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 aw

- 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 aw: Honey at 20% mc is shelf stable, while potato at 20% mc 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)
Metal Box ML-1 Particulate Filler
(Preformed Cup Filler)

Scholle Bag-in-Drum Filler for Low-Acid Foods

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

**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
  - Steam closing 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

- 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 w/o 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

\[
\text{Constant Temperature}
\]

No. of microorganisms (N)

\[
\text{Slope} = \frac{-1}{DT}
\]

N0

\[
\text{Slope} = \frac{-1}{z}
\]

N = N0 \times 10^{\frac{-t}{D_t}}

D_t = D_{ref} \times 10^{\frac{t_{ref}}{z}}

D & z values (By Category of Food)

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>D_{250}, (min)</th>
<th>z Value (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low acid foods: Thermophiles (spores)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat sour group (D. 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. vulgaris)</td>
<td>D_{250} = 2.0 to 3.0</td>
<td>16 to 22</td>
</tr>
<tr>
<td>Low acid foods: Mesophiles (spores) - Putrefactive anaerobes</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>Acid Foods: Thermophiles (spores)</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>Acid Foods: Mesophiles (spores)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Polymyxa &amp; B. maceane</td>
<td>D_{250} = 0.1 to 0.5</td>
<td>12 to 16</td>
</tr>
<tr>
<td>Butyric anaerobes (C. proteocellulans)</td>
<td>D_{250} = 0.1 to 0.5</td>
<td>12 to 16</td>
</tr>
<tr>
<td>High Acid Foods: Mesophiles (non-spore formers)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lactobacillus sp., Leuconostoc sp., yeasts, molds</td>
<td>D_{250} = 0.5 to 1.0</td>
<td>8 to 10</td>
</tr>
</tbody>
</table>
Which Microorganism is More Resistant to Heat?

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

Log scale

- No. of microorganisms (N)
- Constant Temperature
- Slope = -1/D_1
- Slope = -1/D_2
- Time (seconds)

Slope of #1 is greater
1/D_1 > 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

\[ F = \int_0^\frac{T-\text{ref}}{z} \frac{10^{\frac{T-\text{ref}}{z}} - 1}{\Delta t} \]  

- For a constant temperature process,
  \[ F = 10^{\frac{T-\text{ref}}{z}} \frac{\Delta t}{\Delta t} \]  
  \( \Delta t: \) 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 value when \( T_{\text{ref}} = 250 \, ^\circ F \) & \( z = 18 \, ^\circ F \) (or \( T_{\text{ref}} = 121.1 \, ^\circ C \) & \( z = 10 \, ^\circ C \))
**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**

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

\[
N = N_0 10^{\frac{T}{D}}
\]

\[
D = D_{ref} 10^{\frac{T}{D}}
\]
Note: Generally, for canning & aseptic processing, $T_{ref} = 121.1 ^\circ C$ (or 250 °F).

Also, $z_c \gg z$ in most cases.

## Cook Value (C-Value)

$$F = \int_0^1 \frac{1}{10} e^{-\frac{T-T_{ref}}{z}} \, dt$$

$$C = \int_0^1 \frac{T-T_{ref}}{10} e^{-\frac{T-T_{ref}}{z}} \, dt$$

### Component $z$ value (°C)

<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>10-30</td>
</tr>
<tr>
<td>Vitamins</td>
<td>25-30</td>
</tr>
<tr>
<td>Proteins</td>
<td>15-17</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>

### D & z values of Enzymes & Quality Attributes

<table>
<thead>
<tr>
<th>Enzyme or Quality Attribute</th>
<th>$D_{10, \alpha}$ (min)</th>
<th>$z$ Value (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peroxidase from black radish</td>
<td>$D_{10} = 232$</td>
<td>28</td>
</tr>
<tr>
<td>Peroxidase from green beans</td>
<td>$D_{10} = 15$</td>
<td>27</td>
</tr>
<tr>
<td>Polygalacturonase from papaya</td>
<td>$D_{10} = 20$</td>
<td>6.8</td>
</tr>
<tr>
<td>Lipoygenase from peas</td>
<td>$D_{10} = 0.09$</td>
<td>8.5</td>
</tr>
<tr>
<td>Catalase from spinach</td>
<td>$D_{10} = 0.82$</td>
<td>8.3</td>
</tr>
<tr>
<td>Lipase from <em>Pseudomonas</em> spp.</td>
<td>$D_{10} = 25$</td>
<td>26</td>
</tr>
<tr>
<td>Protease from <em>Pseudomonas</em> spp.</td>
<td>$D_{10} = 300$</td>
<td>28</td>
</tr>
<tr>
<td>Thiamin in carrot puree (pH = 5.9)</td>
<td>$D_{10} = 158$</td>
<td>25</td>
</tr>
<tr>
<td>Thiamin in pea puree (natural pH)</td>
<td>$D_{10} = 247$</td>
<td>27</td>
</tr>
<tr>
<td>Lysine in soybean meal</td>
<td>$D_{10} = 786$</td>
<td>21</td>
</tr>
<tr>
<td>Chlorophyll A in spinach (natural pH)</td>
<td>$D_{10} = 34.1$</td>
<td>45</td>
</tr>
<tr>
<td>Anthocyanin in grape juice (natural pH)</td>
<td>$D_{10} = 17.8$</td>
<td>23.2</td>
</tr>
<tr>
<td>Betanin in beet root juice (pH = 5.0)</td>
<td>$D_{10} = 46.6$</td>
<td>58.9</td>
</tr>
<tr>
<td>Carotenoids in paprika (natural pH)</td>
<td>$D_{10} = 0.04$</td>
<td>18.5</td>
</tr>
</tbody>
</table>

### 8. Process Optimization
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

[Graph showing shelf life vs. temperature]

*Other: Cycling temperature between 0 °C and room temp; controlled shaking*

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**10. Time Temperature Integrator (TTI)**

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**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-temperature 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 *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

- 
<table>
<thead>
<tr>
<th>Product</th>
<th>pH</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquafina/Dasani</td>
<td>5.5</td>
<td>RO, UV, O3, filtration</td>
</tr>
<tr>
<td>Spring</td>
<td>6.8-8.0</td>
<td>(Alkalife Ten. 10)</td>
</tr>
<tr>
<td>Propel zero</td>
<td>3.5</td>
<td>Hot fill</td>
</tr>
<tr>
<td>Gatorade/Powerade</td>
<td>2.7-3.0</td>
<td>pH = CO2</td>
</tr>
<tr>
<td>Infant Formula</td>
<td>5.0-6.0</td>
<td>Hot fill</td>
</tr>
<tr>
<td>Soup (Most)</td>
<td>5.5-7.0</td>
<td>Retorting/Aspetic</td>
</tr>
</tbody>
</table>