvements in efficiency and reductions in cost mean that the rate of adoption of non-thermal processes is likely to increase. Obstacles to commercialization include the lack of systematic inactivation kinetic data, the interpretation of non-linear death kinetics and the need to establish equivalent control measures for non-thermal treatments in comparison with traditional heat processes. The commercialization of new non-thermal technologies, such as high pressure processing and pulsed electric fields, could be expedited by following guidelines given by the International Commission on Microbiological Specifications for Foods (ICMSF). ICMSF has recently proposed a scheme for the management of microbial hazards for foods, which includes the concept of Food Safety Objectives (FSOs). FSOs are intended to communicate the level of a hazard that is required to meet a given public health goal and to facilitate the acceptance of different, but equivalent processes. ICMSF principles of setting FSOs, the use of performance criteria, process criteria and validation in relationship to HACCP and GHP plans are described. Additionally, the use of FSOs as a framework for developing equivalent control measures are discussed in the context of establishing inactivation regimes based on non-thermal technologies. The implications of non-linear death kinetics to the establishment of process criteria are discussed, especially in relation to the development of safe, equivalent processes for commercial food production.

Keywords: Food safety objectives; Non-linear microbial inactivation kinetics; Non-thermal processing regimes

Industrial relevance: This review is of high industrial significance since it deals with one of the key obstacles to commercialization of new non-thermal processes. It addresses the need of systematic microbial inactivation data and their interpretation. Of special industrial relevance is the discussion of process criteria including process validation, process variability and the need for a consistent approach for establishing equivalency of the process.

1. Introduction

Historically, food safety issues have been dealt with as the need arose in the production of food products. Over time, 'best practices', which reflect expert opinion, have been developed, and default values, which represent worst-case situations, were used for the development of processing parameters. These default values were then accepted as regulatory requirements. While some default values should be re-evaluated in response to new information, there has been no widely accepted review process based on scientific information. Additionally, as a result of the lack of a science-based review process, it is currently difficult to compare the protection given to a food product when food safety criteria between countries differ. This leads to difficulties in international trade. Therefore, a scientific basis for comparing the relative level of protection afforded by different process and performance criteria

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is needed, as it would allow for process review as well as aid in the harmonization of international trade where practices in one country differ from the practices in another, yet both practices provide safe products.

The safety of foods in international trade is governed by the World Trade Organization (WTO)/Sanitary and Phytosanitary (SPS) Agreement, which recognizes that governments have the right to reject imported foods when the health of the population is endangered. The criteria used to determine whether a food should be considered safe should be clearly conveyed to the exporting country and should be scientifically justifiable (ICMSF, 2001b). In order to achieve this, the term 'appropriate level of protection' has been used, which is defined as 'the level of protection deemed appropriate by the Member (country) establishing a sanitary or phytosanitary measure to protect human, animal or plant life or health within its territory' (ICMSF, 2001b). The International Commission on the Microbiological Specifications for Foods (ICMSF) has recommended a preventative stepwise approach for the management of microbiological hazards in foods in international trade (Fig. 1). This approach incorporates existing Codex documentation and General Principles of Food Safety Management, as documented by the Food and Agriculture Organization (FAO)/World Health Organization (WHO). The first step is for risk managers to define the problem associated with a hazard in food. This information outlines the parameters to be considered by the risk assessors. Next, a risk estimate is determined and is used to assess the impact of the options available for managing the identified risk(s). Additionally, it should provide a scientific basis for the subsequent risk management decisions. The microbiological risk management options should optimize the interventions necessary to prevent and control microbiological risks. The

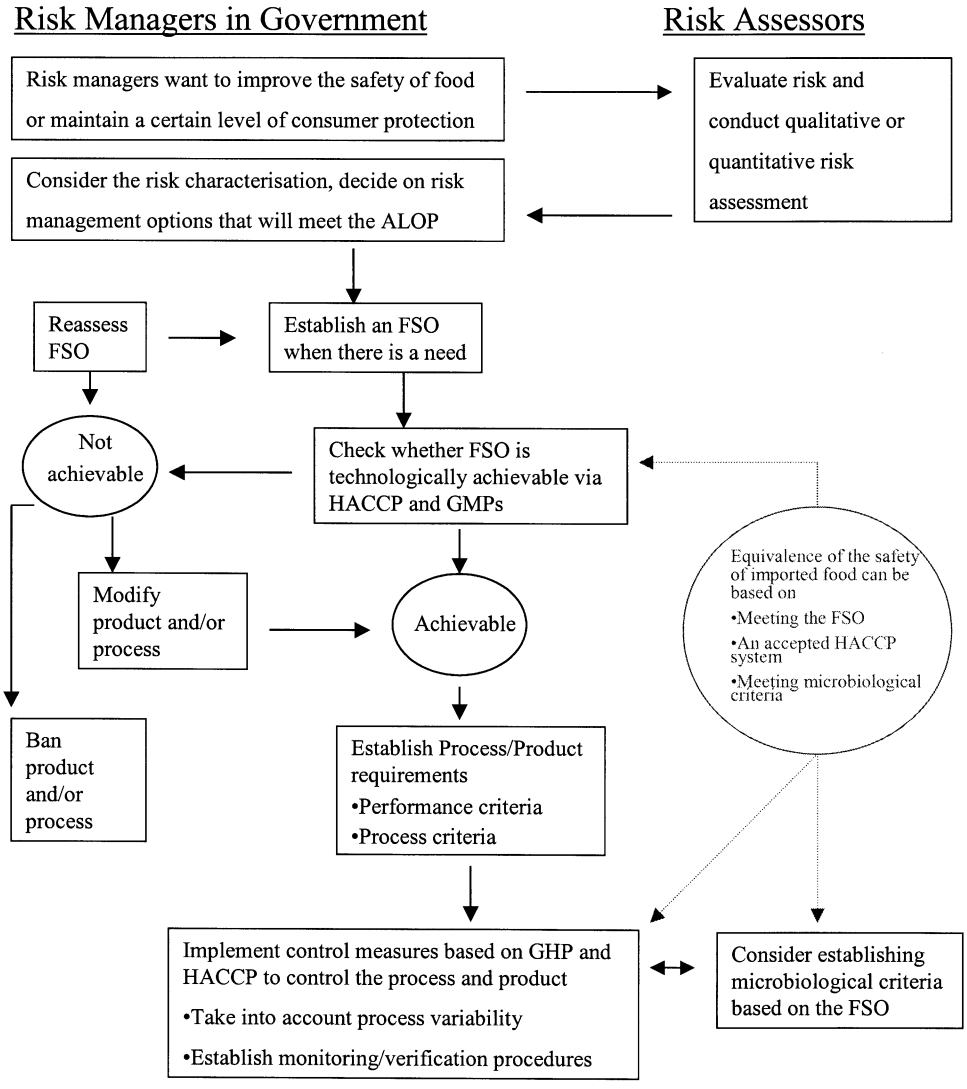

Fig. 1. Management of food safety.

option(s) should achieve or strive toward the chosen level of public health protection in as cost effective manner as possible and within the technological feasibility of the industry (ICMSF, 2001b). The risk management options can then be used to establish a food safety objective (FSO).

The FSO should be evaluated to determine if it is technically achievable through the application of good hygiene practices (GHP) and the Hazard Analysis Critical Control Point System (HACCP). GHPs can be viewed as basic sanitary conditions and practices that must be maintained to produce safe foods including support activities such as raw material selection, product labeling and coding. GHPs form the foundation on which HACCP programs are based. Effective HACCP systems involve a systematic approach to identification, evaluation, and control of food safety hazards in a food operation (ICMSF, 2001a). Once it is determined that the FSO is achievable, performance and process/product criteria are established and the process is then implemented through GHP and HACCP. If the proposed FSO is not technically feasible, then modifications of the product, the process, if technically possible, and/or the FSO may be necessary. If no technically achievable solutions can be found, and the risk is too great, then it may be necessary to ban the product and/or the process. In addition, as new information regarding a particular hazard or product emerges, FSOs may be modified.

2. ICMSF approach to food safety management

Traditionally, risk assessment in international trade has been defined in terms of having a chemical or microbial risk 'as low as reasonable'. This has caused great difficulties for a number of reasons. Although trade is becoming increasingly global, the technological capabilities of different countries, and even different companies within the same country, remain varied. Also, the idea of what is considered 'reasonable' differs from country to country; acceptable risk is culturally defined. Developments in quantitative risk assessments in microbiology (Buchanan, Damert, Whiting & van Schothorst, 1997; Whiting & Buchanan, 1997) have made it possible to link the exposure assessment of a pathogen to likely public health outcomes. The FSO is defined as a statement of the frequency or maximum concentration of a microbiological hazard in a food considered acceptable for consumer protection (van Schothorst, 1998) and allows the equivalence of different control measures to be established. Control measures are the actions and activities used to prevent, eliminate or reduce a food safety hazard to a tolerable level and generally fall into three categories (ICMSF, 2001a):

Controlling initial levels of a hazard

- Avoiding foods with a history of contamination or toxicity (i.e. raw milk, raw molluscan shellfish harvested under certain conditions);
- Selecting ingredients (i.e. pasteurized liquid eggs or milk); and
- Using microbiological testing and criteria to reject unacceptable ingredients or products.

Preventing an increase in the levels of the hazard

- Preventing contamination (i.e. adopting GHPs that minimize contamination during slaughter, separating raw from cooked ready-to-eat foods, using aseptic filling techniques); and
- Preventing growth of pathogens (i.e. chilling and holding temperatures, pH, relative humidity, preservatives).

Reducing the level of a hazard

- Destroying pathogens (i.e. disinfectants, pasteurization, irradiation);
- Removing pathogens (i.e. washing, ultra-filtration, centrifugation).

FSOs differ from microbiological criteria as they are broader in scope and are intended to communicate the level of control considered necessary for consumer protection. They specify goals that can be incorporated into the design of control measures used in food operations. FSOs provide a basis for measuring the effectiveness/adequacy of control systems adopted by industry, government and/or regulatory agencies. They are a risk management tool linking the information from the risk assessment and risk management processes with the establishment of effective measures to control identified risk(s). In order to compare the equivalence of different control measures, it is necessary to be able to relate their performance in terms of achieving a FSO. In other words, their performance needs to be expressed in terms of frequency or concentration of a microbiological hazard. The commercialization of new non-thermal technologies, such as high pressure processing (HPP) and pulsed electric fields (PEF) could be expedited by following the CMSF guidelines as they allow great flexibility in achieving the FSO.

The following definitions of terms will be used throughout the remainder of this paper (van Schothorst, 1998):

- *Food safety objective (FSO):* a statement of the

frequency or maximum concentration of a microbiological hazard considered acceptable for public protection.

For example, the amount of staphylococcal enterotoxin in cheese must not exceed 1 μg/100 g, or the level of *Listeria monocytogenes* in ready-to-eat foods should not exceed 100/g at the time of consumption.

- *Performance criterion:* the required outcome of a step or a combination of steps that can be applied to ensure a FSO is met.

  For example, a performance criterion could be a 6-$\log_{10}$ reduction in the target organism.
- *Step:* a point, procedure, operation or stage in the food chain including raw materials from primary production to final consumption.
- *Process criterion:* the control parameters of a step or combination of steps that can be applied to achieve the performance criterion.

  An example of a process criterion could be heating for 2 min at 70 °C or high-pressure treatment at 500 MPa for 7.5 min.

A diagram of how these principles are linked together is given in Fig. 2. This scheme offers flexibility for the food industry in terms of allowing the use of alternative, but equivalent, means for achieving the same FSO.

Once the FSO is set, the determination of several factors in achieving the FSO must be made. When establishing performance criteria, consideration must be given to the initial level of a hazard and changes in the hazard during production and processing, distribution, storage, preparation and use. A performance criterion can be defined by the equation:

$$H_0 - \sum R + \sum I \leq FSO$$

where:

- H_0 = the initial level of the hazard;
- $\sum R$ = the cumulative (total) decrease of the hazard;
- $\sum I$ = the cumulative (total) increase of the hazard;
- $\leq$ = preferably less than, but at worst equal to;
- FSO = food safety objective; and
- FSO, H_0, R, and I are expressed in $\log_{10}$ units.

Control measures can be put in place to manage each part of the process. For example, H_0 can be minimized through ingredient selection, avoiding food with a history of contamination or toxicity or via the use of microbiological testing and criteria to reject unacceptable ingredients or products. The $\sum I$ value can be managed by preventing contamination and/or growth of pathogens. The $\sum R$ can be achieved by destroying or by removing the hazard. An example is given in Fig. 3. This framework is gaining ground internationally in terms of how processes and food safety systems are established. For example, in the US, a recently published performance criteria for fruit juices is an example of where a 5-D inactivation step is being required; however, the inclusion of an FSO, which states that the level of the target pathogen (i.e. salmonellae) shall be less than X CFU m $^{-1}$ would strengthen the rule (HHS, FDA, 2001).

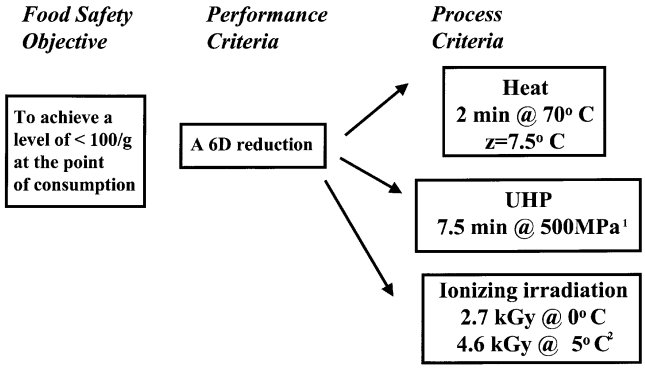

Fig. 2. Example: ready-to-eat extended shelf-life chilled food. Hazard = *Listeria monocytogenes*. Smelt, Rijke & Wouters, 1997; Thayer & Boyd, 1995.

As new processing technologies, such as HPP and PEF, are concerned with reducing the numbers of microorganisms in the final food product, the remainder of this paper will focus on designing inactivation regimes. It is critical that the proper performance and processing criteria are determined and are achievable if non-thermal technologies are to be successfully commercialized. The nature of the inactivation regime will depend on the target organism and the physical properties of the food system. For example, if spoilage organisms, such as yeast or lactobacilli, are the target, then the purpose of the processing steps could be to delay growth, prevent growth or inactivate the organisms to ensure acceptable quality. If the target organisms need to grow and produce toxins to be of concern, such as *Staphylococcus aureus* or *Clostridium botulinum*, the processing should be designed either to prevent growth or to inactivate the organism. Finally, if the target organism is an infectious agent such as *Salmonella* or *Listeria monocytogenes*, then the processing regime must completely inactivate the organism to ensure the safety of the final food product.

3. Inactivation kinetics

In the 1920s, Esty and Meyer (1922) published the first systematic study on the thermal resistance of toxigenic spores, which eventually led to the 'botulinum cook' or commercial sterilization process. The traditional approach of using log-linear models to describe

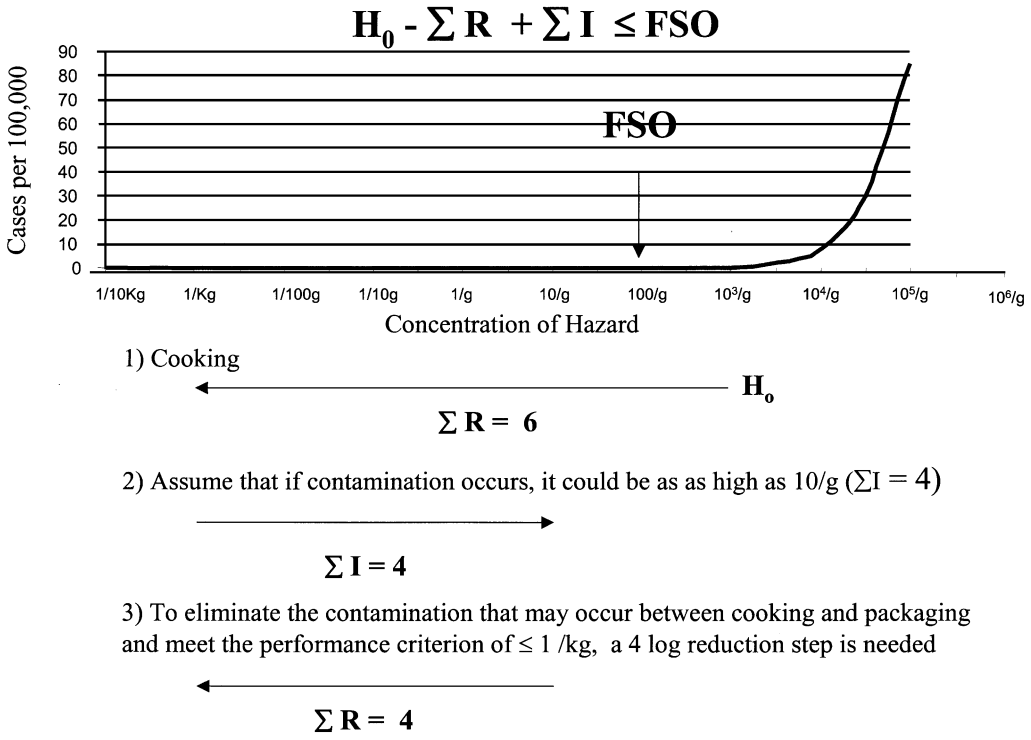

Fig. 3. Control measure: reducing levels using in-package pasteurization (Adapted from ICMSF, 2001a).

microbial death began in the 1920s (Bigelow, Bohart, Richardson & Ball, 1920; Ball, 1923). The familiar term '*D*' to define the time to cause a 1-log reduction in microbial population at a given temperature was not introduced until later (Stumbo, Murphy & Cochran, 1950). Since then, microbiologists have been analyzing thermal inactivation data using the linear *D*- and *z*-value models, even though visual inspection of the data when plotted often showed curvature. Process engineers have also been using the results of these analyses to establish safe food processes. This traditional approach to inactivation kinetics is based on the mechanistic theory, which assumes that microorganisms or their spores die exponentially following first order kinetics, and therefore, all cells or spores within a population have identical heat resistance (Anderson, McClure, Baird-Parker & Cole, 1996). In no other area of biology are either of these two assumptions made. This approach does allow for simple, straightforward calculations and comparisons of thermal process equivalencies to be made. However, throughout the past 80 years, deviations in log-linear models have been repeatedly noted (Whiting & Buchanan, 1992; Cole Davies, Munro, Holyoak & Kilsby, 1993; Buchanan, Golden, Whiting, Phillips & Smith, 1994; Little, Adams, Anderson & Cole, 1994; Anderson et al., 1996).

When semi-logarithmic survival curves are scrutinized, it can be seen that in fact they are not linear, but slightly curved. The vitalistic theory of inactivation explains these observations by viewing the curvature as being due to underlying physiological reactions of the cells/spores to lethal conditions rather than as 'artifacts' of experimentation (Anderson et al., 1996). This theory states that the individual microorganisms in a population do not have identical resistances to inactivation, that these differences are inherent, and that there is a distribution of microbial sensitivity to heat or any other means of inactivation (Anderson et al., 1996). Evidence of biovariability in microbial populations has been demonstrated in work that shows that growth from single cells have a distribution of lag times (Stephens, Joynson, Davies, Holbrook, Lappin-Scott & Humphrey, 1997), that germination of single spores have a distribution in time to germination (Coote, Billon, Pennell, McClure, Ferdinanado & Cole, 1995), and flow cytometry experiments show a variation in injury in a population of microorganisms (Nebe-von-Caron & Balley, 1996). This theory is more in line with the approaches used in other areas of biological study.

When inactivation data are plotted, the curvature of the data can have a significant effect on the calculated inactivation time, particularly when extrapolation is used. Rather than assuming that linear regression will give the best fit, alternate models should be tried. One such alternate model is the Weibull distribution. This simple model can fit data showing upwards or downwards concavity as well as linear data, leading to the best determination of appropriate inactivation regimes when used in its cumulative form (Peleg & Cole, 1998). The cumulative Weibull equation is $S(t) = \exp(-bt^n)$

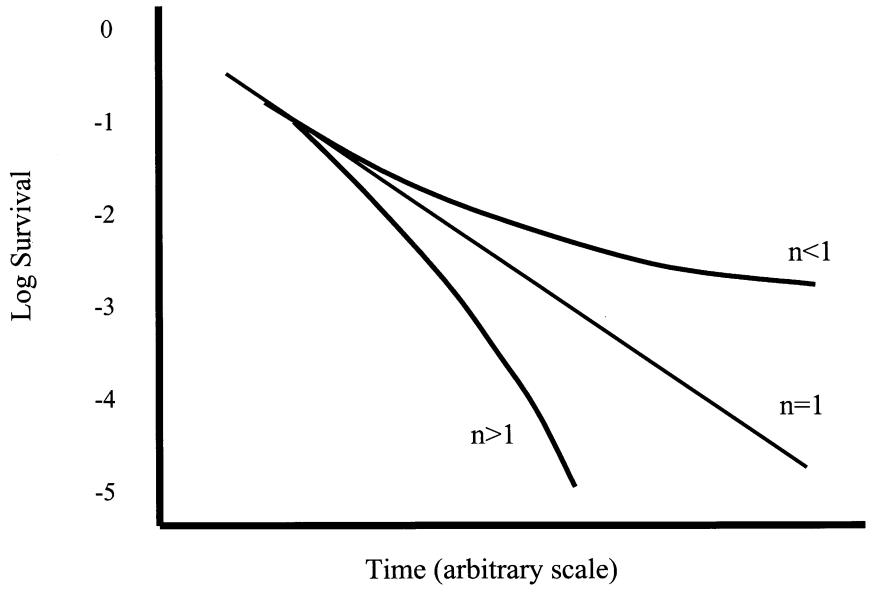

Fig. 4. Simulated microbial inactivation curves: cumulative Weibull distribution Log $S(t) = -bt^n$. (Adapted from Peleg & Cole, 1998).

or, if presented as a semi-logarithmic relationship, log $S(t) = -bt^n$, where $S(t)$ = survival function, t = time, and b and n are constants with n representing the shape and b representing the scale (Peleg & Cole, 1998). The Weibull model more accurately fits the data than the traditional D-value as it takes into account the curvature of the data. A more detailed discussion and alternative methods of modeling microbial inactivation data have been presented by Legan, Stewart, Vandeven and Cole (2002).

When the underlying microbial population's resistance distribution has a strong right skew, the semi-logarithmic survival has a noticeable upward concavity and $n < 1$ (Fig. 4). If a straight line were fit through the data (i.e. via linear regression), the process would have been fail-dangerous. When the survivor curve appears linear in semi-logarithmic coordinates, and hence, has the appearance of first order kinetics, then $n = 1$ (Fig. 4). The ability of the Weibull distribution to accurately fit either linear or curved data makes it quite flexible in its applications. Finally, if the underlying microbial population's resistance distribution has a left skew, the survival curve will have a pronounced downward concavity and $n > 1$ (Fig. 4). If a straight line were fit through the data, the processing time required for inactivation of the microbial load would be over-estimated, leading to over-processing and to the production of a lower quality product.

In order for any non-thermal technology to be widely commercialized, there is a need to obtain systematic inactivation kinetic data. While data exist to develop fail-safe commercial processes under limited conditions, more systematic inactivation kinetic data are required to establish optimized processes that are applicable under a wider range of conditions. Unfortunately, thermal inactivation kinetics cannot be directly applied to inactivation of the same organisms by other processing methods, such as HPP, as heat resistance/sensitivity does not directly correlate to pressure resistance/sensitivity. *Staphylococcus aureus* is an excellent example of this point as it is quite heat sensitive but fairly pressure resistant (Patterson, Quinn, Simpson & Gilmour, 1995; Patterson & Kilpatrick, 1998).

4. Guidelines for establishing process criteria

When establishing the process/product requirements for a new process, including novel processing technologies, it is important to establish a dialogue with the appropriate regulatory agency to ensure commercialization goes as smoothly as possible. In the US, the Food and Drug Administration (FDA) awarded a contract to the Institute of Food Technologists (IFT) to conduct an in-depth scientific analysis on non-thermal processes with particular emphasis on technologies capable of pasteurization and sterilization of foods. In this review titled 'Kinetics of Microbial Inactivation for Alternative Food Processing Technologies' (CFSAN, 2000), the FDA asked IFT to address five issues, which are key to gaining regulatory approval for any new processing technology (IFT, 2000):

1. What are the alternative technologies and what are the critical control points to the process?
2. What organisms of public health significance are most resistant to the alternative technology process

and how to best ascertain this information if it is not immediately available?
3. How to best measure the lethal effects of the process?
4. What is an appropriate surrogate organism(s) that can be used to evaluate the process?
5. How would an alternative technology process deviation be handled?

In the first stages of addressing regulatory issues, consideration of the appropriate regulations should be taken, for example the US the Food Drug and Cosmetic Act is important as it is the basis for all of the regulations promulgated by the FDA. Of particular importance are sections 402(a)(1) and (a)(4), which address microbial pathogens in final food products (IFT, 2000). The next consideration should be specific regulations, for example, in the US, the pre-market approval process for direct and indirect food additives, standards of identity and labeling. Finally, specific commodity based regulations should be addressed, for example in the US, these would include dairy products, low-acid canned foods, seafood and the new fruit and vegetable juice rule (IFT, 2000).

When establishing processing criteria, the following guidelines should be considered. The first step is to define the objective of the treatment and if the target is a spoilage organism, a toxin former or an infectious pathogen. Once the target organism(s) is defined, the next critical steps are to select relevant strains, prepare the inoculum for the studies to give appropriate resistance and stress response that would be expected in the foods. Also, one should consider the use of a cocktail of strains rather than one specific strain. Kinetic studies are preferred as they provide more information than end point measurements, as well as offering flexibility and a depth of understanding that is not obtainable via end point measurements alone. An end point measurement does not show where the failure point is in the process. Experiments should not be designed around the assumption that the data will follow first-order kinetics. The come-up time should be measured and reported and must be minimized or, at the least, relevant to the commercial process. This is especially important when there is a distribution of sensitivities to the treatment in the population, which in reality always occurs. If first order kinetics are assumed, the come-up time is less important as the death rate is measured only after equilibrium has been established. However, if there is a distribution of sensitivities, the position on the death curve will dictate the actual death rate, so the come-up time is extremely important. The zero time point is also important and geometrically distributed time samples are useful in describing the curvature in the data. Sufficiently high initial numbers of organisms should be used so that the performance criteria can be achieved without the need for extrapolation. Enough data points per curve should be collected to describe the data accurately, and mathematically, a minimum of 5–8 points per curve should be used to allow accurate fitting of the distributions. Finally, the methods used should allow for the recovery of injured cells so that inactivation and injury can both be accurately quantified.

4.1. Process validation

Validation is the process of assuring that a defined set of control measures achieves appropriate control over a specific hazard(s) in a specific food(s) (ICMSF, 2001b). Validation of control measures requires that their effectiveness be measured against the expected outcome in controlling a hazard (i.e. performance criterion). Validation can involve (ICMSF, 2001a):

- developing data through predictive microbial models and challenge tests in the laboratory that are intended to mimic conditions of operation;
- collecting data during normal processing in the food operation;
- comparison with similar processes/products; and
- other expert knowledge.

For new, novel processes, it may be necessary to develop information to verify the efficacy of adopted control measures.

4.2. Process variability

Variability in food operation must be considered when establishing the critical limits associated with control measures. Factors that can influence the variability of a process include equipment performance and reliability, the integrity of container seals, processing times and temperatures, pH, humidity, flow rates and turbulence. Critical limits must be based on the capability of the process to achieve an expected outcome under normal operating conditions, taking into account variability (ICMSF, 2001a). The critical limits for a process having a high degree of control (i.e. low variability) can operate at conditions closer to those needed to control the hazard, whereas critical limits for a less controlled or more highly variable process must be more restrictive. An effective process control system is a key element in the management of food safety.

5. Conclusion

New preservation technologies, such as high pressure processing and pulsed electric fields offer advantages in meeting consumer demands of freshness, convenience

and safety. There is no single process that will allow the high-quality production of every food product while ensuring safety; all of these processes, as well as thermal processing, have their own set of limitations and advantages.

Commercialisation, to date, has been slow, but that is changing daily, especially with regards to some of the breakthroughs in high pressure technology. There is a need for a consistent approach for establishing equivalency of the processes. The use of food safety objectives and performance criteria provide the basis for assessing equivalency. Finally, the commercialization of novel processing technologies is dependent on the development of multidisciplinary coordinated programs to assess the efficacy and facilitate the successful development of these processes in a shorter period of time.

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