Hydrated Surface Lethality

Validation of a new processing method to ensure the destruction of *Salmonella* on product surfaces during impingement cooking

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Abstract

This study investigated the effectiveness of cooking processes that incorporated hydrated-surface lethality (HSL) steps for ensuring the reduction of *Salmonella* on the surfaces of meat and poultry products cooked using short-time, high-temperature impingement oven processes. Various small-dimension products made from beef, pork, or chicken were cooked in a two-zone impingement oven using either dry heat or steam-humidified HSL processes. The HSL cooking steps used steam injection to control the wet-bulb temperature at either 160°F or 180°F. The products were whole muscle chicken tenders (3% fat), beef patties (10 and 30% fat), pork patties (10 and 30% fat), and chicken patties (10 and 20% fat). The raw products were surface-inoculated with approximately 8 logs of *Salmonella*. Dry-heat cooking processes using a dry-bulb temperature of 400°F and no steam-injected HSL steps failed to achieve a 6.5 log reduction of surface-inoculated *Salmonella* for the chicken tenders and the low-fat patty products (≤ 10% fat) — most likely because the low-fat products were more prone to rapid surface dehydration. In contrast, processes incorporating a hydrated surface lethality (HSL) step using a 180°F wet-bulb temperature in one or both zones resulted in ≥ 6.5 log reductions of *Salmonella* for all products. Sufficient reductions were achieved regardless of whether this 180°F wet-bulb HSL step was incorporated before or after a dry-cook step. Processes that incorporated an HSL step using a 160°F wet-bulb temperature in both zones also resulted in reductions ≥ 6.5 log for all products. Processes using a 160°F wet-bulb HSL step in only one zone were successful for all of the patty products. For chicken tenders, however, the 160°F HSL step was only successful if the HSL step was used in the first zone of the two-zone oven. When the 160°F HSL step was used in the second zone for chicken tenders after using dry-heat in the first zone, the target reduction of 6.5 log was not achieved. Graphical analysis of the processes revealed that the product surfaces of the chicken tenders were rapidly dehydrated in the dry-heat Zone 1, but not rehydrated in Zone 2, and these conditions apparently created significant numbers of desiccated, heat-tolerant *Salmonella* that survived the process.

Based on the results of this study, we recommend that HSL steps using wet-bulb temperatures ≥ 160°F be incorporated into in all zones of high-temperature, short-time impingement cooking processes to ensure the destruction of *Salmonella* on product surfaces. This study can be used for validation of high-temperature, short-time thermal processes that incorporate the recommended HSL steps to ensure the destruction of *Salmonella* on the surfaces of small-dimension products cooked in impingement, spiral, or cross-flow forced-convection continuous ovens.

Introduction

Most meat processors in the United States use FSIS Appendix A (USDA, 1999) to ensure sufficient thermal lethality for the myriad array of pre-cooked products that are manufactured every day using countless different cooking processes. The thermal lethality guidelines in Appendix A are based on research published in 1978 by Goodfellow and Brown. In their study, large cuts of *Salmonella*-inoculated beef were cooked using processes that lasted several hours. The Appendix A guidelines are currently being applied to a vast variety of products that were never investigated in the original study — including small-dimension products cooked in belt-fed, high-capacity, continuous ovens that use high-temperature, short-time processes of less than 30 minutes. Although Goodfellow and Brown (1978) tested both dry-heat and high-humidity cooking processes, their study did not test high-temperature, short-time cooking processes that are capable of rapid dehydration that may alter the heat tolerance of pathogens on the product surfaces.

The need for hydrated product surfaces to promote pathogen lethality is recognized in the 1999 version of Appendix A, but only indirectly through humidity guidelines that are awkward or even unusable for many products. These humidity guidelines incorrectly infer that specific relative humidity levels alone will lead to sufficient pathogen reductions on product surfaces. A more reliable method of assuring sufficient reductions would be to ensure that surface pathogens are hydrated when subjected to lethal time-temperature conditions.

In 2017, the USDA updated the Appendix A guidelines to include new relative humidity requirements. Under the new guidelines, cooking processes shorter than 60 m would be required to maintain a relative humidity $\geq$ 90% for the entire process. The high-temperature, short-time cooking processes used in impingement, cross-flow, and spiral ovens (hereafter referred to as impingement ovens), therefore, would be required to follow this guideline. However, the 90% relative humidity option is thermodynamically impossible to achieve in impingement ovens that are most often run at dry-bulb temperatures of 350-500°F, and therefore impingement processes cannot conform to the 2017 Appendix A humidity guidelines.

Extrapolation of existing thermal lethality research is often problematic for impingement processes. Most research on thermal lethality for pathogens in cooked meat products is conducted under hydrated conditions using moist heat. For these types of experiments, inoculated samples are usually sealed in moisture-impermeable plastic film, and then heated in water baths. Therefore, this research most often does not account for the increased heat tolerance of desiccated pathogens resulting from the surface dehydration that often occurs when products are cooked in forced-air convection ovens. As such, a comprehensive investigation of the heat tolerance and survival of *Salmonella* during cooking in high-temperature, short-time impingement oven processes is warranted.

The objectives of this study were as follows:

1. Assess the survival of surface-inoculated *Salmonella* on products cooked using impingement cooking processes under hydrating and dehydrating conditions.

2. Determine the effectiveness of hydrated surface lethality (HSL) steps for countering the increased heat-tolerance of desiccated *Salmonella*.

3. Develop scientific-based, regulatory-supported, and industry-useful thermal processing parameters for validating pathogen destruction and regulatory compliance for meat products cooked using impingement ovens.

This research presents a new approach to validating and verifying surface lethality using hydrated surface lethality (HSL) steps. This approach should prove useful for developing validated thermal processes and guidelines that ensure the elimination of *Salmonella* on the surfaces of meat and poultry products cooked in impingement ovens using high-temperature, short-time processes.

Background

Literature values for pathogen lethality

Most pathogen lethality studies use fully hydrated samples to measure the D- and z-values that are published in the literature. In these studies, the inoculated meat samples are usually packaged in moisture-impermeable plastic film and then immersed in hot water for heating (O'Bryan et al, 2006; McMinn et al, 2018). In industrial cooking processes, then, only meat products cooked under hydrated conditions can reliably use the literature values as references. If any pathogens become desiccated, many researchers have found that heat tolerances are much higher for desiccated pathogens than for hydrated ones (Gruzdev et al, 2011; Goodfellow and Brown, 1978; Buege et al, 2005; Sindelar et al, 2016). Gruzdev and co-workers (2011) also found, however, that if desiccated *Salmonella enterica* were rehydrated, the heat tolerance of the desiccated/rehydrated *Salmonella* was similar to that of *Salmonella* that had never been desiccated. Goodfellow and Brown (1978) and Buege and co-workers (2005) also found that re-hydration heating steps were effective in eliminating desiccated *Salmonella* from meat surfaces.

Impingement oven processes use high-velocity, low-humidity hot air to rapidly dry product surfaces to promote Maillard browning. In addition to browning the product, however, the rapid surface drying can also quickly desiccate bacteria on the surfaces, thus potentially creating desiccated, heat-tolerant pathogens capable of surviving the cooking process (Sindelar et al, 2016). Even so, impingement cooking processes can be designed so that the micro-climate surrounding the product is maintained at lethal temperatures under hydrated surface conditions during all or part of the process to ensure sufficient pathogen lethality.

The relative humidity levels in impingement ovens are inherently very low. Typical impingement processes use dry-bulb temperatures of 350-500°F and wet-bulb temperatures of 130-205°F. If an oven was running at a 400°F dry-bulb temperature and 180°F wet-bulb temperature, for example, the relative humidity would be only 4.6%. When impingement ovens are run under ambient conditions without humidity control, the wet-bulb temperature generally drifts between 120-150°F, depending on the naturally available moisture from the surrounding air and the moisture evaporated from

the product. In most impingement ovens, however, steam injection is used to control the wet-bulb temperature at 160-205°F. Theoretically, the highest achievable wet-bulb temperature at standard atmospheric pressure would be the 212°F boiling point of water, but the practical maximum in most impingement ovens is typically a 200-205°F wet-bulb temperature.

Impingement ovens are designed to quickly dry product surfaces to promote rapid browning. These processes are generally very short (eg. < 15 minutes) so that only the surface dries and the product interior remains hydrated. Thus, pathogen lethality values from the literature are valid for predicting reductions for bacteria in the product interior. On the surfaces, however, pathogens may become desiccated, and therefore more heat tolerant, than the literature values would predict. Gruzdev and co-workers (2011), for example, found that desiccated *Salmonella enterica* were able to survive time-temperature conditions that were otherwise lethal for hydrated *Salmonella*. Importantly, though, these researchers also found that if desiccated *Salmonella* were rehydrated, the heat tolerance of the desiccated/rehydrated bacteria was returned to the same level as the original, non-desiccated *Salmonella*.

Development of the HSL method

We developed the hydrated surface lethality (HSL) method with the aim of ensuring that product surfaces are hydrated when lethal time-temperature conditions for pathogenic bacteria are achieved. To qualify as an HSL step, a cooking step must meet the following two criteria:

1. Product surface is heated to a lethal time-temperature combination for the target pathogen.

2. Product surface is fully hydrated when the lethal time-temperature conditions are achieved.

To meet these criteria, the product surfaces should be heated to a lethal time-temperature combination before the surface dries out, so that the HSL step is able to inactivate the target pathogen before desiccation occurs. However, even if the product surfaces dry out before thermally lethal conditions are achieved, the HSL criteria can still be met if the dry surfaces are rehydrated and then exposed to lethal time-temperature conditions while hydrated.

Drying periods

Cooking meat products in a forced-air convection oven is essentially a high-temperature drying operation (Skjoldebrand, 1980). To develop effective HSL steps, then, it is important to understand the phases of drying that occur during cooking. Godsalve and co-workers (1977), Skjoldebrand (1980), and Hanson (1990) found that when meat products were cooked in forced-air convection ovens, the meat surfaces progressed through three drying periods as follows:

1. Pre-heat period
2. Constant-rate drying period
3. Falling-rate drying period

Pre-heat period

In the initial pre-heat period, the product enters the oven with a surface temperature below the dew-point temperature of the air, and therefore

water vapor condenses on the surface until the surface reaches or exceeds the dew-point temperature (Hallstrom et al, 1988). The product remains in this period until the surface heats up to the wet-bulb temperature, and then transitions to the constant-rate drying period (Skjoldebrand, 1980). The surface remains hydrated throughout the pre-heat period.

Constant-rate drying period

When the surface temperature reaches the wet-bulb temperature, the constant-rate drying period begins (Hallstrom et al, 1990; Mujumdar and Devahastin, 2000). This drying period is a saturated-surface drying phase, and the rate of drying during this period is approximately constant (Watson and Harper, 1988). Moisture migrates from the interior to the surface at the same rate or faster than the evaporation rate from the surface. Vaporization occurs at the product surface, and free water with a water activity of 1.0 is always available at the surface to vaporize (Toledo et al, 2018). A continuous layer of water is present over the entire product surface, and the water evaporates from the surface as if the solid matrix is not present (Godsalve et al, 1977; Okos et al, 2007). During this period, the product surface acts like a wet-bulb thermometer, and the cooling effect of evaporation keeps the surface temperature close to the wet-bulb temperature of the air until the end of the constant-rate drying period (Fellows, 2009; Godsalve et al, 1977; Toledo et al, 2017). The constant-rate period continues until water from the interior is no longer freely available at the product surface (Okos et al, 2007). When the surface moisture is reduced to an inflection point known as the critical moisture content, there is an abrupt reduction in the rate of moisture removal, and the product transitions from the constant-rate to the falling-rate drying period (Singh and Heldman, 2009; Toledo et al, 2018). In common industry terms, this transition from the constant- to falling-rate drying periods is known as case-hardening.

Falling-rate drying period

The falling-rate drying period occurs when moisture migration from the interior to the surface becomes slower than the evaporation rate from the surface, and thus the surface dries out (Fellows, 2009). The surface is no longer covered with a continuous film of free moisture. The plane of evaporation moves from the surface to inside the product. Water moves from the interior to the surface as a vapor (Fellows, 2009; Okos et al, 2007). The drying rate falls off and the surface temperature breaks above the wet-bulb temperature (Godsalve et al, 1977; Hanson, 1990; Toledo et al, 2018). At the inflection point where the surface temperature clearly breaks above the wet-bulb temperature, the product surface is no longer fully hydrated, thus increasing the likelihood that a significant population of *Salmonella* may become desiccated on the surface (Fellows, 2009; Sindelar et al, 2016; Watson and Harper, 1988).

Design of HSL processes

Based on these principles of drying and on previous research, we hypothesized that during the pre-heat and constant-rate drying periods of a cooking process, the inoculated *Salmonella* on the product surfaces would be fully hydrated, and thus susceptible to the standard D- and z-values from the literature for hydrated *Salmonella* (O'Bryan et al, 2006; McMinn et al, 2018). To test this

hypothesis, we designed thermal processes for this study that exposed the product surfaces to lethal time-temperature conditions during the saturated-surface, constant-rate drying period.

We further hypothesized that if during cooking, the surface transitioned from the constant-rate to the falling-rate drying period before sufficient reduction of *Salmonella* was achieved, surface dehydration during the falling-rate drying period would increase the proportion of desiccated, heat-tolerant *Salmonella* — thus increasing the likelihood that significant populations of heat-tolerant *Salmonella* would survive (Sindelar et al, 2016). To test this hypothesis, we designed thermal processes for this study that used dry heat for part or all of the thermal processes to measure the effects of surface dehydration on survival rates of surface-inoculated *Salmonella*.

Finally, we hypothesized that if surface dehydration occurred early in the thermal process, we could design heat processes to rehydrate the surfaces at lethal temperatures later in the process using HSL steps, thus rehydrating and inactivating the desiccated *Salmonella* to achieve a sufficient log reduction. This hypothesis was based on the findings of Gruzdev and co-workers (2011), who found that desiccated *Salmonella enterica* that were rehydrated were as susceptible to heat as the original non-desiccated *Salmonella*.

Experimental HSL processes

In previous studies, researchers found the product surface and oven wet-bulb temperatures could be graphed and analyzed to identify the inflection point of transition from the saturated-surface, constant-rate drying period to the dry-surface, falling-rate drying period (Godsalve et al, 1977; Hanson, 1990; Sindelar et al, 2016; Skjoldebrand, 1980). Based on this work, we surmised that we could graphically analyze the process temperature data together with *Salmonella* reduction data to validate the effectiveness of HSL cooking processes for ensuring sufficient reductions of *Salmonella* on product surfaces during high-temperature, short-time impingement cooking processes.

The processes in this study tested HSL steps at two wet-bulb temperatures — 160°F and 180°F — using a pilot-scale impingement oven. Impingement processes were used for this experiment because impingement ovens have the fastest drying rate of any commercially available forced-air convection oven design, thus representing the practical worst case for rapid dehydration of product surfaces. Therefore, a cooking process that provides sufficient *Salmonella* reductions in an impingement oven should also provide sufficient reductions for the same products cooked in slower-drying forced-air continuous ovens such as spiral and cross-flow ovens.

Materials & Methods

Experimental design

Seven products were selected to represent a common commercially available range of meat species, fat levels, and product types. Chicken tenders were cut from boneless chicken breasts (<3% fat). Six ground meat products were manufactured using three species (beef, pork, and poultry) with two different fat levels for each species (10% and 30% for beef and pork; 10% and 20% for chicken) (Tables 1 and 2). Raw meats were surface-inoculated with five strains of *Salmonella* and thermally processed in a two-zone

impingement oven. Seven different cooking processes were used to cook the products in a two-zone impingement oven using pre-determined total cooking times of 3.0 m for processes using HSL steps in both zones, 3.5 m for processes using an HSL step in only one zone, or 4.0 m for dry cooking processes not using HSL steps (Tables 3-6). Steam injection was used to control the wet-bulb temperature as required for the HSL processes. The fixed cooking times were used for each process category to ensure that each product was exposed to the same conditions for the same treatment time within each process category. Preliminary trials were conducted to ensure that when the products were cooked using these processes and times, the surface temperatures exceeded 160°F at the end of the cooking processes. Triplicate samples were assayed for *Salmonella* populations prior to cook (Time 0), midpoint between the two zones, and endpoint after the full cook. Each set of experiments was replicated three times.

Product manufacture

The seven products representing a range of meat species, fat levels, and product types were manufactured with physical dimensions representative of commercially available products. Ground meat products were formulated to represent practical worst-case scenarios for *Salmonella* survival. For example, previous studies have shown that high pH and high salt content enhance the heat tolerance of *Salmonella.* Therefore, the products containing salt and phosphate were intentionally formulated with salt and phosphate levels on the high side of typical industry formulas (Table 1) (Aljarallah and Adams, 2007; Juneja et al, 2003; Kang and Fung, 2000; van Asselt and Zwietering; 2006). The ground pork and chicken patties contained 2.5% salt, 0.35% sodium tripolyphosphate (STPP), and 2.0% water. The ground beef patties contained no additional ingredients as is common industry practice. The whole-muscle chicken tenders (≤ 3% fat) were formulated with 2.5% salt, 0.35% STPP, and 5.0% water. All non-meat ingredient additions were based on a raw-meat weight basis. Prior to inoculation, ground meat products were formed into patties and chilled overnight. The chicken tenders were hand cut to the appropriate size and chilled overnight. Product dimensions were representative of typical commercial products based on measurements of similar commercially available products and on input from local processors.

Ground meat patties

Ground meat patties were manufactured using Good Manufacturing Practices at the University of Wisconsin-Madison Meat Science and Muscle Biology Laboratory. Raw materials were obtained from a commercial supplier and stored at 39°F for ≤ 72 h prior to use. Ground beef patties were manufactured using fresh beef knuckles and fresh, closely-trimmed beef chuck muscles. Ground pork patties were manufactured using fresh, closely-trimmed pork shoulder muscles and fresh pork trimmings (42% lean). Ground chicken patties were manufactured using fresh deboned chicken leg quarters and frozen chicken skins. The chicken skins were thawed for 24 h at 39°F prior to use. For all ground products, lean and fat ingredients were first ground separately through a 0.75 inch plate attached to a grinder (Model 4732, Hobart Corp., Troy, OH). The fat content of a representative sample from

each coarsely-ground raw material was then determined using a CEM SMART Turbo Moisture/Solids Analyzer (CEM Corp., Matthews, NC) using the microwave and nuclear magnetic resonance method (AOAC 2008.06; Jay et al, 2005). The appropriate fat and lean ingredients were then combined to make products containing 10% and 30% fat for ground beef and ground pork, and 10% and 20% fat for ground chicken (Tables 1 and 2). For the pork and chicken patties, the raw meat and non-meat ingredients were combined in a plastic tub and mixed by hand for 2 m. All meat mixtures were ground three times through a 0.19 inch grinder plate. After grinding, the final fat content of each product was confirmed using a CEM SMART Turbo Moisture/Solids Analyzer. Finished products were then weighed in 4.4 lb portions and placed into oxygen- and moisture-impermeable bags (3-mm high barrier pouches; oxygen transmission rate: 50 to 70 cm^3/m^2, 24 h at 25°C and 60% relative humidity; water transmission rate: 6 to 7.5 g/m^2, 24 h at 25°C and 90% relative humidity; UltraSource, Kansas City, MO), vacuum-sealed, and stored frozen at -4.0°F until use. Ground meat formulations were transported to the University of Wisconsin-Madison Food Research Institute and thawed at 39°F for at least 24 h prior to testing. The meat was weighed into 70.0 ± 2.0 g portions, compressed into 3.75 in diameter x 0.3 in thick patties using a custom-made patty press, and placed onto metal trays lined with non-stick aluminum foil. The samples were then held at 39°F overnight, using plastic wrap to prevent excessive moisture loss during storage. All trials for the ground meat products were conducted using meat from a single batch of manufactured product.

Chicken tenders

Chicken tenders were manufactured using Good Manufacturing Practices at the University of Wisconsin-Madison Food Research Institute. Boneless, skinless chicken breasts (< 3.0% fat) were obtained frozen from a commercial supplier and stored frozen at -4.0°F until use. The frozen chicken breasts were thawed for 24 h at 39°F. External fat was removed. Tenders were cut from the chicken breasts to target dimensions of 5.5 in long x 1.45 in wide x 0.45 in thick to be representative of a typical commercial product. The tenders were combined with all non-meat ingredients and mixed by hand for 5 min (Table 1). The tenders were then vacuum-packaged in an oxygen- and moisture-impermeable bag, vacuum-sealed, and stored at ≤ 39°F for 24 h to allow additional absorption of non-meat ingredients. After 24 h, the tenders were removed from the package and weighed individually. To minimize variation in heating rate between samples, only tenders weighing 40.0 ± 2.0 g were used for inoculated testing and temperature data collection. The tenders were then transferred to a fresh vacuum bag, vacuum-sealed, and stored at 39°F prior to testing. New lots of chicken tenders were manufactured prior to each cooking trial.

Proximate and chemical analysis

Triplicate, non-inoculated raw samples from each product replication were assayed for physiochemical properties including moisture (5 h, 100°C vacuum oven method; AOAC, 2000), NaCl (measured as % Cl-, AgNO3 potentiometric titration; Mettler G20 compact titrator, Columbus, OH), water activity (Decagon AquaLab 4TE water activity meter; Pullman, WA), and fat content (microwave and nuclear magnetic resonance method, AOAC 2008.06 with CEM SMART

Turbo Moisture/Solids Analyzer; CEM Corp., Matthews, NC) (Burnett et al, 2000; Jay et al, 2005). In addition, the pH (Accumet Basic pH meter and Orion 8104 combination electrode, Thermo Fisher Scientific) of the raw product was measured using a slurry obtained by removing a representative 10 g of the non-inoculated sample and homogenizing it with 90 ml deionized water using a lab blender (Stomacher 400, A.J. Steward; London, England). Results are reported in Table 2.

Strain selection and inoculum preparation

Five strains of *Salmonella* spp (Enteritidis 6424, phage type 4, baked cheesecake isolate; Enteritidis E40, chicken ovary isolate; Heidelberg S13, clinical isolate; Typhimurium S9, clinical isolate; Typhimurium M-09-0001-A1, peanut butter isolate) were used in this study. All strains were from the University of Wisconsin–Madison Food Research Institute stock culture collection. Strains were grown individually in 9 ml of Trypticase Soy Broth (TSB, Difco, BD Biosciences, Sparks, MD) for 18 to 24 h at 37°C. For each strain, 0.2 ml aliquots of overnight culture were spread onto four Trypticase Soy Agar plates (TSA, BD Biosciences) and incubated at 37°C for 18-22 h. Cells were harvested by scraping the surface of the TSA plates with a sterile inoculating loop and suspending in 4.5 ml of phosphate-buffered saline (PBS, pH 7.2) to achieve approximately 10-log CFU/ml. Equivalent populations of each strain were then combined and diluted to 50 ml with PBS to provide a mixture with a concentration of approximately 10 log CFU/ml. Populations and purity of each strain and the mixture were verified by plating on TSA and Xylose-Lysine-Deoxycholate agar (XLD, BD Biosciences). The plates were incubated at 37°C for 36 to 48 h prior to counting.

Inoculation

Immediately prior to inoculation, product samples were transferred from 39°F storage to individual polystyrene trays sanitized with 70% ethyl alcohol. Samples were inoculated to ~8 log CFU/g with the 5-strain *Salmonella* mixture using a 1.0% inoculum (v/w). The inoculum was spotted onto the upward-facing surface of each sample and spread evenly over the entire surface using the side of a sterile pipette. Trays containing the inoculated samples were then covered with a second polystyrene tray to prevent drying of the product surface. The inoculated samples were stored at 39°F for at least 1 h before cooking to create a consistent internal temperature across all samples, but all samples were processed within ≤ 4 h after inoculation.

Cooking

Products were cooked in a two-zone continuous belt-fed impingement oven (Model 1832-01596 conveyor ovens, XLT Ovens, Wichita, KS) equipped with steam injection for controlling the wet-bulb temperature in each zone (Powis Corporation, Blue Springs, MO). A photograph of the oven is shown in Diagram 3. The cooking procedure consisted of passing samples through both ovens, with the first oven designated as Zone 1 and the second oven designated as Zone 2. The air velocity at the belt level for this oven was measured at approximately 800 ft/minute. This air velocity is representative of common operational air velocities that would be expected at the conveyor-belt level in production impingement ovens (Hanson, 2018).

The seven products were cooked using seven different cooking processes (Process 1-7) that were designed to assess the survival of surface-inoculated *Salmonella* using various combinations of dry-heat (ambient conditions) or steam-injected HSL steps (Tables 3-6). All processes used the same dry-bulb temperature of 400°F. For the HSL steps, the wet-bulb temperature was controlled at either 160°F or 180°F using steam injection. The cooking times varied depending on the process category — dry-heat, one-zone HSL or two-zone HSL — and were selected to ensure a product surface temperature of 160°F or higher at the end of the process. The cooking time was 3.0 m for processes using HSL steps in both zones, 3.5 m for processes using an HSL step in only one zone, or 4.0 m for dry-heat cooking processes with no HSL steps. The focus of the experiment was to measure the effectiveness of the various processes on reductions of surface-inoculated *Salmonella* when the surfaces were exposed to the process conditions for pre-set time periods, and therefore the surface and internal temperatures were not specifically controlled for each process.

Process 1 was a dry-heat, ambient-moisture process with no steam injection in either zone. This process was expected to create the highest level of surface dehydration and bacteria desiccation, and thus determine the effect of high levels of desiccation on *Salmonella* survival.

Processes 2 and 7 had controlled wet-bulb temperature HSL steps using steam injection in both zones — the wet-bulb temperature was controlled at 160°F in both zones for Process 2 and 180°F in both zones for Process 7. These two processes were intended to measure the effectiveness of controlled wet-bulb HSL steps that were applied for the entire cooking process using two different wet-bulb temperatures that were intended to be thermally lethal to *Salmonella*.

Processes 3 and 6 were single-zone HSL process that used controlled wet-bulb HSL steps in Zone 1 followed by a dry-heat, ambient wet-bulb step in Zone 2. The wet-bulb temperature in Zone 1 was controlled at 160°F for Process 3 and 180°F for Process 6 using steam injection. Processes 3 and 6 were intended to test whether or not a single-zone HSL process would provide sufficient lethality if the HSL step was applied in the first-half of a process followed by an ambient-moisture dry-heat step in Zone 2.

Processes 4 and 5 were also single-zone HSL processes, but these processes used an ambient-moisture dry-heat step in Zone 1 followed by a controlled wet-bulb HSL step in Zone 2. The wet-bulb temperature in Zone 2 was controlled at 160°F for Process 4 and 180°F for Process 5 using steam injection. Processes 4 and 5 were intended to test whether or not a single-zone HSL process would provide sufficient lethality if the HSL step was applied in the second-half of a process, following a drying step in Zone 1 that may have created desiccated, heat-tolerant *Salmonella* on the product surfaces.

Sampling

Triplicate samples of the inoculated products were removed at one of three points in the process as follows:

1. Time 0: Initial, raw product prior to cooking
2. Mid-point: After passage through the first zone

3. End-point: After passage through the second zone.

Three replications were completed for each product. A replication was defined as the cooking of samples for a single product using all seven cooking processes in the same day.

For each cooking process, six surface-inoculated *Salmonella* samples (patties or tenders) were taken from storage and placed onto two sanitized stainless-steel grates with the inoculated side facing up (triplicate samples/grate). The grates were designed with openings large enough to allow sufficient airflow across all sides of the samples to simulate an impingement airflow oven (Diagrams 1-2). After the first grate had fully emerged from Zone 1, it was immediately transferred to the next conveyor belt and passed through Zone 2. All three samples from the second grate were removed after exiting Zone 1 for enumeration as mid-point samples. After the remaining grate had fully emerged from Zone 2, all three samples from that grate were removed for enumeration as end-point samples.

Samples were placed into sterile Whirl-Pak filter bags, diluted 1:1 with cold PBS at ≤ 40°F, and immediately submerged into an ice water bath for cooling. The chilled sample bags were hand massaged for approximately 2 m to release cells from the surface. Samples were enumerated for surviving *Salmonella* by plating serial dilutions onto XLD overlaid with a thin layer of TSA (TAX) to enhance recovery of injured cells (Mattick et al, 2000). Plates were incubated at 98.6°F for 36 to 48 h prior to counting.

Temperature Monitoring

The dry-bulb, wet-bulb, product surface, and product internal temperatures were recorded for each product and process combination to create thermal profiles (Figures 1-28). The oven and product temperatures were measured on test runs that were separate from the inoculation test runs. The thermal profiles were composited with data from a maximum of seven calibrated data loggers (HiTemp140 single-point data logger, HiTemp140 X2 multi-channel data logger; MadgeTech, Inc, Warner, NH) that were recorded at 1 s intervals. The battery ends of data loggers were enclosed in protective Teflon heat-shield cases to prevent heat damage to the batteries and to maintain accuracy. An example of logger placement and sample arrangement are shown in Diagrams 1 and 2.

The test runs for collecting wet-bulb and dry-bulb temperatures used two single-channel loggers and three non-inoculated samples placed on a grate that were passed through the impingement oven. Single-channel loggers were used to measure surface and internal temperatures on two samples, and a dual-channel logger with two flexible probes was used to measure surface and internal temperatures on the third sample. The loggers and samples were placed on two sanitized stainless-steel grates and passed through each zone concurrently to collect data for the thermal profiles.

To measure the product surface temperature, a temperature probe was inserted approximately 1.0 inch into the product running parallel with the surface and positioned so that the beveled sensing tip of the probe was positioned just underneath and parallel to the surface. Surface-temperature probes were positioned so that the sensing tip was just visible under a thin

sheen of meat, making sure that the tip did not break through the surface (Diagrams 1-2).

The temperature profiles on Figures 1-28 are composite graphs of surface and internal temperatures from three test runs. If surface or internal temperatures from a single sample were found to be in error, thermal profiles were compiled using data from the remaining two test runs.

Data analysis

The microbiological data are average values and standard deviations (log CFU/g) for triplicate samples per time point and three replications for each product-process combination. Log reduction was calculated by subtracting populations enumerated from individual mid-point or end-point samples from the average *Salmonella* populations at Time 0.

The SAS MIXED procedure (SAS 9.1.3 Service Pack 3, SAS Institute Inc., Cary, NC, USA) was used to determine significance ($P < 0.05$) between the end-point *Salmonella* log reductions of the seven processes within each product type. When significance was found, means were separated using the difference of least squares means. Statistical comparisons are shown in letter assignment to individual means.

Results & Discussion

Summary tables with process parameters and total *Salmonella* reduction for all processes are listed in Tables 3-6. For this study, the reduction level was deemed sufficient if the total average reduction of the surface-inoculated *Salmonella* was ≥ 6.5 log.

A complete set of temperature profiles are shown in Figures 1-28 in the final section. Representative figures that illustrate key findings are included in the body of this paper.

Analysis of thermal profiles and interpretation of graphs

The profiles for chicken tenders are shown in Figures 1-7, beef patties in Figures 8-14, pork patties in Figures 15-21, and chicken patties in Figures 22-28. The figures include the oven set-points for each zone, process and product temperature profiles, and *Salmonella* reduction.

The inflection points for dehydration and rehydration of the product surfaces are noted on all graphs. For dehydration, the inflection point notes the surface transition from a saturated-surface to a dry-surface, thus signifying the transition from the constant-rate to the falling-rate drying period. If a dry surface was rehydrated during cooking, the inflection point of rehydration notes the point of transition from a dry-surface back to a saturated-surface.

To judge the location of these inflection points, the surface temperatures were compared to the wet-bulb temperatures on each thermal profile. When the surface temperature clearly broke above the wet-bulb temperature, this point was designated as an inflection point of dehydration. If later in the process, the wet-bulb temperature was increased high enough to exceed the surface temperature, such that moisture condensed on the product surface, this point was designated as an inflection point of rehydration.

On Figures 1-28, the ▼ symbol identifies the inflection point of dehydration where the surface temperature clearly broke above the wet-bulb temperature. This inflection point notation approximates the time in the process where the

surface became dehydrated, thus increasing the likelihood of *Salmonella* desiccation.

If a dehydrated surface was treated with an HSL step in which the wet-bulb temperature was increased higher than the product surface temperature, condensing moisture would have rehydrated the surfaces, thus most likely rehydrating any desiccated *Salmonella*. The ▼ symbol notes this inflection point of rehydration.

The thermal profile for chicken tenders cooked using Process 1 is a useful example of the graphical analysis that was used for this study (Figure 1). As shown on the graph, the surface temperature tracked with the wet-bulb temperature for most of Zone 1, indicating that the surface was fully hydrated in the constant-rate drying period during this part of the process. After 85 s, however, the surface temperature clearly broke above the wet-bulb temperature, indicating the surfaces had dried and transitioned from the constant-rate to the falling-rate drying period. The ▼ symbol on Figure 1 denotes the approximate time of this transition.

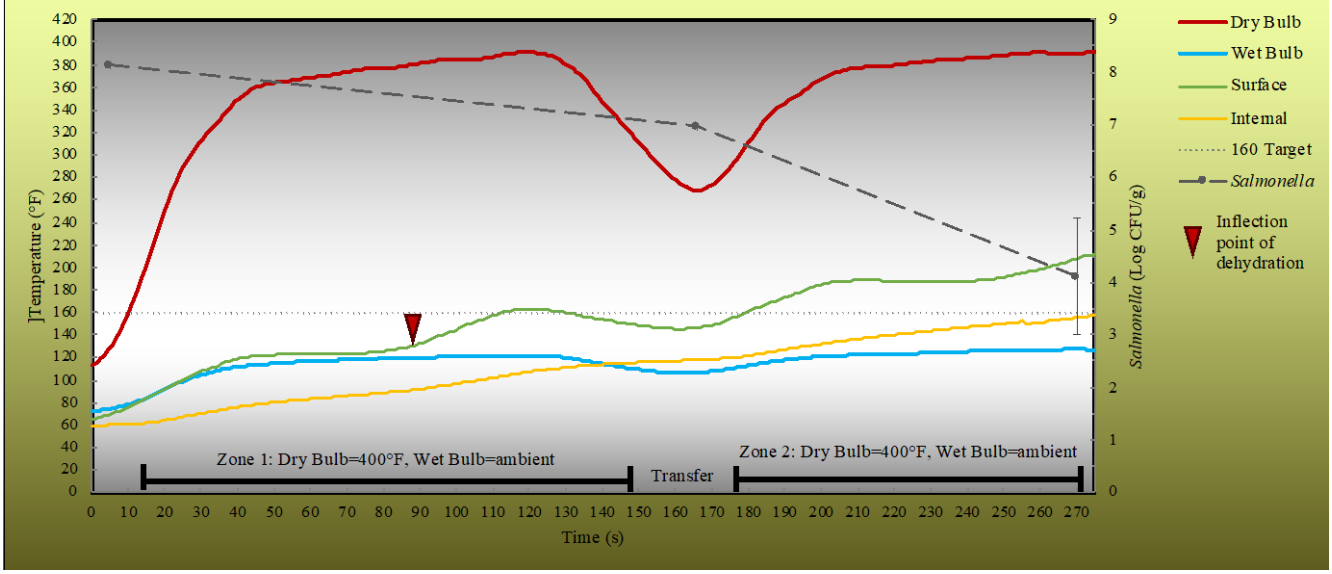
Effectiveness of HSL steps for pathogen reduction

Cooking with dry heat only: Process 1

Process 1 was a dry, ambient heat process with no steam-injected HSL step in either zone. Under these ambient conditions, the wet-bulb temperature drifted between 125-130°F. This dry-heat process failed to achieve the targeted *Salmonella* reduction of ≥ 6.5 log for the chicken tenders and all of the low-fat patty products. Total reductions for the low-fat products cooked using Process 1 were 4.0 log for chicken tenders (<3% fat), 6.2 log for 10% fat beef patties, 5.8 log for 10% fat pork patties, and 6.3 log for 10% fat chicken patties (Tables 3-6).

Process 1 was the driest of the seven processes, and thus had a high likelihood of *Salmonella* desiccation. For chicken tenders, the *Salmonella* reduction of 4.0 log was the second lowest reduction of all products and processes, second only to Process 4 which had a 3.5 log reduction. The *Salmonella* reductions for chicken tenders cooked using Processes 1 and 4 were not

Figure 1. Chicken Tenders, Process 1
(Two-Zone Dry Heat)



significantly different ($p<0.05$), but nonetheless, the tenders cooked using Process 4 had the lowest total *Salmonella* reduction of the entire study at 3.5 log. The reasons for the low reduction of Process 4 are explained in a later section.

Desiccation, reduced water activity, and dry cooking processes have all been associated with decreased thermal lethality for *Salmonella* during cooking, and therefore the low reductions for Process 1 were expected (Buege et al, 2006; Goepfert et al, 1970; Goodfellow and Brown, 1978; Gruzdev et al, 2011; Hiramatsu et al, 2005; Mattick et al, 2000; Mattick et al, 2001).

Graphical analysis of the chicken tenders cooked using Process 1 showed that the hot, dry, high-velocity air quickly dried the surfaces of these whole-muscle, low-fat tenders. The rapid surface dehydration presumably created large numbers of desiccated, heat-tolerant *Salmonella* that survived surface temperatures otherwise lethal to hydrated *Salmonella* (Figure 1). Although the surfaces of the tenders remained hydrated for much of the first zone, the ambient wet-bulb temperatures of 125-130°F were too low to be lethal to *Salmonella* in the short two-minute dwell time in Zone 1. After 110 s, near the end of Zone 1, the surface temperature reached 160°F, a temperature that would have been highly lethal to hydrated *Salmonella* (USDA, 2017; O'Bryan et al, 2006). As shown on Figure 1, however, the *Salmonella* reduction at the end of Zone 1 was only 1.5 log. This low reduction most likely resulted from increased heat tolerance of the desiccated *Samonella*.

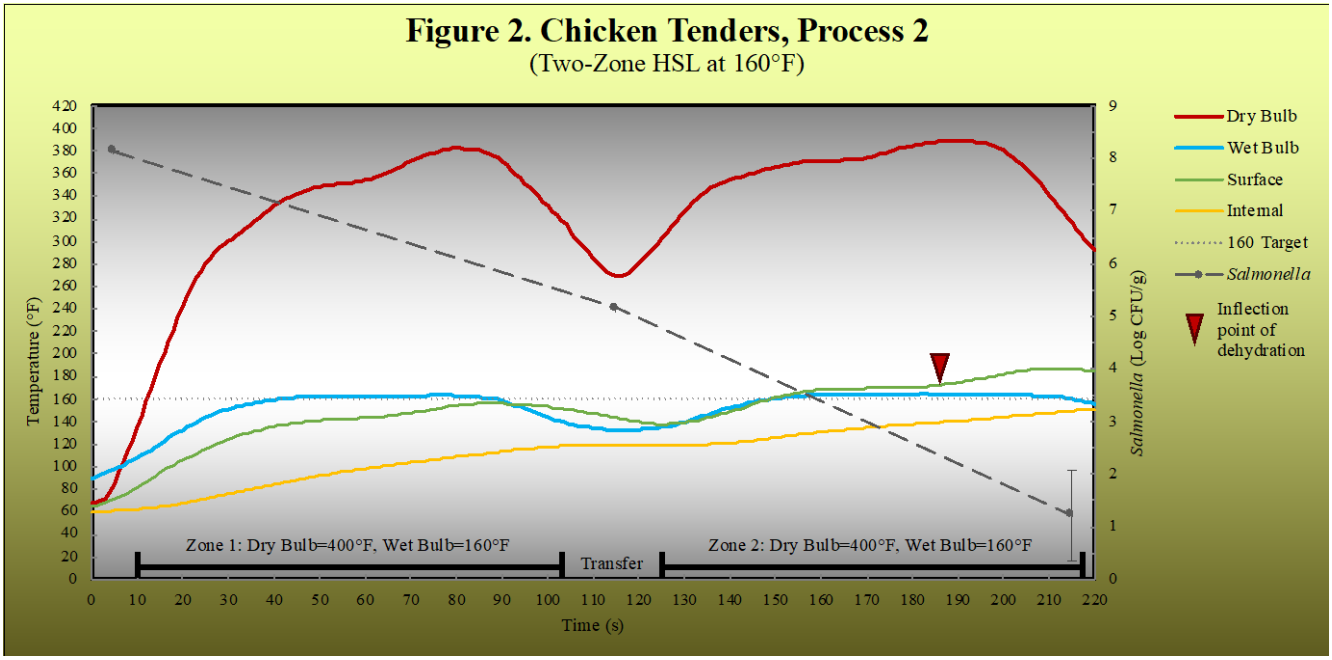
At the end of Zone 2, the surface temperature of the chicken tenders reached 211°F — a temperature that would have been instantly lethal to *Salmonella* if still hydrated. The low overall reduction of only 4.0 log, however, indicates that many of the surface-inoculated *Salmonella* had been desiccated, and thus survived the cooking process (Figure 1, Table 3). This result aligns with research by Gruzdev and co-workers (2011), who found that desiccated *Salmonella enterica* could survive temperatures of 212°F for 60 minutes.

For the ground patty products cooked using Process 1, larger reductions were achieved for the high-fat patties than for the low-fat ones (Tables 4-6). The higher fat levels most likely kept the surfaces moist, thus preventing desiccation and resulting in larger reductions for the higher fat patties; however, the specific mechanism is still not clear. In contrast, the low-fat, whole-muscle chicken tenders and the low-fat patties were more prone to rapid surface dehydration, presumably resulting in larger numbers of desiccated, heat-tolerant *Salmonella* and lower log reductions for the lower-fat products.

Cooking with steam-injected HSL steps for the entire process: Processes 2 and 7

Processes 2 and 7 had HSL steps in both zones, using steam injection to control the wet-bulb temperature in both zones at 160°F for Process 2 (Figure 2) or 180°F for Process 7. These two double-zone HSL processes had the highest and most consistent log reductions of all seven processes (Tables 3-6, Figure 29).

Salmonella reductions for Processes 2 and 7 were ≥ 6.5 log across all products (Tables 3-6). Although the reductions for both processes exceeded the 6.5 log target and were not significantly different ($p<0.05$), Process 7 generally provided greater lethality than Process 2, most likely because Process 7 had a higher wet-



bulb temperature. Processes 2 and 7 used the shortest cooking time of 3.0 minutes, compared to 3.5 minutes for Processes 3-6 and 4.0 minutes for Process 1, but still exceeded the targeted ≥ 6.5 log reduction of *Salmonella* for all products investigated.

Graphical analysis of Processes 2 and 7 showed that the surface temperatures were ≥160°F before the inflection point of dehydration was reached, and thus the product surfaces achieved a highly lethal surface temperature of 160°F under fully hydrated conditions for all products cooked using Processes 2 and 7 (Figures 2, 7, 9, 14, 16, 21, 23, 28) (USDA, 2017). Both of these two-zone HSL steps, then, were highly effective in achieving sufficient *Salmonella* lethality before desiccation, resulting in the highest, most consistent log reductions of all the tested processes (Figure 29).

Cooking with a single HSL step at 180°F wet-bulb: Processes 5 and 6

Processes 5 and 6 were both single-step HSL processes using a 180°F wet-bulb temperature for the HSL step. Process 5 used the HSL step in Zone 2, *after* a dry-heat first zone, while Process 6 used the HSL step in Zone 1, *prior to* a dry-heat second zone. Process 5 was intended to determine if pathogens desiccated in Zone 1 could be re-hydrated and inactivated using an HSL step in Zone 2. In contrast, Process 6 was intended to determine if an HSL step in Zone 1 would provide enough reduction to overcome the presumably lower reductions of a subsequent dry-heat step in Zone 2.

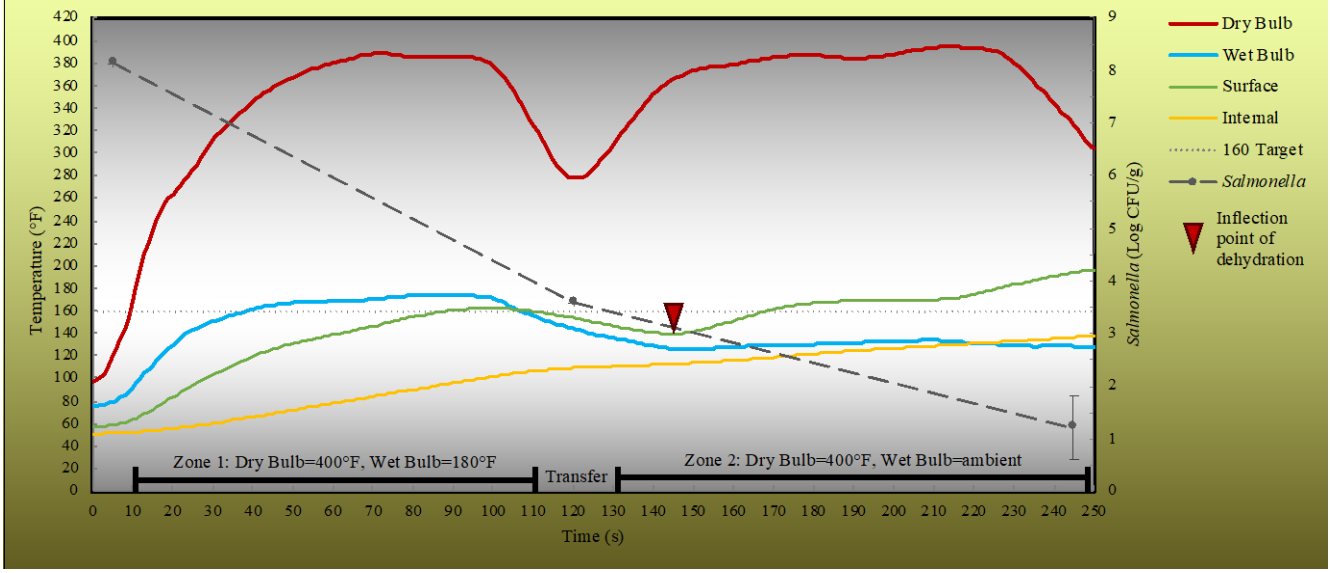
Processes 5 and 6 both achieved sufficient *Salmonella* reductions ≥ 6.5 log for all seven products (Tables 3-6). Although both processes were similarly effective, it is instructive to graphically analyze the temperature profiles for chicken tenders in Figures 5 and 6 to observe how the two processes achieved similar reductions in different ways.

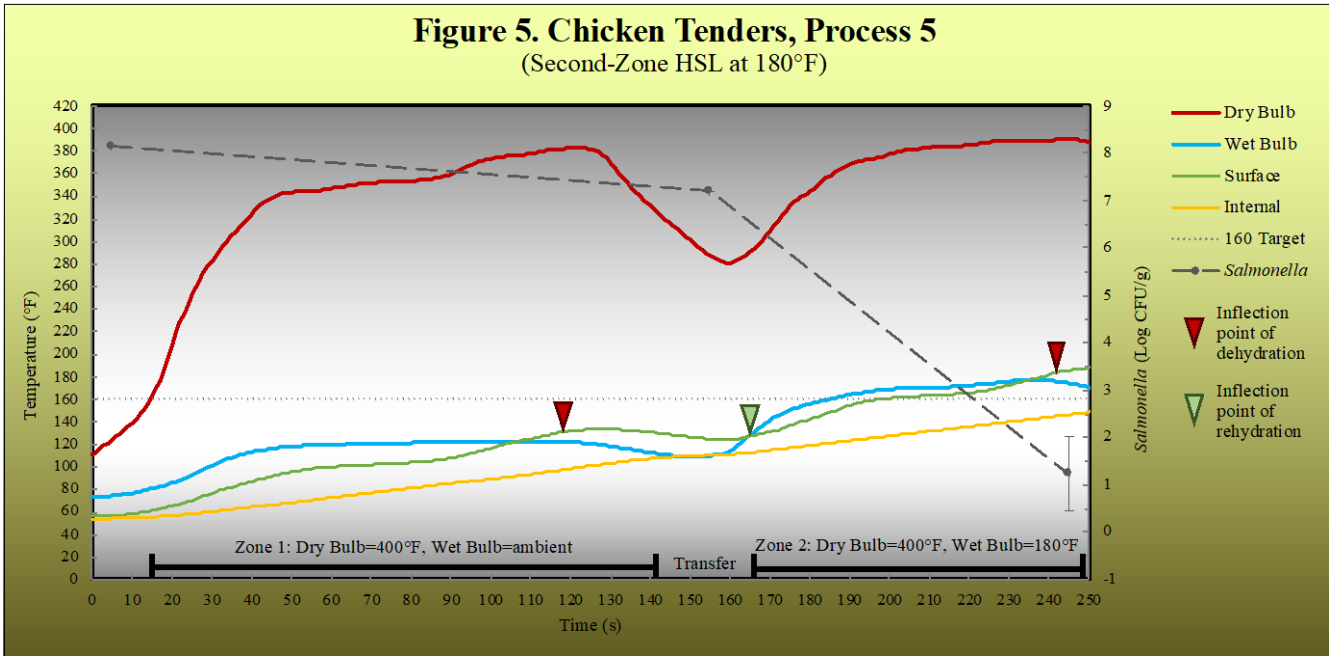
For chicken tenders cooked in Process 6, the product entering Zone 1 was exposed to an HSL wet-bulb temperature that rapidly increased to its set-point of 180°F (Figure 6). The product

surface remained hydrated in the constant-rate drying period throughout Zone 1 and reached a highly lethal temperature of 162°F at the end of the zone, resulting in a mid-point *Salmonella* reduction of 4.8 log in 1.75 minutes. Zone 2 was a dry-heat zone, and the ambient wet-bulb temperature drifted at a sub-lethal temperature of 125-130°F in this zone. As shown on Figure 6, these dry-heat conditions quickly dried out the surface of the chicken tenders almost immediately upon entering Zone 2. At 145 s, the surface temperature clearly broke above the wet-bulb temperature, indicating that at this point the surface had begun to dehydrate and had transitioned from the constant-rate to the falling-rate drying period. The surface temperature continued to rise to approximately 195°F at the discharge of Zone 2, a temperature that would have been highly lethal to hydrated *Salmonella*, but the dry conditions apparently desiccated some of the remaining viable *Salmonella*, so the log reduction in Zone 2 was only 2.2 log. However, the first-zone HSL step at 180°F wet-bulb temperature, when used in combination with a less lethal dry-heat second zone, was still effective enough in total to reach an overall reduction of 7.0 log (Table 3).

For Process 5, Zone 1 was a dry-heat zone followed by an HSL zone using a 180°F wet-bulb temperature in Zone 2. In the first zone, the chicken tenders were exposed to dry-heat conditions where the ambient wet-bulb temperature drifted at a sub-lethal temperature of 125-130°F (Figure 5). Although Zone 1 was a dry-heat zone, the surface temperature still tracked below the wet-bulb temperature until 115 s — indicating that the surface stayed hydrated in the constant-rate drying period for most of Zone 1, albeit at a sub-lethal surface temperature of only 125°F. At the discharge of Zone 1, the surface temperature did achieve 135°F, which would have been a lethal temperature for *Salmonella* if held for a much longer time (USDA, 1999). However, given the short time and the dehydrated surface conditions, the first zone was ineffective, resulting in a log reduction of only 1.1 log for Zone 1. As noted, the surface temperature of the chicken

Figure 6. Chicken Tenders, Process 6
(First-Zone HSL at 180°F)





tenders exceeded the wet-bulb temperature near the end of Zone 1, indicating that the surface was beginning to dry and had transitioned into the falling-rate drying period by the end of the zone.

In Zone 2, the product surfaces were immediately subjected to an HSL step where the wet-bulb temperature quickly rose to the 180°F set-point. At the beginning of this zone, the wet-bulb temperature increased sharply above the surface temperature, thus condensing moisture on the product surfaces which would have rehydrated any desiccated *Salmonella*. The inflection point of rehydration occurred at approximately 165 s — abruptly shifting the surfaces from the falling-rate drying period back to the constant-rate drying period at a highly lethal temperature >160°F for most of Zone 2 (Figure 5). Upon rehydration, the heat tolerance of any desiccated/rehydrated *Salmonella* would have been reduced back to a level similar to that of ordinary hydrated *Salmonella* (Gruzdev et al, 2011). The high 180°F wet-bulb HSL step in Zone 2, then, functioned as intended, re-hydrating and inactivating any desiccated *Salmonella*, resulting in an overall log reduction of 7.0 log for Process 5 — in spite of the desiccation that occurred in the first zone. These findings align with previous studies where researchers found that the heat tolerances were similar for both hydrated and desiccated/rehydrated *Salmonella* (Goodfellow and Brown, 1978; Gruzdev et al, 2011).

Cooking with a single HSL step at 160°F wet-bulb: Processes 3 and 4

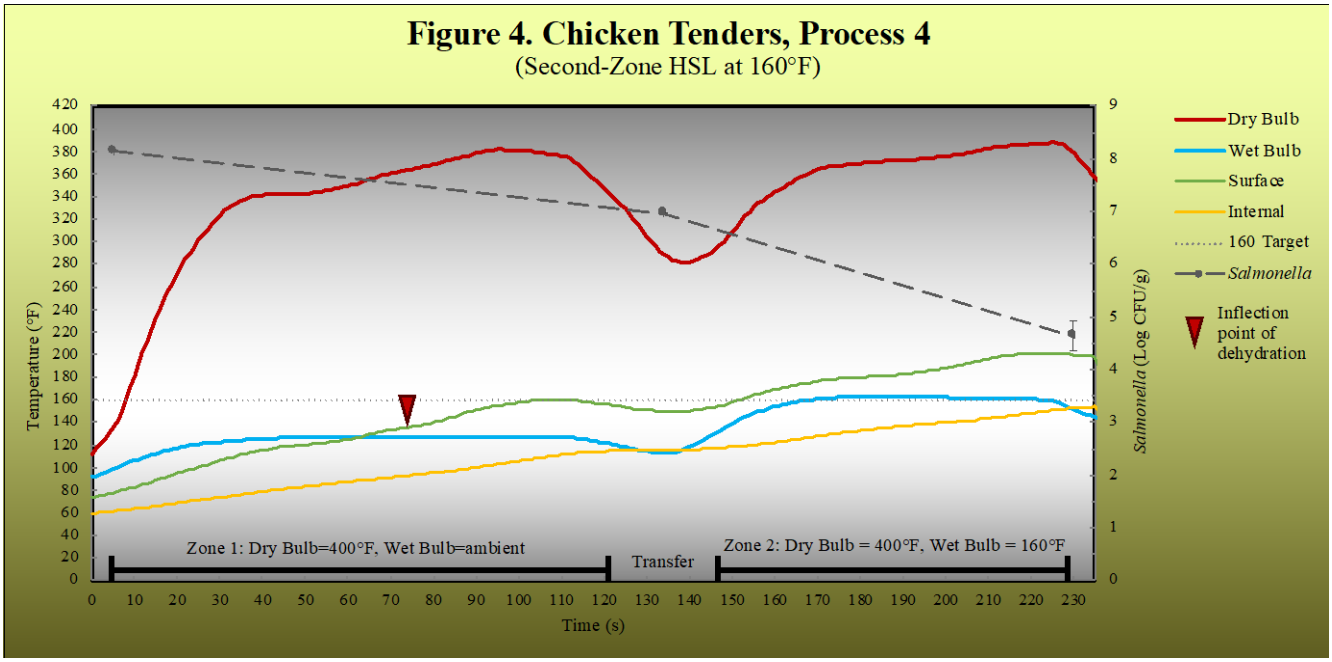
Processes 3 and 4 were both single-step HSL processes using a 160°F wet-bulb temperature for the HSL step. Process 3 used the HSL step in Zone 1, *prior to* a dry-heat zone. This process was intended to determine if a 160°F wet-bulb HSL step in Zone 1 would provide enough reduction to offset the presumably lower reductions of a subsequent dry-heat step in Zone 2. Process 4 used a 160°F wet-bulb HSL step in Zone 2, *after* a dry-heat first zone. This process was intended to determine if any *Salmonella* desiccated in an initial dry-heat zone could then be re-

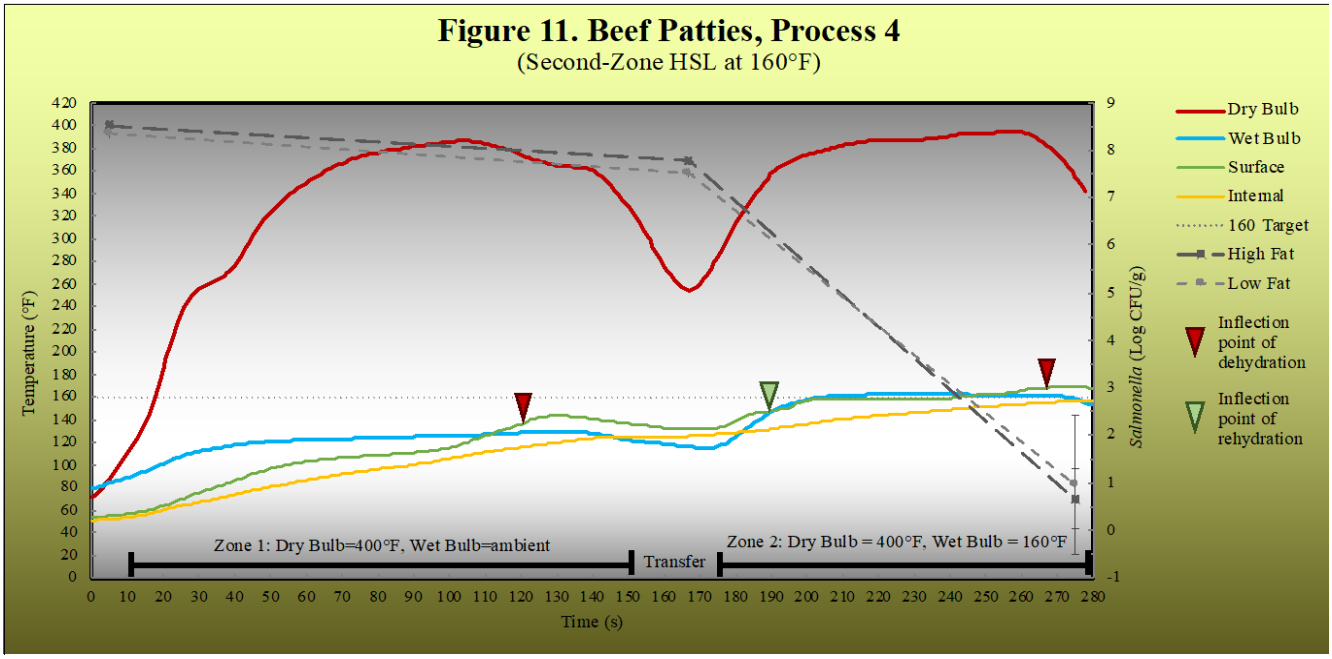
hydrated and inactivated using a 160°F wet-bulb HSL step in Zone 2.

Processes 3 and 4 achieved *Salmonella* reductions ≥ 6.5 log for all seven products except, importantly, for chicken tenders cooked using Process 4 (Tables 3-6). Process 4 achieved a reduction of only 3.5 log for chicken tenders. This reduction was the lowest of all products and processes in this study, although it was not significantly different from the 4.0 log reduction for chicken tenders cooked in Process 1, which used dry-heat in both zones ($p<0.05$). The total cooking time for Process 4 was 3.5 m, compared to 4.0 m for Process 1, which may have resulted in the lower reduction for Process 4.

Graphical analysis of the chicken tenders cooked using Process 4 provides a clear explanation for the ineffectiveness of the 160°F wet-bulb HSL step used in this process (Figure 4). Process 4 used a dry-heat, ambient-humidity step in Zone 1 followed by a 160°F wet-bulb step in Zone 2 that was intended to be an HSL step. Upon entering Zone 1, the product surfaces were exposed to dry-heat, ambient-moisture conditions in which the wet-bulb temperature drifted in a sub-lethal range of 125-130°F. At approximately 75 s, the surface temperature clearly broke above the wet-bulb temperature, indicating that the surface had begun to dry and had transitioned from the constant-rate to the falling-rate drying period approximately half-way through Zone 1. As such, the surfaces were hydrated for the first half of Zone 1, but at a sub-lethal temperature. At the end of Zone 1 (~120 s), the surface temperature had reached 160°F, which would have been highly lethal to the *Salmonella* if still hydrated (USDA, 1999). However, at this point the surfaces were already dried out, and therefore a large population of the surface-inoculated *Salmonella* had most likely become desiccated and heat tolerant, resulting in a reduction of only 1.3 log in the first zone. Upon entering Zone 2 (~145 s), the product was exposed to a 160°F wet-bulb temperature, which was intended to serve as an HSL step to rehydrate any desiccated *Salmonella* at a lethal temperature. However, as shown on Figure 4, upon

Figure 4. Chicken Tenders, Process 4
(Second-Zone HSL at 160°F)





entering Zone 2, the surface temperature for the chicken tenders was already well above the 160°F wet-bulb temperature, and as such, moisture did not condense on the product and the surfaces remained dry. Therefore, the 160°F wet-bulb HSL step in Zone 2 was ineffective. It did not rehydrate the desiccated *Salmonella*, resulting in a cumulative *Salmonella* reduction of only 3.5 log for Process 4. This result aligns with the findings of Sindelar and co-workers (2016), who found similar results for chicken tenders in a previous study on impingement cooking.

As shown on Figure 4, the surface temperature for the chicken tenders cooked using Process 4 was approximately 160°F at the discharge of Zone 1 and 200°F at the discharge of Zone 2 — temperatures that would have been otherwise highly lethal for hydrated *Salmonella*. However, the dry conditions in Zone 1 apparently created a large population of desiccated, heat-tolerant *Salmonella* that survived these high surface temperatures, resulting in a log reduction of only 3.5 log.

In contrast to the chicken tender results, Process 4 resulted in sufficient *Salmonella* reductions for all of the patty products. As shown on Figures 11, 18, and 25 for the beef, pork, and chicken patties, the 160°F HSL step in Zone 2 rehydrated the surfaces of the patties, resulting in sufficient *Salmonella* reductions for the patty products cooked using Process 4 (Tables 4-6).

A representative example of the surface rehydration in Process 4 using a 160°F HSL step in Zone 2 is illustrated for beef patties on Figure 11. As shown, the patty surfaces were hydrated at a sub-lethal temperature of 125°F in Zone 1, but the dehydration inflection point occurred at approximately 115 s, presumably creating significant numbers of desiccated *Salmonella*. However, the 160°F wet-bulb HSL rehydrated the surfaces at the beginning of Zone 2 (190 s), thus rehydrating any desiccated Salmonella at a highly lethal temperature of 160°F. For most of Zone 2, then, the surfaces remained at a highly lethal temperature of 160°F under hydrated conditions, resulting in sufficient *Salmonella* reductions of 7.4

log for 10% fat patties and 7.9 log for 30% fat patties (Table 4).

These sufficient log reductions for the patty products using Process 4, compared to the insufficient 3.5 log reduction for chicken tenders using the same cooking process, demonstrate the importance of validating that HSL steps use a wet-bulb temperature that is high enough to rehydrate product surfaces that were dehydrated earlier in the process.

Influence of HSL steps on variability of *Salmonella* reductions

The mean-average standard deviations for *Salmonella* reductions across all products for each process are shown in Figure 29. Processes 2 and 7, which had wet-bulb controlled HSL steps in both zones, had the lowest average standard deviations, while the highest standard deviation was for Process 1 using dry-heat only with no HSL steps. Processes 2 and 7 provided the most consistent *Salmonella* reductions across all products for both whole-muscle and ground products, suggesting that impingement processes that use wet-bulb controlled HSL steps in all zones provide higher and more reliable *Salmonella* lethality.

Influence of fat levels on process lethality

The 10% fat beef, pork, and chicken patties cooked using Process 1 had lower total *Salmonella* reductions (≤5.8 log) than the patties with higher fat levels of 20% or 30% (Table 4-6). Process 1 had dry-heat in both zones with no HSL steps. The dry-heat process combined with the lower fat levels promoted rapid surface dehydration, presumably resulting in higher populations of desiccated, heat-tolerant *Salmonella* on the surfaces of the low-fat patties than the high-fat patties.

Low-fat products were more prone to surface dehydration than higher fat products, resulting in lower *Salmonella* reductions for low-fat than high-fat products cooked using the same process. For example, the total *Salmonella* reduction for the 10% fat pork patties cooked using the dry-heat Process 1 was 5.8 log compared to 7.1 log for 30% fat pork patties cooked using the same process (Table 5). The low-fat patties would have been more prone to surface dehydration and *Salmonella* desiccation than the high-fat patties, leading to lower reductions for the low-fat patties.

When HSL steps were used in both zones (Processes 2 and 7), sufficient reductions of ≥6.5 log were achieved for both the low- and high-fat patties, and the log reductions were similar for both fat levels (Tables 4-6). For example, when pork patties were cooked using Process 2 with a 160°F wet-bulb HSL step in both zones, the *Salmonella* reductions for the low- and high-fat levels were almost identical — 8.0 log for 10% fat and 7.9 log for 30% fat pork patties (Table 5).

Implications for production processes for impingement ovens

In this study, the dry-heat Process 1 with no steam injection was the most unreliable process for ensuring sufficient destruction of surface-inoculated *Salmonella*. The dry-heat Process 1 failed to achieve sufficient ≥6.5 log reductions for the whole-muscle chicken tenders and for the low-fat beef, pork, and chicken patties. Using dry-heat, ambient-humidity impingement cooking processes in industrial settings, then, increases the risk of desiccated *Salmonella* surviving on product surfaces, thus providing unreliable surface

lethality for some products — even if very high dry-bulb temperatures are used and even the products are cooked to high internal product temperatures. Therefore, dry-heat, ambient-humidity cooking processes are not recommended for impingement ovens.

Single-zone HSL steps using wet-bulb temperatures of 160°F and 180°F were effective if the wet-bulb temperatures were high enough to maintain hydrated surface conditions at lethal temperatures for a sufficient time. If product surfaces were dehydrated early in the process, then subsequent single-zone HSL steps were only effective if the wet-bulb temperature was high enough to exceed the surface temperature so that moisture condensed on the product surfaces at a highly lethal temperature, thus rehydrating and inactivating any desiccated *Salmonella*. If a single-step HSL process is used in an industrial impingement process, then, it is recommended that the effectiveness of the HSL step be validated using graphical analysis of the surface and wet-bulb temperatures to ensure that the wet-bulb temperature used in the HSL step is high enough to rehydrate the product surfaces at a highly lethal temperature.

The most reliable impingement cooking processes in this study were those that used 160°F or 180°F wet-bulb HSL steps in both zones. When HSL steps were used in both zones of cooking processes that were 3-4 minutes long, sufficient *Salmonella* reductions of ≥6.5 log were reliably achieved for all products. Based on these results, it is recommended that impingement cooking processes of 3.0 minutes or longer use wet-bulb temperatures of 160°F or higher as HSL steps in all zones to reliably achieve a *Salmonella* reduction of ≥6.5 log on product surfaces. HSL steps that use wet-bulb temperatures higher than 160°F or cooking times longer than three minutes will provide an additional margin of safety.

Controlling wet-bulb temperatures in high temperature ovens

For most commercial impingement, spiral, and cross-flow continuous ovens, wet-bulb temperatures can be readily measured using a simple wet-bulb sensor and controlled using a steam-inlet valve. Some high-temperature ovens are equipped with wet-bulb controls as standard equipment while others that do not have standard wet-bulb controls can be retro-fitted with wet-bulb sensors and controls. Some ovens are equipped with dew-point temperature sensors instead of wet-bulb sensors, in which case most dew-point sensors can be configured to output the wet-bulb temperature, or if not, the wet-bulb temperature can be readily back-calculated using high-temperature psychrometric charts or software such as PsyCalc (www.linric.com). If an oven does not have a wet-bulb or a dew-point sensor, and retro-fitting is impractical, then a simple, inexpensive wet-bulb sensor, as shown on Diagram 1, can be periodically run through the oven to measure the wet-bulb temperature, and a steam-inlet valve can be used to control the steam input to achieve the desired wet-bulb temperature.

Conclusion

For most pre-cooked meat and poultry products, cooking processes are the primary critical control point for the destruction of vegetative pathogens. As such, cooking processes must act as a firewall between pathogen-laden raw products and pathogen-free cooked products. Meat processors depend on effective cooking processes

to reliably destroy vegetative pathogens that invariably exist on the surface and interior of raw products.

The temperatures required to destroy hydrated *Salmonella* are well known and widely reported in scientific literature (O'Bryan et al, 2006; USDA, 2017). Pathogenic bacteria in the product interior are inherently hydrated, and therefore, the interior can simply be heated to time-temperature conditions that are well-established as lethal conditions for hydrated *Salmonella*. In contrast, the temperatures required to inactivate *Salmonella* that have become desiccated are largely unknown. For example, in this study we found that surface temperatures of 160-200°F and cooking times of 3-4 minutes — common temperatures and times for impingement-cooked products — were ineffective against desiccated *Salmonella*. Furthermore, *Salmonella* inoculated onto the surfaces of dehydration-prone products such as chicken tenders were rapidly desiccated, and heat-tolerant, desiccated *Salmonella* were formed in less than two minutes when cooked using dry-heat, ambient-moisture processes.

Hydrated surface lethality (HSL) steps using wet-bulb temperatures of 160°F or higher in impingement-oven processes proved effective for ensuring *Salmonella* on product surfaces were subjected to lethal time-temperature combinations under hydrated conditions. Because impingement ovens represent the practical worst case for rapid dehydration of product surfaces in forced-air convection continuous ovens, the HSL steps validated in this study can safely be used as validated HSL steps for industrial impingement, spiral, and cross-flow forced-air convection ovens.

Our research has shown that the use of product internal temperatures alone as predictors of overall process lethality is inadequate for ensuring sufficient pathogen reduction. Given the demonstrated capability of impingement ovens to rapidly create desiccated *Salmonella* on the surface of meat products, and given the proven ability of desiccated *Salmonella* to survive impingement processes, industry processors must consider surface lethality when evaluating the safety of impingement processes. This research demonstrates that the proper use of HSL steps will ensure the safety of impingement-cooked products — especially for processes where surface drying is desirable for browning or other quality attributes, thus increasing the risk of desiccation. We recommend that impingement cooking processes incorporate HSL steps with a wet-bulb temperature of ≥160°F for the entire process to ensure the inactivation of desiccated *Salmonella* on product surfaces.

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Diagrams

Diagram 1. Photograph of data logger placement measuring dry-bulb, wet bulb, surface temperature, and internal temperatures for thermal profile generation.

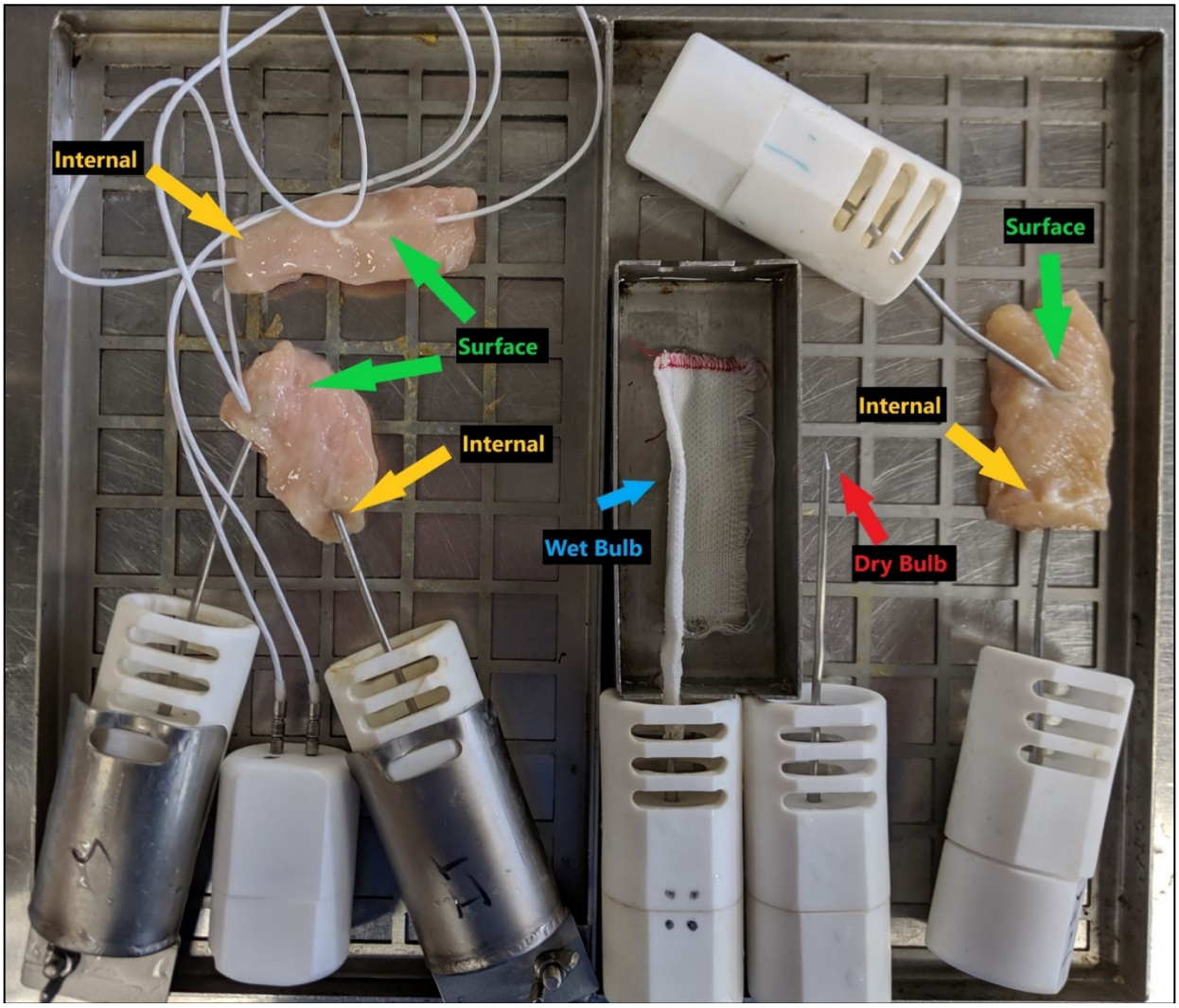

Diagram 2. Data logger placement for measurement of product surface and internal temperatures.

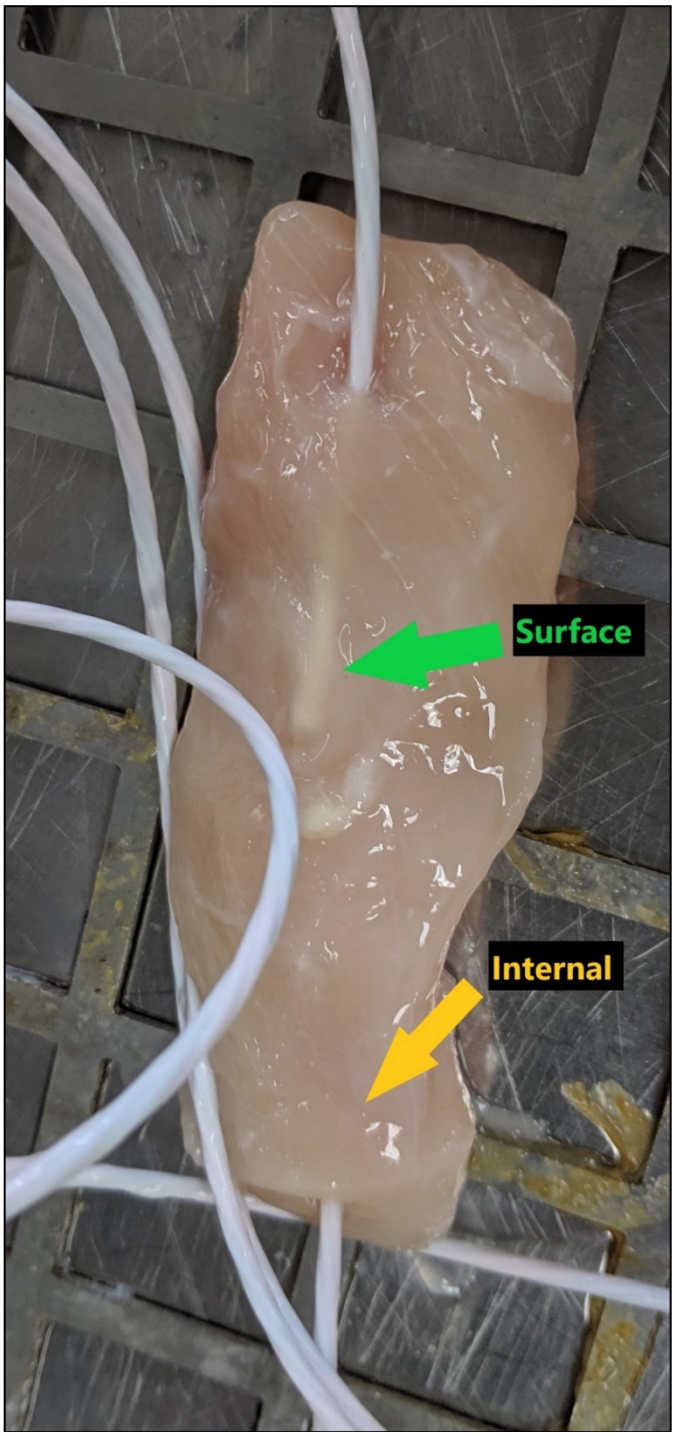

Diagram 3. Belt-fed two-zone continuous impingement oven (Model 1832-01596 conveyor ovens, XLT ovens, Wichita, KS) equipped with steam injection for controlling the wet-bulb temperature in each zone (Powis Corporation, Blue Springs, MO).

Tables

Table 1. Product formulations for manufacture of chicken tenders, beef patties, pork patties, and chicken patties[a].

	Product						
	Chicken Tenders	Beef Patties		Pork Patties		Chicken Patties	
Non-Meat Ingredient	≤ 3% Fat	10% Fat	30% Fat	10% Fat	30% Fat	10% Fat	20% Fat
Water	5.00	0.00	0.00	2.00	2.00	2.00	2.00
Salt	2.50	0.00	0.00	2.50	2.50	2.50	2.50
Sodium tripolyphosphate (STPP)	0.35	0.00	0.00	0.35	0.35	0.35	0.35

[a]Formulated ingredients reported as ingoing percentage on a raw meat weight basis.

Table 2. Physiochemical properties[a] of raw chicken tenders, beef patties, pork patties, and chicken patties.

Product	% Moisture[b]	% Fat[c]	% NaCl[d]	pH[e]	a_w[f]
Chicken Tenders	76.10 ± 0.92	2.64 ± 0.29	2.38 ± 0.05	6.41 ± 0.08	0.979 ± 0.001
Beef Patties – 10% Fat	68.95 ± 0.39	10.37 ± 0.31	0.20 ± 0.02	5.88 ± 0.07	0.986 ± 0.001
Beef Patties – 30% Fat	51.41 ± 0.33	30.57 ± 0.85	0.17 ± 0.06	5.94 ± 0.01	0.983 ± 0.001
Pork Patties – 10% Fat	71.06 ± 0.62	10.37 ± 0.72	2.51 ± 0.11	6.22 ± 0.01	0.976 ± 0.001
Pork Patties – 30% Fat	52.91 ± 0.36	29.53 ± 0.83	2.41 ± 0.08	6.29 ± 0.01	0.974 ± 0.001
Chicken Patties – 10% Fat	72.01 ± 0.37	9.67 ± 0.60	2.42 ± 0.23	6.41 ± 0.03	0.979 ± 0.001
Chicken Patties – 20% Fat	62.61 ± 0.83	19.13 ± 0.49	2.57 ± 0.03	6.52 ± 0.00	0.977 ± 0.001

[a] Values expressed as mean ± standard deviation from all replications (n = 9 for chicken tenders; n = 3 for other products). For chicken tenders, triplicate samples from each replication were analyzed for physiochemical properties. The beef, pork, and chicken patties used meat from a single batch for all three replications. Triplicate samples from each batch were analyzed for physiochemical properties.
[b] Vacuum oven method, 5 h, 100°C; Association of Official Analytical Chemists, method 950.46.
[c] Microwave and nuclear magnetic resonance method; CEM SMART Turbo Moisture/Solid Analyzer; Association of Official Analytical Chemists, method 2008.06.
[d] Measured as % Cl^-, $AgNO_3$ potentiometric titration, Mettler G20 compact titrator.
[e] Indirect pH by using an Accumet Basic pH meter with an Orion 8104 combination electrode, 10 g of meat to 90 ml of distilled water.
[f] Measured using a Decagon Aqua lab 4TE water activity meter

Table 3. Cook process parameters[a] and least square means for reductions of *Salmonella*[b] on the surface of chicken tenders.

	Process Parameters							Total *Salmonella* reduction		
	Zone 1			Zone 2				≤ 3% Fat		
Process	**Dry Bulb** (°F)	**Wet Bulb** (°F)	**Time** mm:ss	**Dry Bulb** (°F)	**Wet Bulb** (°F)	**Time** mm:ss	**Total Time** mm:ss	Log	±	S.E.
1	400	ambient	2:00	400	ambient	2:00	4:00	4.02^{z}	±	0.64
2	400	160	1:30	400	160	1:30	3:00	6.93^{y}	±	0.49
3	400	160	1:30	400	ambient	2:00	3:30	7.22^{y}	±	0.47
4	400	ambient	2:00	400	160	1:30	3:30	3.52^{z}	±	0.17
5	400	ambient	2:00	400	180	1:30	3:30	6.91^{y}	±	0.45
6	400	180	1:30	400	ambient	2:00	3:30	6.94^{y}	±	0.35
7	400	180	1:30	400	180	1:30	3:00	7.20^{y}	±	0.20

[a] Products were cooked in two XLT conveyor ovens (Model 1832-01596) modified to allow for steam injection. Each zone refers to passage through a single oven. For processes where both zones had identical parameters, products were passed through the same oven twice.
[b] *Salmonella* reductions shown are the mean of three replicate experiments and expressed as mean ± standard error.
[yz] Means within a product and fat level with unlike superscript letters are significantly different ($P < 0.05$).

Table 4. Cook process parameters[a] and least square means for reductions of *Salmonella*[b] on the surface of ground beef patties with either 10% or 30% fat.

Process	Process Parameters							Total *Salmonella* reduction					
	Zone 1			Zone 2				10% fat			30% fat		
	Dry Bulb (°F)	Wet Bulb (°F)	Time mm:ss	Dry Bulb (°F)	Wet Bulb (°F)	Time mm:ss	Total Time mm:ss	Log	±	S.E.	Log	±	S.E.
1	400	ambient	2:00	400	ambient	2:00	4:00	6.19^{z}	±	0.46	7.03^{yz}	±	0.49
2	400	160	1:30	400	160	1:30	3:00	7.15^{z}	±	0.38	6.69^{z}	±	0.12
3	400	160	1:30	400	ambient	2:00	3:30	6.89^{z}	±	0.42	7.19^{yz}	±	0.37
4	400	ambient	2:00	400	160	1:30	3:30	7.38^{z}	±	0.85	7.86^{yz}	±	0.36
5	400	ambient	2:00	400	180	1:30	3:30	7.74^{z}	±	0.48	7.82^{yz}	±	0.41
6	400	180	1:30	400	ambient	2:00	3:30	7.01^{z}	±	0.55	7.37^{yz}	±	0.75
7	400	180	1:30	400	180	1:30	3:00	7.87^{z}	±	0.22	7.97^{y}	±	0.25

[a] Products were cooked in two XLT conveyor ovens (Model 1832-01596) modified to allow for steam injection. Each zone refers to passage through a single oven. For processes where both zones had identical parameters, products were passed through the same oven twice.
[b] *Salmonella* reductions shown are the mean of three replicate experiments and expressed as mean ± standard error.
[yz] Means within a product and fat level with unlike superscript letters are different ($P < 0.05$).

Table 5. Cook process parameters[a] and least square means for reductions of *Salmonella*[b] on the surface of ground pork patties with either 10% or 30% fat.

Process	Process Parameters							Total *Salmonella* reduction					
	Zone 1			Zone 2				10% fat			30% fat		
	Dry Bulb (°F)	Wet Bulb (°F)	Time mm:ss	Dry Bulb (°F)	Wet Bulb (°F)	Time mm:ss	Total Time mm:ss	Log	±	S.E.	Log	±	S.E.
1	400	ambient	2:00	400	ambient	2:00	4:00	5.78^{z}	±	0.39	7.05^{z}	±	0.05
2	400	160	1:30	400	160	1:30	3:00	7.97^{x}	±	0.13	7.89^{yz}	±	0.25
3	400	160	1:30	400	ambient	2:00	3:30	7.31^{xyz}	±	0.24	7.56^{yz}	±	0.39
4	400	ambient	2:00	400	160	1:30	3:30	7.01^{yz}	±	0.07	7.71^{yz}	±	0.40
5	400	ambient	2:00	400	180	1:30	3:30	7.64^{xy}	±	0.37	7.89^{yz}	±	0.47
6	400	180	1:30	400	ambient	2:00	3:30	7.64^{xy}	±	0.37	7.56^{yz}	±	0.39
7	400	180	1:30	400	180	1:30	3:00	7.97^{x}	±	0.13	8.23^{y}	±	0.14

[a] Products were cooked in two XLT conveyor ovens (Model 1832-01596) modified to allow for steam injection. Each zone refers to passage through a single oven. For processes where both zones had identical parameters, products were passed through the same oven twice.
[b] *Salmonella* reductions shown are the mean of three replicate experiments and expressed as mean ± standard error.
[xyz] Means within a product and fat level with unlike superscript letters are different ($P < 0.05$).

Table 6. Cook process parameters[a] and least square means for reductions of *Salmonella*[b] on the surface of ground chicken patties with either 10% or 20% fat.

Process	Process Parameters							Total *Salmonella* reduction					
	Zone 1			Zone 2				10% fat			20% fat		
	Dry Bulb (°F)	Wet Bulb (°F)	Time mm:ss	Dry Bulb (°F)	Wet Bulb (°F)	Time mm:ss	Total Time mm:ss	Log	±	S.E.	Log	±	S.E.
1	400	ambient	2:00	400	ambient	2:00	4:00	6.33^{z}	±	0.70	6.79^{z}	±	0.55
2	400	160	1:30	400	160	1:30	3:00	8.80^{y}	±	0.11	8.67^{z}	±	0.11
3	400	160	1:30	400	ambient	2:00	3:30	8.30^{yz}	±	0.40	8.67^{z}	±	0.11
4	400	ambient	2:00	400	160	1:30	3:30	8.39^{yz}	±	0.27	8.12^{z}	±	0.41
5	400	ambient	2:00	400	180	1:30	3:30	8.76^{y}	±	0.10	8.67^{z}	±	0.11
6	400	180	1:30	400	ambient	2:00	3:30	7.67^{yz}	±	0.67	8.67^{z}	±	0.11
7	400	180	1:30	400	180	1:30	3:00	8.76^{y}	±	0.10	8.67^{z}	±	0.11

[a] Products were cooked in two XLT conveyor ovens (Model 1832-01596) modified to allow for steam injection. Each zone refers to passage through a single oven. For processes where both zones had identical parameters, products were passed through the same oven twice.
[b] *Salmonella* reductions shown are the mean of three replicate experiments and expressed as mean ± standard error.
[yz] Means within a product and fat level with unlike superscript letters are different ($P < 0.05$).

Figures

Figure 1. Chicken Tenders, Process 1
(Two-Zone Dry Heat)

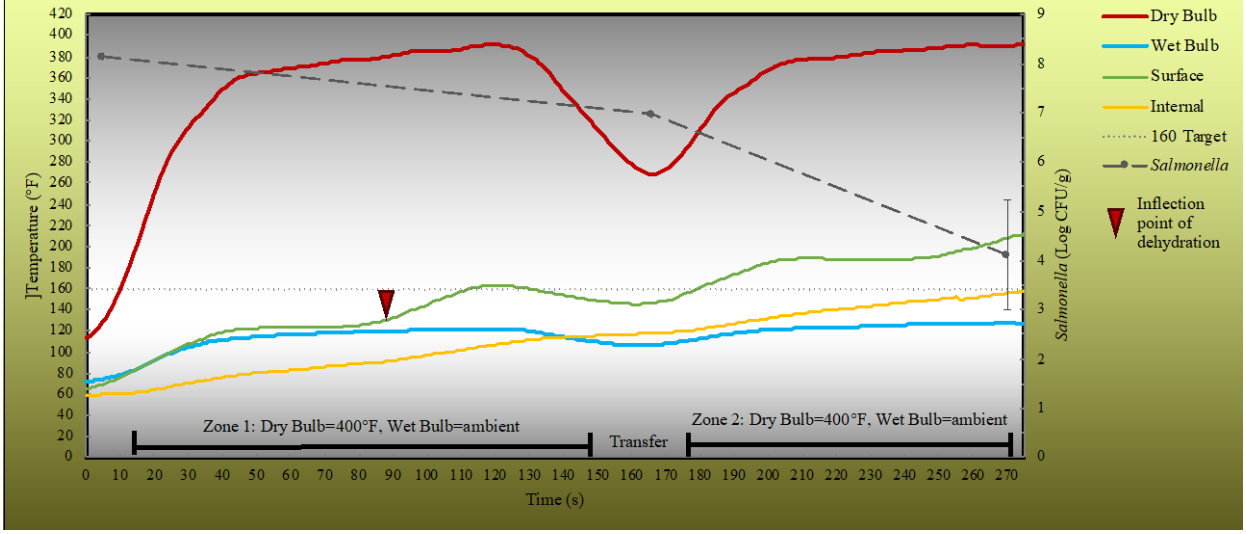

Figure 2. Chicken Tenders, Process 2
(Two-Zone HSL at 160°F)

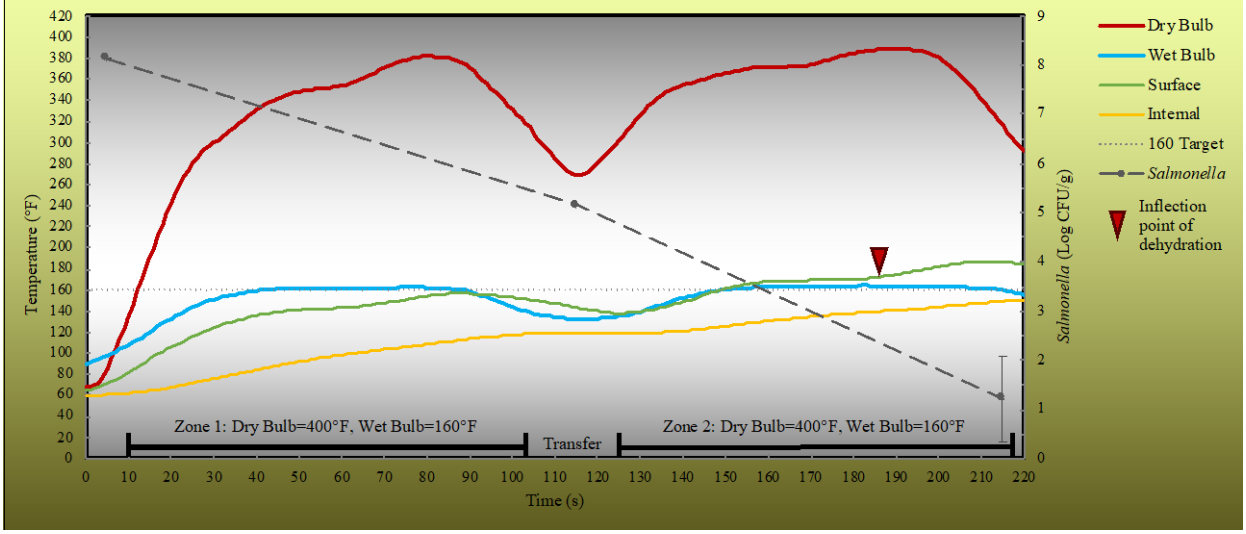

Figure 3. Chicken Tenders, Process 3
(First-Zone HSL at 160°F)

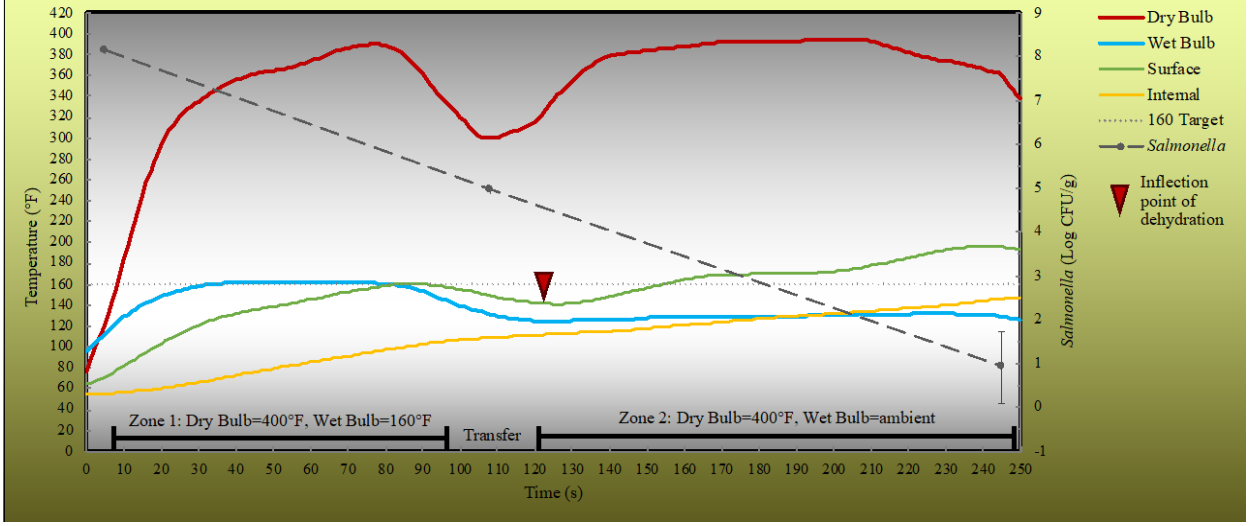

Figure 4. Chicken Tenders, Process 4
(Second-Zone HSL at 160°F)

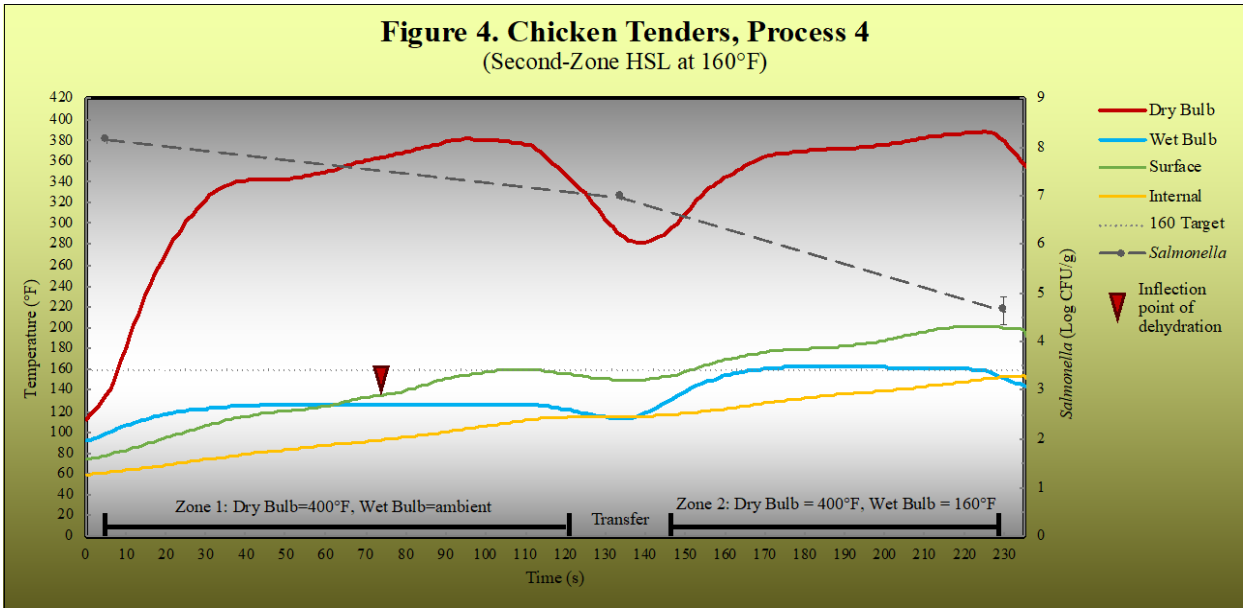

Figure 5. Chicken Tenders, Process 5
(Second-Zone HSL at 180°F)

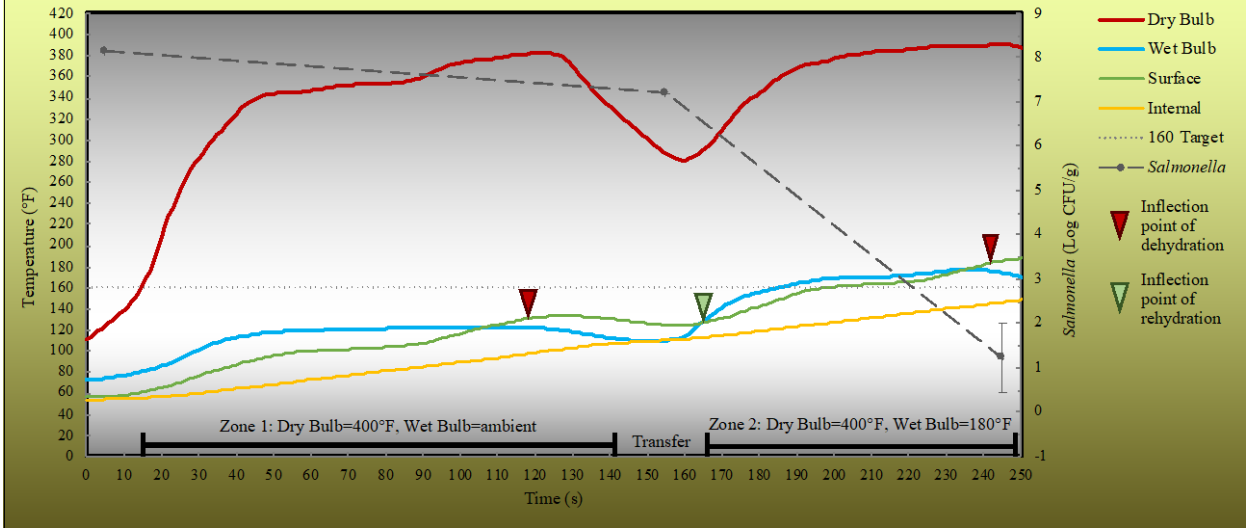

Figure 6. Chicken Tenders, Process 6
(First-Zone HSL at 180°F)

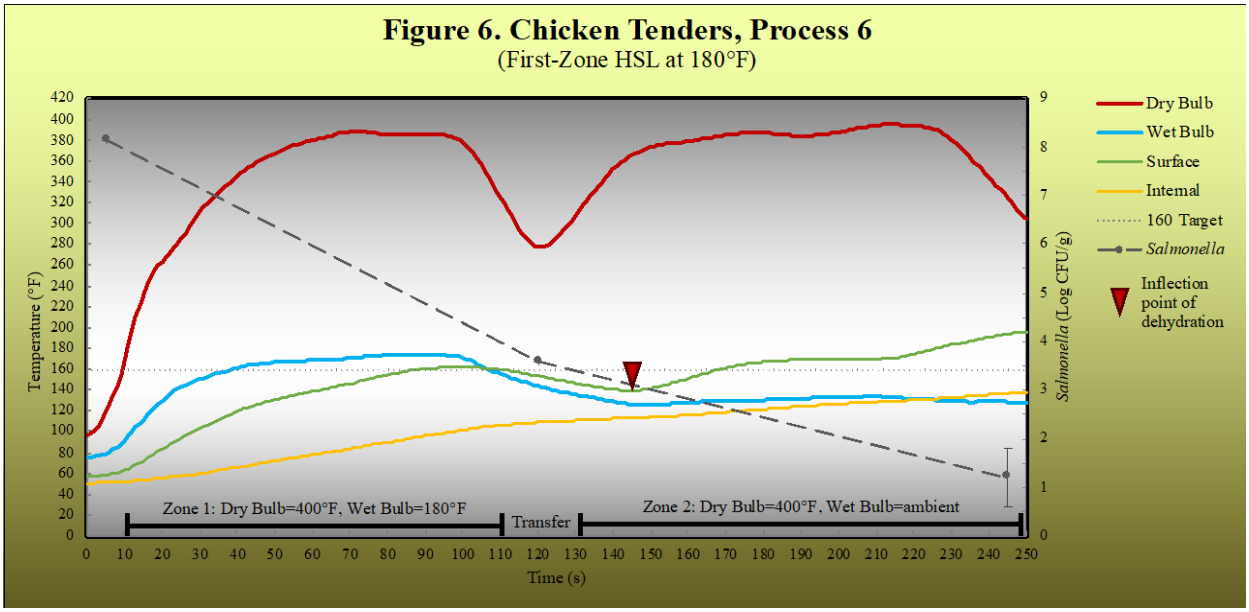

Figure 7. Chicken Tenders, Process 7
(Two-Zone HSL at 180°F)

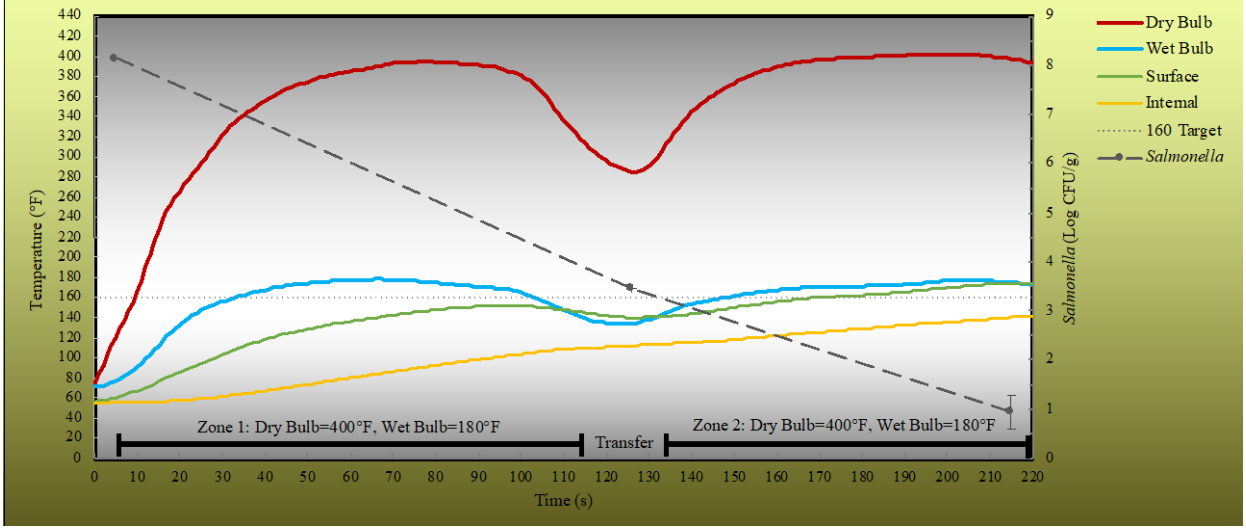

Figure 8. Beef Patties, Process 1
(Two-Zone Dry Heat)

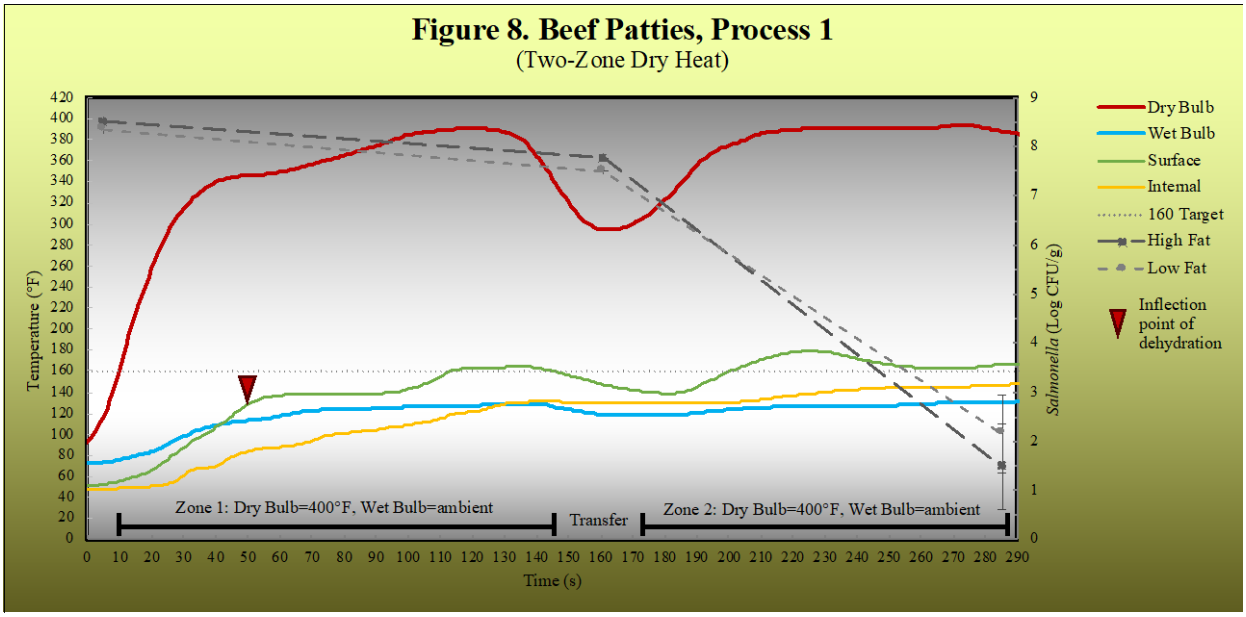

Figure 9. Beef Patties, Process 2
(Two-Zone HSL at 160°F)

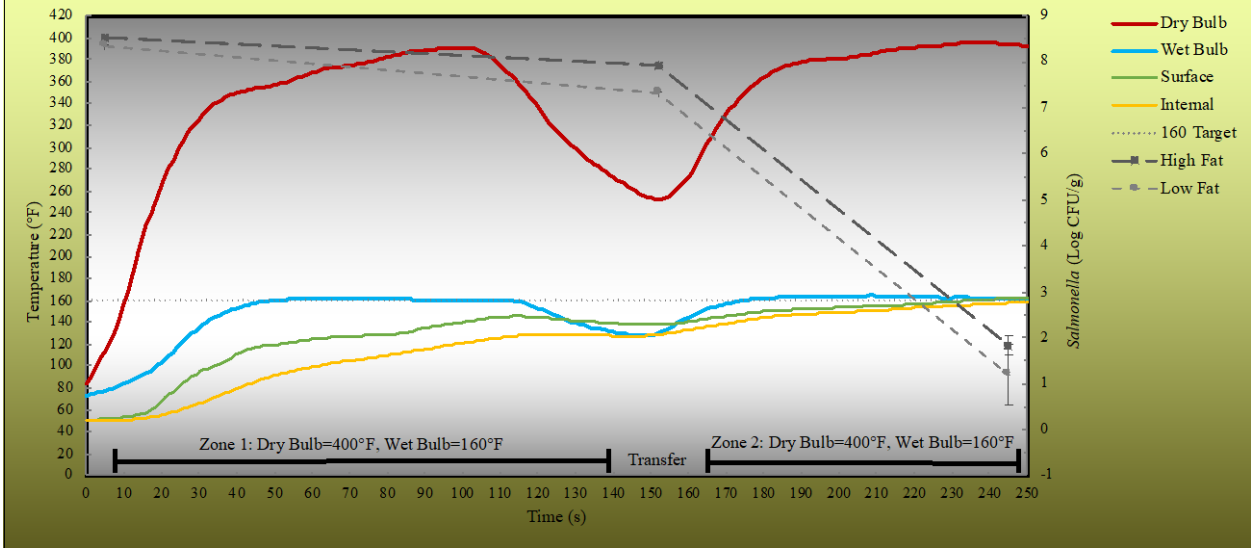

Figure 10. Beef Patties, Process 3
(First-Zone HSL at 160°F)

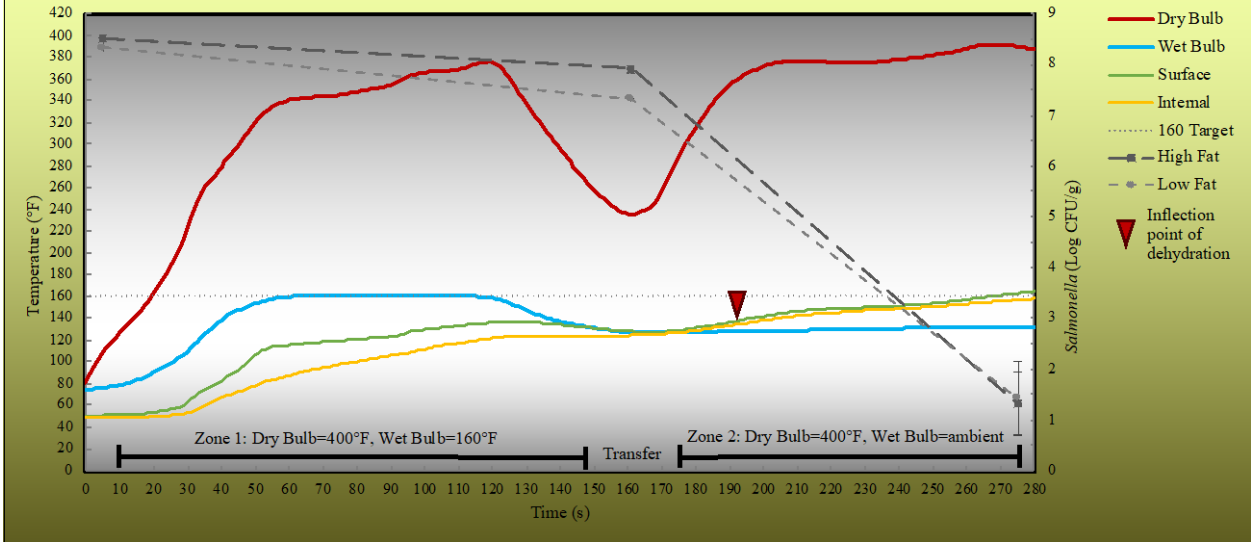

Figure 11. Beef Patties, Process 4
(Second-Zone HSL at 160°F)

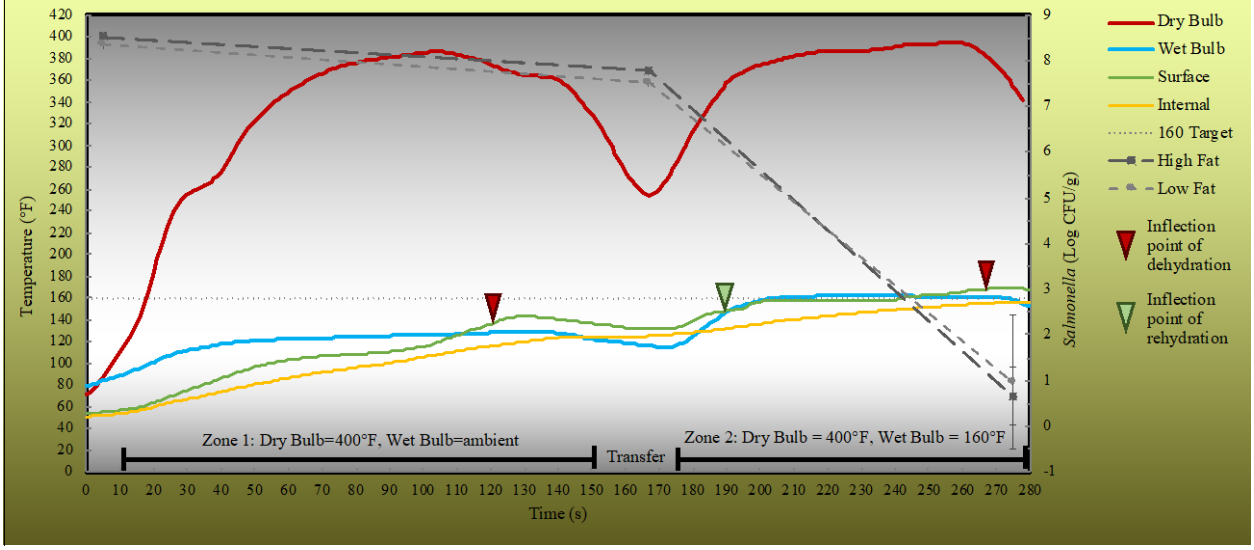

Figure 12. Beef Patties, Process 5
(Second-Zone HSL at 180°F)

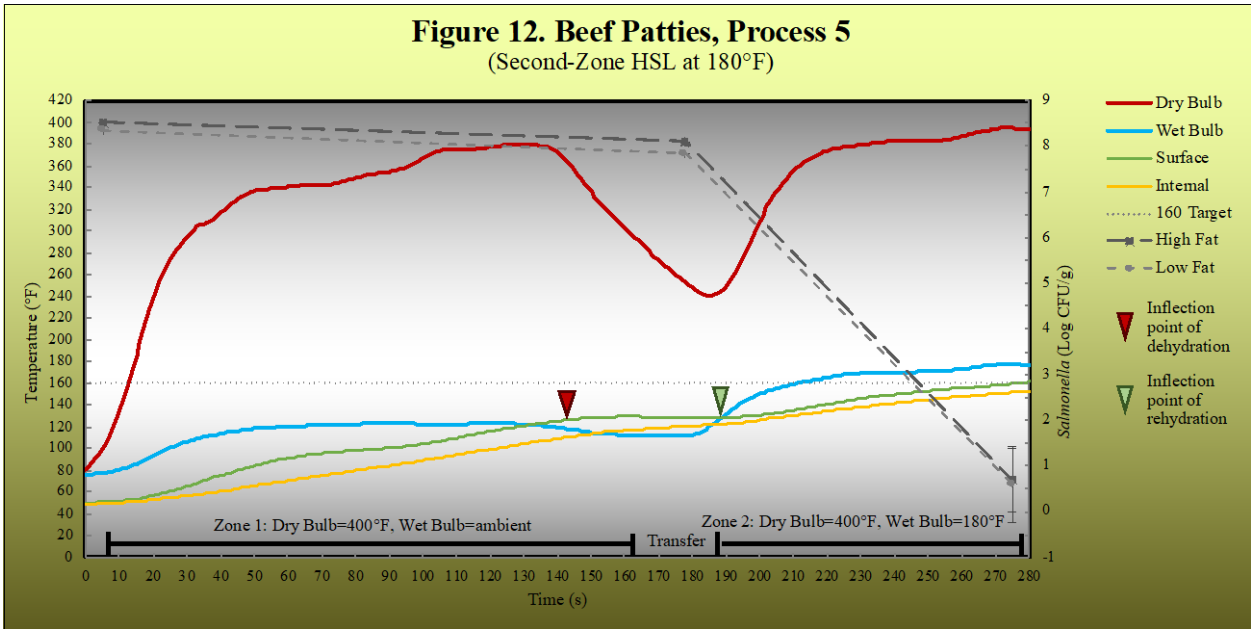

Figure 13. Beef Patties, Process 6
(First-Zone HSL at 180°F)

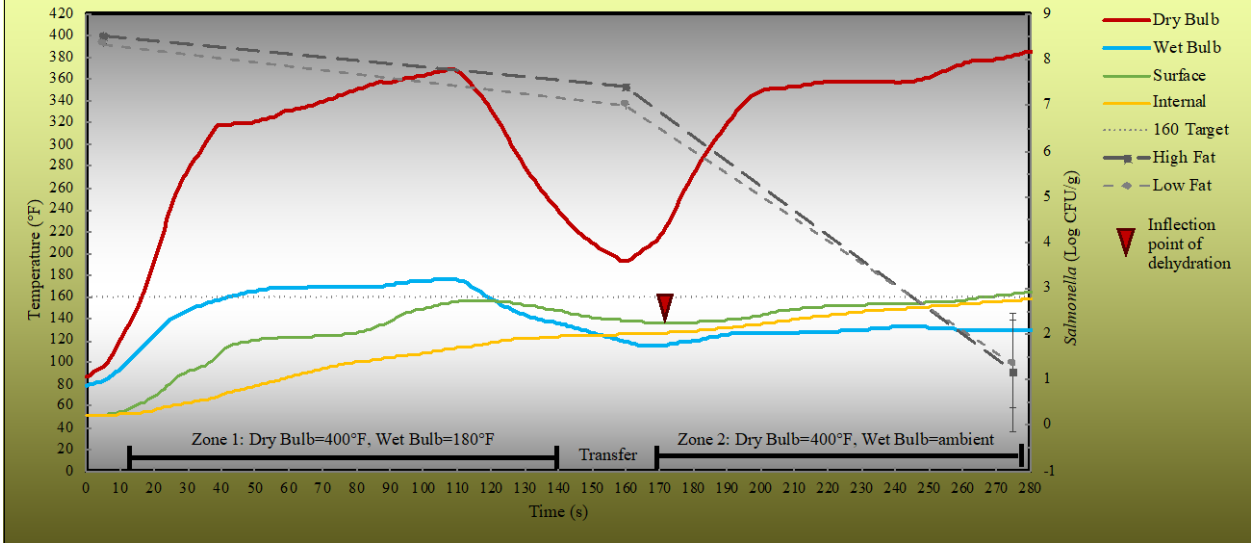

Figure 14. Beef Patties, Process 7
(Two-Zone HSL at 180°F)

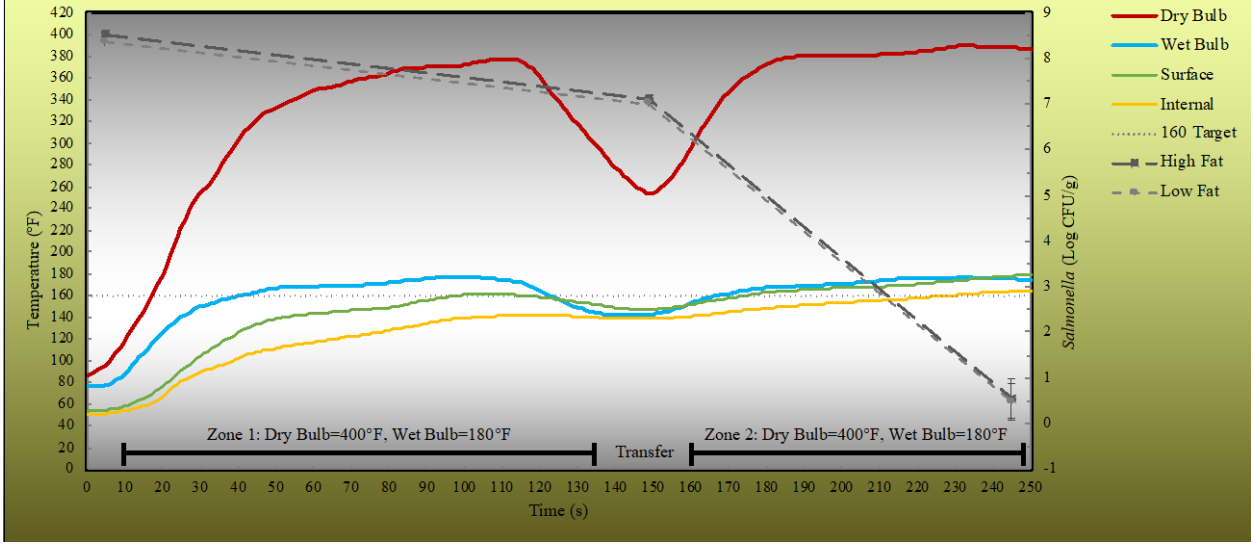

Figure 15. Pork Patties, Process 1
(Two-Zone Dry Heat)

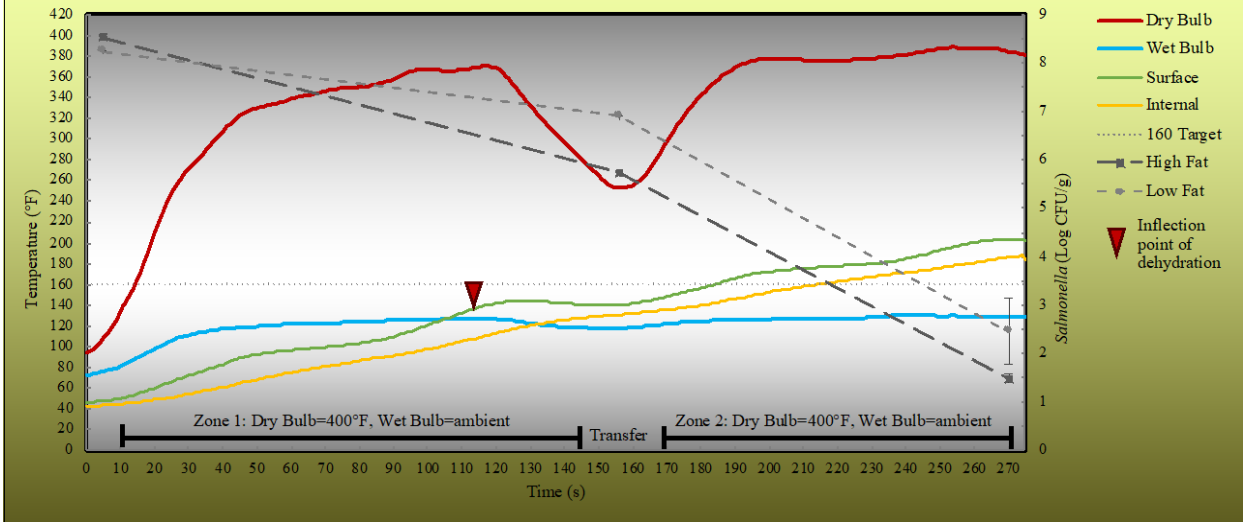

Figure 16. Pork Patties, Process 2
(Two-Zone HSL at 160°F)

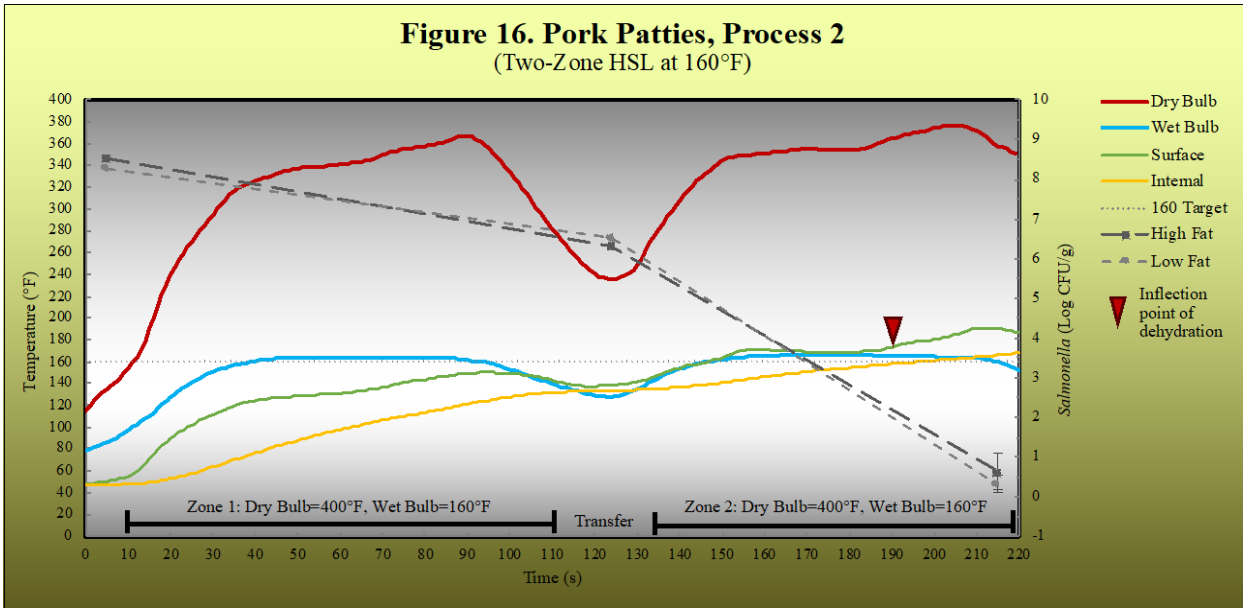

Figure 17. Pork Patties, Process 3
(First-Zone HSL at 160°F)

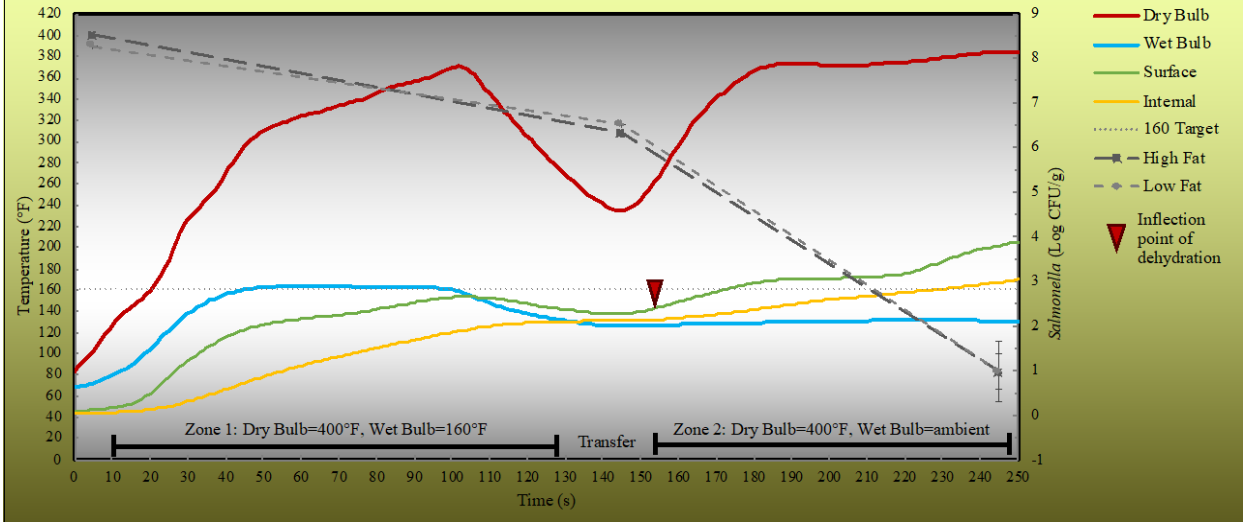

Figure 18. Pork Patties, Process 4
(Second-Zone HSL at 160°F)

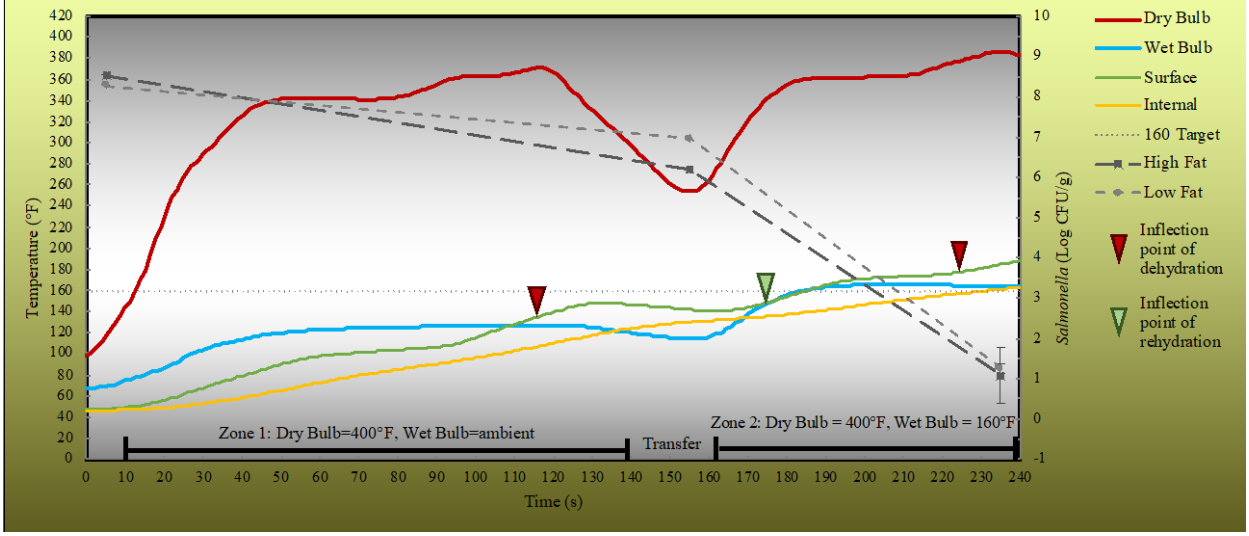

Figure 19. Pork Patties, Process 5
(Second-Zone HSL at 180°F)

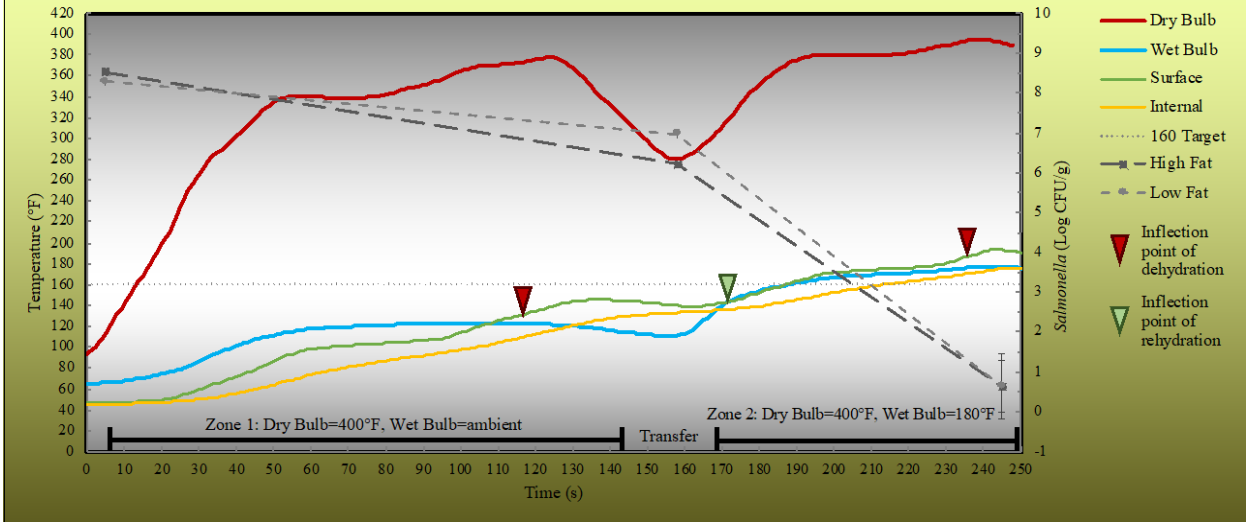

Figure 20. Pork Patties, Process 6
(First-Zone HSL at 180°F)

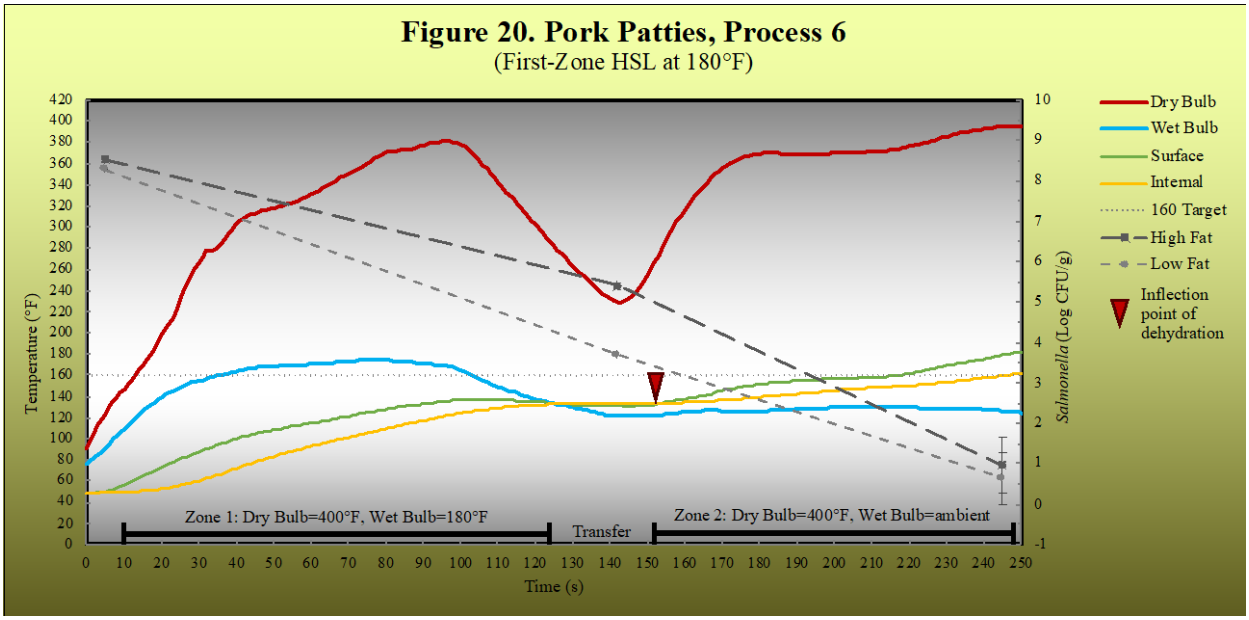

Figure 21. Pork Patties, Process 7
(Two-Zone HSL at 180°F)

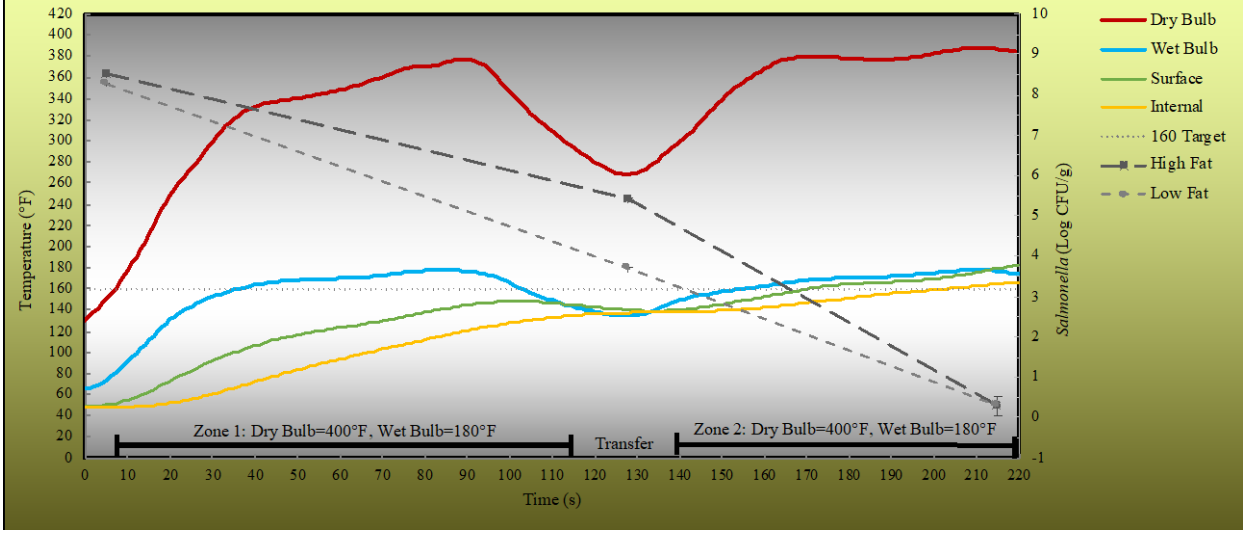

Figure 22. Chicken Patties, Process 1
(Two-Zone Dry Heat)

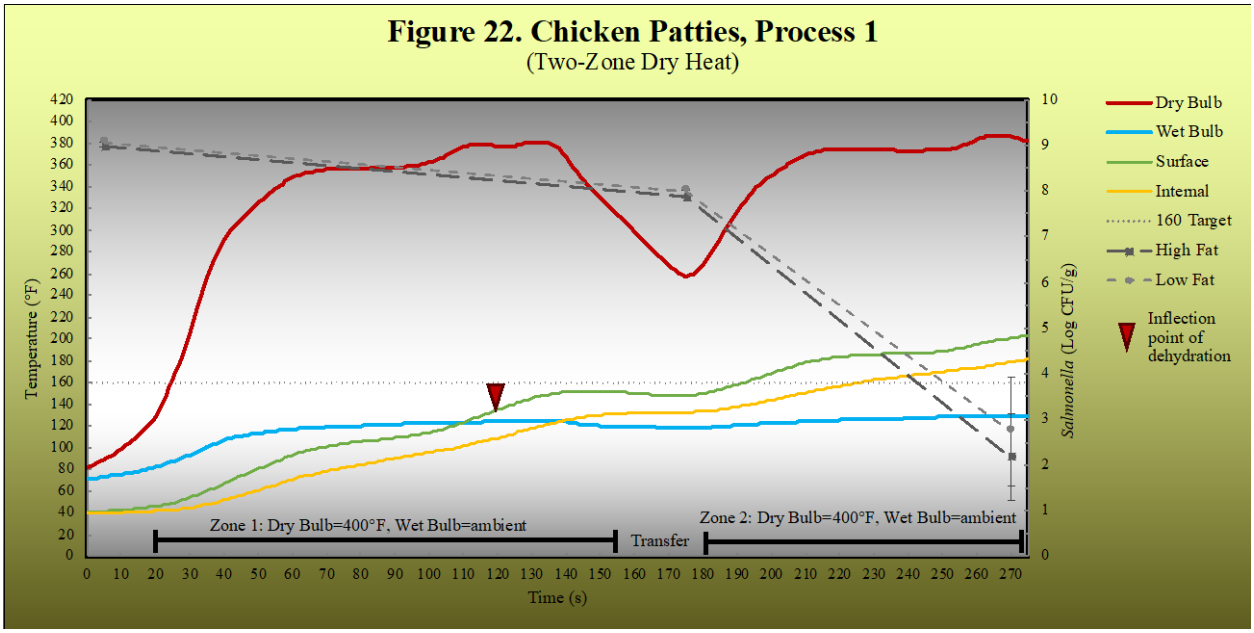

Figure 23. Chicken Patties, Process 2
(Two-Zone HSL at 160°F)

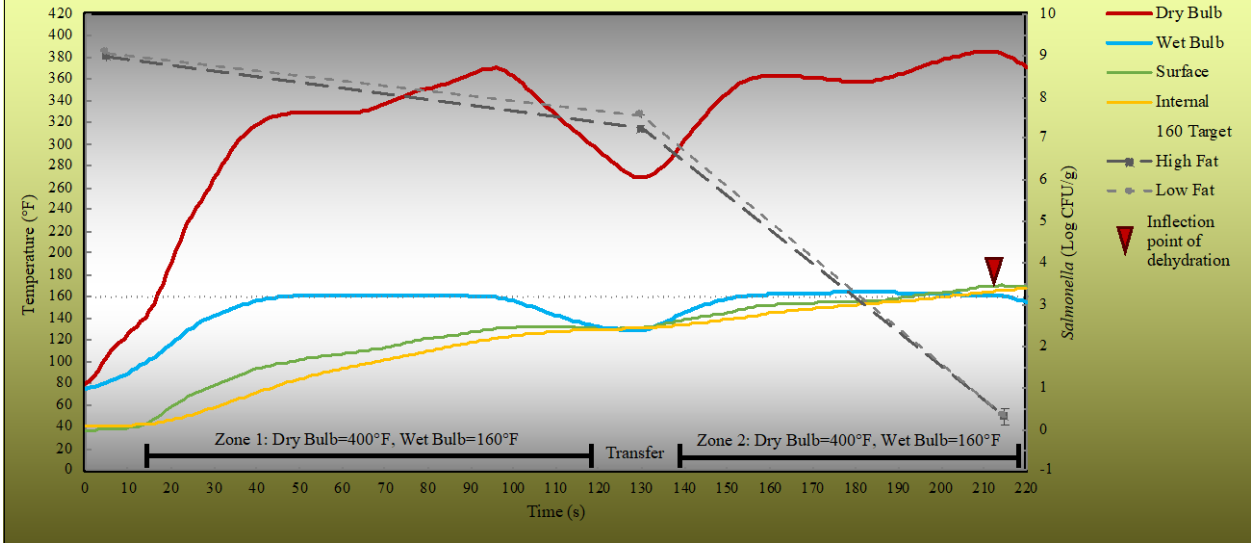

Figure 24. Chicken Patties, Process 3
(First-Zone HSL at 160°F)

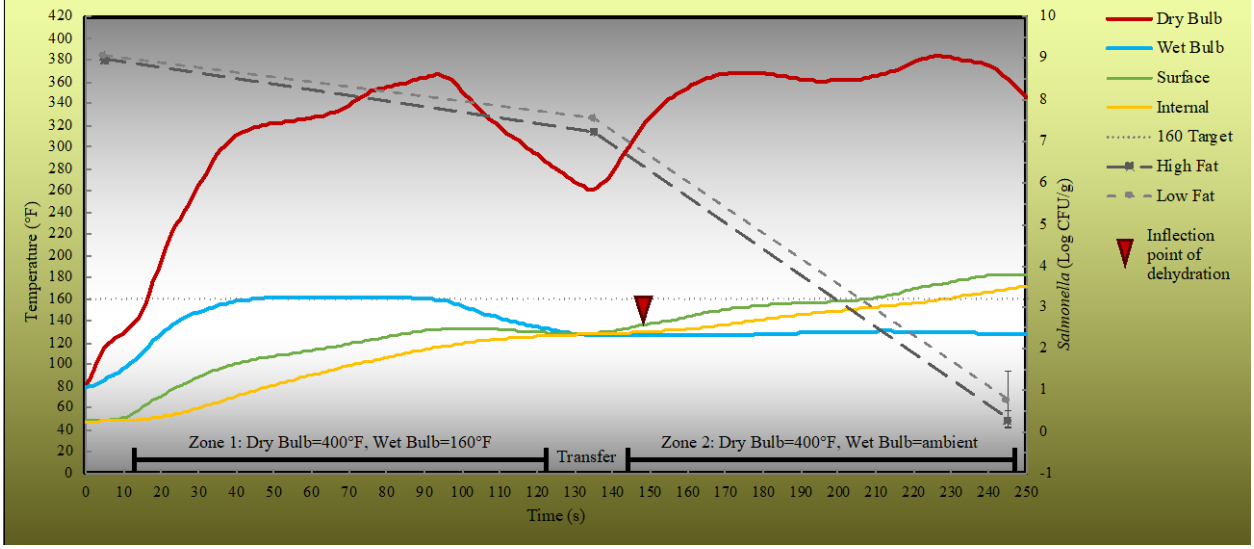

Figure 25. Chicken Patties, Process 4
(Second-Zone HSL at 160°F)

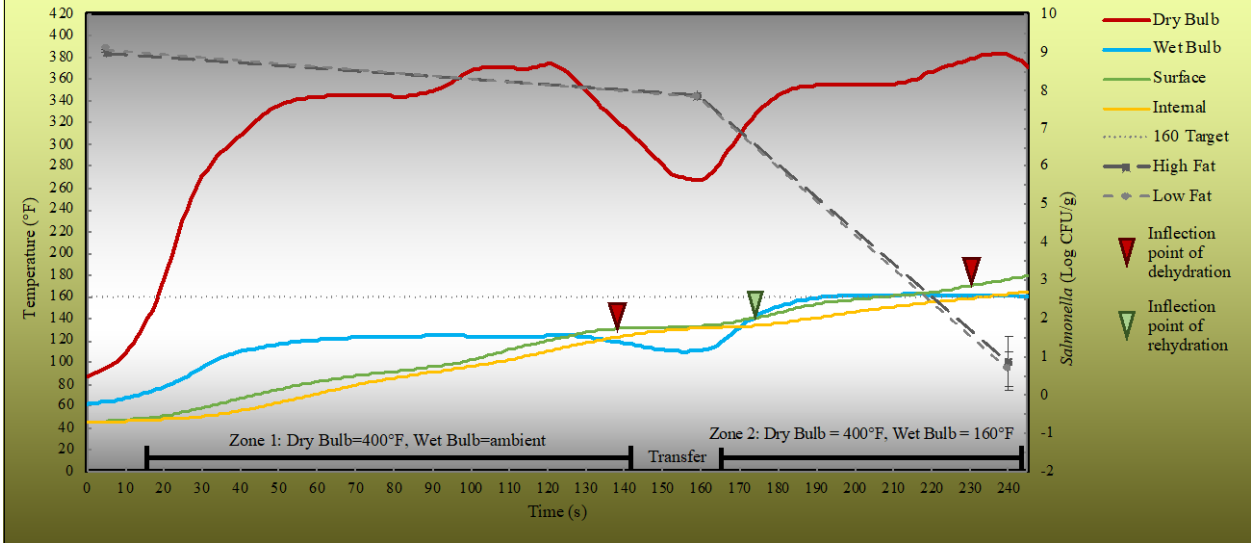

Figure 26. Chicken Patties, Process 5
(Second-Zone HSL at 180°F)

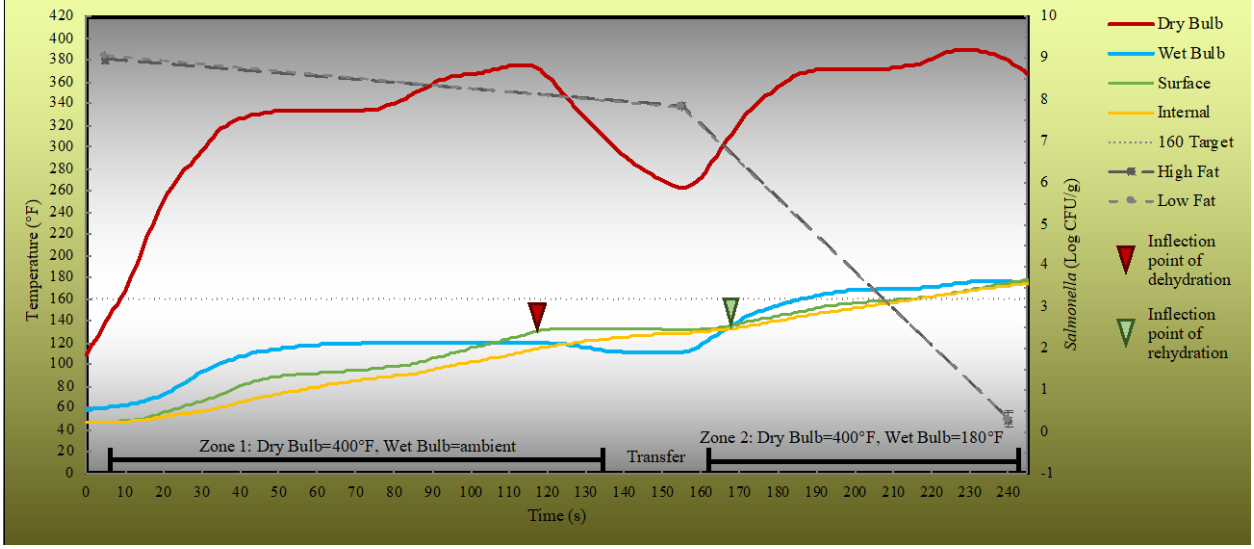

Figure 27. Chicken Patties, Process 6
(First-Zone HSL at 180°F)

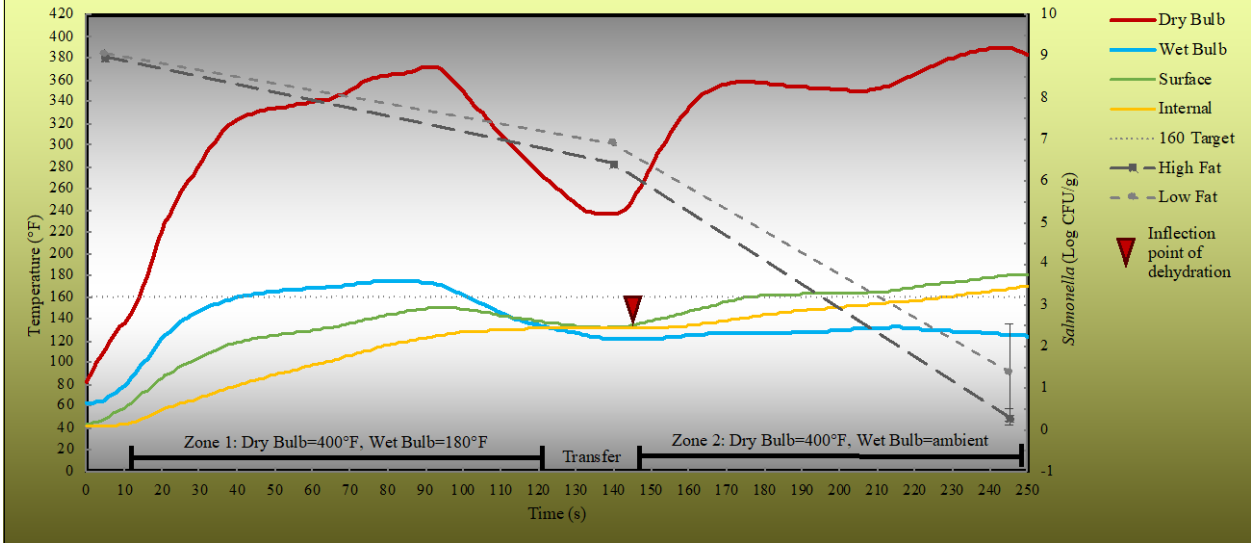

Figure 28. Chicken Patties, Process 7
(Two-Zone HSL at 180°F)

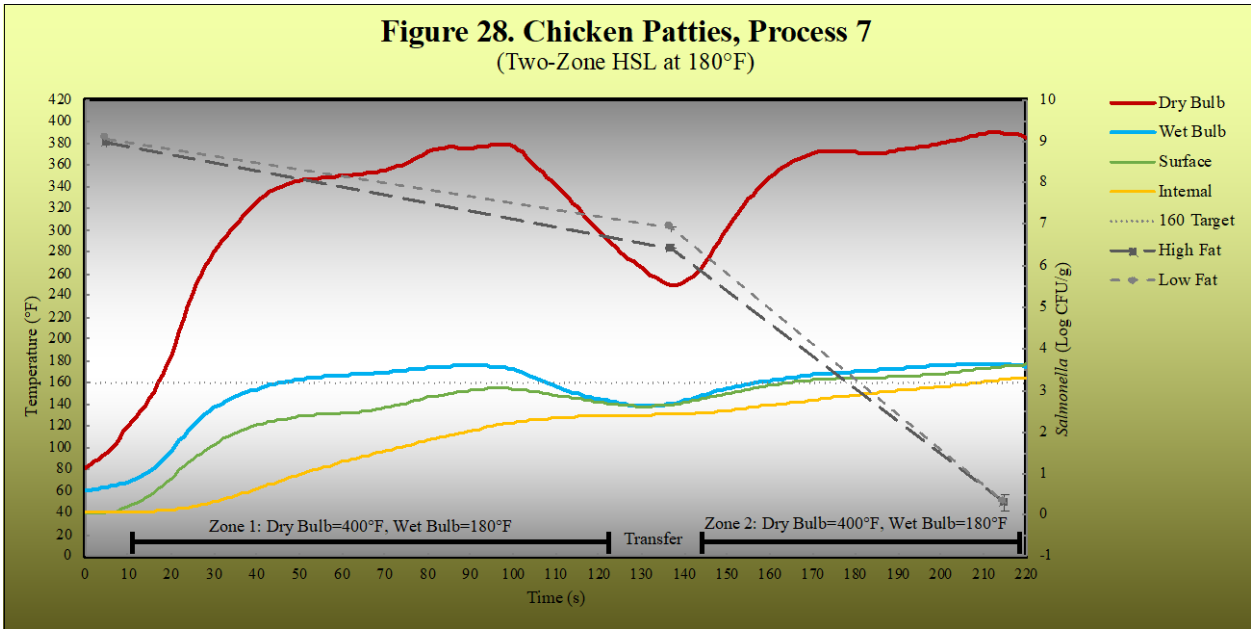

Figure 29. Average least square means standard deviation for each process combining all product end-point means including chicken tenders, beef patties, pork patties, and chicken patties.