Thermal Processing
Outline

1. Classification of Foods based on pH and $a_w$
2. Microbiology
3. Blanching, Pasteurization, ESL (incl. Ultra-Pasteurization), UHT, Hot Fill, Minimal processing
4. Canning Operations
5. Thermal Processing Equipment
6. Kinetics (D & z values)
7. Process Safety (F value) and Product Quality (C value)
8. Process Optimization
9. Shelf Life
10. Time Temperature Integrator (TTI)
1. Classification of Foods Based on pH & $a_w$
Classification of Foods based on pH

- **Low acid**: pH ≥ 4.6; **Acid**: pH < 4.6 (*C. botulinum*)
- **More specific classification**
  - **Low acid**: pH > 5.3
    - Red meat, poultry, seafood, milk, corn, peas, lima beans, potatoes, cauliflower
  - **Medium acid**: 4.5 < pH < 5.3
    - Spaghetti, soups, sauces, asparagus, beets, pumpkin, spinach, green beans, turnip, cabbage
  - **Acid**: 3.7 < pH < 4.5
    - Tomato, pear, fig, pineapple, apricot, yogurt, white cheese, beer
  - **High acid**: pH < 3.7
    - Sauerkraut, pickles, berries, citrus, rhubarb, wine, vinegar, plums, currants, apples, strawberries, peaches
Classification of Foods Based on mc or $a_w$

- **High moisture foods (50+% -- 70-99%)**
  - Fruits, vegetables, juices, raw meat, fish
- **Intermediate moisture foods (15-50%)**
  - Bread, hard cheeses, sausages
- **Low moisture foods (0-15%)**
  - Dehydrated vegetables, grains, milk powder, dry soup mixes

Importance of $a_w$: Honey at 20% mc is shelf stable, while potato at 20% is not
2. Microbiology
Classification of Bacteria

- Based on Oxygen
  - Aerobes (Need oxygen for growth)
    - Microaerophile: Need only small amount of oxygen for growth
  - Anaerobes
    - Obligate: Oxygen prevents growth
    - Facultative: Can tolerate some degree of oxygen
- Based on temperature
  - Psychrophiles (Grow best from 50 - 58 °F; grow slowly at refrigerator temp)
  - Mesophiles (Grow best from 86 - 98 °F -- warehouse temps)
  - Thermophiles (Optimum: 122 - 150 °F; spores can survive 250 °F for 1+ hr)
- Based on salt, acid, water activity (a_w), osmotic pressure
  - Halophiles (Can not grow in absence of salt)
  - Acidophiles (Can grow in high acid conditions – even at pH of 2.0)
  - Xerophiles (Can grow in low a_w conditions)
  - Osmophiles (Can grow in high osmotic pr. conditions – high sugar foods)

Resistance of viruses > spores of bacteria > vegetative cells of bacteria > molds and yeasts
Target organism & surrogate need to be identified for each product-process combination
3. Blanching, Pasteurization, Ultra Pasteurization, Hot Fill, ESL, UHT/Aseptic/Sterilization
Blanching

• Mild heat treatment (~90 °C) for few minutes
• Heating medium
  – Water or steam
• Purposes
  – Inactivate enzymes
  – Reduce microbial load
  – Wilt vegetables for efficient packing into cans
Pasteurization

- Some spoilage organisms may survive
- All vegetative pathogenic organisms inactivated (not spores)
  - Public health significance (earlier target: *Mycobacterium tuberculosis*)
- HTST (Targets veg. state of *Coxiella burnetti* => Q fever)
  - Spoilage organisms that can grow at room temp. are destroyed
  - 15 s at 161 °F (~72 °C)
  - Equivalent batch (Vat): 30 min at 145 °F (~63 °C)
  - If milk product has > 10% fat, is condensed, or is sweetened, increase temperature by 3 °C (or 5 °F)
  - For eggnog, use 155 °F (~69 °C) for 30 mins, 175 °F (~80 °C) for 25 s, or 180 °F (~83 °C) for 15 s
- Shelf life: ~ 3 weeks
- HHST (191 °F for 1.0 s to 212 °F for 0.01 s)

*Coxiella burnetti*: Obligate intracellular bacterium; cat. B bioterrorism agent (*z* = 4.4 °C)

*Other concerns*: Salmonellosis, staphylococcal infection, and streptococcal infection
Extended Shelf Life (ESL)

- Shelf life is between that of pasteurized and UHT product (often minimally processed and refrigerated)
- Advantages: Longer distribution, cheaper than UHT
- If ESL process is to be closer to pasteurization
  - Use filtration/centrifugation to remove spore-formers
  - This may constitute 1-2% of product volume
  - Sterilize this and mix with original product

- Products
  - Lunch meats, cured meats, seafood, salads, fresh pasta, sauces, entrees

- Organisms of concern
  - Mesophiles and psychrotrophs
ESL Categories

• Cook-chill
  – Cooked food is packed hot and blast chilled

• Vacuum packaging
  – Remove air prior to sealing

• *Sous Vide*
  – Raw product is vacuum packed, partially cooked, chilled to below 0 °C
  – Food service/retail market

• Modified atmosphere packaging (MAP)
  – Gas flushed and sealed
  – May use active or passive control later on
Ultra-Pasteurization

• 280 °F (~138 °C) for 2 s
• Vegetative organisms killed; not spores
• Product must be refrigerated
• “Nearly” sterile
  – Filler may not meet aseptic standards
• Shelf life: ~3 months
  – Longer shipping distances
• Products: Cream, specialty dairy products
  – Becoming more popular for milk
Ultra High Temperature (UHT)

- UHT = Aseptic
- All pathogenic and spoilage organisms (including spores) are killed
- Thermophilic organisms may survive
- Commercially sterile product
- 284 °F (140 °C) for 4 s
- Shelf life: 1-2 years
- UHT milk processing covered under
Aseptic Processing

• A continuous thermal process in which the product and container are sterilized separately and brought together in a sterile environment

• Components: Pump, deaerator, heat exchanger, hold tube, cooling unit, back pressure device, packaging unit

• Temperature: 125 - 140 °C (257 – 284 °F)
Aseptic Processing System

- Product Supply Tank
- Deaerator
- Vacuum pump
- Pump
- Heating Section
- Cooling Section
- Holding Section
- Aseptic Surge Tank
- Aseptic Zone
- Sealer
- Container Sterilizer
- BPV: Back pressure valve
- FDV: Flow diversion valve
Combibloc Carton Filler
IP-SA50 Filler
(Cardboard-Plastic Juicebox)
Metal Box ML-1 Particulate Filler
(Preformed Cup Filler)
Bulk Packaging

Carlos Fischer & Premium do Brasil: 7.6 million gallons (676’, 46000 tons, carrying capacity of 36300 tons, 20 knots speed, accommodate 30 people, has fitness center & swimming pool; 3 of 4 compartments for refrigerated/frozen product & 1 for fresh; Nitrogen in headspace); built for Citrosuco; not from concentrate and from concentrate orange & apple juice; Brazil to US, Belgium, Japan, Korea
Hot Fill

• Fill processed product in unsterile container
  – Acid or acidified product (sterilization)
    • Shelf stable product
  – Low acid product (pasteurization)
    • Refrigerated product

• Hot product (~90 °C or 194 °F) sterilizes container

• Invert container for 0.5 to 3 min
  – Sterilize neck area

• Cooling of product
  – Air cool
  – Water spray

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Hot Fill (contd.)

• Package: Glass or plastic with vacuum panels
  – Needs to withstand vacuum during cooling
    • Smooth finish needed for good label application
  – PET or PET/PEN with UV coating
  – Steaming closures for softening closure for tamper-evident band not needed anymore

• Shelf stable product
  – Sodium benzoate or potassium sorbate

• Products: Fruit juices (snapple), jams, jellies, tomato-based sauces, isotonics (gatorade)
Minimal Processing

• Preserve the original wholesome and fresh nature of a food product (flavor, texture, safety, nutritional value) by subjecting it to mild processing conditions

• Traditional minimal processing
  – Cleaning, washing, trimming, coring, slicing, shredding
    • Peeled & sliced potatoes; shredded lettuce & cabbage; washed & trimmed spinach; chilled peach, mango, melon; vegetable snacks such as celery & carrot stick and cauliflower & broccoli florets; packaged mixed salads; cleaned & diced onions; peeled & cored pineapple; fresh sauces; peeled citrus fruits; microwaveable fresh vegetable trays

• Other minimal processing methods
  – Thermal
    • Microwaves, RF, infrared, ohmic sous vide
  – Non-thermal
    • Irradiation, high pressure, pulsed light, PEF, UV, ultrasound, antimicrobial agents, oscillating magnetic field, plasma
Summary of Different Processes

- Pasteurization – HTST (~161 °F for 15 s)
  - Least processing (cooling to ~45 °F)
- Pasteurization – HHST (191 °F for 1.0 s; 212 °F for 0.01 s)
  - Cooling to ~45 °F
- UHT = Aseptic = Commercially sterile (~284 °F for 4 s)
  - Longest shelf life (cooling to ~70 °F)
- ESL (includes ultra-pasteurization -- ~280 °F for 2 s)
  - Anything in between Pasteurization & UHT (cooling to ~45 °F)
- Hot fill (~194 °F for 30 s to 3 min)
  - Maximize benefits of pasteurization & UHT -- mainly for acid/acidified products (cooling to ~70 °F)
4. Canning Operations
Canning Operations

• Receive raw products and packaging material
• Separation of edible portion
• Washing
• Size grading, Inspection
• Blanching, Peeling
• Size reduction
• Cleaning of can & lid
• Filling, pulling vacuum, closing
• Dud detection
• Container coding
5. Thermal Processing Equipment
Thermal Processing Equipment

• Blancher
• Fryer
• Boiling pan and kettle
• Convection oven
• Cooking extruder
• Freezing equipment
• Thawing equipment
• Heating equipment
Types of Heating Equipment

• Direct contact
  – Steam injection, steam infusion

• Indirect contact (Other than plate, tubular, S&T, SSHE)
  – Retorts (Using hot water, steam, or steam-air for heating)
    • Batch (Agitation: None, axial or end-over-end): With or without basket/crate
    • Continuous (With agitation): Conventional, Hydrostatic
  – Plate: Series, parallel, series-parallel
  – Tubular: Double tube, triple tube, multi-tube
  – Shell & tube: Single pass, multiple pass, cross-flow
  – Scraped surface heat exchanger (SSHE)

• Alternative/Novel/Emerging Technologies
  – Microwave and radio frequency heating
    • Uses electromagnetic radiation; polar molecules heat up
  – Ohmic heating
    • Electric current in food causes heating; ions in food, cause heating
6. Kinetics (D & z values)
D & z values

Log scale

No. of microorganisms (N)

Slope = \(-1/D_T\)

Constant Temperature

N_0

Time (seconds)

D value (seconds)

Slope = \(-1/z\)

Temperature (°C)

\[
N = N_0 \times 10^{\frac{-t}{D_T}}
\]

\[
D_T = D_{ref} \times 10^{\frac{T_{ref} - T}{z}}
\]
## D & z values (By Category of Food)

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>$D_T$ (in °F) (min)</th>
<th>z Value (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low acid foods: Thermophiles (spores)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat sour group (B. stearothermophilus)</td>
<td>$D_{250} = 4.0$ to $5.0$</td>
<td>14 to 22</td>
</tr>
<tr>
<td>Gaseous spoilage group (C. thermosaccharolyticum)</td>
<td>$D_{250} = 3.0$ to $4.0$</td>
<td>16 to 22</td>
</tr>
<tr>
<td>Sulfide stinkers (C. nigrificans)</td>
<td>$D_{250} = 2.0$ to $3.0$</td>
<td>16 to 22</td>
</tr>
<tr>
<td><strong>Low acid foods: Mesophiles (spores) -- Putrefactive anaerobes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. botulinum, Type A &amp; B</td>
<td>$D_{250} = 0.1$ to $0.2$</td>
<td>14 to 18</td>
</tr>
<tr>
<td>C. sporogenes group (incl. PA 3679)</td>
<td>$D_{250} = 0.1$ to $1.5$</td>
<td>14 to 18</td>
</tr>
<tr>
<td><strong>Acid Foods: Thermophiles (spores)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Coagulans</td>
<td>$D_{250} = 0.01$ to $0.07$</td>
<td>14 to 18</td>
</tr>
<tr>
<td><strong>Acid Foods: Mesophiles (spores)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Polymyxa &amp; B. macerans</td>
<td>$D_{212} = 0.1$ to $0.5$</td>
<td>12 to 16</td>
</tr>
<tr>
<td>Butyric anaerobes (C. pasteurianum)</td>
<td>$D_{212} = 0.1$ to $0.5$</td>
<td>12 to 16</td>
</tr>
<tr>
<td><strong>High Acid Foods: Mesophiles (non-spore formers)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lactobacillus sp., Leuconostoc sp., yeasts, molds</td>
<td>$D_{150} = 0.5$ to $1.0$</td>
<td>8 to 10</td>
</tr>
</tbody>
</table>
Which Microorganism is More Resistant to Heat?

\[ N = N_0 \cdot 10^{\frac{-t}{D_T}} \]

Log scale

| Slope = -1/D_1 |
| Slope = -1/D_2 |

Constant Temperature

\[ N_0 \]

Time (seconds)

Slope of #1 is greater

\[ \frac{1}{D_1} > \frac{1}{D_2} \]

Thus, \( D_1 < D_2 \)

**Answer:** The microorganism having a D-value of \( D_2 \) is more resistant.
7. Process Safety (F value) & Product Quality (C value)
**F Value**

\[
F = \int_0^t 10^{\frac{T-T_{\text{ref}}}{z}} \, dt = \sum_{i=1}^n 10^{\frac{T_i-T_{\text{ref}}}{z}} \Delta t_i
\]

• For a constant temperature process,

\[
F = 10^{\frac{T-T_{\text{ref}}}{z}} \Delta t
\]

Δt: Process time

• Conservative F value is based on
  – Center temperature of can (for retorting)
  – Center temp. at holding tube exit (for aseptic process)
    • Fastest flowing fluid element or particle

\[F_0 = F \text{ value when } T_{\text{ref}} = 250 \, ^\circ F \text{ & } z = 18 \, ^\circ F \text{ (or } T_{\text{ref}} = 121.1 \, ^\circ C \text{ & } z = 10 \, ^\circ C)\]
# F₀ for Constant Temperature Processes

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>Time (min)</th>
<th>F₀ value (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>232</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>268</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>286</td>
<td>2</td>
<td>200</td>
</tr>
</tbody>
</table>

\[
F₀ = 10^{\frac{T-250}{18}} \Delta t
\]

Concept: When process temperature is increased by an amount equal to the z value, F₀ value increases ten fold.
F Value for a Non-Constant Temp. Process

F value is cumulative and does not decrease as T decreases during cooling.
Microbiological Approach to Calculating F Value

\[ F = D_{\text{ref}} \log \frac{N_0}{N} \]

**Log scale**

- **Constant Temperature**
  - Slope = \(-1/D\)
  - \(N = N_0 10^{\frac{t}{D_T}}\)

**D value (seconds)**

- Slope = \(-1/z\)
  - \(D_T = D_{\text{ref}} 10^{\frac{T-T_{\text{ref}}}{z}}\)

**Log scale**

- \(F = 3 \text{ min}\)
- \(F = 2 \text{ min}\)
Cook Value (C-Value)

\[
F = \int_{0}^{t} 10 \frac{T - T_{\text{ref}}}{z} \, dt
\]

\[
C = \int_{0}^{t} 10 \frac{T - T_{\text{ref}}}{z_c} \, dt
\]

<table>
<thead>
<tr>
<th>Component</th>
<th>z value (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacterial spores</td>
<td>7-12</td>
</tr>
<tr>
<td>Vegetative cells</td>
<td>4-8</td>
</tr>
<tr>
<td>Enzymes</td>
<td>10-50</td>
</tr>
<tr>
<td>Vitamins</td>
<td>25-30</td>
</tr>
<tr>
<td>Proteins</td>
<td>15-37</td>
</tr>
<tr>
<td>Sensory attribute (Overall)</td>
<td>25-47</td>
</tr>
<tr>
<td>Sensory attribute (Texture softening)</td>
<td>25-47</td>
</tr>
<tr>
<td>Sensory attribute (Color)</td>
<td>24-50</td>
</tr>
</tbody>
</table>

Source: Improving the thermal processing of foods (Richardson, 2004)

Note: Generally, for canning & aseptic processing, \( T_{\text{ref}} = 121.1 \, ^{\circ}C \) (or 250 \(^{\circ}F\))

Also, \( z_c \gg z \) in most cases
### D & z values of Enzymes & Quality Attributes

<table>
<thead>
<tr>
<th>Enzyme or Quality Attribute</th>
<th>$D_T$ (in °C) (min)</th>
<th>z Value (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peroxidase from black radish</td>
<td>$D_{80} = 232$</td>
<td>28</td>
</tr>
<tr>
<td>Peroxidase from green beans</td>
<td>$D_{80} = 15$</td>
<td>27</td>
</tr>
<tr>
<td>Polygalacturonase from papaya</td>
<td>$D_{80} = 20$</td>
<td>6.8</td>
</tr>
<tr>
<td>Lipoxygenase from peas</td>
<td>$D_{80} = 0.09$</td>
<td>8.5</td>
</tr>
<tr>
<td>Catalase from spinach</td>
<td>$D_{80} = 0.02$</td>
<td>8.3</td>
</tr>
<tr>
<td>Lipase from <em>Pseudomonas</em> spp.</td>
<td>$D_{120} = 25$</td>
<td>26</td>
</tr>
<tr>
<td>Protease from <em>Pseudomonas</em> spp.</td>
<td>$D_{120} = 300$</td>
<td>28</td>
</tr>
<tr>
<td>Thiamin in carrot puree (pH = 5.9)</td>
<td>$D_{121} = 158$</td>
<td>25</td>
</tr>
<tr>
<td>Thiamin in pea puree (natural pH)</td>
<td>$D_{121} = 247$</td>
<td>27</td>
</tr>
<tr>
<td>Lysine in soybean meal</td>
<td>$D_{121} = 786$</td>
<td>21</td>
</tr>
<tr>
<td>Chlorophyll A in spinach (natural pH)</td>
<td>$D_{121} = 34.1$</td>
<td>45</td>
</tr>
<tr>
<td>Anthocyanin in grape juice (natural pH)</td>
<td>$D_{121} = 17.8$</td>
<td>23.2</td>
</tr>
<tr>
<td>Betanin in beet root juice (pH = 5.0)</td>
<td>$D_{100} = 46.6$</td>
<td>58.9</td>
</tr>
<tr>
<td>Carotenoids in paprika (natural pH)</td>
<td>$D_{60} = 0.04$</td>
<td>18.9</td>
</tr>
</tbody>
</table>
8. Process Optimization
Time-Temperature Optimization

Goal: Achieve required $F_0$ with a minimum $C$ value

Note: Generally, $z_c >> z$
9. Shelf Life
Shelf Life of Foods

• High Quality Life (HQL)
  – Just noticeable change in quality

• Practical Storage Life (PSL)
  – Time after which food is unacceptable

• Factors affecting shelf life
  – Formulation
  – Processing
  – Packaging
  – Storage

• Forms of deterioration during storage
  – Microbial, enzymatic, chemical, nutritional, physical
Accelerated Shelf Life Testing (ASLT)

- Select at least 3 elevated temperatures 5+ °C apart
- Determine shelf life at these temperatures
- Plot shelf life (log scale) on y-axis and temperature (on x-axis)
- Extrapolate graph to determine shelf life at desired temperature

Other: Cycling temperature between 0 °C and room temp; controlled shaking
10. Time Temperature Integrator (TTI)
TTI

- A biological/chemical/physical indicator that undergoes a precise, measurable, and irreversible change in some attribute that depends on the time-temperature combination it experienced

- Classification of TTIs
  - Biological, chemical, physical
  - Single or multiple response
  - Intrinsic or extrinsic
  - Dispersed, permeable or isolated
  - Volume averaged or single point
Applications of TTIs

• $\alpha$-amylase from *B. amyloliquifaciens*
  – Reduction in activity of enzyme is quantified by measuring absorbance using a spectrophotometer

• Commercially available TTIs
  – Cox Technologies: Vitsab
  – 3M: MonitorMark
  – FreshCheck

• Uses
  – Monitoring prod. temp. during transportation and storage
  – Process validation (assurance of time-temp. delivered)
Applications to Think About

- Bottled water, carbonated soft drinks, wine/beer, canned soup, salsa, and juices in a juice box (such as Hi-C) are shelf stable. What is the difference in how they are made shelf stable?

- Can \textit{C. botulinum} be of concern
  - If the can seaming process resulted in a faulty seam in an acid product that could contain acid-loving microbes?

- What should be done to a product if during canning, steam pressure is lost and temperature drops for a short duration?
  - Deliver remaining heat treatment? Re-process? Discard?
Shelf Stable Products

pH
Water

Aquafina/Dasani: ~5.5
Spring: ~6.8 to 8.0 (Alkalife Ten: 10)
Propel zero: 3.5

Soda: 2.5 to 4.2
Gatorade/Powerade: 2.7 to 3.0
Infant formula: 5.0 to 6.0
Soup (Most): 5.5 to 7.0

RO, UV, O₃, filtration

pH + CO₂
Hot fill
Retorting
Retorting/Aseptic