

IFSCC MONOGRAPH

Number 4

Introduction to Cosmetic Emulsions and Emulsification



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Published on behalf of the
**International Federation of Societies
of Cosmetic Chemists**
by



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General Preface to the Series

There are many excellent, authoritative textbooks covering the different areas which comprise Cosmetic Science. However, certain topics cut across these various disciplines and are best studied individually. From the study of such a topic, a better appreciation can be achieved of the practical use of that topic in the cosmetic field. This series of IFSCC monographs is a collection of such intersecting themes.

It is hoped that the knowledge gained from identifying activities common to a number of areas will be transferable when a chemist moves from project to project. This series of monographs will cover a wide range of themes compiled by experts in their fields, providing both the novice and the experienced individual with valuable reference books on the major topics of Cosmetic Science.

Monographs already published in this series are

IFSCC Monograph No. 1: *Principles of Product Evaluation — Objective Sensory Methods*

IFSCC Monograph No. 2: *The Fundamentals of Stability Testing*

IFSCC Monograph No. 3: *An Introduction to Rheology*

In a further series, the IFSCC has also published

Cosmetic Raw Material Analysis and Quality, Vol. 1: Hydrocarbons, Glycerides, Waxes and Other Esters, edited by Hilda Butler

Foreword

This monograph describes methods of preparation and basic properties of cosmetic macroemulsions. Details of the theory of emulsification are held to a minimum. Instead, the reader is exposed to recommendations for overcoming many of the problems encountered during formulation. Among these suggestions are the selection of emulsifiers and auxiliaries; antimicrobial and antioxidant preservation; and stability and its assessment. A limited number of references is provided for further study.

This monograph is intended to answer questions raised by the inexperienced formulator and to introduce the better versed to some of the intricacies of emulsion development.

The IFSCC is grateful to Dr Martin Rieger for preparing this monograph on emulsions and emulsification.

Contents

	<i>Page</i>
<i>IFSCC Benefactors</i>	iii
<i>General Preface to the Series</i>	iv
<i>Foreword</i>	v
1 Introductory Comments	1
1.1 Definitions	2
1.2 Nature of emulsions	4
2 Emulsion Creation	7
2.1 Overview	7
2.2 Agitation	9
2.2.1 Mechanical agitators	9
2.3 Nature of the emulsifier	11
2.3.1 HLB	16
2.3.2 Associative thickeners	20
3 Emulsion Preparation	22
3.1 Oil-in-water emulsions	23
3.1.1 Phase-inversion temperature	23
3.1.2 Auxiliary emulsifiers	28
3.1.3 Practical examples	30
3.2 Multiphase oil-in-water emulsions	32
3.3 Water-in-oil emulsions	35
3.4 Microemulsions	38
3.5 Functionality of cosmetic emulsions	39
3.5.1 Emulsion skin cleanser	39
3.5.2 Emulsion skin treatments	40
4 Emulsion Preservation	43
4.1 Antimicrobial preservation	43
4.2 Antioxidant preservation	46

Introduction to Cosmetic Emulsions and Emulsification

5	Emulsion Stability	51
5.1	Chemical stability	51
5.2	Microbiological stability	53
5.3	Physical stability	54
5.3.1	Viscosity	55
5.3.2	Droplet size	56
5.3.3	Stress conditions and other criteria	57
6	References	60

1 Introductory Comments

This review of some fundamentals of emulsions is intended to be the first in a series of IFSCC monographs describing different emulsions and their methods of preparation. This monograph is designed to provide readers, especially those who have had only limited exposure to the scientific foundation of emulsification, with an understanding of basic principles.

In principle, emulsions are combinations of two or more immiscible phases. Various additives are required for stabilization. Emulsions can then be identified as dispersions of the constituent phases in which the tendency to separate is reduced or, in some cases, eliminated.

Emulsions are usually difficult to formulate and require the presence of many ingredients for preparative purposes as well as for stability. There must be valid reasons for creating emulsions since direct application of a desired component to the skin is feasible. The emulsions of interest in this monograph are cosmetic and are applied topically. The need for emulsified orally administered drugs, for ingested emulsions, and for parenteral emulsion dosage forms is based on experimental evidence and scientific reasoning. It is more complex to explain why cosmetic users are comfortable with and demand emulsions for skin care.

Some reasons for the attractiveness and the utility of cosmetic emulsions have been advanced: the ability to blend immiscible components; reduction of long-lasting unctuousness after application; control of viscosity; lowering of cost by dilution with water; and the ability to control the delivery of actives to the skin. The continuing acceptance of skin-care emulsions by consumers may depend on the above but, in addition, includes traditional, fashion-dictated, and emotional trends.

Consumers view the opaque characteristics of emulsions as a visual signal that the product is gentle and likely to benefit the skin. A clear product, by contrast, may be viewed by some as harsher and potentially harmful but may also convey an image of purity. These perceptions are probably learned responses and have little if any scientific support. Clear water is recognized as innocuous, and the clear vegetable oils used for millennia for religious ceremonies and inunction are well tolerated. Some of the chemicals required for stabilizing opaque (milky or creamy) emulsions are, in fact, more likely to damage skin than a totally unstable two-layer preparation consisting only of water and olive oil. To the formulator, an opaque cosmetic emulsion for commercial use presents a real challenge because such products exhibit only a limited

shelf-life. Opaque emulsions are difficult to prepare and are not robust enough to resist adverse conditions; their long-term instability presents a constant worry. Chemists know how to make a mixture of sodium chloride and water, and the technical literature on this simple procedure is very limited. In contrast, the literature on the making of emulsions is extensive; nevertheless, the majority of chemists do not know how to proceed in making a temporarily stable and homogeneous blend of two essentially immiscible substances.

As a rule, the efficacy and acceptance of cosmetic skin-care preparations depend largely on the presence of lipidic (or oily) substances. In order to avoid leaving the skin greasy, the amounts used must either be severely restricted or the lipid-like constituent must be drastically diluted. Of all the diluents or solvents available, water is not only the least expensive but is also the most innocuous. The use of water in emulsion-type skin-care preparations is mandated primarily by the consumer's desire for a non-greasy skin finish. Dilution with water is a particularly attractive approach so long as such dilution results in a safe and moderately stable preparation. In addition, some investigators have postulated that an emulsified lipidic component is more likely to penetrate into the stratum corneum than the pure emollient and thus can provide enhanced skin benefits.

It is the primary objective of this monograph to provide some insight into the intricacies of preparing cosmetic emulsions. The general coverage of this topic is broad, with minimal emphasis on the frequently complex details concerning emulsions. The IFSCC plans to provide more detailed information through subsequent monographs.

1.1 Definitions

We are now ready to provide a simple definition of a cosmetic emulsion as a blend of one or more lipids with an aqueous component in the presence of suitable emulsion stabilizers. Customarily, the lipid is a fluid at or near room temperature, but there are no theoretical restrictions on the physical nature of the lipid. An emulsifier (or blend of emulsifiers) is normally required to help in the dispersion of the two essentially immiscible phases (oil and water). An emulsion is identified as *water-in-oil* (W/O) if the oil is the *external* or *continuous* phase. By contrast, an *oil-in-water* (O/W) emulsion is one in which the oil represents the *emulsified* (*internal*, *disperse*, *discontinuous*) phase. The *emulsifiers* are the materials which make it possible to disperse the internal

phase in the form of fine *droplets* (or *globules*) in the external phase. A well-known O/W emulsion is milk, in which the droplets of the disperse phase have diameters ranging from about 750 to more than 1000 nm. The short-term stability of milk is due to the presence of some proteinaceous and phospholipid-like emulsifiers. These substances are not efficient emulsifiers, and milk has a tendency to cream under the influence of gravity. During creaming, some of the dispersed oil droplets rise to the surface and may even flocculate (adhere to each other). The droplets do retain their shape, and creaming is reversible by simple shaking. On the other hand, if the creamed droplets coalesce, that is, form larger globules, shaking alone cannot reconstitute the emulsion. Finally, if coalescence is allowed to continue, the system may separate completely, forming a waxy/oily mass, known as butter, and a serum consisting essentially of a solution of a protein with some carbohydrates, known as whey.

The opaque, or coarse, emulsions discussed so far are often referred to as *macroemulsions*. Such emulsions (O/W or W/O) reflect all visible light and, unless tinted, are white. The internal phase in macroemulsions is polydisperse, that is, it consists of particles of various dimensions. Some or most of them reflect light.

Clear emulsions are products in which the internal phase is present in particles which do not reflect light, that is, they are much smaller than those found in macroemulsions. Such emulsions are, therefore, often referred to as *microemulsions*. The division of emulsions into macro- and microemulsions is somewhat arbitrary and is based on perception by the human eye. Another method of viewing or lighting may make a microemulsion appear hazy (Tyndall effect). The polydispersity in most emulsions suggests that even a macroemulsion may contain some of the small particles normally associated with microemulsions.

An additional complication has been created by the concept of *sub-micron emulsion*. These emulsions appear opaque to the human eye, but the particle size is less heterogeneous and might be small enough to allow sterile filtration. Submicron emulsions are formed from coarser emulsions by high-pressure homogenization and filtration to yield essentially monodisperse, low particle size emulsions with particles smaller than 1000 nm, ranging as low as 100 to 200 nm. These emulsions are designed primarily for parenteral drug administration,¹ and some can be sterilized by filtration.² The particle size in these formulations tends to increase with aging. They are not widely used in cosmetics and will not

be discussed further. Reference 1 provides a good introduction to this subject for interested readers.

The definitions given above are almost universally recognized. Typical is the glossary of terms suggested by a workshop cosponsored by the American Association of Pharmaceutical Scientists, the Food and Drug Administration, and the *United States Pharmacopeia* (Scale-up of liquid and semisolid disperse systems, in *Pharm. Technol.* June 1995, pp. 52–62).

1.2 Nature of emulsions

The emulsification processes in the food, drug and cosmetic industries require the use of effective emulsifiers. The first task of these emulsifiers is to make the oil phase and the aqueous phase more compatible. When oil and water are vigorously blended in the absence of any type of emulsifier, the two phases separate rapidly into two layers to minimize interfacial tension. The presence of an emulsifier at or near the interface lowers interfacial tension, and the rate of separation into two phases is decreased significantly. Emulsifiers, however, cannot overcome the thermodynamic instability (tendency to separate) of macroemulsions; instead, they can only *postpone* the ultimate fate of a macroemulsion to separate. In order to delay separation further, formulators must employ auxiliaries which help to retard separation still more.

The only types of emulsion that are thermodynamically stable are the so-called microemulsions. In contrast to macroemulsions, the globule size of microemulsions is only about $1/5$ that of the wavelength of visible light (i.e. about 100 nm or less). For purposes of orientation, some particle size ranges are shown below:

Table 1
Particle sizes of various dispersions

<i>Physical form</i>	<i>Particle size</i>
Solutions	< 5nm
Micelles	5–10 nm
Swollen micelles and microemulsions	5–100 nm
Polymeric latices	15–1000 nm
Emulsions and suspensions	> 1000 nm

Microemulsions are energetically at a minimum and form and reform spontaneously. The exact nature of microemulsions is still disputed. The original concept of Schulman relied on the formation of a clear emulsion by addition of a cosurfactant (usually an intermediate chain-length alcohol) to a coarse macroemulsion. In a somewhat different interpretation, the solubilized substance is believed to be trapped inside a micelized surfactant or surfactant mixture (swollen micelle). An alternative explanation of the nature of transparent emulsions relies on the existence of irregular bicontinuous structures in these oil/water/surfactant/cosurfactant blends. More details concerning this dispute and a more basic description of microemulsions can be found in Attwood's excellent review.³ In practice, microemulsions appear clear within a limited temperature range. Microemulsions require larger amounts of emulsifiers to achieve the desired visual clarity than those required for macroemulsions. Without explaining the intricacies of phase diagrams, one can clarify the relationships between temperature, emulsifier concentration, and the type of emulsion (macro vs micro) formed by reference to

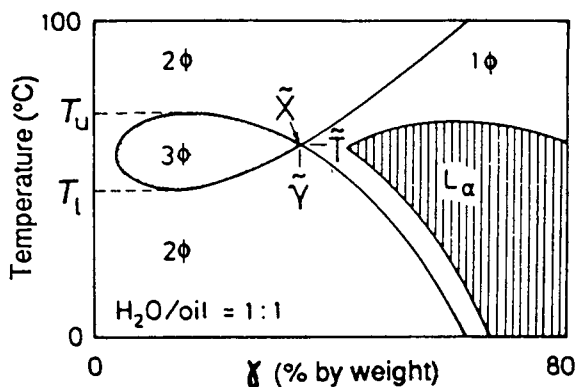


Figure 1. Kahlweit fish. Schematic phase diagram of a mixture of water, oil and nonionic amphiphile of mass fraction γ . To the left (at low γ) a 2-phase W/O macroemulsion forms above T_u , while below T_l a 2-phase O/W macroemulsion exists. At or near T (between T_u and T_l) one finds a 3-phase system. As γ is raised, a coordinate point X is reached at T where γ is just sufficiently high to form a 1-phase microemulsion system. L_α , a lamellar mesophase, exists at still higher γ . [From Ref. 25. Reproduced by permission of the author and from *Science*, **240**, p. 619; copyright 1988, American Association for the Advancement of Science.]

the so-called *Kahlweit fish*⁴ (see Fig. 1). A more classical isothermal presentation of these interactions was provided by Constantinides.⁵

Finally, readers must understand the concept of multiple emulsions. In recent years, formulators have learned how to compound oil-in-water-in-oil (O/W/O) emulsions or the reverse water-in-oil-in-water (W/O/W) emulsions. The principle depends on emulsification of an O/W primary emulsion in an oil phase, or the reverse. The stability of such emulsions depends on the absence of diffusive processes and is severely limited. At the moment, these types of emulsions find only limited cosmetic usage, although their intermediate formation during more conventional emulsion preparations cannot be ignored. Multiple emulsions will not be covered further in this monograph. Some pertinent references for use by interested readers are 6 and 7.

2 Emulsion Creation

The formulator of a cosmetic emulsion has to carry out numerous, often interrelated tasks. The objective is to examine these tasks in an orderly sequence, and they will then be described below in some detail.

2.1 Overview

A primary step in forming an emulsion is the subdivision of the internal phase into the continuous phase, i.e. the creation of a dispersion. The interfacial tension of a blend of the continuous and the dispersed phases causes separation into bulk phases to reduce the contact area between the two phases. The reduction of particle size of the bulk disperse phase into small globules causes a large increase in the contact area of the two phases, with an accompanying rise in the free energy. Coalescence to two or more bulk phases is a thermodynamic necessity. Maintenance of the two phases in the dispersed state is not possible without some modification in the interfacial tension. In modern emulsion practice, the formulator depends on an emulsifier or on a blend to maintain the dispersion of the internal phase, created usually by mechanical means.

Usually, the emulsifier(s) is added to the system at the time of dispersion. The emulsifier(s) is an amphiphilic substance which tends to be adsorbed at the interfaces of two essentially immiscible phases. The physical picture of an emulsifier on the surface of a droplet of the internal phase shows its alignment of the hydrophilic and hydrophobic segments of the molecule to create a palisade covering the interface. In the case of an O/W emulsion, the emulsifier's hydrophobic end contacts or is dissolved in the oil phase, while the hydrophilic end of the molecule preferentially contacts the hydrophilic continuous phase. A second emulsifier which may be predominantly hydrophilic may be concentrated at the surface of the hydrophilic phase, while its hydrophobic segment is expected to contact the dispersed oil phase.

The alignment of an emulsifier at the interface also controls what type of an emulsion (O/W or W/O) is formed. In accordance with Bancroft's rule, the emulsifying agent can be expected to be more soluble in — or at least better wetted — by the continuous phase than by the disperse phase. Although of limited utility in the modern practice of blending nonionic emulsifiers, Bancroft's rule (enunciated before 1940) helps us understand why a blend of benzene and water forms an O/W emulsion with (water-soluble) sodium oleate but forms a W/O emulsion with

(oil-soluble) magnesium oleate. The exact alignment of the emulsifier molecule at the interface is not entirely clarified but is related to the emulsifier's ability to micellize and/or to associate with other molecules.

As a rule, the type of dispersion required in cosmetics cannot be achieved without some mechanical force. The energy required is supplied by agitators or similar devices over a period of time. It is the emulsifier's purpose to prevent coalescence of the internal phase, while the agitation device creates new and additional interfacial areas. Once agitation has been terminated, the formulator normally depends on the presence of the emulsifier to maintain the desired level of dispersion.

Before discussion of agitation devices and emulsifiers, it is essential to address some additional points, as follows:

1. During and after emulsification, the particle size distribution is normally heterogeneous. Thus, an emulsion can be expected to contain some small as well as some large droplets. The latter are especially hazardous to an emulsion's long-term stability, and their elimination is critical for the creation of a high quality emulsion.

2. Even after completion of emulsification, a process known as Ostwald ripening continues. In suspensions both large and small particles are in equilibrium with the external phase, which has some finite solubility for the particle's components. One may expect that small particles dissolve before large ones. The resulting temporary supersaturation is alleviated by deposition (precipitation) on the surviving larger particle. The result of these and related processes encourages growth of large particles at the expense of small particles. Ostwald ripening is one of the contributors to long-term instability of macroemulsions.

3. Exceedingly small components, i.e. those resembling the droplets in a 'clear' emulsion, can also contribute to uncertainties of emulsion stability. The previously noted spontaneous formation/reformation of microemulsion droplets in a macroemulsion creates a pool of free emulsifier in the preparation, or it may withdraw emulsifier from the interface. In other words, a macroemulsion containing a range of droplet sizes is not at or near equilibrium, and changes should be expected. In fact, these changes in particle size are considered an early indication of instability.

Additional tasks for generating an acceptable cosmetic emulsion include: incorporation of stabilizers (coemulsifiers) to prolong the shelf-life of the emulsion; selection of an effective preservative system to prevent microbiological spoilage, and other chemicals to control, for example, oxidative damage, the pH and any other unwanted changes.

2.2 Agitation

Stirring, homogenization and the like are used by formulators to create small particles of the dispersed phase. Small particles are generally viewed as providing better stability than larger particles. Nevertheless, experienced compounders know that excessive agitation after emulsification can lead to instability.

The need for mechanical break-up of the internal phase has already been noted in passing. Although this type of particle size reduction is optimally achieved by introducing the vaporized internal phase into the external phase, this is not a practical means for making cosmetic emulsions. Instead, formulators depend almost exclusively on agitation for creating the initial dispersion. The most widely used equipment is a mechanical stirrer. In addition to this primary dispersion tool, homogenizers, colloid mills, and ultrasonifiers may be employed normally after the primary emulsion has been created.

In principle, the break-up into small particles requires the expenditure of a considerable amount of energy.

2.2.1 Mechanical agitators

The introduction of one immiscible liquid into another regardless of the amount of agitation produces only a temporary dispersion. In order to make a longer lasting dispersion, coalescence must be slowed down through the use of emulsifiers or gums. Shear and turbulence are generated by the agitator. The level and time of agitation required depend on the amount of the mixture, its viscosity, and the phase ratio. During the period of agitation, the initially formed large droplets should be further reduced in size. If the level of emulsifier is too low or if the wrong emulsifier is used, coalescence will occur despite the continuous input of agitation because the interfacial tension is not lowered sufficiently.

This monograph is not intended to acquaint the reader with the intricacies and varieties of mechanical devices designed for use in pilot plant and production of cosmetic emulsions. For specific details, it is best to consult manufacturers of these devices. It is important to remem-

ber that equipment used successfully in the laboratory may not function equally as well during scale-up or in production. In addition, the time required and the heating/cooling cycles vary widely.

Stirrers If the chemical blend employed is correctly compounded, stirring with an impeller mounted on a shaft should result in emulsion formation. The propeller is normally top-mounted for routine laboratory development work. More vigorous agitation, required for more viscous preparations, is achieved by the use of a turbine-type mixer. Paddle blades, counter rotating blades, or planetary types of mixers may also be used in the laboratory. The more sophisticated types of mixers are routinely used in production and may include scraper blades if heat transfer should interfere with uniformity, especially during the cooling cycle. As explained below, most emulsions are prepared at elevated temperatures, and cooling to room temperature is an essential step.

Homogenizers After the initial emulsion is formed by simple agitation, further reduction in particle size can be achieved by passing the product through a homogenizer. This type of equipment generally forces the emulsion through a small orifice at high pressure. The liquid impinges on a homogenizing valve held in place by a spring, the tension on which can be manually adjusted. When the pressure of the incoming liquid compresses the spring, the liquid is forced to pass through the narrow gap between the valve and the valve seat. Homogenizers with multiple valves exist. Other types allow recycling of the effluent. The design of homogenizers can vary widely and includes equipment employing a rotor and a stator.

Ultrasonifiers Ultrasonifiers are particularly useful for fluid emulsions produced in relatively small quantities in the laboratory. Commercial equipment usually requires moderately high pressure to force the liquid (emulsion) to impinge on a blade which vibrates rapidly, producing a cavitation field of high-pressure fluctuation.

Colloid Mills Colloid mills are used primarily for grinding. However, they can also reduce droplet size in emulsions and are widely used to process pigmented emulsions.

Foaming Foaming during the preparation of emulsions is caused by the lowering of surface tension due to the presence of the emulsifier. The presence of stable foams, especially in viscous systems, can be very troublesome. For this reason, the incorporation of air during agitation should be avoided. The use of closed systems and of vacuum-processing is widely practiced. Some substances (long-chain alcohols and silicones) tend to accelerate foam collapse, but their use may affect the character of the emulsion.

Despite a general recommendation to work with suppliers on up-to-date emulsification equipment, readers might find it useful to consult some existing published broader reviews.^{8,9}

2.3 Nature of the emulsifier

Emulsifiers are amphiphilic substances or surfactants. They obey the Gibbs equation which relates the change in concentration of a surfactant to its concentration at any interface. In a dilute aqueous solution of a surfactant, e.g. sodium lauryl sulfate (SLS), the surfactant's concentration in the bulk solution is slightly lower than at the hypothetical air/liquid interface. As the concentration of SLS is increased, the surface tension tends to decrease up to a point, while the concentration in the surface increases. Gibbs derived his famous equation (Eq. 1) from purely thermodynamic arguments, and this equation, shown below, expresses one of the most fundamental concepts in surface chemistry.

$$\Gamma_2 = RT \frac{d\gamma}{d(\ln C_2)} \quad [\text{Eq. 1}]$$

where Γ_2 is the excess surface concentration, γ is the surface tension, and C_2 is the bulk concentration of the surfactant; R and T have their usual meanings.

The physical interpretation of the Gibbs equation — using an aqueous SLS solution as an example — depends on understanding that the hydrophobic portion of the amphiphile is forced to the air/liquid interface to reduce its contact with surrounding water molecules. As the concentration of the amphiphile is increased, space at the surface becomes scarce, and the amphiphilic surfactant tends to form aggregates (micelles) in order to minimize hydrophilic/hydrophobic interactions.

If the concentration is increased still further, the size of the aggregates continues to grow until the aggregation number approaches a maximum at the critical micelle concentration. Any additional increase in the surfactant level does not lower surface tension further but results in the formation of more micelles or of differently shaped micelles. Both the precise shape and the exact size of micelles remain controversial. An entirely analogous interpretation explains the location of a typical emulsifier in systems containing oil and water. In this case, a water-soluble surfactant is driven out of the aqueous phase to the lipid/water interface where it forms a palisade-like structure. The reverse mechanism drives oil-soluble emulsifiers to the water/oil interface. The presence of any emulsifier in these mixtures lowers the interfacial energy. Any excess emulsifier then dissolves (or forms micelles) in one of the two phases on the basis of polarity.

In modern emulsion technology, approximately spherical (Hartley) micelles may become the predominant species. Spherical micelles form at relatively low concentrations, while lamellar (McBain) micelles form at higher concentrations. Details of this type are of limited concern to emulsion formulators since emulsifiers are rarely used at high levels except occasionally in microemulsions. The formulator is likely to work with emulsifiers which have performed well in the past in similar formulations. Development and manufacturing personnel are generally more comfortable with established emulsifiers than with less thoroughly examined novel systems.

Emulsifiers are expected to aid in the emulsification and stabilization process by three widely accepted mechanisms. These concepts are based on theories and principles developed over many years in connection with the compounding of diverse emulsions. Today, investigators believe that the formation and stability of emulsions depend on the cooperative effects of three different mechanisms, as follows:

electrical repulsion;
lowered interfacial tension; and
formation of a rigid film on emulsified droplets.

1. The first of these mechanisms is referred to as the formation of an electrical double layer on the globule's surface. It is presumed that an ionizing (anionic or cationic) surfactant is a prerequisite for creating such a double layer. The presence of an electrical charge on the surface of a dispersed particle tends to repel a like electrical charge on an adjacent particle. This repulsion potential

reduces the tendency for close approach of two particles and can be a powerful emulsion stabilizing force.

For example, in an emulsion of avocado oil in water, stabilized with potassium oleate, the dispersed oil droplets are studied with negatively charged oleate ions. The oleate component is aligned on the surface by contact (or solution) of its hydrophobic tail in the oil droplets. The hydrophilic carboxylate anion heads and their counterions face toward the continuous aqueous phase. As a result, the oil globule can be expected to carry a number of negative surface charges which in turn are neutralized by potassium cations. When two such droplets approach each other, the aqueous shells surrounding the globules experience repulsion due to the presence of identically charged ions. This explanation is admittedly simplistic since the presence of additional ionized species, e.g. potassium chloride, in the aqueous phase, adds to the system's complexity.

2. The second effect is due to the lowering of the interfacial tension, known also as thermodynamic stabilization. Its significance has already been discussed in connection with the Gibbs equation. This mechanism probably plays a most important role in the formation and stabilization of both O/W and W/O emulsions.

3. In recent years, investigators have paid a great deal of attention to the formation of a rigid interfacial film on the globule surface (the third effect). This film is widely believed to consist of a liquid crystalline phase which surrounds each emulsified droplet.¹⁰ The exact nature of these structures (lamellar gel phases, lyotropic hexagonal phases, or lamellar liquid crystalline phases) may vary from emulsion to emulsion. Their precise identification is complicated by the fact that their composition is both concentration- and temperature-dependent.

The existence of a so-called third phase was postulated by Friberg *et al.*^{10,11} The third phase in most cosmetic emulsions consists primarily of liquid crystals. Their formation during emulsification is highly dependent on the nature and concentration of the emulsifier(s). Optical microscopy in polarized light is the primary tool for detecting the presence of these structures in emulsions. They stabilize emulsions against coalescence by altering the van der Waals potential as the drops approach each other.

A liquid crystalline phase surrounding an oil globule is quite viscous and resists compression by forming relatively thick ($\approx 1 \mu\text{m}$) films. They exhibit pseudoplastic rheology, and their resistance to deformation accounts for their ability to stabilize globules against coalescence. The liquid crystals involved in these stabilization phenomena are systems containing quantities of emulsifiers, some of the dispersed phase lipid and water. The long-known fact that mixtures of emulsifiers yield more stable emulsions than a single surfactant may well be the result of enhanced liquid crystal formation by such blends. In another interpretation of the benefits of mixed emulsifiers, it is postulated that the blend creates a more condensed monolayer film at the interface.

To some extent, the presence of some solids can contribute to emulsion stability. The efficacy of solids depends on their wetting angles (in water or in oil) and their resistance to being fully 'immersed' in one of the emulsion's phases.

It is generally recognized today that the formation of liquid crystals on the surface of water droplets emulsified in an oil (i.e. in a W/O emulsion) is unlikely. In the absence of direct and conclusive evidence, the contribution to W/O emulsion stability from liquid crystals is, at best, presumptive.

Despite the important contributions from electrical charges to emulsion stability, most skin-care cosmetic emulsions rely on uncharged emulsifiers (nonionics). The primary reason for formulators to choose nonionics is their purported safety by comparison to anionic or cationic emulsifiers and their high tolerance for the presence of electrolytes. Cationics, as a group, are poor emulsifiers by comparison to other surfactant classes. The frequent use of cationics in emulsions is due to their substantivity to hair and skin protein and their resultant conditioning action.

The number of types and variations within groups of emulsifiers used in cosmetic emulsions are large. Table 2 is intended to classify the more frequently used cosmetic emulsifiers by type.

Table 2
Common types of surfactants used in cosmetic emulsions

<i>Surfactant class</i>	<i>Representative</i>
Anionics	
Carboxylic acids	Soaps
Carboxylic acid esters	Lactylates PEG-Alkyl carboxylates
Sulfuric acid esters	Alkyl sulfates Sulfated monoglycerides
Sulfonic acids	Sulfosuccinate esters Acyl isethionates
Amino acid amides	Sarcosinates Acylated peptides
Cationics	
Amines	PEG-Alkyl amines
Quaternaries	Tetraalkyl ammonium salts
Amphoterics	
Phosphates	Phospholipids
Amine derivatives	N-Alkyl amino acids Alkylamido alkylamines
Nonionics	
Alcohols	Fatty alcohols
Ethers	Alkoxylated fatty alcohols PEG-Phenol ethers
Esters	Alkoxylated fatty acids Acyl sorbitans and PEG derivatives Acyl glycerides
Amides	PEG-Alkyl amides
Polymers ^a	PEG/PPG Block polymers PEG-Silicone derivatives Alkyl-substituted polyvinyl polymers

a. Polymeric emulsifiers may carry positive or negative charges. For convenience, they are grouped here with the nonionics.

2.3.1 HLB

Despite some elaborate schemes for identifying emulsifiers for the formulation of cosmetic and related emulsions, emulsifier selection remains an art based on trial and error. The number of available nonionic emulsifiers is large. The list of ionized emulsifiers — including soaps — is much more limited. Some of the more widely used nonionics are identified in Table 3, which lists them in order of increasing HLB (hydrophile/lipophile balance). The HLB concept was developed by Griffin in the years following the Second World War in order to classify ethoxylated emulsifiers. Griffin reasoned that the ratio of the hydrophobic portion to the hydrophilic portion of the emulsifier molecule determines its water solubility and efficacy as an emulsifier. He computed the HLB value from the following simple equation:

$$\text{HLB} = \frac{\text{Molecular weight of hydrophile}}{\text{Molecular weight of surfactant}} \times 20$$

in which hydrophile is defined as the polyoxyethylene (POE) portion of the molecule. Thus, a molecule consisting only of POE has an HLB of 20. Griffin extended his HLB approach to include ionic surfactants, and some of their HLB values are listed in Table 3. In practice, the best emulsification for most systems is provided by mixed emulsifiers, and most O/W cosmetic emulsions require HLBs ranging from about 6 to 15. Most commercial ethoxylated emulsifiers are mixtures, but formulators tend to blend a relatively low HLB surfactant with a high HLB for optimal results. An HLB of about 13 can be reached by blending 30 parts of PEG-4 oleate (HLB 8.0) with 70 parts of polysorbate 80 (HLB 15.0):

$$13 \approx 0.3 \times 8.0 + 0.7 \times 15$$

The HLB range of 6 to about 15 mentioned above depends on the nature of the emulsified oil phase (Table 4). Based on practical experience, formulators have learned that each oil requires a somewhat different HLB for formation of an O/W emulsion. Stearyl alcohol, for example, requires a moderately high HLB of about 15, while cottonseed oil requires a relatively low HLB of about 6; mineral oils and petrolatum can be emulsified at an HLB of about 8 to 12. In cosmetic practice, these variations are at best guidelines since the oil phase in a typical cosmetic may include as many as 8 to 10 lipids in varying ratios, and HLB requirements vary accordingly. Formulators must always consider the

Table 3
Cosmetic emulsifiers

<i>Chemical designation^a</i>	<i>HLB</i>	<i>Water dispersibility</i>
Ethylene glycol distearate	1.5	No dispersion
Sorbitan tristearate	2.1	"
Propylene glycol stearate	3.4	"
Sorbitan sesquioleate	3.7	"
Glyceryl stearate (non-self-emulsifiable)	3.8	Poor dispersion
Propylene glycol laurate	4.5	"
Sorbitan stearate	4.7	"
Diethylene glycol stearate	4.7	"
Glyceryl stearate (self-emulsifiable)	5.5	"
Diethylene glycol laurate	6.1	Milky dispersion (not stable)
Sorbitan palmitate	6.7	"
Sucrose dioleate	7.1	"
PEG-4 Oleate	8.0	"
Sorbitan laurate	8.6	"
Laureth-4	9.5	Milky dispersion (stable)
Polysorbate 61	9.6	"
Ceteth-6	10.3	"
Polysorbate 65	10.5	Translucent to clear
PEG-8 Oleate	11.4	"
PEG-8 Stearate	11.6	"
Nonoxynol-9	13.0	"
PEG-8 Laurate	13.1	Clear solution
Polysorbate 21	13.3	"
Polysorbate 80	15.0	"
Oleth-20	15.7	"
Polysorbate 40	15.6	"
Ceteth-20	15.7	"
PEG-40 Stearate	16.9	"
Sodium oleate	18.0	"
PEG-100 Stearate	18.8	"
Potassium oleate	20.0	"
Sodium lauryl sulfate	ca. 40	"

a. INCI (International Nomenclature Cosmetic Ingredient) labeling name.

ability of emulsified lipids to contribute to emulsification. This is particularly critical for some of the more polar substances listed in Table 4 (e.g. oleic acid and isostearic acid).

A much lower HLB is required for the preparation of a W/O emulsion. An HLB of about 4 to 6 is reasonable for such emulsions. In modern practice cosmetic formulators rely to a large extent on silicone emulsifiers and associative thickeners (as represented by some of the polymers in Table 2) for creating W/O emulsions. (See sect. 2.3.2, below.)

Unfortunately, the HLB concept does not answer the question of how much emulsifier is required, nor can it clarify the emulsification differences between a POE-ester and a POE-ether having the same HLB. The HLB concept also cannot explain why a purified POE alkyl ether of a lower molecular weight does not yield as stable an emulsion as a similar ether having a higher molecular weight although both emulsifiers have identical HLBs. Some years ago Becher provided some important insights into the HLB concept and its relationship to other physicochemical phenomena.¹²

Schott¹³ recently eloquently argued that:

- a) the HLB is not a universal parameter;
- b) there is no correlation between the HLB and a given physical property;
- c) the (Griffin) definition of HLB lumps together different surfactant molecules and disregards the nature of the lipophilic moiety;
- d) the HLB is useful only as a first approximation.

In contrast to the HLB, Schott found a monotonic relationship between the log of the O/W partition coefficient ($K_{O/W}$) and the solubility parameters (δ_o). He also explained that $K_{O/W}$ and δ_o are independent of each other when water is present.

Despite these limitations, the HLB concept and its extension via solubility parameters or phase-inversion titrations has been an invaluable aid to formulators for years. Table 3 includes a third column, water dispersibility. The significance of this information is the fact that the HLB increases with increasing water solubility. Thus, an unknown non-ionic surfactant's HLB can be estimated within a few units by its water solubility or by the appearance of an aqueous dispersion at or near room temperature. Elaborate procedures for determining the HLB have been devised. Some of these techniques are identified in Table 5.

Table 4
HLB required by lipids to form O/W emulsions

<i>Material</i>	<i>Required HLB</i>
Acetylated lanolin	14
Ascorbyl palmitate	6
C12-15 Alkyl benzoate	13
Caprylic/capric triglyceride	5
Carnauba wax	15
Castor oil	14
Cocoa butter	6
Coconut oil	5
Corn oil	6
Cottonseed oil	5-6
Cyclomethicone	7-8
Dimethicone	9
Isocetyl alcohol	11-12
Isopropyl myristate	11-12
Isopropyl palmitate	11-12
Isostearic acid	15-16
Joboba oil	6-7
Lanolin	9
Mineral oil (light, naphthenic)	11-12
Mineral oil (light, paraffinic)	10-11
Mink oil	5
Oleic acid	17
Paraffin	10
Petrolatum	7-8
Soybean oil	6
Stearyl alcohol	15-16

Table 5
Techniques for determining HLB

<i>Method</i>	<i>Reference</i>
Computational	Davies, J.T. Proc. 2nd Int. Congress Surface Activity, London, I, 426, 1957; Schott, H. <i>J. Pharm. Sci.</i> 79 , 87 (1990)
Relationship to PIT	Shinoda, H., Kunieda, H. In <i>Encyclopedia of Emulsion Technology</i> (P. Becher, ed.), p. 337. M. Dekker, New York (1983)
Calorimetry	Racz, I., Orban, E. <i>J. Coll. Sci.</i> 20 , 99 (1965); Rowe <i>et al. Int. J. Pharm.</i> 79 , 251 (1992)
Phenol Index	Marszall, L. <i>Fette Seifen Anstrichm.</i> 82 , 210 (1980)
GLC	Becher, P., Birkmeier, R.L. <i>J. Am. Oil Chem. Soc.</i> 41 , 169 (1964)
Solubility Parameter	Bearbower, A., Hill, M.W. <i>Amer. Perf. Cosm.</i> 87 , VI, 85-89 (1972)
H-NMR	Rabaron, A. <i>et al. Int. J. Pharm.</i> 99 , 26-36 (1993)

2.3.2 Associative thickeners

Associative thickeners are conventional hydrophilic polymers modified by hydrophobic moieties, such as long-chain alkyl groups. This definition was provided by R.Y. Lochhead in 1993 during a seminar held by the Society of Cosmetic Chemists in Baltimore, Maryland (cf. Ref. 14). The use of these substances in cosmetic emulsification is entirely different from the use of more conventional emulsifiers having a molecular weight rarely exceeding about 500-1000 D.

Viscosity-enhancing polymers are customarily used to increase emulsion stability via the concepts of the Stokes' equation (given in sect. 5. 3 below and noted in passing during the discussion of auxiliary emulsifiers in sect. 3.1.2). Typical examples are the use of partially degraded cellulose and cross-linked polyacrylic acids (carbomers).

Associative thickeners resemble the hydrophilic carbomers, but some (hydrophobic) alkyl substituents are included in the monomer mix before polymerization. The resulting polymers still gel upon neutralization in the aqueous portion of the emulsion. The hydrophobic segments of the polyvinyl backbone in addition associate with the emulsion's lipid phase. Adjustment of the level of hydrophobic monomer and the

nature of the neutralizing alkali modify the polymeric emulsifier. Similar polymers can be generated from other vinyl derivatives.

A typical associative thickening 'gum' is cetyl hydroxyethylcellulose. The better known acrylates/C10-30 alkylacrylate cross-polymer (A) is a close relative of carbomer (B). In practice, B, which is only water dispersible, is neutralized with an alkali to yield a transparent high viscosity solution; this makes B primarily useful as a viscosity increasing polymer. The increase in viscosity during neutralization is attributed to repulsion between the ionized -COO^- groups of the polymer chain and the cross-linking of B resulting from the use of some divinyl derivatives during its synthesis. Polymer A behaves in an analogous fashion, but the pendant alkyl chains can readily associate with the hydrophobic emulsion constituents. In fact, it is possible to make O/W emulsions with A alone in the absence of other types of emulsifiers.

In order to act as an emulsifier, the associative thickener must bond to the emulsion's internal phase through dipole-dipole interactions, hydrogen bonding, and hydrophobic interactions. It is almost certain that such bonding occurs more readily with polymer A than with polymer B or other more hydrophilic polymers.

3 Emulsion Preparation

This section of the monograph is divided into several portions to distinguish between the different types of emulsions. As a rule, cosmetic emulsification depends on the use of emulsifiers selected by the formulator. This selection is based on experience, the nature of the oil constituents, the composition of the aqueous phase, and the desired characteristics of the product (e.g. high, intermediate, or low viscosity). As already noted, blends of surfactants exhibiting differing HLBs perform better than single substances.

The preparation of emulsions is not a simple process. Spontaneous formation of emulsions is rarely encountered in the case of macroemulsions and only if the preparation includes modest amounts, more than about 10%, of emulsifiers. Typical are the so-called self-emulsifying bath oils. These clear solutions of oils and emulsifiers disperse to form a milky emulsion when they are added to the bath water. Clear dispersions, i.e. microemulsions, result when oils, water and emulsifiers are blended in carefully selected concentrations. As a rule, microemulsions can form spontaneously with little or no agitation, and the order of addition of the components is not critical. In contrast, macroemulsions (O/W or W/O) require a controlled mixing sequence and a level of agitation. The additional use of mechanical equipment to yield the desired emulsion is often necessary.

Multiphase (or semisolid) O/W emulsions represent a special type of emulsion in which gel phases form a complex network in the continuous aqueous phase to hold the various phases in place.

For reasons of safety and cost, it is recommended that the level of emulsifier in a cosmetic product be kept as low as possible. It has already been noted that higher molecular weight emulsifiers generally are more efficient than those having a lower molecular weight when the HLBs are the same. Other aspects of good emulsion practice will become apparent from the following discussion, which concerns four types of emulsions: O/W emulsions, multiphase O/W (semisolid) emulsions, W/O emulsions, and microemulsions.

3.1 Oil-in-water emulsions

The discussion of O/W emulsions includes a description of auxiliary (viscosity-increasing) emulsifiers and of the phase-inversion temperature, both of which can contribute to the stability of the other emulsion types.

In *classical O/W emulsification*, it is customary to prepare the oil phase and the aqueous phase separately and to blend the two phases with agitation. In a typical procedure, the emulsifiers are blended with the oil phase and warmed to form a clear homogeneous melt. The oil phase is routinely heated to a temperature exceeding the melting point of the highest melting wax. The aqueous phase may include all types of water-soluble components, including any water-soluble surfactant or thickening agent, and is heated to the same temperature as the oil phase. In order to form an O/W emulsion, the oil phase is typically added to the aqueous phase, while the reverse type of addition is customarily used for W/O emulsions.

Heat-sensitive components, for example, fragrances or preservatives, are added at lower temperatures, while agitation continues. Stirring is usually stopped at a temperature of about 35°C and is rarely continued to below 25°C. At any time during this process, the (warm) emulsion might be subjected to special treatment to help reduce the droplet size of the internal phase. Homogenizers, ultrasonifiers, and colloid mills are widely used in the cosmetic and pharmaceutical industries, even though this extra step is not always required.

In the preparation of laboratory samples, the rate of cooling is not carefully monitored. However, in large-scale production, controlled cooling of the bulk may be required, and the rate of cooling frequently has a critical effect on emulsion viscosity and stability.

3.1.1 Phase-inversion temperature (PIT)

The differences between the above-described classical techniques for emulsification and modern practice are minor but of critical importance. Heating of the phases is still practiced, but most emulsion practitioners prefer to exceed the so-called phase-inversion temperature (PIT). It has been known for some years that soap-stabilized O/W hydrocarbon emulsions form in hot systems but, upon cooling, tend to form W/O emulsions, i.e. invert. The study of this phenomenon resulted in a lot of work intended to determine whether emulsions (at different temperatures) were O/W or W/O. Additional information on the cloud point of non-

ionics (POE derivatives) helped to establish a rationale for the well-known phenomenon of inversion. Water-soluble nonionic emulsifiers tend to become cloudy upon heating, especially if a small amount of an electrolyte is present. At the cloud point, i.e. the temperature above which the system is cloudy, the hydrogen-bonding of water to the surfactant's hydrophilic portion is weakened, and the surfactant becomes water insoluble. This basic principle is well documented for systems comprising POE derived surfactants, but this concept cannot explain the hydrocarbon/sodium stearate system, since the emulsifier's solubility in water increases with temperature.

The importance of the PIT derives from the fact that emulsions prepared above the PIT of the blend are more stable than those mixed below the temperature. It is likely that, in classic emulsification, the practitioners frequently exceeded the PIT, but today the melting point of a wax component to create a homogeneous oil phase is not the critical temperature for preparing an emulsion.

Emulsification at the PIT results in reduction of the particle size of the internal phase. Shinoda provided some theoretical understanding of what happens at the PIT.¹⁵ A nonionic polyether-based emulsion at an ambient temperature may contain some micellar surfactant, some surfactant micelles swollen by the presence of some oil, and some emulsified oil. Raising the temperature alters the HLB of the surfactant, making it more hydrophobic (or lowering its HLB). Micellar stability decreases, and the size of any emulsified oil droplets increases. Ultimately, at some still higher temperature (the PIT) the emulsion separates into an aqueous phase, a surfactant phase and an oil phase. If the temperature is raised still further, the system, originally an O/W emulsion at lower temperature, becomes a W/O emulsion. At the PIT, the hydrophilic properties of the emulsifier(s) are in balance, and this temperature has also been identified as the HLB temperature. It becomes apparent now why the surfactant placement (into the oil or the water phase) during PIT emulsification can be neglected because the three-phase system at the PIT equilibrates during cooling. PIT considerations also control stability testing temperatures. Generally, the PIT of a nonionic O/W emulsion should never be exceeded, nor should a W/O emulsion be stored at temperatures below its PIT. These principles may be modified by the presence of additional (ionic) emulsifiers or of stabilizers which do not obey the rules applicable to heat-sensitive nonionic emulsifiers. Nevertheless, it is useful to store O/W emulsions routinely at temperatures 20°C below the PIT.

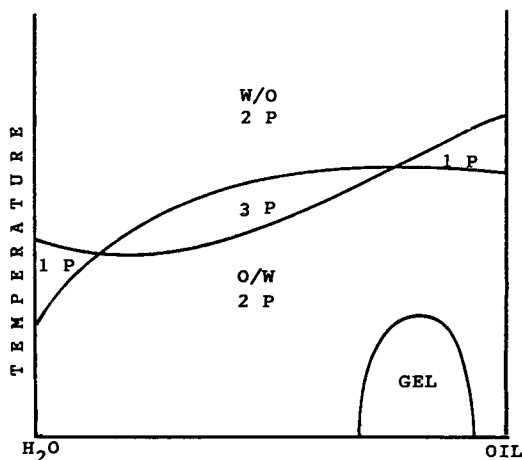


Figure 2. PIT diagram; see text for explanatory comments

The criticality of phase-inversion temperature in emulsion formation is best explained by a simplistic two-dimensional phase diagram of blends of a hydrocarbon oil and water containing 5% of a nonionic emulsifier (Fig. 2).

On the far left side of this diagram, one commonly finds a small 'clear' one-phase emulsion in which a small amount of oil is solubilized in the water-surfactant blend. A similar shaped area is found at the far right in which some water is solubilized in the oil. These segments are essentially one-phase, although they need not be clear. The response of these one-phase emulsions to changes in temperature can be readily followed. Regardless of the water:oil ratio, the system responds to changes in temperature; heating above the PIT results in changes leading to a W/O emulsion, while cooling below the PIT results in the formation of an O/W emulsion. The changes in temperature may, in addition, result in the formation of different phases in the system, and possible gel phase formation is noted in the diagram. The PIT, which is really a range, separates the O/W macroemulsion range from that of the W/O macroemulsion. In the PIT range, three phases are formed at lower levels of emulsifier concentration. At high surfactant levels, the systems may form microemulsions.

Some investigators emphasize the critical differences between macroemulsions and microemulsions. Others view the changes from

macro- to microemulsions (in the absence of cosolvents) as a gradual transition. A comparison of Figures 1 and 2 shows that the former is merely a magnification of either the left or the right side of Figure 2. Evidently temperature, phase ratio, and emulsifier content play key roles in determining emulsion type in these systems.

Conditions for such a sharp distinction between macro- and micro-emulsions may not exist in all combinations. Microemulsions, for example, may break up and exist only within a specific temperature range. In other systems one may never find a microemulsion. The phenomenon of the PIT can occur in a broad range of O:W ratios. Maintaining a system of the type shown in the diagram at the PIT can be expected to cause significant phase separation. The starting O/W emulsion can be restored only by agitation, i.e. a process resembling the original emulsification, and cooling steps.

Table 6
PIT Emulsions

<i>Composition</i>	<i>A%</i>	<i>B%</i>
Cetareth-12	3.8	2.7
Glyceryl stearate	2.4	—
Laureth-4	—	3.5
Dicapryl ether	20.0	20.0
Water	73.8	73.8
<i>Average particle size</i>		
Light microscope (μm) (fresh)	< 1	< 1
" (aged)	< 1	2.7
Zetasizer (nm) (fresh)	305	350
" (aged)	450	3500

Note: After Reference 16

A more practical example has been described and explained by investigators at Henkel, as follows:^{16,17} Simple PIT emulsion systems are based on the compositions shown in Table 6. The preparative approach includes heating to about 95°C and subsequent cooling to room temperature and determination of the PIT with the aid of a conductivity bridge. Both compositions A and B invert at about the same temperature (73° to 74°C) despite the use of a different hydrophobic coemulsifier.

The freshly prepared emulsions are comparable in terms of particle sizes, and this is in accord with the PIT concept (Table 6). However, aging shows that emulsion A is more stable than B, and this is explained by the presence of multilamellar layers (demonstrated by transmission electron microscopy) which surround the oil droplets. The formation of this phase (liquid crystalline) by glyceryl stearate is not a function of the PIT level but is believed to be responsible for the improvement of stability.

It was already noted that the PIT depends on the composition and concentration of the emulsifier mixture. This feature is illustrated in Figure 3, which shows the formation of O/W and W/O emulsions together with that of a microemulsion as a function of temperature and of emulsifier concentration (held constant in Fig. 2).

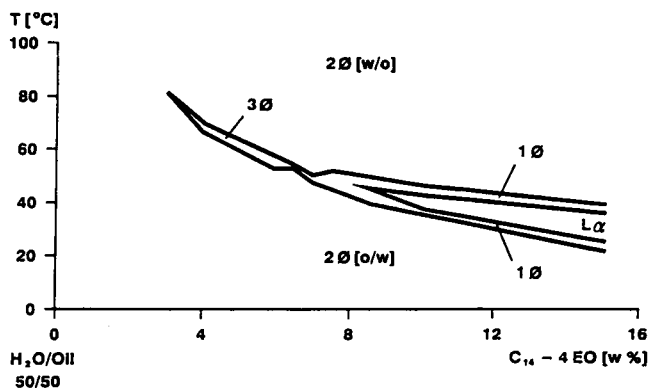


Figure 3. Phase diagram of mixtures of light mineral oil, myreth-4 and water. The PIT, the temperature at which a 3-phase system exists, depends on the level of emulsifier. The 1-phase microemulsion 'surrounds' the lamellar mesophase (L_{α}). [From Ref. 17. Reproduced by permission of the *J. Disp. Sci. Technol.* 13, 185 (1992).]

Computational techniques for selection of emulsifiers based on an assessment of a 'mixed' oil phase have been popularized in recent years.¹⁸

An additional feature of PIT emulsification is its utility in so-called low energy emulsion production. The review of earlier work by Lin and Reng indicates that successful dilution with (energy-saving) cold water

is best carried out by cooling the concentrate below the PIT before dilution.¹⁹ Cooling rates and stirring speeds of PIT emulsions do not have a major effect on droplet size,¹⁷ and this contributes to the ability to carry out low-energy emulsification.

Emulsification by the PIT procedure generally succeeds in yielding low viscosity emulsions. These are characterized by exhibiting a bluish haze when they are spread thinly on a transparent or reflecting surface. Even more viscous O/W emulsions without opaque constituents can show this phenomenon, which is associated with small droplet size. These droplets are small enough to undergo Brownian movement and are not 'stationary'. In accordance with the postulate of Stokes' law, their mobility is a function of the difference in specific gravities of the dispersed and the continuous phases (sect. 5.3.1). In a typical low viscosity emulsion, rising of the internal phase can lead to unsightly creaming even if no coalescence takes place. Formulators try to avoid or retard this creaming by the addition of polymeric viscosity-increasing substances to the continuous aqueous phase. In most instances, the modest rise in viscosity caused by use of these auxiliaries does not detract from the utility or attractiveness of the product.

3.1.2 Auxiliary emulsifiers

The activity of auxiliary or secondary emulsifiers is limited to stabilization of emulsions formed by surfactants. The auxiliary emulsifier may be a finely divided solid such as a viscosity-enhancing water-swelling clay. In addition, formulators have employed all types of water-swelling organic polymers.

Finely divided solids, which contribute to the formation of a third phase, have already been discussed briefly. Polar and nonpolar solids, for example, clays, pigments, insoluble hydroxides, carbon, and even some high melting lipids (glyceryl tribehenate), can be used as auxiliary emulsifiers. The choice of surfactant can be critical: barium sulfate in the presence of sodium laurate is useful for O/W emulsions at high pH, while this solid favors W/O emulsification in the presence of sodium lauryl sulfate. The principles which account for emulsion stabilization by inert solid particles have been reviewed briefly by Friberg *et al.*¹¹

By far the most important inorganic stabilizers are water-swelling clays, such as aluminum silicates, bentonite and related smectite clays. Hydration of these clays is not part of the emulsification process. Instead, they are hydrated separately and then added to the emulsion. Products thickened with clays exhibit pseudoplastic viscosity, i.e. are

shear-thinning. They can frequently be combined with water-soluble viscosity-increasing gums and polymers.

Water-soluble natural gums which increase viscosity have been used as emulsion auxiliaries for many years. Most of them are plant-derived polysaccharides and are safe for ingestion. Typical examples are listed in Table 7. A more comprehensive listing will be found in the INCI Handbook²⁰ under the headings of *Gums, hydrophilic colloids and derivatives* and of *Viscosity-increasing agents — aqueous*. The use of these raw materials in cosmetics is decreasing because they tend to leave a film on the skin that remains somewhat sticky.

Table 7
Some hydrocolloid emulsion stabilizers

Gum karaya	Quince seed gum
Gum arabic	Gum guar
Carrageenan	Cellulosics
Alginates	Gelatin
Locust bean gum	Xanthan gum

It had been assumed for years that the primary function of these gums is to increase viscosity. Recent publications suggest that they may also be adsorbed to the surface of emulsified droplets in the form of loops, trains, and tails.¹¹ This type of polymer/droplet interaction probably does not increase the viscosity of the system, but could constitute a powerful inhibitor of coalescence.

In the case of O/W emulsions, any agent which increases the viscosity of the external (aqueous) phase helps stabilize an emulsion. However, it is important to remember that even an increase in the viscosity of the internal (lipid) phase can help stabilize O/W emulsions. Conversely, in the case of W/O emulsions, thickening of the external phase is critical for stability. Thus, silicas and alkaline earth soaps can improve long-term emulsion stability in many cases.

Finally, a number of synthetic polymers have become available to the formulator. Their use is particularly attractive since these polymers can be tailored to provide both hydrophilic and hydrophobic segments, as described above in section 2.3.2. The most popular of these substances is carbomer, a polymer of acrylic acid cross-linked by divinyl derivatives. Carbomers, like other viscosity-increasing agents, are hy-

drated separately, then added to the emulsion and finally neutralized to form the viscosity enhancing polyionic polymer. Ionization of the polymer causes repulsion between the charged groups, thus accounting for the viscosity-enhancing expansion of polymer conformation. Thus, use of a neutralized simple carbomer (as described in Ref. 14) creates stabilizing viscosity in aqueous emulsion systems. Use of acrylates/C₁₀₋₃₀ alkyl acrylate cross-polymer (an associative thickener) also raises the viscosity but, in addition, stabilizes emulsions by secondary bonding to lipid constituents. As a result, O/W emulsions based on these principles are amongst the most stable emulsions created to date.

In recent years, the utility of synthetic polymers for emulsification and emulsion stabilization has been enhanced by reducing the need for neutralization. Instead, the viscosity-increasing polymer (e.g. polyacrylamide) is provided as a dispersion in an inert hydrocarbon in the presence of a small amount of a nonionic surfactant. This mixture can be blended with the oil phase of the emulsion. The aqueous phase is then introduced at slightly elevated temperature. In another way of using these polymers, a fluid emulsion is prepared by phase inversion at 70° to 75°C. After cooling below the PIT, the polymer dispersion is added to yield a more viscous product.

3.1.3 Practical examples

Not all O/W emulsions are prepared by following the principles of PIT emulsification. In fact, some O/W emulsions do not depend on the presence of polyethoxylated emulsifiers, in which case the PIT concepts cannot be applied. To illustrate the similarity of PIT-controlled emulsification and another technique, two examples follow. They are chosen at random from published formularies and may not meet all the requirements of acceptable cosmetic products.

Formula A utilizes two thickeners in the external phase. The oil phase is a mixture of various cosmetic oils. The emulsifying sorbitan derivatives are blended into the oil phase and provide an HLB of about 13.0.

Formula A
[O/W Moisturizing lotion]

	%	
Magnesium aluminum silicate	0.15	} A
Carbomer	0.15	
Deionized water	73.70	B
Glycerin	5.00	C
Mineral oil	2.50	} D
Lanolin alcohol	1.50	
Cetyl alcohol	2.00	
Isopropyl palmitate	2.00	
Hydrogenated polyisobutene	5.00	
Isopropyl myristate	3.00	
Sorbitan palmitate	1.20	
Polysorbate 40	3.80	
Preservatives and fragrance	q.s.	E
Sodium hydroxide (10% aq.)	to pH 6.0	F

Preparation: The dry blend of A is stirred into B with a propeller mixer at low speed; the speed is steadily raised to about 1600 rpm. After addition of C, the aqueous phase (ABC) is heated to 50°C. The blend of D, also heated to 50°C, is added to ABC at a high rate of stirring over a period of about 10 min. The mixer speed is lowered as the blend cools. Add E at 30°C and adjust the pH with F. Make up with water to replace evaporative loss.

Comment: This nonionic emulsion probably could be improved by operating at a higher temperature. If the emulsion's PIT is close to 50°C, this emulsion is unlikely to be stable at elevated temperatures.

Formula B
[O/W Pearlized body lotion]

	%	
Mineral oil	4.00	} A
Isostearyl neopentanoate	4.00	
Sorbitan monoisostearate	1.00	
Deionized water	75.05	} B
Mica and titanium oxide pigment	3.50	
Carbomer	0.40	C
Propylene glycol	8.00	D
Disodium EDTA	0.05	E
Triethanolamine (99%)	0.60	F
Sucrose cocoate	3.00	G
Fragrance and preservative	q.s. 0.40	H

Formula B represents a pigmented skin-care product.

Preparation: The oil phase A (which may include one of the preservatives) is heated to 80°C and stirred until uniform. Mixture B is heated to 70°C, and C is added with homogenization. D and any water-soluble preservative are added to B plus C. E and F are added next, as well as G. The water phase is now heated to 75°C, and A is added slowly with homogenization over a period of 15 minutes. After cooling to 45°C, H is added, and evaporated water is replaced.

Comment: The procedure for making this product is somewhat unusual: the carbomer is neutralized with the amine before introduction of the oil phase. This modification of the generally practiced sequence may be necessitated by the presence of the pigment. This product is likely to be quite viscous, although it is identified as a lotion.

3.2 Multiphase Oil-in-Water emulsions

Cosmetic chemists have known for many years how to formulate relatively viscous emulsions for skin-care. In these products, the internal oil phase may not be dispersed in minute droplets, and their Brownian movement may be significantly curtailed. The mechanisms for stabilization are likely to be somewhat different from those postulated for the conventional mobile droplet-based O/W emulsions.¹¹

An understanding of the nature of these types of semisolid O/W emulsion can be gained from the simple stearate cream described by Junginger:²¹

Formula C

	%
Stearic acid	12.0
Palmitic acid	12.0
Triethanolamine	1.2
Glycerin	13.5
Water	up to 61.3

This combination contains some TEA soap and free fatty acid. This cream is a dispersion of fatty acids in an aqueous soap solution. In cosmetic (and pharmaceutical) practice, the emulsifying soap is prepared *in situ* by adding the melted oil phase containing the fatty acid to a warmed aqueous solution of the alkali. This procedure avoids the (often slow) dissolution of the neutralized soap in water and generally results in finer dispersions of the emulsified internal phase.

The described stearate cream forms a lamellar liquid crystal into which low levels of water are incorporated between the hydrophilic sites of the lamella. As more water is added, the interlamellar water layer becomes thicker, as shown by small-angle X-ray diffraction and other data. The gel concept is explained by reference to Figure 4, in which the various phases are identified.

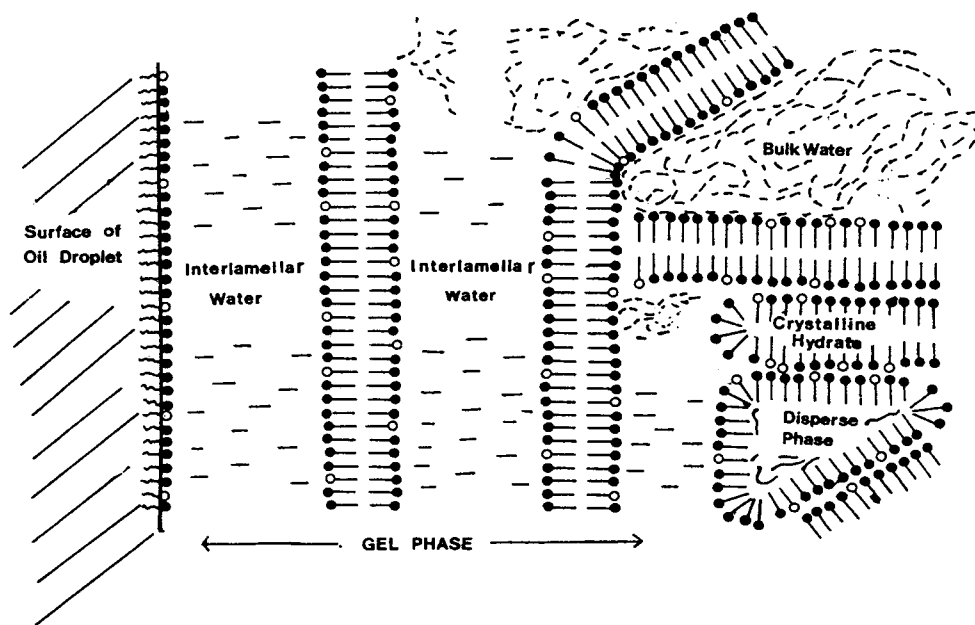


Figure 4. Schematic of a multiphase O/W emulsion. The gel phase consists of mixed crystal bilayers of fatty acids and their TEA soaps. The mixed crystal bilayers may exist simply as hydrates. The existence of bulk water (upper right), of bulk oil (left side) or of a disperse phase (lower right) depends on modifications of Junginger's (Ref. 21) basic composition with other components. [Reproduced from Ref. 22 by permission of the *J. Soc. Cosm. Chem.* 41, 9 (1990).]

Most semisolid products (creams) for cosmetic use are generally based on nonionic emulsifiers but rarely on systems containing an alkyl sulfate. Mixtures of components which yield creams when blended (with heating) with water are commercially available as emulsifying

waxes and are described in various pharmacopoeias. A typical mixture may yield a preparation of the following:

Formula D

	%
PEG-20 glyceryl stearate	5.0
Cetearyl alcohol	10.0
Mineral oil	7.5
Petrolatum	17.5
Glycerin	8.5
Water, demineralized	55.5

The structure of this product is similar to that of the stearate cream described above (Fig. 4). The mixed crystal bilayers of cetearyl alcohol and hydrophilic PEG-20 glyceryl stearate can extend into a fairly thick layer of water. However, above a water level of about 60%, the gel structure becomes unstable despite the extensive ethoxylation of the glyceryl stearate-based emulsifier.

As was pointed out by Eccleston, the term 'lamellar gel phase' may be used differently in different scientific disciplines.²² For the purpose at hand, it is useful self-explanatory nomenclature. The nature of this phase is clearly dependent on the rigidity of the mixed crystal bilayer (Fig. 4), the transition temperature, and the water content. Failure of the gel phase due to adverse storage conditions can be expected to result from emulsion instability. The interlamellarly fixed water is separated from bulk water by a permeable membrane consisting of mixed crystals of an amphiphile phase; water movement to bulk water is likely. Similarly, there may be movement of the disperse phase to or from the droplet (phase) shown in Figure 4.

In practice, mechanical action on creams of this type may destabilize these emulsions. Therefore, formulators commonly stop agitating them at or near about 35°C during the cooling cycle. High-shear pumping of such products after cooling may also be destructive. It is customary, therefore, to support emulsion stability with the aid of thickening agents.

Skeleton formulas were included in the previous discussion, but a more complex cosmetic multiphase emulsion is shown in Formula E.

Formula E
[Protective hand cream]

	%	
Stearic acid	7.50	} A
Lanolin	3.00	
Cetyl alcohol	3.50	
Petrolatum	2.00	
Cetearyl isononanoate	3.00	
Dimethicone	2.00	
Glyceryl stearate	1.50	} B
Propylene glycol	0.75	
Preservatives	0.25	
Sodium hydroxide	0.50	
Water	to make 100.0	
Fragrance	q.s.	C

Preparation: A and B are heated separately to 70°–75°C. A is added to B with stirring. Stirring is continued with cooling. Part C is added at 40°C. The product is packaged between 30° and 35°C.

3.3 Water-in-oil emulsions

In contrast to O/W emulsions, these emulsions require use of an emulsifier with a lower HLB of about 5 to 7. In addition, the phase ratio (oil:water) should favor oil to form a continuous oil phase. The principles of emulsification are the same as those described for O/W preparations except that the aqueous phase is added to the oil phase if the classical procedure is followed. The PIT process is not practical for most W/O emulsions, which are expected to exhibit stability at or above room temperature. A little reflection shows that one would have to start with a cold blend O/W emulsion and warm it beyond the inversion temperature to change it into a W/O emulsion.

In O/W emulsions, the internal oil phase is normally held to levels below about 30% to avoid a greasy after-finish. The reverse is true in W/O emulsions in which a higher water content lowers greasiness. The water droplets formed during the agitation step are stabilized against coalescence by the viscosity of the oil phase and by contact of the hydrophilic portions of the emulsifier with the disperse phase. In the compounding of emulsifiers for O/W emulsions, one may include water-soluble substances with water-insoluble amphiphiles. However, for the preparation of W/O emulsions, the emulsifiers are almost exclusively oil soluble. A list of low molecular weight W/O emulsifiers might include, in addition to low HLB nonionics (Table 3), metallic

soaps, polyglyceryl-3 distearate, glyceryl oleate, and cetearyl alcohol. Lanolin has been used for many years as a W/O emulsifier, although in the case of wool wax this feature was referred to as water absorption.

The consistency of W/O emulsions depends almost exclusively on the viscosity characteristics of the continuous oil phase. It is essential to maintain the emulsion's viscosity over a wide temperature range, a feat rarely achieved in the past. Stable W/O emulsions which could tolerate freezing and storage up to about 40°C were rare unless the oil-phase viscosity was controlled with the aid of waxes and polymers.

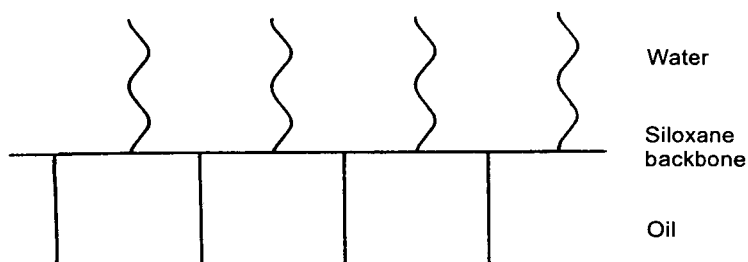


Figure 5. Schematic of configuration of cetyldimethicone copolyol at a hypothetical water-oil interface. Hydrophilic side chains contact the water phase; the lipophilic side chains contact the oil phase.

Today, different types of associative thickeners (2.3.2) have been found useful for creating W/O emulsions. In these associative thickeners, the polymeric backbone (commonly) of dimethicone copolyol has been modified by copolymerizing a dimethyl silane with a methyl/alkyl derivative. The exact nature of these polymers (block or random) and of the hydrophobic alkyl group is still proprietary, but the basic mechanism of W/O emulsification is understood: at a water/oil interface these molecules tend to spread out (which is typical for most polysiloxanes) and position themselves as shown in Figure 5. The adsorption efficacy on the water-oil interface of these hydrophobically modified silicone emulsifiers is about 20 times that of sorbitan oleate,²³ and they are remarkably effective W/O emulsifiers. As a result, W/O emulsions can be prepared at W:O ratios of about 2:1. Such a composition is shown in Formula F.

Formula F
[Day cream]

	%	
Laurylmethicone copolyol	2.0	} A
Avocado oil	5.0	
Tocopheryl acetate	2.0	
Mineral oil	10.0	
Sunflower oil	3.0	
Capric/caprylic triglyceride	5.0	
Electrolyte (sodium chloride)	1.0	} B
Glycerin	4.0	
Water, demineralized	68.0	

Procedure: A and B are heated separately to 75°C. B is added to A with intensive blade stirring in a heated vessel. Stirring is continued until the emulsion has cooled to 25°C.

Comment: The composition does not include a preservative or perfume.

A second formula without a silicone-based emulsifier is included, as follows:

Formula G
[Emollient cream²⁴]

	%	
Cetearyl isononanoate	11.0	} A
Polyglyceryl diisostearate	4.0	
Dicocoyl pentaerythrityl distearyl citrate	2.0	
Cetearyl alcohol	1.0	
Almond oil	10.0	
Microcrystalline wax	7.0	
Water	59.3	} B
Glycerin	5.0	
Magnesium sulfate	0.7	

The *Procedure* is probably similar to that shown above for the W/O day cream.

Comment: This composition includes neither preservative nor fragrance.

In the past, cosmetic chemists dreaded formulation of W/O products. They were generally viewed as greasy and unstable. The use of the modern polymeric associative thickeners and other recently introduced emulsifiers has encouraged investigators to devote more effort to the creation of W/O emulsions. It is too early to conclude that the use of these modern associative thickeners can provide fully satisfactory products.

3.4 Microemulsions

The term *microemulsion* in cosmetics identifies a clear-appearing system containing at least two immiscible (or mutually insoluble) components. Clear emulsions may be W/O or O/W. The former do not appear to have become popularly accepted in finished products. However, those in which the aqueous phase is viewed as the continuous phase have gained prominence in the drug and pharmaceutical industries. Transparent emulsions appeal to some consumers, and the development of clear cosmetics and OTC topical drugs play important roles in commerce. In practice, the pharmacological activity of solubilized systems is hard to evaluate.

A detailed discussion of microemulsions is not included in this monograph since they will be covered separately. Instead, only a few general comments are included to facilitate comparisons between microemulsion and macroemulsion formulation. Reference to Kahlweit's fish^{4,25} identifies the area in which practical clear O/W emulsions may exist: low levels of oil phase; high levels of surfactant; and a relatively narrow temperature range. The definition of microemulsions as transparent is reasonable specific, but the vagueness concerning the exact nature of a macroemulsion persists. The Henkel workers^{16,17} use the term to describe at least a portion of the emulsion spectrum within the 3-phase PIT diagram (Fig. 3). 'Transparent emulsion', 'micellar solution', 'solubilized system', and 'swollen micelles' are some of the descriptive terms which in one form or another are intended to convey information on the nature of microemulsions. Today, two concepts dominate the field; microemulsions can be viewed as liquid-liquid disperse systems with constantly shifting domains;²⁶ alternatively, they may be viewed as micellar systems.²⁷ The arguments about what a microemulsion really is becomes moot since we cannot readily distinguish between the micellar core and a bulk oil phase. Instead, it seems wise to view microemulsions as systems comprising water, oil, and amphiphile(s) which to the human eye are optically isotropic and which are thermodynamically stable.

The delivery of actives from a microemulsion remains a problem in the case of flavorants, fragrances, or drugs. Headspace analysis of volatiles from a solubilized solution shows that solubilization interferes with volatility.²⁸ There is, however, no information on perceived fragrance intensity after a solubilized fragrance is applied to the skin and after the water has evaporated.

Extensive examinations of viscous transparent O/W gels for drug administration have been carried out by Provost and her coworkers,²⁹ with emphasis on *in vitro* drug release by comparison to other cream- or gel-type vehicles. They found the following blend particularly useful:

Formula H

	%
PEG-7 glyceryl cocoate	18.0
Cetareth-30	15.0
Isopropyl myristate	8.0
Water	59.0

The ringing gel formed spontaneously and reformed after heating and cooling. This type of behavior is quite typical for gels based on hexagonal liquid crystal phases. It has been reported by others that drugs incorporated into similar systems are stabilized against hydrolysis.³⁰ In cosmetics, such high levels of surfactants may be undesirable, and more fluid systems might be more useful. For example, 40 g of a blend of PPG-26-buteth-26 and of PEG-40 hydrogenated castor oil can 'dissolve' 10 g of *Pinus sylvestris* oil in 1000 g of water.

3.5 Functionality of cosmetic emulsions

Consumers expect benefits from the use of emulsions on skin or hair. Cosmetic emulsions can provide such benefits either by cleansing the skin surface or by delivering beneficial materials to the skin. Admittedly, some emulsions may provide both benefits or help the user to achieve other goals, but a division of emulsions into cleansing systems and delivery systems is rational.

3.5.1 Emulsion skin cleansers

When used for skin cleansing, emulsions are intended to remove soil from the skin by dissolving unwanted substances from the skin or by facilitating their release during subsequent water rinsing or wiping.

The formulator has the task of selecting ingredients that act as solvents but do not interfere with the formation or stability of the emulsions. The limitations on the choice of solvent are severe (odor, safety, etc.), and formulators are restricted to lipids of low aqueous solubility. The use of hydrocarbon solvents, such as low-viscosity mineral oils, has been practiced for years. Other mobile lipids, such as low molecular

weight triglycerides, synthetic hydrocarbons, or ethoxylated glyceryl esters, can be used. Use of large amounts of solvents which exhibit solubility in both the water and the oil phase must be avoided. As a general rule, such solvents interfere with emulsion stability.

In creating a cleansing emulsion, the formulator may start with a composition such as the following:

	%
Emulsifiers	2-8
Lipids (solvents)	20-50
Polyol	5-10
Preservative/fragrance	q.s.
Water	to make 100

The choice of emulsifiers determines whether the product is a wipe-off cleanser (as is the case with a classic beeswax/borax emulsion) or a rinse-off cleanser (as, for example, with a water-soluble emulsifier such as cetareth-20). The remaining objective is creation of a product that meets the cleansing objective without irritation and leaves the skin with the desired finish.

In wipe-off cleansers, the lipid solvent customarily forms one phase of the emulsion, which may be O/W or W/O. A typical rinse-off product may contain a fairly low level of or no lipid solvent. Such a cleanser may rely primarily on a combination of water-soluble mild surfactants and small amounts of a viscosity-increasing and opacifying lipid, such as glyceryl stearate, to create an O/W emulsion. As a result, rinse-off cleansers function in principle as detergents.

3.5.2 Emulsion skin treatments

When emulsions are used for skin treatment, they are allowed to remain on the skin to deliver diverse beneficial agents to the epidermis. Despite some regulatory restrictions, it is widely accepted practice to deliver humectants, sunscreens, or occlusive substances from emulsions. There is virtually no limitation on the types of ingredients that can be administered to the skin from emulsions.

A typical O/W skin delivery emulsion may include the following:

	%
Emulsifiers	2-8
Inert vehicle	5-30
Polyol	5-10
Delivered agent	0.2-25
Preservative/fragrance	q.s.
Water	to make 100

Such an emulsion delivers not only the presumptive active but all emulsion constituents to the skin. The shown skeleton formula does not further identify the bulk internal phase nor distinguish it from the delivered agent. It is important to remember that these two components may be the same and must meet the emulsion's purported benefit. A massage cream, for example, will be based on lubricious lipids or emollients with little tendency to permeate the skin. By contrast, a lotion designed to deliver antioxidants may combine a lipidic internal phase with a delivered agent, such as ascorbyl palmitate, intended to help the antioxidant status of the skin.

The advantages of delivery from emulsions were already briefly noted in the Introductory Comments (sect. 1). The point of the following discussion is an assessment of the fate of the emulsion after it has been deposited on or inuncted into the skin.

The relative concentrations of the emulsion ingredients do not remain constant after application to the skin regardless of emulsion type. One of the first observable phenomena is the loss of water. Some of the water may penetrate the stratum corneum to reach lower skin layers; much of it is lost by evaporation, as demonstrated by transepidermal water loss measurements. As a consequence of this water loss, the emulsion might invert or temporarily become a microemulsion; continued water loss changes the deposited emulsion into a mixture of its nonvolatile constituents even though some of them may actually permeate the stratum corneum.

The initial sensation of an emulsion on the skin depends on the emulsion's concentration. Emulsions with a high concentration of internal phase (e.g. a high oil content in an O/W emulsion) can be expected to be more viscous and may not spread readily. However, after most of the water has been lost, the skin surface is covered with a blend of the nonvolatile ingredients. Water in an emulsion is lost from the skin almost completely after about 20 to 30 minutes at ambient relative humidity. On the other hand, users expect the emulsion to reach a dry-to-the-touch finish on the skin within about two minutes. Thus, the dryness desired by the consumer is unrelated to the loss of water from a skin/emulsion system, as measured by transepidermal water loss. This suggests that a significant portion of the emulsion's water may have been sorbed by the stratum corneum.

What remains on the skin surface is a high level of surfactant, lipids, and other nonvolatile emulsion constituents. Some of these slowly penetrate into the skin where they blend with the diverse constituents of the

integument. It is beyond the scope of this discussion to track the fate of emulsion components after application to the skin. Based on all the data developed primarily in connection with topical drug administration, it is likely that each ingredient finds its way into and through the stratum corneum. Passage may be enhanced by the presence of the emulsion's surfactant blend and other constituents. These constituents affect not only contact angles on and within the skin but may exert other effects on the barrier properties of skin.

4 Emulsion Preservation

In addition to evidence of stability, marketable cosmetic emulsions require protection against microbial contamination and oxidative damage. This section is devoted to a discussion of antimicrobial and antioxidant preservation.

4.1 Antimicrobial preservation

Emulsions containing both oil-soluble as well as water-soluble nutrients for microbial species require preservation against spoilage. The problem of preservation is of universal concern in the cosmetic industry. However, the preservation of emulsions is particularly difficult, and formulators are urged to exercise extreme care in evaluating an emulsion product's resistance to microbial contamination.

The principles of proper preservation require cleanliness during production and packaging. In addition, all products should be protected against inadvertent contamination during use. Finally, loss of any added preservative may occur as a result of interaction with packaging components. These are the basic problems which must be resolved in all types of cosmetic products. In the case of emulsions, problems of contamination result not only from the above briefly identified causes but, in addition, from the presence of emulsifiers. Water is an essential ingredient for survival of microorganisms, and even W/O emulsions may be contaminated at the oil-water interface. The likelihood of contamination increases with increasing water content until it reaches a maximum in O/W emulsions.

One of the cardinal rules for the manufacture of uncontaminated emulsions is the use of pure raw materials. The most common contaminant is water, and microbial purity of this raw material must be confirmed. As a general rule, water used in cosmetic emulsions may be *potable* (not more than 500 colony-forming units per mL) or *purified* (not more than 100 colony-forming units per mL). Sterile water is not normally required for cosmetic emulsions. Water and all other ingredients formulated into cosmetic emulsions should be free from pathogenic microorganisms. Pharmacopoeial guidelines and CTFA publications recommend continuous monitoring to assure the absence of contaminating species in raw materials used in cosmetic emulsions.

It has been established for about fifty years that surfactants as a group can reduce the efficacy of commonly used preservatives. This

was originally attributed vaguely to complexation but it is now known to be caused by the preferential incorporation of oil-soluble and even some water-soluble preservatives into the oil droplets of an O/W emulsion. In addition, preservatives may be solubilized or micellized by the blend of emulsifiers. Any preservative dissolved in the emulsified oil phase or micellized in a surfactant is not completely available to perform its designated function. Solubilization of a preservative is analogous to solubilization of a drug or of a flavorant.²⁸ Once the compound remains solubilized (or perhaps emulsified), its thermodynamic activity is reduced.

The principle by which solubilization or emulsification reduces a preservative's efficacy can be described with the aid of partition coefficients, as reviewed by Rieger.³¹ The availability of an antimicrobial to function effectively depends on its concentration or more precisely on its chemical potential. In an emulsion, the preservative can be expected to be distributed between the phases comprising the emulsion. If the distribution of the preservative favors one phase, such as the oil phase, the aqueous phase may be inadequately preserved. Preference for the aqueous phase may leave an oil phase (containing solubilized water) unprotected. Excess surfactant micellized in the aqueous phase may solubilize all types of preservatives. Finally, high affinity for plastic packaging components may further deplete the available preservative.³² One of the signs of preservative sequestration is the fact that the preservative blend — although chemically intact — fails to perform in the mandatory challenge tests.

The preservative challenge testing procedures vary from country to country and from compendium to compendium. Any testing program must meet not only the manufacturer's obligation but also regulatory requirements. Current standards justifiably demand that pathogens must be absent in a finished emulsion product and that the number of surviving nonpathogens should be controlled by the product. The choice of available safe preservatives is limited and, unfortunately, no world-wide standards for acceptance or nonacceptance exist. As a result, the emulsion formulator must determine by trial and error whether a particular emulsion is properly preserved and ascertain by appropriate testing that the preservative retains its activity during storage of the product.

Emulsion formulators commonly employ an oil-soluble and a water-soluble preservative in an effort to provide finite levels in both emulsion phases. Thus, combinations of methylparaben and propylparaben have been widely used. The precise location of these two substances in

a complex cosmetic emulsion depends on distribution coefficients, as noted below, and is rarely known. Despite these uncertainties, the practice of combining these two preservatives continues. Some solvents, such as propylene glycol, are sometimes considered as active preservatives, even in low (2–5%) concentration. Their mode of action probably results from solvent effects on distribution coefficient, micelle destabilization, or some other factor.

Compendia and other documents provide information on the solubility of preservatives in different solvents (water, olive oil, mineral oil). Such data are of limited value in identifying the locus of a given preservative in an emulsion. For example, the water-soluble methyl paraben partitions extensively out of the aqueous phase in a nonionic O/W emulsion of mineral oil.³³

Table 8
Preservatives and their efficiency in cosmetic emulsions

<i>Name</i>	<i>CAS No.</i>	<i>Efficacy^a</i>
Methylparaben	99-76-9	3
Propylparaben	94-13-3	3
Imidazolidinyl urea	39236-46-9	4
Diazolidinyl urea	78491-02-8	4
Quaternium-15	51229-78-8	4
Formaldehyde	50-00-0	4
Isothiazolinone blend	26172-55-4/2682-20-4	3
DMDM Hydantoin	6440-58-0	4
Phenoxyethanol	122-99-6	1
Bronopol	52-51-7	3
Dehydroacetic acid	520-45-6	1
Sorbic acid	110-44-1	1
Benzoic acid	65-85-0	1
Dichlorobenzyl alcohol	1777-82-8	2
Chlorhexidine	5556-1	3
Methyl dibromoglutaronitrile	35691-65-7	3
Iodopropynyl butylcarbamate	55406-53-6	3
Polyquaternium 42	31075-24-8	4

Note: This is a partial listing of preservatives for cosmetic products. A more comprehensive listing will be found in Reference 20.

a. Overall estimate: 1 least effective, 4 most effective. Most listed preservatives are more active against gram negatives than gram positives; antifungal activity can differ widely.

Sequestering agents which reduce the availability of certain trace (metal) elements play a role in emulsion preservation. Lists of preservative agents appear in the literature. Such listings commonly include substances of questionable or limited activity. Others list ingredients which rely on their decomposition to formaldehyde. The listing provided in Table 8 includes most substances *believed* to be effective in emulsions as the primary preservative. The efficacy ratings are based on an overall impression of data in the literature with special emphasis on utility in emulsions. Suppliers as a rule provide individual ingredients as well as mixtures based on synergistic action. Some of these preservatives are reported to be sensitizers, while others are banned in some countries. The regulations may allow some preservatives (or concentrations) only for rinse-off products (e.g. shampoos). Preservatives for leave-on products (e.g. skin-care emulsions) are more critically limited.

The level of preservative used in emulsions rarely exceeds about 0.5% and depends on the antimicrobial activity of the preservative. If two or more preservatives are blended, the required level may actually be lower as a result of synergism. Preservative performance depends on the emulsion's likelihood to support the growth of microbiota and on the activity of the preservative used. If microbial nutrients, especially proteins or carbohydrates, are part of the emulsion, the need for a powerful preservative must be met. Products containing high levels of ethanol or anhydrous products may not require any preservative. The likelihood of contamination during use also plays a role in preservative selection. Regulatory restrictions contribute to the difficulty of preservation. Despite its acceptance in the European Union and the United States, diazolidinyl urea, for instance, is not permitted in Japan. The preservative activity of substances against different microbiota varies; as a result, the amounts required for adequate preservation vary from species to species. Thus, the selection of an effective preservative system for a given emulsion must always be confirmed by appropriate testing.

4.2 Antioxidant preservation

The use of antioxidants for skin protection is based on current understanding of the formation of reactive oxygen species on UV exposure. The discussion here will not consider this topic; instead, the information provided is limited to the protection of cosmetic emulsions and emulsifiers against oxidative damage.

The decomposition of the hydroperoxide ROOH can lead to fragments exhibiting malodors, commonly identified as rancid. The initiator for the described Type I (free radical) reaction is UV light; in addition, the presence of most heavy metals reduces the induction period and increases the rates of both propagation and termination steps.

Peroxydation of unsaturated lipids appears to exhibit some pH-dependence, with high pH furthering oxidative decomposition.

Photo-oxidation leads to comparable products but is generally the result of irradiation with UV light in the presence of oxygen. The resulting formation of singlet oxygen (Type II reaction) and subsequent reactions provide another means for the generation of hydroperoxides. Singlet oxygen formation proceeds via a mechanism involving chemical photosensitization in which the irradiated substance is raised to a higher (triplet) state.

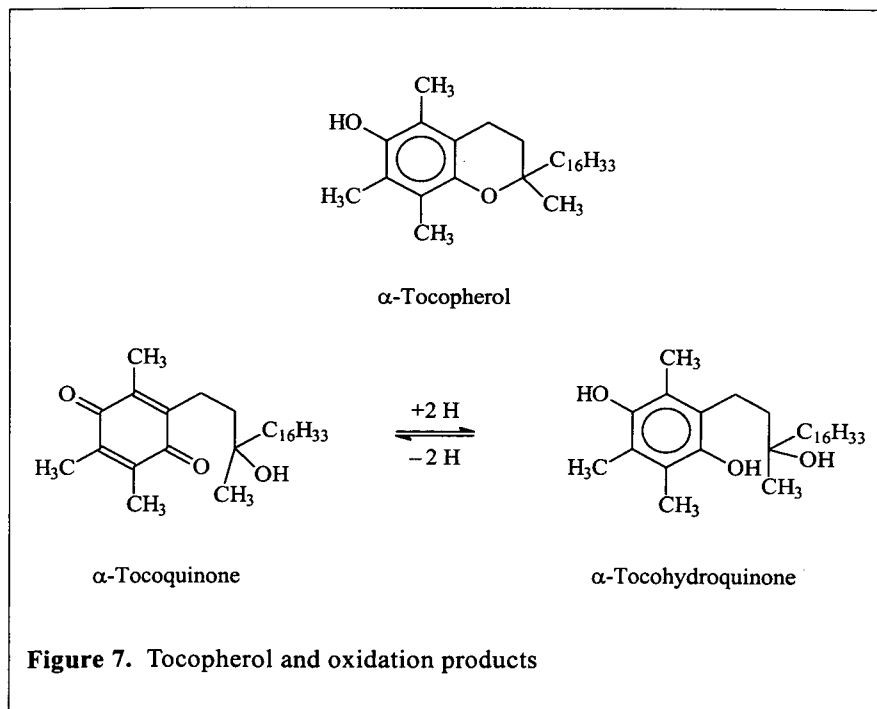
For the emulsion formulator, avoidance of Type I and Type II reactions is important. Therefore, UV light exposure must be avoided, and heavy metal catalysts must be eliminated, often with the aid of sequesterants. Despite these precautions, formulators must protect unsaturated emulsifiers and other constituents with the aid of antioxidants. Effective antioxidants are oxygen scavengers (reducing agents) and substances which can accept the free-radical-forming electron and avoid its participation in propagation steps. On this basis, synthetic and natural antioxidants can be readily identified from a list of reducing agents and 'hindered' phenols. The latter are mono- or polyhydric derivatives of benzene carrying stabilizing alkyl groups; *t*-butyl is a favorite alkyl substituent. A listing of a few better known antioxidants is provided in Table 9.

The phenols in this table can accept electrons and, by virtue of stabilizing resonance forms, can dimerize in a termination step or are oxidized to quinones. The complex chemistry of tocopherol (a common antioxidant) can be used to elucidate some of these effects. Tocopherol (Fig. 7) is a phenol, and its ability to act as an *in vitro* free-radical scavenger is eliminated by esterification of the phenolic hydroxyl group, although the complexity of the molecule may allow it to inactivate reactive oxygen substances formed by a Type II (photo) oxidation. The end-product of tocopherol after free-radical reaction is tocoquinone. *In vivo*, the latter is reduced to tocohydroquinone (Fig. 7), which then — dependent on pH — is reconverted to tocopherol.

Table 9
Common antioxidants in emulsions

Name	CAS No.
Butylated hydroxyanisole (BHA)	5013-16-5
Butylated hydroxytoluene (BHT)	25013-16-5
Propyl gallate	128-37-0
<i>t</i> -Butyl hydroquinone	1948-33-0
Tocopherol (D-alpha)	59-02-9
Ascorbic acid	50-81-7
Ascorbyl palmitate	137-66-6

The table (Table 9) of antioxidants excludes sulfites. Sulfites are still occasionally used in drugs, but their use as antioxidants in cosmetics today has been largely abandoned. A more comprehensive listing of cosmetic antioxidants can be found in the INCI Handbook.²⁰



A rather insidious radical peroxidation can take place on polyoxyethylene (POE) chains. Briefly, POE ethers are subject to free radical attack on any carbon atom α to an oxygen ether atom. The resulting peroxide $R'-O-CH_2-CH_2-O-\underset{\substack{| \\ O-OH}}{CH}-CH_2O-R''$ is ultimately hydro-

lyzed to aldehydes such as $R''-O-CH_2-CHO$, and related compounds. Not only are these fragments undesirable, but the shortening of the POE chain alters the emulsifier's characteristics. The nature of this reaction and its consequences were reviewed a few years ago.³⁴ It is important that users of these widely used emulsifiers control the quality of the raw material before, during, and after product manufacture. In addition, products containing these substances must be protected during storage and use. The important points are tabulated below:

POE derivatives should not contain:

- peroxides
- tramp metals
- off-odor
- titratable low molecular weight acids
- remnants of bleaching agents

POE derivatives require:

- antioxidants
- reducing agents
- cool and dark storage

5 Emulsion Stability

Cosmetic emulsions may show instability upon storage due to chemical changes of the components, the presence of undesirable microbiota in the product, or physical (mechanical or visual) changes. The first two causes of instability are generally not acceptable.

It is the formulator's responsibility to correct an emulsion's deterioration due to chemical, biological, or physical changes in the product. The basic objective is to create as *stable* a product as possible.

As a rule, the slow loss of an ingredient of an emulsion due to chemical (or oxidative) changes should not be tolerated. Similarly, the presence of excessive numbers of (even innocuous) microbiota is a warning that pathogens may invade the product and that it should not be distributed. On the other hand, evidence of physical change is not a valid reason for rejecting a complex cosmetic preparation. Such rejection should be based on consumer acceptance after storage or what has sometimes been called *shelf-life*.

5.1 Chemical stability

An emulsion's long-term chemical stability cannot be predicted. On the other hand, the successful formulator can avoid false starts on the basis of preformulation documents. Such documents are routinely used in the drugs industry before a new drug is compounded into a dispensable dosage form. Requirements for the cosmetic formulator may be somewhat less demanding. The basic principle is not to use ingredients which might react with each other chemically after compounding. This requires knowledge of the chemistry of the ingredients and of their tendencies to hydrolyze, oxidize, discolor, and the like. For example, the inclusion of esters in high or low pH products should be avoided to preclude simple hydrolysis. Hydroxylic solvents (propylene glycol and the like) and other common OH-functional ingredients can transesterify with other esters and even amides in neutral or mildly alkaline conditions.

The formulator should always try to anticipate reactions which are likely to occur and should request raw materials suppliers to provide all pertinent information. The material safety data sheets (required in the United States) are not very useful for someone who must combine a number of chemicals with unpredictable interactions. Instead, the rules

for preventing chemical deterioration, e.g. amide hydrolysis or pH changes, require specific analyses of the constituents of the emulsion.

The supplier should also provide information on impurities and the presence of sophisticants. For example, a propylene glycol diester of a fatty acid is likely to contain some monoester or some free acid with important consequences for emulsion stability. If such an ester has been leached with an oxidant, the product is likely to contain a number of components which might alter the chemical stability of other emulsion components. The approach to making a chemically stable emulsion is above all an effort to select only components that are not likely to interact with each other chemically.

The rate of any chemical reaction is temperature-dependent, proceeding — in the case of a cosmetic emulsion — relatively slowly at ambient temperatures. Despite having taken every precaution to avoid chemically interacting species, the formulator must determine whether relatively slow chemical reactions are taking place and whether predictive testing is needed. Fortunately, raising the temperature accelerates the rates of chemical reactions, and formulators should avail themselves of methodologies based on the Arrhenius equation (Eq. 2) to ascertain the *chemical* stability of a newly developed composition. Integration of the most general form of the Arrhenius equation:

$$\frac{d \ln k}{d t} = \frac{\Delta H_a}{RT^2} \quad [\text{Eq. 2}]$$

yields

$$\log \frac{k_2}{k_1} = \frac{\Delta H_a}{2.303 R} \cdot \frac{T_2 - T_1}{T_2 \times T_1} \quad [\text{Eq. 3}]$$

The general assumption in Equation 2 is that ΔH_a , the activation energy, is not a function of the temperatures (T_1 or T_2) at which the rate constants, k_1 or k_2 , are determined. R is the gas constant. Thus, the activation energy can be computed with the aid of Equation 3 from known values of k_1 and k_2 , one of which is determined at a relatively high temperature. From this value of the activation energy, one can compute the value of k at a third temperature, which in the general case of emulsion stability rarely exceeds 45°C. This rate can be used to compute the rate of *chemical* deterioration of any given component of the emulsion.

Normally, there is no need to consider the order of reactions, and one can routinely utilize first-order kinetics. Other simplifying approaches are described in the extensive literature dealing with methods for establishing chemical stability. In emulsions, the reactions of interest have activation energies of 10–30 kcal/mole, and each 10°C rise in temperature normally doubles the rate of a reaction. It is generally wise to avoid excessive temperatures for assessing chemical stability. Solubilities and distribution coefficients can change drastically as a result of wide temperature fluctuations. Thus, chemical inertness at 80°C is reassuring but does not guarantee absence of reactions at 30°C if the deteriorating chemical species should be transferred from, for example, a hydrolyzing aqueous medium at 30°C to an inert oily medium at 80°C. Pharmaceutical researchers have successfully used nonisothermal degradation data. For the cosmetic emulsion formulator, it seems wise to avoid test temperatures above about 55°C.

It is beyond the scope of this monograph to provide greater details on how to establish long-term chemical stability of the components of an emulsion product. No basic reviews of the specific subject are available. The general principles are described in texts on physical chemistry and physical pharmacy.³⁵

Photochemical stability can be an important requirement for those products which are not protected from light of any type (sun, incandescent or fluorescent). Fading of dyes or browning can occur as a result of light exposure.

5.2 Microbiological stability

Microbiological stability can be ascertained only on the basis of critical microbiological testing, as already noted above under preservation (sect. 4.1). The likelihood of microbial contamination of an emulsion is clearly enhanced in multiphase systems, which require the judicious use of preservatives. Preservatives are subject to chemical changes which may lead to their destruction. Chemical assay procedures cannot, however, ascertain preservative efficacy. The latter requires chemical stability and availability, as discussed above. The growth of uncontrolled or even opportunistic microbiota is normally associated with chemical as well as physical changes in the emulsion. It is important, therefore, to examine the preservation efficacy after storage at some stressful temperature (not exceeding about 55°C). A product which passes a preservative challenge test after three to six months of storage at about 45°C is

generally assumed to be properly preserved if storage conditions include the package components intended for marketing.

As in the case of chemical stability, microbiological assessment after storage at modestly elevated temperatures is generally useful for monitoring long-term microbial stability. Kabara's book³² provides comprehensive coverage of this subject.

5.3 Physical stability

Much of the information on the physical stability of emulsions has already been touched upon above under the general discussion of emulsification. The most difficult task for formulators is prediction of long-term physical stability on the basis of short-term test programs. The literature on this subject is overwhelming, and there is little consensus on the most meaningful test protocols. It is clearly impractical for formulators — who might require a three-year shelf-life at room temperature — to wait for such a long period before the product can be released for distribution.

The first requirement is the need to establish the conditions under which the emulsion must be 'stable'. Few investigators have made any meaningful contribution to this problem. For example, a product stored in a warehouse in Spitzbergen need not meet the stability requirements for a product stored in Nigeria. As a matter of fact, one could argue that the PITs for these products should be chosen with the place of storage and use in mind. Next, it is a known fact that any macroemulsion is inherently unstable and must eventually show signs of instability. Physical instability of an emulsion may ultimately lead to drastic phase separation or to formation of a semisolid gel that cannot be spread.

The formulator's goal is to create a product which can be used successfully for a period of time before it deteriorates. In simple words, the task is generation of an emulsion that exhibits an acceptable shelf-life. What is required is an emulsion that during its projected use-up time meets all the acceptance requirements of the user.

The shelf-life of a cosmetic emulsion is usually more than about two years but rarely exceeds five years at ambient conditions. No formulator can conduct real-time shelf-life studies but instead must rely on predictive testing under some arbitrarily chosen set of stress conditions. The formulator knows that an emulsion deteriorates gradually. During this period, changes in viscosity and droplet size occur slowly. What the formulator needs to know is when the accumulated changes in an emul-

sion stored under normal conditions make the product no longer usable. The formulator thus needs early clues of changes in order to predict the time at which useful shelf-life terminates. However, the accelerative stress to effect these changes in emulsions should never be destructive. The criteria for measurement and the stress conditions must not be unrealistic.

Appearance is a crucial aspect of an emulsion's acceptance. As a rule, macroemulsions prepared from oil and water (either O/W or W/O) reflect all visible light and are white. The attractiveness of cosmetic emulsions is also related to their specular reflections. Any change which alters the smoothness of the reflective surface is not acceptable. The gradual formation of pearly appearing (stearic acid) crystals in an aging emulsion may make the product more attractive; but such a gradual change may also become a consumer negative because the product is now 'different'.

The need for reformulation is obvious whenever evidence of emulsion separation occurs rapidly. Typical slower phenomena include creaming or rising, coalescence, or steady changes in viscosity. Usually the changes are not obvious, and the formulator must depend on minor changes as a result of varying stress conditions to make an early judgment of an emulsion's long-term shelf-life. These criteria commonly depend on some aspect of viscosity or particle size change.

5.3.1 Viscosity

Even minor viscosity changes are often of significance. Viscosity or, more precisely, *viscoelasticity*, of an emulsion should not change appreciably. Shortly after emulsion preparation, one must expect a modest increase in viscosity due to the phenomenon of thixotropy. Agitation or stirring lowers the system's viscosity unless it is dilatant. Reformation of various secondary bonds can be expected in a quiescent system and represents the other half of thixotropy. This phenomenon is widely viewed as useful because agitation allows removal of the product from the container and spreading of the product on the skin's surface. A more detailed discussion of thixotropy and related phenomena can be found in *IFSCC Monograph Number 3: An Introduction to Rheology*. Excessive thickening is clearly undesirable but is not an indication of long-term emulsion separation. On the contrary, the postulate of the Stokes' equation predicts that a viscous suspension of oil droplets in water should be more stable than a fluid one.

The Stokes' equation has been used for many years to explain the speed of creaming of an undisturbed emulsion. Creaming of an emulsion is due to the differences in specific gravities of the dispersed and continuous phases. Sedimentation of the dispersed phase is the opposite phenomenon but is due to the same cause. The velocity, v , of these phenomena in an idealized system is defined by the Stokes equation:

$$v = \frac{2r^2(\rho - \rho')}{9\eta} g \quad [\text{Eq 4}]$$

where r is the (hydrodynamic) radius of the droplets, ρ and ρ' the densities of the two phases, η is the macroscopic shear viscosity and g is the gravitational constant. Stokes' law explains how the rate of separation is reduced by lowering the particle size r or by equalizing ρ and ρ' . Another way of lowering the separation rate is an increase in viscosity η (of the external phase). Equation 4 should not be rigidly applied unless the droplets are spherical, rigid, and monodisperse and do not interact with each other. None of these features is met in the concentrated emulsions employed in cosmetics, but Stokes' law forms the basis for current thinking about dispersions.³⁶

The temperature-dependent changes of viscosity (η) follow the Arrhenius equation, at least in homogeneous systems. Heterogeneous systems, such as emulsions, need not follow these rules, and this relationship is subject to misinterpretation. Raising the temperature of an emulsion from about 25° to 50°C generally lowers its viscosity. This does not mean that the emulsion is unstable. After lowering the temperature from 50° to 25°C, the original viscosity should be restored; sometimes it is found to be higher than that originally determined. The formulator must exercise care in interpreting the impact of these changes on shelf-life.

5.3.2 Droplet size

Creamed or settled droplets may retain their original character, and the emulsion can then be readily reconstituted by shaking. If the droplets associate, they are said to flocculate. This type of reversible aggregation can frequently be overcome by (vigorous) shaking. On the other hand, if the droplets should merge, they become larger, and this coalescence may ultimately become apparent by formation of discrete visible drop-

lets, a defect which can be remedied only by 're-emulsification'. Acceptable shelf-life can be defined on the basis of these three sequentially occurring phenomena: creaming, flocculation, and coalescence. The precursors to flocculation have not been extensively explored, and few parametric methods for assessing creaming are available. Conductivity,³⁷ zeta potential,³⁸ and the like are predictive tools for assessing coalescence and other changes occurring in emulsions. Particle size measurements are the most direct means for monitoring particle coalescence. These measurements generally reflect the basic instability of macroemulsions. The occurrence of such changes in a cosmetic emulsion usually warrants the conclusion that the product does not have an acceptable shelf-life.

It is beyond the scope of this monograph to describe the many available methods for determining the particle size of droplets in a fluid emulsion. Allen's book provides much useful information and describes various optical methods.³⁹

It is customary to attempt to accelerate these subtle and gradual changes by varying the temperature. The increase in temperature lowers the viscosity of the internal phase but has far greater impact on the continuous phase through which particles tend to move, with resultant creaming. The increase in temperature also affects the droplet diameter. A rise in temperature increases the force with which droplets collide and the likelihood of their coalescence. Heat also interferes with the liquid crystalline coating on the droplet surface, alters the electrical double layer, and lowers the adsorption of stabilizing polymers. All these factors tend to cause coalescence or at least adhesion, increasing r in the Stokes' equation.

5.3.3 Stress conditions and other criteria

The only factor in the Stokes' equation not altered by stressing with heat is the gravitational constant, g . This can be controlled at least to some extent by centrifugation. Centrifugation should be conducted at low levels of g and at modestly elevated temperatures. Centrifugation at high g s can destroy all macroemulsions and has been rejected by many investigators as stability indicating.¹¹ On the other hand, these investigators recommend reliance on the modest agitation (rocking) during a shipping test to overcome stabilization due to thixotropy of the system.

The protocol for the study of a cosmetic emulsion's stability should be established at the start of development. The compounder should anticipate all types of problems, some of which may become critical only

during scale-up or production. Some reasons for failure to meet required stability are listed below:

- appearance (separation, color, etc.)
- odor
- viscosity (particle size, dispensability)
- preservation
- chemical reactions (pH, hydrolysis, etc.)
- agitation (rocking, pumping)
- package (compatibility)
- chance contamination (metals)
- weight loss or gain (depending on humidity)
- light exposure

The formulator should examine the product at the suggested temperatures and time intervals in the storage test program noted below. A pattern for withdrawal of samples for examination during storage may be constructed as follows:

Table 10
Recommended pattern for sample examination

<i>Storage conditions</i>	<i>Examination periods</i>
Freezer (-15°C)	1, 2 months
Refrigerator (+4°C)	1, 2, 4 months
Room temperature (25°-30°C)	monthly for 1 year; then semi-annually up to desired shelf-life
37°C	1, 2, 3, 6, 9 months
45°-50°C	weekly up to 4 weeks; then after 2, 3, and perhaps 6 months

A sufficient number of samples should be stored to allow for all required tests at all time stations.

Formulators are not restricted to these suggested temperatures and storage times. They also must constantly re-evaluate their stability programs, taking into account changes in packing components, in raw materials suppliers, and in processing.

It is apparent that any realistic prediction of shelf-life and the use of stress conditions is part science and part intuition. Some additional suggestions for the more conservative formulators follow. They address

some special concerns for low-viscosity emulsions as well as high-viscosity products.

1. Samples of freshly prepared emulsions should be stored at temperatures ranging from -15° to about 50°C . Storage at higher temperatures is rarely useful. The test for viscosity and particle size and the like should be conducted on some of the stored samples. The stability program should include not only storage at elevated temperatures and low temperatures but also cycling between -15° and 40°C .

2. Storage at temperatures above 40°C need not be continued for more than about 90 days.

3. An emulsion which on preparation has a bluish cast in a thin layer should not whiten on storage at modestly elevated temperatures (particle size increase).

4. The electrical conductivity should remain constant (O/W to W/O change).

5. Repeated (four or more) cycling between refrigerator temperature (4°C) and 45° to 50°C should not alter the rheogram (especially any yield point) of the emulsion. A one-point measurement (one shear only) should be used only for quality control.

6. Agitation (on a reciprocal shaker to simulate shipping test) at different elevated temperatures (up to about 50°C) can be a helpful tool for producing coalescence.

7. It is recommended that the performance of a newly developed product be compared to that of a similar commercial product of known and acceptable shelf-life.

8. Centrifugation at low gravities is a useful tool for establishing emulsion stability of low-viscosity emulsions.

9. Emulsions believed to have a phase-inversion temperature should not be stored and studied near the PIT.

10. The microstructure of multiphase emulsions should be examined at intervals by cryogenic scanning electron microscopy.⁴⁰

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