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Ultrasonic innovations in the food industry: From the laboratory to commercial production

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Abstract

High power ultrasound has only recently (<5 years) become an efficient tool for large scale commercial applications, such as emulsification, homogenization, extraction, crystallization, dewatering, low temperature pasteurization, degassing, defoaming, activation and inactivation of enzymes, particle size reduction and viscosity alteration. This can be attributed to improved equipment design and higher efficiencies of large scale continuous flow-through systems. Like most innovative food processing technologies, high power ultrasonics is not an off-the-shelf technology and therefore needs to be developed and scaled up for each application. The objective of the present paper is to present examples of ultrasonic applications that have made it to commercialization and to share some key learnings involving scale up of an innovative food technology in general.

Keywords: Ultrasonics; Ultrasound and process; Food process

Industrial relevance: Due to significant technical advances in the last 5 to 10 years, high power ultrasonics has become an alternative to many conventional food processing steps, such as homogenization, milling, high shear mixing, pasteurization and solid/liquid separation. Also, it has shown to improve the efficiency of traditional processes such as filtration/screening, extraction, crystallization and fermentation (i.e., as an add-on technology). The use of ultrasonics is often driven by economic benefits, yet in some cases a unique product functionality can be achieved. This manuscript presents several examples of commercial installations of this technology in the food industry and highlights some of the challenges in scale up and development.

1. Introduction

Although ultrasonics have been used for years in research and diagnostics, major advances have been made in the last 5 years turning this laboratory-based prototype technology into fully operational commercial processes throughout Europe and the USA. The applications for which high power ultrasound can be used range from existing processes that are enhanced by the retro-fitting of high power ultrasonic technology, to the development of processes up to now not possible with conventional energy sources. The present paper discusses several examples (including the mechanism) of ultrasonic applications in the food industry that have made it to commercialization. Furthermore, some key learning's involving scale up of an innovative technology in general are presented.

2. Principal mechanism of high power ultrasound

The fundamental effect of ultrasound on a continuum fluid is to impose an acoustic pressure (P_a) in addition to the hydrostatic pressure already acting on the medium. The acoustic pressure is a sinusoidal wave dependent on time (t), frequency (f) and the maximum pressure amplitude of the wave, $P_{a,\max}$ (Muthukumaran, Kentish, Stevens, & Ashokkumar, 2006):

$$P_a = P_{a,\max} \sin(2\pi f t) \quad (1)$$

The maximum pressure amplitude of the wave ($P_{a,\max}$) is directly proportional to the power input of the transducer. At low intensity (amplitude), the pressure wave induces motion and mixing within

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the fluid, so called acoustic streaming (Leighton, 1994). At higher intensities, the local pressure in the expansion phase of the cycle falls below the vapor pressure of the liquid, causing tiny bubbles to grow (created from existing gas nuclei within the fluid). A further increase generates negative transient pressures within the fluid, enhancing bubble growth and producing new cavities by the tensioning effect on the fluid (Mason, 1998). During the compression cycle, the bubble shrinks and their contents are absorbed back into the liquid. However, since the surface area of the bubble is now larger, not all of the vapor is absorbed back into the liquid and thus the bubble grows over a number of cycles. Within a critical size range the oscillation of the bubble wall matches that of the applied frequency of the sound waves causing the bubble to implode during a single compression cycle (Moholkar, Rekveld, & Warmoeskerken, 2000). This process of compression and rarefaction of the medium particles and the consequent collapse of the bubbles comprises the well-known phenomenon of cavitation, the most important effect in high power ultrasonics. The conditions within these imploding bubbles can be dramatic, with temperatures of 5000 K and pressures of up to 1000 atmospheres, which in turn produces very high shear energy waves and turbulence in the cavitation zone (Suslick, 1988; Laborde, Bouyer, Caltagirone, & Gerard, 1998). It is the combination of these factors (heat, pressure and turbulence) which is used to accelerate mass transfer in chemical reactions, create new reaction pathways, break down and dislodge particles (when cavitation in proximity of a solid surface) or even generate different products from those obtained under conventional conditions (Suslick, 1988).

When sound waves reflect on a solid surface or an air–water interface a standing wave can be formed. The acoustic pressure at the nodes is equal to zero, whereas at the anti-node the acoustic pressure fluctuates from a maximum to a minimum. Leighton (1994) and Laborde et al. (1998) explain that bubbles smaller than the resonance size accumulate at the anti-node, whereas bubbles larger than the resonance size accumulate at the node and consequently coalesce as they collide. This process of bubble transport and growth at the nodes and anti-nodes is called microstreaming and is the main mechanism for ultrasonic degassing.

Ultrasound (i.e., mechanical waves at a frequency above the threshold of human hearing) can be divided into three frequency ranges; power ultrasound (16–100 kHz), high frequency ultrasound (100 kHz–1 MHz) and diagnostic ultrasound (1–10 MHz).

The work published by Lorimer & Mason (1987) shows that the frequency is inversely proportional to the bubble size. Therefore, low frequency ultrasound (that is, power ultrasound 16–100 kHz) generates large cavitation bubbles resulting in higher temperatures and pressures in the cavitation zone. As the frequency increases the cavitation zone becomes less violent and in the megahertz range no cavitation is observed anymore and the main mechanism is acoustic streaming. While medical imaging operates at frequencies in the megahertz range, most industrial applications (processing of chemicals, food as well as cleaning) operate between 16 and 100 kHz because cavitation can be produced within this frequency range.

The use of ultrasonics in industrial processes has two main requirements; a liquid medium (even if the liquid element forms only 5% of the overall medium) and a source of high-energy vibrations (the ultrasound). The vibrational energy source is called a transducer which transfers the vibration (after amplification) to the so-called sonotrode or probe, which is in direct contact with the processing medium. There are two main types of transducers; piezoelectric and magnetostrictive. Piezoelectric transducers are the most commonly used in commercial scale applications due to their scalability; i.e., the maximum power per single transducer is generally higher than magnetostrictive transducers.

3. Process parameters

3.1. Energy and intensity

Ultrasonic liquid processing can be described by the following parameters: amplitude (see Eq. (1)), pressure, temperature, viscosity and concentration of solids. The result or outcome (e.g., % improved extraction yield and/or rate) is a function of:

1) Energy — the energy input per volume treated material (in kWh/L);
2) Intensity — the actual power output per surface area of the sonotrode (in W/cm^2), where the energy input is the product of power output (kW) and the time of exposure. The time of exposure is directly related to the flowrate through the ultrasonic device (L/h). A very general relationship between flowrate and energy for several ultrasonic applications is shown in Fig. 1.

Both energy and intensity are independent of scale and thus any ultrasonic process will be scaleable using these two parameters (Hielscher, 2005).

3.2. Pressure

Increasing the external pressure (as controlled by the back pressure) increases the cavitation threshold and thus the number of cavitation bubbles is reduced (Muthukumaran et al., 2006). On the other hand, increasing the external pressure will increase the pressure in the bubble at the moment of collapse resulting in a more rapid but violent collapse (Lorimer & Mason, 1987). Therefore, increasing the back pressure can be an effective tool

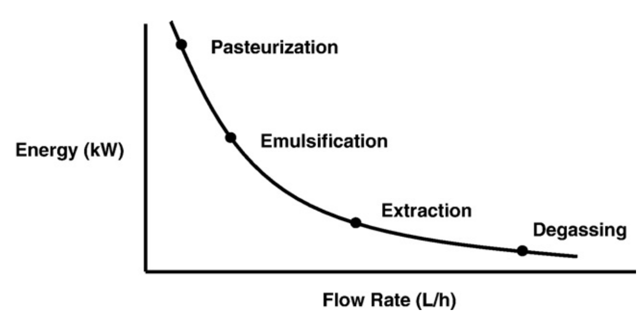

Fig. 1. Generalized relationship of flow rate (liters per hour (L/h)) vs. energy (kilowatts) for several ultrasonic applications.

in intensifying the process without having to increase the amplitude (Hielscher, 2005).

3.3. Temperature and viscosity

Temperature affects the vapor pressure, surface tension, and viscosity of the liquid medium (Muthukumaran et al., 2006). While increased temperature increases the number of cavitation bubbles, the collapse is 'cushioned' or 'dampened' by the higher vapor pressure. Cavitation bubbles form less easily in a highly viscous environment. Increased temperature decreases the viscosity allowing for a more violent collapse. Thus, there is an optimum temperature at which the viscosity is low enough to form enough violent cavitation bubbles, yet the temperature is low enough to avoid the dampening effect by a high vapor pressure.

It becomes clear that there are many process parameters affecting the process output and thus it takes time and effort to scale and fine-tune the process with the goal to achieve the maximum result with a minimum amount of energy (as that determines the number of transducers required for the commercial application).

4. Applications and benefits

4.1. Summary of applications

A broad range of ultrasonic systems and treatment conditions provide a diverse range of food application opportunities, as summarized in Table 1.

4.2. Extraction

The extraction of organic compounds from plants or seeds has classically been based upon the judicious combination of solvent, heat and/or agitation. This can be significantly improved by the use of high powered ultrasound, as the energy generated from collapsing cavitational bubbles provides greater penetration of the solvent into the cellular material and improves mass transfer to and from interfaces (Knorr, 2003; Zhang, Xu, & Shi, 2003; Vinatoru, 2001; Li, Pordesimo, & Weiss, 2004; Vilkhu, Mawson, Simons, & Bates, in press). At higher ultrasonic intensities (i.e., Watts/cm^2), extraction processes can be further improved with the disruption of cell walls and the release of cellular materials. Very recently Balachandran, Kentish, Mawson, and Ashokkumar (2006) studied the effect of ultrasonics on supercritical extraction of ginger. Both rate and final yield were improved significantly. Since cavitational events in a supercritical fluid seem impossible due to the absence of liquid/gas phase boundaries, several other mechanisms, such as acoustic streaming and the presence of gas pockets in the solid causing cavitational collapse, are proposed. Recently it was shown that the same principles of mass transfer in extraction can be used in meat brining. Carcel, Benedito, Bon and Mulet (2007) showed that above a critical ultrasonic intensity the uptake of brine solution into the meat was proportional to the applied ultrasonic intensity. At the highest level studied the total brine uptake was significantly higher than the initial water content of the meat.

Table 1
List of high power ultrasound applications in the food industry (references are listed in the appropriate subsection)

Application	Mechanism	Benefit
Extraction	Increased mass transfer of solvent, release of plant cell material (cavitational dislodgement)	Increased extraction efficiency, yield in solvent, aqueous or supercritical systems
Emulsification/ homogenization	High shear micro-streaming	Cost effective emulsion formation
Crystallization	Nucleation and modification of crystal formation	Formation of smaller crystals
Filtration/ screening	Disturbance of the boundary layer	Increased flux rates, reduced fouling
Separation	Agglomeration of components at pressure nodal points	Adjunct for use in non-chemical separation procedures
Viscosity alteration	Reversible and non-reversible structural modification via vibrational & high-shear micro-streaming. Sono-chemical modification involving cross-linking and restructuring	Non-chemical modification for improved processing traits, reduced additives, differentiated functionality.
Defoaming	Airborne pressure waves causing bubble collapse	Increased production throughput, reduction or elimination of antifoam chemicals and reduced wastage in bottling lines.
Extrusion	Mechanical vibration, reduced friction	Increased throughput
Enzyme and microbial inactivation [a]	Increased heat transfer and high shear. Direct cavitational damage to microbial cell membranes	Enzyme inactivation adjunct at lower temperatures for improved quality attributes
Fermentation [a]	Improved substrate transfer and stimulation of living tissue, enzyme processes	Increasing production of metabolites, acceleration of fermentation processes
Heat Transfer [a]	Improved heat transfer through acoustic streaming and cavitation	Acceleration of heating, cooling and drying of products at low temperature

[a] At time of publication the authors are not aware of any commercial scale installation of this application.

4.3. Emulsification/Homogenization

If a cavitation bubble collapses near the surface of the phase boundary layer of two immiscible liquids, the resultant shock wave can provide very efficient mixing of the two layers. Relatively low energy input can result in the formation of very fine, highly stable emulsions (Canselier, Delmas, Wilhelm, & Abismail, 2002; Freitas, Hielscher, Merkle, & Gander, 2006). This has been well commercialized in the petrochemical, polymer, chemical, textile, cosmetics and pharmaceutical industries and is now being developed in-line for food products such as fruit juices, mayonnaise and tomato ketchup (Wu, Hulbert, & Mount, 2000). Little, if any, additional emulsifier is required to maintain the stability of the system. For applications such as mayonnaise, an excellent white colour is produced which reflects the small particle size and their narrow distribution (unpublished results). An obvious benefit of the ultrasonic emulsification process is that it can be installed in-line within the existing plant.

4.4. Crystallization

High powered ultrasound can assist the crystallization process in several ways: Influence the initiation of crystal nucleation, control the rate of crystal growth, ensure the formation of small and even-sized crystals, and prevent fouling of surfaces by the newly formed crystals (Luque de Castro & Priego-Capote, 2007; Virone, Kramer, van Rosmalen, Stoop, & Bakker, 2006) If such processes are not well controlled, nucleation and subsequent crystallization can occur randomly, (often from small fluctuations in temperature and pressure) which generally produce a poor quality product. This can be of considerable financial significance in a large commercial process (McCausland, Cains, & Martin, 2001).

Ultrasonic crystallization technology can be applied to foods where it can be used to control the size and rate of development of ice crystals in frozen foods (Chow, Blindt, Chivers, & Povey, 2003). As food is frozen, small crystals form within the matrix. With conventional freezing, the time taken from the initiation of crystallization to complete freezing (the dwell time) can be lengthy, and then during storage the crystals can expand. With cellular materials such as meats, fruits and vegetables the extended dwell time and crystal expansion softens and sometimes ruptures cell walls, resulting in textural softening and the release of cellular liquid on thawing. Freezing using ultrasonics ensures rapid and even nucleation, short dwell times and the formation of small, evenly sized crystals, greatly reducing cellular damage and preserving product integrity, even on thawing (Zheng & Sun, 2006). An added benefit from ultrasonics induced crystallization is the continuous cleaning effect from cavitation, which prevents encrustation of crystals on the cooling elements and ensures continuous heat transfer during the process.

4.5. Filtration and screening

The application of ultrasound to filtration or screening processes can benefit the process in several ways. Ultrasound provides vibrational energy to keep particles in suspension and moving, leaving channels in the filter open and free for solvent elution. It also causes the filter or screen to vibrate, creating a ‘frictionless surface’, allowing the liquid or smaller particles to pass through more readily (Telsonic, 2007). An additional advantage is an extension to filter life, as clogging and caking are prevented by continuous cavitation at the filter's surface. Ultrasonic oscillations are transmitted simultaneously to the filter and the material being treated, which improve the flow characteristics of the material (Grossner, Belovich, & Feke, 2005). All these factors are of significance to commercial filtration processes and several companies are offering ultrasonic filtration systems as an add-on to existing (vibratory) screens. More recently the combination of ultrasound and membrane filtration has been investigated (Muthukumaran, Kentish, Ashokkumar, & Stevens, 2005; Muthukumaran et al., 2006). While this area is still in its early phases of development some promising results are obtained in research labs and academia. The same principles as dead-end filtration apply and thus higher fluxes can be maintained for longer periods of time plus that the ‘cleaning-in-place’ cycles can be done more efficiently (Feng, van Deventer, & Aldrich, 2006).

4.6. Separation

A standing ultrasound force allows particles to aggregate to a node or antinode. The acoustic radiation force acts to drive the dispersed phase to either the nodes or antinodes of the stationary field, and acts to hold the droplets in position (and consequently coalesce) relative to the bulk flow. This technology was shown to provide a novel principle for particle separation (Masudo & Okada, 2001). If high powered ultrasound is applied to an emulsion at low frequencies (<30 kHz), it can be used to split an emulsion into its component aqueous and oil phases (Pangu & Feke, 2004; Gardner & Apfel, 1993). The commercialization of this principle requires a great deal of development work and fine tuning since high power ultrasound can easily result in the opposite effect and yield a more stable emulsion or dispersion.

4.7. Viscosity alteration

Many food systems exhibit complex flow behaviour and the viscosity is often determined by multiple factors such as pH, molecular weight of the protein, pectin or polysaccharide, hydrogen bonding, and other inter- and intramolecular forces. Ultrasound can be applied to either increase or decrease the viscosity and, dependent on the intensity, the effect can be temporary or permanent. Cavitation causes shear which in the case of thixotropic fluids causes a decrease in viscosity. This is often a temporary phenomenon. However, if enough energy is applied, the molecular weight may be decreased causing a permanent viscosity reduction (Seshadri, Weiss, Hulbert, & Mount, 2003). Recently, Bates, Bagnall, and Bridges (2006) showed that the opposite is also possible. In some vegetable purees the ultrasound actually allows for better penetration of moisture into the fibre network which causes an increase in the viscosity of tomato puree.

4.8. Defoaming

Airborne ultrasonic technology is being applied commercially to achieve defoaming of carbonated beverages, fermentation systems and other food processes where foaming adversely affects product quality or yields (Gallego-Juárez, 1998; Morey, Deshpande, & Barigou, 1999). Foaming problems can result in product losses and reduced efficiencies as production rates or volumes often have to be reduced. Since ultrasonic energy dissipates quickly in the air, the applications of ultrasonics in the air are very limited. Nevertheless, the energy transmitted in the defoaming application is large enough to break a thin liquid film in the foam and thus provides a unique way of destroying foam without the use of mechanical breakers or by the addition of chemical antifoams, which may not be desirable in food processes.

4.9. Extrusion

A fairly recent development is the use of ultrasound in enhancing extrusion processes. The energy input provided by ultrasonic excitation of a metal tube or extrusion dye can be achieved by perpendicular attachment of the sonotrode onto the tube or dye. The vibration of the metal reduces the drag resistance and thus improves flow behavior (Knorr, 2004; Akbari Mousavi, Feizi, & Madoliat, 2007).

4.10. Enzyme and microbial inactivation

Ultrasound has not only attracted considerable interest in the food industry due to its positive effects in processing, but more recently due to its promising effects in food preservation. Knorr (2004) shows successful reduction of *E. coli* in liquid whole egg using ultrasound. Generally, most micro-organisms showed greater sensitivity to ultrasound at increased temperatures over 50°C (Sala, Burgos, Condon, Lopez, & Raso, 1995; Villamiel & de Jong, 2000). Elevated temperature weakens the bacterial membrane, which enhances the effect of cavitation due to the ultrasound. ‘Ultrasonic pasteurization’ at 50°C has the potential of preserving the quality of many food products in terms of physicochemical properties, color, and flavor compared to conventional pasteurization techniques at much higher temperatures.

4.11. Fermentation

Several processes that take place in the presence of cells or enzymes are activated by ultrasonic waves. High intensity ultrasound can break cells or denature enzymes, however low intensity ultrasound can improve mass transfer of reagents and products through the boundary layer or through the cellular wall and membrane (Sinisterra, 1992; Pitt & Rodd, 2003). Matsuura, Hirotsune, Nunokawa, Satoh, and Honda (1994) showed an increase in the fermentation rate of sake, beer and wine, when a relatively low intensity ultrasound was applied during the fermentation. The proposed mechanism is that the ultrasound (a great degassing tool) drives off CO_2 (produced during the fermentation) which normally inhibits the fermentation.

4.12. Heat transfer

Cavitation can strongly affect the degree of heat transfer enhancement. Close to the boiling point of a liquid no cavitation occurs and acoustic streaming is the major factor in enhancing heat transfer rates, whereas at lower temperatures the effect of ultrasonic vibration is manifested through violent motion of cavitation bubbles (Kim, Kim & Kang, 2004). Very recently, the group of Gallego-Juarez (Fuente-Blanco, Riera-Franco de Sarabia, Acosta-Aparicio, Blanco-Blanco, & Gallego-Juárez, 2006) developed a novel ultrasonic drying process. Many food products (e.g. fruits and vegetables) are sensitive to heat causing structural changes in the product after dehydration. The proposed system applies ultrasonic energy in combination with hot air to accelerate drying at room temperature (!), thereby preserving the integrity of the food product. The system is still in development but has great promise.

5. Commercialization

Ultrasonic processing is establishing itself as a significant food-processing technology with the capability for large commercial scale-up and good payback on capital investment. Significant improvements in product quality, process enhancement and cost reduction are achievable on a commercial scale. The reasons are summarized below:

5.1. Availability of high amplitude/power units for large commercial operations

Manufacturers of high power ultrasound equipment have been focusing on the design of large flow — continuous treatment chambers (flow cells) causing the cost per volume material treated to be reduced. A typical large flow chamber provides 16 kW for flows ranging from 5 to 500 l/min, depending on the application. Larger flow rates would require multiple systems in series or parallel.

5.2. Improved energy efficiency of the equipment

The efficiency of ultrasonic generators and transducers has been improved over the years, thereby reducing internal heating (and subsequent expensive cooling systems), often causing system failure. Current systems have an energy efficiency around 85% which simply means that most of the power send to the transducer is transferred into the medium.

5.3. Easy to install and/or retrofit systems

As mentioned earlier, due to improved efficiencies, the size of generator, cooling system and other parts are easily installed into an existing facility. If necessary, sound prove cabinets are available to reduce the noise generated by the cavitation (not the ultrasound itself!).

5.4. Competitive energy costs

Depending on the application, the amount of energy required per liter material treated (often defined as kWh/L) is comparable to any other unit operation in the industry (for example homogenization, milling, heat shock, etc.).

5.5. Low maintenance cost

One of the main benefits of ultrasonic technology is the absence of moving parts. The lack of rotors, seals, grease, etc.

Table 2
Business case examples of commercialized ultrasonic applications [a]

Application	Description	Benefit (US k$/yr)	Investment [b] (US k$/yr)	Payback time
Defoaming	Increased production capacity	1000	100	6 weeks (!)
Emulsification	Reformulation and improved shelf-life	500	500	1 year
Extrusion	Increased production capacity	600	120	3 months
Extraction	Yield increase	2000	700	4 months
Waste treatment	Enhanced digestion & renewable energy	500	120	3 months

[a] For confidentiality reasons, the annual savings and investment costs are rounded and not exact.
[b] Includes development, capital and installation costs.

makes these systems particular robust. The only part which requires replacement is the sonotrode (probe) which in direct contact with the medium. Depending on the amplitude and the abrasiveness of the medium, the lifetime of a sonotrode ranges from 1–18 months.

5.6. Strong potential for intellectual property

While high power ultrasonic systems become more and more standardized, the way the energy is applied to the medium (for example, flow cell design, number of transducers, piping arrangement, etc.) is unique for every application. Therefore, the potential to obtain patent protection is relatively large.

As a result of the reasons mentioned above, the technology has provided a strong economic business case in a range of food processing applications, which to date are only known by those involved in the application development due to confidentiality restrictions. An outline of several business cases based on realized projects is provided in Table 2. The payback (defined here as investment cost over the benefit) is in general less than 1 year. Note that payback was used here as a simplified way to calculate the business case. Corporations generally use more sophisticated tools, such as Net Present Value (NPV), Internal Rate of Return (IRR), or Return On Investment (ROI) to evaluate the business case (Brealey, Myers, & Allen, 2006).

6. Key lessons in commercializing innovative technologies

While the technology plays an important role in the implementation of an innovative food processing technology, there are some basic guidelines for making the project a success. Based on the authors' experience a list of tips is given below:

a) The technology has to have "dollars" and "Intellectual Property" appeal
b) The economics (total cost, payback, etc.) need to be well understood early on in the process. In other words, is the payback time acceptable to upper management? In many industries the maximum payback time is shorter (for example 2 instead of 4 years) when the risk is higher.
c) Build a road map to commercialization (incl. cost, time and resources required). This helps manage expectations and ensures that management understands what it takes to commercialize the technology. A good approach is the so-called Stage-Gate™ process (Cooper, 2001), which focuses on both doing projects right and doing the right projects following a staged project management process from 'ideation' to 'launch' (note that Stage-Gate™ can be used for both new products and processes).
d) While it is important to get support from plant personnel, it is as important to keep decision makers in the loop and give them frequent project updates.
e) Typically the implementation of a new technology in an existing production facility means a temporary shutdown or production slow down. It is therefore critical that the plant manager and personnel understand the benefits of the implementation. In other words, plant 'buy-in' will only be obtained if there is a 'win–win' situation. This also emphasizes the importance of an 'internal champion' of the project at the plant site, who can in turn delegate tasks to sub-contractors (electricians, technicians, welders, engineers, etc.).
f) Build a culture of recognizing each other for a job well done or going beyond the call of duty.
g) Keep a positive attitude! As Sir Winston Churchill (1874–1965) said, "Success is the ability to go from one failure to another with no loss of enthusiasm."

Even though technology plays a key role in the project, there are uncontrollable factors that impact the last stage of the project, that is, successful launch or full scale implementation. Examples of mostly uncontrollable factors are: The business gets sold off or ceases operation. The 'internal champion' finds another job/resigns/retires. The transition of a new internal champion often results in project delays. A change of management and/or reprioritization of project portfolio. New management needs to be updated on existing projects which may result in delays, in the project being put on hold or even cancelled. The learnings summarized above are all very important issues that need to be considered when commercializing an innovative technology. Therefore, often times, the reason a new technology does not make it to commercialization is not related to the technology itself but due to the unexpected and uncontrollable factors listed above.

The following list of questions indicate an opportunity for better communication during the project, part of which is managing the expectations at all levels of management. Do not even be surprised to hear these questions during start-up of the commercial installation:

a) Can the technology be scaled up? Has this technology been implemented anywhere else?
b) How reliable is the technology? "…We want a patent, but we don't want to be the first to implement it…!"

c) What are the energy costs — will it need a 'nuclear power' plant?
d) What about spare parts ? "Is there a 1–800 number we can call when the equipment breaks down?" Who, how, when?

7. Conclusions

The considerable interest in high-powered ultrasound is due to its promising effects in food processing and preservation, such as higher product yields, shorter processing times, reduced operating and maintenance costs, improved taste, texture, flavour and colour, and the reduction of pathogens at lower temperatures. As one of the more advanced food technologies, it can be applied not only to improve the quality and safety of processed foods but offers the potential for developing new products with unique functionality as well.

Commercial standard ultrasonic equipment is developing at great pace and no novel process for the application of ultrasound in industry is possible without ultrasonic equipment manufacturers willing to build new designs according to the requirements of customers. This implies that while the technology has great promises it will have to be carefully developed and scaled up for every single, unique application.

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