Evaluating Encapsulation Economics

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Encapsulation of flavors and fragrances is a common practice, normally rooted in the need to protect product quality in an often-hostile setting. At the most basic level, encapsulation involves surrounding active molecules with a layer of material that prevents their release, as well as the penetration of environmental factors, until desired. Thus, the goal is to maintain the flavor or fragrance in pristine condition until such time as it is liberated from the product and subsequently perceived by the consumer (Figure 1).

Reality may at times fall a bit short of this idealized view, but there are a number of classes of foods and personal care-products on the market that are made possible only via the knowledgeable application of encapsulation technology. As consumer product companies strive to provide increasingly unique, convenient, healthy, and cost-effective offerings, the need to integrate delivery systems with all types of active ingredients—including flavors and fragrances—continues to grow.

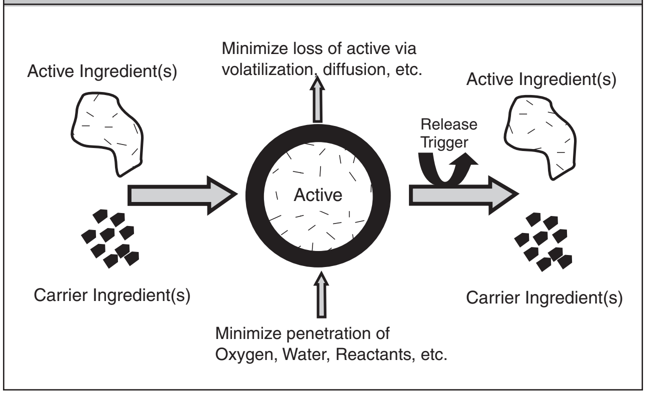
While certain products cannot be effectively produced or distributed without some sort of delivery system playing an integral role, in others there is a choice to be made between encapsulated and neat active materials. Normally, this trade-off involves not just product-quality considerations, but also processing, packaging and distribution variables. Whatever the case, there is still a need to minimize costs and select among the viable encapsulation alternatives. Often, multiple systems are available that can possibly satisfy the technical requirements of the application. Knowledge of how various factors effect the ultimate delivered cost of the flavor or fragrance can help focus the product developer and encapsulation specialist on technologies that meet economic targets as well.

Encapsulation Basics and Definitions

Numerous processes have been evaluated for the encapsulation of flavors and fragrances.[1] However, only a few basic techniques are used commercially at any significant scale due to a combination of technical and economic factors.[2] The major techniques used for flavors and fragrances are listed in Table 1.

As can be seen, these processes use a wide variety of underlying physical/chemical phenomena to produce an encapsulated product. However, regardless of the process used, all may be evaluated economically using a single conceptual model. The generic process diagram shown in Figure 2 is key to defining the factors which control encapsulated product costs. This flow, which can represent virtually any encapsulation process for the purposes of an economic discussion, allows us to define the following key cost elements (Note that these definitions have been cast in a simple manner that is consistent with much of the encapsulation literature—this raises specific issues related to the process mass-balance, which is discussed later):

Figure 1. Pictorial representation of encapsulatoin goals



- Active cost (C_A): the cost of the active ingredients.
- Carrier cost (C_C): the cost of all of the material(s) incorporated into the encapsulated product excluding the active ingredients.
- Process cost (C_P): the cost of converting the active and carrier materials into a single encapsulated product.
- Active retention (R): the percentage of active material that is retained in the encapsulated product in comparison with the original load of active. (Example: the active-carrier ratio is initially 1:4, giving a theoretical "load" of 20 percent. Analysis after encapsulation finds 17 percent loading. Active retention is therefore 17/20 x 100 percent = 85 percent.)
- Product yield (Y): the percentage of encapsulated product that the process actually yields in compari-

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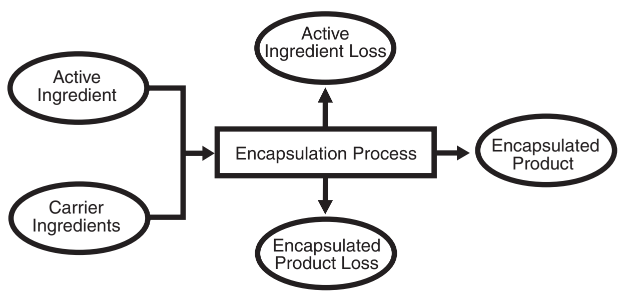
son to the theoretical yield. (Example: a combined carrier and active material weight of 100 kg is processed and yields 85 kg of encapsulated product. Product yield is therefore 85/100 x 100 percent = 85 percent.

A factor that also has a dramatic effect on the total delivered cost relates to the necessary usage level of an active ingredient in both neat and encapsulated forms. In some cases, a flavor or fragrance delivered via an encapsulated system may need to be used at either a higher or lower level than that of the neat material to obtain the desired effect. There are cases in which active material levels can be significantly reduced if an encapsulated version is used. This may be due to a number of factors, which include preventing loss of active materials via either volatilization or reaction during processing, as well as improved dispersion and release in the application. Conversely, encapsulation may sometimes suppress release and perception of the active ingredient. Thus we can define:

- Usage ratio (U): the ratio of neat active usage to encapsulated active usage. Often, this ratio is assumed to be 1:1 (i.e. as much encapsulated active material is required to achieve the same perception as neat material).

Figure 2. Generic encapsulatoin process



Economic Model Development

Using the definitions and concepts above, we can now develop the basic relationships which will allow encapsulated active material costs to be quickly compared to neat material costs based on easy-to-modify estimates or assumptions. For those wishing to avoid the mathematical development, please go to the Case Studies section.

The total cost of the encapsulated product is given by:

$$P = \frac{C_A + C_C + C_P}{(Y/100)} \quad (1)$$

Note that C_A, C_C, and C_P are the cost contributions of the Active, Carrier, and Process based on a unit mass of input. Thus, in order to express P in terms of the cost per unit weight of Active and Carrier we need to define:

- A_I = Percentage Active material in relation to carrier + active initially (i.e. initial load).
- C_I = Percentage Carrier material in relation to carrier + active initially (i.e. 100 - A_I).
- P_A = Cost per unit weight of Active ($/kg, $/ lb, etc.).
- P_C = Cost per unit weight of Carrier ($/kg, $/ lb, etc.).

Then equation (1) can be re-written more explicitly as:

$$P = \frac{P_A(A_I/100) + P_C(C_I/100) + C_P}{(Y/100)} \quad (2)$$

Using equation (1) or (2), we can then easily define the cost of the encapsulated active material as:

$$E = \frac{P}{(R/100)(A_I/100)} \quad (3)$$

Table 1. Major processes used for encapsulation of flavors and fragrances

Process	General Description
Spray-drying	Versatile process that involves rapid drying of a fine spray of an emulsion consisting of actives dispersed in a carrier solution.
Extrusion	Used to produce high-density encapsulated products via mixing of molten carriers with active ingredients and subsequent solidification.
Spray-chilling	Typically involves solidification of fine droplets of molten mixture of fat/wax and active ingredients
Coating/Agglomeration	Normally involves covering an active core with a protective layer of material. Fluid-bed contacting is normally employed.
Adsorption/Plating	While not considered true encapsulation, coating materials on porous or non-porous substrates is often a competitive technique.
Emulsions	Fine dispersions in which the action of an emulsifying agent at the surface of the active provides protection or functionality.
Coacervation	Coats emulsified droplets of active material via phasing polymers out of solution; often followed by cross-linking of the polymer shell.
Cyclodextrin Complexation	Complexation of individual active molecules with a cyclodextrin molecule.

Finally, we may then incorporate usage level (U) to calculate the cost-in-use ratio between the neat and encapsulated active materials:

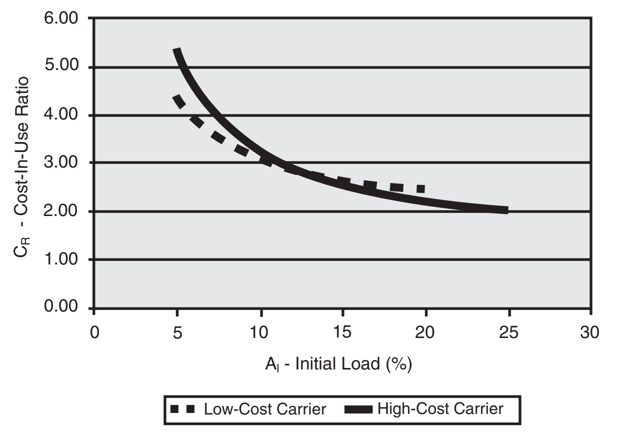
$$C_R = \frac{E}{P_A(U)} \quad (4)$$

C_R offers simple, powerful insight into the impact of encapsulation on actual product costs, and is a convenient way to compare specific situations from an economic viewpoint. Note that the terminology used here requires that R and Y satisfy the following mass-balance constraint: $(1\text{-}R/100)\ (A_I/100) <= (1Y/100)$. This is due to the lumping of all weight losses into the Y term. This then dictates that as R increases (more active loss), less encapsulated product is assumed lost at constant Y. Depending on the specific situation and use of the model, this may not be a good assumption. Encapsulated product losses (separate from pure active material losses) can be calculated from: $(1\text{-}Y/100) - (1\text{-}R/100)\ (A_I/100)$. If desired, C_R may also be used to produce a direct ratio between the costs of two encapsulated versions of the same active material:

$$C_{R1,2} = \frac{C_{R1}}{C_{R2}} \quad (5)$$

Where the 1, 2 subscripts indicate encapsulated products 1 and 2 respectively.

Figure 3. Comparison of cost-in-use ratio of low- and high-cost carriers—case 1



An inspection of equations (1) through (4) provides the following preliminary information regarding the impact of various factors on costs:

- As the cost of the Active (P_A) increases, C_R falls. Thus, expensive actives are less effected by the cost of encapsulation.
- As the Active load (A_I) increases, C_R falls. So high loading is preferred if possible and functional.
- As the Active retention (R) and yield (Y) increase, C_R falls. Therefore, processes that conserve material are heavily favored.
- As the Usage Ratio (U) increases, C_R falls. Thus, encapsulation methods that improve Active impact can help offset encapsulation costs.

Case Studies

Using the relationships defined above it is easy to compare specific encapsulation options to determine whether they economically fit targeted applications. Furthermore, it is also possible to evaluate the relative impact of various cost factors in order to determine where to focus attention on improvement. The following cases were selected to help illustrate a few key economic considerations in flavor and fragrance delivery.

Case 1—spray-drying—impact of loading, retention, and carrier cost: Spray-drying is one of the most basic and widely used flavor/fragrance encapsulation technique. While a variety of processing options exist, often product development centers around selection of a suitable carrier system. Carriers can vary significantly in cost, as well as in their encapsulation abilities. In this case, we compare the impact of low- and high-cost carrier systems on the cost-in-use ratio. Specific assumptions are given in Table 2.

By allowing A_I to vary up to the maximum allowable level for each carrier, we can obtain the overall view of C_R presented in Figure 3 (Equation (4) plotted against varying A_I).

As can be seen, the low cost carrier has an advantage at low loading levels. At approximately 12 percent initial loading, however, the higher cost carrier becomes competitive due to its ability to retain more of the active. If other factors (e.g. application performance, shelf-life, processing limitations, etc.) do not dictate otherwise, the conclusion would be to use the higher cost carrier at a load over 20 percent in order to minimize the delivered active cost. Note that even in the best situation the cost of the active in the application is approximately doubled.

Case 2—technology comparison—impact of active cost: Active mixtures in the flavor and fragrance industry vary greatly in cost. Thus, it is frequently required to select an encapsulation technology that is not only technically appropriate for the application, but also economically appropriate for the active ingredient. In this case, we compare the impact of two technologies on actives of varying cost. Specific assumptions are given in Table 5.

The outcome for this case (shown graphically in Figure 4) indicates that the technologies are relatively comparable in overall cost despite the large differences in the inputs. This shows that it is difficult to assess the economic viability of a specific technology without a quantitative comparison. Note also that both of the technologies add tremendous expense to low-cost actives. This must be balanced against the value added to the ultimate application by the encapsulated product in comparison to that of the neat material.

Case 3—usage level—when encapsulation affects necessary active dosage: Encapsulation may be used in specific cases to reduce the level of active needed in the application. This may be achieved by either reducing losses of flavor or fragrance prior to release, or improving actual

Table 2. Case 1 assumptions

Assumption	Low-Cost Carrier	High-Cost Carrier
P_C = Carrier Cost ($/lb)	0.30	1.00
C_P = Processing Cost ($/lb)	0.40	0.60
A_I Range = Initial load range (%)	5 - 20	5 - 25
R = Retention of Active (%)	60	85
Y = Product Yield (%)	90	90
P_A = Active Cost ($/lb)	10	10
U = Usage Ratio	1	1

impact in the final product. Of course, use of an encapsulated system may also suppress active impact due to the presence of carriers or by effecting release. This case demonstrates the cost differentials encountered if usage level is either positively or negatively changed by encapsulation. Specific assumptions are given in Table 4.

Two main insights can be drawn from Figure 5. First, the economic effect of either halving or doubling the actual active usage is clearly massive. Second, selecting an encapsulation technique that allows the active usage to be significantly lowered can actually result in a lower cost (C_R < 1) than using neat active. Often, encapsulation projects are begun which attempt to keep active costs the same as if using neat material while conferring other benefits to the product (e.g. stability, processing ease, etc.). This can only be achieved if usage levels are substantially reduced. The situation is similar if the objective is to replace an encapsulation system in current use with one affording more protection at a higher cost – usage levels must decline to keep costs constant.

Conclusion

Evaluating encapsulation from a quantitative economic perspective as presented here can be used to advantage by product developers or encapsulation specialists in a number of ways. The primary benefits are:

- Rapid assessment of the feasibility of cost targets prior to the beginning of actual project work.
- Comparison of different encapsulation techniques so that only those which can ultimately meet cost targets are the focus of attention.
- Comparison of the cost effect of different carrier systems used with a single encapsulation technique.
- Comparison of the cost effect of a specific type of encapsulation on active materials of varying costs.

Of course, the impact of encapsulation on the consumer-perceived value of the ultimate application must also be considered. However, consumer value is often intertwined with cost and requires significant market research to fully understand. The techniques presented above can be an important tool in validating technical approaches so that costs are integrated into all stages of the development process. ■

References

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Table 3. Case 2 assumptions

Assumption	Technology A	Technology B
P_C = Carrier Cost ($/lb)	10.00	1.00
C_P = Processing Cost ($/lb)	15.00	3.00
A_l = Load (%)	80	20
R = Retention of Active (%)	100	100
Y = Product Yield (%)	90	95
P_A range = Active Cost Range($/lb)	5 - 50	5 - 50
U = Usage Ratio	1	1

Table 4. Case 3 assumptions

Assumption	Lower Dosage	Higher Dosage
P_C = Carrier Cost ($/lb)	1.00	1.00
C_P = Processing Cost ($/lb)	0.50	3.00
A_l = Load (%)	15	20
R = Retention of Active (%)	90	100
Y = Product Yield (%)	90	95
P_A range = Active Cost Range($/lb)	5 - 50	5 - 50

Figure 4. Comparison of technologies for varying cost actives—case 2

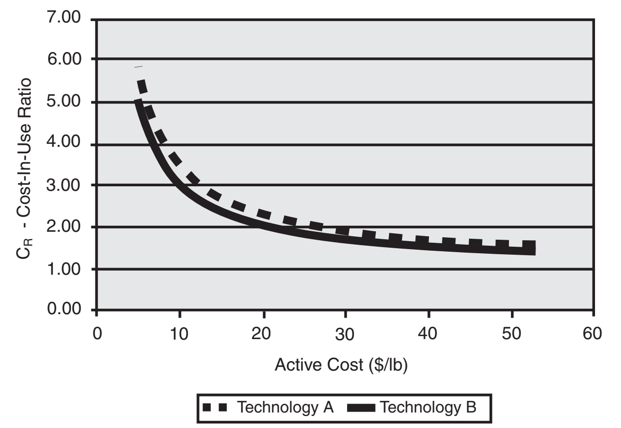

Figure 5. Comparison of the impact of varying usage levels—case 3