Part I. Why We Need to Store Perishables

- Historically for winter storage
- Year-round demand for fresh fruits and vegetables
- Spread production peaks
  - Maximize profits
  - Reduce waste
- Long distance transportation is a kind of storage

Part II. Techniques for Storage

1. On the plant storage
2. Field Storage
3. Common Unrefrigerated Storage
4. Refrigerated Storage
5. Modified and Controlled Atmosphere Storage
1. On the Plant Storage
   - Possible for crops with long harvest windows, e.g., citrus, underground storage organs
   - Overcomes need for capital investment in storage buildings
   - Reduces storage problems, i.e., water loss, storage rots, etc.
   - Problems with idle land and natural disasters

2. Field Storage (clamps)
   - Piles of commodity covered with straw and soil (insulate and waterproof)
   - Traditional storage method
     - Need ventilation
     - Used for potatoes, etc.

3. Common Unrefrigerated Storage
   - One step up from field clamps
   - Insulated, often partly underground buildings
   - Takes advantage of cool (nonfreezing) average temperatures
   - Used for cabbage, potatoes and apples
     - Night air storage: Store opened at night to take advantage of cool night air. Well insulated with a ventilation system
Common Storage with Ventilation

Source: S.K. Lee, Seoul National University, Korea

4. Refrigerated Storage

- By far the most important worldwide
- Refrigeration plant (how the air is cooled)
  - Ice or cold water
  - Evaporative cooling (can cool to 1-2°C above the wet bulb temperature)
  - Mechanical refrigeration

Being promoted recently as the “ZECC” (Zero Energy Cool Chamber)
4. Refrigerated Storage: Mechanical refrigeration

- Materials can exist as liquid or gas at the same temperature depending on the pressure (see phase diagram)

- Energy required for conversion from liquid to gas produces cooling
- Work is done to compress the refrigerant gas; heat is released

- A continuous loop with a high pressure side and a low pressure side separated by a compressor and expansion valve (see schematic)
- Evaporator coils (low pressure side) cool air as vaporized refrigerant boils
- Compressed refrigerant (high pressure side) is cooled by air or water in a condenser
4. Refrigerated Storage: Mechanical refrigeration

- Refrigerants are chosen based on:
  - Ozone and environment friendly
  - Low boiling point
  - High heat of vaporization
  - Vaporization pressure lower than atmospheric pressure
- Main Refrigerants:
  - Ammonia (R-707): most common for large refrigeration systems
  - Freon (CFC) – concern over ozone depletion
  - Replacements for CFC-12, R-902, and HCFC-22

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4. Refrigerated Storage: Mechanical refrigeration

Respiration – Heat Generation

- Maximum Heat Generation (W/kg):

<table>
<thead>
<tr>
<th></th>
<th>0°C</th>
<th>5°C</th>
<th>10°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apples</td>
<td>0.010</td>
<td>0.019</td>
<td>0.030</td>
</tr>
<tr>
<td>Raspberries</td>
<td>0.053</td>
<td>0.094</td>
<td>0.177</td>
</tr>
<tr>
<td>Cabbage</td>
<td>0.009</td>
<td>0.021</td>
<td>0.024</td>
</tr>
<tr>
<td>Peas</td>
<td>0.317</td>
<td>0.290</td>
<td>0.490</td>
</tr>
<tr>
<td>Potatoes</td>
<td>0.059</td>
<td>0.045</td>
<td>0.060</td>
</tr>
</tbody>
</table>

4. Refrigerated Storage: Mechanical refrigeration

- Transpiration – Moisture Loss

\[ \frac{1}{k_{\text{m}}} = \frac{1}{k_{\text{a}}} + \frac{1}{k_{\text{s}}} \]

- \( M \) = Rate of moisture loss
- \( k_{\text{m}} \) = Overall mass transfer coefficient
- \( k_{\text{s}} \) = Skin mass transfer coefficient
- \( k_{\text{a}} \) = Air mass transfer coefficient
- \( A \) = Surface area of product
- \( P \) = Water pressure at surface of the product
- \( P_{\infty} \) = Ambient water pressure

\[ \bar{y} = \bar{z} + \frac{1}{2} \bar{y} \left( \frac{P - P_{\infty}}{\bar{z}} \right) \]

\( \bar{y} = 1 + \frac{1}{\bar{y}} \) (1)

\( \bar{y} = 1 + 1 \) (2)


### Transpiration Coefficient (mg/kg-s-MPa)

<table>
<thead>
<tr>
<th>Product</th>
<th>Transpiration Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>87 - 94</td>
</tr>
<tr>
<td>Brussels sprouts</td>
<td>3550 - 9770</td>
</tr>
<tr>
<td>Cabbage</td>
<td>16 - 60</td>
</tr>
<tr>
<td>Orange</td>
<td>25 - 32</td>
</tr>
<tr>
<td>Potatoes</td>
<td>10 - 15</td>
</tr>
</tbody>
</table>

Part III. Storage design

- Temperature uniformity
  - Refrigeration system capacity - adequate to maintain temperature under peak load conditions
  - ±2°C (±2°F) is desirable
  - Large coil size reduces temperature fluctuation
  - Fans able to circulate 7.5 air changes per hour (15-25 meters/min)
  - Adequate stacking for air circulation
Storage design

- Humidity management
  - 90-95% RH is desirable
  - Large coil size reduces water condensation (i.e., air does not have to be cooled below the dew point)
  - 5-10°C ST maintains 70-80% RH
  - >5°C AT maintains 95% RH
  - In practice, supplementary humidification is used (fog, steam, spinning disk)
  - Dehumidification of air, e.g., onions

- Building design considerations
  - Location
  - Power and water supply, zoning
  - Provision of proper facilities for handling the product (forklift movement, pallets, racks)
  - External vapor barrier in floor, walls and roof
  - Adequate insulation: R20 to R60 (required R-value determined by exposure)

Part IV. Modified and Controlled Atmosphere Storage

- Modified atmosphere (MA) = commodity-generated atmosphere maintained by restricted diffusion
  - Storage rooms, transport vehicles, and packages ("MAP")
- Controlled atmosphere (CA) = feedback control and active adjustment of atmosphere
  - Storage rooms and transport vehicles

\[ \text{Sugars} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{Chemical Energy} + \text{Heat} \]
Relationship Between \( \text{O}_2 \) and \( \text{CO}_2 \) Concentrations and Respiratory Metabolism

Source: A.A. Kader, UC Davis

Reduced \( \text{O}_2 \) Effect on Pears

Modified Atmosphere Effect on Bananas

Air Control  Modified Atmosphere

2 weeks at 15°C
**Controlled Atmosphere Effect on Raspberries**

Air Control  Controlled Atmosphere

21 days at 2°C plus 3 days in air at 7°C

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**Response of Green Beans to Reduced O₂ and Elevated CO₂**

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**Modified and Controlled Atmosphere Storage**

- Diffusion gradients for respiratory gases depend on:
  - Surface-to-volume ratio
  - Resistance to diffusion (cuticle structure, stomata, lenticels)
  - Metabolic rate (i.e., rate of O₂ consumption and CO₂ production)

➤ This is an important reason why different commodities have different CA optima
Relationship Between Biological Gas Concentrations Within a Fruit and Diffusion Through the Various Barriers

H₂O (Variable)
N₂ (%a/a)
O₂ (20.8%)
CO₂ (0.03%)
C₂H₄ (Trace)

BARRIER 1: Commodity
BARRIER 2: Packaging
BARRIER 3: Storage / Transit vehicle

Gradient of CO₂ Concentration Within a Head of Iceberg Lettuce

Potato Low O₂ Injury (“Blackheart”)
Modified and Controlled Atmosphere Storage

- CA & MA effects on commodities
  - Beneficial (optimum atmospheres)
    - Retards senescence (slows respiration, softening, compositional changes, etc.)
    - Inhibits ethylene biosynthesis
    - Reduces sensitivity to ethylene action
    - Alleviates some physiological disorders
    - Slows decay development (especially CO₂)
Modified and Controlled Atmosphere Storage

- CA & MA effects on commodities
  - Detrimental (incorrect atmospheres)
    - Aggravates some physiological disorders
    - Causes irregular ripening
    - Results in off-flavor and off-odor (related to anaerobic fermentation)
    - Increases susceptibility to decay
    - Stimulates sprouting and inhibits periderm formation in underground storage organs

Modified and Controlled Atmosphere Storage

- Supplemental treatments
  - Prestorage high CO$_2$ to inhibit ripening and chilling injury
  - Ethylene removal (“scrubbing”) to enhance CA effects
  - Use of carbon monoxide to inhibit discoloration and microbial growth
    - Very limited use in transport MA/CA of lettuce

Modified and Controlled Atmosphere Storage

- Commercial CA storage
  - O$_2$ levels controlled by flame burners, catalytic burners or converters, membranes, or flushing with N$_2$
  - CO$_2$ added from pressurized gas cylinders
  - CO$_2$ removed by sodium hydroxide, water, activated charcoal, molecular sieve or Ca(OH)$_2$ (hydrated lime) scrubbers
Modified and Controlled Atmosphere Storage

- Commercial CA storage
  - Remote gas measurements support feedback control of O<sub>2</sub> and CO<sub>2</sub> levels
  - Gas-tight rooms inhibit leakage, but require breather bags to compensate for pressure changes
Modified and Controlled Atmosphere Storage

- Commercial CA storage
  - Ethylene removed by potassium permanganate, activated/brominated charcoal, and catalytic or ozone scrubbers
  - Low pressure (hypobaric) systems reduce O₂ partial pressure and accelerate gas diffusion
    - Beneficial for ethylene; detrimental for water vapor

Modified and Controlled Atmosphere Storage

- Transport MA/CA storage
  - MA in shipping cartons or pallets
    - e.g., Banavac and Tectrol, respectively
  - MA or CA in trailers and containers (i.e., truck and marine transport)
    - Membrane systems, N₂ flushing
    - CO₂ addition from cylinders; scrubbing with lime

Banavac Carton MAP System
Modified Atmosphere Packaging

- Film permeability, film area, produce mass, and produce respiration rate interact to create a modified atmosphere
  - reduced O₂ levels (2-10%)
  - elevated CO₂ levels (1-15%)

\[
\text{CO}_2^\text{ext} = \frac{w}{A} \times \text{film permeability} \times \text{mass} \times \text{respiration rate}
\]

- Atmosphere may be actively or passively established
**Modified Atmosphere Packaging**

- Semipermeable Film
- Microperforated Film
- Carton Liner

**Fresh-cut Products**

- Semipermeable Film (MAP) Packages