CHAPTER II

THEORY AND LITERATURE REVIEW

2.1 Background and History of Microencapsulation Techniques

The development of the microencapsulation products started in 1950s by the research of pressure-sensitive coats for the manufacture of carbonless copying paper. The first research leading to the development of microencapsulation procedure for carbonless copy paper was published by the National Cash Register Corporation (NCR) and their name had become synonymous with the product: "NCR Paper". Over the past 30 years, carbonless copy paper has achieved a special position in the sector of office papers and forms. All industrial countries were eventually developing the carbonless paper followed by the discovery in the USA in the early 1950s. From 1966 to 1986, which showed a 100 percent growth in paper consumption, the annual consumption of carbonless copy paper systems increased from about 60,000 t to about 1.7Mt, i.e. by about 3000 percent.[1,2]

The impressive market success of these systems is to a large extent due to the excellent cooperation between the paper-making and paper processing industry on one hand and the chemical industry on the other hand. The contribution of chemistry has made it possible to transform white paper, familiar to every consumer as writing paper, into copy paper without altering its outward appearance. This transformation is based on a sophisticated technology, which essentially involves coating the back of a paper sheet with microcapsules with a diameter of about 3 to 8 micrometers.

These microcapsules contain dye precursors, for example leuco dyes, which are dissolved in colorless solvents and then converted into the visible color by a chemical process during copying. If such a coated back (CB) sheet is brought into contact with a paper sheet treated on the upper surface with an electron acceptor (coated front (CF)), a copy is obtained on the upper surface of the CF page when pressure is exerted during writing on the upper surface of the CB page, as illustrated in Figure 2.1. The effect is based on the fact that the pressure on the CB page causes the microcapsules to break down and the dissolved dye precursor to be released. The latter thus comes into contact with the coating of the CF page, starting a chemical reaction which converts the initially colorless dye precursor into a dye. If one or more paper sheets, containing both a CB coat and a CF coat (CFB sheets), are inserted between the CB sheet and the CF sheet, a form set for several copies is obtained. The carbonless copy paper principle is thus based on the interaction of mechanical and chemical effects.

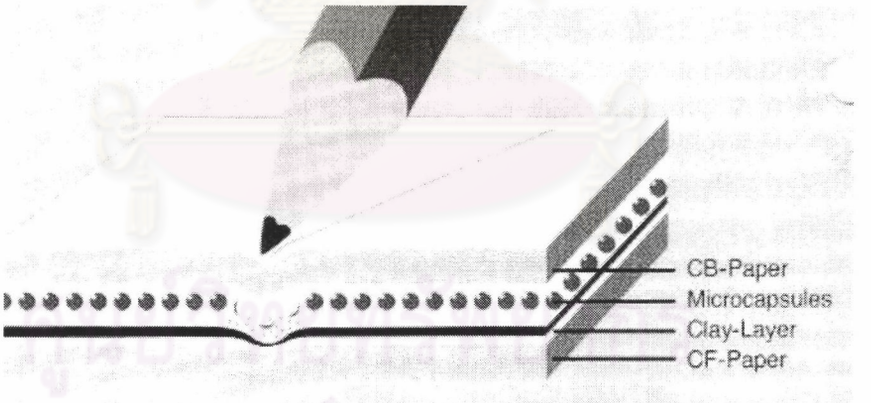

Figure 2.1 Pressure-activated release of encapsulated dye precursor to give a color reaction on paper coated with an acidic clay.

Development of the microencapsulation process was the technical breakthrough that made carbonless copy paper a commercial reality. The original method of NCR manufacturing carbonless microcapsules involved a process called

coacervation. At that time, the capsule walls were produced using natural water-soluble polymers, for example gelatin, gum arabic or essential cellulose. The microcapsules containing a colorless dye precursor (3,3-bis- (p-dimethylaminophenyl)-6-dimethylamino phthalide) were affixed to the under surface of the top page and released the dye precursor upon rupture by pressure from tip of the writing tool. The liberated dye precursor then reacted with an acid clay (attapugite) coating on the top surface of the underlying page to form a copy image, dark blue color.[3-6]

2.2 The Microcapsules System

Microencapsulation is a known technique by which either hydrophilic or hydrophobic active compounds can be incorporated in individual protective coatings and matrices consisting of natural or synthetic polymers. Microencapsulation can generally modify the color, shape, volume, apparent density, reactivity, durability, pressure sensitivity, and photosensitivity of the encapsulated substance. Depending on the type of the encapsulated material and the ultimate product use, the size of the polymer microcapsules can range from a few nanometers to several millimeters.

Control of the microcapsule membrane thickness and its morphological properties as well as control of the capsule size and its distribution are the main requirements for the selection of an encapsulation technique. Many different methods have been proposed for the production of polymeric microcapsules and microparticles with many different variations, depending on core and wall-polymer solubility, particle size, wall thickness and wall permeability, type and rate of release of core contents required, physical properties and detailed and overall economics on manufacture.

The microencapsulation systems can be extensively characterized in terms of active ingredient content, process efficiency, process loading, particle size, particle morphology, swelling characteristics and release profile of the entrapped material. The

release of encapsulated active ingredients from polymeric particles is governed by a number of parameters e.g. capsule surface area, wall thickness, and physicochemical constitution of the wall material in relation to each environment. Both the encapsulation efficiency and the availability of the encapsulated material can be optimized by suitable selection of the wall material. The ability to control the particle size in order to produce particles in a desired size range is also an important consideration.

The technique of microencapsulation has gained popularity because of its potential applicability in a wide variety of situations. The microencapsulation processes have been used in many industries such as food, food additives, cosmetics, adhesives, household products, agriculture materials, an aerospace industry, and many others. Generally, there are a number of reasons why substances should be encapsulated to protect the active components from climatic effects and external damage (improving storage life):

a) Conversion of a liquid active component into a dry 'solid' system.
b) Separation of incompatible components, for functional reasons. A good example of this requirement is the production of carbonless (NCR) copying paper, where a microencapsulated acid sensitive dye formulation is used as one layer of a coated paper, while the facing side of the next sheet is coated with an acid clay, bonded to the paper upon pressure. The dye containing microcapsules are ruptured and the color is developed in the ruptured area.
c) Masking of the undesired properties of the active component - for example 'odor masking', or masking of the chemical properties (pH or catalytic activity) of the active component.

d) Protection of the immediate environments of the microcapsules from the active component – for example, reduction of gastric irritation in medication, as with 'coated' aspirin.

e) Controlled release of active components for delayed (times) release or long-acting (sustained) release. [7-9]

2.3 Core Material

A core material, which is defined as the specific material to be encapsulated, plays a significant role in microencapsulation. It dictates the process as well as the polymer used as a wall material. It should be insoluble and nonreactive with the wall material and the manufacturing vehicle. Water soluble and insoluble solids, water immiscible liquids, solutions, and dispersions of solids in liquids can be microencapsulated. The solid core can be a mixture of active constituents, stabilizers, diluents, excipients, and release rate retardants or accelerators. [10,11]

The criteria for selecting a core material for microencapsulation of carbonless copying paper are composed of solvent and color formers.

2.3.1 Solvent

In the carbonless copying process, it is important that the writing on the copies develops within seconds as the user of such form will not want to wait for a long time for the print to appear on the copy. The solvents for the dye precursors make an important contribution in this aspect. [5,12,13]

In the carbonless copy system described, the solvents must meet the following requirements:

1. The color former should be dissolved as quickly and completely as possible without being chemically altered or influenced.
2. In the production of the carbonless copy paper, the still moist paper sheets pass through infrared and/or hot air dryers, with the result that temperatures of over 100°C are reached at the paper surface. The solvent must not evaporate at these temperatures; otherwise pressure would build up inside the microcapsules and cause them to burst prematurely.
3. During the writing process, the color former must be transported immediately from the CB page to the CF page, for this reason, the viscosity of the solvent should not be too high.
4. Once the dye precursor solution has reached the surface of the CF page, the CF coating must be satisfactorily wetted, i.e. the surface tension of the solvent must not be too high and should be less than the surface tension of the CF coating
5. Once the copy color has developed on the CF surface due to the reaction with the CF coating, the color must not be transported away by the solvent; otherwise the copy would bleed and become illegible as result of this chromatographic effect. Accordingly, the solvent must have very little or no dissolving power for the developed dye; moreover, the viscosity of the solvent should not be too low, since this would promote the chromatographic effect.
6. The solvent should, as far as possible, be odorless in order to avoid annoyance to the users of carbonless copy paper, especially in close rooms.

7. The solvent should be toxicologically safe so that the end user is not adversely affected and environmental pollution is kept at as low as possible during disposal of the used paper.

Figure 2.2 shows the oils usually employed for microencapsulation. These oils are requiring to dissolve the color–forming agents and also to realize the color formation reaction efficiently. The physical properties of some solvents for carbonless paper are illustrated in Table 2.1. Out of the large number of known solvents, there are only few special products, which meet some or all of these complex requirements. The most well known from the class composing the aromatic hydrocarbons are partially hydrogenated terphenyls, the alkylated biphenyls, alkylated diphenylmethanes, chloralkylation tetralins and alkylated naphthalenes. The chlorinated paraffin occupies a special position and, owing to their high viscosity and reactivity, it cannot be used without further additives. [14]

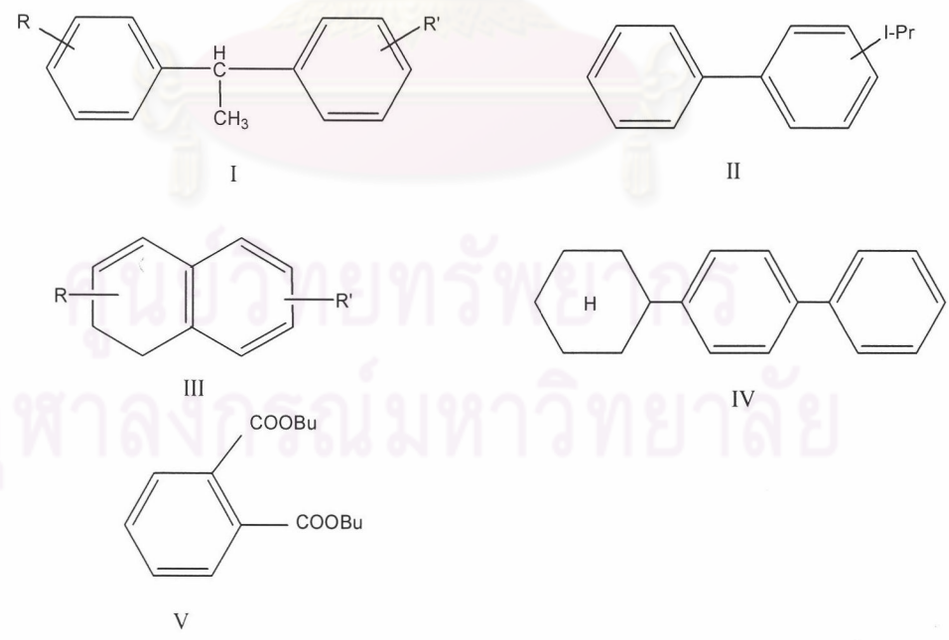

Figure 2.2 Oils used to dissolve color former in carbonless copy paper microcapsules.

Table 2.1 Physical properties of some solvents for carbonless copy paper

Properties	Solvents			
	Diisopropyl -napthalene[a]	Phenylethyl -tetralin[b]	Terphenyl, partially hydrogenated[c]	Chloro-paraffin[d]
Color	Colorless	Colorless	Colorless	Colorless
Beginning of boiling range (°C) 1013 mbar	290	330	350	NA[e]
Viscosity (25°C) mPas	12	30	95	160
Density (15°C) g/ml	0.96	1.03	1.00	1.16
Flash point (°C)	>130	194	180	>200
Pour point (°C)	<-40	-34	-25	-28

Diisopropylnaphthalene has become particularly well accepted in the market for carbonless copy paper over the past few years. It combined all required chemical and physical properties with very low toxicity and environmental compatibility. The product is colorless and odorless and is not subject to labeling requirements in accordance with the regulations applicable.

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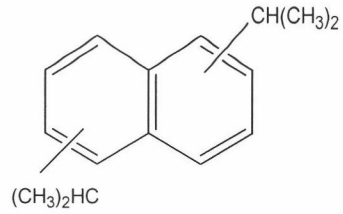
[a] Rutgers Kureha Solvents.

[b] Exxon Chemicals.

[c] Monsanto

[d] ICI Chemical & Polymers

[e] not available owing to decomposing prior to boiling



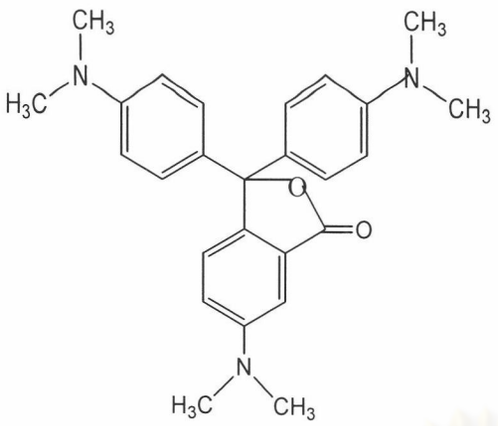
Diisopropylnapthalene.

Figure 2.3 Chemical structure of diisopropylnapthalene.

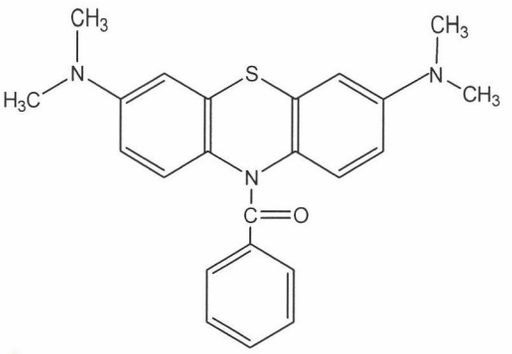
2.3.2 Color Formers

Once hardened, the microcapsules hermetically seal up the oil phase, consisting of the solution of the dye precursor in an organic solvent. The composition of the color former conforms to the manufacturer's recommendations, so that blue or black copies are obtained on the paper after writing. Figure 2.4 shows the representative examples of color formers to be encapsulated. Various colors such as blue, black, or red can be obtained by selecting suitable species. A typical example of a color former is crystal violet lactone, in which the lactone ring opens upon reaction with the color-developing agent to form a triphenylmethane dye. [12]

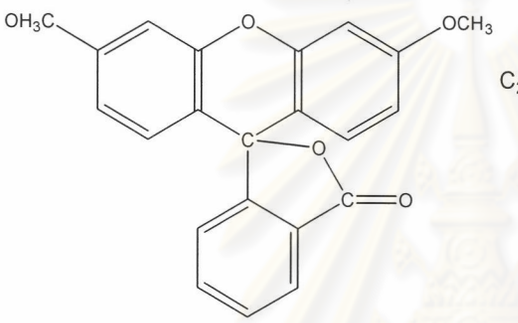
Crystal violet lactone (CVL) and bensoyl leuco methylene blue (BLMB) are traditional dye precursors, which can be used for the both blue and black copies. CVL belongs to the class comprising the triphenyl-methane dyes and is, in the water-insoluble form, a colorless phthalide. The color is developed by interaction with the CF page, which is treated with a proton releasing layer (for example, clay mineral treated with acid, such as kaolin or modified phenol resin). During this procedure, the phthalide bond is cleaved, leading to a leveling out of the angular molecular structure and hence to the formation of the chromophore.



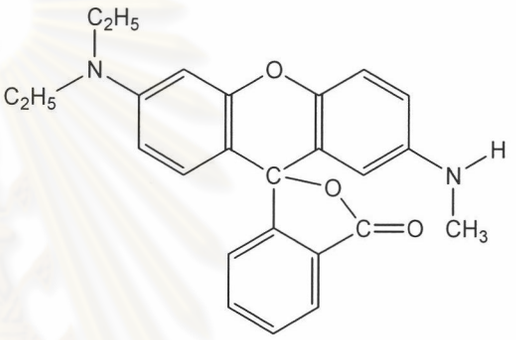
Blue



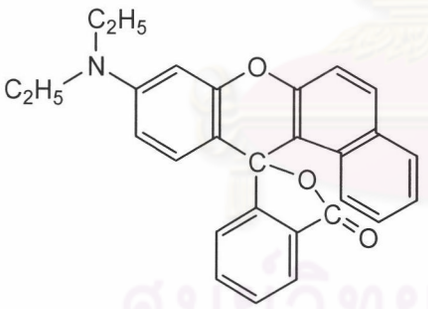
Light Blue



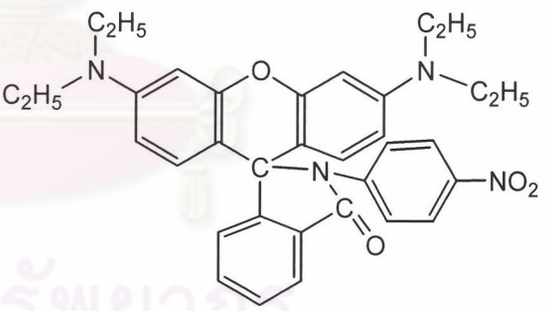
Yellow



Black



Red

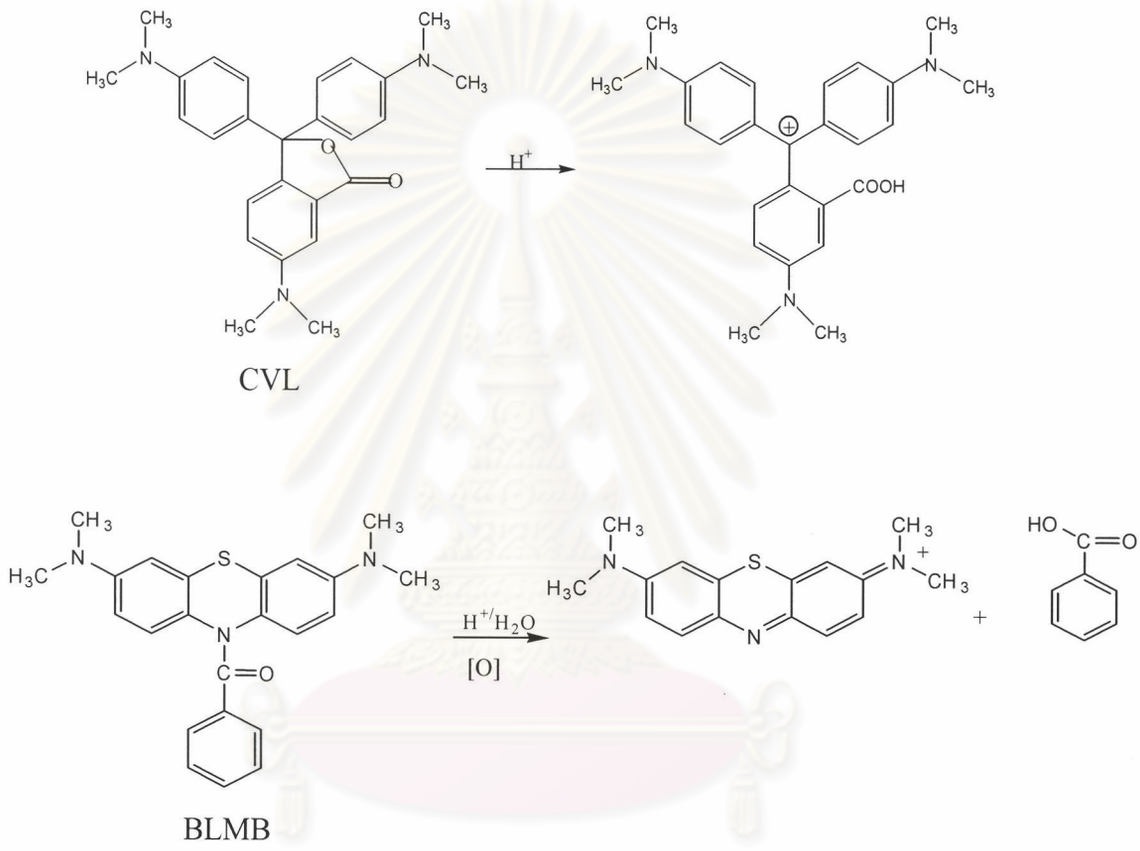


Magenta

Figure 2.4 Color formers, leuco dyes, used in carbonless copy paper microcapsules

The CVL has poor light-fastness, resulting in rapid fading of the copy on the CF page. To prevent this, BLMB is added as a second component to the dye precursor solution. The BLMB undergoes cleavage by acid catalysis and by the action of oxidizing agents, such as oxygen, to give the thiazine chromophore of methylene

blue, which has good light-fastness (see Scheme 2.1). Since the oxidation with atmospheric oxygen takes place slowly, BLMB has only a low development rate, which is compensated by the rapid reaction of the CVL. The CVL ensures rapid color development while BLMB gives a very light-fast copy. [14,15]



Scheme 2.1 The color developing of CVL and BLMB

Another important group of dyes for carbonless copy paper is the fluoran group, which is used in all formulations for achieving black shades. Flourans are related to the triphenylmethane phthalides and are obtained by insertion of an oxygen bridge slightly differing with respect to the substitution pattern of the molecule.

2.4 Wall Materials

The microcapsules wall can be chosen from a wide variety of natural and synthetic polymers. Each wall polymer has its own particular encapsulation efficiency and release property. The stability of the compounds against oxidation is also influenced by the chemical nature of the wall polymer.

Physicochemical criteria of the wall polymer such as molecular weights, solubility, glass/melting transition, crystallinity, reactivity, film formation and diffusibility are always the important parameters in choosing suitable wall polymers when considering the cost of the wall-forming polymer. A part of typical coating materials commonly used in the various microencapsulation methods is suggested in Table 2.2. [13, 15-17]

Table 2.2 Representative coating materials and applicable microencapsulation processes.

a) Water Soluble Resins

Wall Material	Processes				
	Coacervation	Solvent Evaporation	Air Suspension	Pan Coating	Spray Drying
Gelatin	✓	✓	✓	✓	✓
Gum Arabic	✓	✓	✓	✓	✓
Starch	✓		✓	✓	✓
Poly(vinyl pyrolidone)	✓		✓	✓	✓
Carboxymethyl cellulose	✓	✓	✓	✓	✓

Table 2.2 Continued representative coating materials and applicable microencapsulation processes.

Wall Material	Processes				
	Coacervation	Solvent Evaporation	Air Suspension	Pan Coating	Spray Drying
Gelatin	✓	✓	✓	✓	✓
Gum Arabic	✓	✓	✓	✓	✓
Starch	✓		✓	✓	✓
Poly(vinyl- pyrolidone)	✓		✓	✓	✓
Carboxymethyl cellulose	✓	✓	✓	✓	✓
Hydroxyethyl cellulose	✓		✓	✓	✓
Methylcellulose	✓		✓	✓	✓
Arabinogalactam	✓		✓	✓	✓
Poly(vinyl alcohol)	✓	✓	✓	✓	✓
Poly(acrylic acid)	✓	✓	✓	✓	✓

b) Water Insoluble Resins

Wall Material	Processes				
	Coacervation	Solvent Evaporation	Air Suspension	Pan Coating	Spray Drying
Ethylcellulose	✓	✓	✓	✓	✓
Polyethylene		✓	✓		
Polymethacrylate	✓	✓	✓	✓	✓
Polyamide (Nylon)		✓	✓		
Poly (ethylene co-vinyl acetate)	✓	✓	✓	✓	✓

Table 2.2 Continued representative coating materials and applicable microencapsulation processes.

Wall Material	Processes				
	Coacervation	Solvent Evaporation	Air Suspension	Pan Coating	Spray Drying
Cellulose nitrate	✓	✓		✓	✓
Silicones				✓	✓
Poly(lactide-co-glycolide)	✓	✓		✓	
Waxes and lipids					
Paraffin	✓	✓	✓	✓	✓
Carnauba			✓	✓	✓
Spermaceti	✓		✓	✓	✓
Beewax			✓	✓	✓
Stearic acid				✓	✓
Stearyl alcohol			✓	✓	✓
Glyceryl sterates			✓	✓	✓
Enteric resins					
Shellac	✓		✓	✓	✓
Cellulose acetate phthalate	✓	✓	✓	✓	✓
Zein	✓		✓		

2.5 Technology of Production

Methods for preparing microcapsules have been developed and improved significantly. They may be classified into 3 major categories that are physical methods, chemical methods, and mechanical methods. There are a number of techniques used in the industry and laboratory to produce the microcapsules. The choice of an appropriate microencapsulation technique depends upon the end use of the product and the processing conditions involved in the manufacturing product. These major microencapsulation procedures are summarizing briefly in Table 2.3. In this review, only techniques related to this project will be described and interfacial polymerization technique will be described in more details. [18-21]

Table 2.3 Summary of major microencapsulation processes.

Process	Principle
1. Physical Methods	
1.1 Coacervation/Phase Separation (using aqueous and non-aqueous vehicles)	The solvation of polymeric solute(s) in a medium is reduced to form coacervated droplets to deposit and coat the dispersed phase.
1.2 Solvent Evaporation	A polymer solution containing core material is emulsified into an immiscible liquid phase to form a dispersion and the solvent is removed from the dispersed droplets to leave a suspension containing polymer microcapsules.

Table 2.3 Continued summary of major microencapsulation processes.

Process	Principle
2. Chemical methods	
2.1 Interfacial polymerization	Various monomers are reacted at the interface of two immiscible liquid phases to form a film of polymer that encapsulates the dispersed phase.
2.2 In-situ polymerization	A water soluble pre-polymer is further polymerized to the point where it becomes water insoluble after the oil phase is emulsified. When it precipitates out of solution, surfactant is added to cause the precipitated polymer to migrate to the water oil interface where it forms a wall around each droplet. The wall is hardened or cured by using a cross-linking agent.
3. Mechanical Methods	
3.1 Air suspension	Polymer solution is sprayed to the suspending and moving particles in the coating zone portion of the coating chamber of air suspension apparatus.
3.2 Pan coating	Polymer solution is sprayed to the desired solid core material, which is deposited onto spherical substrates, e.g. nonparallel seeds or other solid substrates, in the coating pan while rotating.
3.3 Spray drying	A core material is dispersed into a coating solution and then the mixture is atomized into a hot air stream to remove the solvent from the coating material.

Various microencapsulation processes give rise to the formation of microcapsules with various characteristic size ranges as shown in Table 2.4.

Table 2.4 Microcapsule size ranges produced by various production procedures.

Production Process	Size Range (μm)
Coacervation/Phase separation	1-5000
Solvent evaporation	1-5000
Interfacial polymerization	2-2000
Air suspension	50-1500
Pan coating	200-5000
Spray drying	5-800

2.5.1 Coacervation

In carbonless technology, coacervation is the method initially employed by Green and Schleicher in the 1950s to produce pressure-sensitive dye microcapsules for the manufacturing of carbonless paper. They described the macromolecular aggregation (phase separation) by partial desolvation of fully solvated macromolecules. Coacervation in the presence of a liquid or solid core material (i.e., microcapsule formation by coacervation) is complicated because of different surfaces and in different media. Generally, the core material used in the coacervation must be compatible with the recipient polymer, and be insoluble (or scarcely soluble) in the coacervation medium.

There are two types of coacervation procedures: simple and complex. Simple coacervation involves only one type of polymer with an addition of strongly

hydrophilic agents to the colloidal solution. For complex coacervation, it uses two or more types of polymers. A schematic diagram in Figure 2.5 shows a simple coacervation process. [9, 22-24]

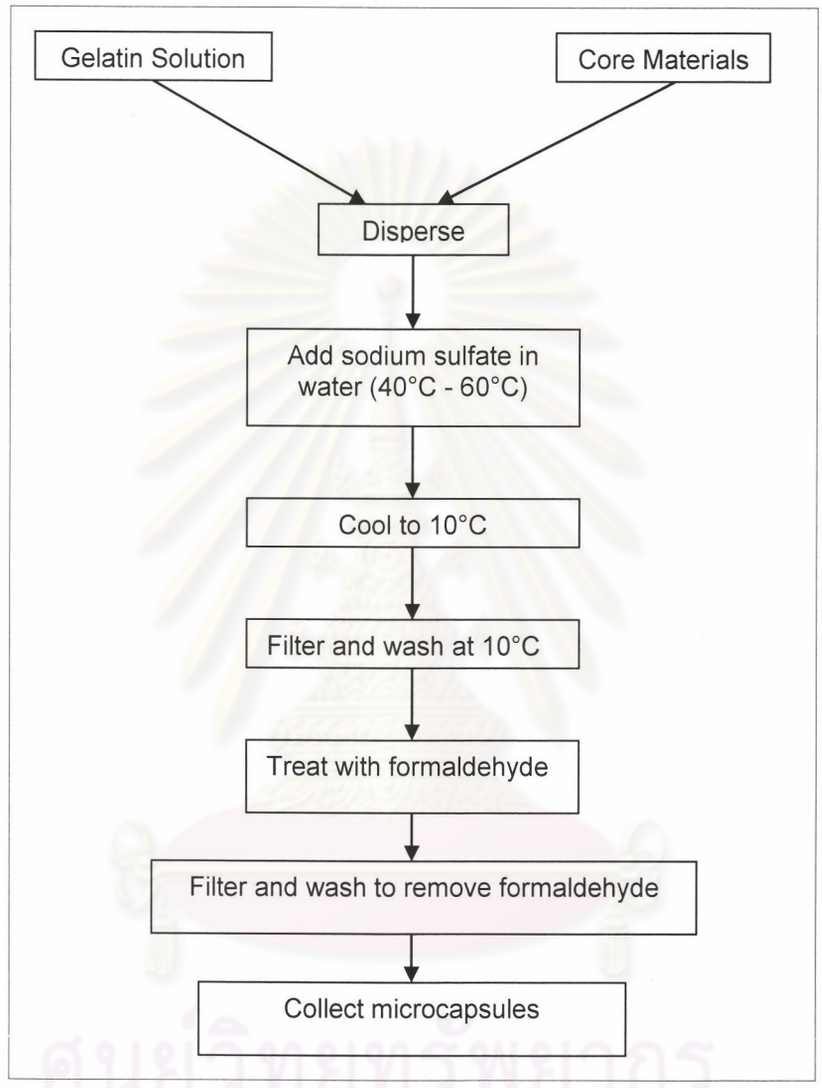


Figure 2.5 Simple coacervation process.

Generally, these microencapsulation processes consist of three steps, as shown in Figure 2.6, carried out under continuous agitation.

1. Formation of three immiscible phases: the liquid-vehicle phase, the core material, and the liquid polymer coating.

2. Deposition of the coating.

3. Solidification of the coating.

In step one, the three immiscible chemical phases are found. The core material is dispersed in a solution of the coating polymer. The solvent for the polymer is the liquid vehicle. The coating material, the immiscible polymer is the liquid state, is formed as coacervate droplets of colloid-rich phase by utilizing one of the methods of phase separation or coacervation, that is, by simple or complex coacervation, temperature change, addition of a nonsolvent, or polymer-polymer in compatibility.

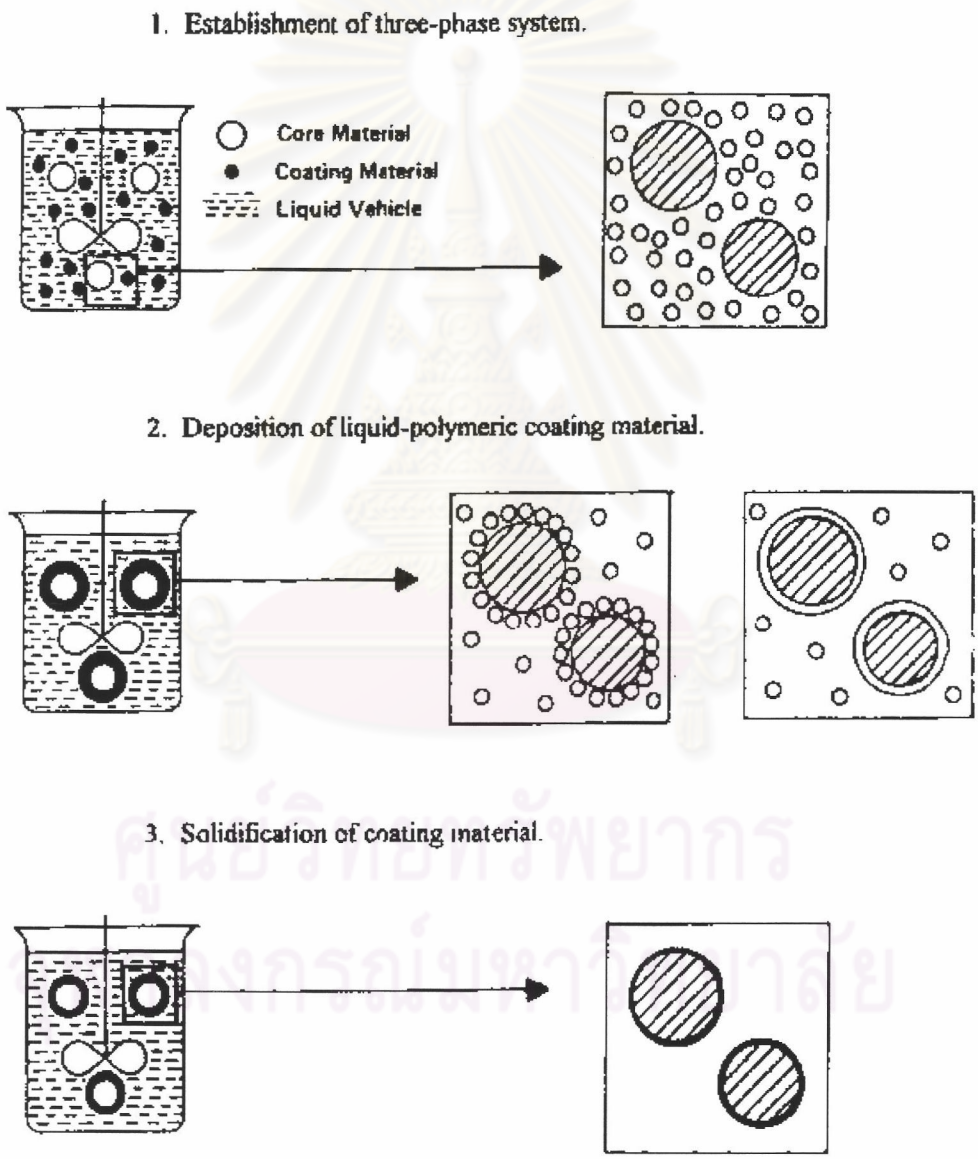


Figure 2.6 General process description of coacervation technique

core Coacervation droplets coating harden coating

In step two, the liquid polymer coating (coacervated droplets) is deposited around the core material by controlled physical mixing of the coating (white fluid) and the core material in the liquid manufacturing vehicle. Deposition of the liquid polymer coating around the core material occurs if the polymer is adsorbed at the interface formed between the core material and the liquid manufacturing vehicle. This sorption phenomenon is a prerequisite to effective coating. The continued deposition of the coating is promoted by a reduction of the total free interfacial energy of the system, which is brought about by a decrease in the coating material surface area during coalescence of the liquid polymer droplets.

Step three of the process involves solidifying of the coating, which is usually induced by thermal, cross-liking, or desolvation methods to form rigid microcapsules. The desolvation can be performed by addition of a non-solvent or phase-inducing polymer or by a change in pH.

2.5.2 Interfacial Polymerization

Interfacial polymerization involves the reaction of various monomers at the interface between two immiscible liquid phases to form a film of polymer that encapsulates the disperse phase. Usually two reactive monomers are employed, one dissolved in the aqueous disperse phase containing a solution or dispersion of core material, and the other dissolved after the emulsification step in the nonaqueous continuous phase. The water-in-oil (w/o) emulsion formed requires the addition of a suitable emulsifying agent as stabilizer. Figure 2.7 shows a diagrammatic representation of the process, which is often referred to as interfacial polymerization. The monomers diffuse together and rapidly polymerize at the interface between the phase to form a thin coating, and the product of the reaction is neutralized by added material such as an alkaline buffer. [12]

The degree of polymerization can be controlled by the reactivity of monomers chosen, their concentration, the composition of either phase vehicle, and by the temperature of system. Variation in particle size of dispersed phase controls the particle size of the product. The reaction between the monomers is quenched by depletion of monomer, which is frequently accomplished by adding an excess continuous-phase vehicle to the emulsion.

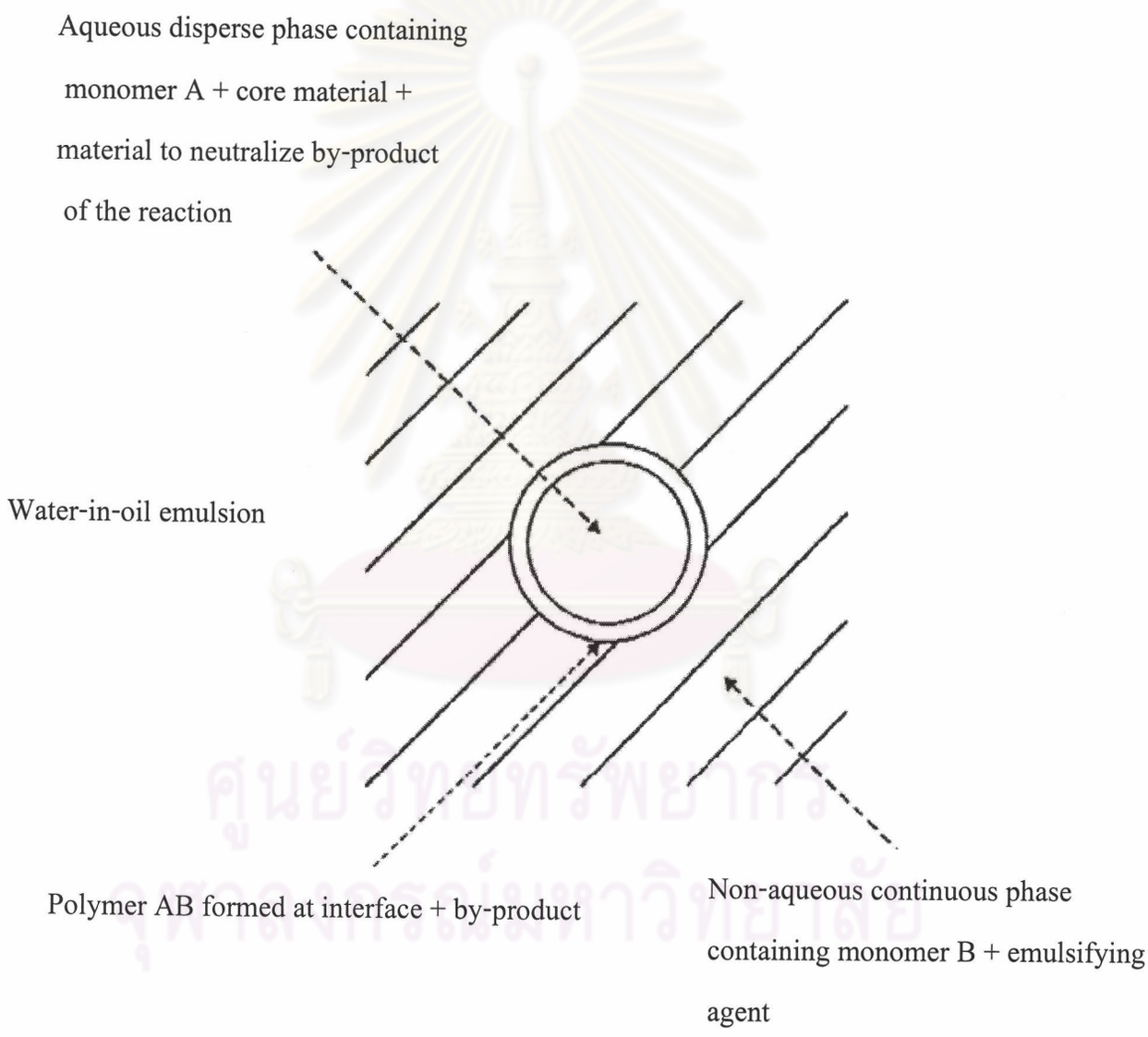


Figure 2.7 Schematic representation of microencapsulation of a droplet by interfacial polymerization.

This process does not require special equipment, but the presence of a reactive component limits the kinds of liquids that may be encapsulated. Representative examples of wall materials are polyamide, polyurea, polyurethane, polyphenylester, and epoxy resin. The interfacial process utilizes wall formation by interfacial polymerization reaction of two monomers dissolved in an organic and/or aqueous phase as shown in Figures 2.8. [15, 19, 25]

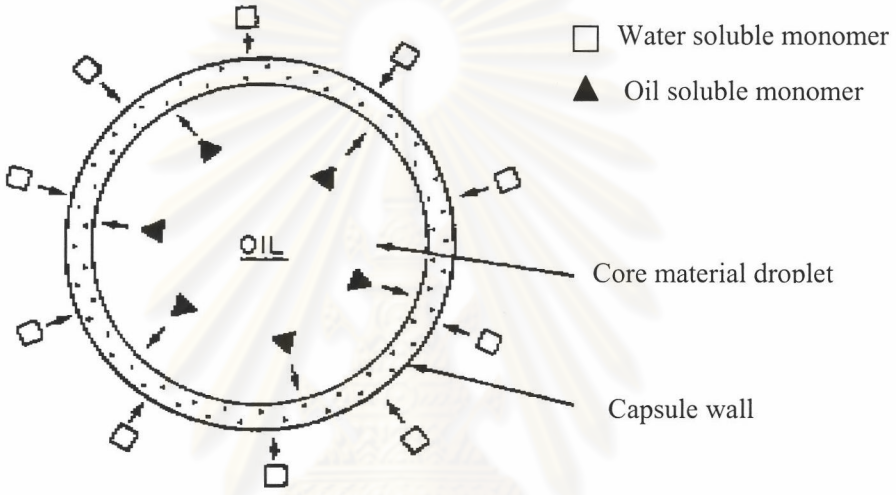


Figure 2.8 Schematic representation of microencapsulation of a droplet by interfacial polymerization.

The microcapsules in this process are obtained by emulsifying the core material in to the dispersion phase and merely continuing the agitation with heating as shown in Figure 2.9. This process is capable of encapsulating hydrophilic or hydrophobic liquids by selecting a suitable emulsion state. When the polymerization reaction is very rapid, it is desirable to gradually add a monomer after the emulsification. The monomers A and B are polyfunctional and capable of causing polycondensation or polyaddition reactions. An advantage of this process is that the properties of microcapsules can be modified by the combination of monomers.

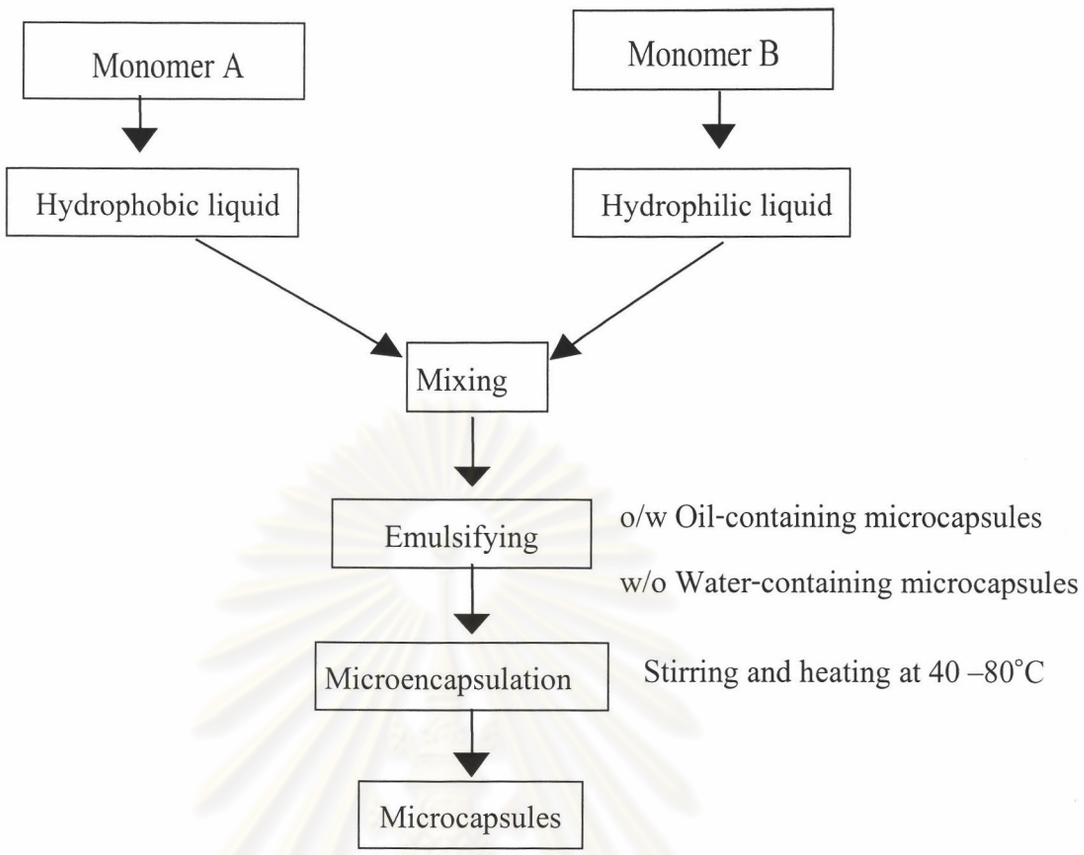


Figure 2.9 Schematic diagram for the interfacial polymerization method of microencapsulation.

In this process certain side reactions other than the interfacial reaction can significantly affect the microencapsulation. Figure 2.10 shows the possible side reactions. Obviously, satisfactory microencapsulation cannot be expected when there are side reactions between the core material and monomer A or B, or between additives and monomers, or when there is hydrolysis of monomer B. Particularly the side reaction between the core material and monomer seriously affects the microencapsulation and limits the usable core material. For example, certain dyes and perfume are attacked during the process and cannot therefore be encapsulated by this process. The monomer in the solvent phase can be hydrolyzed at the interface. In other words, the monomers whose rate of hydrolysis is faster than the interfacial reaction are unable to produce microcapsules.

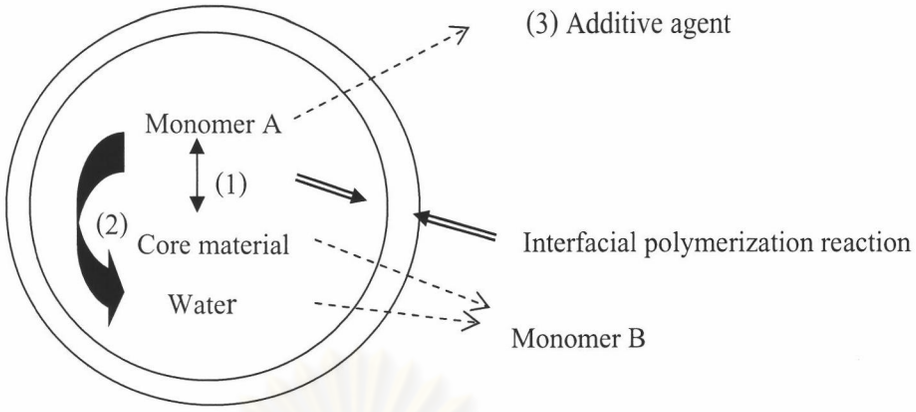


Figure 2.10 Side reactions affecting the interfacial polymerization technique for microcapsulation: (1) side reactions of the core material and monomer; (2) hydrolysis of the monomer; (3) reaction between additive and monomer.

The additives in the system can also give rise to side reactions. However, the materials associated with such side reactions can be utilized in the microencapsulation if they do not reach the region of interfacial polymerization.

It has been previously reported that the interfacial reaction takes place on the organic side of the interface. For this reason, the materials present in the aqueous phase have less effect on the microencapsulation than those in the solvent phase. Nevertheless those present in the aqueous phase can affect the microencapsulation if their coefficient of distribution is large enough to reach the region of interfacial reaction.

2.6 Areas of Application

Microcapsules have many useful functions and have been employed in many different fields of technology, frequently connected with applications in which the contents of the microcapsules are released under controlled conditions into the surrounding environment. Microencapsule-base products are used in the graphic arts,

in pharmaceutical technology as drug delivery systems, in cosmetic and food industry, in adhesives and coating industry, as well as in agriculture in the field of microencapsulated pesticides. [26, 27]

2.6.1 Food Industry

The applications of microencapsulation in food industry are:[28]

- Liquid delivery by coating with pre-designed release mechanism;
- The retention of volatile compounds for release under desired condition;
- Protection against the effect of evaporation and moisture, oxygen and ultraviolet light;
- Mixing of normally incompatible ingredients;
- Taste and odor masking-usually by encapsulation in coating that resists release in the mouth, but allows release in the digestive system;
- Use of coating to change the texture of density of solid materials;
- Special effects with unusual release system.

2.6.2 Aquaculture Industry

Microencapsulation techniques have been implemented to protect microencapsulated nutrients from degradation during processing, handling and reaction with other components in the formulation. Furthermore, they are also for feeding supplements in the aquaculture industry and can be potentially used as a replacement of feed. [29-32]

Types of microcapsules which have been developed are:

(1) Nylon cross-linked protein membrane

This was the first capsule type to be used in feeding experiment with marine organisms (i.e. rotifiers, *Artmis nauplii*, mollusca, crustacea and larval fish). The method for preparing nylon-protein-walled capsules is based on a process of interfacial polymerization, which occurs at the surface of aqueous droplets of protein and diamine emulsified in an organic solution of an anhydride acid dichloride.

(2) Liquid-wall microcapsules

This type of microcapsule consists of an aqueous core encapsulated within a wall of solidified lipid, which has been used for crustacea, mollusca and larva fish cultures.

(3) Gelatin-acacia microcapsules

Microcapsules produced by complex coacervation to incorporate lipids in experiments with larvae and spat of oysters.

2.6.3 Agricultural Industry

Agricultural chemicals have been used to fertilize land and to protect plants from insects. The controlled release of the substance which can limit the replication is achievable by the implementation of encapsulation.

2.6.4 Pharmaceutical Industry

Controlled release, for example aspirin, by the microcapsulation method (i.e. Phase separation and coacervation) had been reported by D'Onofrio *et al.* (1979). It is an example where drugs can be encapsulated to improve their product performance by taste or color masking to prevent oxidation, and enhancing other product characteristics. [33]

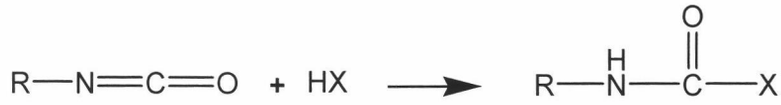
2.7 Isocyanate Chemistry

2.7.1 Primary Reactions

The chemistry involved in the synthesis of a polyurethane elastomer is centered on the isocyanate reactions. The high reactivity of isocyanate toward nucleophilic reagents is mainly due to the pronounced positive character of the C-atom in the cumulative double bond sequence consisting of nitrogen, carbon and oxygen, especially in aromatic systems. The electronic structure of the isocyanate group can be represented by several resonance structures, which are illustrated in Scheme 2.2. [34]

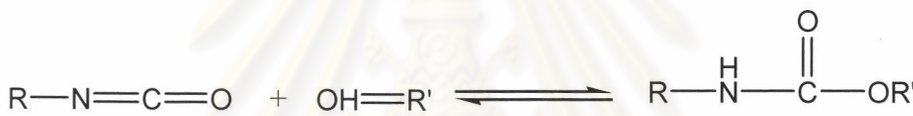
Scheme 2.2 Resonance structures of the isocyanate group

From the resonance structures, the positive charge at the C-atom becomes obvious. On the other hand, the negative charge can be delocalized onto the oxygen atom, nitrogen atom, and the R group, if R is an aromatic group. This explains why an aromatic isocyanate has a distinctly higher reactivity over an aliphatic isocyanate. Furthermore, the substituents on the aromatic ring can also influence the positive character of the NCO group: an electron withdrawing group in the para or ortho position increases reactivity, while an electron donating group reduces reactivity. The most important reaction of isocyanate is the formation of a arbamic acid derivative through the insertion of an acidic H-atom from the nucleophilic reactant to the C=N, which is illustrated in Scheme 2.3 This nucleophilic reaction is strongly influenced by the catalyst: e.g., acid compounds (mineral acid, acid halide, etc.) slow the reaction, whereas basic compounds (tertiary amines) and metal compounds (Sn, Zn, Fe salts) accelerate the reaction.



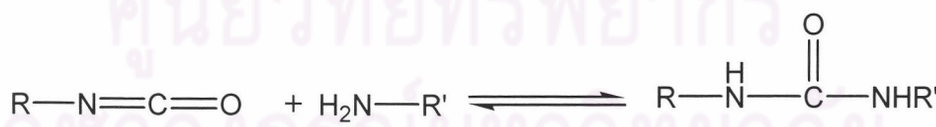
Scheme 2.3 Formation of carbamic acid derivative

When the nucleophilic reactants are OH containing compounds, carbamic acid ester, or urethane is formed. The reactivity of the hydroxy group decreases in the order of primary hydroxy, secondary hydroxy, and phenol, which is very unstable. The addition reaction is an equilibrium reaction and the isocyanate group can be regenerated at elevated temperatures, as shown in Scheme 2.4.



Scheme 2.4 Urethane linkage formation

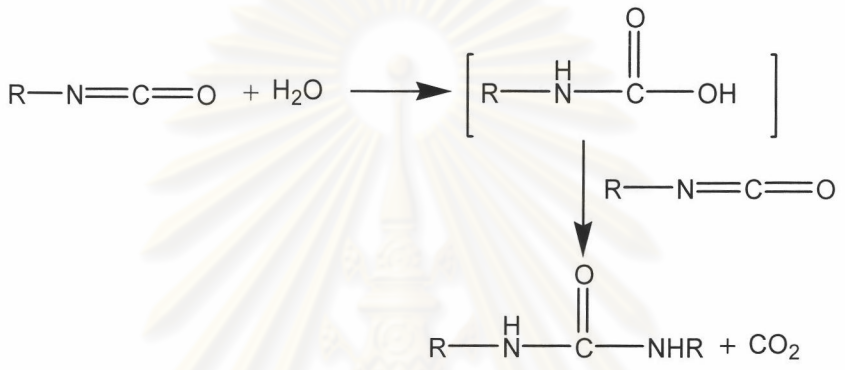
If the nucleophilic reactant is an amine-containing compound, the reaction between the nucleophilic reactant and the isocyanate will be much more vigorous. As a result, a urea linkage is formed as shown in Scheme 2.5.



Scheme 2.5 Urea linkage formation

The reaction between isocyanate and water is a special case of an alcohool/isocyanate reaction. In this reaction, the primary product is the carbamic acid, which is not stable and will decompose to the corresponding amine and carbon dioxide.

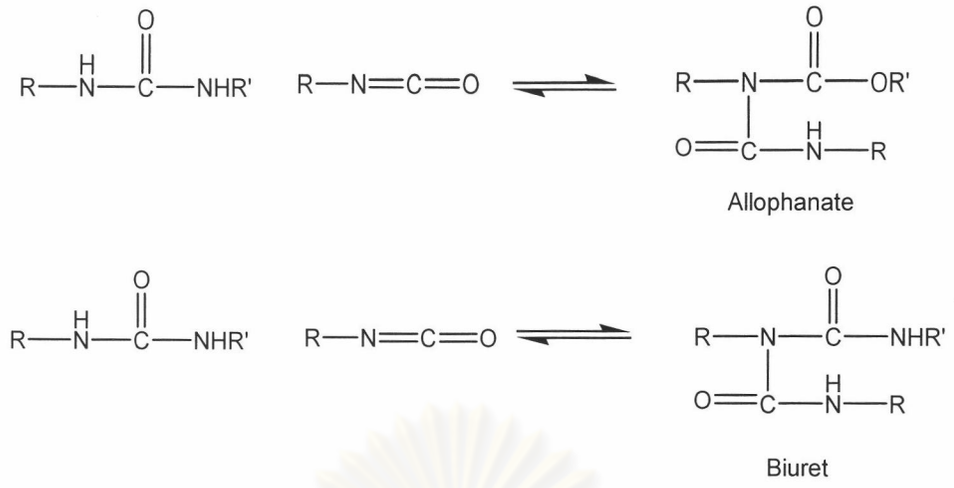
The amine formed will then react immediately with the isocyanate group in the system and forms a urea. This reaction is very important for the formation of polyurethane foam, since the carbon dioxide acts as a blowing agent. However, this reaction can also create problems in the storage of isocyanate. Moreover, to obtain a high molecular weight linear thermoplastic polyurethane, it is essential to completely exclude water from the reaction system, as illustrated in Scheme 2.6 .



Scheme 2.6 Reaction between water and isocyanate.

2.7.2 Secondary Reactions

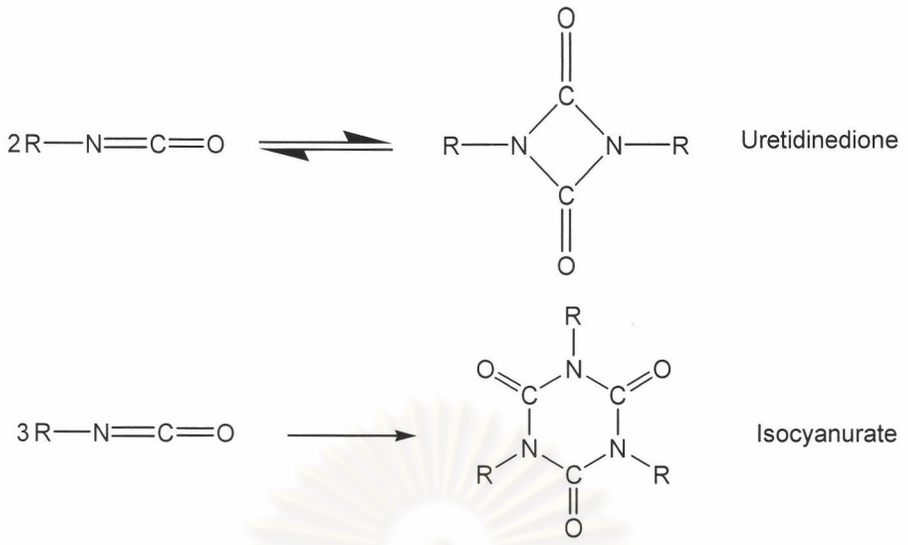
The urethane and urea formed from the previous reactions still contain active hydrogen. Even though the reactivity of these compounds is lower than the starting reactants, alcohol and amine, they are still capable of a nucleophilic attack at the isocyanate under more rigorous reaction conditions, which results in an allophanate and a biuret. Allophanates are usually formed between 120°C and 150°C and biurets are formed between 100°C and 150°C. Due to their low thermal stability, allophanates and biurets will dissociate into starting components above 150°C, as shown in Scheme 2.7.



Scheme 2.7 Formation of allophanate and biuret

The formation of allophanates and biurets can result in the polyurethane cross-linking. Since these bonds dissociate at elevated temperatures, a small amount of excess isocyanate functionality is often used in the polymerization to promote cross-linking while the polymer can still be melt processed.

In addition to these secondary reactions, isocyanate can also react with itself, especially in the presence of a basic catalyst. Isocyanate can dimerize and trimerize to give uretdione and isocyanurate, respectively, as shown Scheme 2.8. Dimerization is limited to aromatic isocyanates and it is inhibited by ortho substituents. For example, 2, 4- and 2, 6- TDI do not dimerize, while MDI dimerizes slowly at room temperature. Moreover, dimerization is also a readily reversible reaction above 150°C. However, the isocyanurates, which can be formed by heating both aliphatic and aromatic isocyanate, are very stable and the reaction cannot be easily reversed.

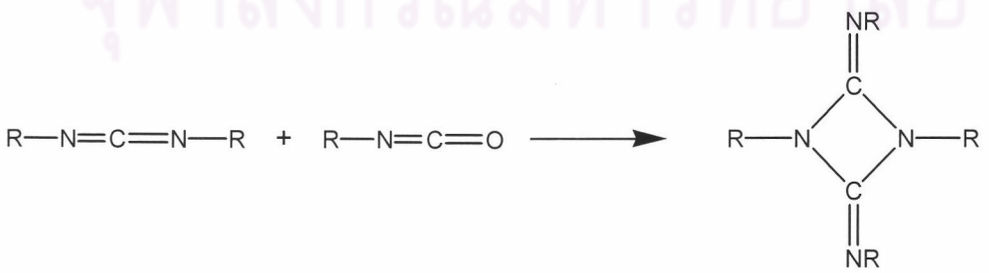


Scheme 2.8 Dimerization and trimerization of isocyanate

Another important reaction between an isocyanate and itself is the formation of carbodiimides , which is a condensation reaction that can only take place at high temperature without catalyst. However, with a catalyst, such as 1-ethyl-3-methyl-3-phospholine-1-oxide, it can occur at room temperature, as illustrated in Scheme 2.9.

Scheme 2.9 Formation of carbodiimide

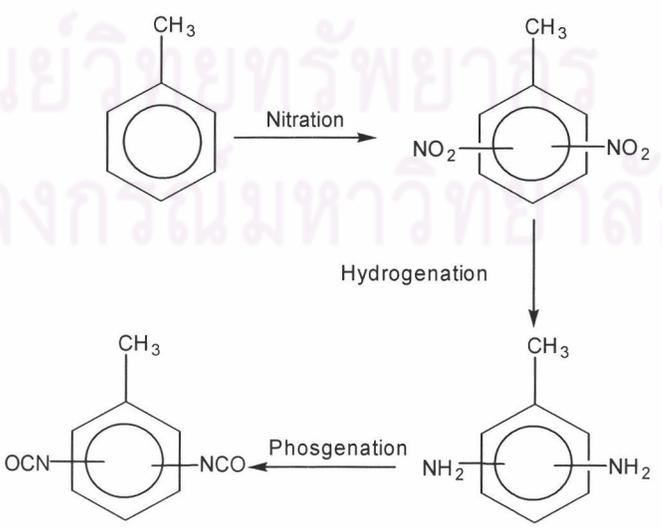
The carbodiimides formed in this condensation reaction can further react reversibly with an isocyanate group to form a uretoneimine as Scheme 2.10.



Scheme 2.10 Formation of uretoneimine

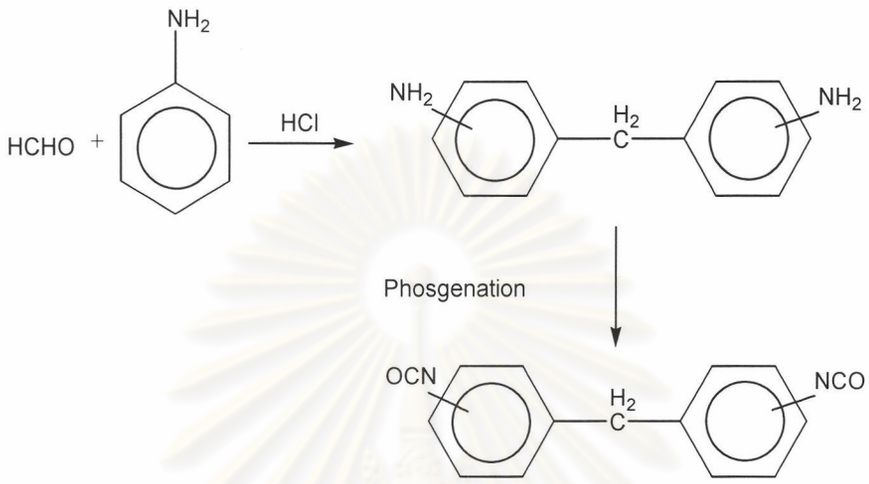
The most widely used diisocyanates are shown in Table 2.5. The aromatic isocyanates are more reactive than aliphatic isocyanates, which can only be utilized if their reactivities match the specific polymer reaction and special properties desired in the final product. Furthermore, the reactivity of an isocyanate group can vary dramatically even for the same class of isocyanate. The structure, substituents, and steric effect can all influence reactivity. For example, in 2, 4-toluene diisocyanate, the isocyanate group para to the methyl group is 25 times more reactive than the other NCO group at the ortho position. Moreover, the reactivity of the second NCO group can change as a result of the initial reaction.

Two of the most important aromatic isocyanates are TDI and MDI. TDI consists of a mixture of the 2, 4- and 2, 6-toluene diisocyanate isomers. The commercially available TDI is a mixture of these two isomers with various ratios, although the pure 2, 4- compound is also available commercially. TDI can be synthesized in a variety of ways, but is primarily produced by the phosgenation of the corresponding diamine, as shown in Scheme 2.11. This synthetic route often starts with toluene via nitration, hydrogenation, and phosgenation to generate the diisocyanate. The nitration process leads to a mixture of ortho-, meta-, para-nitrotoluene isomers and the mixture can be separated by several distillation steps.



Scheme 2.11 Synthesis of toluene diisocyanates

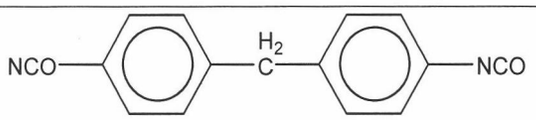
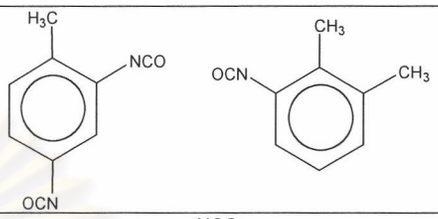
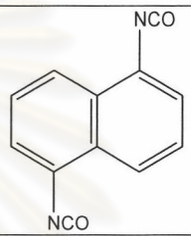
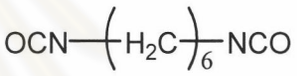
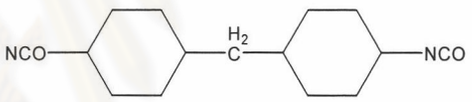
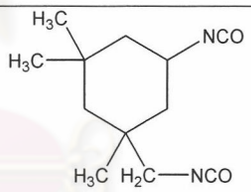
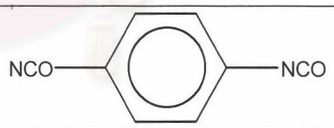
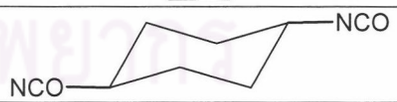
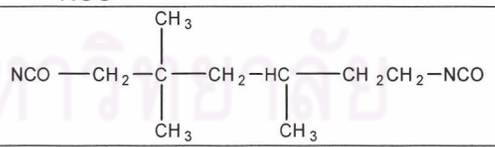
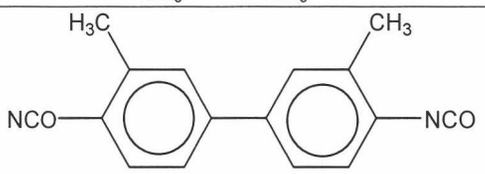
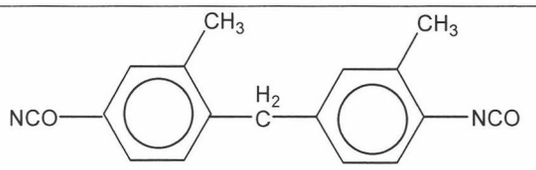
The starting materials for MDI are aniline and formaldehyde, which are reacted using hydrochloric acid as a catalyst, followed by phosgenation of the corresponding diamine as shown in Scheme 2.12.



Scheme 2.12 Synthesis of diphenylmethylene diisocyanates

Aliphatic isocyanates can also be made from the corresponding aliphatic diamines via the phosgenation process. Cyclic aliphatic diamines are, in many cases, available through ring hydrogenation of the corresponding aromatic amines, such as the hydrogenation of diamino diphenyl methane (MDA) to give diamino dicyclohexyl methane. The most important aliphatic isocyanates are 1, 6-hexamethylene diisocyanate (HDI), 1-isocyanato-3-isocyanatomethyl-3, 5, 5-trimethyl-cyclohexane (IPDI) and 4, 4'- diisocyanato dicyclohexylmethane (H_{12}MDI). These aliphatic isocyanates, or their modified forms, are widely used in the coating industries.

Table 2.5 The most widely used diisocyanates.

Diisocyanate	Structure
4,4'-methylenediphenyl diisocyanate (MDI)	
2,4-,2,6-toluene diisocyanate (TDI)	
1,5-naphthalene diisocyanate (NDI)	
1,6-hexamethylene (HDI)	
4,4'-dicyclohexylmethane diisocyanate (H_{12}MDI)	
3-isocyanalomethyl-3,5,5-trimethylcyclohexyl isocyanate (isophorne diisocyanate IPDI)	
Para-phenylene diisocyanate	
Cyclohexyl diisocyanate	
2,2,4-trimethyl-1,6-hexamethylene diisocyanate (TMDI)	
3,3'-toluene-4,4'-diisocyanate	
3,3'-dimethyl-diphenylmethane-4,4'-diisocyanate	

2.8 Literature Review

Ichikawa, [35] studied the polyurethane-urea microcapsules prepared by an interfacial polymerization method with various core-to-wall ratios. Tricresylphosphate and cumenphenetyle were used as core materials; triisocyanate monomer and hexamethylenediisocyanate were used as wall-forming materials. In this work, dynamic mechanical measurements were carried out on the microcapsules coated on a paper substrate. The shift factor in the Williams-Landel-Ferry equation was described for the mechanical properties of microcapsules and discussed in term of a morphological change of microcapsules. T_g as the temperature of tan δ peaks decreased with increasing amounts of core materials without affecting the apparent activation energies. The apparent activation energies of the glass transition were estimated at about 100 kcal/mol. The results indicate that the glass transition region of the microcapsule wall polymer does not change when introducing the core material. Thermal expansion of microcapsule increases when increasing the core-to-wall ratio. The shift factors were found to depend on the core-to-wall ratio and the morphological change described in term of the dependences of C_1 and C_2 on the core-to-wall ratio.

Dobashi, et al., [36] studied the structure of polyurethane-urea microcapsules containing phosphoric acid; triisocyanate monomer was used as a wall-forming material. Microcapsules with a diameter of the order of 0.1 micron have been investigated by means of static and dynamic laser light scattering, synchrotron small-angle X-ray scattering (SAXS), viscosimetry, and electron microscopy. Static light scattering and SAXS were used to investigate in the concentration range of 1×10^{-5} - 5×10^{-4} g/cm^3 and 1×10^{-3} - 0.14 g/cm^3, respectively, gave the same z-average radius of gyration (R_g= 110 nm). The hydrodynamic radius R_h = 143 nm as determined by dynamic light scattering is close to the viscosity radius R_η = 151 nm obtained from intrinsic viscosity measurements of the microcapsule suspension. By assuming the

microcapsule as a solid sphere, the radius of gyration estimated from R_h was $R_{g,cal}$ = $0.78R_h$ =112 nm. The agreement of R_g and $R_{g.cal}$ as well as R_h and R_η strongly suggests that in a wet form, the protective colloid has stuck tightly onto the surface of the microcapsule. The number-average radius R_η obtained from electron microscopy was $R_{g,\,cal,e}$ = 91 nm, being slightly smaller than those obtained in the wet state.

Dobashi, et al., [37] studied the scattering of poly(urea-urethane) microcapsules in suspension, containing tris(3-2-chloroethyl)phosphate as the core material. These results were compared with the previously published data for microcapsules with the same membrane but different core materials. The *z*-average radius of gyration R_g = 130 $\pm$ 4 nm from static light scattering and 120 $\pm$ 8 nm from ultrasmall angel X-ray scattering, which coincide with the calculated value of R_h from dynamic light scattering (DLS).

Hong and Park [38] studied the polyurea microcapsules containing migrin oil as core material, 1,4-diamino anthraquinone (DAA) as penetrator, one of three different compositions of ethylene diamine (EDA) and 1,6-hexane diamine (HDA), and 2,4-toluene diisocyanate (TDI) as a wall material. The effects of dimaine type on structure, thermal properties, particle size distribution, morphologies, loading content and release behavior of core materials of the resulting microcapsules were investigated. The rapid wall forming of EDA, faster than HDA can describe the rougher surface, wider particle size distribution and higher loading content of EDA-based polyurea microcapsules. The release rate and thermal properties seem to be related to wall thickness of the microcapsules from different compositions, irrespective of the size of emulsion globules.

Hong and Park [39] studied the morphologies and release behavior of polyurea microcapsules containing migrin oil, 4,4-diamino anthraquinone (DAA) prepared from

different molar ratios of isophorone diisocyanate (IPDI) and toluene diisocyanates (TDI) as wall materials in an emulsion polymerization. The transmittance (%) of a spectrophotometer used for the measurement decreased with the content of aliphatic IPDI in the wall; the completely dissolved microcapsules in dimethyl acetamide (DMAc) by UV/Visible increase the wall thickness due to its inferior reactivity to aromatic TDI. Morphology results showed that polyurea microcapsules from the higher TDI had rougher surfaces than IPDI-base polyurea microcapsules which demonstrated the relation of the release rate to DAA via the polyurea wall.