Extending the Shelf-life of Fresh-cut Produce
(Including the Many Advantages of AFFINITY™ Polyolefin Plastomers)

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Packaging fresh-cut produce in a modified atmosphere or controlled atmosphere environment offers the opportunity for several important benefits:

- Longer shelf-life
- Improved quality
- Convenience to the consumer

Modified atmosphere packaging (MAP) systems can be used to dramatically extend the shelf-life of fresh-cut produce. Many bulk produce items that have historically been shipped and sold unpackaged or minimally packaged can benefit from proper containment in a modified atmosphere package.

Different levels of packaging are illustrated in the following examples:

- Bulk carrots sold in bunches directly from a shipping crate are considered to be “unpackaged,” although it is recognized that they must be contained in some type of box or crate for shipment.
- Lettuce that is loosely wrapped in a protective cover would be considered to be to be minimally packaged because, although some degree of protection is provided by the wrap, the package can breathe freely and the lettuce can be contaminated fairly easily.
- A mixture of cleaned and ready-to-eat iceberg lettuce, carrots, and cabbage in a sealed bag is an example of fresh-cut produce contained in a modified atmosphere package.

Modified atmosphere packaging offers an opportunity to extend the life of fresh-cut produce by reducing the respiration rate and associated aging of the produce. After produce is picked, it continues to live and breathe, or respire. During this time, the produce consumes oxygen and gives off carbon dioxide. This is the opposite of photosynthesis, during which plants consume carbon dioxide and give off oxygen. One reaction that occurs during the respiration process is the conversion of glucose and oxygen to water and carbon dioxide.

Reducing the rate of the aging process is generally achieved by reducing the concentration of oxygen and increasing the concentration of carbon dioxide in the package. When the fresh-cut produce is exposed to an environment in which the oxygen concentration has been reduced, the respiration and aging of the produce is also reduced. This extends usable shelf-life and improves the quality of the produce.

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Utmost care must be taken to keep the oxygen concentration in the package high enough that some aerobic respiration can occur. If there is no oxygen present, anaerobic respiration and rapid spoilage will occur. For this reason, high barrier packages, which prevent most transmission of oxygen and other gases, are generally not suitable for long-term packaging of living fresh-cut produce. Packages designed with selective barrier properties that effectively control oxygen transmission rates and the resulting oxygen concentration inside the package are the essence of modified atmosphere packaging used for fresh-cut produce.

Increased carbon dioxide concentration may also reduce the respiration rate of the produce. For some foods, carbon dioxide also inhibits the growth of certain microorganisms and is helpful in the extension of shelf-life. Carbon dioxide acts as a fungicide for strawberries, for example. Some types of produce, however, are sensitive to high concentrations of carbon dioxide.

In the example presented in Equation 1 (below), one mole of carbon dioxide is generated for each mole of oxygen consumed. The ratio of CO₂ produced to O₂ consumed is called the respiratory quotient (RQ). For this example, the RQ is 1.0. For other aging reactions, the RQ may be less than one or greater than one. Each type of produce undergoes different types of reactions, and it is important to understand the RQ for the type of produce being packaged. The RQ is assumed to be 1.0 for the sample calculations in this paper. This is a reasonable assumption for many types of produce when stored under typical refrigerated conditions.

\[ C_6H_{12}O_6 + 6 O_2 \rightarrow 6 H_2O + 6 CO_2 + 686 \text{ kcal} \]

In addition to oxygen and carbon dioxide concentration, there are many other factors that determine the rate at which the produce respires. One of the most important of these factors is temperature. When produce is stored at room temperature, it ages rapidly. When refrigerated, it respires much more slowly and, therefore, lasts longer. For this reason, many types of produce are stored at or below 40°F (4.4°C). Care must be taken not to expose the produce to temperatures that are below its tolerance limit, however, because most produce will undergo irreversible damage at very low temperatures. The temperature at which this occurs varies with each type of produce. Other factors that determine produce respiration rates include the age and condition of the produce, water content, and ethylene concentration in its environment.
In addition to the benefits provided by the reduction in respiration, modified atmosphere packaging also offers an opportunity for increased protection from contamination. When the produce is cleaned and packaged immediately after harvesting, its handling and the associated risk of contamination from bacteria are reduced. Although the possibility for contamination can never be completely eliminated, packaging produce in a hermetically sealed bag greatly reduces the opportunity for contamination during storage.

Fresh-cut produce packaging provides an additional benefit to the consumer, one of convenience. There is a persistent consumer trend towards more prepared and convenience foods; fresh-cut produce provides excellent convenience because it is ready to eat. Produce is also a healthy alternative to many convenience snack foods.

There are many variables to be considered when designing a modified atmosphere or controlled atmosphere package. Some highlights of the many important considerations in the process of designing a package for fresh-cut produce are suggested in the steps listed here, but are not intended to exclude other design steps or criteria.

**Step 1: Understand Basic Requirements**
- Avoid anaerobic respiration and spoilage – Keep the produce fit for human consumption
- Minimize aging by inhibiting aerobic respiration
- Prevent contamination of the produce

**Step 2: Understand the Produce**
- Type of produce – For example, lettuce, carrots, salad mixture
- Reactions anticipated – e.g., Conversion of glucose to water and CO₂
- Respiratory rate – At the conditions anticipated
- Respiratory quotient – Determined from reactions or assumed to be 1.0
- Anticipated variability in respiration
- Limitations – For example, does high CO₂ cause problems?

**Step 3: Understand the Package**
- Storage conditions – Temperature and time, worst case scenario
- Weight of produce per package
- Package dimensions – Volume and surface area
- Package requirements – In addition to transmission rates
Step 4: Determine the Optimum Atmosphere in the Package
- Optimum O₂ concentration at steady state — Selected to inhibit but not completely eliminate aerobic respiration
- Optimum CO₂ at steady state
- Optimum relative humidity

Step 5: Select a Film Structure that Meets All Requirements
- Oxygen Transmission Rate = O₂ Consumption Rate at Desired Steady State
- Carbon Dioxide Transmission Rate = CO₂ Production Rate at Steady State
- Heat Seal Initiation Temperature and Strength
- Hot Tack Initiation Temperature and Strength
- Optical Properties
- Printability
- Machinability
- Toughness
- Resistance to Pinholes

Specific issues to consider when designing the proper film structure include:
- Resin Selection – Polyolefin plastomer (POP), ultra low density polyethylene (ULDPE), linear low density polyethylene (LLDPE), low density polyethylene (LDPE), polypropylene (PP), styrene-butadiene copolymers, ethylene vinyl acetate (EVA), etc.
- Film Construction – Monolayer, co-extruded, or laminated
- Film Thickness – Total thickness and layer ratios
- Additives – Slip, antiblock, antifog
- Processing Conditions – Extrusion temperature, post treatments

Step 6: Check that All Minimum Requirements Are Met
- Can the selected thickness film be easily fabricated and formed into bags on high speed vertical form, fill, and seal equipment?
- Can the selected film be easily manufactured?
- Will the CO₂ concentration in the package ever exceed the maximum acceptable CO₂ concentration?
- Does the package meet U.S. Food and Drug Administration (FDA) requirements for materials and labelling?
- Will the package meet requirements of the grocer?

Step 7: Validation
- Package produce
- Check shelf-life
- Measure oxygen and carbon dioxide concentrations at different times
Step 8: Document and Adjust Package Design Procedures

- Fully document design procedures
- Adjust design parameters to obtain packages that work

Why designs might fail (assumes manufacturing was okay):
- Produce respiration rate data was not accurate
- Mixtures of different types of produce did not follow simple mixture rules
- If packages are stacked, they may not have 100% of their surface area available for transmission of oxygen and carbon dioxide
- The effect of surface printing may not have been considered when estimating film transmission rates
- Film transmission data was inaccurate or used the wrong temperature or units

Material Selection – Benefits of AFFINITY™ Polyolefin Plastomers

Polyolefin plastomers (POPs) have found widespread use in fresh-cut produce packaging and other high performance applications. Because they offer a unique combination of high oxygen transmission, relatively low water vapor transmission, excellent seal performance, excellent optics, and low contribution to off-taste and off-odor, they are a product of choice for use in fresh-cut produce packaging. There are different types of polyolefin plastomers. Some plastomers are “linear” molecules and contain branches that result only from the incorporation of a comonomer such as butene, hexene, or octene. Another type of polyolefin plastomer contains long chain branching as well as short chain branching. AFFINITY™ Polyolefin Plastomers, manufactured by The Dow Chemical Company using its proprietary INSITE™ Technology, are specially designed to contain a specific amount of long chain branching. The incorporation of low levels of long chain branching improves the processability of these polymers compared to competitive plastomers. This is an important benefit of AFFINITY Polyolefin Plastomers, because it allows easier extrusion and provides greater flexibility in the conditions used to manufacture film.

ATTANE™ Ultra Low Density Polyethylene (ULDPE) Resins are also well suited for use in fresh-cut produce packaging, especially in packaging food for institutional and food-service use where optics are not as critical as in the retail segment. ULDPE resins provide good sealability and high oxygen transmission rates. ATTANE ULDPE Resins are preferred over competitive very low density polyethylene (VLDPE) resins because they provide better optics and better seal performance.

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Oxygen transmission rates (OTRs) for two AFFINITY™ POPs and two ATTANE™ ULDPE Resins are compared to two typical EVA resins in Figure 1 (above). As indicated, the POP and ULDPE resins provide excellent oxygen transmission, up to about 1500 cc(at STP)•mil/100 in²•day•atm at 25°C (77°F). OTR values are reported in cubic centimeters at standard temperature and pressure (STP = 0°C and 1 atmosphere) rather than the reported temperature (25°C). Some previous Dow reports provided OTR values based on the actual test conditions, so proper care should be taken to determine that the correct units, as well as test conditions, are reported along with values. Note that OTR values obtained from measurements made using instruments such as MOCON’s Ox-Tran are generally reported in cc(at STP)•mil/100 in²•day•atm, even though the measurements are normally not made at standard temperature and pressure and the notation “at STP” is frequently not included.

Figure 2 (see page 8) shows the dependence of oxygen transmission rate on temperature. The relationship is approximately logarithmic. Oxygen transmission actually follows an Arrhenius relationship and, therefore, the logarithm of oxygen transmission rate is proportional to the inverse of temperature (1/T) where temperature is expressed in °K. Due to the strong dependence of oxygen transmission rate on temperature, great care should be taken during testing to assure accurate temperature control. Temperature should always be measured in the test cell to determine the actual temperature of the test. Care should also be used when comparing data from different data sets. “Room temperature” oxygen transmission rate is reported at several different temperatures, including 25°C (77°F), 23.8°C (75°F), and occasionally 22.2°C (72°F). A temperature of 73°F (22.8 °C) is also commonly used. To convert from 25°C to 73°F, simply multiply the OTR by 0.894.
For high transmitters such as AFFINITY™ PF 1140G POP (the 0.896 g/cc density POP), the difference can be fairly large. For example, the oxygen transmission for this material is about 6 percent lower at 23.8°C than at 25°C, a significant difference of about 90 units. Since some produce cannot be stored at room temperature, any of these numbers are equally useful, but it is essential to understand the test conditions used to obtain the numbers.

Many other factors also affect oxygen transmission rate. These include fabrication conditions and additive levels. For example, a faster quench rate will result in a lower crystallinity film with a higher oxygen transmission rate. A film that contains a significant amount of antiblock additive may have a noticeably lower oxygen transmission rate than a film that contains no antiblock. This effect is most noticeable in materials with the highest oxygen transmission rates.
Figure 3 shows the dependence of carbon dioxide transmission rate on temperature. Like oxygen transmission, carbon dioxide transmission also exhibits a nearly logarithmic dependence on temperature. Figure 4 shows the water vapor transmission rates (WVTRs) for the comparative materials. Since they do not contain significant polarity, the POP and ULDPE resins have much lower water vapor transmission rates than the comparative EVA resins. This is a distinct advantage for the POP and ULDPE resins because it is desirable to have a low WVTR to prevent the fresh-cut produce from drying out. The water vapor transmission rate for POP and ULDPE resins generally increases as density or crystallinity decreases.
Figure 5 shows the excellent hot tack strength and low hot tack initiation temperatures for the POP and ULDPE resins. EVA resins, by comparison, have very poor hot tack strength. Figure 6 compares heat seal strength at various seal temperatures. The POP resins have the best seal performance, followed by the 0.905 g/cc density ULDPE resin, and the EVA resins. As seal temperature increases, hot tack strength increases and then decreases. It is therefore important to optimize sealing conditions to obtain the best package integrity. The best package integrity will not necessarily occur at the maximum seal temperature.
Figure 7 compares haze for the resins. The POP resins have excellent optical properties as demonstrated by their low haze. The ULDPE resins have higher haze, and are therefore better suited for institutional food packaging applications where optics are not as critical as they are in retail food packaging. Puncture strength is compared in Figure 8. Both the POP and ULDPE resins have excellent puncture resistance. This provides for maximum package integrity.
In high performance retail packages, polyolefin plastomers are typically combined with another, stiffer material to provide good machinability on vertical form, fill, and seal equipment and a crinkly feel to the consumer. Examples of materials used with POPs include polypropylene (PP), styrene-butadiene copolymers, polystyrene (PS), high density polyethylene (HDPE), and linear low density polyethylene (LLDPE). The materials can be combined via co-extrusion or lamination. The type of process that works best will depend on the particular performance criteria for a given application.

Figure 9 (above) shows a typical multilayer film construction and provides the equation for calculating the transmission rate of multilayer film structures. The equation requires taking the inverse of the sum of each component’s thickness divided by its transmission rate, as shown in Equation 2 below.

**Equation 2**

\[
\text{Overall oxygen transmission rate} = \frac{1}{\left( \frac{t_1}{\text{OTR}_1} + \frac{t_2}{\text{OTR}_2} + \frac{t_3}{\text{OTR}_3} + \ldots \right)}
\]

Where \( t_i \) is the thickness of component \( i \) and \( \text{OTR}_i \) is the oxygen transmission rate of component \( i \).

**Important Note:** To determine the actual oxygen transmission for a package, the oxygen transmission rate of the film must be multiplied by the driving force, or difference in oxygen concentration between the inside and outside the package, and the surface area of the package (see Figure 9 above).
Because of the above relationship for multilayer films, the material with the lowest oxygen transmission rate has the most significant effect on the overall oxygen transmission rate. This effect is most prominent when the thickness of that layer is high relative to the total thickness of the film. Conversely, materials with very high OTR will reduce a co-extruded film’s OTR very little from that of the lower transmitting material.

Three hypothetical examples of film oxygen transmission rate for multilayer films containing polypropylene (OTR = 150 cc•mil/100 in²•day•atm), low density polyethylene (OTR = 300 cc•mil/100 in²•day•atm), and polyolefin plastomer (OTR = 1500 cc•mil/100 in²•day•atm) are provided below. Transmission rates used and calculated values are approximate and actual values should be confirmed on actual packages prior to use.

**Structure #1: 0.2 mil PP + 1.8 mils LDPE:**
\[ \text{OTR} = \frac{1}{\left( \frac{0.2}{150} + \frac{1.8}{300} \right)} = 136 \text{ cc•mil/100 in²•day•atm} \]

**Structure #2: 1.0 mil PP + 1.0 mil POP:**
\[ \text{OTR} = \frac{1}{\left( \frac{1.0}{150} + \frac{1.0}{1500} \right)} = 136 \text{ cc•mil/100 in²•day•atm} \]

**Structure #3: 0.2 mil PP + 1.8 mil POP:**
\[ \text{OTR} = \frac{1}{\left( \frac{0.2}{150} + \frac{1.8}{1500} \right)} = 395 \text{ cc•mil/100 in²•day•atm} \]

These examples provide a demonstration of the range of properties that can be obtained by changing materials and layer thicknesses in a multilayer film structure. For example, compared to structure #1, structure #2 offers improved stiffness, better machinability, improved heat resistance, lower hot tack and heat seal initiation temperatures, higher hot tack and heat seal strength, and better optics. However, it retains the same transmission rate as structure #1. Also compared to structure #1, structure #3 provides nearly three times the oxygen transmission, lower hot tack and heat seal initiation temperatures, higher hot tack and heat seal strength, and improved optics. Compared to structure #2, structure #3 provides greatly increased oxygen transmission and similar seal characteristics but noticeably less stiffness.
Modified atmosphere packages for fresh-cut produce must be carefully designed and manufactured to provide maximum quality in the final product. The respiration rate of the package must be carefully matched to the respiration rate of the fresh-cut produce inside the package. The goal of modified atmosphere packaging is to reduce the rate of respiration of the produce but not to completely inhibit aerobic respiration. This is generally achieved by reducing the oxygen concentration and increasing the carbon dioxide concentration inside the package.

One process of designing a produce package has been broken down into the following steps:
1. Understand Basic Requirements
2. Understand the Produce
3. Understand the Package
4. Determine the Optimum Atmosphere in the Package
5. Select a Film Structure that Meets All Requirements
6. Check that All Minimum Requirements Are Met
7. Validation
8. Document and Adjust Package Design Procedures

If the respiration rate of the package is too high, the shelf-life of the produce will not be extended. If the respiration rate of the package is too low, the produce may undergo anaerobic respiration and rapid bacterial growth.

The use of high performance materials such as AFFINITY™ Polyolefin Plastomers (POPs) allows the proper package respiration rate to be combined with other essential properties such as low heat seal initiation temperature, high hot tack strength, good puncture resistance, excellent optical properties, and low contribution to off-taste and odor. ATTANE™ Ultra Low Density Polyethylene (ULDPE) Resins also provide a useful combination of properties whenever film optics are not as critical.
References

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