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Patent Law and Miscellaneous Topics

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20.1 Patents and Other Intellectual Property

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The purpose of this chapter is to provide some very general information about intellectual property protection (especially patents) to nonlawyers.[**] It is also intended to provide some suggestions for "self-help" to engineers that will enable them to improve the possibility of obtaining and securing appropriate protection for their ideas and developments even before they consult a lawyer. One of the questions an intellectual property attorney frequently hears is: "I have a great idea. How do I protect it?" This section should provide at least a starting point for answering that question.

In the case of patents, this section is designed to assist engineers and/or inventors in understanding what is expected of them and how to assist their patent lawyers or agents in the process of protecting their inventions. Be forewarned, however; the process of obtaining patent, trade secret, and/or copyright protection on such a development is not necessarily a linear one and is often neither short nor easy.

Patents[***]

What is a patent? The authorization for a patent system stems from the United Sates Constitution, which provides:

> The Congress shall have power… to promote the progress of science and useful arts, by securing for limited times to authors and inventors the exclusive right to their resective writings and discoveries. U.S. Const. Art. I, § 8.

Although the concept of a patent system did not originate in the United Sates, the drafters of the Constitution thought patents and copyrights significant enough to provide for them in the fundamental predicates on which our government is founded. Indeed, Thomas Jefferson, as Secretary of State, was one of the first patent "examiners."

The premise of the Constitutional provision is to encourage the disclosure of inventions in the interest of promoting future innovation. Specifically, if inventors were not provided with patent protection for their innovations, they would seek to exploit them in secret. Thus, no one else would be able to benefit from and expand on their inventions, so technology would not move as rapidly as it would with full disclosure. Following enactment of the Constitution, Congress promptly adopted and has continuously maintained and updated laws implementing a patent system.

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[**] This section is in no way intended to provide the reader with all of the information he or she may need to evaluate or obtain intellectual property protection in particular situations on their own. Additional information is available from the Patent and Trademark Office and the Copyright Office in Washington, D.C. and other published references on these subjects. For information on patents and trademarks, the reader may contact the Commissioner of Patents and Trademarks, Washington, D.C. 20231, (703)308-3457. For information regarding copyrights, contact the Register of Copyrights, Library of Congress, Washington, D.C. 20559, (202)707-3000. When applying the legal requirements to a specific issue, the reader is encouraged to consult with a knowledgeable lawyer.

[***] The patent laws are codified in 35 United States Code (i.e., "U.S.C.") § 100 *et seq*. Regulations implementing these patent laws, particularly as they relate to the operation of the Patent Office, are found in volume 37 of the Code of Federal Regulations (i.e., "C.F.R."). The internal rules of the Patent Office relating to the examination of patents are contained in the Patent Office "Manual of Patent Examining Procedure" or "M.P.E.P." For more information on patents, the following treatises may be helpful: *Patents*, Donald S. Chisum, Matthew Bender & Co., New York, 1995; *Patent Law Fundamentals*, Peter D. Rosenberg, 2nd ed., Clark Boardman Callaghan, Rochester, NY, 1995.

Strictly speaking, patents are not contracts; however, because of the premise behind the Constitutional provision, patents have sometimes been analogized to contracts between inventors and the U.S. Government. The Government agrees to allow the inventor exclusive rights to his or her invention for a period of time. In exchange, the inventor agrees to disclose his or her invention, thereby allowing other inventors the benefit of the patentee's work and enabling others to practice the invention after the patent has expired.

What rights does a patent confer? After a patent issues, the patentee has the right to exclude others from making, using, or selling the subject matter claimed in the patent. Currently, the term of a U.S. patent is 20 years from the date the patent was filed. The patentee is not required to license others to use the invention.

Nevertheless, a patent does not confer the right to do anything. In fact, it is frequently the case that an inventor will receive a patent but will be unable to use the patented invention because it infringes on another's patent. For example, if A obtained the first patent on a laser and B later obtains a patent on the use of a laser in surgery, B cannot make or use the laser in surgery, because it would infringe A's patent. By the same token, however, A cannot use this laser in surgery, because it would infringe B's patent. In addition, patent rights are territorially limited, and the use of the same invention in different countries may have different ramifications. Finally, regardless of patent rights, the use of certain technologies (e.g., pharmaceuticals) may be limited by other government regulations and practical considerations.

A significant advantage of a patent over other forms of intellectual property protection, such as copyright or trade secret, is that a patent can be enforced against anyone who utilizes the claimed technology regardless of whether that person copied or misappropriated the technology. Independent development of an infringing device is not a defense.

Who can obtain a patent? Anyone who is the first to invent something that falls into a category of subject matter that is deemed to be patentable may obtain a U.S. patent. A single patent can have several inventors if the subject matter of one or more claims in the patent was jointly conceived or reduced to practice. In that case, each inventor, in essence, obtains his or her own rights to the patent, subject to an obligation to account to the other inventor(s) for their respective share of the remuneration. The patent must be obtained by the true inventors or it may be invalid. Thus, persons who did not contribute to an invention should not be named as inventors regardless of the desirability of recognizing their moral or economic support to the process of inventing.

What subject matter is patentable? U.S. patent law provides that:

> Whoever invents or discovers any new and useful *process, machine, manufacture, or composition of matter*, or nay new and useful *improvement* thereof, may obtain a patent therefore, subject to the conditions of patentability and requirements of this title. [emphasis added.] 35 U.S.C. § 101.

Although the categories of patentable items seem archaic, Congress acknowledged that it intended this language to "include anything under the sun that is made by man."

The development of significant new technologies, such as computers and biotechnology, have challenged the limits of proper patentable subject matter. Nevertheless, with some diversions along the way, courts have continued to expand those boundaries so that they now include computer software and engineered life forms when embodied in properly drafted patent claims. In general, however, laws of nature, scientific truths, and mathematical algorithms are not patentable subject matter in and of themselves. New and useful applications of those concepts, however, may be patented.

What are the standards for patentability? In order to merit a patent, an invention must be new, useful, and nonobvious. The "new" and "useful" standards are defined precisely as one might expect. One may not obtain a patent on an invention that has been invented before and, therefore, is not novel or on one that has no practical utility.

The "nonobvious" standard is a more difficult one. Even if an invention has not been created before, in order to be patentable, it must not have been obvious to one of ordinary skill in the technical field of the invention at the time the invention was made. In other words, a valid patent cannot be obtained on an invention that merely embodies a routine design or the application of principles within the ordinary skill of the art. Whether an invention meets the standard for nonobviousness involves a factual inquiry into the state of the art, the level of ordinary skill in the art, and the differences between what was known in the art and the invention at the time it was made. In addition, both the Patent Office and courts will look at objective evidence of nonobviousness, including the context in which the invention was made (e.g., whether or not there was a long-standing problem that had not been solved by others), recognition of the invention, and its success in the marketplace. Nevertheless, the determination of nonobviousness is not precise. Indeed, the "beauty" of many of the most significant inventions is embodied in their simplicity. As such, they are temptingly "obvious" after the fact, even though courts are theoretically constrained from utilizing hindsight in determining nonobviousness.

How is a U.S. patent obtained? The process of obtaining a patent starts with the invention. Invention, under U.S. patent law, has two parts. First, there is the "conception" of the invention, which literally refers to the date when the inventor first thought of the novel aspect of his or her invention. Second, there is the "reduction to practice" of the invention, which can refer to a variety of activities. In the case of a mechanical invention, for example, reduction to practice occurs when a working version of the machine is built embodying the invention. However, there is also a legal concept called "constructive" reduction to practice, which occurs when the inventor files a patent application with the Patent Office.

The date of invention is very important in the United States. Unlike every other country in the world, the United States awards patents to the first person to invent it, rather than the first person to file a patent application. Importantly, the date of conception serves as the date of invention in the United States so long as the inventor was "diligent" in reducing the invention to practice. If the inventor is not continuously "diligent" (and there is some question as to what that word means, exactly), then the date of invention is considered the date on which the inventor was continuously diligent until the invention was reduced to practice.

The date of invention can be critical to obtaining a patent in the United States. In foreign countries, however, the only date that matters is the date on which the inventor first filed the patent application. Filing a patent application in the United States will normally preserve the inventor 's rights abroad if the appropriate foreign patent applications are filed within 1 year of the U.S. filing date and the other requirements of the Patent Cooperation Treaty are met. Ideally, an inventor should file a patent application directly after the conception of the invention in order to achieve the earliest effective date in both the United States and abroad.

Before filing a patent application, an inventor should have a "prior art search" performed. *Prior art* is a term used to refer, in part, to any printed materials published before the inventor files the application that are relevant to the issues of novelty and nonobviousness. Having a search done for prior art is a good way to ensure that the invention for which the application is written is patentable and may also provide some insight into whether or not practice of the invention would infringe the rights of others. The prior art search enables a preliminary determination of the patentability of the invention and, if it appears patentable, the identification of the patentable features to be focused upon in drafting the application. Nevertheless, there is always some prior art that will not be accessible using economically viable means at the time of application, so an inventor can never be completely sure about the novelty of his/her invention at the time of filing.

An inventor can apply for a patent from the Patent Office either *pro se* (i.e., on his own) or through a registered patent agent or attorney. The process of obtaining a patent is a complex one, and the inventor's chances of obtaining a valid patent of the broadest possible scope are greatly increased by the use of a qualified agent or attorney. Lists of registered patent attorneys and agents are available from the Patent Office. Patent attorneys may also be located through the *Martindale-Hubbell Law Directory*, state and local bar associations, and other publications, directories, and professional organizations.

This is not to say that inventors, themselves, have not successfully obtained patents from the Patent Office. Nevertheless, busy patent examiners are easily frustrated by *pro se* applicants' lack of familiarity with patent application requirements and Patent Office rules, and those frustrations are evidenced, consciously or unconsciously, in Patent Office "rejections." Familiarity with the stated requirements of the Patent Office and knowledge of its informal workings greatly increase the chances of successfully obtaining a valid patent with the broadest possible scope.

A patent application contains a number of parts, all of which generally fall into two main categories. The first group, known as the "specification," contains a detailed written description of the invention including relevant drawings or graphs and any examples. The purpose of the specification is to "enable" one of ordinary skill in the art to make and use the invention. In addition, the applicant must disclose the "best mode" of practicing the invention. The "enablement" and "best mode" requirements are intended to fulfill the constitutional purpose of full disclosure of the invention. Thus, a patent that was otherwise properly granted by the Patent Office may nevertheless be invalidated if it is later determined that the inventor failed to teach others how to utilize the invention or tried to maintain the best mode of practicing the invention as a secret.

The second major part of the patent application is the "claims," which are the separately numbered paragraphs appearing at the end of a patent. The claims define the scope of protection that the patent will confer, and they must be clear, definite, and unambiguous. The goal of the applicant in prosecuting a patent is to obtain claims that cover the invention as broadly as possible without including subject matter that is obvious or not novel. For example, if A invented the two-wheeled bicycle, he might claim a vehicle utilizing two round rotating objects for conveyance. Such a claim might prove to be invalid, for example, if carts were previously known. In such a situation, it would be better to claim the bicycle more narrowly as a vehicle with two wheels in tandem.

Once the application is drafted and submitted to the Patent Office, the Patent Office classifies the invention and sends it to an appropriate "art unit." The Patent Office is divided into separate art units that employ examiners who are knowledgeable about, or at least familiar with, particular fields of technology. Eventually, an examiner will read the application, focusing mainly on the claims since they define the legal parameters of the invention. After performing his own patentability search and reviewing the application for other technical defects, the examiner may either "allow" the application to become a patent or reject the application on the grounds that it lacks substantive merit and/or fails to comply with the formalitites of a proper patent application. If the examiner rejects some of the claims, he will explain why the claims are not patentable in light of the specific prior art references. This will start a series of communications (in writing, by telephone, or in person) between the examiner and the applicant (or the registered attorney of record). During that process, the claims of the patent will be amended as becomes necessary in an attempt to define patentable subject matter.

If the application is eventually allowed, then the patent will be valid from the date of issuance until 20 years after the date the application was originally filed. If the application is not allowed by the examiner and is finally rejected, the inventor can (1) abandon the application and the effort to obtain a patent, (2) file a "continuation" application and start the process over, or (3) appeal the rejection to the Board of Patent Appeals and Interferences and eventually to other courts. It is not uncommon for the process from filing of the application until allowance to take several years.

After the application is submitted, it is appropriate to advise the public that a patent is "pending." This remains true until the application has been abandoned or has issued as a patent. Generally, neither the contents of the application nor even the fact that an application has been filed are publicly available from the Patent Office absent the consent of the applicant. After the patent issues, the patent number should be marked on products embodying the patent. This notice serves to start the period running for the collection of damages for patent infringement. Absent such notice, damages do not begin to run until the infringer receives actual notice of the patent.

Several aspects of this process bear particular note. First, once an application has been filed, the Patent Office does not permit the introduction of "new matter" into the application. Although typographical and other simple errors in the application may be corrected, an applicant may not insert additional written material or drawings (e.g., an additional embodiment or further improvement). The reason for this is simple — because the date of invention and the date of filing are both important for U.S. and foreign priority purposes, the Patent Office could not operate efficiently if the subject matter of the application were constantly amended. There would be numerous continuing disputes as to the effective date to be afforded the subject matter of an amended application. Instead, if it is necessary to amend the application substantively, a new "continuation-in-part" application must be filed. If it is filed while the original or "parent" application is still pending, the subject matter common to both applications will retain the original filing date, while the new material will only be afforded the filing date of the later continuation-in-part application. The prohibition on adding "new matter," therefore, places a premium on filing an original application that completely and accurately describes the invention.

Second, the patent application process frequently is not linear. Seldom does an invention constitute a static concept or a single finished embodiment. The concept may change as its full ramifications are slowly revealed through practical experience, and its embodiment in physical articles, compositions, or processes may change after the patent application is filed. Thus, as the invention evolves, it may be necessary to file further continuation-in-part applications to cover the developments which appear during this evolutionary process. To achieve the ultimate objective of obtaining patent protection on commercially viable aspects of the invention, it may be necessary for the inventor and legal counsel to reevaluate the merits of the original application and to take appropriate corrective action in the patent prosecution process.

How can the inventor help? There are a variety of ways in which the inventor can and, in fact, should aid in the process of obtaining a patent.

First, and perhaps foremost, an inventor should keep detailed notes on his research and development throughout the inventive process. All research and/or discoveries should be documented, dated, and witnessed by a noninventor because they may become important later for purposes of determining who was the first to invent. The date of invention may also be useful in convincing the Patent Office or a court that certain prior art dated before the filing of the patent application should, nevertheless, not be applied. In preparing this documentation, it is important to realize that the testimony of the inventor himself or documents authenticated only by the inventor are generally not sufficient to prove priority. There are many reasons for this. Suffice it to say that there is a premium on having the records witnessed contemporaneously by at least one noninventor. Getting a noninventor to witness pages of a lab notebook is one way to accomplish this. Alternatively, the Patent Office will, for a nominal fee, accept and provide validation of "disclosure" documents evidencing the date of conception. This is probably the most unquestionable evidence of a date of conception.

An inventor can also assist by performing an informal prior art search of his own before contacting a patent attorney. Filing a patent application is expensive. An inventor should be as confident as possible that he has created something novel before spending the money to draft an application. Typically, a patent attorney will urge that a formal search be performed to ensure that the prior art that the Patent Office examiner is likely to access has been considered. Due to the proliferation of electronic databases for scientific and industry literature, however, there may be additional prior art which is more readily accessible to the inventor. A search of this material can be very helpful to the patent attorney in isolating the patentable features of the invention and improving the chances of obtaining a valid patent.

All prior art located by or known to the inventor should be disclosed to the patent attorney so that it can be evaluated and disclosed to the Patent Office, if necessary. In that regard, both an applicant and his attorney are under an affirmative duty to disclose relevant prior art to the Patent Office, and failure to do so can lead to invalidation of the patent.

Once a prior art search has been performed, an inventor should file an application as early as practically possible. As noted previously, this will protect the inventor's rights in foreign countries as well as provide constructive reduction to practice of the invention if it has not already been embodied in a working prototype. Nevertheless, some delay in filing may be desirable in order to permit further testing and corroboration. This is permissible, and in many instances desirable, bearing in mind that under U.S. patent law an application *must* be filed within 1 year of the first public use, disclosure, sale, or offer of sale of the invention. This deadline cannot be extended and, if violated, will automatically result in the invalidation of the patent. Many other countries do not have a 1 year "grace" period; a patent application is immediately barred once there has been a public disclosure in that country or elsewhere. Although there is an "experimental use" exception in the United States, it is limited to technical experiments (as opposed to test marketing) that are appropriately documented. To be safe, the inventor should contact a patent attorney before publicly disclosing or using an invention or offering it for sale. If any of those events have already occurred, they should be immediately called to the patent attorney's attention.

The inventor is also instrumental in drafting the patent application. The inventor must make sure that the specification is accurate, enables one skilled in the art to practice the invention, and discloses the best way to make and use the invention. Although the art of claim drafting is somewhat of an acquired skill, the inventor should also be very involved in that process to make sure that the claims cover the invention and are not easily designed around. Sometimes a patent attorney will draft claims that do not expressly state a physical element or process step, but utilize "means-plus-function" language. In that case, it is highly desirable to describe as many means as possible for fulfilling that element in the application itself, and the inventor is the best source of that type of information. In other words, the inventor should continuously be asking questions of his attorney about whether or not certain variations of his invention will be adequately protected by the claims as drafted. Finally, the inventor can and should be instrumental in helping the attorney identify the technical/practical differences between the invention and prior art. In short, the prosecution of a patent application should be a team effort between inventor and attorney at each step in the process.

Trade Secrets*

In some instances it may be desirable to protect new technology as a trade secret rather than by patent. For example, an invention may not be patentable; it may be one of numerous small items or "know how" that improve one's business. Such items are typically protected as trade secrets. While there is no formal method of acquiring trade secret protection as there is for patents and copyrights, attention must still be paid to their identification and protection. Also, unlike patents and copyrights, trade secrets are protected under state, rather than federal laws. Therefore, the nuances of trade secret protection may vary depending on which state's laws apply. There are, however, some general principles of trade secrets that are common to most jurisdictions.

What is a trade secret? A "trade secret" may include anything that gives a person an advantage over his competitors and is not generally known to them. It includes compilations of information such as customer lists, compositions, process techniques and parameters, and software. In determining whether or not something is a protectable trade secret, courts look at the following factors: (1) the extent to which the information is known outside of the trade secret owner's business; (2) the extent to which it is known by employees or others involved in the trade secret owner's business; (3) the extent of measures taken by the trade secret owner to guard the secrecyof the information; (4) the value of the information to the trade secret owner and to his competitors; (5) the amount of effort or money expended by the trade secret owner in developing the information; and (6) the ease or difficulty with which the information could be properly acquired or duplicated by others.

What protection does a trade secret provide? A trade secret protects the owner from improper appropriation of the secret through use or disclosure by a person having an obligation not to do so. The major advantage of a trade secret is that it may last indefinitely; the major defect is that if it is lost, it generally cannot be reclaimed. Unlike patent infringement, a person accused of stealing a trade secret can successfully defend such an accusation by showing that he independently developed the subject matter of the secret. Trade secret protection, therefore, is only as good as the inability of competitors to "reverse engineer" or independently develop it.

How can one obtain a trade secret? Whether or not one has a trade secret is ultimately determined judicially in an action for enforcement. The court will look at all of the factors previously noted. At that time it is usually too late to take the actions necessary to establish trade secret protection. Thus, there is a premium for the periodic review and implementation of a program for trade secret protection. Among

* See, generally, the Uniform Trade Secrets Act § 1(4), 14 U.L.A. 537 (1980) and *Milgrim on Trade Secrets*, Roger M. Milgrim, Matthew Bender & Co., New York, 1995.

the steps that can be taken to protect trade secrets are (1) identifying the types of materials that are deemed to be trade secrets by an organization and notifying employees of the organization's policy to treat this information as trade secrets; (2) restricting access to the trade secrets to only those individuals who have a need to know and who are obligated by contract or otherwise not to use or disclose them; (3) taking physical precautions to limit access to trade secrets such as using locked file cabinets, vaults, etc. These are the most fundamental steps that can be taken.

Although legal counsel is frequently consulted in establishing a plan for protecting trade secrets, including the drafting of appropriate confidentiality agreements, the physical steps required should be put in place by the trade secret owner prior to legal consultation.

Copyrights*

Copyright protection is usually associated with writings, songs, paintings, sculpture, and other artistic endeavors. However, it also extends to certain technology, particularly software, databases, and certain architectural plans.

What protection does a copyright provide? Copyright protection is a matter of federal law. Under the federal Copyright Act, protection is available for "original" works of appropriate subject matter, such as those mentioned in the previous paragraph. A copyright provides the exclusive right to reproduce, publicly distribute, publicly perform, publicly display, and make derivative works from an original work of authorship. However, it protects only against "copying" of the protected work and does not provide protection where a work has been independently developed by another. Copying can be presumed where the third party had access to the copyrighted work and there is "substantial similarity" between the third party's work and the original. Further, in certain limited instances, a small portion of a work may be reproduced without liability as a "fair use." The parameters of the "fair use" doctrine are complicated, however, and they are beyond the subject of this section.

Only a modicum of creativity is needed to satisfy the requirement of "originality." On the other hand, protection is limited. It has frequently been stated that a copyright only protects the manner in which something is expressed, rather than the idea or content, which can be an extremely difficult distinction to make. For example, there is significant debate as to the appropriate scope of copyright protection, for both software and databases. Nevertheless, an advantage of a copyright is that it may last for a relatively long period of time. At a minimum, copyright in works created at this time last for the life of the author plus 50 years.

How is a copyright obtained? Theoretically, in order to obtain a copyright an author need only show that a work is original to him (i.e., that he is in fact the author). Federal protection for copyright attaches as soon as a writing is fixed in a tangible medium (i.e., as soon as it is put on paper, or in memory on a computer, or anywhere else that it can be "perceived"). Nevertheless, there are two important steps that should be taken to realize the full scope of that protection.

First, it is highly advisable to affix a copyright notice to the work. "Notice" is provided by affixing to the work: (1) the word "Copyright" or the "©" symbol, (2) the date of first publication, and (3) the name of the copyright owner. Notice should be affixed to the work in an obvious position (such as one of the first pages of a book, an entry screen of a computer program, etc.). A copyright notice should be placed on all drafts of material that may be subject to protection under copyright law. If an author fails to put the notice on his work, copyright protection is not lost; however, an infringer may then use the defense that he innocently thought that the work was within the public domain. Adequate notice precludes the "innocent" infringer defense, and, because it does not cost anything, notice is always a good idea.

In addition, registration of the copyright with the Register of Copyrights at the Library of Congress is also highly recommended. This procedure is relatively simple and inexpensive. It consists of filling

* The federal laws on copyright are codified in the Lanham Act, § 1 *et seg*. For further information on copyrights, the following treatise may be helpful: *Nimmer on Copyright*, Melville B. & David Nimmer, Matthew Bender & Co., New York, 1995.

out a government form and submitting it with the appropriate filing fee and a sample of the work sought to be copyrighted. If the application is acceptable, the Copyright Office returns a copy of the application stamped with the copyright registration number.

In the case of software and databases, there has been concern that an unscrupulous competitor might attempt to purloin valuable information from the sample submitted with the application. In recognition of this problem, the Copyright Office has promulgated rules allowing the submission of only a limited portion of the software or database adequate to identify the copyrighted work.

Although federal registration is not necessary to perfect a copyright, it does have some significant advantages. First, it is necessary to obtain a registration in order to bring suit against an infringer. While it is possible to register the work on an expedited basis immediately prior to commencing the lawsuit, it is not advisable. Early registration (i.e., within 3 months of the first publication of the work) allows an author to elect to sue for "statutory" damages, which can be considerably easier to prove and, possibly, more munificent than "actual" damages. In addition, an author may be able to recover attorneys' fees from a defendant in some cases, but only if the work in question was registered before or soon after publication. In sum, if an author believes that a work is important and might be copied, he should promptly register the work.

Trademarks*

Although trademark protection does not encompass technology per se, any summary of intellectual property protection would be incomplete without a few comments on the scope and availability of trademark rights.

What is a trademark? A trademark is anything that serves to identify the source of a product or service. Trademark protection can be obtained on a wide variety of items such as words, symbols, logos, slogans, shapes (if they are not functional), tones (such as NBC's three-note tone), and even colors. A trademark owner may assert his rights against a third party that is engaged in conduct that is likely to cause consumers to believe that his goods or services emanate from, are associated or affiliated with, or are sponsored by the trademark owner.

The purpose of trademark protection is twofold: (1) to ensure the public that goods or services offered under a trademark have the quality associated with the trademark owner and (2) to preserve the valuable goodwill that the trademark owner has established by promoting the mark. Trademark rights may last indefinitely.

How are trademark rights established? Trademarks are protected under both federal and state law. There are two ways to obtain rights in a trademark: use or federal registration. Rights in a mark can be acquired simply by using the mark in connection with the goods and services. If the mark is a distinctive one (i.e., coined or "made-up" like "POLAROID") rights are established immediately. On the other hand, if the mark is descriptive, the use must be so prominent and lengthy that the mark has acquired a "secondary meaning," (i.e., the public has come to recognize the term as identifying the source of the goods and services rather than as a reference to the product or service itself). In either case, to establish rights through use, it is desirable to use the designation "™" in connection with the mark, thereby indicating that the owner of the mark asserts that it is a trademark under common law.

In contrast, the process of obtaining a federal trademark registration involves the filing of an application with the U.S. Patent and Trademark Office. The application identifies the mark, the goods and services with which it is used, and, if it is already in use, the date of first use and the date of first use in interstate commerce. A filing fee is also required but is relatively minimal. A trademark examiner will check the application substantively, including the review of previously issued trademarks, to see if there is any conflict. If the examiner allows the application, the mark is published in the *Official Gazette*, which is

* The federal trademark laws are codified at 17 U.S.C. § 1 *et seg*. For further information on trademarks, the following treatise may be helpful: *McCarthy on Trademarks and Unfair Competition*, J. Thomas McCarthy, Clark Boardman Callaghan, Rochester, NY, 3rd ed., 1995.

a weekly publication of the Patent Office. If no one opposes the registration within 30 days after publication, then a registration will be issued. If there is an objection, then an opposition proceeding is initiated, and the applicant and the opposer essentially litigate to determine who should obtain the trademark registration. Provided that certain documents are subsequently filed with the Patent Office to affirm and renew the registration, the registration may last indefinitely. The existence of a federally registered trademark is designated by the symbol "®", which is frequently seen on the shoulder of the mark.

A federal trademark registration is a powerful tool in protecting a trademark. By law it serves as "constructive" (i.e., assumed) notice of the registrant's claim of rights throughout the United States. In essence, the registration acts like a recorded deed to real estate, and anyone who subsequently purchases that property without checking the recorded information does so subject to the interests of record. In contrast, the rights of one who attempts to acquire a trademark only through use are generally limited to the geographic area in which the mark is actually used. Others who subsequently use the mark in other areas of the country may also establish rights. Thus, the first step in selecting a trademark is to search the records of the Patent Office to determine whether or not a confusingly similar mark has previously been registered. Typically, a trademark search performed by a professional search organization will also reveal state registrations and other common law uses that might cause conflicts with the mark under consideration.

One other advantage to federal registration is that the registrant may begin to acquire protection on a mark prior to actual use. This is accomplished by filing an "intent-to-use" application on a mark that the applicant has made a *bona fide* decision to use. The application is examined as described previously. Although the mark must actually be placed in use before the registration is issued, the registration will be effective from the date of its filing. Thus, the public is on notice of the applicant's potential rights as soon as the application is filed. The examination process will also give the applicant significant comfort that the mark is available for use before investing a great deal of money in its promotion.

Final Observations

Selecting an appropriate method of acquiring intellectual property protection for a new development may involve several forms of protection. Software, for example, may be protected by patent, trade secret, and copyright protection and may be sold using a registered trademark. In addition, other legal means may be used to protect the software, including appropriate contractual provisions limiting and restricting the rights of a user acquired by license. Those contractual commitments may survive, even if the intellectual property protection is lost.

It is hoped that this section has provided at least a general overview by which the nonlawyer can begin to understand how to protect intellectual property. There are almost never any easy answers to the question of how to protect products, ideas, and services, and it is always advisable to consult a qualified attorney with specific questions. A knowledgeable client, however, can make a significant difference in achieving the strongest protection available.

20.2 Product Liability and Safety

George A. Peters

Introduction

Almost all engineers, at some time in their career, can expect some direct contact or indirect involvement with the legal system. The contact may be in the form of having to answer written interrogatories on technical issues for a company defendant or plaintiff, being personally deposed and having to respond to oral questions under oath, appearing for a company during trial, assisting lawyers in a lawsuit, or personally being a defendant in a lawsuit. Most important is having the ability to translate legal requirements into engineering specifications to assure compliance with the law.

The old maxim "ignorance of the law is no excuse" should be supplemented by an understanding that ignorance of the law may result in unnecessary mistakes (illegal acts) and personal fear when first confronted by an unknown aspect of the legal process. It is essential that the engineer have sufficient understanding to avoid gross errors and omissions, to react appropriately to legal proceedings, and to want to build a basic foundation of knowledge that can be quickly enhanced when needed. This section is only a brief overview that might be illustrative and helpful in both understanding potential legal liability and how to avoid, prevent, or proactively minimize any such legal exposure. If product liability is legal fault for an unsafe design, the question then becomes how to achieve an appropriate level of safety.

Legal Concepts

Fundamental to determining who might be legally "at fault" is the concept of *negligence* which is utilized worldwide in the apportionment of damages (legal redress). Negligence is the failure to exercise ordinary or reasonable care, which persons of ordinary prudence would use to avoid injury to themselves or others. The exact definition is given to jurors, usually in the form of approved jury instructions (the actual operative law), who then apply the law given to them to the facts and circumstances of the case before them. The defenses to allegations of negligence (absence of due care) are, usually, *contributory negligence* (fault) on the part of the plaintiff or *assumption of the risk* on the part of the plaintiff (that risk that is specific and voluntarily assumed, not general or coerced). If there is a violation of a statute or regulation there may be a rebuttable presumption of negligence. Compliance with a technical standard may be some evidence of the exercise of due care. Concepts of *strict liability* involve the presence of a defect that legally caused personal injury or property damage. There are many definitions of a *defect*, such as a failure to perform as safely as an ordinary consumer would expect when used in an intended or reasonably foreseeable manner or "excessive preventable risks."

Foreseeability means that the personal injury, property damage, or environmental harm must have been predictable or knowable at the time of design, manufacture, or sale of the product. Generally, the law requires only *reasonable efforts* to prevent defects, deficiencies, or unsafe conditions. In other words, there should be efforts to predict possible harm and reasonably practical risk reduction efforts to minimize the harm.

The term *engineering malpractice* includes conduct that has personal legal consequences (professional liability) for the individual engineer, conduct that has adverse legal consequences for his or her employer (such as product liability or toxic torts), and conduct having moral or ethical consequences even though it may be legally protected (Peters, 1996a).

There are many other supplemental legal concepts and each state or jurisdiction has summaries of the law (Witkin, 1987–1990), approved jury instructions (Breckinridge, 1994), statutes enacted by the legislature, compendiums of case law decisions by the courts, and regulations issued by executive agencies (all of which are constantly being revised and expanded). Thus, the engineer should always consult with an attorney-at-law before making an interpretation or taking any action that might be within the province of a licensed professional.

There are thousands of technical standards issued by professional associations, trade groups, standards formulation organizations, and government agencies. Compliance with such standards is the first line of liability prevention, but such standards should be exceeded by a confortable margin to accommodate design, material, fabrication, and in-use process variance (Council, 1989). However, there are other important liability prevention measures that should be undertaken during the design process and described in a product liability prevention plan.

Risk Assessment

A central theme in liability prevention is "risk assessment". The first step in such an assessment is to identify all probable *hazards* (those faults, failures, or conditions that could cause harm), then determine the quantitative *risk* for each (the frequency and severity of harm), and, finally, render a subjective judgment as to *danger* (the presence of excessive preventable danger). It is important to determine what kind of risk assessment is being made and to identify its objective as follows:

1. *Compliance*. The exact method of conducting a risk assessment may be specified by procurement specifications, industry standards, or government regulations. The design objective may be only compliance with the assessment requirement. However, in the process of performing a written risk assessment and classifying the risk into some severity level, it may result in a beneficial safety audit of the product. Where there is "residual risk," the design of specific warnings and instructions may be required.
2. *Major Compliance Tasks*. Where safe performance is very important, a detailed engineering analysis may be required by contract or regulation. This might involve listing all probable hazards for each component, part, and subsystem, then attempting to quantify the risk estimate for each hazard at the 10^{-6} level of attempted precision. Since this requires a major effort, the primary design and management objective should be product improvements and informed product assurance.
3. *Comparative Analysis*. Some risk assessments involve only an overall risk estimate which is then compared with other similar products or a wide range of products. The objective or use may be for marketing purposes or liability defense. Since the results are gross or macroscopic, such risk assessments generally do not result in product improvement.
4. *Risk Ratings*. Some trade associations may provide generic risk ratings for materials or products. The objective may be for an "informed choice" of procedures and field equipment in order to satisfy a legal "duty of care" or to help determine the "best practical means" of job performance.
5. *System Effectiveness*. Some risk assessments are performed early in the design process, perhaps as part of a reliability analysis, for the purpose of predicting final system effectiveness. The objective may be to check design efforts, reallocate available funds, or refocus management audits to achieve a desired level of system effectiveness. The process may be used to assure that desired system-of-systems performance is achievable.

From the societal viewpoint, some level of risk can be tolerable, acceptable, required, and specified. What is desired at a given locality or time period can be made known by the local common law, government regulations, trade standards, practices, customs, and expectations. From the engineering viewpoint, *risk levels are controllable, adjustable, manageable, and a consequence of the application of appropriate engineering techniques, skills, and information resources*.

Engineering Analysis

Rather than rely only upon an engineer's subjective and often biased judgment as to what constitutes a safe design, it is advisable to perform specific objective engineering analyses for design safety. This usually includes some systematic approach to identifying failure modes and field hazards, their risk consequences, and alternative design options that might improve the safety performance. This should be supplemented by formal design review sessions that consider information from or about customers and learned intermediaries in the fabrication, packaging, shipping, distribution, and marketing system. Written hazard analyses should include consideration of legal duties (Peters, 1991a,b), liability prevention techniques (Peters, 1996b), and cultural attributes and technical information resources in the worldwide marketplace (Murakami, 1987, 1992). There should be a systems perspective, a cradle-to-ultimate-disposal philosophy, a true understanding of customer needs and characteristics, and appropriate application of specific design safety techniques.

Testing is required to *verify* the engineering analyses, to *prove* the inherent safety of the product or process system, and to *discover* all potential problems before they become manifest postsale. As part of a *product liability mitigation plan*, procedures and costs should be determined for possible accident investigations, product recalls, retrofits, and injury reparations. A continuing (postsale) *product surveillance plan* should cover all foreseeable users, servicing, maintenance, repair, modification, transport, disposal, and recycling of the product and its components. This permits early discovery and resolution of safety problems. It should also include a means for updating a knowledge bank of scientific, engineering, legal, insurance, patent, and foreign standards information useful for future design efforts as well as postsale obligations.

Human Error

Human error is a major source of undesirable variance in human–machine interfaces. Unfortunately, many engineers neglect or virtually ignore the human factors aspects of product and system design. There should be some effort to control human performance and prevent human failure by designing for a wide range of human dimensions, characteristics, and predictable responses (Peters, 1996a). If possible, the physical attributes, kinetics, and creative perceptual abilities of human operators, maintenance and repair personnel, and bystanders should be utilized in design. Human factors should be part of any early engineering analysis, with appropriate testing and safeguarding for human error that cannot otherwise be eliminated. This includes mechanical guards, tamper-resistant features, safe-stop and limited movement switches, proximity sensors with directional control, built-in time for protective behavioral reactions, and the prevention of inadvertent activation and operation. One of the most important sources of helpful information on human error comes from incident and accident reconstruction, but the scope and bias of the inquiry may severely limit the design usefulness of the data obtained; for example,

1. The *fatalistic approach* where human error is considered as being inevitable in an imperfect world. If there is "no fault" other than by the person committing an error or omission, there is little incentive to investigate in detail to determine other factors for purposes of corrective action. This fosters the continuance of tolerable human error, persistent undesirable human error, and a lack of true recognition of causation and preventive actions.
2. The *behavioral approach* which has a focus on individual behavior in an attempt to develop "safer people," safer attitudes, and to develop motivation to "act responsibly." This may result in closer supervision and additional training, with some short-term benefits, but it does not permanently alter the error-inducing situation.
3. The *situational approach* to human error is to blame the situation, the work environment, group interactions, sociotechnical factors, and the overall circumstances of the situation. There is some benefit from a broader perspective to human error since it provides a better understanding of causation.
4. The *product design approach* has an emphasis on the interaction between the user and the engineered product to provide information useful to the design engineer.
5. The *multifactorial approach* is based on the assumption that there is multiple causation for each injury, damage, loss, harm, or error. If special attention is given to each substantial factor or cause, valuable design-oriented information can result. This multifaceted perspective of accident reconstruction has the greatest benefit and is compatible with concepts of pure comparative negligence and the allocation of damages in proportion to the degree of fault.

During any accident investigation or accident reconstruction, care should be exercised to prevent any "spoliation" or distruction of evidence. This requires trained specialists, since even slight changes to the product may obliterate information that becomes critical in later product evaluations.

Warnings and Instructions

As a last resort, for residual risk, appropriate use of warnings and instructions is essential for product liability prevention and the safe use of products (Peters, 1993). Such communications require a specific design engineering effort, plus relevant testing, if they are to be effective. They include warning devices, warnings on labels and packaging, material safety data sheets, instructions for training, insertions in owner's or operator's manuals, and postsale advertisements and letters to all owners. Some regulations require that they be in two languages and in nonlanguage pictorials. Such hazard communications and procedural directions should not be the result of a cursory afterthought, but an ongoing integral part of the design process. There may be neuropsychological considerations in the presentation of information by visual or auditory displays, machine condition and status indicators, and computer-generated information that requires specialized knowledge and testing. The basic premise is to design a referent about a specific hazard so the target individual is adequately informed as to risk and has a reasonable choice as to avoidance behavior. Warnings that fail to communicate their intended message are functionally useless. There is considerable scientific and engineering information regarding the design of warnings and instructions, and the failure to heed such information may result in legal allegations about a failure to warn, instruct, test, or appropriately market a product. The issue becomes what proof exists about whether or not warnings, instructions, or representations would have significantly influenced user behavior, purchaser choices (as, for example, in available options), and use of protective equipment. Warnings are an important liability prevention and design safety objective.

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Further Information

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20.3 Bioengineering

Jeff R. Crandall, Gregory W. Hall, and Walter D. Pilkey

The interdisciplinary field of **bioengineering** combines personnel and principles from the physical and life sciences. Although a relatively young field, it is developing rapidly by incorporating experimental and computational techniques from traditional disciplines of engineering and applying them to biological problems. In particular, finite-element techniques and computer modeling are revolutionizing the manner in which bioengineering is conducted and interpreted.

Although based on the principles of traditional disciplines, bioengineering differs from classical engineering because the human body is a living system capable of responding to a changing environment. This results in several challenges for the bioengineer:

- Material properties can vary due to intrinsic and extrinsic factors, e.g., physical properties change with specimen age, gender, and health;
- The human body is capable of self-repair and adaptation, e.g., muscle size increases in response to physical training;
- Many structures within the body cannot be isolated for laboratory testing, e.g., the heart cannot be removed to study circulatory system mechanics.

The discipline of bioengineering includes, but is not limited to, the topics of

- Biomechanics
- Biomaterials
- Biomedical instrumentation and sensors
- Biotechnology
- Genetic engineering
- Medical imaging
- Clinical engineering.

Due to the vast breadth of the field, the authors of this section have not attempted to provide an exhaustive overview of the field of bioengineering but rather have tried to select those areas believed to be of most interest to mechanical engineers. Therefore, this summary of bioengineering is intended to acquaint the reader with the concepts and terminology within the fields of **biomechanics** and **biomaterials** and to provide basic material properties for both tissues and implanted devices.

Biomechanics

The field of biomechanics applies the theories and methods of classical mechanics to biological systems. More precisely, it is concerned with the forces that act on and within a biological structure and with the effects that these forces produce. An overview of topics within the field of biomechanics is provided in Figure 20.3.1. It is evident that the study of stress and strain distributions in biological materials for the development of constitutive equations is a major research emphasis. A review of the constitutive equations and the associated material properties are provided in this section for the most commonly tested tissues.

Hard Tissue Mechanics

The term *bone* refers to two types of hard tissue structure: cortical and cancellous bone. Cortical bone is the dense, structured compact bone that composes the shaft of long bones such as the femur and tibia. Cancellous or trabecular bone is found within the ends of tubular bones and the body of irregularly shaped bones. The mechanical and structural properties of the two types of bone can vary substantially. In addition, bone is capable of **remodeling** in response to its environment. Table 20.3.1 summarizes the general physical and material properties for the two bone types.

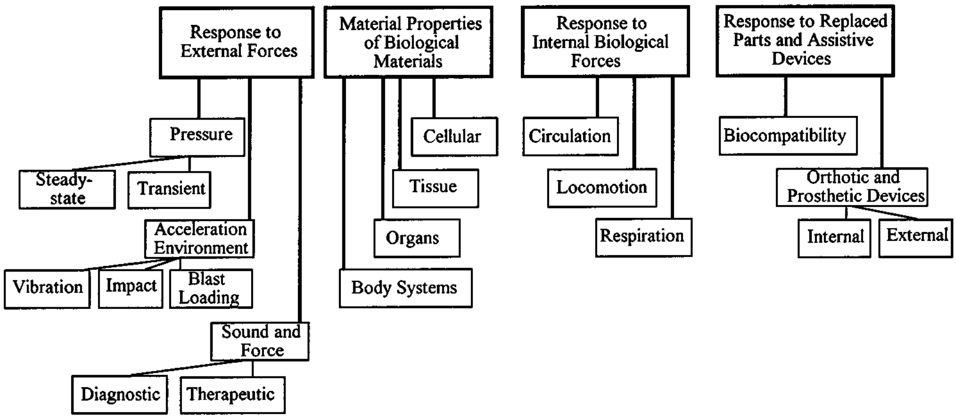

FIGURE 20.3.1 Topics of biomechanics.

TABLE 20.3.1 Physical and Material Properties of Cancellous and Cortical Bone

Bone	Density (kg/m³)	Poisson's Ratio	Elastic Modulus (GPa)	Tensile Strength (MPa)	Compressive Strength (MPa)	Ref.[a]
Cortical	1700–2000	0.28–0.45	5–28	80–150	106–224	1
Cancellous	100–1000	—	0.1–10	—	1–100	2

[a] 1, Nigg and Herzog (1994); 2, Mow and Hayes (1991).

Like most biological materials, bone behaves as an anisotropic, nonhomogeneous, viscoelastic material. Therefore, the values in Table 20.3.1 exhibit a wide range of scatter and variability due to the simplified model of bone as a linearly elastic isotropic material. It is generally adequate, however, to model bone as a linearly elastic anisotropic material at the strain rates found in most experiments. To address the anisotropy of bone, bone is generally considered to exhibit either transverse isotropic or orthotropic behavior. The constitutive equation for a linearly elastic material can be written using a single-index notation for stress and strain as

$$\sigma_i = c_{ij}\varepsilon_j \tag{20.3.1}$$

where the standard summation convention is used with the indexes possessing a range of 6. The stress-strain relationship can be similarly expressed in terms of the compliance matrix $\mathbf{s_{ij}}$ such that

$$\varepsilon_i = \mathbf{S}_{ij}\sigma_j \tag{20.3.2}$$

Equation (20.3.3) represents the compliance matrix of an orthotropic material in terms of the Young's moduli (E_i), the Poisson's ratio (ν_{ij}), and the shear moduli (G_{ij}).

$$\mathbf{S}_{ij} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_2 & -\nu_{31}/E_3 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & -\nu_{32}/E_3 & 0 & 0 & 0 \\ -\nu_{13}/E_1 & -\nu_{23}/E_2 & 1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{31} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix} \tag{20.3.3}$$

For an orthotropic material the compliance matrix can be expressed in terms of 12 components, 9 of which are independent. The additional symmetry of the transverse isotropic model results in a further simplification with

$$E_1 = E_2, \quad \upsilon_{12} = \upsilon_{21}, \quad \upsilon_{13} = \upsilon_{31}, \quad G_{23} = G_{31}$$
$$G_{12} = \frac{E_1}{2\left(1+\upsilon_{12}\right)} \tag{20.3.4}$$

Table 20.3.2 provides a summary of the material constants for bone. Both mechanical and ultrasonic testing have been used to determine the independent elastic coefficients for bone. The anisotropy of bone requires that mechanical tests be applied in several different directions in order to determine all of the independent elastic coefficients. Ultrasound has the advantage that all elastic coefficients can be measured on a single specimen.

TABLE 20.3.2 Material Constants for Cortical Bone from the Human Femur

Model	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	ν_{12}	ν_{13}	ν_{23}	ν_{21}	ν_{31}	ν_{32}
TI	11.5	11.5	17.0	3.6	3.3	3.3	0.58	0.31	0.31	0.58	0.46	0.46
Orth.	12.0	13.4	20.0	4.53	5.61	6.23	0.376	0.222	0.235	0.422	0.371	0.350

Note: TI = transverse isotropic; Orth. = orthotropic.

Mechanics of Soft Tissue

The biomechanical properties of soft tissues depend on both the chemical composition and the structure of the tissue. Most soft tissue structures within the body demonstrate aspects of nonhomogeneous, anisotropic, nonlinear viscoelastic behavior. Given the complexity of the constitutive equations, the material properties are difficult to measure and many tests are required. To simplify the test procedures, homogeneity and linearity are frequently assumed.

The simplest representation of viscoelastic material behavior uses combinations of three discrete models comprising linear springs and dashpots: the Maxwell solid, the Voigt model, and the Kelvin model. While these models are generally linear approximations of the nonlinear behavior of biological materials, they can often describe material behavior with reasonable accuracy and can help to visualize tissue behavior.

For improved characterization of the soft tissue response, Fung (1993) developed an approximate theory that was based on the theory of linear viscoelasticity but incorporated nonlinear stress-strain characteristics. More-complex nonlinear viscoelastic models can provide additional improvements in describing tissue response but require extensive experimental testing to determine the model coefficients.

Cartilage

In most joints of the body, the ends of the articulating bones are covered with a dense connective tissue known as hyaline articular cartilage. The cartilage is composed of a composite organic solid matrix that is swollen by water (75% by volume). The cartilage serves to distribute load in the joints and to allow relative movement of the joint surfaces with minimal friction and wear. The coefficient of friction for articular cartilage ranges from 0.001 to 0.1 (Duck, 1990; Mow and Hayes, 1991).

The biomechanical properties of articular cartilage are summarized in Table 20.3.3. The experiment of preference for the testing of articular cartilage has historically been the indentation test. Analysis of the test results has used elastic contact theory, the correspondence principle, and the assumption of material incompressibility ($\nu = 0.5$). This analysis ignores the nonhomogeneous and directional properties of articular cartilage and does not take into account considerable finite deformational effects or the flow

TABLE 20.3.3 Biomechanical Properties of Articular Cartilage

Tissue	Ultimate Compressive Strength (MPa)	Ultimate Compressive Strain	Ultimate Tensile Strength (MPa)	Ultimate Tensile Strain	Elastic Modulus (MPa)	Poisson's Ratio	Ref.[a]
Cartilage	5.0–8.0	0.136	2.8–40	0.182	1.63–220	0.42–0.47	1, 2, 3

[a] 1, Duck (1990); 2, Skalak and Chien (1987); 3, McElhaney (1976).

of the interstitial fluid relative to its porous permeable solid matrix. More-recent models of cartilage have used a biphasic (i.e., an elastic solid and a fluid phase) model to describe more accurately the mechanical response of cartilage.

Muscle

Three types of muscle make up the muscular system: cardiac muscle, smooth or involuntary muscle, and skeletal or voluntary muscle. The focus of this section will be on the skeletal muscle used to maintain the body's posture and to provide movement of the body's segments. The response of skeletal muscle is determined by a combination of active and passive components. The force exerted by a muscle is dependent on the length at which it is stimulated, on the velocity of contraction, on the duration of contraction, and on factors such as fatigue, temperature, and prestretching. A general estimate of the strength of the muscle assumes that its strength is proportional to the physiological cross-sectional area, defined as the muscle volume divided by its true fiber length. The average unit force per cross-sectional area that is exerted by a muscle ranges from 20 to 80 N/cm^2. For more-precise calculations, the relationship between the maximum force of muscle and instantaneous rate of change of its length must be considered. Hill's equation is an empirical relationship expressing the rate of muscle shortening as a function of the isotonic force

$$V = \frac{b\left(F_0 - F\right)}{F + a} \quad \text{or} \quad F = \frac{F_0 b - av}{b + v} \tag{20.3.5}$$

where v is the velocity of shortening, F_o is the force at zero velocity (isometric condition), and F is the instantaneous force. The constants a and b have units of force and velocity, respectively, determined empirically using the relationship

$$K = \frac{a}{F_0} = \frac{b}{V_{\text{max}}} \tag{20.3.6}$$

where $v_{\text{max}} = bF_o/a$, the shortening velocity against no load. For most muscles, the range of the muscle constant is $0.15 < k < 0.25$ (Skalak and Chien, 1987).

Tendon/Ligaments

Tendons and ligaments are connective tissues composed primarily of collagen fibers and are normally loaded in tension. Tendons transmit forces from muscles to bone in order to

- Execute joint motion and
- Store energy.

Ligaments attach articulating bones across a joint in order to

- Guide joint movement;
- Limit the joint range of motion;

- Maintain joint congruency; and
- Assist in providing joint stability.

The biomechanical properties of ligaments and tendons are provided in Table 20.3.4.

TABLE 20.3.4 Biomechanical Properties of Tendon and Ligament

Tissue	Ultimate Tensile Strength (MPa)	Ultimate Tensile Strain	Elastic Stiffness (MPa)	Ref.[a]
Ligament	2.4–38	0.20–1.60	2–111	1, 2, 3
Tendon, calcaneal	30–60	0.09–0.10	600	4, 5

[a] 1, Yamada (1970); 2, Skalak and Chien (1987); 3, Nahum and Melvin (1993); 4, Bronzino (1995); 5, Duck (1990).

The general stress-strain behavior of connective soft tissue can be represented by four distinct loading regions (Figure 20.3.2). Region I is commonly referred to as the "toe region" and is associated with the straightening or alignment of the randomly ordered structural fibers. Most physiological loading occurs in this region where there is a small increase in stress for a given increase in strain. Region II characterizes the linear region where the straightened fibers are more uniformly loaded. The tangent to the stress-strain response curve in this linear region is frequently referred to as the elastic stiffness or tangent modulus rather than the elastic modulus in order to emphasize that the soft tissue is not truly behaving as a perfectly elastic material. At the initiation of Region III, small fluctuations in the stress can be observed resulting from microfailures in the soft tissue. The final loading profile shown in Region IV exhibits catastrophic failure of the soft tissue.

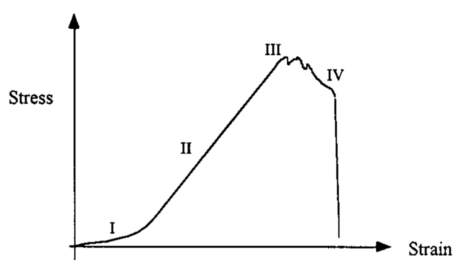

FIGURE 20.3.2 General stress-strain behavior of connective soft tissue.

Factors Affecting Biomechanical Properties

Due to the nature of biological testing, a great deal of variability in the material properties of tissue is evident in the published literature. Unlike traditional engineering materials, there are no standard protocols or procedures for the testing of biological materials. Although some variability can be attributed to differences in the experimental approaches undertaken by the researchers, mechanical behavior of biological materials can also be affected by

- Geometric characteristics;
- Loading mode (i.e., tension, compression, torsion);
- Rate and frequency of loading;
- Specimen preparation (i.e., temperature, preservation method, hydration);
- Age or health of specimen donor;
- Gender;
- Temperature;
- Anatomic location of load and specimen;
- Species.

Rate of Loading. The rate of load can affect both the material properties and the patterns of failure of biological materials. Due to their viscoelastic nature, many biological materials are stronger and stiffer at high rates of loading.

Loading Mode. The stress-strain behavior of biological materials is highly dependent on the orientation of the tissue structure with respect to the direction of loading (Table 20.3.5). Many tissues such as cortical bone, tendon, and muscles have organized structures which result in anisotropy of the physical properties. In some cases, the anisotropy exists but is not incorporated in the constitutive model or experiments and results in increased variability of the data.

TABLE 20.3.5 Material Properties Variation in Bone Due to Specimen Orientation and Loading Mode

Cortical Bone Orientation	Mode	Ultimate Strength (MPa)	Elastic Modulus (MPa)	Ref.
Longitudinal	Tension	133	—	Currey (1984)
	Compression	193	17	
	Shear	68	3.3	

Anatomic Location. Although homogeneity is often assumed, biological tissues typically exhibit significant differences in material properties depending on the anatomic location. Table 20.3.6 illustrates the variability of material properties with anatomic location using articular cartilage from the knee.

TABLE 20.3.6 Dependence Tensile Modulus (*E*) of Human Articular Cartilage on Location

Region	Medial Anterior	Medial Central	Medial Posterior	Lateral Anterior	Lateral Central	Lateral Posterior	Ref.
E (MPa)	159.6	93.2	110.2	159.1	228.8	294.1	Mow and Hayes (1991)

Age. The material properties of biological materials can vary depending on whether the specimens are obtained from immature, mature, or aging tissue. In general, the ultimate strength of tissues decreases with increasing age. Bone, muscle, tendon, cartilage, and ligaments all show decreases in the ultimate strength and elastic moduli after maturity with increasing age (Table 20.3.7). Several tissues, such as skin and teeth, are exceptions to this general rule and can exhibit increases in some material properties with age.

TABLE 20.3.7 Ratio of Age Changes for Ultimate Tensile Strength

Tissue	10–19years	20–29years	30–39years	40–49years	50–59years	60–69years	70–79years
Cortical bone	0.93	1.00	0.98	0.91	0.76	0.70	0.70
Cartilage	1.02	1.00	0.93	0.80	0.56	0.33	0.29
Muscle	1.27	1.00	0.87	0.73	0.67	0.60	0.60
Tendon	1.00	1.00	1.00	1.00	1.00	0.95	0.78
Skin	—	1.00	1.26	1.26	1.08	0.96	0.77

Storage/Preservation. The increasing complexity of biomechanical testing requires a considerable period of time for each individual test and necessitates tissue storage and preservation. It is essential to ensure that the storage and preservation of biological materials is controlled so that the material property measurements in the laboratory accurately reflect the properties of the tissue in the living state. Biological materials are preserved using one of three methods depending on the required storage interval:

- Refrigeration for short-term storage;
- Freezing for long-term storage;
- Embalming for long-term storage.

Refrigeration and freezing have no effect on the properties of hard tissue. Although the effects of refrigeration on soft tissue properties are tissue dependent, stable properties can generally be achieved within 3 days of storage. Freezing of soft tissue can result in ice cavities that disrupt the tissue architecture and result in property changes. The effects of embalming on soft and hard tissue structures exhibit conflicting results.

Because many biological materials are composed primarily of water, humidity can strongly affect the stress-strain relationships (Table 20.3.8). Therefore, care must be taken to keep biological specimens moist prior to and during testing. The control of the moisture level of specimens is most important when analyzing the elastic properties of surface tissues such as skin and hair. Young's modulus of skin at 25 to 30% relative humidity may be 1000-fold greater than that at 100% humidity (Duck, 1990).

TABLE 20.3.8 Comparison of Material Properties between Wet and Dry Cortical Bone

Test Condition	Ultimate Tensile Strength (kg/mm^2)	Ultimate Percentage Elongation (%)	Elastic Modulus (kg/mm^2)	Ref.
Wet tibia	14.3 ± 0.12	1.50	1840	Yamada (1970)
Dry tibia	17.4 ± 0.12	1.38	2100	Yamada (1970)

Species. Animal tissues have been used extensively in biomechanical testing because of their availability. When extrapolating results to humans, care must be taken since significant differences can exist in the structure and material properties between humans and other animals due to physiological and anatomic differences. Table 20.3.9 shows a comparison of elastic moduli of femoral bone specimens obtained from different animals.

TABLE 20.3.9 Comparison of Bone Elastic Modulus between Different Species

Tissue Source	Tissue	Elastic Modulus (MPa)	Ref.
Human	Femur	18	Currey (1984)
Cow	Femur	23	
Sheep	Femur	22	
Tortoise	Femur	10	

Impact Biomechanics

The prevention of injury through the development of countermeasures is most effectively achieved through biomechanical testing and analysis. The prevalence of injuries resulting from motor vehicle crashes, sporting activities, and industrial accidents has led to the development of a branch of biomechanics referred to as impact biomechanics. In order to achieve the principal aims of prevention of injury through environmental modification, this branch of biomechanics must develop an improved understanding of the mechanisms of injury, descriptions of the mechanical response of the biological materials involved, and information on the human tolerance to impact. Injury criteria for the human body as interpreted by anthropometric dummies are provided in Table 20.3.10. The injury criteria are provided in terms of engineering parameters of resultant acceleration $a(t)$, force $F(t)$, velocity $V(t)$, displacement $s(t)$, and anthropometric scaling factors such as the chest depth D.

Computational Biomechanics

Computational mechanics provides a versatile means of analyzing biomechanical systems. Modeling uses either rigid-body models composed of rigid masses, springs, joints, and contact surfaces or flexible-

TABLE 20.3.10 Adult Midsize Male Injury Criteria for an Impact Environment

Body Region	Injury Criteria	Formulation	Threshold
Head	Head injury criteria (HIC)	$\text{HIC} = (t_2 - t_1)\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5}$	1000
Chest	Compression criteria	$s(t)$	7.5 cm
	Acceleration criteria	$a(t)$	65 g
	Viscous criteria ($V * C$)	$V(t) * s(t)/D$	1 m/sec
Femur	Force criteria	$F(t)$	10 kN

TABLE 20.3.11 Comparison of Rigid Body and Finite Element Modeling Methods

Model Characteristics	Multibody Model	Finite-Element Method
Complexity	Relatively simple	Relatively complex
Fidelity	Requires engineering intuition	Can achieve high fidelity
Efficiency	Very efficient	Computationally expensive
Model Elements	Springs, point masses, rigid bodies, ellipsoids, joints, and contact planes	Flexible elements: bricks, beams, plates, shells

body models with finite or boundary elements (Table 20.3.11). Software is now available that incorporates the two modeling techniques and uses multibody modeling to capture overall kinematics of a biomechanical system and flexible body modeling to provide an in-depth study of those regions of particular interest.

The complexity of biological systems and limited constitutive model data often require that simplifying assumptions be made during the development of models. Therefore, it is necessary to verify the model before conducting parametric and sensitivity studies.

Biomaterials

The application of engineering materials to replace, support, or augment structures in the human body has become a major thrust of medical research in the last half of the 20th century. These efforts have helped to improve quality of life and longevity in individuals suffering from a variety of diseases and injuries. Since the materials involved with this repair are implanted within the biochemically and mechanically active environment of the body, the response of both the host and material has been investigated.

A biomaterial is defined as a nonviable material used in a medical device that is intended to interact with biological systems. The interaction of a biomaterial with its host can be classified into four categories (Black, 1992):

- *Inert* — implantable materials which elicit a minimal host response.
- *Interactive* — implantable materials which are designed to elicit specific, beneficial responses, such as ingrowth and adhesion.
- *Viable* — implantable materials, possibly incorporating live cells at implantation, which are treated by the host as normal tissue matrices and are actively resorbed and/or remodeled.
- *Replant* — implantable materials consisting of native tissue, cultured ***in vitro*** from cells obtained previously from the specific implant patient.

The concept behind *inert* implants is to introduce an "innocuous" implant to the host that will perform its mechanical role without altering the local environment. Decades of research on host and implant response have informed the biomedical community that no implant is inert and that every material will elicit a response from the host. For many biomaterial applications, the objective is to elicit a *minimal* host response. Those implants that are *interactive* with the biological environment do so in a desired and planned fashion. *Viable* implants are at their infancy, but already show promise in assisting and possibly directing tissue repair. The concept of an entire organ *replant* is still unrealized, but current strides in deciphering the human genetic code will make replants of **autologous** materials a clinical method of the future.

Material and Host Response

The Physiological Environment. The first reaction of the body to an implant is to "wall off" or build a fibrous tissue capsule around the implant. The biomaterial will be enclosed in a fibrous capsule of varying tissue thickness that will depend on the material and the amount of motion between the tissues and the implant. When the biomaterial elicits a minimal encapsulating response, it is possible for the tissue to integrate with the implant mechanically. This has been demonstrated in total-joint replacement when new bone is formed to interdigitate with a porous surface. Another approach to **biocompatibility** has been to use the tissue response to a material to benefit the function of the implant. This approach is used when bone chemically bonds to the hydroxyapetite coatings on hip implants.

The interaction between implant material and the host occurs at both the chemical and mechanical level. There are several parameters that affect the response of the biomaterial to the host environment and the overall performance:

- *The pH and salt content of the implant site* — A Pourbaix diagram for saline environments should be consulted to see if the metal will be passivated.
- *Lipid content of the implant site* — Lipophilic materials may swell or lose strength.
- *Mechanical environment* — Implant materials may wear, creep, and/or fatigue.
- *Corrosive potential of the material* — Metallic implants are susceptible to galvanic, crevice, and other types of corrosion.
- *Method of manufacture and handling* — Scratches and other defects will increase the likelihood of crack development and/or crevice corrosion.
- *Method of sterilization* — Some methods of sterilization will cross-link polymers or affect the degradation of biodegradable materials.

The host response to an implanted material is also affected by both chemical and mechanical factors. A few parameters that affect host response are

- *Leached materials from the implant* — Leached material, consisting of metallic ions, polymeric molecules, or solvents from manufacturing, may denature proteins. The pathway and effects of leached material should be examined.
- *Surface tension and electric charge of the material.*
- *Stiffness of the biomaterial* — Stress shielding of the bone by a stiff implant has been shown to affect bone remodeling.
- *Geometry of the implant* — Sharp edges have been shown to increase the fibrous tissue capsule thickness.
- *Method of cleaning and sterilization* — Solvents, filings, or residues left from the manufacturing, handling, or sterilization processes will likely cause unwanted host response and increase the probability of infection.

The expected life span of an implant varies with application. Some implants are used for temporary structural support, such as intermedullary nails for fracture fixation. In this application, corrosion is not as critical an issue as cost and mechanical fatigue. Another approach to temporary applications has been the use of biodegradable materials that eventually dissolve into the body. Biodegradable materials have been used for fracture fixation and drug delivery with success.

Current Biomaterials

Metallic Biomaterials. Metals are typically selected for biomedical applications because of their high tensile strength (Table 20.3.12). With the high tensile strength of metals comes a high elastic modulus that can lead to stress shielding of the bone. Bone, which remodels in response to its loading environment, resorbs in regions of low stress which can lead to implant loosening.

TABLE 20.3.12 Common Metallic Biomaterials

Metal	Form	Density (g/cm³)	*E* Modulus (GPa)	Yield Strength (MPa)	Fatigue Strength @ 10^7 Cycles (MPa)	Characteristics	Medical Applications	Ref.[a]
Ti-6Al-4V	AN CP-Ti	4.4 —	127 120	830–896 470	620 —	Chemically inert, poor wear properties, good fatigue properties, high strength-to-weight ratio, closest modulus to that of bone	Total hip and knee stems	1, 5
Co-Cr-Mo, ASTM F-75	C/AN W/AN	7.8 9.15	200 230	450–492 390	207–310 —	Excellent wear properties, castable, Co and Cr ions have been found mutagenic *in vitro*	Articular surfaces in hips and knees, dental implants, hip stems	2, 3
AISI-316LVM Stainless	AN 30% CW	7.9 —	210 230	211–280 750–1160	190–230 530–700	Inexpensive	Temporary applications, bone screws, bone plates, suture	5–7
Tantalum	CW	16.6	190	345	—	Very inert, very dense	Transdermal implant testing, suture	4

Note: AN: annealed, CW: cold worked, C: cast, W: wrought, CP: chemically pure.

[a] 1, ASTM F136-79; 2, ASTM F75-82; 3, ASTM F90-82; 4, ASTM F560-86, p. 143, 1992; 5, Green and Nokes (1988); 6, ASTM F55-82; 7, Smith and Hughes (1977).

Another issue when using metals in the body is corrosion since very few metals are in a passivated state while ***in vivo***. Metallic implant materials are subject to several types of corrosion: galvanic, crevice, pitting, intergranular, and stress/fatigue. For metallic biomaterial selection, it is best to refer to the corrosion potential of a material in seawater, rather than tap water since seawater is a reasonable approximation for the ***in vivo*** environment. Implant designs that involve dissimilar metals or multiple pieces have increased susceptibility to galvanic corrosion (Cook et al., 1985). A reasonable prediction of the reactivity between dissimilar metals can be made upon consideration of the galvanic series.

Polymers. The number of polymers available for biomedical applications has been increasing rapidly in the last few decades. Polymers are viscoelastic materials whose mechanical properties, host response, and material response depend on molecular weight, degree of cross-linking, temperature, and loading rate, among other factors. Therefore, it should be recognized that tabular data representing the mechanical properties of polymers only indicates the general range of properties for a class of polymers (Tables 20.3.13 and 20.3.14). Common applications of polymers in biomedical engineering include articular wear components, drug-delivery devices, cosmetic augmentation, blood vessels, and structural applications.

Biodegradable Polymers. There are a plethora of degradable polymers available to the modern biomedical engineer. Each is unique in mechanical properties, degradation time, degradation products, and sensitivity of strength to degradation. Recent efforts in polymer development have focused on biodegradable materials that serve as either temporary support or drug-delivery devices during the healing

TABLE 20.3.13 Bulk Material Properties of Some Thermoset Polymers

Thermoset	Density (g/cm^3)	Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)	Applications	Comments	Ref.[a]
Polyethylene terephthalate (dacron, polyester)	1.40	2.41	62.06	150–250	70–130	Suture, mesh, vascular grafts, heart valves, fluid transfer implants, artificial tendons	Subject to negligible creep, heat resistance up to 250°F, steam sterilizable, poor wear resistance, susceptible to hydrolysis and loss of strength	1, 2
PMMA thermoset	1.15–1.20	2.4–3.1	15.8	9.7–32	2.4–5.4	Acrylic bone cement	Very biologically inert, poor tensile strength, monomer lowers blood pressure, may cause thermal necrosis during curing at 95°C, radiolucent without addition of barium sulfate	2, 3
Polyurethane	1.10	5.9	—	45	750	Implant coatings	Good resistance to oil and chemicals	2
Silicone Rubber						Cosmetic augmentations, nose, ear, chin, and breast implants	Polymer backbone is silicon, rubbery mechanical properties, lipophylic, material elicits a minimal host response and has very flexible, cartilage-like stiffness, may cause local sclerosis and inflammatory phenomena. Recent *in vitro* studies on silicone have demonstrated an absence of cytotoxic response. There is no current epidemiological data to support termination of its use	2, 4, 5
Heat vulcanized	1.12–1.23	<1.4	—	5.9–8.3	350–600			
High performance	0.98–1.15	2.4	—	8.3–10.3	700			

[a] 1, Park (1979), 2, Lee et al. (1995); 3, Lautenschlager et al. (1984); 4, Frisch (1984); 5, Polyzois et al. (1994).

TABLE 20.3.14 Thermoplastic Biomedical Polymers

Thermoplastic	Density (g/cm^3)	Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	T_{glass} (°C)	Elongation (%)	Applications	Comments	Ref.[a]
PMMA thermoplastic	1.19	2.4–3.1	—	50–75	105	2–10	Contact lenses, blood pump	Very biologically inert, excellent optical properties, radiolucent without barium sulfate added, losses strength when heat sterilized	1–3
Polypropylene	0.85–0.98	1.5	—	30–40	–12	50–500	Disposable syrine, suture, artificial vascular grafts	High flex life, excellent environment stress cracking resistance	2, 1
Polyvinylchloride (PVC) rigid	1.35–1.45	3.0	—	40–55	70–105	400	Blood and solution bags, catheters, dialysis devices	High melt viscosity, thus difficult to process	2, 1
Polysulfone	1.23–1.25	2.3–2.48	65–96	106	—	20–75	Hemodialysis, artificial kidney circulatory assist, composite matrix	High thermal stability and chemical stability, unstable in polar organic solvents such as ketones or chlorinated hydrocarbons	2, 3
Polytetra-flouroethylene (Teflon)	2.15–2.20	0.5–1.17	—	17–28	—	320–350	Catheter, artificial vascular grafts	Heat sterilizable, low coefficient of friction, not recommended as a bearing surface, inert in solid form	1, 5
UHMWPE molded and machined extruded	0.93–0.97 0.93–0.94	— 1.24	21 21–28	34 34–47	— —	300 200–250	Articular bearing surfaces	UHMW has MW > 2E6 g/mol, very inert, induces minimal swelling *in vivo*, high concentration of wear particles leads to bone resorbtion, creeps under load, has heat resistance up to 180°F which is too low for steam sterilization	4

[a] 1, Park (1979); 2, Lee et al. (1995); 3, Dunkle (1988); 4, ASTM 648-83; 5, ASTM F754.

TABLE 20.3.15 Properties of Degradable Polymer Fiber

Polymer	Crystallinity	T_{melt}/T_{glass} (°C)	Modulus/Strength (GPa/MPa)	Ultimate Elongation (%)	Common Material Applications
Polyglycolic acid PGA	High	230/36	8.4/890	30	Suture, nerve guidance channels, chondrocyte scaffolds
Poly-L-lactic acid PLLA	High	170/56	8.5/900	25	Suture, stents, bone plates, screws
Polyglactine910	High	200/40	8.6/850	24	Skin regeneration
Polydioxanone	High	106/<20	8.6/850	35	Monofilament suture

Source: Kimura, Y., in *Biomedical Applications of Polymeric Biomaterials,* Tsuruta, T. et al., Eds., CRC Press, Boca Raton, FL, 1993. With permission.

process. One of the primary advantages to the use of biodegradable implants and suture is that they do not require surgical removal. This aspect decreases both the risk of infection and cost. The main mechanism of *in vivo* degradation is hydrolytic degradation, although some enzymes may also serve a role (Piskin, 1995). For use of these biomaterials, an in-depth knowledge of the candidate polymer is recommended. A basic description of several degradable polymers is provided in Table 20.3.15.

Ceramics. Ceramic materials are some of the strongest and hardest material structures used in engineering. Ceramics are composed of primarily inorganic compounds and are generally characterized by unstable crack growth that leads to poor tensile strength (Table 20.3.16). There are two categories of ceramic biomaterials: relatively inert and **bioactive**. Relatively inert ceramics have high compressive strength and hardness and are commonly used for wear applications. Bioactive ceramics are designed to bond with the host tissue and do not possess great strength characteristics (Table 20.3.17).

Optimum biocompatibility of ceramic degradable biomaterials occurs only with special proportions of the material constituents. Unfortunately, the confines of these proportions limit the mechanical properties of the material. These materials are not strong enough for structural applications, but have been successfully used as coating material to enhance tissue bonding, as dental restorative material, and as filler in bone cement (Bajpai and Billotte, 1995).

Composite Biomaterials. Composite biomaterials combine the properties of two or more different materials in order to obtain a biomaterial with tailored properties. With composite biomaterials, the opportunity exists to fabricate an implant that is stronger and lighter than conventional implants while exhibiting a stiffness that is very similar to surrounding tissues. The material properties of composite materials depend on the matrix material, reinforcement material, volume fraction of reinforcement material, interfacial bond strength, orientation of reinforcement, number of inclusions, and other factors. Use of composite biomaterials is in its infancy but has already been used to improve the strength, stiffness, and toughness in current biocompatible materials.

In biodegradable composite materials, the method used to acquire final implant geometry will affect the service life of the implant. Machining has been shown to expose fiber ends on the surface and to promote the wicking of surrounding fluid into the device, which can increase the rate of degradation.

Materials of Natural Origin. Materials from natural origin may be xenogenous (i.e., obtained from other species) or autogenous (i.e., obtained from the patient). Xenogenous biological materials from nonhuman animals are commonly used for soft tissue replacement. These materials exhibit mechanical properties that are very similar to the surrounding living human tissue but may cause an immune response due to their non-self proteins. Examples of a xenogenous biomaterial are the porcine heart valve, catgut suture, and collagen-based implants. Recent research on heart and kidney transplants from primates have demonstrated the feasibility of using living xenogenous biomaterials.

TABLE 20.3.16 Material Properties of Relatively Inert Biomedical Ceramics

Material	Density (g/cm^3)	Grain Size (nm)	*E* Tensile Modulus (GPa)	Hardness (HV) (N/mm^2)	Fatigue Strength (MPa)	Comments	Applications	Ref.[a]
Alumina (AL_2O_3)	3.9–4	3000–4000	380	23,000	550	Very inert, excellent wear and friction properties, may increase tissue aluminum causing bone demineralization	Articular bearing surfaces, dental implants, total joint prostheses	1, 2, 6–8
LTI carbon	1.7–2.2	3–4	18–28	150–250	280–560	Excellent blood compatibility, low density	Coating or structural material for heart valves and blood vessels	3
Vitreous carbon	1.4–1.6	1–4	24–31	150–200	70–210	Known as glassy carbon due to lack of crystal structure	Artifical heart valves	3
Zirconia (ZrO_2)	6.1	<0.5	200	16,000	1200	Nonreactive in rhesus monkey bone *in vivo,* excellent wear and friction properties	Articular bearing surfaces	4, 5, 8

[a] Boutin et al. (1988); 2, ASTM F560-78; 3, Intermedics Orthopedics (1983); 4, Christel et al. (1989); 5, Ducheyne and Hastings (1984); 6, Graves et al. (1972); 7, Toni et al. (1994), 8, Hentrich et al. (1971).

TABLE 20.3.17 Bioactive Ceramic Materials

Material	Chemical Content	Comments	Ref.[a]
Hydroxyapatite	$Ca_{10}(PO_4)_6(OH)_2$	Actual mineral phase of bone, used as a coating or solid, synthetic versions available, good mechanical properties, excellent biocompatibility, subject to osteoclastic resorbtion, chemically bonds to bone	1, 2
Bioglass 46S5.2	46.1% SiO_2, 26.9% CaO, 24.4% Na_2O, 2.6% P_2O_5 mol%	Fine-grained, glassy ceramics, 46S5.2 exhibits best tissue bonding, other constitutent ratios are available	3, 4
Ceravital	Bioglass materials with Al_2O_3, TiO_2, and Ta_2O_5 added	Very similar composition to bioglass with additional metal oxides to control dissolution rate	4

[a] 1, Gessink et al. (1987); 2, Kay (1988); 3, Hench and Ethridge (1982); 4, Bajpai and Billotte (1995).

Autogenous materials are used when skin and bone are relocated on a patient. As human ability to manipulate the human genetic code continues, it may be possible to replace failed human organs with identical organs that have been grown either *in vitro* or *in vivo*.

Biomaterial Testing

The human body is a biologically and mechanically active environment that reacts to all materials. Biomaterials should be initially selected for their engineering mechanical properties to serve a specific function. Careful consideration must be given to the fatigue and creep properties of the material because of the rigorous loading incurred by many implants. The anterior cruciate ligament of a moderately active person, for example, will be subjected to 4.2 million loading cycles annually (Black, 1992). This frequency of cyclic loading is consistent with the cyclic loading of other orthopedic structures.

Once a candidate material has been selected, the material must be tested to determine both the material response to its proposed biological environment and the host response to that material. Valuable host and material response information may be obtained from the use of *in vitro* tests that simulate a specific physiological environment. The final step before implantation into a human is to test the performance of a candidate material with an animal model.

In Vitro Studies. Experimental *in vitro* studies should be conducted prior to testing on living animals. *In vitro* studies provide essential information on the response of the candidate biomaterials to a simulated host environment and on the chemical interactions that ensue. It is important to observe the effect of the biomaterial on proteins to determine if any coating, denaturing, or other processes result. These studies are inexpensive and can be tailored to simulate specific implant sites. Initial tests may simply expose the candidate material to the expected inorganic chemical and thermal conditions. More complex *in vitro* tests may include appropriate, viable, active cells with their associated cell products. The cell survival count, reproduction rate, metabolic activity, effective motion activity, and cell damage should be observed during testing (Black, 1992). Some sample *in vitro* materials tests are described in Table 20.3.18.

Biomaterials intended for vascular applications must be tested for their interaction with blood. Examination of blood-biomaterial interactions should include protein absorption, platelet interactions, intrinsic coagulation, fibrinolytic activity, erythrocytes, leukocytes, and complement activation. Since the circulatory system has both an oxygen- and nutrient-rich arterial side and a carbon dioxide-rich venous side, a candidate material must be tested in the environment for which it is intended.

In Vivo Studies. Animal studies are extremely valuable for examining the host and material response of a specific test material. These studies must be in complete accordance with the Animal Welfare Act (7 U.S.C. 2131, December 23, 1985). Initial animal tests are nonfunctional and involve placing a test specimen in an anatomic location similar to the expected implant location. These locations may be subcutaneous, intramuscular, intraperitoneal, transcortical, or intramedullar. Depending on the study, the duration of implantation can vary from weeks to years. Factors that affect the outcome of nonfunctional

TABLE 20.3.18 Sample *In Vitro* Tests

In Vitro Test	Brief Description
ASTM F895-4 cytotoxicity	Place sterile agar over mouse fibroblast cells. Place the test material on top and incubate for 24 hr; examine the culture for the extent of cell lysis
Ames test for mutagenicity	Expose autotrophic *Salmonella typhinurium* bacteria cells to the test material and histidine for 48 hr at 37°C; if cells mutate to non-autotrophic state, histidine levels will be lower after testing
Lee–White coagulation rate	Place a small volume of fresh-drawn blood on a test surface and similar amount on control surface; compare coagulation times
Ex vivo blood compatibility	Tap into the bloodstream of a canine; let blood flow at typical rates and pressure through a test specimen for a short time; examine specimen for platelet adhesion and blood for hemolysis

tests include the degree of relative motion between implant and host and the geometry of the test specimen.

Functional testing of biomedical materials is performed in order to evaluate a test material or design as it performs its intended function. Species are selected for an animal model based on similarities with human models and then scaled to size. Some factors to consider are the life span, activity level, metabolic rate, and size of the test animal. Results are determined from macroscopic and histological evaluations.

Defining Terms

Autologous: Related to self; materials obtained from the same organism.

Bioactive: The ability of a material to chemically interact with the host environment in a predetermined manner.

Biocompatibility: The ability of a biomaterial to perform with an appropriate host response in a specific manner.

Bioengineering: The application of principles from engineering, applied mathematics, and physics to the study of biological problems.

Biomaterial: A nonviable material used in a medical device that is intended to interact with biological systems.

Biomechanics: The study of forces that act on and within a biological structure and the effects that these forces produce.

In vitro: Within a glass; observable in an artificial environment such as a test tube.

In vivo: Within the living body.

Remodeling: Changes in internal architecture and external conformation of biological tissues in accordance with applied strain.

Sterilization: The complete elimination or destruction of all living microorganisms. The most common methods are steam, radiation, and chemical sterilization.

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The *Journal of Biomedical Materials Research* is a monthly publication that reports advancements in the field of biomaterial development and testing. For subscription information contact: Journal of Biomedical Materials Research, Subscription Fulfillment and Distribution, John Wiley and Sons, Inc., 605 3rd Avenue, New York, NY 10158.

The *Journal of Biomechanics* covers a wide range of topics in biomechanics, including cardiovascular, respiratory, dental, injury, orthopedic, rehabilitation, sports, and cellular. For subscription information, contact: Elsevier Science, Inc., 660 White Plains Road, Tarrytown, NY 10591-5153.

20.4 Mechanical Engineering Codes and Standards

Michael Merker

What Are Codes and Standards?

A **standard** can be defined as a set of technical definitions, requirements, and guidelines for the uniform manufacture of items; safety, and/or interchangeability. A **code** is a standard which is, or is intended to be, adopted by governmental bodies as one means of satisfying legislation or regulation. Simply put, they can range from a general set of minimum requirements to very specific "how to" instructions for designers and manufacturers.

Voluntary standards, and they can run from a few paragraphs to hundreds of pages, are written by experts who sit on the many committees administered by standards-developing organizations (SDOs), such as ASME International.

They are not considered voluntary because they are created by volunteers; rather they are voluntary because they serve as guidelines, but do not of themselves have the force of law. ASME International publishes its standards; accredits users of standards to ensure that they have the capability of manufacturing products that meet those standards; and provides a stamp that accredited manufacturers may place on their product, indicating that it was manufactured according to the standard. ASME International cannot, however, force any manufacturer, inspector, or installer to follow ASME International standards. Their use is voluntary.

Why are voluntary standards effective? Perhaps the American Society for Testing and Materials (ASTM) said it best in its 1991 annual report. "Standards are a vehicle of communication for producers and users. They serve as a common language, defining quality and establishing safety criteria. Costs are lower if procedures are standardized; training is also simplified. And consumers accept products more readily when they can be judged on intrinsic merit."

A dramatic example of the value and impact codes and standards have had on our society is provided by ASME International's Boiler and Pressure Vessel Code. Toward the end of the 19th century, boilers of every description, on land and at sea, were exploding with terrifying regularity for want of reliably tested materials, secure fittings, and proper valves. They would continue to do so into the 20th century. Engineers could take pride in the growing superiority of American technology, but they could not ignore the price of 50,000 dead and 2 million injured by accidents annually.

The mechanical engineers who tackled the problems in 1884 began by seeking reliable methods for testing steam boilers. The need for the establishment of universally accepted construction standards would take many more years and resulted in the first edition of the Boiler and Pressure Vessel Code being published by ASME International in 1915.

Codes and Standards–Related Accreditation, Certification, and Registration Programs

Accreditation

Shortly after the Boiler Code was first published, the need emerged for a recognizable symbol to be affixed to a product constructed in accordance with the standards. ASME International commissioned appropriate seals that are now the internationally acknowledged symbols of the Society. The symbol is stamped onto the product.

But how does a manufacturer obtain permission to use one of the symbols? Through the ASME International **accreditation** process, the manufacturer's quality control process is reviewed by an ASME International team. If the quality control system meets the requirements of the applicable ASME International code or standard and the manufacturer successfully demonstrates implementation of the program, the manufacturer is accredited by ASME International. This means that the manufacturer may certify the product as meeting ASME International standards and may apply the stamp to the product.

The stamp consists of a modified cloverleaf (from the shape of the ASME International logo), with letter(s) in the center. The letter(s) indicate the code or section of the code met by the product upon which it is placed. Boiler and pressure vessel stamps issued are

A	Field Assembly of Power Boilers,
E	Electric Boilers,
H	Heating Boilers, Steel Plate, or Cast-Iron Sectional,
HV	Heating Boiler Safety Valves,
HLW	Lined Potable Water Heaters,
M	Miniature Boilers,
N	Nuclear Components,
NPT	Nuclear Component Partial,
NA	Nuclear Installation/Assembly,
NV	Nuclear Safety Valves,
PP	Pressure Piping,
RP	Reinforced Plastic Pressure Vessels,
S	Power Boilers,
U, U2	Pressure Vessels,
UM	Miniature Pressure Vessels,
UV	Pressure Vessel Safety Valves,
V	Boiler Safety Valves.

ASME International also has accreditation programs for nuclear materials, offshore safety and pollution prevention equipment, fasteners, authorized inspection agencies, organizations that certify elevator inspectors, and reinforced thermoset plastic corrosion-resistant vessels.

Certification

ASME International has also expanded its scope of activity to cover **certification** of individuals. The first program became available in 1992 and covered the qualification and certification of resource recovery facilities operators. They have since added programs to cover operators of hazardous waste incinerators and medical waste incinerators. Programs to certify an individual's knowledge and ability in the area of geometric dimensioning and tolerancing and operators of fossil fuel–fired plants are under development.

Registration

Registration is similar to accreditation; however, it is the term used more frequently in the international arena, particularly when dealing with the International Organization for Standardization (ISO) 9000 program on quality assurance systems. ASME International's ISO 9000 Registration Program has been accredited by the American National Accreditation Program for Registrars of Quality Systems (ANSI-RAB) and the Dutch Council for Certification (RvC) in the following industrial sectors:

Primary Metals Industries
Fabricated Metal Products
Industrial and Commercial Machinery and Equipment
Reinforced Thermoset Plastic Tanks and Vessels
Engineering Services

How Do I Get Codes and Standards?

Role of ASME International in Mechanical Engineering Standards

ASME International is a nonprofit educational and technical organization with more than 125,000 members, most of whom are practicing engineers. About 20,000 are students. ASME International has a wide variety of programs: publishing, technical conferences and exhibits, engineering education, government relations, and public education, as well as the development of codes and standards, all aimed at serving the engineering profession, the public, industry, and government.

The ASME International Board of Governors has delegated the codes and standards activity to a 22-member Council on Codes and Standards, which directs all aspects of the program. Under the Council are ten boards, also made up of ASME International members and other interested persons; supervisory boards in turn oversee committees, each responsible for a specific area of standard development.

Committees in one form or another have dealt with standards since the first test code in 1884. Currently, there are more than 100 main committees dealing with over 500 standards that are under regular review and revision. Once a standard is accepted, it is printed and made available to manufacturers, regulatory agencies, designers — anyone with an interest in that particular subject. Close to 4000 individuals serve on these committees and their subcommittees, subgroups, and working groups.

After a standard has been considered and reconsidered at meetings and through many drafts, it is sent to the main committee, representing all interests, which votes on the standard. But this is not the final step. Before the draft becomes a standard and is published and ready for distribution, it is made available for public comment and must be approved by the appropriate ASME International supervisory board. This process is illustrated graphically in Figure 20.4.1.

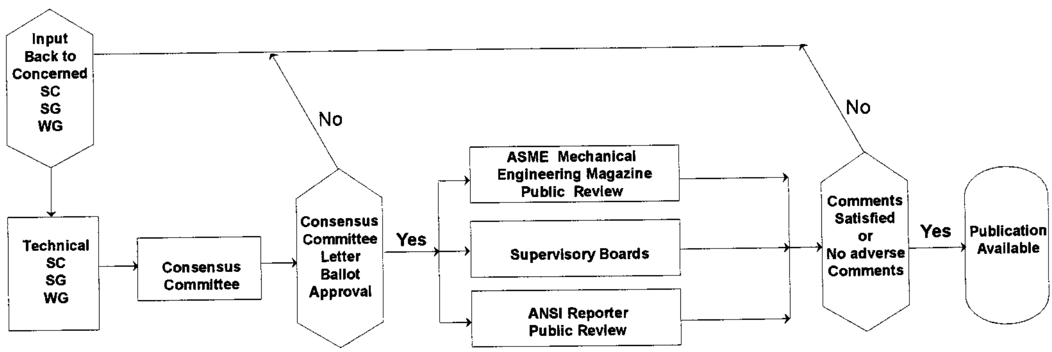


FIGURE 20.4.1 A typical path for standards approval.

ASME International has been a consistent supporter of the policy of prior announcement of meetings, open meeting rooms, **balanced committees**, public announcements and reviews, appeal mechanisms, and overall procedural **due process**.

Role of ANSI in These and Other Related Standards

In 1911, ASME International was one of a number of organizations which recommended the establishment of an organization to help eliminate conflict and duplication in the development of voluntary standards in the U.S. Such an organization was formed in 1918 and is currently known as the American National Standards Institute (ANSI). ANSI is the U.S. member of the ISO and the administrator of the U.S. National Committee of the International Electrotechnical Committee (IEC). ANSI also serves as a bookseller of domestic and international standards.

The intent of obtaining ANSI approval of a standard is to verify that in establishing the standard, the originating organization has followed principles of openness and due process and has achieved a **consensus** of those directly affected by the standard.

What Standards Are Available?

Listing of Topics Covered by ASME International Standards

Abbreviations
Accreditation
Air Cooled Heat Exchangers
Air Cylinders & Adapters
Air Heaters
Atmospheric Water Cooling Equipment
Automatically Fired Boilers
Automotive Lifting Devices
Backwater Valves
Boilers
Bolts
Building Services Piping
Cableways
Cargo Containers
Carriers
Castings and Forgings
Centrifugal Pumps
Chemical Plant and Petroleum Refinery Equipment
Chucks and Chuck Jaws
Cleanouts
Coal Pulverizers
Compressors
Consumable Tools
Conveyors
Coordinate Measuring Machines
Cranes
Deaerators
Density Determination
Derricks
Dial Indicators
Diaphragm Seals
Dies
Diesel and Burner Fuels
Digital Systems
Dimensional Metrology
Dimensioning and Tolerancing
Drafting
Drains
Dumbwaiters
Ejectors
Elevators
Escalators
Exhausters
Fans
Fasteners
Feedwater Heaters
Fittings
Flanges
Floor Drains
Flue Gas Desulfurization
Fluid Flow in Pipes
Fuel Gas Piping
Gage Blanks
Gage Blocks
Gas Flow Measurement
Gas Transmission and Distribution Piping Systems
Gas Turbine Power Plants
Gas Turbines
Gaseous Fuels
Gaskets
Gauges
Graphic Symbols
Hand Tools
High Lift Trucks
Hoists
Hooks
Hydroelectric Equipment
Incinerators
Indicated Power
Industrial Sound
Industrial Trucks and Vehicles
Internal Combustion Engine Generator Units
Ion Exchange Equipment
Jacks
Keys
Keyseats
Knurling
Letter Symbols
Lifts
Limits and Fits
Line Conventions and Lettering
Linear Measurements
Liquid Transportation Systems
Low Lift Trucks
Machine Guarding
Machine Tools
Manlifts
Material Lifts
Measurement
Mechanical Power Transmission Apparatus
Mechanical Springs
Metric System

- Milling Machines
- Model Testing
- Monorails
- Moving Walks
- Nuclear Facilities and Technology
- Nuts
- Offshore Oil and Gas Operations
- Oil Systems
- Optical Parts
- Pallets
- Particulate Matter
- Performance Test Codes
- Pins
- Pipe Dimensions
- Pipe Threads
- Piping
- Pliers
- Plumbing
- Pressure Transducers
- Pressure Vessels
- Pumps
- Quality Assurance
- Reamers
- Refrigeration Piping
- Resource Recovery Facility Operators
- Retaining Rings
- Rivets
- Safety and Relief Valves
- Screw Threads
- Screws
- Slings
- Slip Sheets
- Spray Cooling Systems
- Stainless Steel Pipe
- Stands
- Steam-Generating Units
- Steel Stacks
- Storage/Retrieval Machines
- Storage Tanks
- Surface Texture
- Temperature Measurement
- Thermometers
- Tools
- Transmission Apparatus
- Transmission Chains
- Turbines
- Valves
- Washers
- Waste Facility Operators
- Water Hammer Arresters
- Weighing Scales
- Welded Aluminum-Alloy Storage Tanks
- Wheel Dollies
- Wheelchair Lifts
- Whirlpool Bathtub Appliances
- Wind Turbines
- Window Cleaning
- Wrenches

Where Do I Go If the Subject I Want Is Not on This List?

With the constant creation and revision of standards, not to mention the large number of different SDOs, it is impractical to search for standards-related information in anything other than an electronic format. The latest information on ASME International's codes and standards can be found on the World Wide Web (WWW). ASME International's home page is located at http://www.asme.org. It contains a searchable catalog of the various codes and standards available as well as general information about the other areas ASME International is involved with. Additional information on drafts out for public review and committee meeting schedules will be added as the home page continues to evolve.

Another useful Web site is provided by the National Standards System Network (NSSN). This is a project which is still under development, but has the goal of presenting a comprehensive listing of all bibliographic information on standards and standards-related material. Eventually, this site may also provide direct electronic access to the standards themselves. The NSSN page is located at http://nssn.org. This site is also useful in that it provides links to many of the SDO's Web sites.

Defining Terms

Accreditation: The process by which the ability of an organization to produce a product according to a specific code or standard is evaluated. It is not an actual certification of a specific product, but does provide a third-party evaluation of the manufacturer's competence to certify that individual products are in compliance with the applicable standards.

Balanced committee: A committee in which the consensus body responsible for the development of a standard comprises representatives of all categories of interest that relate to the subject (e.g., manufacturer, user, regulatory, insurance/inspection, employee/union interest). A balanced committee ensures that no one interest group can dominate the actions of the consensus body.
Certification: The process by which an individual's training or abilities to perform a task according to a specific code or standard is evaluated.
Code: A standard which is, or is intended to be, adopted by governmental bodies as one means of satisfying legislation or regulation.
Consensus: This means that substantial agreement has been reached by directly and materially affected interest groups. It signifies the concurrence of more than a simple majority, but not necessarily unanimity. Consensus requires that all views and objections be considered and that an effort be made toward their resolution.
Due process: A procedure by which any individual or organization who believes that an action or inaction of a third party causes unreasonable hardship or potential harm is provided the opportunity to have a fair hearing of their concerns.
Registration: Similar to accreditation, it is the term used more frequently in the international arena, particularly when dealing with the ISO 9000 program on quality assurance systems.
Standard: A set of technical definitions, requirements, and guidelines for the uniform manufacture of items; safety, and/or interchangeability.

Further Information

The Engineering Standard, A Most Useful Tool by Albert L. Batik is a comprehensive work covering the impact of standards in marketing and international trade as well as their application to traditional areas such as design, manufacturing, and construction.

The Code: An Authorized History of the ASME Boiler and Pressure Vessel Code by Wilbur Cross provides an in-depth look at events which led to need for codes and the pioneers who created the Boiler and Pressure Vessel Code.

20.5 Optics*

Roland Winston and Walter T. Welford (deceased)

Geometrical Optics

Geometrical optics is arguably the most classical and traditional of the branches of physical science. By the time Newton wrote his *Principia*, geometrical optics was already a highly developed discipline. Optical design of instruments and devices has been worked out and improved over the centuries. From the telescopes of Galileo to the contemporary camera lens, progress while impressive has been largely evolutionary with modern design benefiting enormously from the availability of fast, relatively inexpensive digital computers. It is noteworthy that even in the last 20 years progress has been made by extending the classical model to problems where image formation is not required, or desired. We shall touch on these developments of "nonimaging optics" later in this section. But first we treat classical geometrical optics. In this model, a "point source" emits rays which are straight lines in a vacuum or in a homogeneous isotropic dielectric medium. Light travels at different speeds in different dielectrics. Its speed is given by c/n, where c is the speed in vacuum (299,792,458 m sec^{-1}) and n, the *refractive index*, depends on the medium and on the frequency of the light.

A ray is refracted at an interface between two media. If $\mathbf{r}$ and $\mathbf{r}'$ are unit vectors along the incident and refracted directions, n and n' are the respective refractive indexes, and $\mathbf{n}$ is the unit normal to the interface, then the ray directions are related by

$$n\mathbf{n} \times \mathbf{r} = n'\mathbf{n} \times \mathbf{r}' \tag{20.5.1}$$

which is the law of refraction, *Snell's law*, in vector form. More conventionally, Snell's law can be written

$$n \sin I = n' \sin I' \tag{20.5.2}$$

where I and I' are the two angles formed where the normal meets the interface, the angles of incidence and refraction. The two rays and the normal must be coplanar. Figure 20.5.1 illustrates these relationships and shows a reflected ray vector $\mathbf{r}''$. Equation (20.5.1) can include this by means of the convention that after a reflection we set n' equal to $-n$ so that, for reflection,

$$\mathbf{n} \times \mathbf{r} = -\mathbf{n} \times \mathbf{r}'' \tag{20.5.3}$$

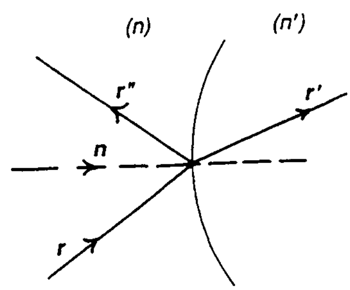


FIGURE 20.5.1

With a bundle or pencil of rays originating in a point source and traversing several different media, e.g., a system of lenses, we can measure along each ray the distance light would have traveled in a given time t; these points delineate a surface called a *geometrical wavefront*, or simply a *wavefront*. Wavefronts are surfaces orthogonal to rays (the Malus–Dupin theorem). (It must be stressed that wavefronts are a

*From Welford, W.T., *Useful Optics,* reproduced with permission of University of Chicago Press.

concept of geometrical optics and that they are *not* surfaces of constant phase, phase fronts, of the light waves in the scaler or electromagnetic wave approximations. However, in many situations the geometrical Earth are a very good approximation of phase fronts.) Thus, if successive segments of a ray are of length $d_1, d_2, \ldots$, a wave front is a locus of constant Σnd or, passing to the limit, $\int n\, dl$. This quantity is called an *optical path length*. (See Figure 20.5.2.)

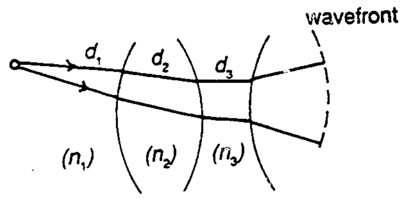


FIGURE 20.5.2

Optical path lengths enter into an alternative to Snell's law as a basis for geometrical optics. Consider any path through a succession of media from, say, P to P'. We can calculate the optical path length W from P to P', and it will depend on the shape of this path, as shown in Figure 20.5.3. Then *Fermat's principle* states that, if we have chosen a physically possible ray path, the optical path length along it will be stationary (in the sense of the calculus of variations) with respect to small changes of the path. (The principle as originally formulated by Fermat proposed a *minimum* time of travel of the light. Stationarity is strictly correct, and it means roughly that, for any small transverse displacement δx of a point on the path, the change in optical path length is of order δx^2.) For our purposes, Fermat's principle and Snell's law are almost equivalent, but in the case of media of continuously varying refractive index it is sometimes necessary to invoke Fermat's principle to establish the ray path. Apart from such cases, either one can be derived from the other.

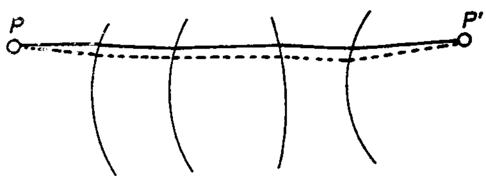


FIGURE 20.5.3

Either Fermat or Snell can be used to develop the whole edifice of geometrical optics in designing optical systems to form images.

Symmetrical Optical Systems

The axially symmetric optical system, consisting of lenses and/or mirrors with revolution symmetry arranged on a common axis of symmetry, is used to form images. Its global properties are described in terms of *paraxial* or *Gaussian* optics. In this approximation only rays making small angles with the axis of symmetry and at small distances from the axis are considered. In Gaussian optics, we know from symmetry that rays from any point on the axis on one side of the system emerge on the other side and meet at another point on the axis, the *image point* . This leads to the well-known formalism of principal planes and focal planes shown in Figure 20.5.4. A ray entering parallel to the axis passes through F', the second, or image-side, principal focus on emerging from the system, and a ray entering through F, the first principal focus, emerges parallel to the axis. A ray incident on the first, or object-side, principal plane P at any height h emerges from the image-side principal plane P' at the same height h so that the principal planes are *conjugated* planes of unit magnification. Excluding for the moment the special case

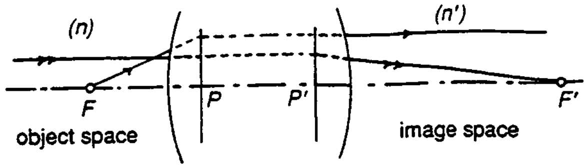


FIGURE 20.5.4

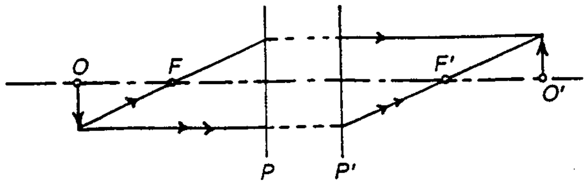


FIGURE 20.5.5

in which a ray entering parallel to the axis also emerges parallel to the axis, these four points yield a useful graphical construction for objects and images, as depicted in Figure 20.5.5.

The two focal lengths f and f' are defined as

$$f = PF, \quad f' = P'F' \tag{20.5.4}$$

Their signs are taken according to the usual conventions of coordinate geometry, so that in Figure 20.5.4 f is negative and f' is positive. The two focal lengths are related by

$$n'/f' = -n/f \tag{20.5.5}$$

where n and n' are the refractive indexes of the object and image spaces, respectively.

Conjugated distances measured from the principal planes are denoted by l and l', and the conjugate distance equation relating object and image positions is

$$n'/l' - n/l = n'/f' = -n/f \tag{20.5.6}$$

The quantity on the right — that is, the quantity on either side of Equation (20.5.5) — is called the *power* of the system, and is denoted by K.

Another form of the conjugate distance equation relates distances from the respective principal foci, z and z'.

$$zz' = ff' \tag{20.5.7}$$

This equation yields expressions for the transverse magnification:

$$\eta'/\eta = -f/z = -z'/f' \tag{20.5.8}$$

This is useful to indicate paraxial rays from an axial object point O to the corresponding image point O' as in Figure 20.5.6 with convergence angles u and u' positive and negative, respectively, as drawn in the figure. (Paraxial angles are small but diagrams like Figure 20.5.6 can be drawn with an enlarged transverse scale. That is, convergence angles and intersection heights such as h can all be scaled up by the same factor without affecting the validity of paraxial calculations.) Then, if η and η' are corresponding object and image sizes at these conjugates, the following relation exists between them:

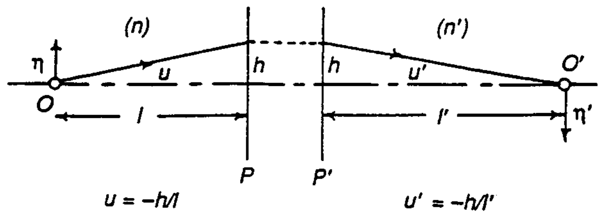


FIGURE 20.5.6

$$nu\eta = n'u'\eta' \quad (20.5.9)$$

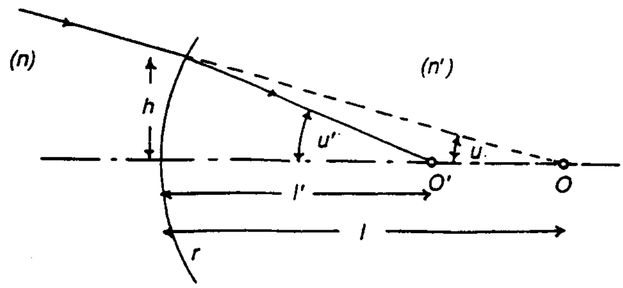
In fact, for a given paraxial ray starting from O, this quantity is the same at any intermediate space in the optical system. That is, it is an invariant, called the Lagrange invariant. It has the important property that its square is a measure of the light flux collected by the system from an object of size η in a cone of convergence angle u.

The above discussion covers all general Gaussian optic properties of symmetrical optical systems. We next look at particular systems in detail. To do this, we abandon the skeleton representation of the system by its principal planes and foci and consider it as made up of individual refracting or reflecting surfaces.

Figures 20.5.7 and 20.5.8 show the basic properties of a single spherical refracting surface of radius of curvature r and of a spherical mirror. In each case r as drawn is positive. These diagrams suggest that the properties of more complex systems consisting of more than one surface can be found by tracing paraxial rays rather than by finding the principal planes and foci, and this is what is done in practice. Figure 20.5.9 shows this with an iterative scheme outlined in terms of the convergence angles. The results can then be used to calculate the positions of the principal planes and foci and as the basis of aberration calculations. For details see Welford (1986). The actual convergence angles which can be admitted, as distinguished from notional paraxial angles, are determined either by the rims of individual components or by stops deliberately inserted at places along the axis chosen on the basis of aberration theory. Figure 20.5.10 shows an *aperture stop* in an intermediate space of a system. The components of the system to the left of the stop from an image (generally virtual) which is “seen” from the object position (this image is usually virtual, i.e., it is not physically accessible to be caught on a ground-glass screen like the image in an ordinary looking glass); this image is called the entrance pupil, and it limits the angle of beams that can be taken in from the object. Similarly, on the image side there is an exit pupil, the image of the stop by the components to the right, again usually virtual. This pupil may also determine the angles of beams from off-axis object point O and O'; the central ray of the beam from O passes through the center of the entrance pupil (and therefore through the center of the aperture stop and the center of the exit pupil) and it is usually called the *principal*, *chief*, or *reference ray* from this object point. The rest of the beam or pencil from O may be bounded by the rim of the entrance pupil, or it may happen that part of it is *vignetted* by the rim of one of the components.

Although the aperture stop is usually thought of as being inside an optical system, as in a photographic objective, it is sometimes placed outside, and one example is the *telecentric stop* shown in Figure 20.5.11. The stop is at the object-side principal focus, with the result that in the image space all the principal rays emerge parallel to the optical axis. A telecentric stop can be at either the object-side or the image-side principal focus, and the image conjugates can be anywhere along the axis. The effect is that the pupil on the opposite side of the telecentric stop is at infinity, a useful arrangement for many purposes. It may happen that the telecentric stop is between some of the components of the system.

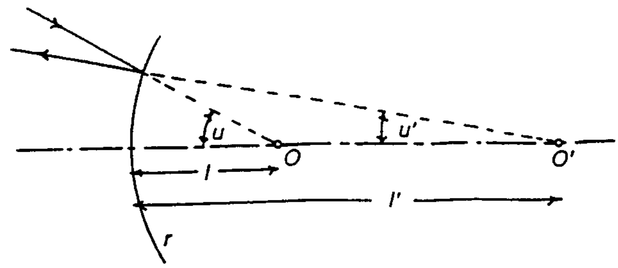
The above information is all that is needed to determine how a given symmetrical optical system behaves in Gaussian approximation for any chosen object plane. Suitable groups of rays can be used to set out the system for mechanical mounting, clearances, etc.; however, it is often easier and adequate in terms of performance to work with the *thin-lens model* of Gaussian optics. This model uses complete



$$\frac{n'}{l'} - \frac{n}{l} = \frac{n' - n}{r} = K$$

$$n'u' - nu = -hK$$

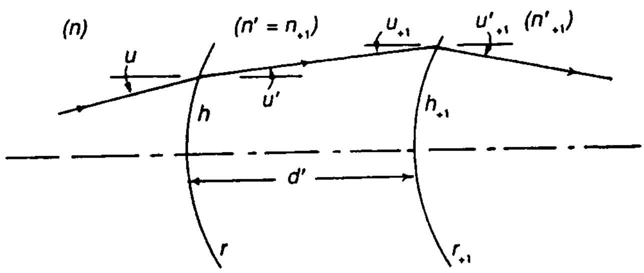
FIGURE 20.5.7



$$\frac{1}{l'} + \frac{1}{l} = \frac{2}{r} = -K$$

$$u' + u = hK$$

FIGURE 20.5.8



$$n'u' - nu = -hK$$

$$u_{+1} = u'$$

$$h_{+1} = h + d'u'$$

$$n'_{+1}u'_{+1} - n_{+1}u_{+1} = -h_{+1}K_{+1}$$

FIGURE 20.5.9

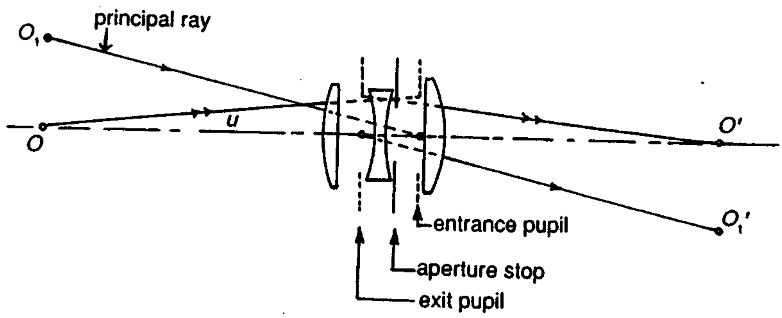


FIGURE 20.5.10

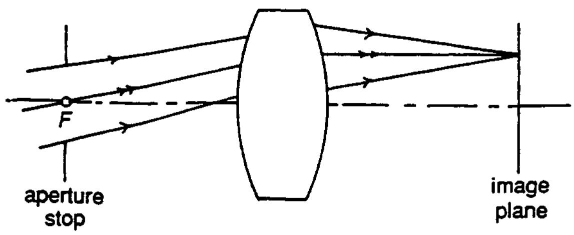


FIGURE 20.5.11

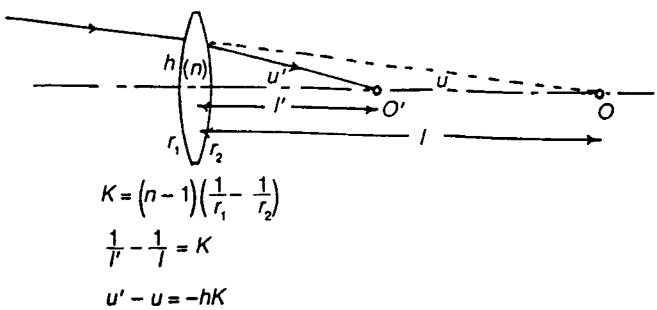


FIGURE 20.5.12

lenses of negligible thickness instead of individual surfaces. Figure 20.5.12 shows the properties of a thin lens. A system of thin lenses can be ray traced to find its properties, locate foci and ray clearances, etc., and very often the results will be good enough to use without further refinement. This is particularly true of systems involving unexpanded laser beams, where the beam diameters are quite small.

We omitted from our discussion of Figure 20.5.4 the special case in which a ray incident parallel to the optical axis emerges parallel to the axis, as in Figure 20.5.13. This is an *afocal* or *telescopic* system; it forms an image at infinity of an object at infinity, and the angular magnification is given by the ratio of the ray incidence heights. An afocal system also forms images of objects at finite distances, as indicated by the rays drawn in the figure. The transverse magnification is then constant for all pairs of conjugates.

Plane Mirrors and Prisms

A single-plane mirror used to deflect or rotate an optical axis needs no explanation, but some useful points can be made about combinations of mirrors. Two mirrors at an angle θ turn the beam through 2θ about the line of intersection of the mirror planes, whatever the angle of incidence on the first mirror, as in Figure 20.5.14. The diagram is drawn for a ray in the plane perpendicular to the line of intersection

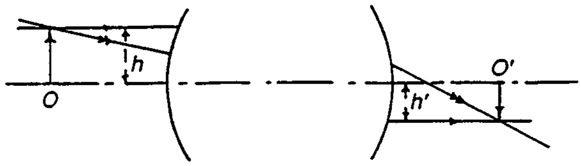


FIGURE 20.5.13

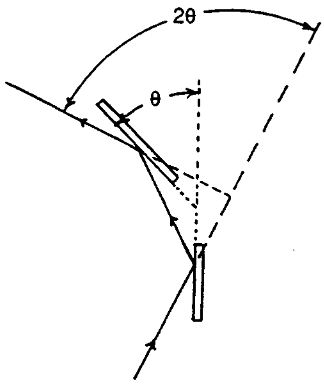


FIGURE 20.5.14

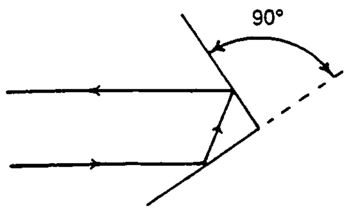


FIGURE 20.5.15

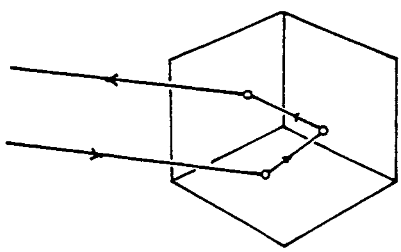


FIGURE 20.5.16

of the mirror planes, but it is equally valid if the ray is not in this plane, i.e., the diagram is a true projection. In particular, if the mirrors are at right angles, as in Figure 20.5.15, the direction of the ray is reversed in the plane of the diagram. Three plane mirrors at right angles to each other, forming a corner of a cube as in Figure 20.5.16, reverse the direction of a ray incident in *any* direction if the ray meets all three mirrors in any order.

These properties are more often used in prisms in the corresponding geometry. Total internal reflection, as in, for example, the right-angle prism (Figure 20.5.17), is a great advantage in using prisms for turning beams. The condition for total internal reflection is

$$\sin I > 1/n \tag{20.5.10}$$

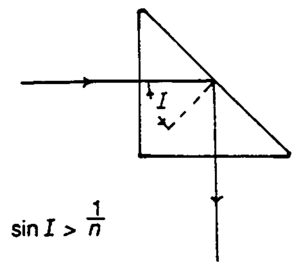


FIGURE 20.5.17

The *critical angle* given by $\sin I = 1/n$ is less than 45° for all optical glasses, and probably for all transparent solids in the visible spectrum. Total internal reflection is 100% efficient provided the reflecting surface is clean and free from defects, whereas it is difficult to get a metallized mirror surface that is better than about 92% efficient. Thus, with good anti-reflection coating on the input and output surfaces a prism, such as that shown in Figure 20.5.17, transmits more light than a mirror.

Roof prisms and cube-corner prisms, the analogs of Figure 20.5.15 and 20.5.16, have many uses. The angle tolerances for the right angles can be very tight. For example, roof edges form part of the reversing prism system in some modern binoculars, and an error ε in the right angle causes an image doubling in angle of $4n\varepsilon$. The two images are those formed by the portions of the beam incident at either of the two surfaces, which should have been at exactly 90°.

In addition to turning the axis of a system, mirror and prism assemblies sometimes rotate the image in unexpected ways. The effect can be anticipated by tracing, say, three rays from a notional object such as the letter F (i.e., an object with no symmetry). A more direct and graphic method is to use a strip of card and mark arrows on each end as in Figure 20.5.18a. The card is then folded without distorting it as in Figure 20.5.18b to represent, say, reflection at the hypotenuse of the right-angle prism, and the arrows show the image rotation. The process is repeated in the other section, as in Figure 20.5.18c. Provided the folding is done carefully, without distortion, this procedure gives all image rotations accurately for any number of successive reflections.

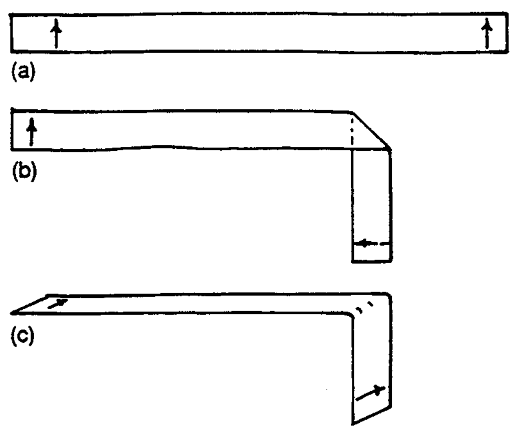


FIGURE 20.5.18

The Dove prism (Figure 20.5.19) is an example of an image-rotating prism. When the prism is turned through an angle ϕ about the direction of the incident light, the image turns in the same direction through 2ϕ. A more elaborate prism with the same function is shown in Figure 20.5.20. The air gap indicated between the hypotenuses of the two component parts needs to be only about 10 μm or so thick to ensure total internal reflection. Any prism or mirror assembly like this with an odd number of reflections will serve as an image rotator. Figure 20.5.20 illustrates an elegant advantage of prisms over mirrors; the system can be made compact by using the same optical surface both for reflection and for transmission.

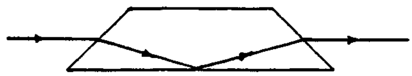


FIGURE 20.5.19

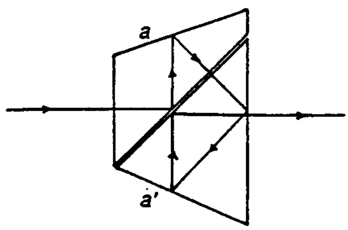


FIGURE 20.5.20

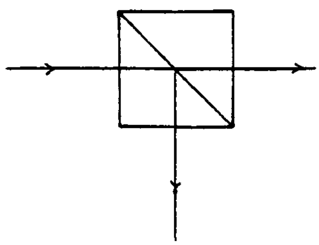


FIGURE 20.5.21

Figure 20.5.21 shows a typical beam-splitting (or combining) prism, a component of many diverse optical systems. The beam-splitting surface may be approximately neutral, in which case it would be a thin metal layer, or it may be dichroic (reflecting part of the spectrum and transmitting the rest), or it may be polarizing (transmitting the p-polarization and reflecting the s-polarization of a certain wavelength range). In the last two cases the reflecting-transmitting surface is a dielectric multilayer and its performance is fairly sensitive to the angle of incidence.

Prisms as devices for producing a spectrum have been largely replaced by diffraction grating (See Figure 20.5.22). The latter have several advantages for direct spectroscopy, but here are a few specialized areas where prisms are better. Losses in grating through diffraction to unwanted orders are a nuisance in certain astronomical applications where every photon counts. Another example of an area where prisms are preferable is wavelength selection in multiwavelength lasers: a prism inside the laser resonator with adequate angular dispersion ensures that only one wavelength will be produced, and one scans through the available wavelengths by rotating the prisms at and away from the position of minimum deviation. The significance of the minimum deviation position is that the effects of vibrations and placement errors are least. Also, if the shape of the prism is isosceles, the resolving power will be a maximum at minimum deviation. The main formulas relating to dispersing prisms are as follows.

Spectroscopic resolving power:

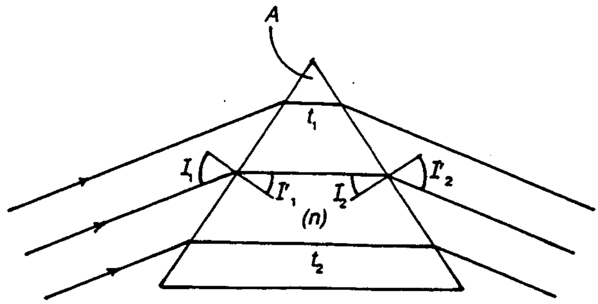


FIGURE 20.5.22

$$\lambda/\Delta\lambda = (t_1 - t_2)\, dn/d\lambda \tag{20.5.11}$$

where $t_1 - t_2$ is the difference between the path lengths in glass from one side of the beam to the other.

Angular dispersion:

$$dI'_2/d\lambda = \sin A(dn/d\lambda)/(\cos I'_1 \cos I'_2) \tag{20.5.12}$$

$$= 2\sin(A/2)(dn/d\lambda)/\cos I_2 \tag{20.5.13}$$

at minimum deviation.

Spectrum line curvature:

$$1/\text{radius} = \left[(n^2 - 1)/nf\right]\sin A/(\cos I'_1 \cos I'_2) \tag{20.5.14}$$

$$= \left[(n^2 - 1)/n^2 f\right] 2\tan I_1 \tag{20.5.15}$$

at minimum deviation, where f is the focal length of the lens which brings the spectrum to a focus.

The spectrum line curvature refers to the observation that the image of the entrance slit of the spectroscope produced by placing a lens after the prism is actually parabolic. The parabola is convex toward the longer wavelengths. The reason the image is curved is that rays out of the principal plane of the prism are deviated more than rays in the plane, a straightforward consequence of the application of Snell's law. For rays with angle out of the plane the extra deviation can be parametrized by an additional contribution to the index of refraction given by

$$dn \approx \varepsilon^2 (n^2 - 1)(2n) \tag{20.5.16}$$

If the length of the slit image is L, then $\varepsilon \approx L/(2f)$, where f is the focal length of the lens. Moreover, from Equation (20.5.12) we have

$$dI'_2/dn = \sin A/(\cos I'_1 \cos I'_2) \tag{20.5.17}$$

$$= (2/n)\tan I_1 \tag{20.5.18}$$

at minimum deviation. The curvature of the slit image readily follows from these relations.

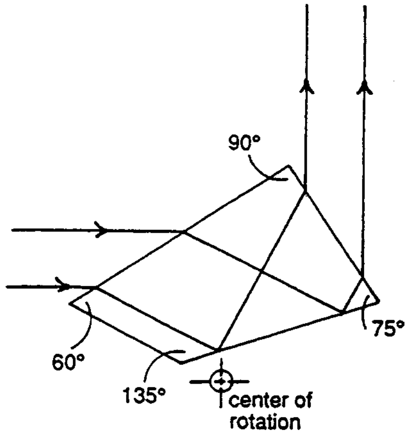


FIGURE 20.5.23

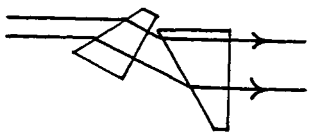


FIGURE 20.5.24

The typical dispersing prism of constant deviation shown in Figure 20.5.23 has the property that, if it is placed in a collimated beam, the wavelength which emerges at right angles to the incident beam is always at minimum deviation so that the spectrum is scanned by rotating the prism about a suitable axis such as the one indicated.

A prism used a long way from minimum deviation will expand or contract a collimated beam in one dimension. Figure 20.5.24 shows a pair of prisms used in this way to turn a laser beam of elliptical profile (from a diode laser) into a beam of circular profile by expanding it in the plane of the diagram only.

Nonimaging Optics

In one important respect conventional *image-forming* optical design is quite inefficient, that is, in merely concentrating and collecting light. This is well illustrated by an example taken from solar energy concentration (Figure 20.5.25). The flux at the surface of the sun ($\approx$63 W/mm^2) falls off inversely with the square of the distance to a value $\approx$1.37 mW/mm^2 above the Earth's atmosphere or typically 0.8 to 1 mW/mm^2 on the ground. The second law of thermodynamics permits an optical device (*in principle*) to concentrate the dilute solar flux at Earth so as to attain temperatures up to but not exceeding that of the sun's surface. This places an upper limit on the solar flux density achievable on Earth and correspondingly on the concentration ratio of any optical device. From simple geometry, this limiting concentration ratio is related to the sun's angular size (2θ) by $C_{max} = 1/\sin^2\theta \approx 1/\theta^2$ (small angle approximation). We will call this thermodynamic limit the *sine law of concentration*. Therefore, since $\theta = 0.27°$ or 4.67 mrad, $C_{max} \approx 46{,}000$. When the target is immersed in a medium of refractive index n, this limit is increased by a factor n^2, $C_{max} = n^2/\sin^2\theta$. This means that a concentration of about 100,000 will be the upper limit for ordinary ($n \approx 1.5$) refractive materials. In experiments at the University of Chicago we actually achieved a solar concentration of 84,000 by using a nonimaging design with a refractive medium (sapphire). We would not even have come close using conventional designs, not for any fundamental reason but because imaging optical design is quite inefficient for delivering maximum concentration. For example, consider the paraboloidal mirror of a telescope used to concentrate sunlight at its focus (Figure 20.5.26). We can relate the concentration ratio to the angle 2ϕ subtended by the paraboloid at

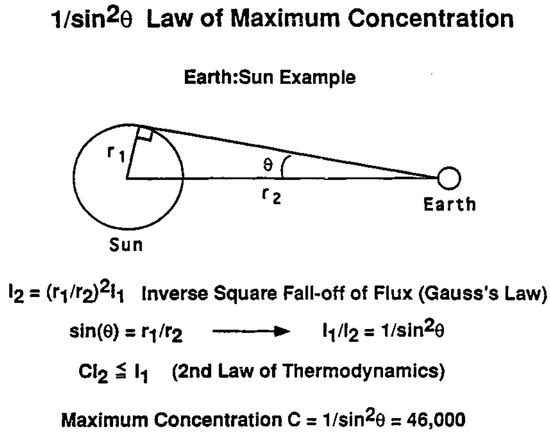


FIGURE 20.5.25

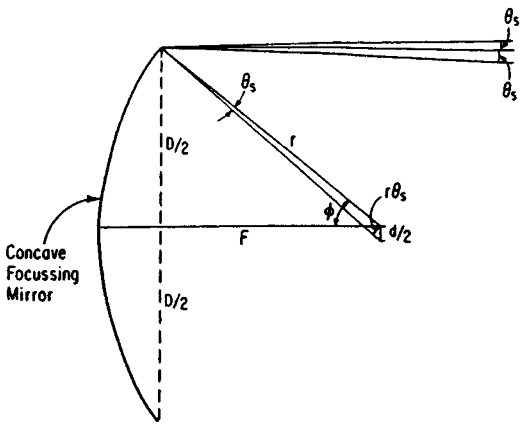
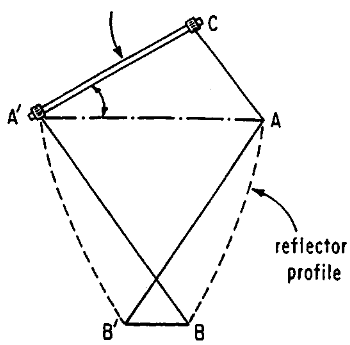


FIGURE 20.5.26

its focus and the sun's angular size ($2\theta_s$), $C = (\sin\phi\cos\phi/\theta_s)^2 = (^1/_4)\sin^2 2\phi/\theta_s^2$, where we have used the small angle approximation for θ_s. Notice that C is maximized at $\phi = \pi/4$, or $C = 1/(4\theta_s^2) = (^1/_4)\, C_{max}$. In fact, this result does not depend on the detailed shape of the paraboloid and would hold for any focusing mirror. One fares no better (and probably worse) with a lens (a refracting telescope), since the optimum paraboloid in the above example is equivalent in concentrating performance to a lens with focal ratio $f = 1$ which has been corrected for spherical aberration and coma. Such high-aperture lenses are typically complex structures with many components. The thermodynamic limit would require a lens with focal ratio $f = 0.5$ which, as every optical designer knows, is unattainable. The reason for this large shortfall is not hard to find. The paraboloid images perfectly on-axis, but has severe off-axis aberration (coma) which produces substantial image blurring and broadening. Nonimaging optics began in the mid 1960s with the discovery that optical systems could be designed and built that approached the theoretical limit of light collection (the sine law of concentration). The essential point is that requiring an image is unnecessarily restrictive when only concentration is desired. Recognition of this restriction and relaxation of the associated constraints led to the development of nonimaging optics. A nonimaging concentrator is essentially a "funnel" for light. Nonimaging optics departs from the methods of traditional optical design to develop instead techniques for maximizing the collecting power of concentrating elements and systems. Nonimaging designs exceed the concentration attainable with focusing techniques by factors of four or more and approach the theoretical limit (ideal concentrators). The key is simply to dispense with image-forming requirements in applications where no image is required.

Since its inception, the field has undergone three periods of rapid conceptual development. In the 1970s the "string" (see Figures 20.5.27 and 20.5.28) or "edge-ray" method (see Welford and Winston, 1989) was formulated and elaborated for a large variety of geometries. This development was driven by the desire to design wide-angle solar concentrators. It may be succinctly characterized as $\int n\, dl$ = constant along a string. (Notice that replacing "string" by "ray," Fermat's principle, gives all of imaging optics.) In the early 1980s, a second class of algorithms was found, driven by the desire to obtain ideally perfect solutions in three dimensions (3D) (The "string" solutions are ideal only in 2D, and as figures of revolution in 3D are only approximately ideal, though still very useful.) This places reflectors along the lines of flow of a radiation field set up by a radiating lambertian source. In cases of high symmetry such as a sphere or disk, one obtains ideal solutions in *both* 2D and 3D. The third period of rapid development has taken place only in the past several years; its implications and consequences are still in the process of being worked out. This was driven by the desire to address a wider class of problems in illumination that could not be solved by the old methods, for example, uniformly illuminating a plane (e.g., a table or a wall) by a lambertian light source (e.g., a fluorescent light). It is well known that the far-field illuminance from a lambertian source falls off with a power of the cosine of the radiating angle θ. For example, cylindrical radiators (such as a fluorescent lamp) produce a $\cos^2\theta$ illuminance on a distant plane, strip radiators produce a $\cos^3\theta$ illuminance, while circular disk radiators produce a $\cos^4\theta$ illuminance. But suppose one desires a predetermined far-field illuminance pattern, e.g., uniform illuminance? The old designs will not suffice; they simply transform a lambertian source radiating over 2π into a lambertian source radiating over a restricted set of angles. The limitation of the old designs is that they are too static and depend on a few parameters, such as the area of the beam A_1 and the divergence angle θ. One needs to introduce additional degrees of freedom into the nonimaging designs to solve a wider class of problems.



$$\int_W^{B'} n\,dl = \text{Constant.}\quad AC + AB' = A'B + BB'$$
$$AC = AA' \sin\theta$$
$$AB' = A'B$$
$$\Rightarrow AA' \sin\theta = BB'$$

FIGURE 20.5.27

Edge-Ray Optics

One way to design nonimaging concentrators is to reflect the extreme input rays into the extreme output rays. We call this the "edge-ray method." An intuitive realization of this method is to wrap a string about both the light source and the light receiver, then allow the string to unwrap from the source and wrap around the receiver. In introducing the string picture, we follow an insight of Hoyt Hottel (Massachusetts Institute of Technology), who discovered many years ago that the use of strings tremendously simplified the calculation of radiative energy transfer between surfaces in a furnace. Our string is actually a "smart"

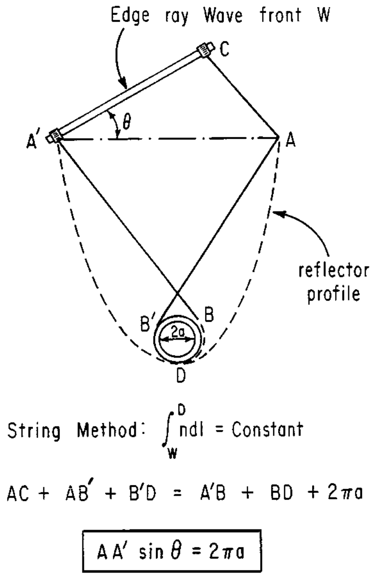


FIGURE 20.5.28

string; it measures the optical path length (ordinary length times the index of refraction) and refracts in accordance with Snell's law at the interface between different refracting materials. $\int n\,dl$ = constant. The locus traced out turns out to be the correct reflecting surface! Let's see how this works in the simplest kind of problem nonimaging optics addresses: collecting light over an entrance aperture AA' with angular divergence $\pm\theta$ and concentrating the light onto an exit aperture BB' (Figure 20.5.27). We attach one end of the string to the edge of the exit aperture B and the loop at the other end over a line WW' inclined at angle θ to the entrance aperture (this is the same as attaching to a "point at infinity"). We now unwrap the string and trace out the locus of the reflector taking care that string is taut and perpendicular to WW'. Then we trace the locus of the other side of the reflector. We can see with a little algebra that when we are done the condition for maximum concentration has been met. When we start unwrapping the string, the length is $AB' + BB'$; when we finish, the same length is $WA' + A'B$. But $WA' = AA'\sin\theta$, while $AB' = A'B$. So we have achieved $AA'/BB' = 1/\sin\theta$ which is maximum concentration! To see why this works, we notice that the reflector directs all rays at $\pm\theta$ to the edges BB' so that rays at angles $> \pm\theta$ are reflected out of the system and rejected. Now there is a conservation theorem for light rays called conservation of phase space or "etendue" which implies that if the rays at angles $> \pm\theta$ are rejected, then the rays that have angles $<\theta$ are all collected. Next we can try a more-challenging problem, where the "exit aperture" is a cylinder of radius a (Figure 20.5.28). Now we attach the string to a point on the cylinder and wrap it around the cylinder. When the string is unwrapped, we find that $AA'/2\pi a = 1/\sin\theta$ which is maximum concentration on the surface of the cylinder! Such designs are useful for solar-thermal concentrators since the typical receiver is a tube for carrying fluid. A solar plant for powering air conditioners that uses this design is shown in Figure 20.5.29. As already mentioned, there is an alternative method for designing "ideal" optical systems which bears little resemblance to the "string method" already described. We picture the aggregate of light rays traversing an optical system as a fluid flow in an abstract space called phase space.This is the "space" of ray positions and ray directions multiplied by the index of refraction, so it has twice the number of dimensions of ordinary space. By placing reflectors along the lines of flow of this vector field, nonimaging designs are generated. Flow-line designs are perfect in three dimensions, while the string designs rotated about an axis are not. On the other hand, the number of flow-line designs are much more restricted. For details see Welford and Winston (1989).

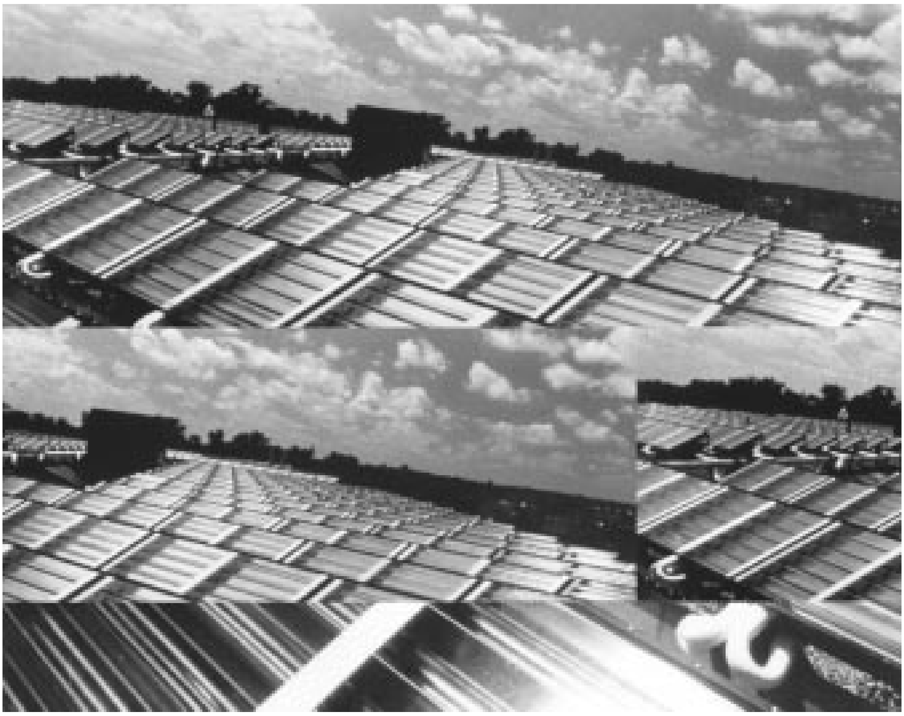


FIGURE 20.5.29

Lasers

Lasers are by now a ubiquitous light source with certain properties in addition to coherence and monochromaticity which have to be taken account of in some applications. Aside from many research applications of lasers, the HeNe laser at 632.8 nm wavelength has been available for several decades for alignment, surveying, and the like. But the explosive uses of lasers have come only recently with the advent of the solid-state diode laser. To appreciate the convenience of diode lasers one can draw upon the analogy between transistors and vacuum tubes. Inexpensive diode lasers are in widespread use in compact disk players, optical disk readers, and fiber-optics communications. The list of consumer applications is growing rapidly (e.g., laser pointers). In addition, diode lasers are used in arrays to optically drive (pump) more powerful lasers. The radiation that lasers emit can be highly coherent, and, except for the wavelength, of the same general character as the radiation from a radio frequency oscillator. We can identify four elements common to nearly all lasers (we follow the discussion in Mandel and Wolf, 1995, which should be consulted for details):

1. An optical resonator, generally formed by two or more mirrors;
2. A gain medium in which an inverted atomic population between the laser energy levels is established;
3. An optical pump or energy source to excite the gain medium;
4. A loss mechanism by which energy is dissipated or dispersed.

Figure 20.5.30 shows a typical form of laser, in which the resonator is a Fabry–Perot interferometer, and the amplifier is a gas plasma tube wherein a discharge is maintained. To reduce reflection losses from the plasma tube, its end windows are generally arranged at the Brewster angle for linearly polarized light at the laser frequency. The end mirrors are usually provided with multilayer dielectric coatings to make them highly reflecting. Of course, the output mirror needs to have its reflectivity, R, less than

100%, so that (1 – R) is commonly the main source of the energy loss that has to be compensated by the gain medium. The cavity mirrors play the important role of feeding photons belonging to the laser modes back into the laser cavity. Most of the spontaneously emitted photons traveling in various other directions are lost. However, photons associated with a cavity resonance mode interact repeatedly with the atoms of the gain medium, and their number grows through stimulated emission, as illustrated in Figure 20.5.31. Once one mode is sufficiently populated, the probability for stimulated emission into that mode exceeds the spontaneous emission probability. In general, when the rate at which photons are fed into the optical cavity mode exceeds the rate at which they are lost from the cavity by the loss mechanism, the amplitude of the laser field starts to grow until a steady state is reached. At that point the rate of radiation by the laser equals the net rate at which energy is supplied. It is easy to see that this is achievable by an inverted population between the two atomic laser levels, with more atoms in the upper laser state than in the lower. If N_2, N_1 are the upper state and lower state populations, the rate of absorption of laser photons by the atomic system is proportional to N_1, and the rate of stimulated emission of laser photons by the system is proportional to N_2, with the same constant of proportionality for both. If N_2 exceeds N_1 sufficiently, all the radiation losses can be made good by the atomic system. It can be shown that the condition for laser action (in a single mode) is

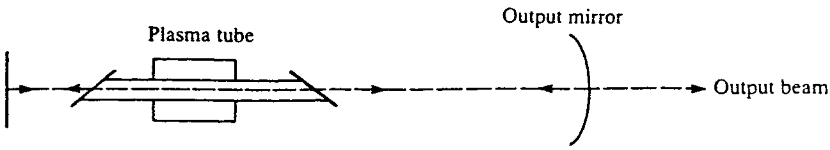


FIGURE 20.5.30 A simple form of laser.

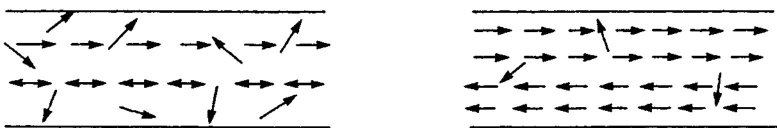


FIGURE 20.5.31 Illustration of the growth of the stimulated emission probability with the intensity of the mode.

$$N_2 - N_1 > 2A(1 - R)/\lambda^2 \tag{20.5.19}$$

where A is the cross-sectional area of the laser and λ is the wavelength.

We next summarize how the special properties of laser beams are to be taken into account in optical design. The well-known Gaussian intensity profile of laser beams persists if it is taken through a sequence of lenses along the axis, and at certain points that can be more-or-less predicted by paraxial optics a “focus” is formed. But when, as often happens, the convergence angle in the space in which this occurs is small, say, 1 mrad or less, some departures from the predictions of the paraxial optics occur. We shall examine these effects, since they are of importance in many of the systems already mentioned.

Gaussian Beams

In paraxial approximation the simplest form of a single-mode beam is the TEM_{00} Gaussian beam shown in Figure 20.5.32. Starting from the narrowest part, known as the waist, the beam diverges with spherical phase fronts. The complex amplitude at the waist has the form

$$A = A_0 \exp\left(-r^2/\omega_0^2\right) \tag{20.5.20}$$

where ω_0 is called the beam width and r is a radial coordinate.

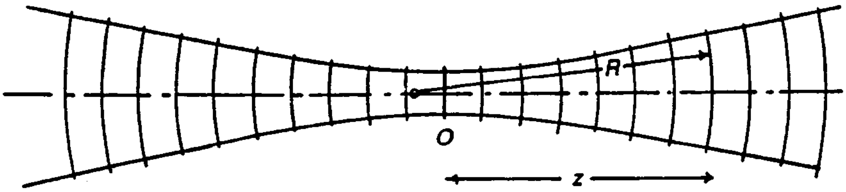


FIGURE 20.5.32

At a distance z along the beam in either direction, the complex amplitude is, apart from a phase factor,

$$A = (\omega_0/\omega) A_0 \exp(-r^2/\omega_0^2) \tag{20.5.21}$$

where ω is given by

$$\omega(z) = \omega_0\left[1 + (\lambda z/\pi\omega_0^2)\right]^{1/2} \tag{20.5.22}$$

At a distance z from the waist, the phase fronts have a radius of curvature R given by

$$R(z) = z\left[1 + (\pi\omega_0^2/\lambda z)^2\right] \tag{20.5.23}$$

The beam contour of constant intensity A_0^2/e^2 is a hyperboloidal surface of (small) asymptotic angle given by

$$\theta = \lambda/\pi\omega_0 \tag{20.5.24}$$

It can be seen that the centers of curvature of the phase fronts are not at the beam waist; in fact the phase front is plane at that point. The geometrical wavefronts are not exactly the same as true phase fronts, and if in this case we postulate that geometrical wavefronts should have their centers of curvature at the beam waist, we have an example of this. However, the difference is small unless the convergence angle is very small or, more precisely, when the Fresnel number of the beam is not much larger than unity:

$$\text{Fresnel number } = \omega^2/\lambda R \tag{20.5.25}$$

There is nothing special about Gaussian beams to cause this discrepancy between phase fronts and geometrical wavefronts; a similar phenomenon occurs with beams which are sharply truncated by the pupil (“hard-edged” beams). But it happens that it is less usual to be concerned with the region near the focus of a hard-edged beam of small Fresnel number, whereas Gaussian beams are frequently used in this way. Thus, Born and Wolf, *Principles of Optics* (1959) show that the phase front at the focus of a hard-edged beam is also plane, but with rapid changes of intensity and phase jumps across the zeros of intensity.

Tracing Gaussian Beams

If the beam is in a space of large convergence angle, say, greater than 10 mrad, it can be traced by ordinary paraxial optics, i.e., using the assumption that for all practical purposes the phase fronts are the same as geometrical wavefronts. In a space of small convergence angle it is necessary to propagate the beam between refracting surfaces by means of the proper Gaussian beam formulas and then use paraxial optics to refract (or reflect) the phase front through each surface in turn. To do this, we need two more formulas to give the position, z, and size of the beam waist starting from the beam size and phase front curvature at an arbitrary position on the axis, i.e., given ω and R. These are

$$z = R\left[1 + \left(\lambda z/\pi\omega^2\right)\right]^{-1} \tag{20.5.26}$$

and

$$\omega_0 = \omega\left[1 + \left(\pi\omega^2/\lambda R\right)^2\right]^{-1/2} \tag{20.5.27}$$

Equations (20.5.22) to (20.5.27) enable a Gaussian beam to be traced through a sequence of refracting surfaces as an iterative process. Thus, starting from a beam waist of given size ω_0 (and angle given by Equation (20.5.24)), we move a distance z to the first refracting surface. At this surface the beam size ω is given by Equation (20.5.22) and the radius of curvature R of the phase front is given by Equation (20.5.23). The radius of curvature R' of the refracted phase front is obtained by paraxial optics using the equation of Figure 20.5.7 and taking R and R' as the conjugate distances l and l'. Then the position and size of the new beam waist are found from Equations (20.5.26) and (20.5.27). These procedures can be carried through all the refracting surfaces of the optical system.

It can be seen from Equation (20.5.26) that z and R are substantially equal when $\lambda R/\pi\omega^2$ is very small. When this is so, there is no need to use these special equations for transferring between surfaces; the iterative equations in Figure 20.5.9 can be used, with the understanding that the paraxial convergence angle u is the equivalent of the asymptotic angle θ in Equation (20.5.24).

There are no simple equations for hard-edged beams corresponding to Equations (20.5.23) to (20.5.27) for use with very small convergence angles. Numerical calculations of the beam patterns near focus have been published for some special cases, and these show, as might be expected, very complex structures near the "focal" region; however, that is defined.

Truncation of Gaussian Beams

The theoretical origin of the Gaussian beam is as a paraxial solution of the Helmholtz equation, i.e., a solution concentrated near one straight line, the axis, but although most of the power is within the region near the axis the solution is nonzero, although very small, at an infinite distance from the axis. Thus, the Gaussian profile is truncated when it passes through any aperture of finite diameter — e.g., a lens mount, an aperture stop, or even the finite-diameter end mirror of a laser resonator — after which it is no longer Gaussian and the above equations are no longer valid! In practice, this need not be a problem, for if the radius of the aperture is 2ω, the complex amplitude is down to 1.8% of its value at the center and the intensity is 0.03% of its value at the center. Thus, it is often assumed that an aperture of radius 2ω has no significant effect on the Gaussian beam, and this assumption is adequate for many purposes, although not all.

Sometimes it is useful to truncate a Gaussian beam deliberately, i.e., turn it into a hard-edged beam, by using an aperture of radius less than, say, ω. In this way an approximation to the Airy pattern is produced at the focus instead of a Gaussian profile waist, and this pattern may be better for certain purposes, e.g., for printers where the spot must be as small as possible for an optical system of given numerical aperture.

Gaussian Beams and Aberrations

In principle, a Gaussian beam is a paraxial beam, from the nature of the approximations made in solving the Helmholtz equation. However, Gaussian beams can be expanded to large diameters simply by letting them propagate a large distance, and they can acquire aberrations by passing through an aberrating lens or mirror system. The beam is then no longer Gaussian, of course, in the strict sense, but we stress that the conventional optical design idea involving balancing and reduction of aberrations can be applied to systems in which Gaussian beams are to propagate. For example, a *beam expander*, of which one form in shown in Figure 20.5.33, is an afocal system intended to do what its name implies: if it has aberrations

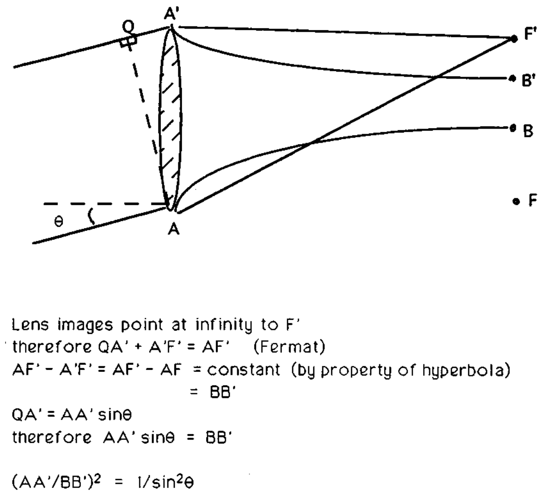


FIGURE 20.5.33

as an afocal system, the output beam from a Gaussian input beam will not have truly plane or spherical phase fronts.

Non-Gaussian Beams from Lasers

Not all lasers produce Gaussian beams, even ignoring the inevitable truncation effects of resonator mirrors. Some gas lasers (e.g., helium-neon at any of its lasing wavelengths) produce Gaussian beams when they are in appropriate adjustment, but they can produce off-axis modes with more structure than a Gaussian beam. Other gas lasers (e.g., copper vapor lasers) produce beams with a great many transverse modes covering an angular range of a few milliradians in an output beam perhaps 20 mm across. Some solid-state lasers, e.g., ruby, may produce a very non-Gaussian beam because of optical inhomogeneities in the ruby. Laser diodes, which as already mentioned are becoming increasingly useful as very compact coherent sources, whether cw or pulsed, produce a single strongly divergent transverse mode which is wider across one direction than the other. This mode can be converted into a circular section of approximately Gaussian profile by means of a prism system, as in Figure 20.5.24.

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20.6 Water Desalination

Noam Lior

Introduction and Overview

Water desalination is a process that separates water from a saline water solution. The natural water cycle is the best and most prevalent example of water desalination. Ocean waters evaporate due to solar heating and atmospheric influences; the vapor consisting mostly of fresh water (because of the negligible volatility of the salts at these temperatures) rises buoyantly and condenses into clouds in the cooler atmospheric regions, is transported across the sky by cloud motion, and is eventually deposited back on the earth surface as fresh water rain, snow, and hail. The global freshwater supply from this natural cycle is ample, but many regions on Earth do not receive an adequate share. Population growth, rapidly increasing demand for fresh water, and increasing contamination of the available natural fresh water resources render water desalination increasingly attractive. Water desalinaiton has grown over the last four decades to an output of about 20 million m^3 of fresh water per day, by about 10,000 sizeable land-based water desalination plants.

The salt concentration in the waters being desalted ranges from below 100 ppm wt. (essentially fresh water, when ultrapure water is needed), through several thousand parts per million (brackish waters unsuitable for drinking or agricultural use) and seawater with concentrations between 35,000 and 50,000 ppm. Official salt concentration limits for drinkable water are about 1000 ppm, and characteristic water supplies are restricted to well below 500 ppm, with city water in the United States being typically below 100 ppm. Salinity limits for agricultural irrigation waters depend on the type of plant, cultivation, and soil, but are typically below 2000 ppm.

Many ways are availiable for separating water from a saline water solution. The oldest and still prevalent desalination process is distillation. The evaporation of the solution is effected by the addition of heat or by lowering of its vapor pressure, and condensation of these vapors on a cold surface produces fresh water. The three dominant distillation processes are multistage flash (MSF), multieffect (ME), and vapor compression (VC). Until the early 1980s the MSF process was prevalent for desalination. Now membrane processes, especially reverse osmosis (RO), are economical enough to have taken about one third of the market. In all membrane processes separation occurs due to the selective nature of the permeability of a membrane, which permits, under the influence of an external driving force, the passage of either water or salt ions but not of both. The driving force may be pressure (as in RO), electric potential (as in electrodialysis, ED), or heat (as in membrane distillation, MD). A process used for low-salinity solutions is the well-known ion exchange (IE), in which salt ions are preferentially adsorbed onto a material that has the required selective adsorption property and thus reduce the salinity of the water in the solution.

The cost of desalted water is comprised of the capital cost of the plant, the cost of the energy needed for the process, and the cost of operation and maintenance staff and supplies. In large seawater desalination plants the cost of water is about \$1.4 to \$2/m^3, dropping to less than \$1/m^3 for desalting brackish water. A methodology for assessing the economic viability of desalination in comparison with other water supply methods is described by Kasper and Lior (1979). Desalination plants are relatively simple to operate, and progress toward advanced controls and automation is gradually reducing operation expenses. The relative effect of the cost of the energy on the cost of the fresh water produced depends on local conditions, and is up to one half of the total.

The boiling point of a salt solution is elevated as the concentration is increased, and the **boiling point elevation** is a measure of the energy needed for separation. Thermodynamically reversible separation defines the minimal energy requirement for that process. The minimal energy of separation W_{min} in such a process is the change in the Gibbs free energy between the beginning and end of the process, ΔG. The minimal work when the number of moles of the solution changes from n_1 to n_2 is thus

$$W_{\min} = \int_{n_1}^{n_2} (\Delta G)\, dn_W \tag{20.6.1}$$

The minimal energy of separation of water from seawater containing 3.45 wt.% salt, at 25°C, is 2.55 kJ/(kg fresh water) for the case of zero fresh water recovery (infinitesimal concentration change) and 2.91 kJ/(kg fresh water) for the case of 25% freshwater recovery. $W_{\min}$ is, however, severalfold smaller than the energy necessary for water desalination in practice. Improved energy economy can be obtained when desalination plants are integrated with power generation plants (Aschner, 1980). Such dual-purpose plants save energy but also increase the capital cost and complexity of operation.

Two aspects of the basically simple desalination process require special attention. One is the high-corrosivity of seawater, especially pronounced in the higher-temperature distillation processes, which requires the use of corrosion-resistant expensive materials. Typical materials in use are copper–nickel alloys, stainless steel, titanium, and, at lower temperatures, fiber-reinforced polymers (George et al., 1975). Another aspect is scale formation (Glater et al., 1980; Heitman, 1990). Salts in saline water, particularly calcium sulfate, magnesium hydroxide, and calcium carbonate, tend to precipitate when a certain temperature and concentration are exceeded. The precipitate, often mixed with dirt entering with the seawater and with corrosion products, will gradually plug up pipes, and when depositing on heat transfer surfaces reduces heat transfer rates and thus impairs plant performance. While the ambient-temperature operation of membrane processes reduces scaling, membranes are much more susceptible not only to minute amounts of scaling or even dirt, but also to the presence of certain salts and other compounds that reduce their ability to separate salt from water. To reduce corrosion, scaling, and other problems, the water to be desalted is pretreated. The pretreatment consists of filtration, and may inlude removal of air (deaeration), removal of CO_2 (decarbonation), and selective removal of scale-forming salts (softening). It also includes the addition of chemicals that allow operation at higher temperatures without scale deposition, or which retard scale deposition and/or cause the precipitation of scale which does not adhere to solid surfaces, and that prevent foam formation during the desalination process.

Saline waters, including seawater, contain, besides a variety of inorganic salts, also organic materials and various particles. They differ in composition from site to site, and also change with time due to both natural and person-made causes. Design and operation of desalination plants requires good knowledge of the saline water composition and properties (Fabuss, 1980; Heitman, 1991).

The major water desalination processes that are currently in use or in advanced research stages are concisely described below. Information on detailed modeling can be found in the references.

Distillation Processes

Multistage Flash Evaporation (MSF)

Almost all of the large desalination plants use the MSF process shown schematically in Figure 20.6.1. A photo of an operating plant is shown in Figure 20.6.2. The seawater feed is preheated by internal heat recovery from condensing water vapor during passage through a series of stages, and then heated to its top temperature by steam generated by an external heat source. The hot seawater then flows as a horizontal free-surface stream through a series of "stages," created by vertical walls which separate the vapor space of each stage from the others. These walls allow the vapor space of each stage to be maintained at a different pressure, which is gradually decreased along the flow path due to the gradually decreasing temperature in the condenser/seawater-preheater installed above the free stream. The seawater is superheated by a few degrees celsius relative to the vapor pressure in each stage it enters, and consequently evaporates in each stage along its flow path. The latent heat of the evaporation is supplied by equivalent reduction of the sensible heat of the evaporating water, thus resulting in a gradual lowering of the stream temperature. The evaporation is vigorous, resulting in intensive bubble generation and growth with accompanying stream turbulence, a process known as **flash evaporation** (Lior and Greif, 1980; Miyatake et al., 1992; 1993). One of the primary advantages of the MSF process is the fact that evaporation occurs

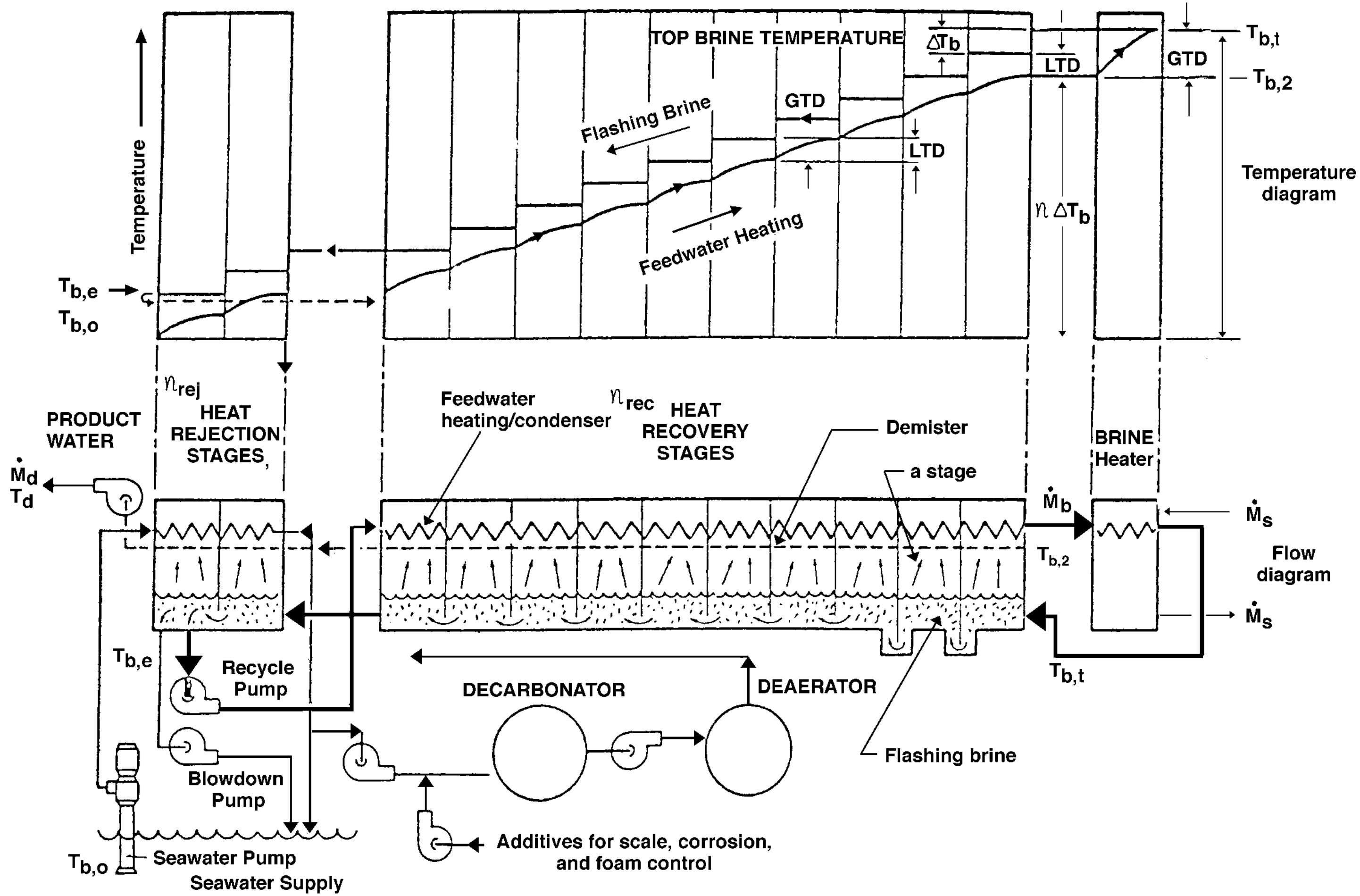

FIGURE 20.6.1 Schematic flow and temperature diagram of the MSF process, for a recirculation type plant.

FIGURE 20.6.2 One of the six units of the 346,000 m³/day MSF desalination plant Al Taweelah B in Abu Dhabi, United Arab Emirates. (Courtesy of Italimpianti S. p. A.) It is a dual-purpose plant, composed of six identical power and desalination units. Five of the six boilers are seen in the background. The desalination units were in 1996 the largest in the world. They have 17 recovery and 3 reject stages and a performance ratio (PR) of 8.1. The plant also produces 732 MWe of power.

from the saline water stream and not on heated surfaces (as in other distillation processes such as submerged tube and ME evaporation) where evaporation typically causes scale depostition and thus gradual impairment of heat transfer rates. Also, the fact that the sensible heat of water is much smaller than its latent heat of evaporation, where the specific heat c_p = 4.182 kJ/kg/°C change of water temperature and the latent heat is h_{fg} = 2378 kJ/kg, and the fact that the top temperature is limited by considerations of scaling and corrosion, dictate the requirement for a very large flow rate of the evaporating stream. For example (in the following, the subscripts *b*, *d*, and *s* refer to brine distillate, and steam, respectively), operating between a typical top temperature $T_{b,t}$ of 90°C at the inlet to the evaporator and an exit temperature $T_{b,e}$ of 40°C corresponding to the ambient conditions, the overall temperature drop of the evaporating stream if 50°C. By using these values, the heat balance between the sensible heat of the water stream, flowing at a mass flow rate $\dot{m}_b$, and the latent heat needed for generating water vapor (distillate) at a mass flow rate $\dot{m}_d$ is

$$\left(\dot{m}_b - \dot{m}_d\right) c_p \left(T_{b,t} - T_{b,e}\right) \approx \dot{m}_d h_{fg} \tag{20.6.2}$$

which yields the brine-to-product mass flow ratio as

$$\frac{\dot{m}_b}{\dot{m}_d} = \frac{h_{fg}}{c_p\left(T_{b,t} - T_{b,e}\right)} + 1 = \frac{2378}{(4.182)(50)} + 1 = 12.37 \tag{20.6.3}$$

Therefore, 12.37 kg of saline water are needed to produce 1 kg of distillate. This high flow rate incurs corresponding pumping equipment and energy expenses, sluggish system dynamics, and, since the stream level depth is limited to about 0.3 to 0.5 m for best evaporation rates, also requires large evaporator vessels with their associated expense.

The generated water vapor rises through a screen ("demister") placed to remove entrained saline water droplets. Rising further, it then condenses on the condenser tube bank, and internal heat recovery is achieved by transferring its heat of condensation to the seawater feed that is thus being preheated. This internal heat recovery is another of the primary advantages of the MSF process. The energy performance of distillation plants is often evaluated by the *performance ratio*, PR, typically defined as

$$\text{PR} \equiv \frac{\dot{m}_d}{\dot{m}_s} \tag{20.6.4}$$

where $\dot{m}_s$ is the mass flow rate of heating steam. Since the latent heat of evaporation is almost the same for the distillate and the heating steam, PR is also the ratio of the heat energy needed for producing one unit mass of product (distillate) to the external heat actually used for that purpose. Most of the heating of the brine stream to the top temperature $T_{b,t}$ is by internal heat recovery, and as seen in Figure 20.6.1, the external heat input is only the amount of heat needed to elevate the temperature of the preheated brine from its exit from the hottest stage at $T_{b,2}$ to $T_{b,t}$. Following the notation in Figure 20.6.1, and using heat balances similar to that in Equation (20.6.3) for the brine heater and flash evaporator, the PR can thus also be defined as

$$\text{PR} = \frac{\dot{m}_b\left(\overline{c_{p,b}}\right)_{e\to t}\left(T_{b,t} - T_{b,e}\right)/h_{fg,b}}{\dot{m}_b\left(\overline{c_{p,b}}\right)_{2\to t}\left(T_{b,t} - T_{b,2}\right)/h_{fg,s}} \approx \frac{T_{b,t} - T_{b,e}}{T_{b,t} - T_{b,2}} \tag{20.6.5}$$

where $(\overline{c_{p,b}})_{e\to t}$ and $(\overline{c_{p,b}})_{2\to t}$ are the specific heats of brine, the first averaged over the temperature range $T_{b,e} \rightarrow T_{b,t}$ and the second over $T_{b,2} \rightarrow T_{b,t}$. The rightmost expression in Equation (20.6.5) is nearly correct because the specific heat of the brine does not change much with temperature, and the latent heat of evaporation of the brine is nearly equal to the latent heat of condensation of the heating steam. It is obvious from Equation (20.6.5) that PR increases as the top heat recovery temperature $T_{b,2}$ (at the exit from the condenser/brine-preheater) increases. It is also obvious (even from just examining Figure 20.6.1) that increasing the number of stages (matched with a commensurate increase in condenser heat transfer area and assuming no significant change in the overall heat transfer coefficient) for a given $T_{b,t}$, will raise the flash evaporator inlet temperature $T_{b,3}$, which will lead to a rise in $T_{b,2}$ and thus also in the PR.

Assuming that the temperature drop of the flashing brine, ΔT_b, is the same in each stage, the relationship between the number of stages (n) and the performance ratio is

$$\text{PR} = \frac{1}{\dfrac{\text{LTD}}{T_{b,t} - T_{b,e}} + \dfrac{1}{n}} \tag{20.6.6}$$

where LTD is the lowest temperature difference between the flashed vapor and the heated feedwater, in each stage (Figure 20.6.1). Equation (20.6.6) shows that increasing the number of stages increases the PR. This implies that more heat is then recovered internally, which would thus require a larger condenser/brine-preheater heat transfer area. The required heat transfer area, A, *per unit mass of distillate produced* for the entire heat recovery section (composed of n_{rec} stages), and taking average values of the overall vapor-to-feedwater heat transfer coefficient U and LMTD, is thus

$$A = n_{\text{rec}} A_n = n_{\text{rec}} \frac{h_{b,fg}}{U(\text{LMTD})} \tag{20.6.7}$$

LMTD, the log-mean temperature difference between the vapor condensing on the tubes and the heated brine flowing inside the tubes, for an average stage is

$$\text{LMTD} = \frac{\text{GTD} - \text{LTD}}{\ln \dfrac{\text{GTD}}{\text{LTD}}} = \frac{\left(T_{b,t} - T_{b,2}\right) - \text{LTD}}{\ln\left(\dfrac{T_{b,t} - T_{b,2}}{\text{LTD}}\right)} \tag{20.6.8}$$

where GTD is the greatest temperature difference between the flashing brine and the brine heated in the condenser. The size of the heat transfer area per unit mass of distillate is

$$A = \frac{h_{fg,b}}{U} \frac{n_{\text{rec}}}{\left(T_{b,t} - T_{b,e}\right)} \ln\left(\frac{n_{\text{rec}}}{n_{\text{rec}} - PR}\right) \tag{20.6.9}$$

Examination of this equation will show that the required heat transfer area for the heat recovery section per unit mass of distillate produced, A, increases significantly when PR is increased, and decreases slightly as the number of heat recovery stages, n_{rec}, is increased.

The MSF plant shown in Figure 20.6.1 is of the *recirculation* type, where not all of the brine stream emerging from the last evaporation stage is discharged from the plant (as it would have been in a *once-through* type of plant). A fraction of the emerging brine is mixed with pretreated seawater and recirculated into the condenser of the heat recovery section of the plant. Since only a fraction of the entire stream in this configuration is new seawater, which needs to be pretreated (removal of air and CO_2, i.e., deaeration and decarbonation, and the addition of chemicals that reduce scale deposition, corrosion, and foaming), the overall process cost is reduced. The recirculation plant is also easier to control than the once-through type.

While most of the energy exchange in the plant is internal, steady-state operation requires that energy in an amount equal to all external energy input be also discharged from the plant. Consequently, the heat supplied in the brine heater (plus any pumping energy) is discharged in the heat rejection stages section of the plant (Figure 20.6.1). Assuming an equal temperature drop in each stage, and that the pumping energy can be neglected relative to the heat input in the brine heater, indicates that the ratio of the number of the heat-recovery to heat-rejection stages is approximately equal to the performance ratio PR.

Further detail about MSF desalination can be found in Steinbruchel and Rhinesmith, (1980) and Khan (1986). A detailed design of an MSF plant producing 2.5 million gals. of freshwater per day was published by the U.S. government (Burns and Roe, 1969).

Multi-Effect Distillation (ME)

The principle of the ME distillation process is that the latent heat of condensation of the vapor generated in one effect is used to generate vapor in the next effect, thus obtaining internal heat recovery and good energy efficiency. Several ME plant configurations, most prominently the horizontal tube ME (HTME, shown in Figure 20.6.3) and the vertical tube evaporator (VTE, shown schematically in Figure 20.6.4) are in use. In the HTME, vapor is circulated through a horizontal tube bundle, which is subjected to an external spray of somewhat colder saline water. The vapor flowing in these spray-cooled tubes condenses, and the latent heat of condensation is transferred through the tube wall to the saline water spray striking the exterior of the tube, causing it to evaporate. The vapor generated thereby flows into the tubes in the next effect, and the process is repeated from effect to effect.

In the VTE the saline water typically flows downward inside vertical tubes and evaporates as a result of condensation of vapor coming from a higher temperature effect on the tube exterior. While internal heat recovery is a feature common to both MSF and ME processes, there are at least three important differences between them. One is that evaporation in the ME process occurs on the heat transfer surfaces (tubes), while in the MSF process it takes place in the free stream. This makes the ME process much more susceptible to scale formation. At the same time, the heat transfer coefficient between the vapor and the preheated brine is lower in the MSF process because the heated brine does not boil. In the ME

FIGURE 20.6.3 Two HTME desalination units, each producing 5000 m^3/day, in St. Croix, U.S. Virgin Islands. (Courtesy of I.D.E. Technologies Ltd.)

process it does boil, and it is well known that boiling heat transfer coefficients are significantly higher than those where the heating does not result in boiling. In using direct transfer of latent heat of condensation to latent heat of evaporation, instead of sensible heat reduction to latent heat of evaporation as in MSF, the ME process requires a much smaller brine flow than the MSF. Limiting brine concentration in the last effect to about three times that of the entering seawater, for example, requires a brine flow of only about 1.5 times that of the distillate produced. At the same time, a pump (although much smaller than the two pumps needed in MSF) is needed for each effect.

The PR of ME plants is just sightly lower than the number of effects, which is determined as an optimized compromise between energy efficiency and capital cost. Six effects are typical, although plants with as many as 18 effects have been built.

Further detail about ME desalination can be found in Steinbruchel and Rhinesmith (1980) and Standiford, (1986a).

Vapor Compression Distillation (VC)

As stated earlier, the vapor pressure of saline water is lower than that of pure water at the same temperature, with the pressure difference proportional to the boiling point elevation of the saline water. Desalination is attained here by evaporating the saline water and condensing the vapor on the pure water. Therefore, the pressure of the saline water vapor must be raised by the magnitude of that pressure difference, plus some additional amount to compensate for various losses. This is the principle of the vapor compression desalination method. Furthermore, as shown in Figure 20.6.5, the heat of condensation of the compressed vapor is recovered internally by using it to evaporate the saline water. Additional heat recovery is obtained by transferring heat from the concentrated brine effluent and the produced freshwater (which need to be cooled down to as close to ambient conditions as possible anyway) to the feed saline water which is thus preheated. The schematic flow diagram in Figure 20.5.5 shows a design in which the preheated seawater is sprayed onto a bank of horizontal tubes carrying condensing compressed vapor at a temperature higher than that of the seawater. The spray thus evaporates on contact with the exterior of the tube and provides the cooling needed for the internal condensation. Considering the fact that the energy required for vapor compression over a typical overall temperature difference of 4°C and a vapor compressor efficiency of 0.8 is 34 kJ/kg (easily calculated from an enthalpy balance), and that the latent

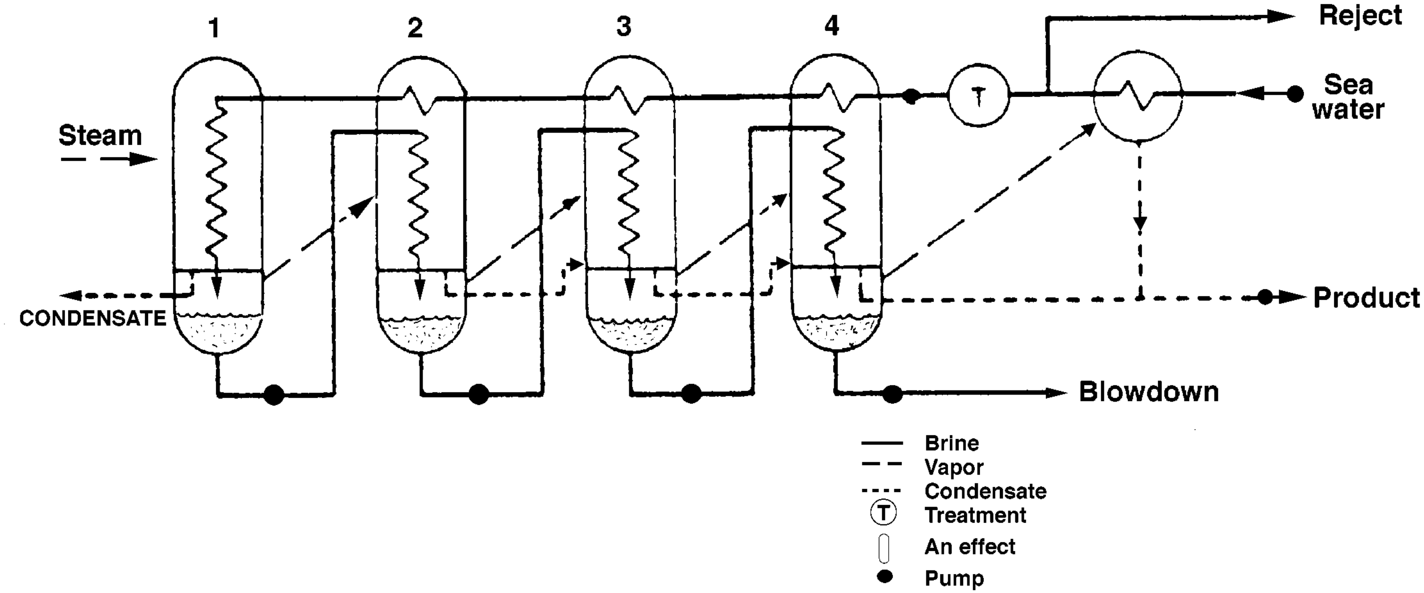

FIGURE 20.6.4 Simplified schematic flow diagram of a typical four-effect VTE desalination plant.

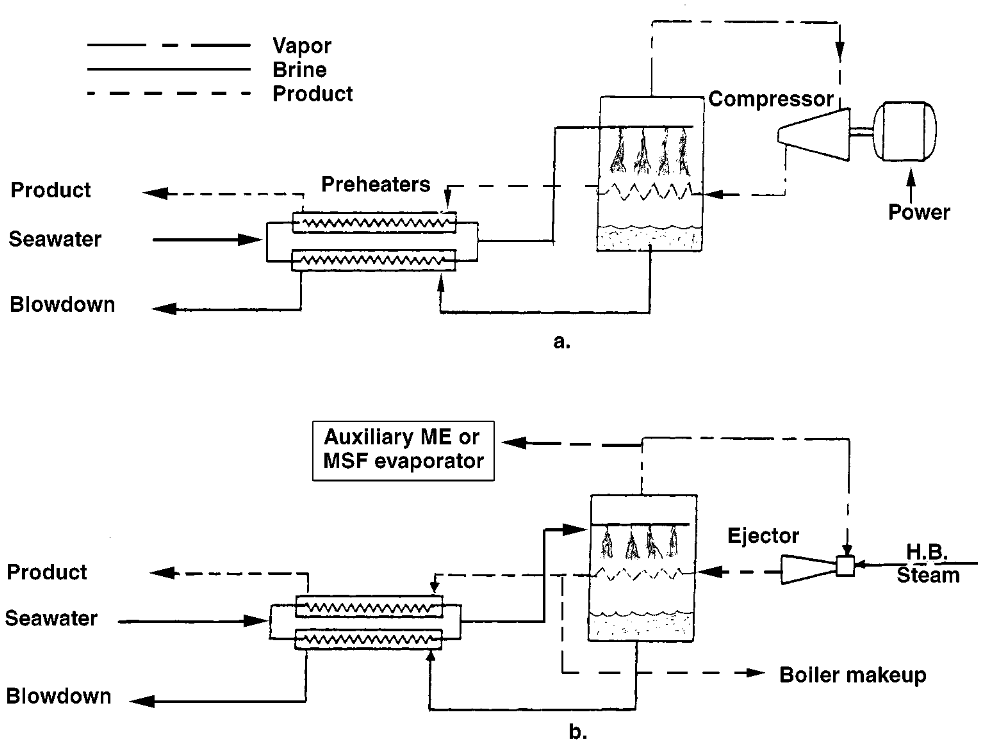

FIGURE 20.6.5 Schematic flow diagram of a basic horizontal-tube VC desalination plant (a) with mechanical, motor-driven compressor; (b) with a thermo-compressor, using an ejector.

heat of condensation is about 2400 kJ/kg, one can see that a small amount of compression energy enables a large amount of heat to be used internally for desalination. One can thus envisage the VC plant as a large flywheel, wheeling a large amount of energy around at the expense of a small amount needed for sustaining its motion.

The compressor can be driven by electric motors, gas or steam turbines, or internal combustion (usually diesel) engines. The compressor can also be a steam-driven ejector (Figure 20.6.5b), which improves plant reliability because of its simplicity and absence of moving parts, but also reduces its efficiency because an ejector is less efficient than a mechanical compressor. In all of the mentioned thermally driven devices, turbines, engines, and the ejector, the exhaust heat can be used for process efficiency improvement, or for desalination by an additional distillation plant.

Figure 20.6.6 shows a multi-effect VC plant. Using more than a single effect reduces the vapor volume that needs to be compressed. Furthermore, the overall required heat transfer area is also decreased because much of the single-phase heat transfer process in the preheater of the single-effect plant is replaced by the high-heat-transfer condensation–evaporation processes in the effects. Although the ME feature also increases the required compression ratio, the cost of produced water is reduced overall.

Further detail about VC desalination can be found in Steinbruchel and Rhinesmith (1980), Khan (1986), and Standiford, (1986b).

Solar Distillation

The benefits of using the nonpolluting and practically inexhaustible energy of the sun for water desalination are obvious. Furthermore, many water-poor regions also have a relatively high solar flux over a large fraction of the time. The major impediment in the use of solar energy is economical: the diffuse nature of solar energy dictates the need for constructing a large solar energy collection area. For example,

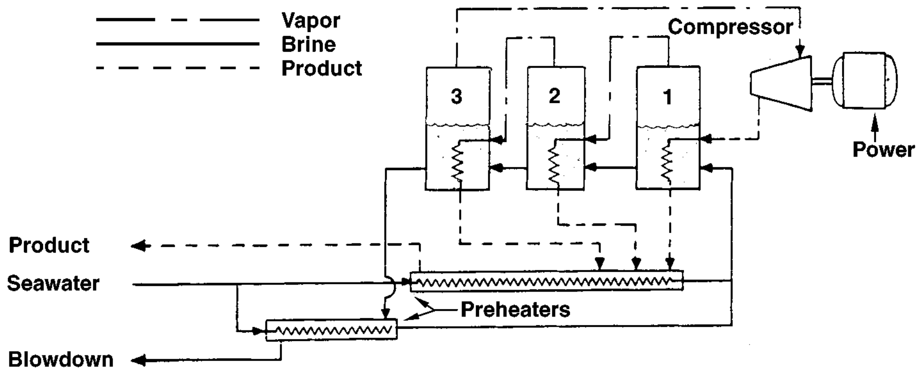

FIGURE 20.6.6 Schematic flow diagram of a ME vapor compression submerged-tube desalinaton plant with three effects.

assuming a single-effect solar still efficiency of 50% (which is the upper practical limit for conventional designs), the still would produce at most about 3.5 to 4.8 kg fresh water per m^2 per day, or a 208 to 286 m^2 solar still would be required to produce 1 m^3 of fresh water per day. More realistic still efficiencies increase the area requirement about twofold.

Shown in Figure 20.6.7, a typical solar still consists of a saline water container in which the water is exposed to the sun and heated by it. The temperature rise to above ambient causes net evaporation of the saline water, thus separating pure water vapor from the solution. The vapor condenses on the colder cover, and this destilled water flows to collection troughs.

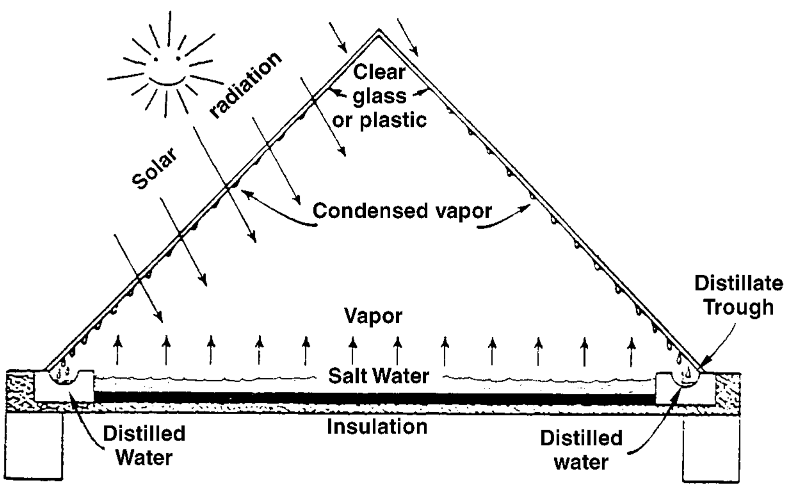

FIGURE 20.6.7 A typical basin-type solar still.

Solar stills of the type depicted in Figure 20.6.7, in many sizes and constructional variants, have been built and used successfully in many countries in the world. They are simple, easy to construct, reliable, and require very little maintenance although in some regions the covers must be cleaned frequently from accumulated dust or sand.

Since the heat of condensation in single-effect stills of the type shown in Figure 20.6.7 is lost to the ambient, more-energy-efficient operation can obviously be achieved in a multi-effect design, where the heat of condensation is used to evaporate additional saline water. A number of such stills were built and tested successfully, but are not commercially competitive yet.

Solar stills integrate the desalination and solar energy collection processes. Another approach to solar desalination is to use separately a conventional desalination process and a suitable solar energy supply system for it. Any compatible desalination and solar energy collection processes could be used. Distillation, such as MSF or ME, can be used with heat input from solar collectors, concentrators, or solar ponds (Hoffman, 1992; Glueckstern, 1995). Net average solar energy conversion efficiencies of solar collectors (Rabl, 1985; Lior, 1991) are about 25% and of solar ponds (Lior, 1993) about 18%, similar to the efficiencies of solar stills, but the MSF or ME plants can operate at preformance ratios of 10 or more, thus basically increasing the freshwater production rate by at least tenfold, or reducing the required solar collection area by at least tenfold for the same production rate.

Solar or wind energy can also be used for desalination processes that are driven by mechanical or electrical power, such as VC, RO, and ED. The solar energy can be used to generate the required power by a variety of means, or photovoltaic cells can be used to convert solar energy to electricity directly.

Freeze Desalination

It is rather well known that freezing of saline water solutions is an effetive separation process in that it generates ice crystals that are essentially salt-free water, surrounded by saline water of higher concentration. This process requires much less energy than distillation, and the problems of corrosion and scaling are markedly reduced due to the much lower operating temperatures. Several pilot plants were constructed and have proven concept viability. Nevertheless, the process has not yet reached commercial introduction for several reasons, such as the difficulty in developing efficient and economical compressors for vapor with the extremely high specific volume at the low process pressure, and difficulties in maintaining the vacuum system leak free and in effecting reliable washing of the ice crystals. A review of freeze desalination processes is given by Tleimat (1980).

Membrane Separation Processes

Reverse Osmosis (RO)

Separation of particulate matter from a liquid by applying pressure to the liquid and passing it through a porous membrane, whereby particles larger than the pore size remain on the upstream side of the membrane and the liquid flows to its downstream side, is well known as *filtration*. Semipermeable very dense membranes that actually separate salt molecules (ions) from the water, by similarly keeping the salt on the upstream side and allowing the pressurized pure water to flow through the membrane, were developed in the 1950s. The reverse of this process, **osmosis**, is well known: for example, if a membrane is placed to separate water from an aqueous salt solution, and the membrane is semipermeable (here meaning that it permits transfer of water only, not the salt components in the aqueous solution), the water will tend naturally to migrate through this membrane into the salt solution. Osmosis is, for example, the major mass transport phenomenon across living cells. The driving force for this water flux is proportional to the concentration difference between the two sides of the membrane, and is exhibited as the so-called **osmotic pressure**, which is higher by 2.51 MPa on the water side of the membrane for typical seawater at 25°C. If a pressure higher than the osmotic pressure is applied on the saline solution side of the membrane, the water flux can be reversed to move pure water across the membrane from the saline solution side to the pure water one. This process is called *reverse osmosis* (and sometimes *hyperfiltration*), and is the basic principle of RO desalination

Unlike filtration of particulates, the selective "filtration" of the water in RO is not due to the relationship of the membrane pore size to the relative sizes of the salt and water molecules. Rather, one way to explain the process is that the very thin active surface layer of the membrane forms hydrogen bonds with water molecules and thus makes them unavailable for dissolving salt. Salt thus cannot penetrate through that layer. Water molecules approaching that layer are, however, transported through it by forming such hydrogen bonds with it and in that process displacing water molecules that were previously hydrogen bonded at these sites. The displaced water molecules then move by capillary action through the pores of the remainder of the membrane, emerging at its other side.

The most prevalent membrane configurations used in RO plants are of the spiral-wound or hollow-fiber types. The basic spiral-wound-type module (Figure 20.6.8) is made of two sheets placed upon each other and rolled together in an increasing diameter spiral around a cylindrical perforated tube. One of the sheets is in the form of a sandwich typically composed of five layers bonded together along three edges. The two outer layers are the semipermeable membranes. Each of them is backed by a porous material layer for mechanical strength, and the very central layer is a thicker porous material layer that takes up the produced fresh water. The second sheet is a porous mesh through which the high-pressure saline water feed is passed in an axial direction. Product water separates from the saline solution and permeates through the two adjacent semipermeable membranes into the central product water–carrying layer, which conducts it spirally to the unbonded edge of the "sandwich" and to the inner perforated tube. The semipermeable membranes are typically made from cellulose acetate, and more recently from composites of several polymers.

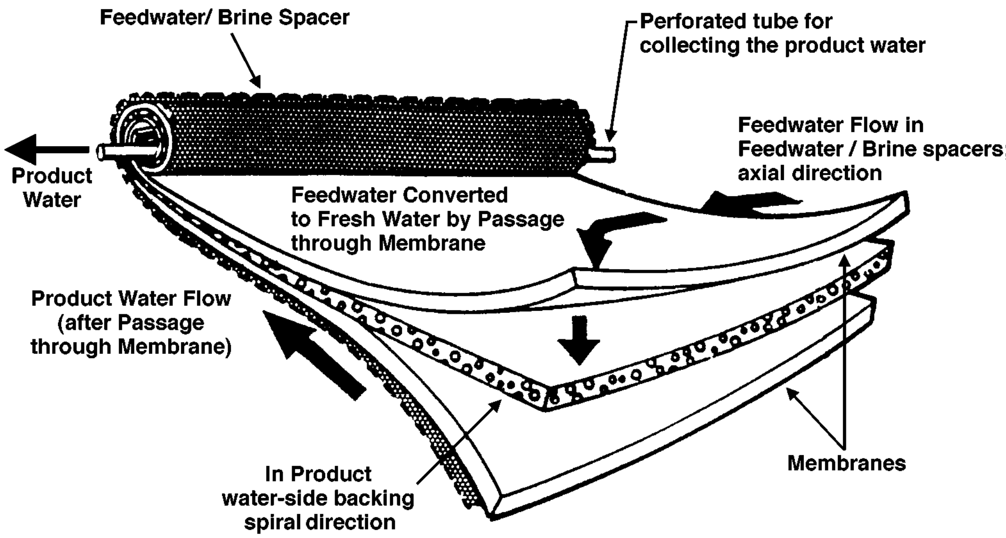

FIGURE 20.6.8 A spiral-wound RO membrane element.

Hollow fiber modules have a configuration similar to a shell-and-tube heat exchanger, with the fibers taking the place of the tubes. A very large number of typicallly 25 to 250 μm outside-diameter semi-permeable hollow fibers (wall thickness typically 5 to 50 μm) are bundled together and placed in a saline water pressure vessel. The hollow core of each fiber is sealed on one end. The pressurized saline water is brought into the module (through a central porous feed tube, Figure 20.6.9) to circulate on the exterior surface of the fibers, and water permeates through the fiber wall into its hollow core, through which it flows to a permeate collection manifold at the open end of the fiber bundle. The increasingly concentrated saline water flows radially and is discharged at the exterior shell of the bundle. The hollow fibers are typically made of polyamide or cellulose triacetate, and offer about 20 fold more surface (separation) area per unit volume than the spiral-wound configuration.

The basic approximate equation for the separation process gives the water flux $\dot{m}''_w$ (kg/m^{2}sec) across an RO membrane, in the absence of fouling, as

$$\dot{m}''_w = K_{pe} K_{cf} \left[\left(P_f - P_p \right) - \left(\pi_f - \pi_p \right) \right] \tag{20.6.10}$$

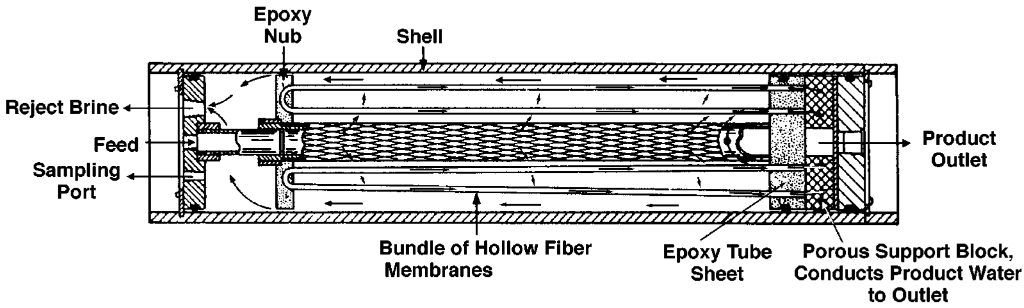

FIGURE 20.6.9 A hollow-fiber RO membrane module. (Du Pont Permasep™.)

where

K_{pe} *water permeability constant* of the membrane (in kg/m^{2}sec Pa), typically increasing strongly as the temperature rises: a plant designed to operate at 20°C may produce up to 24% more water if the water temperature is 28°C,

K_{cf} *compaction correction factor* (dimensionless) which corrects for the fact that the flux is reduced due to densification of the barrier layer (a phenomenon similar to creep) of the membrane, and which increases with the operating pressure and temperature. It is often calculated by the relationship

$$K_{cf} = BC(T)C(P)C(t) \qquad (20.6.11)$$

where B is a constant,
$C(T)$ represents the temperature dependence of the Compaction Correction Factor for the particular membrane of interest,
$C(P)$ represents its pressure dependence: while a higher pressure difference across the membrane is shown in Equation (20.6.10) to increase the water flux, higher feed pressure (P_f) also tends to compact the membrane and thus reduce its water flux, typically according to

$$C(P) = P_f^n \qquad (20.6.12)$$

where n is a negative number,
and where the time dependence $C(t)$ is represented by

$$C(t) = t^m \qquad (20.6.13)$$

where t is the operating time (say, in days) and m is a negative number depending on the membrane.

P water or saline solution pressure (Pa),

π osmotic pressure (Pa),

and the subscripts f and p pertain to the saline feed water and to the desalted product water, respectively.

The required membrane area A can be estimated by

$$A = \frac{\dot{m}_p}{\dot{m}''_p f} \qquad (20.6.14)$$

where $\dot{m}_p$ is the freshwater mass production rate of the plant (kg/sec), and f ($0 < f \leq 1.0$) is the *area utilization factor* that corrects for the fact that the membrane surface is incompletely in contact with the saline water feed stream due to the porous mesh and other devices, such as turbulence promoters, placed in the feed stream path; in a good design $f > 0.9$.

Examination of Equation (20.6.10) shows that water separation rate increases with the water permeability constant K_{pe}. Unfortunately, so does the salt flux across the membrane, resulting in a saltier product. An approximation for this salt flow is

$$\dot{m}_s = KK_s\left(C_{fm} - C_p\right) \tag{20.6.15}$$

where

- $\dot{m}_s$ salt mass transfer rate across the membrane, kg/sec,
- K a proportionality constant, dimensionless,
- K_s *salt permeation constant,* kg/sec, which increases with pressure and temperature.

The salinity of the product water (C_p) can be estimated by the formula

$$C_p = K_{cp}(1 - \eta)\bar{C} \tag{20.6.16}$$

where

- K_{cp} *concentration polarization coefficient*, $\equiv C_{fm}/\bar{C}$ is a measure of the increase of the feedwater salinity at the membrane wall beyond that of the bulk solution,
- C_{fm} salt concentration at the membrane wall,
- $\bar{C}$ bulk salinity of the saline water feed, $\approx (C_f + C_r)/2$,
- C_r salt concentration of the reject brine,
- η *salt rejection factor*, $\equiv$ (amount of salts rejected by the membrane)/(amount of salts in the brine feed).

The pressure to be used for RO depends on the salinity of the feed water, the type of membrane, and the desired product purity. It ranges form about 1.5 MPa for low feed concentrations or high-flux membranes, through 2.5 to 4 MPa for brackish waters, and to 6 to 8.4 MPa for seawater desalination. In desalination of brackish water, typical product water fluxes through spiral-wound membranes are about 600 to 800 kg/(m^{2}day) at a recovery ratio (RR) of 15% and an average salt rejection of 99.5%, where

$$\text{RR} = \frac{\dot{m}_p}{\dot{m}_f} \cong 1 - \frac{C_f}{C_r} \tag{20.6.17}$$

The fluxes in hollow-fiber membranes used in seawater desalination are 20- to 30-fold smaller, but the overall RO system size does not increase, because the hollow-fiber membranes have a much larger surface area per unit volume. The RR and salt rejection ratio are similar to those of spiral-wound membranes.

Since the concentrated reject brine is still at high pressure, it is possible to recover energy by passing this brine through hydraulic turbines, and thus reduce the overall energy consumption by up to 20%. The energy requirements of seawater RO desalination plants with energy recovery are about 5 to 9 kWh, or 18 to 33 MJ, of mechanical or electric power per m^3 fresh water produced. In comparison, the MSF desalination process requires about 120 to 280 MJ of heat and about 15 MJ of mechanical/electric power (for pumping and auxiliaries) per m^3. The energy requirement of the RO process is thus smaller than that of the MSF process even if the RO energy requirement is multiplied by the thermal-to-mechanical (or electrical) power conversion factor of 3 to 4. The specific *exergy* consumption of the MSF process using 120°C steam is about 2- to 3-fold higher than that of the RO process, but becomes comparable in magnitude if the steam temperature is lowered to 80°C.

The life of membranes is affected by gradual chemical decomposition or change. For example, cellulose acetate membranes **hydrolyze** with time. The rate of hydrolysis has a steep minimum at a solution pH of 4.5 to 5.0, and increases drastically with temperature.

Membranes are susceptible to plugging by dirt and to deterioration in their selectivity caused by various species present in the saline water. Careful pretreatment of the feed water is therefore necessary. It typically consists of clarification, filtration, chlorination for destroying organic matter and microorganisms, removal of excess chlorine to prevent membrane oxidation, and dosing with additives to prevent calcium sulfate scaling and foam formation. Periodical chemical or mechanical cleaning is also necessary. Pretreatment and cleaning are significant and increasing fractions of the RO plant capital and operating costs.

Further detail about RO desalination can be found in Sourirajan and Matsuura (1985) and Amjad (1993).

Electrodialysis (ED)

In ED, the saline solution is placed between two membranes, one permeable to cations only and the other to anions only. A direct electrical current is passed across this system by means of two electrodes, cathode and anode, exposed to the solution (Figure 20.6.10). It causes the cations in the saline solution to move toward the cathode, and the anions to the anode. As shown in Figure 20.6.10, the anions can leave the compartment in their travel to the anode because the membrane separating them from the anode is permeable to them. Cations would similarly leave the compartment toward the cathode. The exit of these ions from the compartment reduces the salt concentration in it, and increases the salt concentration in the adjacent compartments. Tens to hundreds of such compartments are stacked together in practical ED plants, leading to the creation of alternating compartments of fresh and salt-concentrated water. ED is a continuous-flow process, where saline feed is continuously fed into all compartments and the product water and concentrated brine flow out of alternate compartments. The flow along the membranes also improves the mass transport there, and the separators between the membranes are constructed to provide good flow distribution and mixing on the membrane surfaces. Membrane sizes are roughly 0.5 × 1 m, spaced about 1 mm apart. Many typed of polymers are used to manufacture these ion-exchange selective membranes, which are often reinforced by strong fabrics made from other polymers or glass fibers.

Careful and thorough feed water pretreatment similar to that described in the section on RO is required. Pretreatment needs and operational problems of scaling are diminished in the electrodialysis reversal (EDR) process, in which the electric current flow direction is periodically reversed (say, three to four times per hour), with simultaneous switching of the water flow connections. This also reverses the salt concentration buildup at the membrane and electrode surfaces, and prevents concentrations that cause the precipitation of salts and scale deposition.

The voltage used for ED is about 1 V per membrane pair, and the current flux is of the order of 100 A/m^2 of membrane surface. The total power requirement increases with the feed water salt concentration, amounting to about 10 MW/m^3 product water per 1000 ppm reduction in salinity. About half this power is required for separation and half for pumping. Many plant flow arrangements exist, and their description can be found, along with other details about the process, in Shaffer and Mintz (1980) and Heitman (1991).

Defining Terms

Boiling point elevation: The number of degrees by which the boiling point temperature of a solution is higher than that of the pure solute at the same pressure.

Flash evaporation: An evaporation process that occurs when a liquid with a free surface is exposed to its vapor, where the vapor is below the saturation pressure corresponding to the temperature of the liquid.

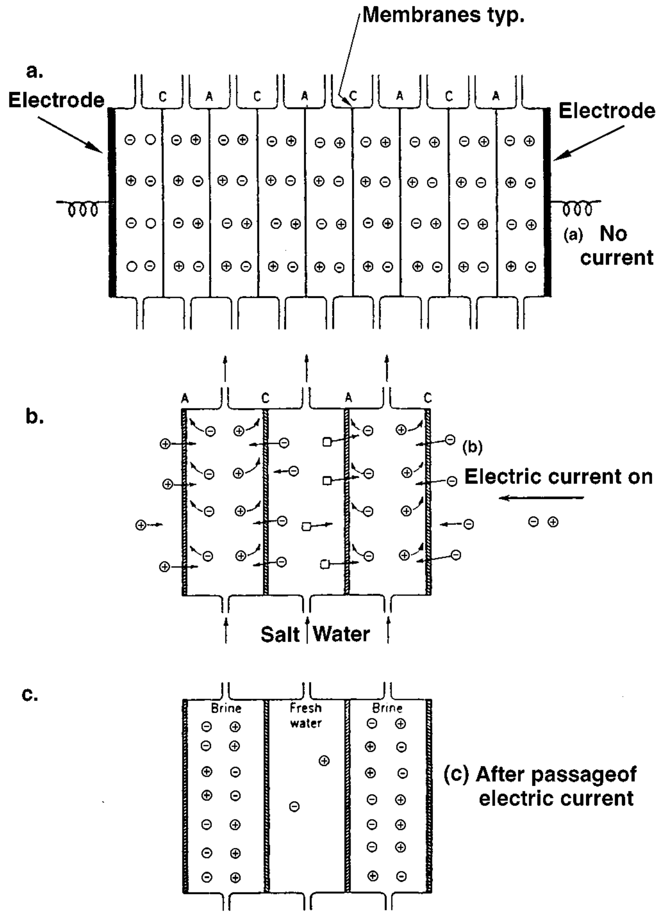

FIGURE 20.6.10 The ED process. *C* and *A* are cation- and anion-permeable membranes, respectively. Application of electric current causes ion transport in a way that salt is depleted in alternate compartments, and enriched in the remaining ones.

The process is typically vigorous, accompanied by rapid growth of bubbles and associated turbulence in the liquid.

Hydrolysis: Decompostion in which a compound is split into other compounds by taking up the elements of water.

Osmosis: The diffusion process of a component of a solution (or mixture) across a semipermeable membrane, driven by the concentration difference (or gradient) of that component across the membrane.

Osmotic pressure: The minimal pressure that has to be applied to the solution (mixture) on the lower concentration side of a membrane permeable to one solution component, for stopping the osmosis of that component through the membrane.

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Further Information

The major texts on water desalination written since the 1980s are Spiegler and Laird (1980), Khan, (1986) (contains many practical design aspects), Lior (1986) (on the measurements and control aspects), Heitman (1990) (on pretreatment and chemistry aspects), and Spiegler and El-Sayed (1994) (an overiew primer). Extensive data sources are provided in George et al. (1975) and M. W. Kellog (1975).

The two major professional journals in this field are *Desalination, The International Journal on the Science and Technology of Desalting and Water Purification* and *Membrane Science*, which often addresses membrane-based desalination processes, both published by Elsevier, Amsterdam.

The major professional society in the field is the International Desalination Association (IDA) headquartered at P.O. Box 387, Topsfield, MA 01983. IDA regularly organizes international conferences, promotes water desalinaton and reuse technology, and is now publishing a trade magazine T*he International Desalination & Water Reuse Quarterly.*

The *Desalination Directory* by M. Balaban Desalination Publications, Mario Negri Sud Research Institute, 66030 Santa Maria Imbaro (Ch), Italy, lists more than 5000 individuals and 2000 companies and institutions in the world of desalinaiton and water reuse.

Two useful (though by now somewhat dated) books on desalination are by Howe, E. D. 1974. *Fundamentals of Water Desalination*, Marcel Dekker, New York, and by Porteous, A. 1975. *Saline Water Distillation Processes*, Longman, London.

Much information on oceans and seawater properties is avaiable in the book by Riley, J. P. and Skinner, Eds. 1975. *Chemical Oceanography*, Academic Press, New York.

20.7 Noise Control

Malcolm J. Crocker

Introduction

Noise is usually defined as unwanted sound. Noise in industry experienced over an extended period can cause hearing loss. Noise in other environments — in buildings, vehicles, and communities from a variety of sources causes speech interference, sleep disturbance, annoyance, and other effects (Crocker, 1997b,d). Noise propagates as sound waves in the atmosphere and as vibration in buildings, machinery, vehicles, and other structures. Noise can be controlled at the *source*, in the *path*, or at the *receiver*. The ear is more sensitive to noise in the mid- to high-frequency range, but fortunately high-frequency is easier to control than low-frequency noise. Several passive methods of noise and vibration control are described. An example of successful noise control is the considerable reduction in passenger jet aircraft noise in the last several years which has made them considerably quieter.

Sound Propagation

Sound waves propagate rather like ripples on a lake when a stone is thrown in (Crocker, 1997c). The ripples spread out from the source of the disturbance as circular waves until they reach a solid body or boundary (such as the lake edge) where reflections occur. The water does not flow from the source, but the disturbance propagates in the form of momentum and energy which is eventually dissipated. Sound waves in air cannot be seen but behave in a similar manner. Sound waves propagating in three dimensions from a source of sound are spherical rather than circular like the two-dimensional water wave propagation. Sound waves propagate at the wave speed (or *sound speed* c) which is dependent only on the absolute temperature T. It is 343 m/sec (1120 ft/sec) at a normal atmospheric temperature of 20°C. The *wavelength* λ of sound is inversely proportional to the *frequency* f in cycles/sec (known as hertz or Hz) and is given by $\lambda = c/f$ Hz. The sound waves result in fluctuations in the air pressure as they propagate. The air pressure difference from the mean atmospheric pressure is defined as the *sound pressure*. A logarithmic measure, the sound pressure level SPL or L_p, is usually used with sound and noise and the units are *decibels* (dB). The sound pressure level is $L_p = 10 \log_{10} (p^2 / p_{\text{ref}}^2)$, where p is the rms sound pressure and p_{ref} is the reference sound pressure 20 μPa (or 20×10^{-6} N/m^2). See Figure 20.7.1 (Crocker, 1997c).

Human Hearing

The human ear has a wide frequency response from about 15 or 20 Hz to about 16,000 Hz (Crocker, 1975; Greenberg, 1997). The ear also has a large dynamic range; the ratio of the loudest sound pressure we can tolerate to the quietest sound that we can hear is about ten million (10^7). This is equivalent to 140 dB. The ear can be divided into three main parts: the outer, middle, and inner ear. The outer ear, consisting of the fleshy pinna and ear canal, conducts the sound waves onto the ear drum. The middle ear converts the sound pressure at the ear drum into the mechanical motion of three small bones (named auditory ossicles: malleus, incus, and stapes) which in turn convert the mechanical motion into waves in the inner ear. Hair cells in the inner ear respond to the excitation and send neural impulses along the auditory nerves to the brain (Figure 20.7.2).

The higher the sound pressure level of a sound, the louder it normally sounds, although the frequency content of the sound is important too. The ear is most sensitive to sound in the mid-frequency range and hears sound only poorly at lower frequencies (below 200 or 300 Hz). Most people have a maximum sensitivity to sound at about 4000 Hz (corresponding to a quarter wave resonance in the ear canal, with a pressure maximum at the eardrum). Electrical filters have been produced corresponding approximately to the frequency response of the ear. The A-weighting filter is the one most used and it filters off a considerable amount of the sound energy at low frequencies. The sound pressure level measured with an A-weighting filter is normally known as the A-weighted sound level (or the sound level for short).

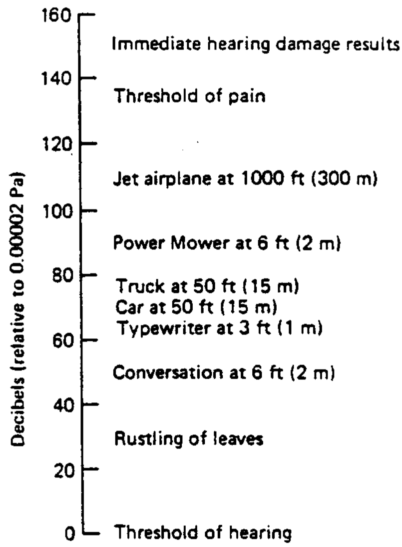

FIGURE 20.7.1 Some typical sound pressure levels.

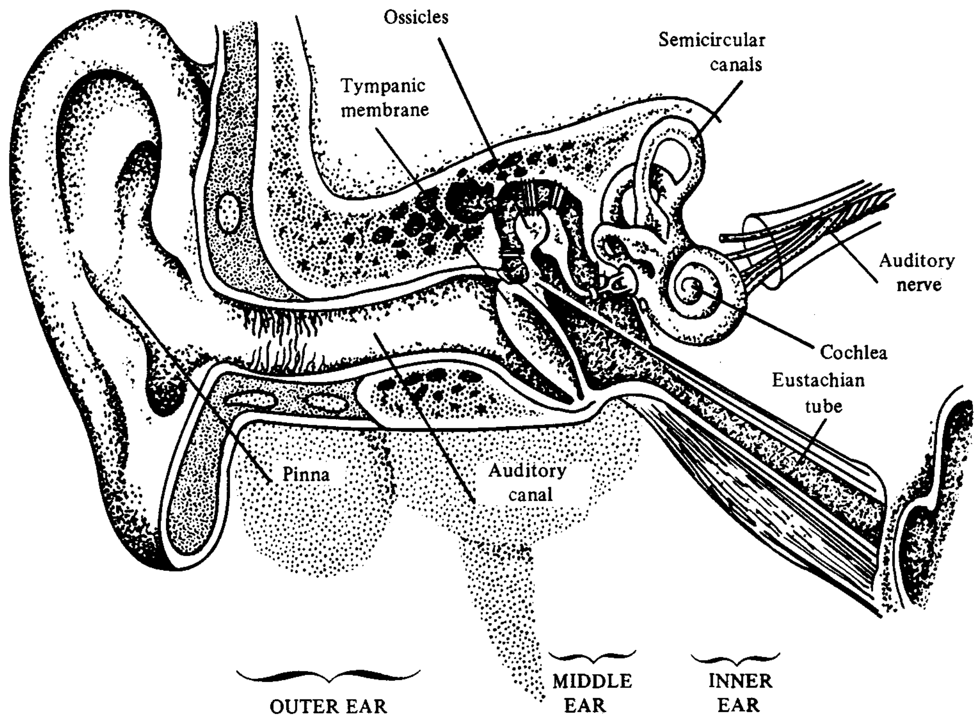

FIGURE 20.7.2 Cross section of the human ear showing the three main parts: outer, middle, and inner ear.

The anatomy and functioning of the ear are described more completely in several books (Crocker, 1997; Greenberg, 1997).

Noise Measures

There are several rating measures and descriptors used to determine human response to noise. Only a few of the most important can be discussed here. The reader will find more such measures discussed in the literature. [1] Criteria derived from such measures can be used to produce regulations or legislation.

The speech interference level (SIL) is a measure used to evaluate the effect of background noise on speech communication. The SIL is the arithmetic average of the sound pressure levels of the interfering background noise in the four octave bands with center frequencies of 500, 1000, 2000 and 4000 Hz.[1,6]

The speech interference level of the background noise is calculated; then this may be used in conjunction with Figure 20.7.3 to determine if communication is possible at various distances for different voice levels. This figure is for male voices. Since the average female voice is normally quieter, for female voices the horizontal scale should be moved to the right by 5 dB. Use of the results obtained with Figure 20.7.3 and criteria for various spaces in buildings enable decisions to be made whether they are suitable for their desired uses.

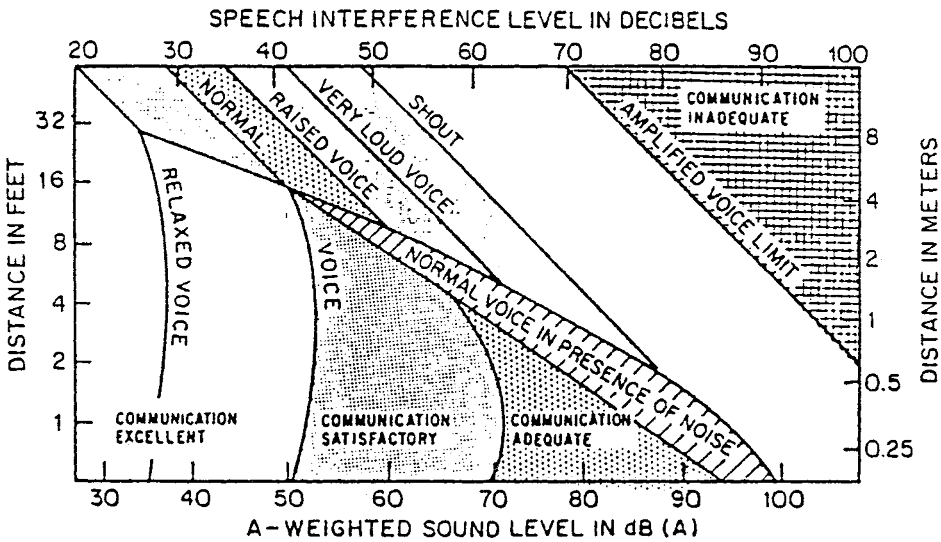

FIGURE 20.7.3 Recommended distances between speaker and listener for various voice levels for just reliable speech communication. (From C.M. Harris *Handbook of Noise Control,* McGraw-Hill, New York, 1979. With permission.)

The equivalent sound level L_{eq} is the A-weighted sound pressure level averaged over a suitable time period T. The averaging time T can be chosen to be a number of minutes, hours or days, as desired.

$$L_{eq} = 10\log_{10}\left[(1/T)\int p_A^2\, dt/p_{ref}^2\right] dB$$

where p_A is the instantaneous sound pressure measured using an A-weighting frequency filter. The L_{eq} is also sometimes known as the *average sound level* L_{AT}.

The *day-night equivalent sound level* (DNL) or L_{dn} is a measure that accounts for the different human response to sound at night. It is defined (Crocker, 1997d) as:

$$L_{\mathrm{dn}} = 10\log_{10}\left\{(1/24)\left[15\left(10^{L_d/10}\right) + 9\left(10^{(L_n+10)/10}\right)\right]\right\} dB$$

where L_d is the 15-hr daytime A-weighted equivalent sound level (from 0700 to 2200 hr) and L_n is the 9-hr nighttime equivalent sound level (from 2200 to 0700 hr). The nighttime level is subjected to a 10-dB penalty because noise at night is known to be more disturbing than noise during the day.

There is some evidence that noise that fluctuates markedly in level is more annoying than noise which is steady in level. Several noise measures have been proposed to try to account for the annoying effect of these fluctuations. The percentile levels are used in some measures. The *percentile level* L_n is defined to be the level exceeded *n%* of the time (Crocker, 1997d). The A-weighted sound level is normally used in Ln.

Response of People to Noise and Noise Criteria and Regulations

In industry, noise is often intense enough to interfere with speech and to create noise conditions that are hazardous to hearing. By using Figure 20.7.3 it is seen that if the SIL is above 50 dB, then the noise will interfere with normal speech communication between male voices at 4 m. If it is above 60 dB, then speech communication even when shouting is barely possible at the same distance. For women the comparable values of SIL are 45 and 55 dB at the same distance. If the SIL is 90 dB, then communication between male voices is only possible at distances less than 0.25 m, even when shouting. A-weighted sound levels are sometimes used instead of SIL values but with somewhat less confidence. It is seen that if one has difficulty in communicating in an industrial situation, then the A-weighted sound level is likely to be above 90 dB. In the United States, OSHA regulations start at this level for an 8-hr period. There is a halving in the allowable exposure time for every 5-dB increase in sound level. See Table 20.7.1. In almost all other countries the allowable exposure time is halved for every 3-dB increase in sound level (Ward, 1997).

TABLE 20.7.1 Maximum A-Weighted Sound Levels Allowed by the U.S. Occupational Safety and Health Administration (OSHA) for Work Periods Shown during a Workday

Duration per Day (hr)	Sound Level in dB(A)
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25 or less	115

Noise in communities is caused by many different sources. In most countries, the maximum equivalent A-weighted sound level L_{eq} is recommended for evaluating different types of noise source (Gottlob, 1995). In some countries there are regulations which use L_{eq} for road traffic noise and railroad noise, although some countries use L_{10} (e.g., the U.K.) or L_{50} (e.g., Japan) for planning permission in which road traffic noise is of concern (Crocker, 1997d; Gottlob, 1995). In the United States the L_{dn} has been used for community noise situations involving aircraft noise at airports and road traffic noise. Table 20.7.2 presents levels of noise given by the U.S. EPA and several other bodies to protect public health.

TABLE 20.7.2 Guidelines from the U.S. Environmental Protection Agency (EPA), World Health Organization (WHO), Federal Interagency on Community Noise (FICON), and Various European Agencies for Acceptable Noise Levels

Authority	Specified Sound Levels	Criterion
EPA Levels Document	$L_{dn} \leq 55$ dB (outdoors) $L_{dn} \leq 45$ dB (indoors)	Protection of public health and welfare with adequate margin of safety
WHO Document (1995)	$L_{eq} \leq 50/55$ dB (outdoors: day) $L_{eq} \leq 45$ dB (outdoors: night) $L_{eq} \leq 30$ dB (bedroom) $L_{max} \leq 45$ dB (bedroom)	Recommended guideline values (Task Force consensus)
U.S. Interagency Committee (FICON)	$L_{dn} \leq 65$ dB	Considered generally compatible with residential development
	$65 \leq L_{dn} \leq 70$ dB	Residential use discouraged
Various European road traffic regulations	$L_{eq} \geq 65$ or 70 dB (day)	Remedial measures required

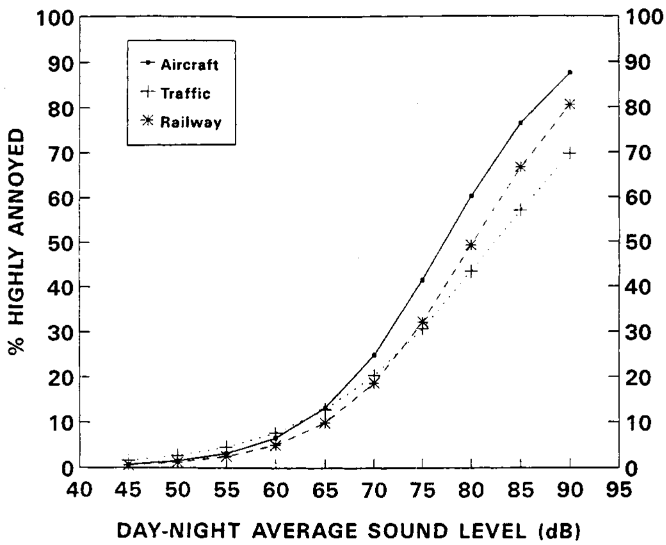

FIGURE 20.7.4 Percentage of survey respondents highly annoyed vs. day-night equivalent sound level for aircraft, road traffic, and railway noise.

Social surveys in several countries have been used to relate the percentage of respondents highly annoyed by noise to the day-night equivalent sound level, L_{dn} (Crocker, 1997d; Gottlob, 1995). See Figure 20.7.4. (Finegold et al., 1994). It is seen that many studies have shown that aircraft noise appears to be more annoying than other sources, perhaps because of the larger fluctuation in levels with time compared with the other sources. However, some other studies suggest that railroad noise is less annoying than traffic noise and this is borne out by the lower levels used for railroad noise than traffic noise regulations in several European countries (Gottlob, 1995).

Various investigations have shown that noise disturbs sleep (Crocker, 1997d). It is well known that there are several stages of sleep and that people progress through these stages as they sleep. Noise can change the progress through these stages and if sufficiently intense can awaken the sleeper. Recently, sleep disturbance data from several analyses have been reanalyzed and the preliminary sleep disturbance curve given in Figure 20.7.5 has been proposed. A regression fit to these sleep disturbance data (Finegold et al., 1994) gave the following expression (which is also shown graphically in Figure 20.7.5) (Crocker, 1997d; Finegold et al., 1994):

$$\% \text{ Awakenings} = 7.1 \times 10^{-6} L_{AE}^{3.5}$$

where L_{AE} is the indoor A-weighted sound exposure level ASEL.

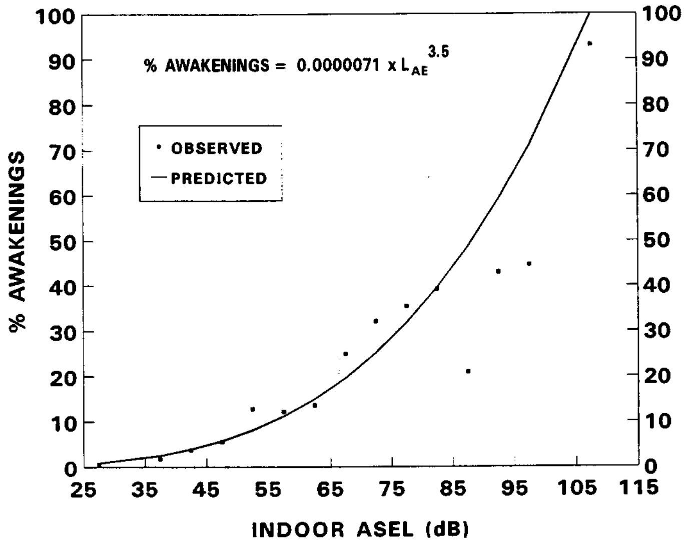

FIGURE 20.7.5 Proposed sleep disturbance curve: percentage of subjects awakened as a function of indoor sound exposure level.

Noise Control Approaches

The main noise control approaches include use of sound absorption, enclosures, barriers, and vibration isolation and damping (Crocker, 1997c). Most porous materials absorb sound and those materials specially made for this purpose include materials such as porous foams and fiberglass. However, ordinary materials such as carpets and drapes are also effective and can be used in building spaces to reduce reverberant sound buildup and noise. Although all these materials are rather ineffective at low frequency, at frequencies above 500 to 1000 Hz they can absorb almost all of the sound energy incident on them and in this case are said to have an absorption coefficient α of one. In industry they are used inside machine enclosures or placed on the walls and inside ceilings of manufacturing buildings to reduce the reverberant noise buildup (Crocker, 1997c).

Enclosures can be used to partially or completely enclose machines (machine enclosures) or to enclose operators of machines (personnel enclosures). The first approach may be regarded as *path* control and the second as *receiver* control. The improvement in noise reduction that these enclosures can achieve is related not only to the so-called transmission loss TL of the enclosure material used, TL = 10 log mf – 34 dB, where m is the mass/unit area of the enclosure walls in kg/m^2 and f is the frequency in Hz, but also to the absorption coefficient α by 10 log($1/\alpha$). Thus, enclosures that have massive walls and absorbing material inside are the most effective at reducing noise both as machine enclosures or personnel enclosures. The enclosures should be well sealed to prevent sound being transmitted through leaks. If it is necessary to have a vent or hole in the enclosure for ventilation or for access, then the vent should be lined with sound-absorbing material and be bent or constructed like a labyrinth to try to reduce the direct transmission of noise through the vent or hole. As the relationship for TL indicates, enclosures are generally more effective at high frequency (Crocker, 1997c).

Barriers are used to shield personnel from sound sources. The effectiveness of a barrier depends not only on the effective height of the barrier in wavelengths, but also how far the receiver point is into the sound shadow. Barriers are thus most effective when they are taller (in wavelengths) and thus best for high-frequency noise and also best when placed close to the source or close to the receiver, since such placement increases the shadowing effect. Barriers are used in industry where it is desired to shield personnel from machinery noise sources. It is important in such cases to put sound-absorbing material on the ceiling of the building just above the barrier or on walls just behind a barrier where these surfaces could allow the reflection of sound to bypass the barrier and thus severely reduce its effectiveness (Crocker, 1997c).

The vibration isolation of machine sources from their supports can be particularly useful in reducing the noise produced especially if the machine is small compared with a large flexible support or enclosure that can act as a sounding board and radiate the sound. Soft metal springs or elastomeric isolators are often used as isolators. They should be designed so that the natural frequency of the machine mass on its isolators is much less than the forcing frequency, if possible. Care should be taken that such a design condition does not produce excessive static deflection of the system that could interfere with the proper machine operation. Vibrating pipes and ducts can also be vibration-isolated from walls of buildings using pipe hangers or soft rubber isolators. Vibration breaks made of rubber or similar soft material can be built into elements such as walls in buildings or structural elements in vehicles or machine enclosures to prevent vibration being propagated throughout the building or other structure and being reradiated as noise (Crocker, 1997c).

Damping materials can also be effective at reducing noise when applied properly to structures if their vibration is resonant in nature. Damping materials that are viscous, applied with thicknesses two or three times that of the vibrating metal panel, are particularly effective. Constrained damping layers can be very effective even when the damping layer is relatively thin (Crocker, 1997c).

Figure 20.7.6 shows the reduction in the A-weighted sound level that can be expected using these passive noise control approaches discussed above. Often it is insufficient to use one approach, and greater, more-economic noise reduction can be achieved by using two or more approaches in conjunction.

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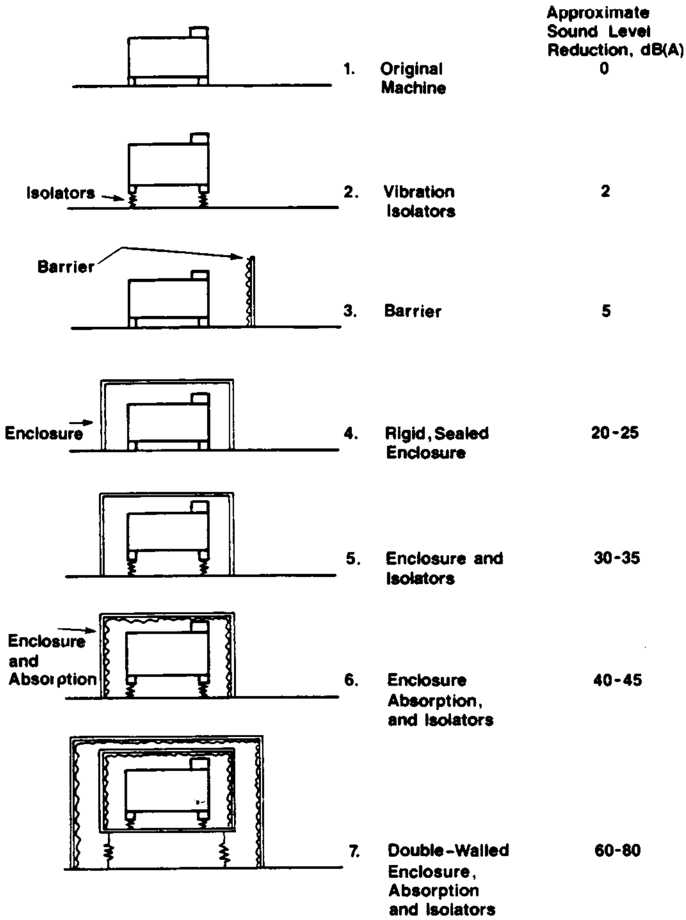

FIGURE 20.7.6 Approximate A-weighted sound level reductions expected from different noise control approaches.

20.8 Lighting Technology*

Barbara Atkinson, Andrea Denver, James E. McMahon, Leslie Shown, Robert Clear, and Craig B. Smith

In this section, we describe the general categories of lamps, ballasts, and fixtures in use today. In addition, we briefly discuss several techniques for improving the energy-efficiency of lighting systems.

Because the purpose of a lamp is to produce light, and not just radiated power, there is no direct measure of lamp efficiency. Instead, a lamp is rated in terms of its **efficacy**, which is the ratio of the amount of light emitted (lumens) to the power (watts) drawn by the lamp. The unit used to express lamp efficacy is lumens per watt (LPW). The theoretical limit of efficacy is 683 LPW and would be produced by an ideal light source emitting monochromatic radiation with a wavelength of 555 nm. The lamps that are currently on the market produce from a few percent to almost 25% of the maximum possible efficacy.** The efficacies of various light sources are depicted in Figure 20.8.1. Lamps also differ in terms of their cost; size; color; lifetime; optical controllability; dimmability; **lumen maintenance*****; reliability; simplicity and convenience in use, maintenance, and disposal; and environmental effects (e.g., emission of noise, radio interference, and ultraviolet (UV) light).

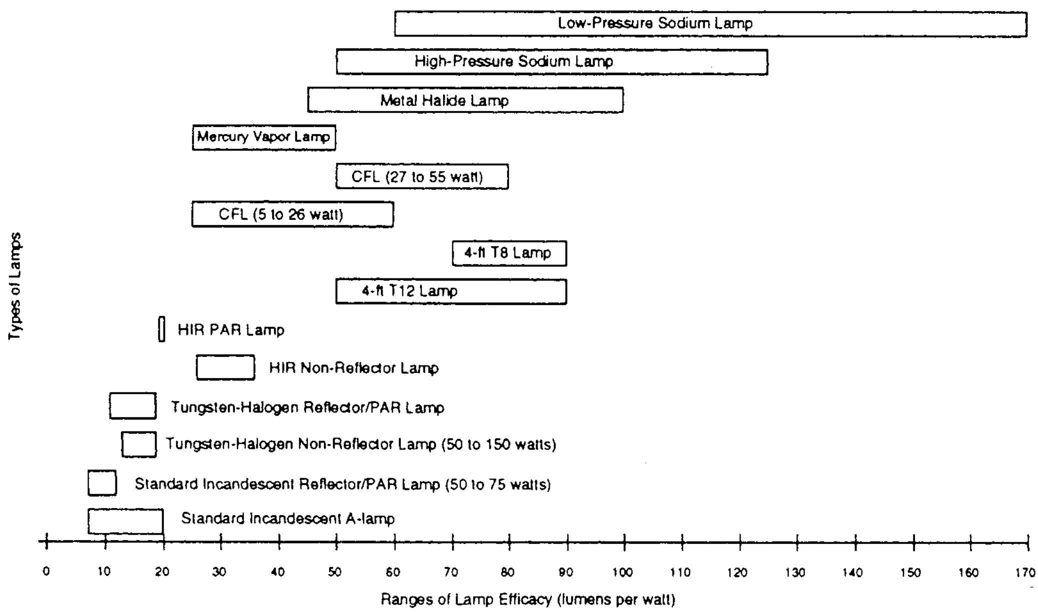

FIGURE 20.8.1 Ranges of lamp efficacy. (Ballast losses are included for all discharge lamps.) (Compiled from U.S. DOE, 1993a; Morse, personal communication, 1994; and manufacturer's catalogs.)

* The contents of this section have been abstracted from Chapers 10 (Electrical Energy Management in Buildings by Craig B. Smith) and 12B (Energy Efficient Lighting Technologies and Their Applications in the Commercial and Residential Sectors by Barbara Atkinson, Andrea Denver, James E. McMahon, Leslie Shown, and Robert Clear) published in the CRC *Handbook of Energy Efficiency*, Frank Kreith and Ronald E. West, Eds., 1997.

** The efficacies of fluorescent lamp/ballast combinations reported in this section are based on data compiled by Oliver Morse from tests by the National Electrical Manufacturer's Association; all comparisons assume SP41 lamps. Efficacies of incandescent lamps are based on manufacturer catalogs. Efficacies of high-intensity discharge lamps are based on manufacturer catalogs and an assumed ballast factor of 0.95.

*** Over time, most lamps continue to draw the same amount of power but produce fewer lumens. The lumen maintenance of a lamp refers to the extent to which the lamp sustains its lumen output, and therefore efficacy, over time.

The color properties of a lamp are described by its color temperature and its color rendering index. **Color temperature**, expressed in degrees Kelvin (K), is a measure of the color appearance of the light of a lamp. The concept of color temperature is based on the fact that the emitted radiation spectrum of a blackbody radiator depends on temperature alone. The color temperature of a lamp is the temperature at which an ideal blackbody radiator would emit light that is closest in color to the light of the lamp. Lamps with low color temperatures (3000 K and below) emit "warm" white light that appears yellowish or reddish in color. Incandescent and warm-white fluorescent lamps have a low color temperature. Lamps with high color temperatures (3500 K and above) emit "cool" white light that appears bluish in color. Cool-white fluorescent lamps have a high color temperature.

The **color rendering index (CRI)** of a lamp is a measure of how surface colors appear when illuminated by the lamp compared to how they appear when illuminated by a reference source of the same color temperature. For color temperatures above 5000 K, the reference source is a standard daylight condition of the same color temperature; below 5000 K, the reference source is a blackbody radiator. The CRI of a lamp indicates the difference in the perceived color of objects viewed under the lamp and under the reference source. There are 14 differently colored test samples, 8 of which are used in the calculation of the general CRI index.

The CRI is measured on a scale that has a maximum value of 100 and is an average of the results for the 8 colors observed. A CRI of 100 indicates that there is no difference in perceived color for any of the test objects; a lower value indicates that there are differences. CRIs of 70 and above are generally considered to be good, while CRIs of 20 and below are considered to be quite poor. Most incandescent lamps have CRIs equal to or approaching 100. Low-pressure sodium lamps have the lowest CRI of any common lighting source (–44); their light is essentially monochromatic.

The optical controllability of a lamp describes the extent to which a user can direct the light of the lamp to the area where it is desired. Optical controllability depends on the size of the light-emitting area, which determines the beam spread of the light emitted. In addition, controllability depends on the fixture in which the lamp is used. Incandescent lamps emit light from a small filament area: they are almost point sources of light, and their optical controllability is excellent. In contrast, fluorescent lamps emit light from their entire phosphored area: their light is extremely diffuse, and their controllability is poor.

Because of the many different characteristics and the variety of applications by which a lamp can be judged, no one type of source dominates the lighting market. The types of lamps that are commonly available include incandescent, fluorescent, and high-intensity discharge (HID).

Lamps

The *incandescent lamp* was invented independently by Thomas Edison in the United States and Joseph Swan in England in the late 1800s. An incandescent lamp produces light when electricity heats the lamp filament to the point of incandescence. In modern lamps the filament is made of tungsten. Because 90% or more of an incandescent's emissions are in the infrared (thermal) rather than the visible range of the electromagnetic spectrum, incandescent lamps are less efficacious than other types of lamps.

The two primary types of standard incandescent lamps are general service and reflector/PAR (parabolic aluminized reflector) lamps. General-service lamps (also known as A-lamps) are the pear-shaped, common household lamps. Reflector lamps, such as flood or spotlights, are generally used to illuminate outdoor areas or highlight indoor retail displays and artwork. They are also commonly used to improve the optical efficiency of downlights (discussed later). Downlights are used where controlling glare or hiding the light source is important.

In spite of the fact that they are the least efficacious lamps on the market today, standard incandescent lamps are used for almost all residential lighting in the U.S. and are also common in the commercial sector. They have excellent CRIs and a warm color; they are easily dimmed, inexpensive, small, lightweight, and can be used with inexpensive fixtures; and, in a properly designed fixture, they permit excellent optical control. In addition, incandescent lamps make no annoying noises and contain essentially no toxic chemicals. They are simple to install, maintain, and dispose of.

Although they account for less than 3% of the incandescent market, *tungsten-halogen* and now *tungsten-halogen infrared-reflecting (HIR) lamps* are the incandescents that offer the greatest opportunity for energy savings. Halogen lamps produce bright white light and have color temperatures and CRIs that are similar to, or slightly higher than, those of standard incandescents. In addition, they have longer lives, can be much more compact, are slightly more efficacious, and have better lumen maintenance than standard incandescent lamps.

HIR lamps have been promoted to residential- and commercial-sector customers primarily as low-wattage reflector lamps. In general, HIR lamps have a small market share due to their high cost.

Fluorescent lamps came into general use in the 1950s. In a fluorescent lamp, gaseous mercury atoms within a phosphor-coated lamp tube are excited by an electric discharge. As the mercury atoms return to their ground state, ultraviolet radiation is emitted. This UV radiation excites the phosphor coating on the lamp tube and causes it to flouresce, thus producing visible light. Fluorescent lamps are far more efficacious than incandescent lamps. The efficacy of a fluorescent lamp system depends upon the lamp length and diameter, the type of phosphor used to coat the lamp, the type of **ballast** used to drive the lamp, the number of lamps per ballast, the temperature of the lamp (which depends on the fixture and its environment), and a number of lesser factors.

Fluorescent lamps have long lives and fairly good lumen maintanance. While the standard-phosphor (cool-white (CW) and warm-white (WW)), lamps have CRIs of 50 to 60, the new rare earth phosphor lamps have CRIs of 70 to 80. The majority of lighting used in the commercial sector is fluorescent. Fluorescent lighting is also common in the industrial sector. The small amount of full-size fluorescent lighting in the residential sector is primarily found in kitchens, bathrooms, and garages. The most common fluorescent lamps are tubular and 4 ft (1.2 m) in length (see Figure 20.8.2).

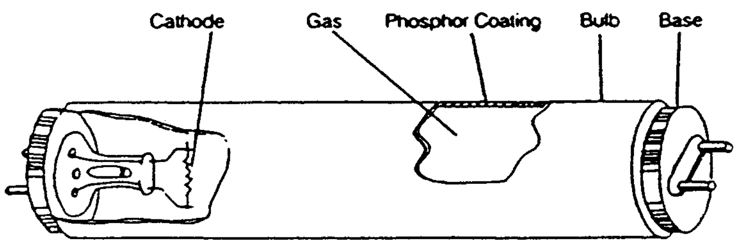

FIGURE 20.8.2 Typical full-size fluorescent lamp. (From Atkinson, B. et al., *Analysis of Federal Policy Options for Improving U.S. Lighting Energy Efficiency: Commercial and Residential Buildings*, Lawrence Berkeley National Laboratory, Berkeley, CA, 1992. With permission.)

Lamp tubes with a diameter of 1.5 in. (38 mm) are called T12s, and tubes that are 1 in. (26 mm) in diameter are called T8s. The 8 and 12 refer to the number of eights of an inch in the diameter of the lamp tube. Lamp tubes are available in other diameters as well. Four-foot T12s are available in 32, 34, and 40 W. The specified wattage of a lamp refers to the power draw of the lamp alone even if lamp operation requires a ballast, as do all fluorescent and high-intensity discharge light sources. The ballast typically adds another 10 to 20% to the power draw, thus reducing system efficacy.

Even the smallest, least efficacious fluorescent lamps (≈30 LPW for a 4-W lamp) are more efficacious than the most efficacious incandescent lamps (≈20 LPW). Of the full-size fluorescent lamps available today, *rare earth phosphor lamps* are the most efficacious. In these lamps, rare earth phosphor compounds are used to coat the inside of the fluorescent lamp tube. Rare earth phosphor lamps are also called tri-phosphor lamps because they are made with a mixture of three rare earth phosphors that produce visible light of the wavelengths to which the red, green, and blue retinal sensors of the human eye are most sensitive. These lamps have improved color rendition as well as efficacy. Fluorescent lamps with diameters of 1 in. (26 mm) and smaller use tri-phosphors almost exclusively. Rare earth coatings can also be used for lamps of larger diameter.

The most efficacious of the fluorescent lamps available today are T8 lamps operating with electronic ballasts. The efficacy of two 32-W T8 lamps operating with a single electronic ballast is about 90 LPW, approximately 30% more efficacious than the more standard lighting system consisting of two 40-W T12 lamps and a high-efficiency magnetic ballast. T12 lamps are also available with rare earth phosphors, and can attain over 80 LPW when used with a two-lamp electronic ballast. The characteristics and applications of 4-ft T8 lamps are summarized in Table 20.8.1.

TABLE 20.8.1 Characteristics and Applications of 4-ft Full-Size Fluorescent T8 Lamps

Available wattages	32 W
Efficacy	For two T8s and a single electronic ballast, ≈90 LPW
Rated lifetime	Typically 12,000 to 20,000 hr
Color rendition	Typically 75–84
Color temperature	2800–7500 K
Lumen maintenance	Very good (light output typically declines by 10 to 12% over rated lamp life)
Optical controllability	Poor (very diffuse light but slightly better than a T12)
Typical uses	The majority of lighting used in the commercial sector is fluorescent. Fluorescent lighting is also used in the industrial sector. In the residential sector, full-size fluorescent lighting is used in some kitchens, bathrooms, and garages
Technologies for which these lamps are energy-efficient alternatives	These lamps are most often replacements for less-efficient fluorescents (T12s)
Notes	Some T8 lamps are now available with CRIs above 90, especially those with high color temperature; however, these lamps are less efficacious than lamps with lower CRIs

In spite of their much greater efficiency, fluorescent lamps have several disadvantages when compared to incandescent lamps. Fluorescent lamps can be dimmed, but only with special equipment that costs much more than the dimming controls used for incandescent lamps. Standard fluorescent lamps are much bigger than incandescent lamps of equivalent output and are much harder to control optically. In addition, fluorescent lamps contain trace amounts of mercury, a toxic metal, and emit more UV light than incandescent lamps. The ballast equipment that drives the lamps is sometimes noisy and may emit radio interference.

Circular fluorescent lamps in 20- to 40-W sizes have been available for many years, but have always had a fairly small market. Essentially, a circular lamp is a standard fluorescent lamp tube (as described earlier) that has been bent into a circle. Although they have a more compact geometry than a straight tube, circular lamps are still moderately large (16.5 to 41 cm in diameter).

Compact fluorescent lamps (CFLs), which are substantially smaller than standard fluorescent lamps, were introduced to the U.S. market in the early 1980s. In a CFL, the lamp tube is smaller in diameter and is bent into two to six sections (see Figure 20.8.3). CFLs have much higher power densities per phosphor area than standard fluorescents, and their design was therefore dependent on the development of rare earth phosphors, which could hold up much better than standard phosphors at high power loadings. CFLs are available as both screw-in replacements for incandescent lamps and as pin-base lamps for hard-wired fixtures. They may be operated with separate ballasts or purchased as integral lamp/ballast units.

High-intensity discharge lamps produce light by discharging an electrical arc through a mixture of gases. In contrast to fluorescent lamps, HID lamps use a compact “arc tube” in which both temperature and pressure are very high. Compared to a fluorescent lamp, the arc tube in an HID lamp is small enough to permit compact reflector designs with good light control. Consequently, HID lamps are both compact and powerful. There are currently three common types of HID lamps available: mercury vapor (MV), metal halide (MH), and high-pressure sodium (HPS).

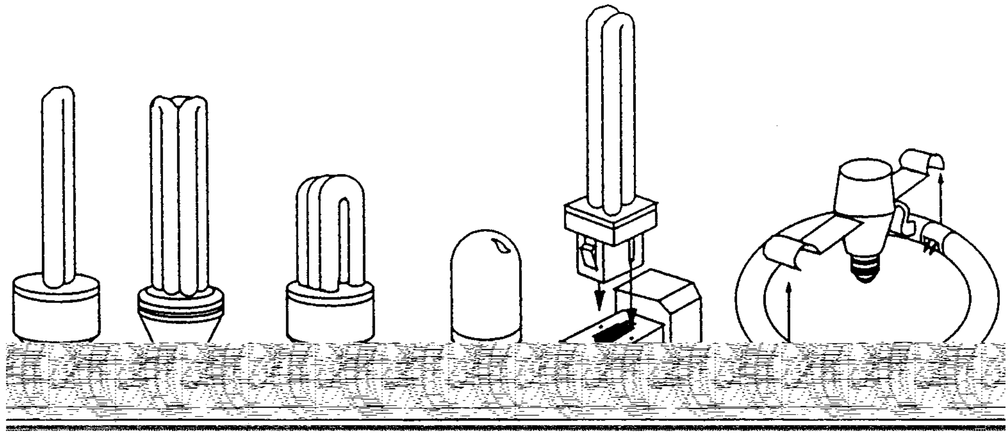

FIGURE 20.8.3 A variety of compact fluorescent and circular lamps: (a) twin-tube integral, (b and c) triple-tube integrals, (d) integral model with glare-reducing casing, (e) modular quad tube and ballast, and (f) modular circline and ballast. (Courtesy of Katherine Falk and *Home Energy* magazine, 1995.)

Because of their very high light levels, except in the smallest lamps, and their substantial cost ($15 to 80 for lamps up to 400 W), HID lamps are most often used for exterior applications such as street lighting and commercial, industrial, and residential floodlighting (sports and security lighting). They are also used in large, high-ceilinged, interior spaces such as industrial facilitites and warehouses, where good color is not typically a priority. Occasionally, HID lamps are used for indirect lighting in commercial offices. Interior residential applications are rare because of high cost, high light level, and the fact that HID lamps take several minutes to warm up to full light output. If there is a momentary power outage, the lamps must cool down before they will restrike. Some HID lamps are now available with dual arc tubes or parallel filaments. Dual arc tubes eliminate the restrike problem and a parallel filament gives instantaneous light output both initially and on restrike, but at a cost of a high initial power draw.

The *mercury vapor lamp* was the first HID lamp developed. Including ballast losses, the efficacies of MV lamps range from about 25 to 50 LPW. Uncoated lamps have a bluish tint and very poor color rendering (CRI $\approx$ 15). Phosphor-coated lamps emit more red, but are still bluish, and have a CRI of about 50. Because of their poor color rendition, these lamps are only used where good color is not a priority. Although MV lamps generally have rated lifetimes in excess of 24,000 hr, light output can diminish significantly after only 12,000 hr (Audin et al., 1994). Both metal halide and high-pressure sodium HIDD lamps have higher efficacies than mercury vapor lamps and have consequently replaced them in most markets.

Including ballast losses, *metal halide lamps* range in efficacy from 46 to 100 LPW. They produce a white to slightly bluish-white light and have CRIs ranging from 65 to 70. Lamp lifetimes range from only 3500 to 20,000 hr, depending on the type of MH lamp. Lower-wattage metal halides (particularly the 70-W and 100-W) are now available with CRIs of 65 to 75 and color temperatures of 3200 to 4200 K. Good lumen maintenance, longer life, reduced maintenance costs, and the fact that they blend more naturally with fluorescent sources have made MH lamps a very good replacement in the commercial sector for 300-W and 500-W PAR lamps. New fixtures utilizing these lamps, particularly 1-ft by 1-ft recessed lensed troffers (downlights), are becoming common in lobbies, shopping malls, and retail stores.

Including ballast losses, *high-pressure sodium lamps* have efficacies ranging from 50 LPW for the smallest lamps to 124 LPW for the largest lamps. Standard HPS lamps emit a yellow light and have very poor color rendition. Like MV lamps, HPS lamps are only used where good color is not a priority. The rated lifetimes of HPS lamps rival those of MV lamps and typically exceed 24,000 hr.

Ballasts

Because both fluorescent and HID lamps (discharge lamps) have a low resistance to the flow of electric current once the discharge arc is struck, they require some type of device to limit current flow. A lamp ballast is an electrical device used to control the current provided to the lamp. In most discharge lamps, a ballast also provides the high voltage necessary to start the lamp. Older “preheat” fluorescent lamps require a separate starter, but these lamps are becoming increasingly uncommon. In many HID ballasts, the ignitor used for starting the lamp is a replaceable module.

The most common types of ballasts are magnetic core-coil and electronic high-frequency ballasts. A *magnetic core-coil ballast* uses a transformer with a magnetic core coiled in copper or aluminum wire to control the current provided to a lamp. Magnetic ballasts operate at an input frequency of 60 Hz and operate lamps at the same 60 Hz. An *electronic high-frequency ballast* uses electronic circuitry rather than magnetic components to control current. Electronic ballasts use standard 60 Hz power but operate lamps at a much higher frequency (20,000 to 60,000 Hz). Both magnetic and electronic ballasts are available for most fluorescent lamp types.

Of the ballasts that are currently available for fluorescent lamps, the most efficient options are the electronic ballast and the cathode cutout ballast. Because an electronic ballast is more efficient than a standard core-coil magnetic ballast in transforming the input power to lamp requirements, and because fluorescent lamps are more efficient when operated at frequencies of 20,000 Hz or more, a lamp/ballast system using an electronic rather than magnetic ballast is more efficacious. Where there are two lamps per ballast, electronic ballast systems are approximately 20% more efficacious than magnetic ballast systems; where there is only one lamp per ballast, electronic ballast systems are almost 40% more efficacious than magnetic ballast systems.

In addition, electronic ballasts eliminate flicker, weigh less than magnetic ballasts, and operate more quietly. Since electronic ballasts are packaged in “cans” that are the same size as magnetic ballasts, they can be placed in fixtures designed to be used with magnetic ballasts. Electronic ballasts are widely available, but their use is limited because of their high cost and some technological limitations for certain applications. Fluorescent electronic ballasts are available for standard commercial-sector applications.

The *cathode cut-out (hybrid) ballast* is a modified magnetic ballast. It uses an electronic circuit to remove the filament power after the discharge has been initiated for rapid-start lamps. Cathode cut-out ballasts use approximately 5 to 10% less energy than energy-efficient magnetic ballasts. Almost all ballasts used for HID lamps are magnetic, and a number of different types are available. The various types differ primarily in how well they tolerate voltage swings and, in the case of HPS lamps, the increased voltage required to operate the lamp as it ages.

Lighting Fixtures

A lighting fixture is a housing for securing lamp(s) and ballast(s) and for controlling light distribution to a specific area. The function of the fixture is to distribute light to the desired area without causing glare or discomfort. The distribution of light is determined by the geometric design of the fixture as well as the material of which the reflector and/or lens is made. The more efficient a fixture is, the more light it emits from the lamp(s) within it. Although a lighting fixture is sometimes referred to as a luminaire, the term *luminaire* is most commonly used to refer to a complete lighting system including a lamp, ballast, and fixture.

Types of fluorescent lighting fixtures that are commonly used in the nonresidential sectors include recessed troffers, pendant-mounted indirect fixtures and indirect/direct fixtures, and surface-mounted commercial fixtures such as wraparound, strip, and industrial fixtures.

Most offices are equipped with *recessed troffers*, which are direct (downward) fixtures and emphasize horizontal surfaces. Many forms of optical control are possible with recessed luminaires. In the past, prismatic lenses were the preferred optical control because they offer high luminaire efficiency and uniform illuminance in the work space. Electronic offices have become increasingly common, however, and the traditional direct lighting fixtures designed for typing and other horizontal tasks have become less useful because they tend to cause reflections on video display terminal (VDT) screens.

No lighting system reduces glare entirely, but some fixtures and/or components can reduce the amount of glare significantly. Because the glossy, vertical VDT screen can potentially reflect bright spots on the ceiling, and because VDT work is usually done with the head up, existing fixtures are sometimes replaced with indirect or direct/indirect fixtures, which produce light that is considered more visually comfortable. Most indirect lighting systems are suspended from the ceiling. They direct light toward the ceiling where the light is then reflected downward to provide a calm, diffuse light. Some people describe the indirect lighting as similar to the light on an overcast day, with no shadows or highlights. Generally, indirect lighting does not cause bright reflections on VDT screens. A *direct/indirect fixture* is suspended from the ceiling and provides direct light as well as indirect. These fixtures combine the high efficiency of direct lighting systems with the uniformity of light and lack of glare produced by indirect lighting systems.

A *wraparound fixture* has a prismatic lens that wraps around the bottom and sides of the lamp, and is always surface mounted rather than recessed. Wraparound fixtures are less expensive than other commercial fixtures and are typically used in areas where lighting control and distribution are not a priority. *Strip and industrial fixtures* are even less expensive and are typically used in places where light distribution is less important, such as large open areas (grocery stores, for example) and hallways. These are open fixtures in which the lamp is not hidden from view. The most common incandescent fixture in the nonresidential sector is the *downlight*, also known as a recessed can fixture. Fixtures designed for CFLs are available to replace downlight fixtures in areas where lighting control is less critical.

Lighting Efficiency*

There are seven techniques for improving the efficiency of lighting systems:

- Delamping
- Relamping
- Improved controls
- More efficient lamps and devices
- Task-oriented lighting
- Increased use of daylight
- Room color changes, lamp maintenance

The first two techniques and possibly the third are low in cost and may be considered operational changes. The last four items generally involve retrofit or new designs.

The first step in reviewing lighting electricity use is to perform a lighting survey. An inexpensive hand-held light meter can be used as a first approximation; however, distinction must be made between raw intensities (lux or footcandles) recorded in this way and *equivalent sphere illumination* (ESI) values.

Many variables can affect the "correct" lighting values for a particular task: task complexity, age of employee, glare, and so on. For reliable results, consult a lighting specialist or refer to the literature and publications of the Illuminating Engineering Society.

The lighting survey indicates those areas of the building where lighting is potentially inadequate or excessive. Deviations from adequate illumination levels can occur for several reasons: overdesign, building changes, change of occupancy, modified layout of equipment or personnel, more efficient lamps,

* It should be noted that the "Lighting Efficiency" discussion was written by a different author than the earlier material in the chapter, and that there are some discrepancies between the lamp efficacy ranges reported in the two sections. These discrepancies are likely the result of the different data sources used to calculate efficacy ranges, the different time periods during which they were calculated, and different assumptions regarding which lamp types are most typical.

improper use of equipment, dirt buildup, and so on. Once the building manager has identified areas with potentially excessive illumination levels, he or she can apply one or more of the seven techniques listed earlier. Each of these will be described briefly.

Delamping refers to the removal of lamps to reduce illumination to acceptable levels. With incandescent lamps, bulbs are removed. With fluorescent or HID lamps, ballasts account for 10 to 20% of total energy use and should be disconnected after lamps are removed.

Fluorescent lamps often are installed in luminaires in groups of two or more lamps where it is impossible to remove only one lamp. In such cases an artificial load (called a "phantom tube") can be installed in place of the lamp that has been removed.

Relamping refers to the replacement of existing lamps by lamps of lower wattage or increased efficiency. Low-wattage fluorescent tubes are available that require 15 to 20% less wattage (but produce 10 to 15% less light). In some types of HID lamps, a more efficient lamp can be substituted directly. However, in most cases, ballasts must also be changed. Table 20.8.2 shows typical savings by relamping.

TABLE 20.8.2 Typical Relamping Opportunities

Change Office Lamps (2700 hr per year)		Energy Savings/Cost Savings		
		kWh	GJe	5¢ kWh
From	To	To save annually		
1 300-W incandescent	1 100-W mercury vapor	486	5.25	$24.30
2 100-W incandescent	1 40-W fluorescent	400	4.32	20.00
7 150-W incandescent	1 150-W sodium vapor	2360	25.5	$118.00
Change industrial lamps (3000 hr per year)				
1 300-W incandescent	2 40-W fluorescent	623	6.73	$31.15
1 100-W incandescent	2 215-W fluorescent	1617	17.5	80.85
3 300-W incandescent	1 250-W sodium vapor	1806	19.5	90.30
Change store lamps (3300 hr per year)				
1 300-W incandescent	2 40-W fluorescent	685	7.40	$34.25
1 200-W incandescent	1 100-W mercury vapor	264	2.85	13.20
2 200-W incandescent	1 175-W mercury vapor	670	7.24	33.50

Improved controls permit lamps to be used only when and where needed. For example, certain office buildings have all lights for one floor on a single contactor. These lamps will be switched on at 6 A.M., before work begins, and are not turned off until 10 P.M., when maintenance personnel finish their cleanup duties. Energy usage can be cut by as much as 50% by installing individual switches for each office or work area, installing time clocks, installing occupancy sensors, using photocell controls, or instructing custodial crews to turn lights on as needed and turn them off when work is complete.

There is a great variation in the efficacy (a measure of light output per electricity input) of various lamps. Since incandescent lamps have the lowest efficacy, typically 8 to 20 LPW, wherever possible, fluorescent lamps should be substituted. This not only saves energy but also offers economic savings, since fluorescent lamps last 10 to 50 times longer. Fluorescent lamps have efficacies in the range of 30 to 90 LPW.

Compact fluorescent lamps are available as substitutes for a wide range of incandescent lamps. They range in wattage from 5 to 25 W with efficacies of 26 to 58 lm/W and will replace 25- to 100-W incandescent lamps. In addition to the energy savings, they have a 10,000-hr rated life and do not need to be replaced as often as incandescent lamps. Exit lights are good candidates for compact fluorescent lamps. Conversion kits are available to replace the incandescent lamps. Payback is rapid because of the lower energy use and lower maintenance cost, since these lamps are normally on 24 hr a day. There are also light-emitting diode exit lights that are very energy efficient.

Still greater improvements are possible with HID lamps such as mercury vapor, metal halide, and high-pressure sodium lamps. Although they are generally not suited to residential use high light output and high capital cost) they are increasingly used in commercial buildings. They have efficacies in the range of 25 to 124 LPW.

Improved ballasts are another way of saving lighting energy. A comparison of the conventional magnetic ballast with improved ballasts shows the difference:

Type Lamp	2 Lamp 40 W	F40 T-12 CW	2 Lamp 32 W	F32 T-8
Ballast type	Standard magnetic	Energy-efficient magnetic	Electronic	Electronic
Input watts	96	88	73	64
Efficacy	60 lm/W	65 lm/W	78 lm/W	90 lm/W

The best performance comes from electronic ballasts, which operate at higher frequency. In addition to the lighting energy savings, there are additional savings from the reduced air-conditioning load due to less heat output from the ballasts. The environmental benefit for the electronic ballast described earlier, as estimated by the U.S. Environmental Protection Agency, is a reduction in CO_2 production of 150 lb/year, a reduction of 0.65 lb/year of SO_2, and a reduction of 0.4 lb/year of NO_x.

In certain types of buildings and operations, daylighting can be utilized to reduce (if not replace) electric lighting. Techniques include windows, an atrium, skylights, and so on. There are obvious limitations such as those imposed by the need for privacy, 24-hr operation, and building core locations with no access to natural light. Also, the use of light colors can substantially enhance illumination without modifying existing lamps.

An effective lamp maintenance program can also have important benefits. Light output gradually decreases over lamp lifetime. This should be considered in the initial design and when deciding on lamp replacement. Dirt can substantially reduce light output; simply cleaning lamps and luminaries more frequently can gain up to 5 to 10% greater illumination, permitting some lamps to be removed.

Reflectors are available to insert in fluorescent lamp fixtures. These direct and focus the light onto the work area, yielding a greater degree of illumination. Alternatively, in multiple lamp fixtures, one lamp can be removed and the reflector keeps the level of illumination at about 75% of the previous value.

Defining Terms

Ballast: A lamp ballast is an electrical device used to control the current provided to the lamp. In most discharge lamps, a ballast also provides the high voltage necessary to start the lamp.

Color Rendering Index (CRI): A measure of how surface colors appear when illuminated by a lamp compared to how they appear when illuminated by a reference source of the same color temperature. For color temperature above 5000 K, the reference source is a standard daylight condition of the same color temperature; below 5000 K, the reference source is a blackbody radiator.

Color temperature: The color of a lamp's light is described by its color temperature, expressed in degrees Kelvin (K). The concept of color temperature is based on the fact that the emitted radiation spectrum of a blackbody radiator depends on temperature alone. The color temperature of a lamp is the temperature at which an ideal blackbody radiator would emit light that is the same color as the light of the lamp.

Efficacy: The ratio of the amount of light emitted (lumens) to the power (watts) drawn by a lamp. The unit used to express lamp efficacy is lumens per watt (LPW).

Lumen maintenance: Refers to the extent to which a lamp sustains its lumen output, and therefore efficacy, over time.

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Further Information

For additional information on performance characteristics of lamps, ballasts, lighting fixtures, and controls, the reader is referred to the CRC *Handbook of Energy Efficiency* from which this section has been extracted. If interested in more discussions of energy-efficient lighting design strategies and technologies, consult the references and request information from the Green Lights program: Green Lights U.S. EPA, Air and Radiation (6202-J), Washington, D.C., 20460.