II. REVIEW OF THE LITERATURE

A. Hydrodynamic Shock Waves

1. Characteristics

Glass (1974) describes a shock wave as a very sharp thin wave front naturally formed from thunderstorms, volcanic eruptions, cosmic explosions, or as in the case of the hydrodynamic shock wave processing, a wave front created from an electrical discharge or an explosive charge detonated in an aqueous medium. Once a shock wave is generated, the pressure of materials surrounding the shock wave is raised. An aftershock of subsiding pressure waves follows the rise in pressure (Glass, 1974; Meek, 1997).

2. Methods of Generation

a. Explosives

A chemical explosion is an exothermic reaction. It is created when a chemical compound (or a mixture of compounds) of low kinetic (but high potential) energy is detonated, resulting in a release of a large amount of kinetic energy. In general, the mass of an explosive charge is proportional to the amount of energy released upon detonation for that specific explosive material (Karfakis, 2002: personal communication). The mass of an explosive charge may therefore directly affect the magnitude of the shock wave produced in an aqueous treatment system contained within a treatment chamber. Explosive materials with a large shattering effect (high brisance) would be expected to produce a greater amount of physical disruption to microbial membranes as well as to the tissues of treated whole meats (Long, 2001). Explosives composed of different materials exhibit different burn rates and produce different types of shock waves in an aqueous medium, thus they might be expected to yield different effects on the bacterial flora of treated meats.

1) Binary

A binary (2 part) explosive composed of solid ammonium nitrate and liquid nitro methane was used to generate an explosively-generated hydrodynamic shock wave (EHSW) (Meek, 2000, O'Rourke et al., 1998; Solomon, 1998b). Liquid nitro methane is classified as high explosive with a burn rate of 6,705 m/s (Cook, 1974; Long 1994). Neither component is explosive until mixed on site and detonated with an electric blasting cap connected to an electronic detonation bridge (Long, 1994). The binary explosive is molded around an electric blasting cap connected to an electronic detonation bridge by wire leads. Detonation of the explosive produces carbon dioxide, nitrogen dioxide, carbon monoxide, and hydrogen (Karfakis, 2002: personal communication; Long, 1994). The detonation of a chemical explosive causes a release of energy. This energy of chemical reaction is distributed to a high energy shock wave and to the generation of a high energy gas bubble composed of CO_2, CO, NO_2, and H_2. Typically, only 25-30% of the energy of chemical reaction is distributed to the shock wave, leaving the remainder to the high energy gas bubble (Long, 2001).

Meek (1997) and Long (1993,1994) describe the course of events which occur during explosively (binary explosive) generated hydrodynamic shock wave treatment. After the packaged sample is submerged into the treatment chamber, the explosive is submerged at a set distance from the top surface of the sample. The vented lid to the treatment chamber is closed and secured and the binary explosive detonated. Detonation of the binary explosive in the liquid medium produces a high-energy primary shock wave. This primary wave radiates in all directions from the epicenter of the explosive. This is the first wave front to reach the surface of the packaged sample on the bottom of the sample chamber (Long, 1993; 1994; Meek, 1997). This wave passes through the packaged sample and dissipates some of the energy into portions which are an acoustical mismatch to the wave (Long, 1993; 1994; Meek, 1997). The remainder of the wave is reflected off the bottom of the sample chamber (Long, 1993; 1994; Meek, 1997). A gas bubble (composed of CO_2, CO, NO_2, and H_2) formed during the chemical reaction of detonation creates a secondary wave front containing approximately one-third (or less) energy than the initial shock wave. This secondary wave intersects with the reflected portions of the primary wave, dissipating additional energy into the packaged sample. A compression force created within the meat is equivalent to the passage of multiple wave fronts through the sample (Long, 1993; 1994; Meek, 1997). Shaping the binary explosive into the shape of a sphere allows the explosively generated shock waves to travel forth from the site of detonation equidistantly, thus striking the packaged muscle food uniformly within the treatment chamber (Batsonov, 1994). The tenderization effects observed in treated samples suggests the meat is uniformly exposed to pressure treatment from the top surface to the bottom (Solomon et al., 1997a,b,c).

Researchers report estimates of the magnitude of the pressure fronts observed in hydrodynamic shock wave processing as a function of the mass of the explosive charge and the radius between the charge and bottom of the treatment vessel (Appendix A, Table 1). The radius between the center of the explosive charge and the bottom of the vessel is equivalent to the distance between the center of the explosive and the wall of the treatment vessel (tank) (Long, 2000a). In reporting the pressure fronts observed, researchers cite either the distance between the explosive and the sample (Berry et al., 1997; Gamble et al, 1998; Meek et al., 2000; Spanier and Romanowski, 2000; Solomon et al., 1997a; Solomon, 1998a,b; Williams-Campbell and Solomon, 2001, 2002; Zuckerman and Solomon, 1998) or the distance between the explosive and the bottom of the treatment vessel (Moeller, et al., 1999). Because the sensitive instruments used to measure pressure fronts obtained during EHSW treatments would be damaged during detonation (Long, 2000a: personal communication), these pressure fronts have not been directly measured, but are calculated from explosion curves specifically derived for binary explosives (Appendix A, Table 1. [Eastridge, 1998; Long, 2000a: personal communication]). As expected, the estimated psi within the treatment vessel increases as both the mass of the explosive increases and as the distance between the explosive and the wall of the treatment vessel is reduced (Appendix A. Table 1). The estimates depend only on the distance between the explosive and the wall of the treatment vessel, thus the estimates derived from the explosion curves can be applied to all EHSW prototypes (Long, 2002: personal communication). Since much of the work performed in the field of EHSW and the static process of Hydrostatic Pressure Processing (HPP) is reported in either MPa or psi units, the conversion between the two units is shown below (Equation 1).

$$(1)\quad 1\text{MPa} = 6.894 \times 10^{-3} \text{ psi}$$

Gamble et al. (1998) cites the use of a binary explosive composed of two liquids, nitro methane and ethylene diamine to create an EHSW within the large hemi shell (LH) prototype. The components are only explosive when mixed and detonated with an electric blasting cap.

Table 1. Pressure fronts reported in explosively-generated hydrodynamic shock wave treatments using binary explosives.

Prototype	Mass of charge (g)	Distance from meat surface (cm)	Pressure (MPa)	Pressure (psi)	Reference
LH[a]	200	20	142	20,600	Meek et al., 2000
LH[a]	350	23	159	23,000	Meek et al., 2000
LH[a]	275	20	163	23,600	Meek et al., 2000
LH[a]	350	20	177	25,700	Meek et al., 2000
LH[a]	N.R.[c]	46	50-60	7,300-8,700	Gamble et al., 1998
LH[a]	150	56	38	5,500	Solomon, 1998b
LH[a]	350	56	52	7,500	Solomon, 1998b
LH[a]	350	46	72	10,400	Solomon, 1998b
LH[a]	105	26.7	83	12,000	Schilling et al., 2002
LH[a]	200	26.7	104	15,000	Schilling et al., 2002
LH[a]	305	26.7	124	18,000	Schilling et al., 2002
LH[a]	150	N.R. [c]	69	10,000	Moeller et al., 1999
ST[b]	100	30.5	70	10,100	Williams-Campbell and Solomon, 2002
ST[b]	100	30.5	70	10,100	Williams-Campbell and Solomon, 2001
ST[b]	25	30.5	41	5,900	Williams-Campbell and Solomon, 2001
ST[b]	50	30.5	54	7,800	Williams-Campbell and Solomon, 2001
ST[b]	75	30.5	62	9,000	Williams-Campbell and Solomon, 2001

Prototype	Mass of charge (g)	Distance from meat surface (cm)	Pressure (MPa)	Pressure (psi)	Reference
ST [b]	75	15.2	138	20,000	Williams-Campbell and Solomon, 2001
PHC [d]	N.R. [c]	N.R. [c]	69	10,000	O’ Rourke et al., 1998
PHC [d]	N.R. [c]	30.5	46	6,700	Gamble et al., 1998

[a] LH = Large Stainless Steel Hemi shell prototype with 1060 L capacity

[b] ST = Small Stainless Steel Tank prototype with 54 L capacity

[c] N.R. = not reported

[d] PHC = Plastic Holding Container prototype with 208 L capacity

Although this mixture is cited as the preferred binary mixture for use in EHSW processing, the only published study utilizing this mixture was that of Gamble et al (1998).

2) Pentaerythritol tetranitrate

Pentaerythritol tetranitrate (PETN) is a manufactured commercially available substance classified as a special industrial explosives material. It is available as a shaped material and in flat sheet forms and is used for high-energy-rate forming, expanding, and shaping in metal fabrication. It is also used for dismemberment and quick reduction of scrap metal (Anon., 2002). PETN is a single molecule chemical explosive with a burn rate of 8,260 m/s (Karfakis, 2002; Long, 2001). Although all explosives generate gases as the result of chemical reaction, the relative size and energy of the gas bubble is dependent on the makeup of the explosive (Karfakis, 2002). For all practical purposes, the effects of the released gases from PETN are insignificant since the shock wave preceding the gas release carries most of the energy and causes most of the structural damage to the sample before the lower energy gas bubble reaches the sample (Karfakis, 2002). The shock wave produced is therefore mostly dependent on the rate of chemical reaction after detonation and should therefore produce a higher shock energy than the binary explosives discussed previously (Karfakis, 2002). Molecular explosives (such as PETN) can produce 55% of the energy or more in the shock wave because of their more rapid detonation velocity (Long, 2001). Theoretical pressure calculations have been devised for the use of this explosive in EHSW processing (Appendix A. Table 2). The magnitude of the pressure front increases as the mass of the explosive increases and as the distance between the explosive and the wall of the treatment vessel decreases (Appendix A., Table 2). As with the pressure front estimates calculated for the binary explosive, the estimates derived for the molecular explosive depend only on the distance between the explosive and the wall of the treatment vessel and can therefore be applied to all EHSW prototypes (Long, 2002: personal communication).

b. Electricity

1) High Voltage Arc Discharge

Long (2000b) describes the course of events which take place during the treatment of meat by an electrically-generated hydrodynamic shock wave (high voltage arc discharge [HVADH]). Electrical energy is stored in a bank of capacitors and is discharged within a few seconds through the electrodes. Upon discharge, virtually all of the energy is placed in the space between the electrodes resulting in outward pressure as a shock wave. During HVADH processing, the whole muscle food does not come into direct contact with the electric discharge, but the electric arc is discharged between electrodes within close proximity to the meat. Martin (1960) states that below the surface of water, the discharge of high voltage across an electrode gap is similar to the detonation of explosives. Both methods create high pressures in the surrounding aqueous medium, generating high pressure shock waves.

B. Hydrodyne Prototypes

The equipment utilized in the Hydrodyne™ (Hydrodyne Inc., Canovanas, PR) process (for both EHSW and HVADH) has undergone numerous changes in attempts to find the combination of materials and processing parameters yielding reproducible tenderization effects in whole meat products. The violent nature of the EHSW process has not allowed for accurate instrumental measurements of the detonation pressure fronts. Researchers cite only approximate pressure values based on pressure curve equations derived for binary explosives in published studies (Appendix A, Table 1).

1. Plastic Holding Containers

Preliminary work performed during initial design stages describes the treatment vessel as a 208 L plastic holding container (PHC) 51 cm in diameter (Fig.1). The container is fitted with a 2 cm. thick, 40.6 cm diameter steel plate resting on the bottom of the container which would act to reflect the hydrodynamic shock wave back into the product being treated (Berry et al., 1997; Solomon et al., 1997a,b,c; Solomon, 1998a,b; Zuckerman and Solomon, 1998). Spanier and Romanowski (2000) report placing the PHC on a foundation of concrete while Solomon (1998a,b) and other researchers (Solomon et al., 1997a,b,c; Zuckerman and Solomon, 1998) report partially burying the PHC underground without resting the PHC on a concrete foundation. The whole raw muscle sample is vacuum packaged in a "double bag" system, consisting of an interior polyolefin resin (Cryovac; Sealed Air Corp., Duncan, SC) bag and an exterior isoprene (rubber) bag and placed atop of the steel plate. The double packaging system provides a protective wrap around the packaged meat in order to maintain the structural integrity of the bag immediately surrounding the meat. The PHC is filled with cold water. The hydrodynamic shock wave is generated with the use of a binary explosive (liquid nitro methane + solid ammonium nitrate) suspended at a set distance above the packaged sample. During the PHC trials, researchers cite varying the amount of explosive charge used, the number of sequential detonations used (1 blast, two sequential blasts), and the muscle food tested. Tenderness improvements are reported for a wide variety of animal and muscle types (Tables 1, 3-5). The inherent flaw in the PHC prototypes results in the complete destruction of the PHC's upon

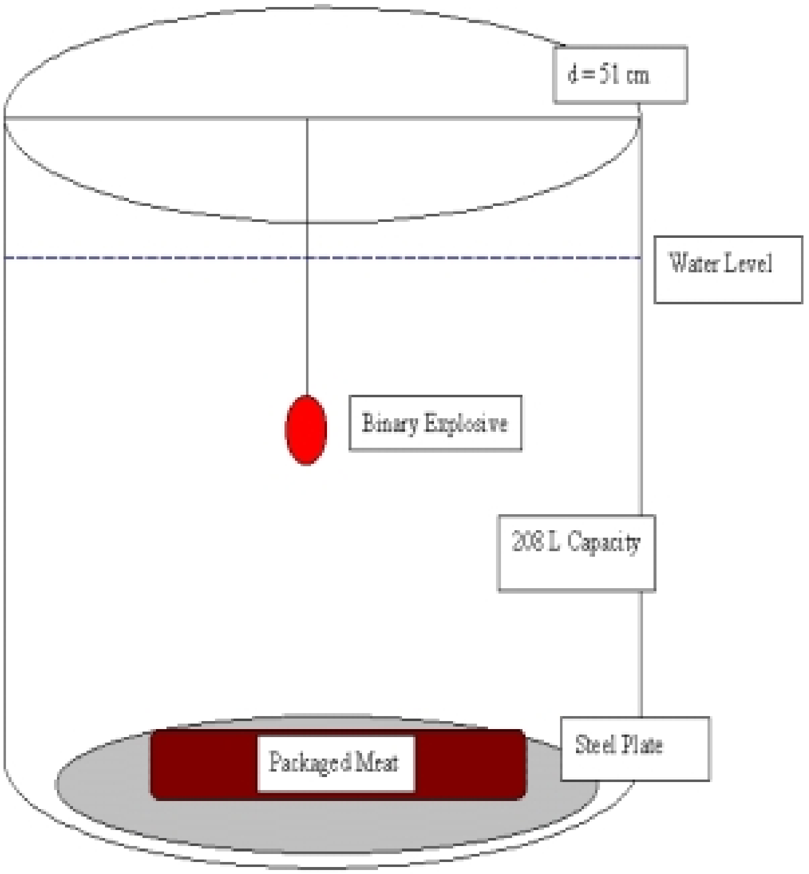

Figure 1. Diagram of Plastic Holding Container (PHC) prototype for explosively-generated hydrodynamic shock wave (EHSW) treatment of meats.

detonation of the explosive, limiting the applicability of the technology in an industrial setting (Raloff, 1998). Researchers cite improvements in instrumental tenderness for beef, pork, and lamb when submitted to EHSW processing with the PHC prototype (Tables 1,3-4; Berry et al., 1997; O'Rourke et al, 1998; Solomon, et al., 1996; Solomon et al., 1997c; Solomon, 1998b).

2. Large Stainless Steel Hemi Shell

The first large commercial stainless steel prototype is suitable for use as a batch processor and also withstands repeated blasts. (Anon., 1998; Raloff, 1998). The large hemi shell (LH) prototype consists of a large stainless steel hemi shell with a 1060 L capacity (Fig. 2.) with an inner diameter of 122 cm fitted inside a shock-absorbing frame. Samples are vacuum packaged in a variety of materials, namely an interior polyolefin resin bag and an exterior isoprene (rubber) bag or Boneguard bag and submerged into the tank (Meek et al., 2000; Solomon, 1998a,b). Studies cite the use of two types of explosives in this prototype, a binary explosive (liquid nitro methane + solid ammonium nitrate) and Pentaerythritol Tetranitrate (PETN) (Berry et al., 1997; Meek et al., 2000; Schilling et al., 2002; Solomon, 1998a,b). As in the PHC, the explosive used is suspended at a set distance above the packaged sample, allowing researchers to observe any differences in tenderization attributable to the distance of the explosive to the sample or the mass of the charge (Table 1) (Meek et al., 2000). Meek et al. (2000) and Solomon et al. (1997b) report instrumental tenderization effects for poultry and beef.

3. Small Steel Tank

The Small Steel Tank (ST) is similarly shaped to the previously mentioned LH prototype. It is a two part system consisting of an inner and an outer tank and a hemi shell top, but of a much smaller scale than the LH prototype with the ability to hold only 54 L of water. The inner tank is 76.2 cm deep with an inner diameter of 31.1 cm, an outer diameter of 42.5 cm, a wall thickness 5.1 cm, and has 8 rods to hold the hemi shell. The outer tank (101.9 cm o.d., 97.8 cm i.d.), and the hemi shell “lid” (87.2 cm o.d.) are all composed of stainless steel. Published studies cite only the use of binary explosives to generate the EHSW within this prototype (Williams-Campbell and Solomon, 2001; 2002). A small cylindrical insert is placed upright within the steel tank and used to reduce the distance between the sample and explosive charge, thus increasing the magnitude of the pressure front which strikes the sample. This insert is composed of stainless steel with a wall thickness of 2.5 cm, an outer diameter of 20.2 cm, and a height of 48 cm (Claus et al., 2001; Schilling, 2000). Claus et al. (2001) describe its use to tenderize early deboned broiler breasts. The researchers suspend the packaged broiler breasts within the center of the cylinder between two PETN charges placed 180° from each other. This placement reduces the distance between the packaged sample and the closest steel wall. The shock wave generated upon detonation of the PETN has a smaller distance to travel in order to strike the sample and will therefore strike the sample with a force of greater magnitude than it would without the aid of the steel insert.

4. High Voltage Arc Discharge Unit

The electrical discharge (HVADH, Fig. 4.) prototype generates reproducible tenderization effects in unpackaged meats. This system relies on the use of a high voltage arc discharge unit to create an electrically-generated hydrodynamic shock wave. Researchers cite HVAD processing as a method to pasteurize liquids within units requiring direct contact between the foodstuff and the electrodes (Edebo and Selin, 1968; Gilliland and Speck, 1967a,b).

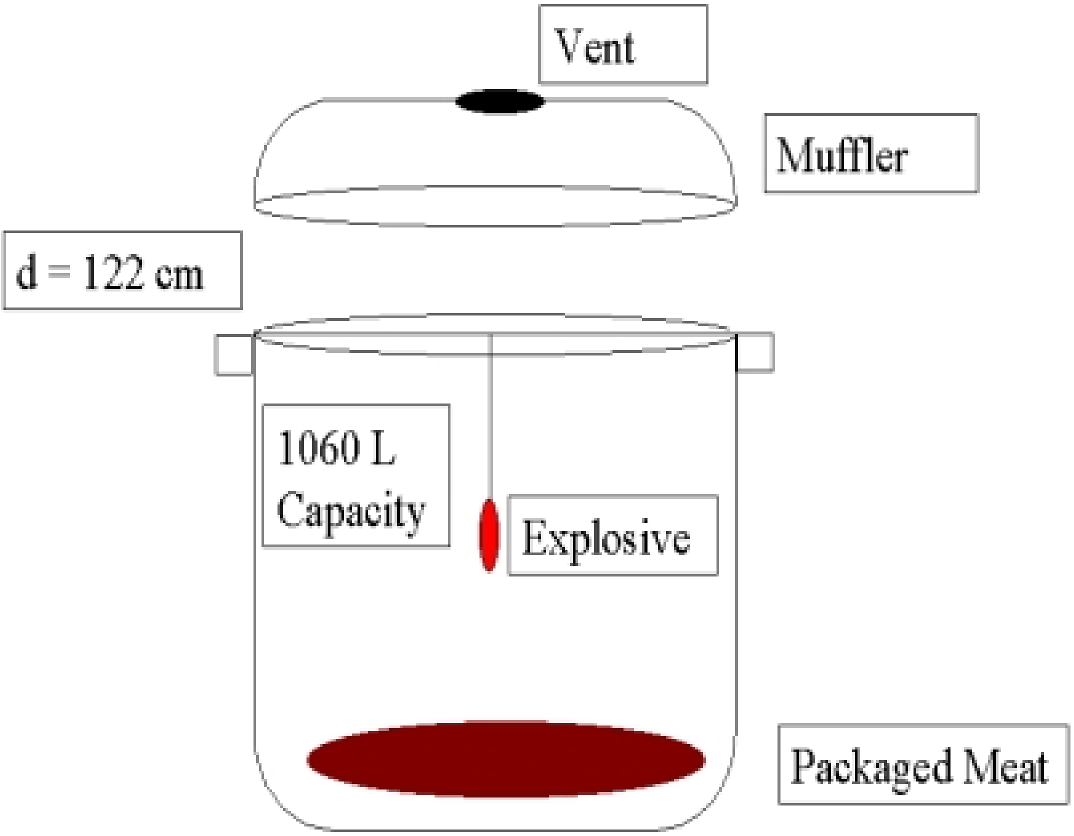

Figure 2. Diagram of Large Stainless Steel Hemi Shell (LH) prototype for explosively-generated hydrodynamic shock wave (EHSW) treatment of meats. The Small Steel (ST) prototype is similarly shaped, with a 54 L capacity.

Hydrodyne's adaptation of HVADH into the field of tenderization of muscle foods is a novel application. The HVADH unit is composed of an electrode housing, sample treatment chamber area, and power supply. The unpackaged muscle food does not come into direct contact with the electrodes or the high voltage arc, but rather sits on top of a food grade rubber diaphragm situated within close proximity to the electrodes. An inflated rubber inner tube lightly presses the muscle food onto the diaphragm, holding it in place during the discharge. The need for water (to transmit the shock waves to the meat) and a protective packaging material are both eliminated in this prototype. The sample is surrounded on the top and bottom with a food grade rubber material (rubber tube on top and diaphragm on the bottom) with the ability to transmit the shock wave directly to the boneless skinless raw meat. In effect, this unit subjects an unpackaged boneless meat or poultry sample to an instantaneous shock wave produced by an underwater electrical discharge through an electrode gap from a capacitor bank. Long (2000a,b) describes the course of events which take place during HVADH processing. One discharge of the HVADH unit produces a large bang and a bright flash of light, with the generation of a positive pressure shock wave and the emission of photon radiation within the treatment area. The initial wave traverses the meat, strikes the bottom of the stainless steel treatment chamber and is reflected back through the meat as a "negative wave". As the secondary wave passes through the meat it encounters a portion of the primary wave. In essence producing a doubling in the intensity of the shock applied to the cellular components, producing a maximum tenderization effect. Unpackaged samples placed approximately 16.5 cm above the electrode receive either single or multiple sequential discharges of 2μs duration with enough time in between discharges to allow the unit to charge. The pressure changes observed during treatment may be viewed as a

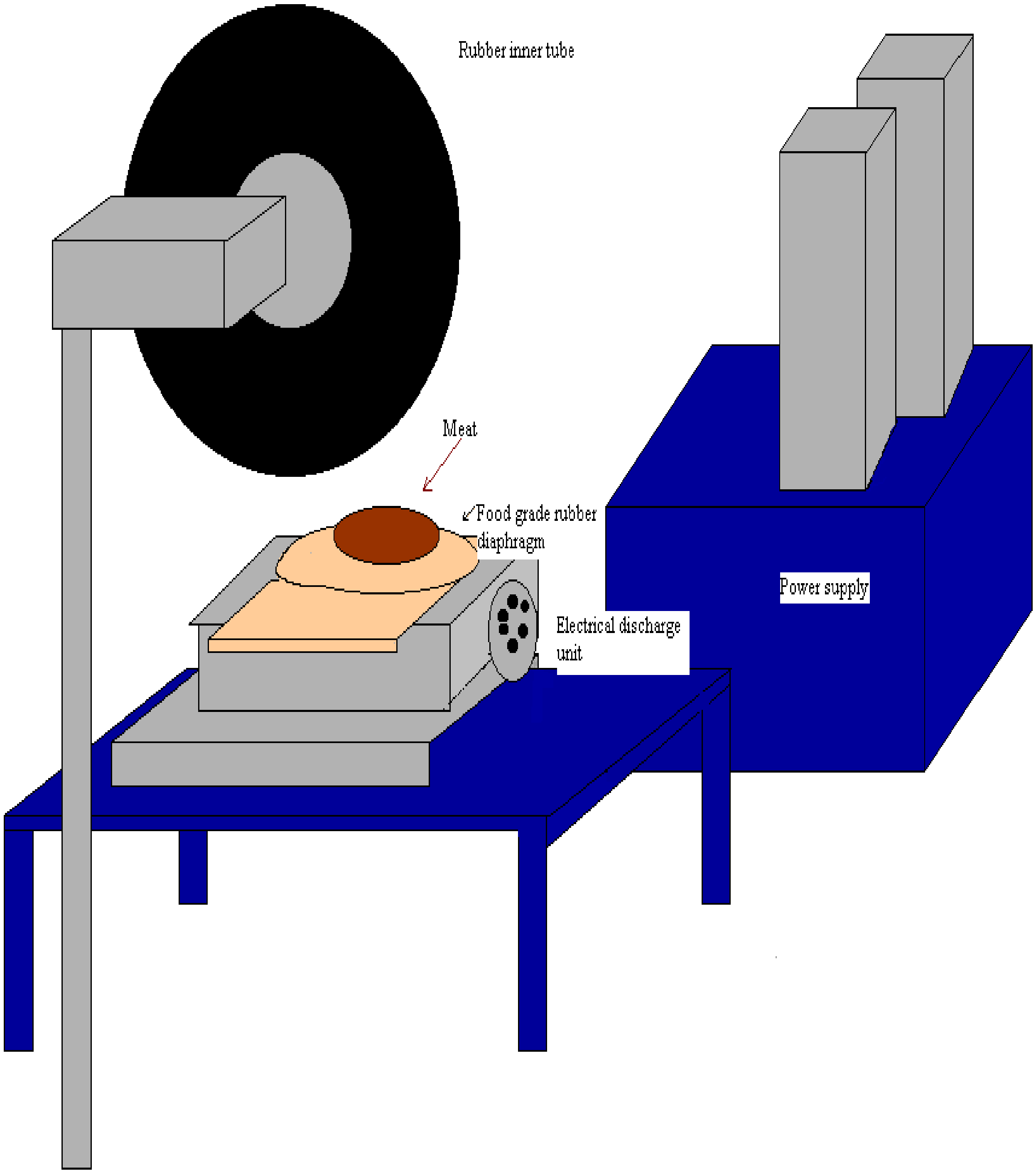

Figure 3. Diagram of High Voltage Arc Discharge (HVADH) prototype for electrically-generated hydrodynamic shock wave treatment of meats.

sequence of sudden application followed by a rapid release. Measurements of the pressures produced during HVADH treatment reveal two pressure peaks per discharge. It has been suggested that the first pressure peak corresponds to the primary wave generated by the electrode upon discharge and the second peak corresponds to the wave that reflects back from the treatment chamber to the transducer. The reflected wave is referred to as a negative pressure wave (Thomsen, 2000 personal communication). The negative wave produces changes in the structural integrity of the sample tissue during treatment (Long, 2000a, personal communication). The tenderization principles behind EHSW processing are applied to HVADH. As with EHSW processing, the passage of the shock wave through the muscle food produces the tenderization effect as the wave encounters structural components with an acoustical mismatch to that of the traveling wave (Long, 2000b). The wave discharges a portion of its energy onto the mismatched structure, producing a breakdown of the integrity of the component (Long 2000b). Pressures achieved during HVADH treatment have been consistently measured and extrapolated for 80% and 90% power settings for the unit, 73,300 psi (505 MPa) and 82,500 psi (569 MPa) respectively (Thomsen, 2000: personal communication).

The proprietary design of the unit allows for integration into an automated beef or poultry processing line. Utilizing an electrical discharge system to produce a shock wave induced tenderizing effect poses many advantages over utilizing a chemical explosive to generate shock waves. HVADH treatment does not create the chemical byproducts that EHSW processing produces and therefore the chance of leaving a chemical residue on a treated is minimal. The need for certified explosive technicians during is eliminated as the use of explosives is eliminated. The lack of explosives in the processing environment also eliminates the likelihood of accidents. An HVADH system can be adapted to an existing processing line with much less difficulty than an EHSW system, requiring only the large power supply and small treatment chamber. Because an HVADH system can be fitted into an existing continuous processing line, a tenderization step can be added following the de-boning stage without the need to halt the line and treat the chicken in batch form. The capacitors can be charged and discharged once every two seconds without much lag time, resulting in a much faster continuous process whose frequency of tenderization treatments is limited only to the time required for a product to be placed into the treatment area (Long, 2000b). Optimizing the HVADH treatment for a product requires manipulation of the resistance, capacitance, and inductance of the system in addition to manipulating the number of sequential discharges applied (Long, 2000b).

C. Applications

Hydrodynamic shock wave treatment of a boneless muscle food has been most recently explored within the "Hydrodyne" technique (Long, 1994; Long, 1995). This technique is described as an improvement of the patent submitted by Godfrey in 1970 in which he described an apparatus for tenderizing meat with the use of explosives (Long, 1993; 1994; Meek, 1997). The Long patents (1993,1994) describe an improved design of the treatment chamber and vented muffler which would hold the sample within the unit after detonation of the explosive. EHSW processing involves placing a boneless-skinless piece of meat (beef, poultry, etc.) into a protective plastic package, vacuum-packaging the product, and submerging it in a vented secured water-filled chamber with an explosive (Meek et al., 2000; Solomon et al, 1997b). Researchers cite the use of one binary and one molecular explosive to generate the explosive force (Gamble et al., 1998; Meek et al., 2000; O'Rourke et al., 1998a,b; Schilling et al., 2002; Solomon et al., 1997a,b,c; Zuckerman and Solomon, 1998b). Upon detonation of the explosive (by way of an electronic detonation bridge device located outside the chamber connected to the explosive with wire leads), a shock wave is generated within the chamber. The shock wave travels rapidly through the fluid (water) and any objects in the fluid that are a mechanical impedance match to water (Kolsky, 1963). Because meat is 75% water, the shock wave passes through the meat, disrupting substances which are an acoustical mismatch to water (Lawrie, 1966; Long, 1993; Long, 1994; Long, 2000a). Researchers suggest that proteins (myofibrilar and those structural proteins surrounding the z-disk) sarcomeres, and z-disks are disrupted by the action of the shock wave (Meek et al., 2000; O'Rourke et al, 1998a,b; Solomon et al 1997a,b,c,d; Solomon, 1998a,b; Solomon et al. 1997a; Zuckerman and Solomon, 1998). Transmission electron micrographs reveal visible disruptions of the myofibrils in and near the Z-lines in EHSW treated samples, with the I-bands showing visible tears at the Z-disk junctures (Zuckerman and Solomon, 1998). Since the I-bands are rich in actin, tropomyosin, and troponin, it is possible that the mechanical force of the EHSW process disrupts all or one of these proteins. The mechanical force of the shock wave on the cellular components of the meat thus produces a more tender product.

The Hydrodyne (EHSW) method is described in the popular media and in trade journals as a technique to improve tenderness, shelf-life, and possibly reduce the population of bacterial pathogens in a raw meat product. Researchers suggest that by using the Hydrodyne method to improve the tenderness of naturally less tender and less expensive cuts of meat, processors may add value to these cuts and may thus be able to command a higher purchase price on these kinds of cuts (Anon., 1998; Mirsky, 1998; Donovan, 1998; Raloff, 1998). The Hydrodyne technique has been applied to many muscle foods, including poultry, pork, lamb, and beef (Meek et al, 2000; Moeller, et al., 1999; O'Rourke et al., 1998; Solomon, 1998a,b; Solomon and Eastridge, 1999; Solomon et al., 1997a,b,c; Zuckerman and Solomon, 1998).

1. Tenderization

a. Beef

The tenderization effects of EHSW processing on several bovine cuts (biceps femoris, longissimus, and semimembranosus) are cited by many researchers (Table 2). Within all three prototypes used in tenderization tests (PHC, LH, and ST), studies show both the mass of the explosive charge and the distance between the charge and the sample impact the instrumental tenderization effects observed in EHSW processing (Table 2, Table 3, Table 4). Differences in the reduction of instrumental tenderness for the same muscle type are observed between treated and untreated samples among different studies (Tables 2,3,4). These differences may be the result of the natural variation in Warner-Brazler (WBS) values of meat observed among multiple animals and may also be influenced by the design of each treatment vessel. Each of the three EHSW prototypes has a unique set of dimensions and two of the prototypes (LH and the small stainless tank (ST)) were composed of stainless steel, a material with different acoustical characteristics than the plastic in the PHC.

Solomon et al., 1997 and Solomon 1998 cite an overall reduction in WBS of 37-57% when compared to non-treated controls (Table 2.). The researcher states that decreasing the distance between the packaged sample and the explosive has more of an effect on reduction in WBS values than does merely increasing the size of the charge. EHSW treatment has been shown to yield a 53-66% improvement in shear force values for treated cold-shortened beef muscles (longissimus, semimembranosus, biceps femoris, and semitendinosus) when compared to cold shortened untreated controls, suggesting the process might be useful in reducing the toughness effects induced by a combination of hot-boning and reduced carcass chill time (cold shortening). In a study comparing the tenderizing effects of the EHSW treatment to controlled aging, Solomon (1998) states the process reduces shear force values of treated beef longissimus by 33% when compared to untreated controls. EHSW treatment is shown to be equivalent to controlled aging for periods of 17,21,28, and 35 d. In a 1997 study (Berry et al., 1997) sensory evaluation by an expert taste panel reveals that only the perception of tenderness was significantly different (and rated as more tender) for Hydrodyne treated beef longissimus muscle when compared to untreated controls, not the perception of juiciness or intensity of flavor. Berry et al. (1997) reports large reductions in shear values of hot boned cold shortened beef samples subjected to EHSW treatment in both the PHC and LH prototypes (Table 2). In this 1997 publication, the researchers do not provide detailed materials and methods used and therefore the validity of their results may be questioned.

Although the WBS reduction values Schilling et al. (2002) reports were only used to determine whether the EHSW treatment was effective, the values are consistent with those obtained by other researchers and are reported in Table 2. Treated samples were analyzed for protein functionality and used to manufacture frankfurters (2.0% NaCl, 0.5% sodium tripolyphosphate, 156 ppm sodium nitrite, 0.42% sodium erythorbate, 2% sucrose, and 25% water). Results of the studies suggest EHSW processed trimmings could be used

Table 2. Tenderization effects of explosively-generated hydrodynamic shock waves on beef as related to mass of binary explosive charge, and distance between charge and top surface of the sample, and EHSW prototype.

Meat	Prototype	Mass charge (g)	Distance of charge from sample (cm)	Pressure reported (MPa)	Reduction in WBS [a] values as compared to respective control (%)	Reference
Longissimus	PHC[b]	50	30.5	N.R. [c]	56 [d]	Solomon,1998b
Longissimus	PHC[b]	75	30.5	N.R. [c]	67 [d]	Solomon,1998b
Longissimus	PHC[b]	100	30.5	N.R. [c]	72 [d]	Solomon,1998b
Longissimus	PHC[b]	50 [d]	30.5	N.R. [c]	49 [d]	Solomon,1998b
Longissimus	PHC[b]	100	30.5	N.R. [c]	66 [d]	Solomon,1998b
Longissimus	PHC[b]	100	30.5	N.R. [c]	33 [d]	Solomon,1998b
Longissimus	PHC[b]	100	30.5	N.R. [c]	37 [d]	Solomon,1998b
Longissimus	PHC[b]	80	30.5	N.R. [c]	23 [d]	Solomon,1998b
Longissimus	LH [f]	125	56	N.R. [c]	37 [d]	Solomon,1998b
Longissimus	LH [f]	160	56	N.R. [c]	45 [d]	Solomon,1998b
Longissimus	LH [f]	192	56	N.R. [c]	47 [d]	Solomon,1998b
Longissimus	LH [f]	350	56	N.R. [c]	57 [d]	Solomon,1998b
Longissimus	LH [f]	150	56	38	12	Solomon,1998b
Longissimus	LH [f]	350	56	52	17	Solomon,1998b

Longissimus	LH[f]	350	46	72	28[d]	Solomon,1998b
Longissimus	PHC[b]	100	30.5	60-70	37[d]	Zuckerman and Solomon, 1998
Longissimus	LH[f]	350	55.9	N.R.[c]	26.7	Berry et al., 1997
Longissimus (hot boned and cold shortened)	LH[f]	350	55.9	N.R.[c]	66[c]	Berry et al., 1997
Top round (hot boned & cold shortened)	PHC	100	N.R.[c]	N.R.[c]	59[c]	Berry et al., 1997
eye of round(hot boned & cold shortened)	PHC	100	N.R.[c]	N.R.[c]	56[c]	Berry et al., 1997
Longissimus	LH[f]	105	26.7	83	22[d]	Schilling et al., 2002
Longissimus	LH[f]	200	26.7	104	10	Schilling et al., 2002
Longissimus	LH[f]	305	26.7	124	24[d]	Schilling et al., 2002
semimembranosus	LH[f]	150	56	38	0.6	Solomon,1998b
semimembranosus	LH[f]	350	56	52	9	Solomon,1998b
semimembranosus	PHC[b]	100	30.5	N.R.[c]	59[d]	Solomon,1998b

biceps femoris	PHC[b]	100	30.5	N.R. [c]	53 [d]	Solomon,1998b

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[a] WBS = Warner-Brazler Shear force values (kg)

[b] PHC = Plastic Holding Container (208 L capacity, d=51 cm)

[c] N.R. = Not reported

[d] Reduction in WBS level found to be significantly different than their respective control ($P<0.05$)

[e] 2 successive detonations of 50 g binary explosive

[f] LH = Large Stainless Steel Hemi shell (1060 L capacity, d = 122 cm)

interchangeably with non-treated meat trimmings in the production of further processed meat products (frankfurters and other further processed products). EHSW treatment does not affect (P>0.05) myofibrillar and sarcoplasmic protein solubility, cooking yield, color (CIE L*a*b*), or textural properties (hardness, cohesiveness) or gel strength as measured by torsion testing). Spanier and Romanowski (2000) cite SDS-PAGE evidence linking EHSW treatment to redistribution of proteins in treated beef.

Claus (2001, personal communication) has achieved consistent instrumental and subjective improvements in tenderness in HVADH treated beef and poultry as compared to untreated controls. In paired early deboned boneless skinless broiler breasts, Claus cites a 44% reduction in shear force between HVADH treated (1 single treatment at 80% power) and untreated controls (WBS 6.5 kg control vs. 3.6 kg HVADH, with standard deviation of shear force values 3.3 control vs. 1.8 HVADH). Early sensory evaluation studies indicate that HVADH treatment of early deboned broiler breasts produces a difference perceptible to a trained panel. In a study by Claus (2001, personal communication), panelists rate the HVADH chicken a 6.9 (very tender) and the controls a 5 (slightly tender). The researcher notes that each treated breast was rated numerically higher than its paired non-treated control, indicating a perceived improvement in tenderness due to HVADH treatment. HVADH treatment produces an average 2.5 kg*mm/g reduction in Kramer Shear values in treated samples when compared to non-treated controls. Kramer Shear values for treated breasts have an average of 2.5 kg*mm/g (S.D. 0.8 kg*mm/g) vs. 5.0 kg*mm/g (S.D. 1.9 kg*mm/g) for the paired non-treated control breasts. Cooking losses among the treated and non-treated samples differ, with the HVADH breasts exhibiting a 21.7% (S.D. 7.4%) loss as compared to 20.7% (S.D. 8%), respectively. Subjecting cuts to subsequent multiple discharges at given power levels results in severe physical changes in the treated steaks (Claus, 2001 personal communication). Pressures achieved during HVADH treatment at 80 and 90% power 16.5 cm above the electrode have been measured at 73, 300 and 82,500 psi, respectively (Thomsen, 2000 personal communication).

b. Poultry

Only one researcher has explored the use of EHSW processing for the mechanical tenderization of poultry (Table 3; Meek et al., 2000). A trained sensory evaluation panel finds no difference in subjective tenderness between EHSW treated breasts and untreated control breasts (Meek et al., 2000). WBS values of the treated breasts are equivalent to aged controls deboned 6 hr. post-mortem (WBS = 3.1 kg). EHSW treatment results in raw breasts that are less red than raw aged control breasts, a color difference reduced upon cooking the breasts. Overall, the researchers note a 19.1-28.3% improvement in instrumental tenderness (Table 3) of breasts treated by EHSW as measured by WBS over untreated early deboned control breasts, though subjective tenderness analysis by a trained sensory panel did not detect any significant difference. Trained panelists cite the aged control breasts as more tender, juicier and flavorful than both early deboned control and EHSW breasts. Initial moisture release shows EHSW breasts were juicier than untreated early deboned breasts within the first 5 chews. Researchers show no difference in intensity of chicken flavor, sustained moisture release, or overall tenderness between EHSW and untreated early deboned breasts. The researchers add that EHSW treatment of the early deboned broiler breasts did not render the breasts visually nor physically “mushy” which would indicate over tenderization (Meek et al, 2000).

Table 3. Tenderization effects of explosively-generated hydrodynamic shock waves on early deboned broiler breasts as related to mass of binary explosive charge, and distance between charge and top surface of the sample. [a]

Mass charge (g)	Distance of charge from sample (cm)	Pressure reported (MPa)	Reduction in WBS [b] values as compared to respective control (%)	Reference
200	20	142	13	Meek et al., 2000
350	23	159	23 [c]	Meek et al., 2000
275	20	163	13	Meek et al., 2000
350	20	177	28 [c]	Meek et al., 2000

[a] Large Stainless Hemi Shell prototype ([LH] 1060 L capacity, d = 122 cm)

[b] WBS = Warner-Brazler Shear force values (kg)

[c] Reduction in WBS level found to be significantly different than their respective control ($P<0.05$)

c. Lamb

Solomon explores the use of EHSW processing to improve the instrumental tenderness of genetically tough lamb. Callipyge is the term for the genetic phenotype responsible for increased muscle mass, decreased carcass fat, and decreased tenderness in lamb longissimus muscles (Solomon, 1998b; Yaguchi, 1996). In a series of experiments, the researcher compares the reduction in WBS values for both normal (non-Callipyge) lamb and Callipyge lamb subjected to ESHW processing compared to their respective controls (EHSW treated normal lamb v. non-treated normal lamb and EHSW treated Callipyge lamb compared to non-treated Callipyge lamb) (Table 4). According to results of the study, EHSW treatment of Callipyge lamb produces a cut of lamb that is more tender than untreated lamb of the normal genotype, but only in longissimus samples and not in semitendinosus samples. The longissimus from EHSW-treated Callipyge lamb has a lower WBS shear force value than the untreated normal lamb (4.3 v. 5.7 kg), whereas the EHSW-treated Callipyge semitendinosus samples has a slightly higher WBS value than does the untreated normal lamb (3.7 kg v. 3.2 kg).

d. Pork

Both the PHC and LH prototypes have been used increase the instrumental tenderness of raw pork (Table 5). Moeller et al. (1999) cite a 17% improvement in WBS values for boneless pork loins subjected to EHSW processing (69 MPa [10,000 psi]) without affecting evaluations of meat quality (both subjective and objective). The researchers note no differences in sensory attributes between EHSW treated pork loins and non-treated control pork loins when evaluated by a trained sensory panel. EHSW treatment produces pieces which appear less red (a*; 14.9 v. untreated control =14.4) and had a lower degree of marbling than untreated controls (2.9 v.

Table 4. Tenderization effects of explosively-generated hydrodynamic shock waves on lamb as related to mass of binary explosive charge, and distance between charge and top surface of the sample. [a]

Sample	Mass charge (g)	Distance of charge from sample (cm)	Pressure reported (MPa)	Reduction in WBS [b] values as compared to respective control (%)	Reference
Lamb longissimus normal phenotype	100	30.5	N.R. [c]	67 [d]	Solomon,1998b
Lamb longissimus Callipyge phenotype	100	30.5	N.R. [c]	34 [d]	Solomon,1998b
Lamb semitendinosus normal phenotype	100	30.5	N.R. [c]	6	Solomon,1998b
Lamb semitendinosus Callipyge phenotype	100	30.5	N.R. [c]	11	Solomon,1998b

[a] Plastic Holding Container ([PHC] 208 L capacity, d=51 cm) prototype

[b] WBS = Warner-Brazler Shear force values (kg)

[c] N.R. = Not reported

[d] Reduction in WBS level found to be significantly different than their respective control ($P<0.05$)

Table 5. Tenderization effects of explosively-generated hydrodynamic shock waves on pork as related to mass of binary explosive charge, and distance between charge and top surface of the sample.

Pork sample	Prototype	Mass charge (g)	Distance of charge from sample (cm)	Pressure reported (MPa)	Reduction in WBS [a] values as compared to respective control (%)	Reference
Longissimus	PHC [b]	100	30.5	N.R. [c]	17	Solomon,1998b
Longissimus	PHC [b]	100	30.5	N.R. [c]	2	Solomon,1998b
Longissimus	PHC [b]	100	30.5	N.R. [c]	33	Solomon,1998b
Longissimus	PHC [b]	100	30.5	N.R. [c]	33	Solomon et al., 1996
loin	PHC [b]	N.R. [c]	N.R. [c]	69	33 [d]	O’Rourke et al., 1998
loin	PHC [b]	N.R. [c]	N.R. [c]	69	17 [d]	O’Rourke et al., 1998
Longissimus	LH [e]	150	36	69	17 [d]	Moeller et al., 1999

[a] WBS = Warner-Brazler Shear force values (kg)

[b] PHC = Plastic Holding Container (208 L capacity, d=51 cm)

[c] N.R. = Not reported

[d] Reduction in WBS level found to be significantly different than their respective control (P<0.05)

[e] LH = Large Stainless Steel Hemi sell (1060 L capacity, d= 122 cm)

untreated controls 3.0). EHSW treatment produces a 15% improvement in tenderness in EHSW treated loins cooked for 11 min and an 18% improved tenderness in EHSW treated cooked for 16 min), with a cooking loss of 31.7% in the treated samples as compared to 29.7% for untreated samples. A trained sensory panel scored the EHSW treated pork loins as less juicy than untreated controls (4.9 v. 5.2, with 1 = very dry, 10 = very juicy) (Moeller et al., 1999).

2. Current Studies

Although much information has been collected and documented regarding the tenderization effects of the EHSW and HVADH processing since the inception of the project in the late 1990's, there has been little work published on the bacterial effects of the process. It has been suggested in trade journals and the popular media that EHSW treatment of raw muscle foods may destroy spoilage and potentially pathogenic microorganisms while producing a product with improved tenderness (Anon., 1998; Donovan, 1998; Raloff, 1998). Prior to the publication of research studies, Solomon et al. (1997 a,b,c) suggested EHSW treatment may inactivate pathogens naturally present in whole muscle foods, making treated steaks a more bacteriologicaly safe product than untreated steaks. Treatment with the EHSW or HVADH systems may alter the microbial flora of a whole muscle food. Treatment may reduce the microbial flora naturally present on the surface or throughout the bulk of the muscle. By reducing the overall flora or perhaps just reducing members of the flora typically associated with refrigerated spoilage such as the lactic acid or psychrotrophic bacteria, EHSW or HVADH treatment may increase the microbial shelf-life of the treated steak or of treated ground beef. By extending the shelf-life, all times related to transport and consumption are thus extended, allowing processors, retailers, and consumers to benefit. Positive bacteriological effects would thus add to the tenderization effects and help justify the added monetary cost (to both processor and consumer) of EHSW or HVADH treatment. However, EHSW or HVADH treatment may also offer negative bacteriological effects which could outweigh the tenderization benefits observed thus far. Treatment may spur the growth of the natural microflora, promoting spoilage and thus reducing the bacteriological shelf-life of the treated product. This may occur if all of the bacteria are equally affected by either EHSW or HVADH treatment or also if only certain segments of the bacterial population are affected. Proliferation of psychrotrophic microorganisms leads to the development of slime, off odors, and discoloration of the muscle (Gill and Newton, 1978; Patterson and Gibbs, 1978). An outgrowth of the lactic acid bacterial population may produce sour off-flavors and aromas or perhaps structural changes in the muscle as metabolic waste products accumulate and the pH of the treated product falls (Patterson and Gill, 1978; van Laack, 1994).

Only a few published studies discuss the effects of the EHSW process on the natural flora of treated meat samples. To date, one report and four detailed studies have been published which discuss the topic. Berry et al. (1997) report EHSW treatment of pork loins reduced levels of *Trichinella spiralis* by 28% and total plate counts by 14% after a 7 d storage period. In their report, the researchers did not provide detailed materials and methods used in their studies. For example, the specific EHSW treatment, the number of samples used, statistical methods, or treatment of samples (EHSW or control, before and after treatment) were not described and therefore the validity of their results cannot be supported by the published report. The 14% difference in microbiological levels the researchers cite may have been the result of a number of factors, including temperature abusing the control samples during the EHSW treatments (Berry et al., 1997). Gamble et al. (1998) state the process (PHC approx. 46 MPa [6,700 psi]) is effective at reducing the levels of the parasite *T. spiralis* in infected pork loins ($P<0.05$). This was only noted in pork loins treated within the PHC prototype (46 MPa) and not in pork loins treated within the LH prototype (50-60 MPa) ($P>0.05$). Larvae recovered from all EHSW treated loins were inoculated into mice and recovered from the musculature of the mice following a 28 d incubation period, illustrating that all of the EHSW treatments used did not affect the infectivity of the treated larvae (Gamble et al., 1998). EHSW (69 MPa) processing has no significant effect on the aerobic plate count (APC CFU/g, 25°C, 72 hr. aerobic incubation) nor in the coliform count (MPN/g, 37°C, 48 hr. aerobic incubation) of treated pork (Moeller et al., 1999). Williams-Campbell and Solomon (2001) cite a significant 1.7 log difference among APC (48 hr at 30°C) in temperature abused (22 hrs at 23°C) beef and pork stew pieces subjected to EHSW treatment (100g binary explosive at 30.5 cm, ~ 70 MPa [~ 10,000 psi]) when compared to untreated control samples. The APC of temperature abused ground beef is reduced by 3 logs with 54 MPa, 70 MPa, and 138 MPa treatment (Williams-Campbell and Solomon, 2002). An initial 1 and 2 log reduction in APC is achieved when fresh ground beef and stew pieces are subjected to 70 MPa treatment. Treated ground beef (70 MPa) shows a 3 log reduction in APC following a 7 day 5°C aerobic storage. The published results are based on studies using small sample sizes (n=3, 5, or 10 for both EHSW and untreated controls), non-standard microbiological plating methods (48hr at 30°C, The Association of Official Analytical Chemists [AOAC], Food and Drug Administration [FDA] and the United States Department of Agriculture [USDA] list 35°C for 48 hr. as the incubation protocol for APC), and a lack of speculation on the biological importance of their findings. When dealing with microorganisms capable of doubling in number every 20 min. under ideal conditions, one must question the importance of reducing a microbiological population by 1 log when the population has the ability to recover by a minimum of 1 log within 60 minutes. (Jay, 1996).

Williams-Campbell and Solomon (2002) state the process (70 MPa) produces a 4.5 log difference in the APC of treated fresh ground beef after a 14 d storage study of aerobic storage at 5°C when compared to untreated ground beef (4.5 log CFU/g vs. 9.0 log CFU/g). All ground beef samples are stored in a single layer of Cling Wrap (Glad; Danbury, CT; 100% polyethylene, oxygen permeability not specified but expected between 550-600 cc/24 hr [Hanlon, 1992]) to simulate retail storage. Although the results of Williams-Campbell and Solomon (2002) conflict with the data presented by Moeller et al. (1999), one must keep in mind that the researchers appear to be sampling the mesophilic (30°C for 48 hr.) portion of the ground beef biota as opposed to the psychrotrophic biota sampled in that by Moeller et al. (1999). As with the 2001 studies, Williams-Campbell and Solomon (2002) use a small sample size for their microbiological examinations (n=5).

Because EHSW treatment physically disrupts the integrity of whole muscle foods, the process may push bacteria naturally present on the surface of the whole muscle product to the interior of the muscle, as has been observed with other mechanical tenderization techniques (Johnston et al., 1979 Phebus et al., 1999). The transfer of surface bacteria may produce a potential bacterial safety hazard to consumers if cookery techniques fail to inactivate bacteria which now may be insulated from thermal destruction within the bulk of the muscle. This would be of concern if EHSW or HVADH treated whole muscle foods were undercooked.

a. Similarities with High Pressure Processing

Although hydrodynamic shock wave processing (both explosively and electrically generated) involves the active movement of pressure waves through a liquid medium and is dynamic rather than static, researchers have suggested its potential impacts on bacteria may be similar to those observed in hydrostatic processes such as high pressure processing (Williams-Campbell and Solomon, 2001; 2002). Hydrostatic pressure processes (HPP) refer to those in which a liquid medium is compressed within a sealed treatment vessel. Williams-Campbell and Solomon (2001) suggest the dynamic nature of EHSW may contribute to the bactericidal effects they have observed thus far even though the pressures (and the microsecond exposure time) obtained in EHSW processing are decidedly smaller than those reported in HPP. Evaluations of bacterial populations of products subjected to high hydrostatic pressures has produced mixed results. Researchers report both bacterial reductions and no changes in bacterial populations (Heinz and Knorr, 1996; Hoover et al., 1989; Kalchayanand et al., 1996; Ludwig et al., 1992; Palou et al., 1998; Pevish, 1998; Smelt et al., 1995). The effects exerted by high-pressure processes depend on many factors, including the nature of the liquid or food matrix, the temperatures achieved during processing, the magnitude of the pressure created, the time held at pressure (including also come-up and release times), and the nature of the bacterial population (type, age, population level of biota). Proteins, enzymes, or membranes may be susceptible to denaturation during high pressure processing (MacFarlane,1985; MacFarlane and McKenzie, 1986). In order to reduce HPP times, other parameters such as temperature or the magnitude of pressure used are typically raised. Elevated treatment temperatures used in HPP may reduce the keeping quality (as determined by undesirable sensory and microbiological changes) of HPP treated meats (Williams-Campbell and Solomon, 2001). The great variations (and thus lack of reproducibility) in the types of experiments performed thus far have made developing pressure processing bacterial inactivation kinetics a difficult task. Scientists suggest additional research be performed in the area so that inactivation kinetics and their parameters can be established and compared to existing thermal processing inactivation kinetics to further the application of HPP technologies (Barbosa-Canovas et al., 2000).

Nagamachi et al. (1991) reports a disruption in the cellular membrane of *Lactobacillus plantarum* cells subjected to high pressure processing, finding *L. plantarum* cells grown at 10°C were more resistant to pressure (300 MPa [43,500 psi]) than those grown at 30°C. They cite a steady reduction in log numbers as both the duration and the magnitude of pressure applied increases (250 - 400 MPa [36,300-58,000 psi]). Growth at different temperatures alters the lipid composition of the cellular membranes of *L. plantarum*, enhancing its ability to withstand a rise in applied pressure (Nagamachi et al., 1991). The application of pressure may damage the cellular membrane of bacterial cells (Smelt et al., 1995). Smelt et al., 1995 report a positive correlation between the death rate of *L. plantarum* cells and the intensity of propidium iodine staining of DNA within cells. Propidium iodine can only enter the cell when the membrane is damaged. A plot of the intensity of propidium iodine staining (measured as fluorescence) v. log reduction factor produces an exponential curve with a positive slope, with the intensity of staining increasing with intensity of the pressure applied. Measurements of the proportion of internal and external ATP (with the presence of external ATP indicated damage to the membrane) shows a decrease in internal ATP concurrent with an increase in external ATP as the intensity of pressure increases and as the duration of pressurization increases. Membrane-bound ATPase may play a role in pressure-induced bacterial inactivation. By measuring the internal pH of bacterial cells, researchers can gage the ability of cells to utilize glucose to produce ATP. Supplying pressure treated bacterial cells with glucose as the sole energy source allows the cells to produce ATP only if the ATP synthesizing system is not damaged by the pressure treatment. Failure to produce ATP or finding that the treated cells have a lower internal pH than cells not subjected to HPP indicate a damaged ATPase. Smelt et al. (1995) report that cells treated to a more severe pressure treatment have a reduced ability of producing ATP and also have a lower internal pH (approx. 0.2 units lower) than cells not subjected to HPP.

Anath et al. (1998) reports D values for two pathogens in a study in evaluating the effects of high pressure processing on the shelf life of pork loins inoculated with *Listeria monocytogenes* Scott A and *Salmonella typhimurium.* Pork loins artificially surface inoculated wit *L. monocytogenes* Scott A require a 2.17 min 414 MPa (at 25°C) HPP treatment to achieve a 1 log reduction of the pathogen while those inoculated with *S. typhimurium* require a 1.48 min 414 MPa treatment to achieve a 1 log reduction.

In a review of alternative processing technologies, Farkas and Hoover (2000) characterize the events that take place during high pressure processing techniques within a sealed steel vessel which may contribute to the inactivation of vegetative cells in a given packaged food stuff. Treatment of a liquid or solid food to pressures between 100-800 MPa (14,500 – 116,000 psi) is achieved by placing the packaged foodstuff within the treatment chamber, closing the chamber, and replacing any air in the chamber with water. The pressure relief valve is closed as the treatment chamber is filled with water to reach the desired processing pressure. This first produces compression in the foodstuff. This compression is instantaneous and uniform, producing a rise in temperature (3°C/ 100 MPa [3°C/14,500 psi]) as well as a shift in pH. Critical factors involved in microbial inactivation during HPP include pressure, temperature, composition of the food, and the packaging used. The magnitude of pressure achieved and the time required to reach and be held at the pressure, are of critical importance as well as the time it takes to decompress the system. Temperature parameters that need to be defined and monitored including the temperature of the foodstuff prior to treatment, the treatment vessel, temperature of the food during treatment, and any adiabatic heating which may result as a consequence of treatment. The nature of the product to be treated also needs to be examined carefully. Not only the absolute composition of the food, but the pH or water activity of the product is of importance because of any added effects they may impose in the inactivation of bacterial cells already weakened by HPP or any protective effects they might provide to the bacterial cells in the foodstuff. The researchers note that some constituents of a food (such as proteins or fats) might have the ability to shield bacteria from the detrimental effects of HPP, perhaps by acting as a protective barrier, absorbing the brunt of the pressures applied. The researchers stress the importance of further research, citing that there was no absolute indicator of sterility for HPP because some types of spores of *Clostridium botulinum* had been shown to survive extreme temperatures and pressures encountered in HPP. No marker bacterium has been found to mimic the survival of the heartiest *C. botulinum* spores, therefore establishing inactivation kinetics for the process require a great deal of further research.

No material has been published showing the bacteriological effects of HVADH processing within the Hydrodyne system. As with EHSW processing, possible bacteriological effects of Hydrodyne's HVADH system may be attributed to the nature and magnitude of the pressure wave produced. Thomsen (2000: personal communication) finds the HVADH unit is able to produce pressures of 73,300 psi (505 MPa) and 82,500 psi (569 MPa) for 80% and 90% power settings. Transducer tests reveal two pressure peaks per discharge, the first corresponding to the primary wave generated by the electrode upon discharge and the second a negative pressure wave which reflected back from the treatment chamber to the transducer. In addition to the generation of the two pressure waves, the discharge produces a bright flash of light, emitting photon radiation within the treatment area. The photon radiation may produce additional bacteriological effects if the diaphragm is made from a translucent foodgrade material capable of allowing photon radiation to pass through the diaphragm and into the food.

Studies performed in the 1960's with HVAD treatment chambers in which the foodstuff was placed into direct contact with the electrodes may add insight to bacteriological effects which may be observed in the electrically-generated hydrodynamic shock wave treatment (HVADH). High voltage arc discharge (HVAD) processing achieves pasteurization of fluids by applying rapid discharge voltages through an electrode gap below the surface of an aqueous medium (Barbosa-Canovas et al., 2000, Gilliland and Speck, 1967a,b). The effects of HVAD treatment on bacteria are attributed to the pressure waves and the formation of highly reactive compounds formed by the electrolysis of components within the medium, both of which occur with the electrical discharge (Barbosa-Canovas et al., 2000, Gilliland and Speck, 1967a,b). Edebo and Selin (1968) suggest that pressure waves generated during HVAD treatment (40-250 MPa) have no bactericidal effect on their own, that microbial reductions observed in treated aqueous *E. coli* suspensions are attributed to the combination of pressure and the generation of chemical compounds within the medium during treatment, termed electrohydraulic shock (Edebo and Selin, 1968; Gilliland and Speck, 1967a,b). Pressure gradients created during treatment produce shearing stress and a squeezing effect on bacterial cells, both of which are thought to contribute to bactericidal qualities of HVAD treatment. Edebo and Selin (1968) argue that the pressure difference created along the edge of an individual bacterial cell is small compared to the internal pressure of the bacterial cell itself, making the mechanical shearing stress during treatment is negligible. Electron photomicrographs of cells subjected to 40 discharges show no morphological changes in the treated cells. Bacterial reductions are observed in suspensions packaged in clear cellophane material but not in those packaged in stainless steel. The researchers suggest the UV radiation produced upon discharge, rather than the pressure exerted on the bacterial cells from the shock waves, may play a key bactericidal role. HVAD treatment reduces bacterial levels in water suspensions but not in milk or broth (Edebo and Selin, 1968). Gilliland and Speck (1967b) cite bacterial reductions as a consequence of HVAD treatment (MPa not reported) of *E. coli* and *Streptococcus faecalis* cultures suspended in sterile distilled water. The nonselective reaction of free radicals generated in the water during HVAD treatment with multiple enzyme systems may be responsible for the inactivation of vegetative *E. coli, S. faecalis, and Bacillus subtillis* suspensions in sterile distilled water. Phase microscopy and cell staining preparations reveal no physical cellular breakage or damage (Gilliland and Speck, 1967b). In another study, the researchers note that adding 0.05% bovine serum albumin to an aqueous suspension of *E. coli* (approx. 10^8 CFU/ml) reduces the bactericidal activity of HVAD treatments. They found HVAD treatment produces a 4 log reduction in suspensions containing only *E. coli* and only a 1 log reduction in suspensions containing both *E. coli* and 0.05% BSA.

In a review of microbial inactivation kinetics for alternative food processing technologies, Barbosa-Canovas et al. (2000) discuss the lack of sufficient information available in the literature upon which to create critical process factors for high voltage arc discharge systems (HVAD). The authors conclude further research is required in order to collect enough data to devise critical process factors and suggest examining the discharge field, discharge energy, discharge repetition rate, and the aeration of the product are process variables which need further study.

There is currently little consistent information available on the effects that hydrodynamic shock waves generated by chemical explosions (EHSW) have on the bacterial flora of whole raw muscle foods and raw ground beef in terms of keeping quality and bacteriological safety. Because its application as a non-thermal tenderization treatment has been shown in numerous published studies, researchers must determine whether the process impacts the bacterial flora of treated meats on the surface by examining any possible bactericidal action or migration of surface bacteria into the bulk of the meat. Since the treatment has been shown to tenderize evenly throughout the bulk of the meat, ground samples could be used to evaluate any bactericidal effects which EHSW processing may produce throughout the entire bulk of the meat. If either EHSW or HVADH treatments are found to be bactericidal in ground samples, they may serve as a non-thermal alternative to irradiation to reduce the bacterial flora of ground meats. There is no information available on the effects that hydrodynamic shock waves generated by electrical discharges have on the bacterial flora of whole raw muscle foods and raw ground beef.

The purpose of the following work was to evaluate the effects the two processing techniques may have on the bacterial flora of beef (whole and ground) and whole boneless skinless chicken breasts. During the course of the studies, variables which were expected to impact the nature, magnitude, and propagation of the shock waves were manipulated in order to determine which variables (or combination of variables) might exert a bactericidal effect on treated ground beef.