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the cover

No electrical power is required to switch on this novel source of illumination, yet it hardly competes with the energy-conserving light sources, fixtures, and techniques described beginning on page 28.

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Let there be light, but just enough

The end of cheap energy gave the lighting industry a corporate headache and the user more lumens per watt

On December 13, 1973, the Federal Energy Office (FEO)—now the Federal Energy Administration (FEA)—issued a fact sheet on national energy conservation that called for the reduction of lighting in all commercial and industrial buildings, including retail establishments, factories, and offices. The nonmandatory guidelines specified lighting levels of 50 footcandles at workstations, 30 footcandles for general work and sales areas, and 10 to 15 footcandles in hallways and corridors.

For the lighting industry, December 13th might just as well have been Pearl Harbor Day. Before the public became so painfully aware of the energy crunch in those oil-short days during the winter of '73, illumination levels in commercial and industrial areas sometimes exceeded 100 footcandles. Consequently, the effects of the 50–30–10 recommendations on the lighting industry were considerable—particularly in the area of incandescent and fluorescent light sources.

Influenced by the Government recommendations, owners and tenants of both public and private buildings reduced the lighting electrical load by removing two fluorescent tubes from four-tube luminaires—often ignoring the fact that small amounts of current were still consumed by the ballast. And, although the oil and gasoline crisis was alleviated temporarily in early '74, the rapidly rising cost of electricity, combined with inflation, continue to slow the growth of the lighting industry.

U.S. Census figures, for example, indicate a reduction in 1974 in the shipment of incandescent and fluorescent light sources. Fluorescent lamp sales dropped about 8 percent and incandescent sales about 5 percent because of reduced usage in both the replacement and new construction markets.

None of these statistics, however, can be interpreted as signaling a return to candlelight—the proponents of "low technology" notwithstanding. Candlelight is outlandishly expensive. In cost per million lumen hours, the lighting value of a 400-watt high-pressure sodium lamp is 31 cents; a 100-watt incandescent source, \$2.26; and a common candle, \$3000.

And, even though the 50–30–10 concept of illumination levels has been incorporated into the FEA "Lighting and thermal operations guidelines," other Government agencies have advocated a watts-per-

Charles W. Beardsley
Lighting Design & Application

I. Characteristics of basic lamp types

Characteristics	Incandescent (Including Tungsten Halogen)	Fluorescent	High-Intensity Discharge (HID): Mercury—Vapor	High-Intensity Discharge (HID): Metal—Halide	High-Intensity Discharge (HID): High-Pressure Sodium
Wattages (lamp only)	15 to 1500	40 to 219	40 to 1000	400, 1000, 1500	75, 150, 250, 400, 1000
Life (hours)	750 to 12 000	9000 to 30 000	16 000 to 24 000	1500 to 15 000	10 000 to 20 000
Efficacy (lumens per watt, lamp only)	15 to 25	55 to 88	20 to 63	80 to 100	100 to 130
Color rendition	Very good to excellent	Good to excellent	Poor to very good	Good to very good	Fair
Light direction control	Very good to excellent	Fair	Very good	Very good	Very good
Source size	Compact	Extended	Compact	Compact	Compact
Relight time	Immediate	Immediate	3 to 5 minutes	10 to 20 minutes	Less than 1 minute
Comparative fixture cost	Low because of simple fixtures	Moderate	Higher than incandescent, generally higher than fluorescent	Generally higher than mercury—vapor	Highest
Comparative operating cost	High because of relatively short life and low efficacy	Lower than incandescent; replacement costs higher than HID because of greater number of lamps needed; energy costs generally lower than mercury—vapor	Lower than incandescent; replacement costs relatively low because of relatively few fixtures and long lamp life	Generally lower than mercury—vapor; fewer fixtures required, but lamp life is shorter and lumen maintenance not quite as good	Generally lowest; fewest fixtures required

spectral lines

In the swim, or on the beach?

In recent years, as never before in history, whole platoons of engineers and scientists have together "ridden the waves" of expanding electrotechnology. The experience has been exciting and rewarding. Their careers (and, for the most part, their salaries) have crested with the waves. But many are finding themselves in the troughs, or even worse, on the beach. What is the reason, and what can be done?

For one thing, young technologists fresh from school are seen by some companies as the "wave of the future." Still others argue that younger engineers are "better and cheaper," and that the pace of technology makes it virtually impossible for the middle-aged engineer to keep technologically up to date.

The result is that layoff threats are particularly ominous to the older engineer. Once "on the beach," his confidence is understandably shaken and his deflated self-image may even communicate itself to potential employers who look at his salary and experience in the context of just another exercise in cost–benefit analysis. Worse, some employers are simply biased against the older applicant and this bias is abetted by recruitment ads that, consciously or otherwise, tend to rule him out. The IEEE opposes such bias. The IEEE Ethics and Employment Practices Committee urges recruiters to avoid introducing any such bias. *Spectrum* returns biased ads for revision. And the IEEE Board of Directors, at its September meeting, endorsed a "position on age discrimination" (see p. xx). In part, it states that engineers who continue to grow in their ability to solve society's problems should have the opportunity to exploit that expertise with age. It further observes that "some industries in a rapidly changing environment are prone to display bias against older engineers." The Institute exhorts industry, government, and educational institutions to examine their practices to assure that such biases do not exist with regard to their own endeavors.

Looking to the future, it is conceivable that legislation designed to avoid age bias will be strengthened and made even more explicit. Some managers, as well as some engineers, see dangers in such a course, believing that while it may be necessary and beneficial for low-skilled workers, it may quell the initiative required of professionals to keep skills current.

Surely the problem of engineer obsolescence caused by rampant technology will get worse, not better. In our judgment the long-term solution lies in finding satisfactory ways to keep technologists productive for a lifetime career. The present methods are clearly unsatisfactory, or, at best, limited in application.

There are many factors that contribute to these limitations. We have noted previously in these columns that motivation is all important. For example, studies confirm that individual engineers, despite what they may *want* to do in the area of continuing education, instead do those things for which they will be duly rewarded by their companies. We further question the types of continuing education offered to mid-career engineers. We grant that in some instances an older engineer might gain through the detailed study of some basic new technology. Yet would it not make sense for such an engineer to study new techniques and technologies at the "black box," or systems level? Does he not have a wealth of ability ranging over broad areas that stems from his experience alone? Even though most or all of his career might have been spent in one industry, or even in one specialty, he simply cannot have escaped exposure to interdisciplinary problems, systems interfacing tasks, human factors and management problems—to name but a few of the areas that can be learned well only in practice.

We think it makes good sense to reinforce these skills with a knowledge of new tools and techniques—but *not* necessarily at the "nitty gritty" level at which a young Ph.D. might be involved. We believe that managements can benefit from pairing the seasoned practitioner who is sensitive to systems problems, tradeoffs, shortcuts, and the like, with the younger engineer who is prepared to dig deeply into a specialized problem. In partial support of this theory, the observation was made at a recent Engineers Joint Council meeting on productivity through engineering[1] that keeping engineering teams intact over a period of years is often a key factor to high productivity of a high-technology manufacturing organization.

The design of appropriate continuing education programs for engineers, it seems to us, can be the only real deterrent to engineering obsolescence. The related problems of obsolescence and age discrimination can be alleviated but surely not cured by legislation. The engineer himself cannot solve them. The task, with emphasis on the core problem of education, must be a cooperative effort of industry, educators, and professional societies. Perhaps IEEE itself can assume a leadership role.

Donald Christiansen, Editor

1. Conference on Productivity Through Engineering—II, New York, N.Y., October 29–30, 1975. Sponsored by the National Commission on Productivity and Work Quality and the Engineers Joint Council.

square-foot or a BTUs-per-square-foot approach to the electrical design of new buildings.

Most significant, however, is the emphasis on energy-efficient lighting—more lumens per watt. The lumen, the international unit of luminous flux, is used to specify the light output of lamps. Lumens per watt, therefore, are an indication of the light output per quantity of electrical input for various sources of white light. Incandescent and self-ballasted mercury lamps, for example, have relatively low efficacies (Table I, Fig. 1). Fluorescent lamps do much better, with the efficacy of sodium and metal–halide being even better.

High-intensity discharge (HID) sources are especially popular because of their efficiency and long life, which minimizes relamping costs. These advantages are reflected in market statistics: high-intensity discharge lamp sales rose about 18 percent in 1974, and it is expected that this trend will continue.

Of course, high-efficacy, more expensive sources have been available for years. In fact, there has been no significant increase in lumens per watt since the energy crisis, only greater promotion of these lamps, which may now prove more economical because of the higher cost of energy.

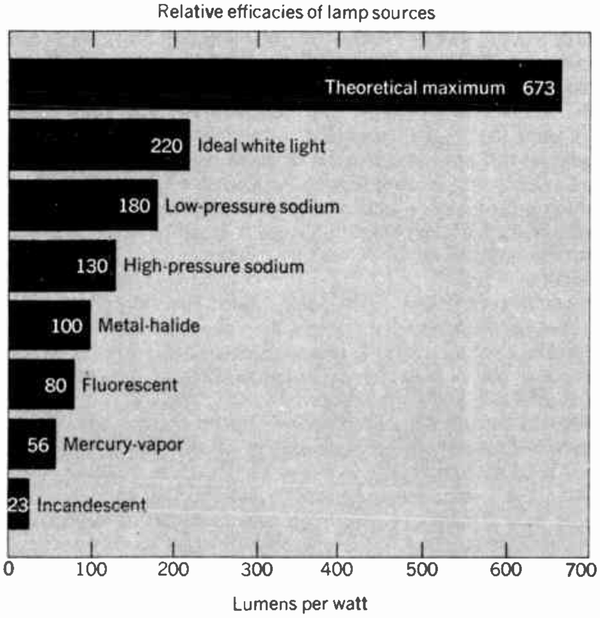
Legislating lighting

But there's more to the energy story than source selection. Before this article explores such factors as luminaires, visual tasks, controls, and other aspects of energy management, it's important to note that economics and energy aren't the sole factors influencing the electrical design of new buildings. The influence of U.S. regulatory agencies and professional organizations presently involved in energy legislation must also be considered.

The U.S. General Services Administration (GSA),

(Continued on page 31.)

[1] The wide variety of lamps available today have different characteristics that must be considered—color, life, and physical size are a few. Of increased importance in an era of expensive electrical energy, however, is the efficacy of lamps, stated as lumen output per watt of input. This ranges from 23 lumens per watt to over 180 lumens per watt.



Light sources: a primer

Incandescent. The efficacy of light production by incandescent filament lamps depends on the temperature of the filament—the higher the temperature, the greater the portion of radiated energy that falls in the visible region. And, although early incandescent lamps used carbon, osmium, and tantalum filaments, tungsten's high melting point (3655°K) and low vapor pressure permit higher operating temperatures and, as a result, high efficacies. Because filament configuration is also a factor—coils increase efficacy—past improvements in incandescent lamps have involved changes in filament shape. Recent improvements, however, are primarily a result of changes in the atmosphere inside the glass bulb that encloses the filament. Although early incandescent sources were manufactured with evacuated bulbs to prevent filament burn-up, the discovery that inert gases retard evaporation of the filament made it possible to design lamps for higher filament temperatures. Today, most incandescent lamps use a fill mixture of argon and nitrogen; however, Superman's anathema, krypton, is also used, for much the same reason that it's found in reduced-wattage fluorescent sources: improved efficacy and lumen maintenance because of the reduced filament heat loss.

Tungsten–halogen lamps are a variation of incandescent filament sources. A halogen additive in the bulb reacts chemically with the tungsten, removing deposited tungsten from the bulb and redepositing it on the filament. This results in a lumen maintenance factor of close to 100 percent. (Lumen maintenance refers to the ability of a lamp to maintain a constant light output. In an ordinary tungsten filament lamp, light output is reduced by the sublimed tungsten that collects on the inner surface of the bulb.) However, such a lamp does have a definite life, usually a maximum of 3000 hours. Although important in general lighting, these characteristics of tungsten–halogen have meant significant changes for specialized applications like stage and studio lighting. The smaller size, good optical control, and high color temperatures of tungsten–halogen lamps, as well as a continuous spectrum, fit theatrical lighting needs.

The most popular incandescent lamps are general service (GS) ones, which range from the 15-watt A-15 to the 1500-watt PS-52 types and are designed for 120-, 125-, and 130-volt circuits. (The letter prefix refers to the lamp shape—for example, PS is a pear straight neck; A is the standard incandescent shape. Other common designations are G for globe and PAR for parabolic aluminized reflector. The number following the letter prefix is the bulb diameter in eighths of an inch.)

Higher-wattage GS lamps are more efficient than lower-wattage GS ones. For example, one 100-watt GS lamp produces more light than two 60-watt lamps (1750 lumens versus 2 times 860 lumens, or 1720 lumens).

For the same wattage, GS lamps (750 to 1000 hours of life) are more efficient than extended service (ES) lamps (2500 hours of life). ES lamps—for use where replacement costs are relatively high, such as hard-to-reach locations—achieve long life by use of a filament that is stronger, but less efficacious. A 100-watt GS lamp produces 17.5 lumens per watt, whereas a 100-watt ES lamp produces 14.8 lumens per watt. For equal lighting results in this instance, 18.2 percent more lamps and energy are required when using the ES lamps. But in many applications, the actual level of illumination is not of significance, and the longer socket life offers economies.

Because of its versatility, the incandescent lamp survives in spite of its poor economics and efficacy. The interchangeability of many types and ratings in the same socket, easy dimming, and a variety of shapes and kinds all contribute to the lamp's popularity.

Fluorescent. Fluorescent lamps offer three to five times the efficacy of incandescent sources and compare favorably with most HID sources. Efficacies vary with lamp length, lamp loading, and lamp phosphor coating.

This lamp uses an electric-discharge source, in which light is produced predominantly by fluorescent powders activated by ultraviolet energy generated by a mercury arc. The fluorescent lamp cannot be operated directly from the nominal 120-volt ac source because the arc discharge would not be established, and—even if it were—current would rise until the lamp was destroyed. As a result, it must be operated in series with a ballast that limits the current and provides the starting and operating lamp voltages.

Fluorescent lamps are tubular bulbs of small cross-sectional diameter. Two electrodes are hermetically sealed into the bulb, one at each end. Electrodes for glow or "cold cathode" operation operate at a current in the order of a few hundred milliamperes, with a high cathode fall-over voltage of 50 volts. The more common arc mode or "hot cathode" electrode is usually constructed from tungsten wire coated with a mixture of alkaline earth oxides. During lamp operation, the coil and coating reach temperatures of approximately 1100°C, at which the coil/coating combination thermally emits large quantities of electrons at a low cathode fall-over voltage of 10 to 12 volts. Because of the lower cathode fall-over voltage of the hot cathode fluorescent lamp, more efficient lamp operation results; consequently, most fluorescent lamps are designed for "hot" cathode operation.

Both geometric design and operating conditions of a fluorescent lamp affect the efficacy with which electrical energy is converted into visible radiation. For example, as lamp diameter increases, efficacy increases, passes through a maximum, then decreases. The length of the lamp also influences its efficacy: the longer it is, the higher the efficacy.

The starting process occurs in two stages: once a sufficient voltage exists between an electrode and ground, ionization of the gas (mercury plus an inert gas) in the lamp occurs; then, a sufficient voltage must exist across the lamp to extend the ionization throughout the lamp and to develop an arc. Three basic types of ballasts—preheat, instant start, and rapid start—provide means of starting.

Early lamps were all of the preheat variety, which required a starting switch. As the name suggests, the electrodes are heated before the application of high voltage across the lamp—usually by means of the automatic switch, which places the lamp electrodes in series across the output of the ballast. (As ambient temperature decreases, starting of all fluorescent lamps becomes more difficult.) Arc initiation in instant start lamps depends entirely on the application of a high voltage (400 to 1000 volts) across the lamp, which ejects electrons by field emission. These electrons ionize the gas and initiate arc discharge, which provides electrode heating. The rapid start principle makes use of electrodes that are heated continuously by means of low-voltage windings built into the ballast. A power-saving feature of rapid-start circuits is that the lamps show little change in rated life as a result of frequent on/off/on cycles. And, at a time when consumers are urged to turn off the lights to save energy, this feature has particular significance. In instant-start and preheat circuits, the electrodes erode during the starting and burning cycle; consequently, rated life decreases if the lamp is turned on and off with great frequency.

Although widely used in offices, schools, stores, and industry, fluorescent lamps have had limited acceptance in residential applications because of their shape and color; however, the energy crunch may change this. Because of their long life and high efficacy, fluorescent lamps in utility areas like kitchens and bathrooms can reduce wattage requirements in the home.

In addition to improvements in light output and life, progress in color rendering ranks high in fluorescent lamp developments, as evidenced by intensive research into new phosphors. Infrared phosphors, for example, are a possibility and already exist in some lamp types. Most users, though, are most concerned with the shade of white that is best for a specific environment.

As their names imply, warm- and cool-white refer to the color appearance of a fluorescent lamp—a warm shade creates a more relaxing atmosphere than a cool color, which connotes efficiency. Both are widely used in industrial and office areas, although a "deluxe" version of the same sources provides better color rendering by emitting more pink radiation.

Mercury. Mercury lamps, which were widely used in street lighting in the early 1960s and are now popular choices for lighting commercial interiors, use argon gas to ease starting because mercury has a low vapor pressure at room temperature. When the lighting circuit is energized, the starting voltage is impressed across the gap between the main electrode and the starting electrode, which creates an argon arc that causes the mercury to vaporize. The lamp warm-up process takes 5 to 7 minutes, depending on ambient-temperature conditions. Most mercury lamps are constructed with two envelopes—an inner one that contains the arc, and an outer one that shields the arc tube from outside drafts and changes in temperature. The outer envelope usually contains an inert gas that prevents oxidation of internal parts and maintains a high breakdown voltage across the outer bulb parts, as well as providing an inner surface for the coating of phosphors.

The pressure at which a mercury lamp operates accounts in part for its characteristic spectral power distribution: within the visible range, the mercury spectrum results in greenish-blue light at efficacies of 30 to 65 lumens per watt. Nevertheless, as Fig. 1 indicates, the mercury lamp is far from being an efficacious source, and it ranks between incandescent and fluorescent lamps in lumen-per-watt output. Economics favor mercury where burning hours are long, service is difficult, and replacement labor is high. However—all other factors considered equal—a fluorescent system tends to be less costly because of its higher efficacy. But this hardly rules out use of the mercury lamp, which is still very much alive and well.

Low-wattage mercury lamps, for instance, have replaced less-efficient incandescent lamps in small luminaires. There have been improvements in color rendering as well. New phosphors improve color, increase light output, and reduce surface brightness. A "warm deluxe white" mercury produces an apparent color temperature of 3300°K and can be used in indoor commercial applications in place of fluorescent lamps.

A challenge for manufacturers is improvement in light-output depreciation characteristics. Many mercury lamps lose as much as 50 percent of their initial output during their rated life of 24 000 hours or more.

Another challenge to manufacturers of mercury lamps is the health hazard resulting from eye and face burns suffered by those exposed to radiation from broken mercury lamps used in gymnasiums. The inner quartz arc tube of the lamp continues to burn for up to 100 hours, and, without the outer glass to absorb excess radiation, a dangerous level of ultraviolet rays are emitted. The U.S. Bureau of Radiological Health has asked the major lamp manufacturers to supply information about the radiation characteristics of their lamps, and it presented a report to the Technical Electronic Product Radiation Safety Standards Committee in September. Meanwhile, at least one manufacturer has developed a mercury lamp with an arc tube that extinguishes rapidly after air enters the ruptured outer bulb.

Other developments in the mercury category include a 300-watt self-ballasted lamp that incorporates solid-state starting and higher efficacy. The solid-state circuit is "potted" in the base and acts as a voltage doubler. This eliminates the need for a bimetal switch on the 120-volt lamp and provides a high degree of reliability throughout the 16 000 hours of rated life. In addition, the ratio of arc-tube watts to ballast watts is increased. These lamps can be used where high temperatures are likely to damage external ballasts and where insertion in incandescent luminaires provides an increase in illumination.

Derated mercury lamps are also available. They yield lower lumen outputs for a lesser corresponding reduction in energy consumed. For example, a 300-watt mercury lamp is available that operates on either 400-watt constant wattage or regulated output ballasts.

Metal-halide. Metal-halide lamps are similar in construction to the mercury lamp, except that the arc tube contains various metal halides in addition to mercury. When the halide vapor approaches the high-temperature, central core of the discharge, it disassociates into the halogen and the metal, with the metal radiating its appropriate spectrum. As the halogen and metal move near the cooler arc tube wall by diffusion and convection, they recombine and the cycle repeats itself. This cycle has two advantages: metals that cannot be vaporized at the temperatures that a fused silica arc can withstand can be introduced into the discharge by disassociation of the halides, which vapo-

(Continued from page 29)
for example, has issued a document called "Energy Conservation Design Guidelines for Office Buildings." It is to be used by architects and engineers in the design of Federal buildings and by the GSA in reviewing and evaluating designs. The document, which sets forth the concept of an energy budget, advocated a goal of 55 000 BTU/ft^2 per year for energy consumption in the typical office building. Although most architects and engineers regard this figure as low, it is, nevertheless, only a guide. The real disadvantage of such an approach is that most design professionals would probably not be willing to devote the additional man-hours to design for an uncertain goal. The alternative is to lower standards—and this would probably mean lower illumination levels without regard for the visual tasks to be performed.

And, on the subject of legislation, more needs to be said about the FEA guidelines—the initial draft of which created the furor of December '73. The current guidelines for lighting and thermal operations (1974 0-562-404) state that the document's objective, from a lighting standpoint, is to provide "useful assistance in the design and operation of lighting systems to minimize energy consumption." It also notes that "the expert assistance of architects and lighting engineers can provide additional guidance." Furthermore, although the guidelines have been publicized as limiting illumination to 50, 30, and 10 footcandles, the actual recommended maximums are different. One hundred footcandles are recommended for prolonged office work that is visually difficult and critical in nature. Also, for certain industrial tasks, Illuminating Engineering Society/American National Standards Institute (IES/ANSI) levels of illumination are recommended.

Nevertheless, the uninformed designer, if he must depend only on the guidelines, may offer installations with reduced energy use, but not energy efficient, economical lighting designs in the spirit of the guidelines. According to John E. Kaufman, technical director of the IES, "Designers need to have an understanding of lighting as it relates to human performance, esthetics, and economics." Mr. Kaufman lists maintenance and measurement procedures, calculation, life-cycle costing and cost–benefit analysis, brightness distribution, visual comfort probability (VCP), and equivalent

rize at much lower temperatures; and other metals that react chemically with the arc tube can be used in the form of a halogen, which does not readily react with the fused silica.

These lamps generate light with more than half the efficacy of the mercury arc, offer a small light-source size for optical control, and provide good color rendition as compared with clear mercury. They have been applied in nearly every type of interior and exterior lighting application because they offer an efficient "white" light source.

Like mercury lamps, metal-halide sources produce less light in certain burning positions than others. For example, mercury lamps may produce from 3 to 11½ percent less light when operated horizontally instead of vertically. The most extreme case is the 1500-watt metal-halide lamp, for which an angle of 70 degrees from the vertical or 20 degrees above the horizontal can produce a drop of as much as 25 percent. Part of the reason for this loss is that the arc stream in the horizontal operating lamp is bowed into an arch within the arc tube by convection currents from the hot fill gases. A newly designed arc tube, arched so that the arc stream flows through the center of the quartz tube, provides lumen gains of 10 percent (the 175-watt lamp) and 25 percent (the 400-watt lamp) over its vertical-operating counterparts.

Sodium. Low-pressure sodium (LPS) lamps have been used in public lighting for some 40 years and are seen most frequently in Europe, where they are used for roadway, lighting. Because of their distinctive monochromatic, deep yellow color, they are also used in the United States for lighting tunnels and toll plazas, as well as in industrial areas where security is more important than color rendition. HPS lamps which became available in 1965, are used in many U.S. cities for roadway and sidewalk illumination and offer more suitable color rendition characteristics. With either lamp, sodium is particularly suitable because most of its radiation is concentrated in a wavelength interval where the sensitivity of the human eye is high. It also has a relatively low excitation energy.

Light from the LPS lamp is emitted from a long, U-shaped arc tube placed inside an outer tubular glass enclosure. A vacuum surrounding the arc tube—along with a heat-reflecting coating on the other bulb—conserves heat and improves luminous efficacy. It is the most efficient commercial light source, with an efficacy of 180 lumens per watt in the largest size of 180 watts. It looks somewhat like an oversized fluorescent tube, but because of its length, does not fit into a compact luminaire as do other sources.

In both low- and high-pressure sodium sources, light is produced by electricity passing through sodium vapor. In the LPS lamp, a starting gas of neon produces a red glow when the lamp is initially ignited. As heat is generated, the sodium metal vaporizes, and the emitted light turns into the characteristic yellow color. The vapor pressure of the sodium must be in the order of 5×10^{-3} mm of mercury to achieve the maximum efficacy. This corresponds to an arc tube bulb wall temperature of about 260°C (500°F), which is why the arc tube is enclosed in a vacuum.

The HPS lamp is constructed with two envelopes—the inner being polycrystalline alumina, which is resistant to sodium attack. The arc tube contains xenon as a starting gas and a small amount of sodium–mercury amalgam. The outer borosilicate glass envelope is evacuated and protects against chemical attack of the arc tube and maintains the arc tube temperature.

HPS sources are compact, yet have high efficacies (up to 140 lumens per watt) and high lumen maintenance characteristics. They radiate energy across the visible spectrum and produce a golden-white color. They are available in sizes from 70 to 1000 watts, with the low-wattage sources finding application in residential streetlighting and shopping-mall illumination.

HPS lamps have five times the efficacy of incandescent sources, more than twice that of mercury, and 50 percent more than metal–halide—which is one of the reasons for their popularity at a time when energy is both scarce and expensive.

One manufacturer has introduced a family of HPS lamps for use in existing mercury luminaires. This lamp can increase illumination in certain installations by 70 percent and reduce energy consumption by 10 percent. A tungsten glow coil wound around the arc tube enables this lamp to operate without the usual high-voltage starting aid. When power is applied to the lamp, the tungsten coil heats the tube to the required 300°C temperature, and two bimetallic switches remove the heater from the circuit at full light output. This permits a standard 400-watt, 240-volt mercury reactor or lag-type transformer to be used with the HPS lamp.

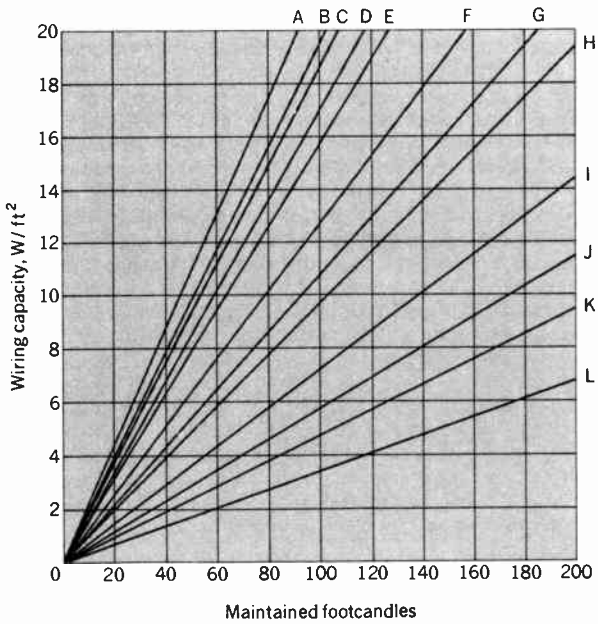
Because of its high efficacy, the HPS lamp is finding application in areas other than roadway lighting. Not only is it being specified for industrial interiors, but several manufacturers have used this HID source in office areas. "Streetlights" in offices may sound extreme, but the lamps used ranged from only 100 to 400 watts, and special lenses and reflectors were used to achieve a broad light distribution appropriate for low-ceiling applications.

sphere illumination (ESI) as some of the factors essential to such an understanding. Of such concepts, more will be said shortly; however, it is appropriate to note at this point that not all the regulatory literature is based on a footcandle approach. The recently released American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) Standard 90-75, "Design and Evaluation Criteria for Energy Conservation in New Buildings," offers a lighting power budget determination procedure, developed by the IES Task Committee on Energy Budgeting Procedures, that Mr. Kaufman should find quite acceptable. Here's how it works:

The procedure for determining a lighting power budget uses a set of criteria relating to illumination levels, light sources, luminaires, and calculations. The criteria include illumination levels for task, general, noncritical general, and exterior lighting. IES recommended levels are used for task and exterior lighting; general lighting is considered to be one third that of the task level, but not less than 20 footcandles; noncritical general levels—stairways and toilets—are one third of the general, but not less than 10 footcandles.

Three light-source categories listed in the document are 55, 40, and 25 lumens per watt; for moderate, good, and high-color renditions, respectively. As indicated in the source discussion (see box, p. 29), high-efficacy lamps like high-pressure sodium (HPS) sources do not provide the high-color rendition of less efficacious sources like incandescent lamps.

[2] Maintained illumination levels for a variety of luminaires based on their wiring capacity expressed in watts per square foot. Efficient fixtures produce a greater amount of light on the task with less wattage. Approximate wiring capacity to provide a given maintained level of illumination is by means of: A—indirect, incandescent filament (silvered bowl); B—direct, incandescent filament (with diffuser); C—direct, incandescent filament (downlight); D—general diffuse incandescent filament; E—direct, incandescent filament (lens); F—direct, incandescent filament (industrial), and indirect, fluorescent (cove); G—indirect, fluorescent (extra high output); H—direct, fluorescent (extra high output, louvered); I—direct, fluorescent (louvered); J—luminous ceiling, fluorescent; K—direct, fluorescent (lens), and direct, HID (mercury); L—direct, semidirect, fluorescent (industrial).



The procedure also breaks down luminaires into three categories based on the coefficients of utilization (CU), which are ratios of the light reaching the workplane to the light emitted by the lamps within the luminaires.

These factors, together with a step-by-step procedure and worksheet, offer a means of calculating a total lighting power budget in watts.

ASHRAE generated Standard 90-75 at the request of the National Conference of States on Building Codes and Standards (NCSBCS). NCSBCS was formed in the late '60s to deal with the alleged inefficiency of the model building codes in the U.S., and was an attempt to foster the development of a single, national building code.

Will 90-75 affect the average U.S. citizen? Very definitely. Even before it was approved, several U.S. communities had incorporated previous drafts of the standard into their building codes. William J. Collins, Jr., ASHRAE president, estimates that the standard will save at least 10 to 20 percent of the energy now used in residential structures and possibly twice as much in industrial, commercial, governmental, and institutional buildings. The FEA has commissioned a study to determine exactly how much. Areas other than lighting covered by the standard include insulation, the building envelope, window construction and design, building configuration, and heating, air-conditioning, and ventilating systems.

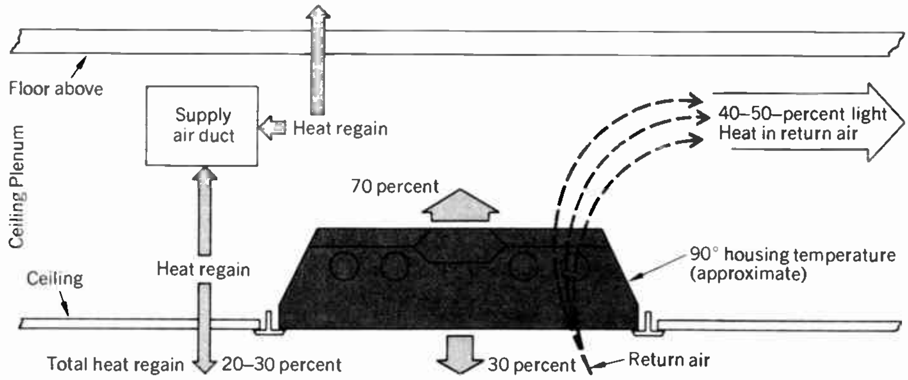
And that's not all as far as energy recommendations go. Add NEMA and NECA to the list of acronyms. The Total Energy Management (TEM) program developed by the National Electrical Manufacturers Association (NEMA) and the National Electrical Contractors Association (NECA) uses an energy budget approach somewhat like that developed by the IES for ASHRAE, except that it applies to the entire energy consumption of a building, not just lighting. The concept of the program is that an energy budget be set that is based on the average reduction in BTU use per square foot in the building (somewhat like the GSA guidelines already referred to). Conversion tables permit the building operator to translate energy input—whether billed by a utility or a supplier—into average BTU input. This figure, divided by the gross square feet within the building, can be used to examine the efficiency of building services.

The TEM document recommends the use of nonuniform ("task") lighting, as does 90-75. It also suggests the use of HID sources and lower-wattage fluorescent tubes. And it proposes retrofits and group relamping—a subject that deserves further attention.

Retrofits save dollars and watts

Retrofitting—substituting lower wattage or more efficacious lamps for higher wattage or less efficacious ones—produces gains in efficiency and lower power consumption, without disturbing fixtures or ballasts. For example, new incandescent lamps in 54-, 90-, 135-, and 185-watt sizes can replace conventional 60-, 100-, 150-, and 200-watt sizes, offering savings of up to 10 percent in electrical power consumption. Or, parabolic aluminized reflector (PAR) lamps can be substituted for R-type reflector lamps. Ordinary R-type reflector lamps have gained wide popularity in retail stores, lobbies, and similar areas for display and general

[3] **Putting the air return function through the luminaire itself improves the heat pickup potential of the return air. Here, about 50 percent of the luminaire heat is removed by the return air directly. Passing the air through the fixture in this manner offers another benefit related to energy management: increased luminaire efficiency.**



lighting. However, the R-lamp's frosting on the inner surface of the bulb results in excess diffusion and low efficacy. The PAR lamp is made with a clear bulb and specular deflector and depends upon a textured bulb face for proper diffusion. As a result, use of PAR lamps has increased—particularly indoors and in merchandising applications where the PAR provides more sparkle and better color rendition. There is an energy savings too. For example, 75-watt PAR38 flood lamps can often be substituted for 150-watt R40 lamps.

Fluorescent sources also lend themselves to retrofitting and group relamping. Fred A. Dickey, a lighting specialist with General Electric's Lamp Business Div., offers a merchandising example using 1000 8-foot slimline fluorescent lamps. A lamp-cost increase of $245 is more than offset by a net decrease in energy costs of $2100 and a net decrease in labor of $268, for a total savings of $2368. Net savings here are $2123.

Even though many group relamping programs use the most attractive old lamps from the previous cycle for interim spot replacement, this example excludes this, because the group relamping involves a switch to the lower wattage slimline fluorescent lamps. Estimated annual energy cost reduction assumes a 17.5-watt reduction for each lamp and ballast. And labor may be either a hard or soft cost factor, depending on whether the store's philosophy is that its in-house labor for spot relamping has a cost. A 3-year group relamping interval was chosen to keep interim spot replacements within the 5- to 10-percent range. (Actual is 6.8 percent.) New lamp price in this hypothetical case is $1.80 for the reduced wattage slimline lamp.

One of the biggest problems in real, not hypothetical, examples is that a store may not be able to "see" a lighting cost reduction of $2123 over a year's time simply because operating costs are experiencing continuous escalation. Perhaps a more accurate description, then, of group relamping with reduced-wattage fluorescent lamps is that it involves a cost avoidance rather than a cost reduction.

Such a cost avoidance can have considerable leverage if it is equated to before-tax, net profit. Assuming, for instance, that the store used in the Dickey example was operating on a 2-percent before-tax net, a cost avoidance of $2123 would equate to the profit on 50 × $2123, or over $100 000 in annual sales.

HID sources can also be used in group relamping. For example, the self-ballasted mercury lamp mentioned in the discussion of sources can be directly substituted for many higher-wattage incandescent lamps to reduce electrical power consumption by 10 to 20 percent and provide the same or more light output.

An additional, beneficial result of group relamping is that it provides an opportunity for thorough fixture cleaning, which can improve the efficiency of the luminaires by as much as an additional 50 percent, depending on how dirty they have been allowed to become. Still another benefit is that the replacement lamps are at the beginning of their life span and are, therefore, more efficient. And metal-halide and sodium sources can also be used in retrofitting operations.

What else can be done?

How else can lighting systems be designed to provide adequate illumination as well as the maximum utilization of energy? The IES, in February 1972, almost two years before the crisis of December '73, prepared 12 recommendations for the better utilization of the energy used for lighting—all without reducing the quality of lighting design (see box below). And, although some of these points have already been touched on here, the others warrant brief mention.

Lighting should be designed for expected activity—the highest levels for the seeing tasks, and lower levels for corridors, storage, and circulation areas. Quality can be assured by following IES-developed VCP and ESI systems. VCP evaluates lighting by statistical predication—the percentage of people who would be visually comfortable in a given area with a particular luminaire. ESI tells how well a lighting system renders

The IES 12 recommendations

1. Design lighting for expected activity (light for seeing tasks with less light in surrounding nonworking areas).
2. Design with more effective luminaires and fenestration (use systems analysis based on life cycle).
3. Use efficient light sources (higher lumen per watt output).
4. Use more efficient luminaires.
5. Use thermal-controlled luminaires.
6. Use lighter finish on ceilings, walls, floor and furnishings.
7. Use efficient incandescent lamps.
8. Turn off lights when not needed.
9. Control window brightness.
10. Utilize daylighting as practicable.
11. Keep lighting equipment clean and in good working condition.
12. Post instructions covering operation and maintenance.

And, in this corner . . .

There are almost as many viewpoints regarding lighting and energy conservation as there are authorities. This article reflects the philosophy of the IES, but many practitioners may feel that it puts too much emphasis on the use of equipment for solving energy problems. Donald K. Ross, a consulting engineer who has advised the FEA on such matters, read an advance copy of the article and felt that it presented "a picture biased too much toward equipment-use." The emphasis should have been more on design to use less energy, according to Dr. Ross, who is a principal of the St. Louis firm of Ross & Baruzzini.

Dr. Ross also feels that in existing installations, many lamps should be removed altogether, citing the example of the General Services Administration, where more than 3 million fluorescent lamps were removed from sockets, amounting to approximately 30 percent of the lamps previously installed. The savings in electricity for the first year was 17 percent for the buildings surveyed, or 347 million kWh annually. The GSA concluded that the 50/30/10 illumination levels were "not only in consort with good health, but generally will not result in any reduction of worker efficiency or effectiveness, or result in any strain on the individual employee."

Lighting designers represent another faction of professionals who have objected to a hardware-oriented approach. Moreover, many lighting designers oppose the design procedure outlined in section 9 of ASHRAE 90-75 (see article). Howard Brandston, a New York designer and a spokesman for the International Association of Lighting Designers (IALD), says that "Section 9 does nothing for energy conservation." The IALD has issued a policy statement that notes that, "in its present form, most designers would try to use section 9 as a practice manual. It does not achieve its goal of conserving energy and, in some applications, might mandate energy waste. . . . Engineers have a tendency to 'handbook' themselves to death. The answer is not another handbook, but an energy ethic . . . "

One of the reasons for so many differences of opinion has nothing to do with energy, but is instead a result of the uneasy alliance between engineer and designer, and designer and manufacturer, a situation that seems unlikely to change, regardless of what happens on the energy scene.

the contrast of a seeing task.

Luminaire (fixture) and fenestration (windows, skylights) illumination should be controlled for maximum visibility and minimum veiling reflections and disability glare. More efficient and thermal-controlled luminaires should be used wherever possible. For example, in a given room, incandescent, indirect luminaires may require 11 watts per square foot of floor area to produce 50-footcandle levels (Fig. 2). Direct fluorescent troffers on the other hand may require only 2.5 watts per square foot for the same output. Fig. 3 shows how recessed lighting fixtures offer an opportunity to control or modify the amount of heat directed into an occupied space (as much as 80 percent of a lamp's input power is converted directly into heat) for more efficient winter and summer usage.

Lighter, and hence more reflective surface finishes mean more efficient light utilization. Window brightness should be controlled to limit glare and heat-producing radiation (less air-conditioning requirements). By reducing the time span between relamping, painting, and cleaning of lamps, increased lighting (as much as 20 percent more) is possible.

Flexibility should be provided in the control of lighting by the use of switching and dimming devices for areas that have different use patterns. Circuit breakers and switches, while not highly desirable, are frequently used in industrial, office, and store applications. Lighting circuits can also be controlled by dimmer switches. Unlike the older style rheostat dimmers that offered no power reduction during operation, solid-state SCR dimmers actually reduce power consumption and can be used to control incandescent, fluorescent, and HID light sources. In areas where adequate daylighting is possible, photoelectric control systems can be used to turn off the electric lighting. Or, timed controls can be used to adjust the lighting of spaces having predictable traffic patterns. Electronic sensing devices are another alternative.

What now?

The immediate challenge, then, for both the industry and the user is to use less lighting energy without affecting the quality of illumination or the performance and safety of an area's occupants. In the longer term, though, the challenge will mean approaching lighting system design as an integral part of the total interior environment. The latter is the approach taken by U.S. Federal and state agencies in the creation of energy-related standards. This article has only mentioned those documents that deal directly with lighting. But there are others—like the U.S. President's Title X legislative package, which calls for standards to be developed in three stages: phase I to provide for thermal standards for residential buildings; phase II to offer minimum performance standards for energy in commercial buildings; and phase III to develop minimum performance standards for energy in residential dwellings.

The immediate effect of this and other legislation remains to be seen, as all the standards discussed here are voluntary. What is apparent, however, is that the public has already forgotten the realities of December '73. The sale of incandescent lamps has—like the consumption of gasoline in the U.S.—increased during the first six months of 1975, according to sources in the U.S. Department of Commerce—an indication, perhaps, that the haphazard bulb-snatching of two years ago has been replaced by a disregard for the energy savings that can be achieved by effective lighting design. This is unfortunate, because most experts agree that high power costs will be with us for a long time to come. And new lighting products—particularly HID sources—can do much to provide the necessary light at a more reasonable power cost. ◆

Charles W. Beardsley is editor of *Lighting Design & Application* and *Journal of the Illuminating Engineering Society.* Both are published by the IES. Prior to assuming these positions in 1973, he was associate editor of *IEEE Spectrum* and managing editor of the *IEEE Student Journal.* He received the B.S. degree in mechanical engineering from Newark College of Engineering in 1961 and the M.S. degree in technical writing from Rensselaer Polytechnic Institute in 1962. Before joining IEEE Headquarters staff in 1968, he held engineering positions with General Electric's aerospace divisions. He is a member of Tau Beta Pi.

Ultrasonic imaging exploits phase contrast

One way to ultrasonically image objects with negligible acoustic absorption is to use an optical microscopy technique

Soft tissues in the human body that are almost invisible to X-rays can often be imaged by ultrasonic techniques. When an ultrasonic wave enters the human body, it may pass through many different kinds of tissue, each with somewhat different acoustic properties. At each tissue interface, such as the boundary between a heart valve and the surrounding blood, some of the incident sound will be reflected and may be detected for use in forming an ultrasonic image. Ultrasound is now being used routinely by medical practitioners to measure the motion and condition of heart valves, to check on the growth of fetuses, to detect changes in the brain, and in numerous other applications.

Unfortunately, medical use of ultrasound is often more of an art than a science, requiring a practiced eye and sometimes strong intuition. For this reason, researchers are constantly on the alert for new ways to improve the ultrasonic images so that less skill is needed to interpret the results. The phase-contrast method to be described is one such approach. It can in certain instances improve images, compared to those obtained by ultrasonic visualization techniques which depend upon amplitude changes of the ultrasonic wave as it is either absorbed by, or reflected from, a material that is different from its surroundings. The phase-contrast method has been applied to a recently developed system to visualize ultrasonic waves. First, the basic system will be described and then the phase-contrast application to that system.

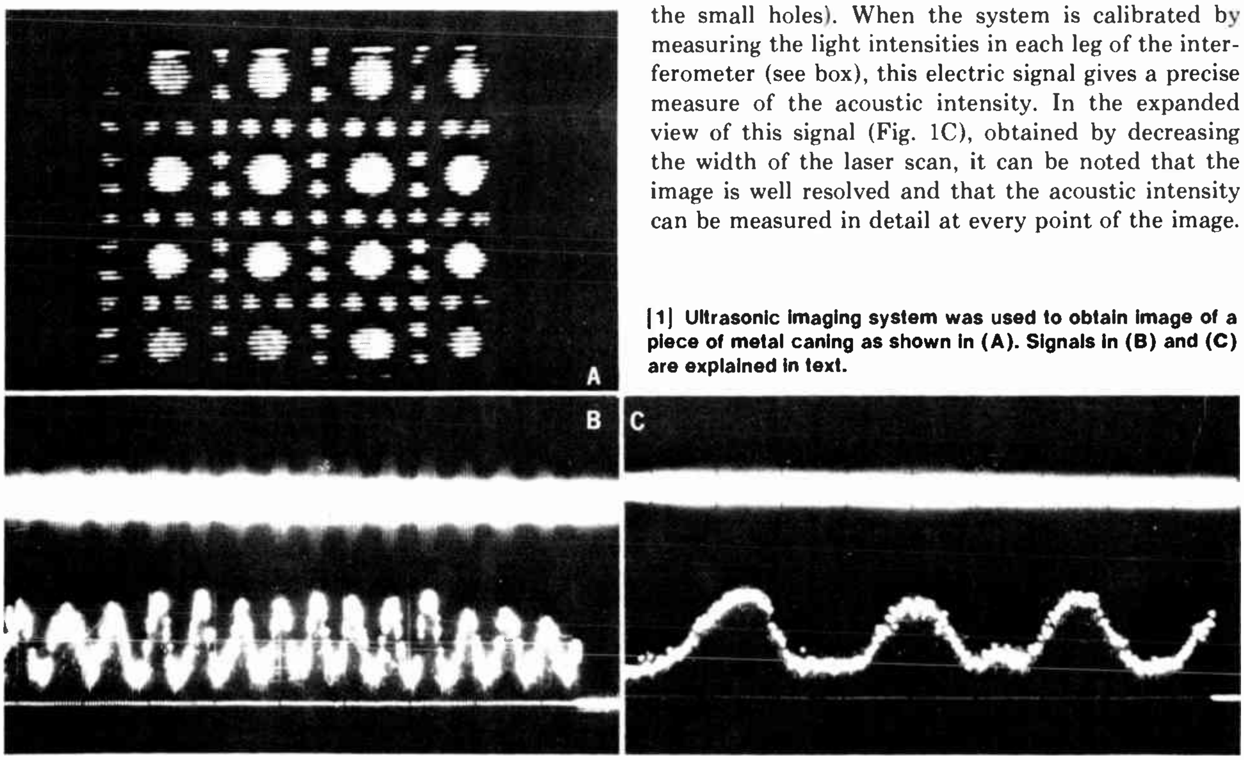
R. Mezrich, D. Vilkomerson, K. Etzold
RCA Laboratories

Testing for defective transducers

The large-aperture ultrasonic visualization system to which phase contrast has been applied is described in the box on page 36. It is being used at present to measure the characteristics of transducers and to study and display interactions of ultrasound with tissue.

Figure 1 illustrates the features of the system as well as some of the capabilities of ultrasound. The object used in this example was a piece of metal caning with 2.7- and 6.4-mm holes. It was illuminated (insonified) with a 3-MHz plane acoustic wave. With the use of f:2 acoustic lenses, the caning pattern is clearly resolved, as indicated in Fig. 1A.

Figure 1B shows the electric signal along one horizontal line through the image (a scan along a row of the small holes). When the system is calibrated by measuring the light intensities in each leg of the interferometer (see box), this electric signal gives a precise measure of the acoustic intensity. In the expanded view of this signal (Fig. 1C), obtained by decreasing the width of the laser scan, it can be noted that the image is well resolved and that the acoustic intensity can be measured in detail at every point of the image.



[1] Ultrasonic imaging system was used to obtain image of a piece of metal caning as shown in (A). Signals in (B) and (C) are explained in text.

How the system with a wiggle works

The ultrasonic visualization system to which phase contrast has been applied is a large-aperture system based on the optical interferometric measurement of the displacement amplitude of the acoustic wave. Although the original intent was to use the system as a laboratory instrument for basic research on ultrasound, it nevertheless has sufficient sensitivity and versatility for possible *in vivo* imaging of certain portions of the human body as well.

Operation of the system is based on the fact that, as an ultrasonic wave propagates through a medium such as water, the particles of the medium vibrate at the acoustic frequency with a peak amplitude proportional to the square root of the local acoustic intensity. By measuring the peak displacement amplitude at every point of the wavefront, the complete ultrasonic field is determined. Displacements to be measured are extremely small. With an acoustic intensity of 1 $\mu W/cm^2$ at 1.5 MHz, for example, the peak displacement amplitude is only 0.1 Å (usual interatomic distances are 2 Å). Optical interferometric techniques are sufficiently sensitive to be able to measure these, and even smaller, displacements.

The system arrangement, as shown in the illustration, is that of a Michelson interferometer in which the key elements are a laser, a beam splitter, and two mirrors—one external to the sound field, acting as a reference, and one in a water bath. The mirror in the bath is a thin ($\sim$6 μm) metallized plastic film, or pellicle, which is placed so that the acoustic waves pass through it. The pellicle is the sensitive surface of the system and is similar to the faceplate of a television camera. Waves scattered by objects, or emitted by transducers, can be measured and displayed by simply placing the object or transducer near the pellicle. Acoustic lenses, appropriately positioned, can then be used to image objects onto the pellicle.

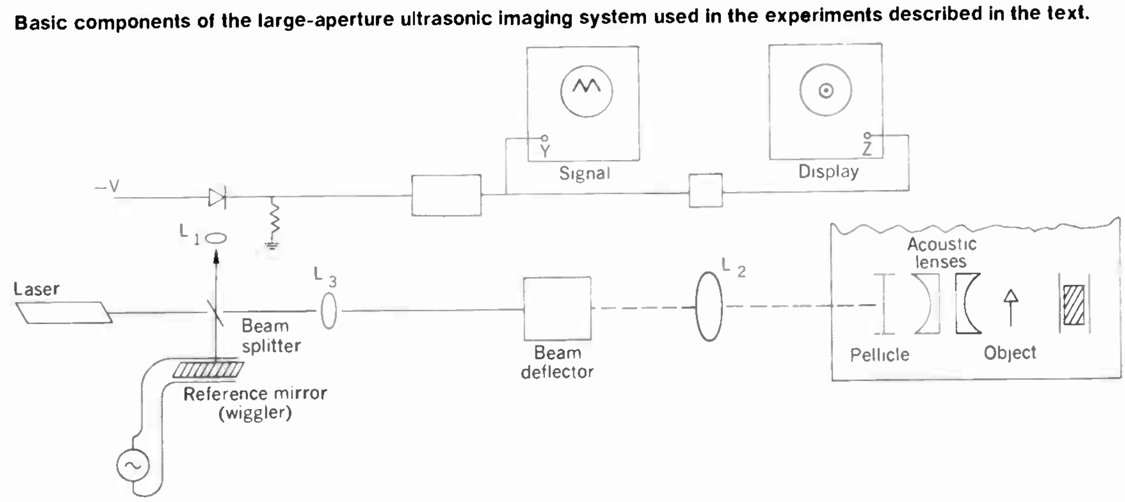
The pellicle moves as waves pass through it and, because it is so thin, the motion of the pellicle at every point is nearly identical to the displacement amplitude of the wave, even for acoustic frequencies up to 10 MHz and angles of incidence from 0 to $\pm$40 degrees. Since the displacement amplitude is small ($<$1 Å) and the acoustic wavelength is large ($\simeq$1 mm), the motion at any point of the pellicle is essentially independent of the motion of its neighbors. Wavelength-limited images of the acoustic field are obtained by scanning a small laser beam over the pellicle, which can be as large as 15 cm, interferometrically detecting and measuring the motion at each point, and then processing the signal for *Z*-axis modulation on a synchronously scanned cathode-ray tube.

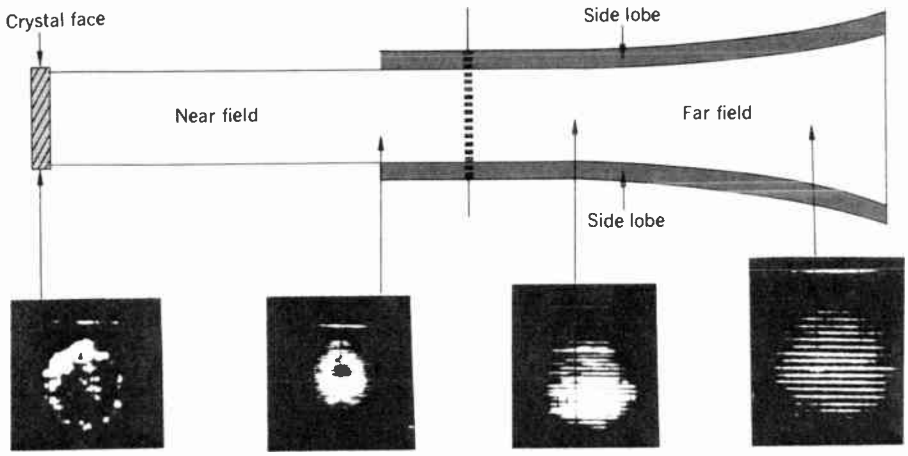
When the mirrors—the reference mirror and the pellicle—are equidistant from the beam splitter, the light from each leg of the interferometer arrives in phase (0-degree phase shift) at the photodiode and interferes constructively. As one of the mirrors moves relative to the other, the interference and the intensity decrease. When they have moved until the relative path difference between the two mirrors is a half-wave (180-degree phase shift), the light waves from the two paths arrive out of phase, and interfere destructively. Halfway between these two points (90-degree phase shift), the slope of the photodiode intensity vs. relative mirror spacing curve is linear and a small change in relative path length, caused by the pellicle motion, produces a proportional change in the light intensity at the photodiode. The slope of the curve at this point, or the sensitivity, is proportional to the total light intensity. With a 15-mW He–Ne laser, displacement amplitudes as small as 0.007 Å, corresponding to acoustic intensities of 5 nW/cm^2 at 1.5 MHz, are measured. With a 1-watt argon laser, the minimum sensitivity can be increased to measure acoustic intensities as small as 10^{-11} W/cm^2, which is adequate for use in imaging deep-lying parts of the human body.

In order to maintain the relative phase difference at 90 degrees where the response is linear and calibrated, a novel stabilization scheme was developed. The relative phase difference between the two beams is purposely varied over at least 180 degrees by vibrating or "wiggling" the reference mirror. The effect of wiggling is that the instantaneous operating point of the system traces out the interferometer response curve as the reference mirror, or wiggler, moves and, at least once per cycle, passes through the desired quadrature condition. Since the slope is maximum at this point, the peak value of the measured signal will give the same value as if the system were always adjusted to a relative 90-degree phase shift. With use of the wiggler, which is a mirror mounted on a vibrating piezoelectric disk, and a peak detector, the system is stable and shows none of the effects that plague ordinary interferometers, such as drift due to thermal or mechanical disturbances. Wiggle frequencies of 20 to 100 kHz are used to ensure at least one cycle of the wiggler at each scanned element of the picture.

Scan rate of the system, mainly limited by acoustic reverberations inside the water tank, is about four frames per sound.

Basic components of the large-aperture ultrasonic imaging system used in the experiments described in the text.





[2] **When the ultrasonic system was used to test this transducer, it was found to be faulty, with most of its power being emitted from just a few locations.**

By decreasing the scan even further, even stopping it and positioning the laser beam to any point on the pellicle, the intensity at any point can be measured with precision. The image can be displayed and the acoustic energy measured simultaneously.

An example of how the system can be used to test a transducer is shown in Fig. 2. For this test, the transducer surface was first imaged onto the pellicle with an acoustic lens. Then the lens was removed and the transducer held at various distances behind the pellicle to obtain far-field patterns. The acoustic intensity at the transducer surface and the far-field radiation were determined by measuring the electric signal from the photodiode while the image is displayed. For the transducer tested, almost all the power is emitted from just a few locations around the periphery. The transducer had been used with a diagnostic scanner and had been giving poor results. After the tests, examination showed that the surface of the transducer had delaminated, trapping an air bubble over the crystal.

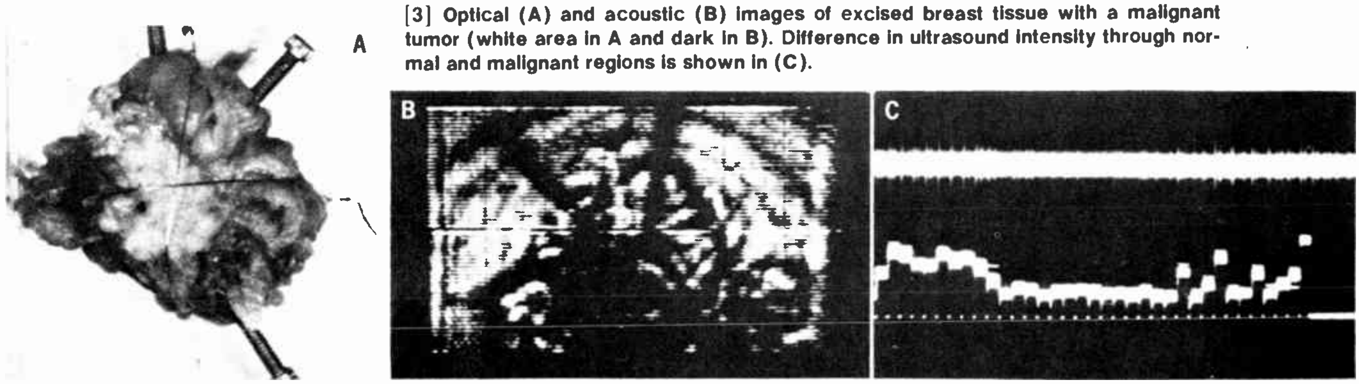
Testing for malignant tissue

Different tissues have different effects on an ultrasonic wave. A particularly important example of this fact is demonstrated by the differences in ultrasound transmission through normal and malignant tissue. Figure 3 shows an optical (Fig. 3A) and acoustic (1.5-MHz) image of a section of excised breast tissue (about 4 by 4 by 1 cm) with a malignant tumor. The tumor appears white in the optical image and dark in the acoustic image (the screws shown were used as markers). Ultrasound intensity measured through the normal parts of the tissue was −2 dB, compared with the clear field, whereas that through the malignant region was −14 dB. In other experiments, tumors as small as 2 mm in similar tissue sections have been identified and later confirmed as malignant by a pathologist.

A series of experiments have indicated that in almost all cases—with the single exception of a relatively rare cancer known as medullary carcinoma—malignant, benign, and normal breast tissue can be differentiated by their markedly different acoustic transmission, at least in excised tissue preserved in formalin. These experiments are continuing with the obvious goal of extending the technique to living patients.

The ultrasonic images in Figs. 1–3 were made using a 15-mW laser as the illumination source. With this laser, sensitivity is ~1 μW/cm^2 when using a broadband optical detector. This sensitivity, together with the inherent wide bandwidth, large dynamic range, wavelength-limited resolution, and large aperture, makes the system a useful tool for the laboratory study of such acoustic elements as transducers and ultrasonic lenses. It is also useful in the basic study of the interaction of ultrasonic waves with tissue and the determination of the effects of various pathological conditions on the ultrasonic wave.

Sensitivities greater than 1.0 μW/cm^2, which are necessary for imaging tissue deep within the body, can be obtained by limiting the bandwidth of the detector and using more powerful lasers. With a 50-kHz bandwidth, which is adequate for a 1/s frame rate, and a 1-watt argon laser, acoustic intensities of 10^{-11} W/cm^2 can be detected. Such intensities are adequate for internal tissue visualization. To date, the system has not been used in clinical applications but rather as a labo-



[3] **Optical (A) and acoustic (B) images of excised breast tissue with a malignant tumor (white area in A and dark in B). Difference in ultrasound intensity through normal and malignant regions is shown in (C).**

ratory tool to study ultrasound; as an archtypical system to study the characteristics of ultrasonic imaging systems in general; and by the U.S. Bureau of Radiological Health to study and set standards for ultrasonic transducers.

Adding phase contrast

Many objects of interest are either too thin, do not absorb enough sound, or do not differ sufficiently in absorption from their surroundings to give meaningful changes in the amplitude of the ultrasonic signal. Often, however, these same objects can affect the phase of the ultrasonic wave. For this reason, a technique known as phase contrast, which has been in common use in optical microscopy to aid in the visualization of essentially transparent objects, has been applied to ultrasonic imaging.

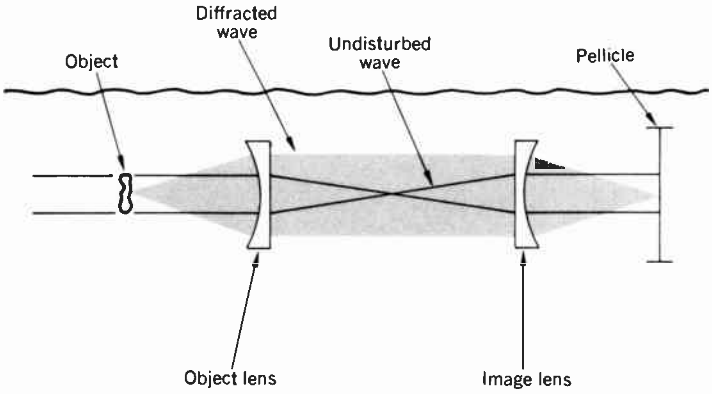
The phase-contrast technique makes possible the production of ultrasonic images of materials that have negligible acoustic absorption but which show spatial variations in acoustic velocity. Hopefully, the phase-contrast method may extend the usefulness of ultrasonic imaging in clinical applications.

Atherosclerotic plaque, which, in the early stages of the disease, consists of small (2–5-mm) deposits on the interior surfaces of arteries, is an example of a low-absorption acoustic structure that can be difficult to image by amplitude-sensitive techniques. A phase-sensitive system, based on the relatively large difference in acoustic velocity in blood and fat, may have a better chance of imaging such structures. Phase-contrast imaging provides the basis for such a system.

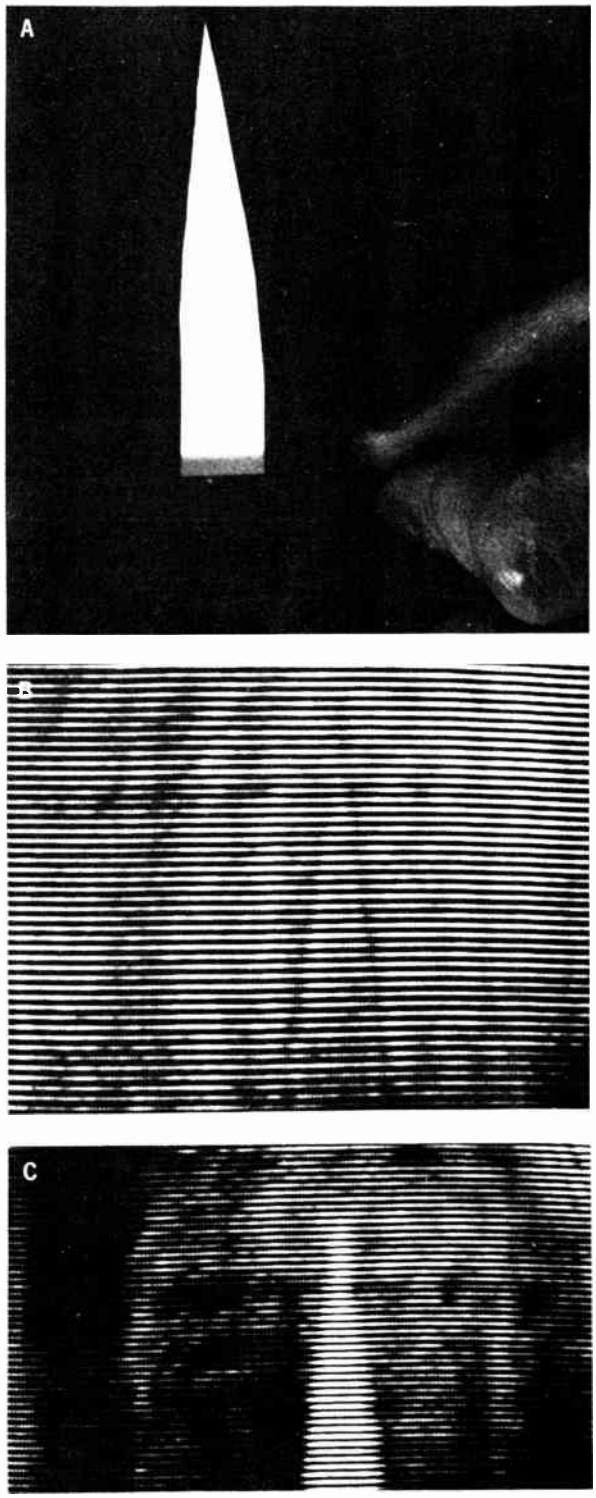
The wave amplitude scattered by a transparent object may be described by a vector in the complex plane, with components along the real axis (at the same phase as the incident wave) and a quadrature component along the imaginary axis. The magnitude of this quadrature component, for small phase shifts, is proportional to the phase angle. For a transparent object, the magnitude of the vector is independent of the phase shift, and a system sensitive to the magnitude will not show the transparent object. In the phase-contrast method, the unscattered sound vector, which is normally along the real axis, is shifted by 90 degrees. The vectors for the scattered and unscattered sound are no longer in quadrature and, therefore, add algebraically. The resultant magnitude, for small phase shifts, is proportional to the phase shift. If the phase is advanced by the transparent object, the components add constructively and a bright image is seen. If the phase is delayed, a dark image results. Alternatively, the phase of the quadrature component can be changed to produce the same effects. The important fact is that the change in brightness, seen in the image and measured on an oscilloscope, is proportional to the phase shift in the scattered wave.

The phase-contrast method is implemented with the simple acoustic lens arrangement of Fig. 4. As the incident wave propagates through the object, part of the

[4] Acoustic lens arrangement for phase-contrast method.



[5] Usual ultrasonic image of plastic object in (A) is shown in (B). Phase contrast gives image shown in (C).



wave (the "undisturbed" wave) passes directly through and is brought into focus at the focal plane of the object lens. The remainder of the wave is diffracted by the object and is spread out over the focal plane. For transparent objects, this diffracted component has a 90-degree phase shift relative to the undisturbed wave. The effect of the lens is to separate spatially the two components of the complex wave scattered by the object.

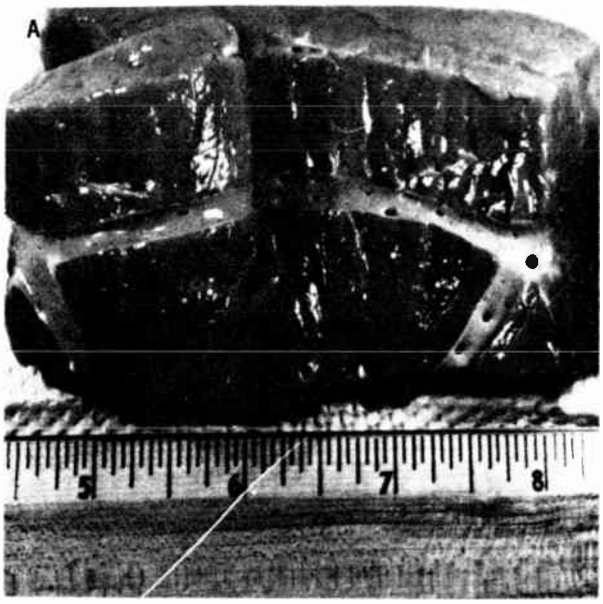
By inserting a phase plate (a piece of plastic of the appropriate thickness) at the focal plane, the phase of either component can be changed without affecting the other component. In the simplest case, the phase plate can be a thin plastic disk placed over the focused undisturbed wave. When the waves recombine at the pellicle, the brightness of the image will be proportional to the phase shift of the object.

The fact that both object and reference waves travel together is of great importance when imaging through thick objects like the leg. Because the two waves travel together, the effects of random phase shifts in overlying tissue are minimized. Such phase shifts have been a problem in conventional phase detection schemes, since in these the reference signal is added electronically.

Figure 5 illustrates the effectiveness of the phase-contrast method. The object used is the 0.5-mm-thick polystyrene piece shown in Fig. 5A. The polystyrene is transparent (it has negligible absorption) but, at 2.25 MHz, the phase of the ultrasonic wave is advanced by approximately 36 degrees. The normal ultrasonic image, without the phase plate, is shown in Fig. 5B. Although the edges are visible due to sound scattering, there is a lack of contrast between the object and background. When the phase plate, a 0.6-mm-thick polyethylene strip which at 2.25 MHz advances the phase by 90 degrees, is placed at the focal plane, the phase-contrast image shown in Fig. 5C results. Since both the object and the phase plate advance the phase, the image is bright against a dark background.

A second example of ultrasonic phase-contrast imaging is shown in Fig. 6. Figure 6A shows a 3- by 3- by 5-cm section of calf's liver. The section was made after the imaging experiments and shows several blood vessels. Figure 6B shows the normal amplitude image. The blood vessels are seen in outline but, because of sound scattering, there is little contrast against the surrounding tissue. The phase-contrast image in Fig. 6C has greater contrast and the vessels can be seen in detail. In both cases, the blood vessels contained water during the experiments. ◆

[6] Calf's liver (A) is shown in usual ultrasonic image (B) and with phase contrast (C).



Reuben S. Mezrich received an RCA Laboratories Achievement Award, his third, in 1974 for a team effort leading to the development of novel methods for ultrasonic visualization. His previous two Achievement Awards, in 1970 and 1972, were for his work on magnetic holography, and for a team effort on read-write optical memories. Dr. Mezrich has been with RCA Laboratories since 1963 and has worked in such diverse fields as read-only memories, image storage and retrieval systems, cryogenics, and holographic storage on magnetic films.

David Vilkomerson is also the recipient of a 1974 RCA Laboratories Achievement Award as a member of the team on ultrasonic visualization. Dr. Vilkomerson has done research at RCA—where he has worked since 1963, except for educational leave—on alloy semiconductor lasers, solid-state cryogenic devices, superconducting amplifiers, holographics, and optical memories.

K. F. Etzold is the third member of the team that received the Achievement Award for ultrasonic visualization. He has been with RCA Laboratories since 1973. Dr. Etzold has been working on new ultrasound equipment for medical diagnostic purposes.

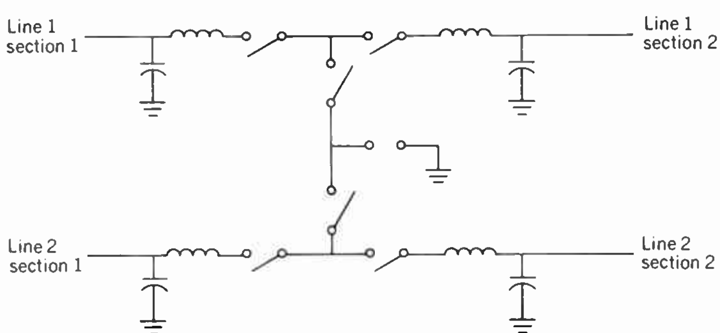
the purpose of being relay stations for the power-line carrier (PLC) system. Situated at Kinshasa, Kikwit, Kananga, and Kamina, these stations will each have six 500-KV single-pole disconnect switches. At Kolwezi, the eastern terminus of the system, a second converter station will change the direct current back to alternating current.

New design for terminal converter stations

The specification for the Inga–Shaba HVDC transmission calls for developing the terminals in three stages. The power to be transmitted from the Inga station, therefore, will be 560 MW in Stage 1, 840 MW in Stage 2, and 1120 MW in Stage 3.

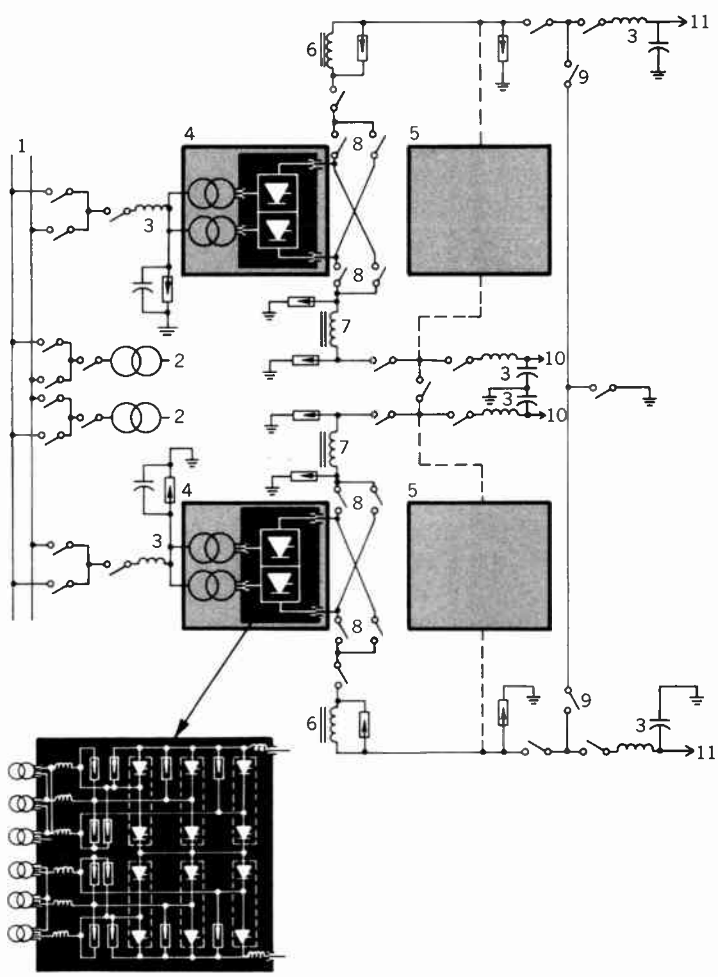
For the first time in an HVDC transmission project, the terminal stations will have converters connected in parallel instead of in series. The installation will also utilize thyristor valves, which give the possibility of selecting the valve voltage and current ratings to optimize economically the line and station costs. (The arrangement was chosen with regard to low line losses in the first stage when operating at full voltage and reduced current, as opposed to the line losses obtained if initial low-voltage high-current operation were selected with series-connected converters similar to those used in earlier HVDC systems.)

During Stage 1, which is now under construction, each terminal will be equipped with two converters, each rated 500 kV, 560 amperes (normally operating in different poles as shown in Fig. 3). Stages 2 and 3 will each add one converter of the same size per terminal at a later date.



[2] The line section paralleling possibilities are shown for a typical switching station.

[3] Main circuit for a converter station: 1—220-kV ac double bus; 2—auxiliary power; 3—noise filter; 4—converter; 5—future converter; 6—line reactor; 7—smoothing reactor; 8—polarity reversal switches; 9—pole-paralleling switches; 10—electrode line; 11—±500-kV lines.



Each converter has an overload rating of 135 percent for 30 minutes' duration, thereby enabling it to compensate when a persistent fault occurs on one line. Essentially, this has the effect of maintaining the remaining power-handling capability at 67 percent—assuming a balanced number of converters in each pole prior to the fault. By means of an arrangement of disconnect switches (see switches 8 and 9 in Fig. 3), converters of both poles can be paralleled on the operating line. This rather simple procedure is accomplished without disturbing the operation on that line. When the faulty line is repaired, reswitching should be accomplished well within the overload time limit and without disturbance to the operating line.

At both converter stations, the ac switchyard will have a double-bus arrangement operating at 220 kV nominal voltage. The Inga Station (to be built within the Inga hydrosite area) will be fed by two 220-kV lines that run 2 kilometers from the Inga 2 power plant switchyard. In Shaba province, the terminal near Kolwezi will be tied to the existing electrical network by means of four 220-kV lines and one 220/120-kV autotransformer which connects to an adjacent copper refinery plant.

The smoothing reactors are located on ground potential, thereby reducing the consequential overcurrent amplitudes at ground fault within the station as well as the direct voltage stress on the reactor itself. Overvoltages entering the station from the dc line are limited by an arrester, and the converters are further protected by a line reactor located in series with the converters.

Of converters and valves—in detail

Each converter consists of two 6-pulse bridges with different transformer connections (Y/Y and Y/Δ) in series so that it functions in 12-pulse mode. No separate bypass valves are used; the bypass function is attained by firing opposite valves in the bridges when required. Two valves, each containing a string of series-connected thyristors, are built into a common structure, one on top of the other. This consitutes a "double valve," (Fig. 4) of which there are three for one six-pulse bridge of 250 kV, or six in each 500-kV twelve-pulse converter. The lower dc terminal is always connected to a potential of 250 kV so that the upper dc terminal will be on either zero or 500-kV potential.

The valves are air-insulated and air-cooled for indoor installation; and, for easy maintenance, a modular design is used wherein each module contains six thyristors, voltage-dividing circuits, and thyristor-control units.

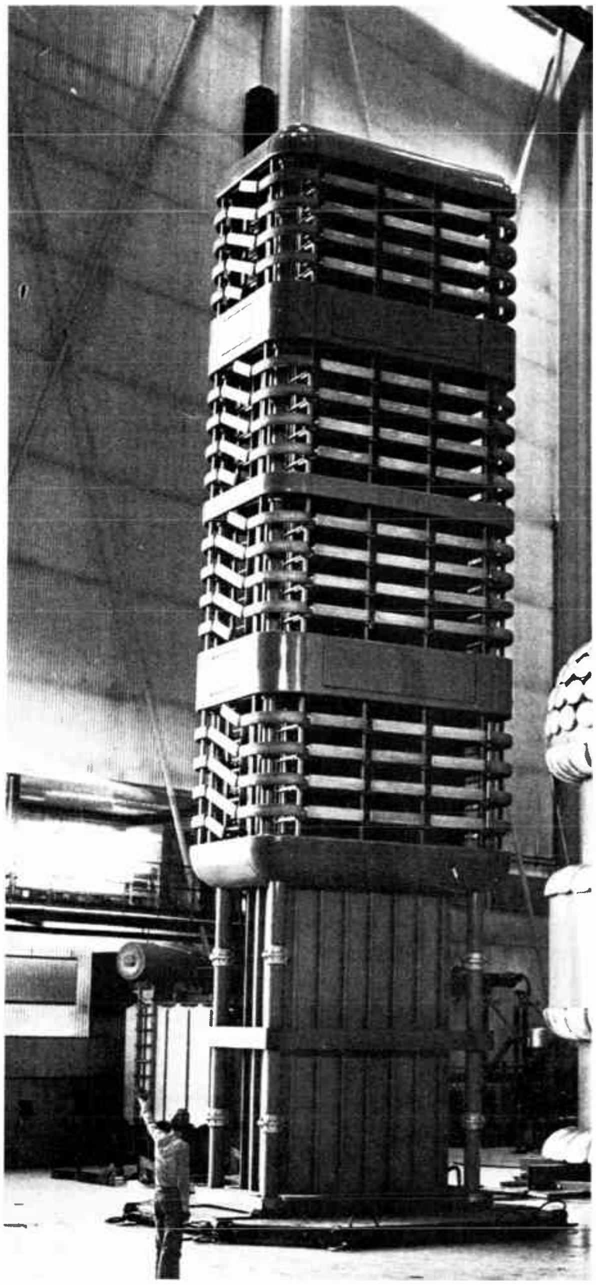
Auxiliary power to the thyristor-control units is obtained from the main circuit itself by tapping the voltage across the thyristor. An "optronic" system is employed for control signals within the valve; that is to say, each valve has a centrally positioned control unit from which light beams distribute the firing signal to each thyristor. In the opposite direction, other light guides transmit a return signal from each thyristor for monitoring its functions. The valves are fully independent of auxiliary electric power supply from an external source. A signal converter below the valve is the interface between the optronic system of the valve and the electric control signals from and to the control room (Fig. 5).

Monitoring equipment for the valves will be located in the control room to:

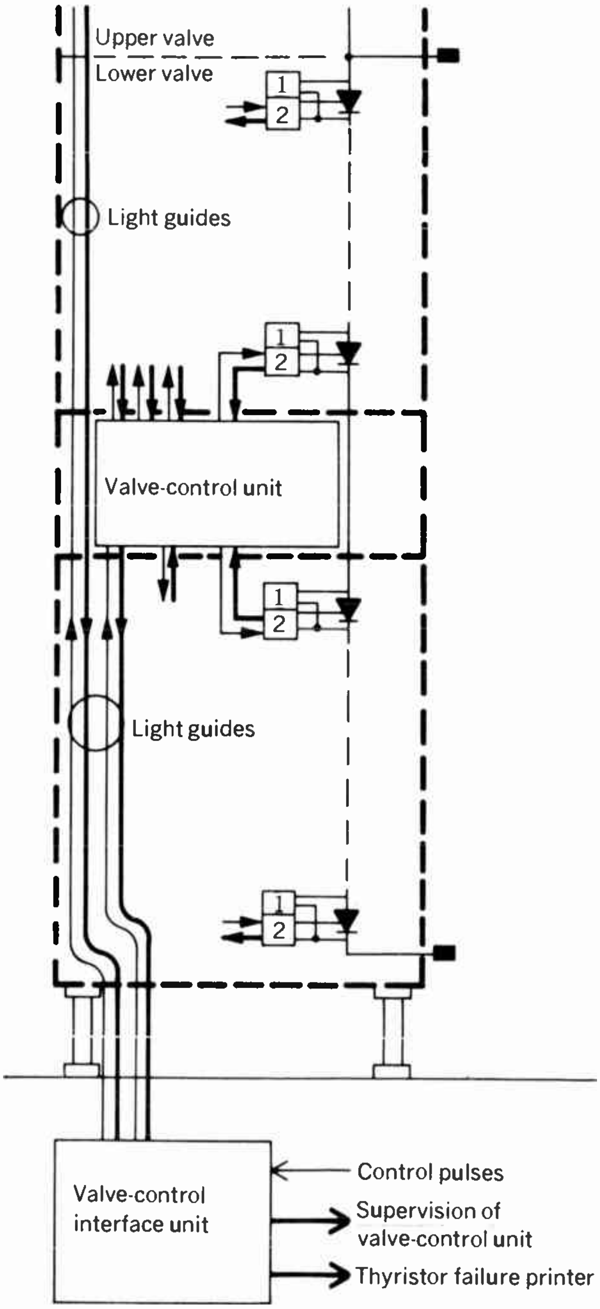
- Inform the operator of any thyristor failure.
- Provide a location code to pinpoint the position of such failure.

However, each valve contains a small surplus of thyristors as a safety margin so that some failures can be ac-

[4] An ASEA prototype double valve for the Zaire HVDC project. The height of the valve, from floor to top, is 15.3 meters; its width and depth are 4.1 and 2.65 meters, respectively. Three valves of this type are required for one six-pulse bridge.



[5] Valve control and supervision. A valve-control interface unit, located beneath the valve, "optronically" transmits and receives electrical control signals through light guides to and from the control room.



cepted without halting a valve's operation. This type of valve is of the same design as a test valve for handling 125 kV, 1000 amperes that has been operating successfully in the Danish terminal of the Konti–Skan HVDC transmission since early 1973. The monitoring system and the modular arrangement ensure the shortest possible planned downtime for replacement of thyristor modules.

Filtered cooling air enters the valves from below and flows upward through a duct. The modules are arranged so that all thyristors are cooled in parallel. To supply the valves with clean, dehumidified air, a recirculating system is employed in conjunction with water-to-air heat exchangers in the loop. The rate of air exchange is carefully controlled: recooling is handled by conventional open-circuit evaporative cooling towers.

The valves are designed to withstand overcurrents caused by a short circuit or a ground fault. Thus, short-circuiting switches to divert the overcurrent are not required.

Overvoltage protection

Overvoltage protection for the valves is provided by arresters connected phase-to-phase, and also across the valves connected to the dc line side. The arresters are located indoors where a well-controlled environment will benefit their functioning and, thereby, the valve rating.

To reduce the valve stresses at firing, there is a reactor in each phase connection. For the equipment in the valve hall, switching-impulse stresses determine the insulation requirements. Lightning surges entering the valve hall are reduced in amplitude by the line and smoothing reactors on the dc side, and by the converter transformers on the ac side.

The switching impulse requirements within the converter are 1300 kV phase-to-ground, 1175 kV for the dc side. This calls for 5-meter and 4-meter clearance distances, respectively, even when reducing the field strength around equipment by screens, for which special tests were carried out.

Converter-control system

A system with an equidistant firing system of 12 valves is used for converter control. However, the current-control subsystem is subordinated to a power-control system in which a reference power signal is set by the operator. The system then determines the required current order with respect to the line voltage. This function is carried out by means of an order-setting unit (both converter stations have one for each pole). The positions of the units in the two stations on the same pole are synchronized via a telecommunication link. The desired power, and rate of change to obtain this power, is entered on "thumb wheels" either for each individual pole or, normally, for the entire station. In the latter case, one pole will automatically pick up power as needed, up to its overload limit, if the other pole trips out.

An additional control feature, designed to be the predominantly used control mode, is frequency control of the Shaba network. Here, a frequency-error signal will be initiated at the Kolwezi station and induced into its power-control system. For the initial operation, the frequency control may be set with a "deadband" so that only major disturbances in the Shaba system will require intervention.

After conducting simulator studies, special sequences have been developed for startup and shutdown of converters in parallel. These sequences permit paralleling and planned tripout of converters without disturbance to the power flow.

As an extra precaution against overcurrent in the main circuit due to fault in current-response circuits, redundant current measuring is used.

I. Reactive power specifications from installed equipment at Inga and Kolwezi stations

Station	Stage	Filters, Mvar	Synchronous Condensers, Mvar	Total Installed Mvar
Inga	1	2 × 34.5		69
	2	2 × 34.5		69
	3	3 × 34.5		103.5
Kolwezi	1	2 × 95	3 × 70	400
	2	2 × 95	5 × 70	540
	3	3 × 95	8 × 70	845

For further reading

The author recommends two reference papers for those interested in further information on HVDC systems of the type to be installed for the Inga–Shaba project. These are:

Anderson, E., and Ekström, Å., "Design and testing of the thyristor valve installed in the Vester Hassing converter station of the Konti–Skan HVDC transmission," CIGRE, 14-03, 1974.

Ekström, Å., and Liss, G., "A refined HVDC control system," *IEEE Trans.* Paper 69 TP 680-PWR.

Protection of HVDC equipment

For the HVDC equipment, a few special protective measures are required; these include:

- Commutation failure protection
- Ground-fault protection
- Short-circuit protection

These are strategically arranged so that there is a primary and a backup protection against any major fault.

The transmission line is protected by a line-protection sensor in the rectifier end. The fault most common to transmission lines is a conductor-to-tower flashover triggered by lightning; this protection therefore provides for automatic restart. The protective action is to retard the rectifier toward inverter operation for fast deenergization of the line.

Reactive power and harmonics

At full-load conditions in Stage 1, the rectifiers at Inga will consume 332 Mvar; and the inverters at Kolwezi, 290 Mvar. Because 12-pulse converters are used, filters can be limited to tuned branches for the 11th and 13th harmonics, plus high-pass filters for higher harmonics. Table I indicates what the installed equipment in Stages 1–3 will be. As noted in the table, the Inga generating station will supply reactive power to the Inga converters while the Kolwezi station is designed to be overcompensated to deliver reactive power to the Shaba network.

For the Lower Zaire network, the steady-state frequency variations are within ±0.5 Hz. For the Shaba network, the frequency will be kept within the same limits by the aid of frequency control. An automatic adjustment of the tuning of the filters could therefore be avoided.

Telecommunications

Each line will carry a PLC system to be used for the control and voice communication. The PLC operates between the lightning shield wire (which will be insulated from the towers) and the main conductors. Each switching station has transceiver equipment. The PLC of the line with positive polarity to ground will normally be in standby mode, but will automatically be cut into any line section where signals from the negative line are not received. There will be eight 1200-baud duplex channels of 4 kHz.

One of the channels will be used as a line-fault locator system along each transmission line section. Flashovers on the line will be sensed and the location will be encoded within ±8 km. This function is accomplished by comparing the time between arrival of the traveling wave produced by the flashover and the arrival of an impulse on the PLC of the other line—transmitted at the time the traveling wave reaches the far end of the line section.

The Inga–Shaba consortium, and suppliers

In February 1973, the Zaire government agency, Société Nationale d'Électricité (SNEL) awarded the "turnkey" contract for the Inga–Shaba project to the consortium Constructeurs Inga–Shaba (CIS) that has been formed by

- Morrison-Knudsen International Co., Boise, Idaho.
- International Engineering Co., San Francisco, Calif.
- Fischbach and Moore International Corp., Dallas, Tex.

CIS will be responsible for the design engineering and construction of the transmission lines and terminals. The principal subcontractors for the supply of converter valves, controls, and HVDC system design will be ASEA of Sweden; General Electric (U.S.) will be responsible for the ac-side equipment plus the PLC.

As of now, the erection of the 1700-km-long HVDC line is well underway. Of the 150 000 tonnes of materiel expected to pass through the ocean ports of Matadi and Boma, 90 000 tonnes have already been received. The construction work force numbers more than 4000—the majority of which are Zairois. These personnel are at work all along the route of the transmission line and at the two converter stations.

The contract calls for commissioning of the system in early 1977. Development of the Inga dam complex will be handled under separate contracts.

Among the HVDC projects now under development, only Cabora Bassa in Mozambique (see *IEEE Spectrum*, pp. 51–58, Oct. 1974) will exceed the ±500-kV level; however, that will not be reached until the final stage of that project.

Two U.S. Government agencies, the Bureau of Reclamation and the Bonneville Power Administration, are providing technical assistance to the Government of Zaire on this vast power development scheme.

To attenuate converter noise, filters will be installed on both the dc and the ac side. This is in order to protect existing and future PLC systems from interference.

Ground electrodes

In normal operation, substantial electrode current will only flow in Stage 2, when the number of converters per pole is unbalanced. However, during abnormal operating conditions, such as when a line or converter is out of service, ground current up to full line current can flow.

For Stage 1, two ground electrode fields per terminal about 2 km apart are provided, at a distance of about 40 km from the Inga and 16 km from the Kolwezi terminal. Each field is designed for 85 percent of the rated line current. For Stage 2, it is planned to add another equally sized ground field for each terminal.

The design with normally redundant fields permits any of these to be taken out of service for inspection with only a minor reduction in transmission capacity under the worst condition, and with no reduction in most cases.

The dimensions of the development

Perhaps the most challenging aspect of the huge construction effort required to build this transmission line and the power interconnections is that of sheer logistics and its associated problems. For example, about 150 000 tonnes of materiel—including 34 items that weigh between 65 and 100 tonnes apiece—will be required for the project. This materiel must be distributed along a tropical route where transportation facilities are presently inadequate for the task. Thus, the design and construction consortium, Constructeurs Inga–Shaba (CIS) use rail transport initially to move materiel from the port of Matadi (see map Fig. 1) to Kinshasa. From there, some of the equipment will be transshipped by road to nearby construction sites, and the remainder of the materials will be transported eastward via self-propelled barges that will proceed up the Kasai River to Ilebo. From Ilebo, a combination of rail and road transport will be employed. In all, about 6500 km (4000 miles) of roads will either be built, improved, or maintained by the CIS consortium.

Among the primary equipment needed—in addition to the transmission towers—are 750 000 disk-type insulators, 20 000 grounding rods, and thousands of kilometers of conductor, shield, and grounding wire. The construction fleet will consist of more than 300 heavy-duty trucks, 26 truck-mounted cranes, 55 tractors, 50 motors-generator sets, three self-propelled barges, and four aircraft. ◆

Lars Engström is a HVDC project engineer with ASEA. Since early 1974, he has been that firm's representative in San Francisco, Calif., in a technical liaison capacity between International Engineering Co. and ASEA's HVDC headquarters in Ludvika, Sweden. He received his engineering degree at Chalmers Institute of Technology in Gothenburg, Sweden. Since joining ASEA in 1965, he has been engaged in various fields of HVDC engineering as well as the commissioning of projects.

For solar power: sunny days ahead?

The future of sun-derived electric power is clouded by budgetary constraints, institutional and public inertia, and poor incentives

Conventional fuel costs are escalating, supplies are depleted, and the environmental hazards of both the coal and nuclear alternatives are being stressed by an increasingly vocal opposition. In a torrid climate of national debate—one that tends to generate more heat than light—solar power seems to have become the darling of a substantial portion of the R&D community. And with some justification: the sun, for one thing, is virtually inexhaustible. Nevertheless, progress toward large-scale implementation of solar energy for electric power generation has so far been hampered by an array of economic, technical, and institutional barriers.

Various technologies are being examined as potential avenues for large-scale conversion of solar energy to electricity (see box on pp. 48–49). For some concepts, such conversion is still far down the road. But the technical feasibility of at least two technologies—photovoltaic conversion and the use of wind power—has been well established.

Wind power is, of course, an indirect application of solar energy in that winds are byproducts of temperature conditions. The successful application of wind power to generate electricity in the U.S. goes back four decades and more. Wind-power technology was almost totally abandoned, during the 1930s, in the face of cheap fossil-fueled electric power, but has come back into favor since about 1968.

Solar cells, for their part, have already been successfully used in space applications. And on earth, photovoltaic technology is in use on a small scale for low power generation, typically in remote places on land or at sea, where costs of installing special power lines for such applications would be prohibitive. Examples are solar power isolated radio transceivers (SPIRTs), installed on mountain tops in the state of Arizona, to support the mobile radio communication network of the state's highway police, and the 400-watt solar-powered water pumping station, installed in Dakar, Senegal, by a French company. Also, a small solar-thermal power plant, intended to supply electricity to a population of about 10 000 persons, is expected to be installed by the end of the year in San Luis de la Paz, Guanajuata, Mexico.

Economic hurdles

Outside of such special applications, the use of solar energy is not yet considered to be economically feasible. Piet Bos, program manager for solar energy at the Electric Power Research Institute (EPRI), Palo Alto, Calif., points out that the sun's rays are diffused and that solar radiation is available only during hours of sunlight, and even then the radiation is unreliable due to clouds. For these reasons, Bos believes that solar energy's role in electric utility operations can only be complementary to conventional power generation methods.

Analyzed on the basis of life-cycle costs—that is, including fuel, maintenance, and operational costs, through the lifetime of a proposed power plant, in addition to capital costs for putting the plant on line—most proposed solar energy conversion concepts do not seem to be immediately competitive with conventional power generation methods. Even without a fuel-cost element, the direct capital investment for solar power

(Continued on p. 50)

Solar-powered isolated radio transceivers (SPIRTs), like this one, being installed on an Arizona mountain, are being used to support mobile radio operations for Arizona Highway Patrolmen. A battery bank, which carries a reserve capacity of seven days, powers the radio during the dark hours and on overcast days. On a ten-year basis, it is estimated that such solar-powered systems will save at least 50 percent of the cost of running conventional power supplies (fossil-fueled generators and transmission lines) to these remote locations for the low-power radio systems.

Gadi Kaplan Associate Editor

Solar electric technologies

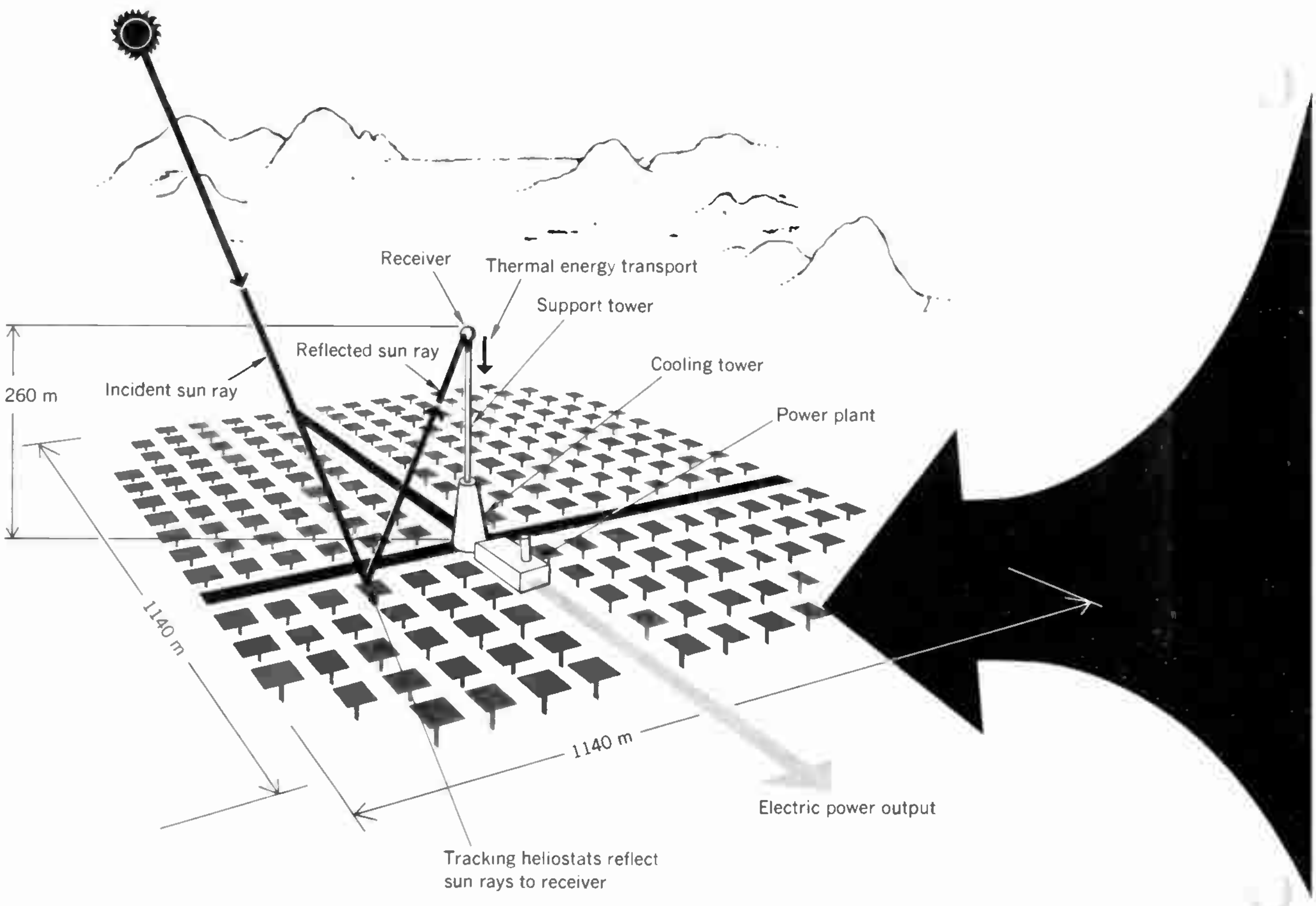
Various technologies are being considered as means of generating electric power, in large quantities, through solar energy. Among these, solar-thermal, photovoltaic, and geosynchronous satellite solar power systems (see *Spectrum*, Mar. 1973, pp. 38–47) are based on extracting energy from the sun's radiation, whereas wind power conversion systems and ocean-thermal energy conversion systems (see *Spectrum*, Oct. 1973, pp. 22–27) use the sun's energy indirectly, the former by employing the power from winds which are affected by the sun's influence on the weather, and the latter by taking advantage of sun-induced temperature differences between water layers in oceans.

Solar thermal conversion (*STC*) *systems* collect solar radiation, converting it first to thermal energy, then further converting it into electrical energy. There are two basic types of STC systems—the central receiver (popularly known as the "power tower") and the distributed collector types. In the former, the sunlight is reflected by many individual heliostats (mirrors mounted on bidirectional tracking systems) to a central receiver (boiler), on top of a tower. Here, the heat energy is absorbed and converted into electricity by conventional methods. According to estimates, a collector area of 1 km^2 for each 100 MW (electric) of rated plant capacity, and a thermal storage capacity of six hours, will yield near-minimal busbar energy costs—about 25–30 mills/kWh (in 1974 dollars), assuming projected heliostat costs of $30/$m^2$ and thermal storage costs of $15/kWh (electric).

In proposed distributed systems, the sunlight is absorbed by many individual absorbers, each having its own solar collector that tracks the sun in one direction only. The thermal energy is then transferred by a fluid (such as water) to a central location for conversion into electric power. Central receiver systems can obtain higher working fluid temperatures than in their distributed counterparts (up to about 800 K) and are therefore more efficient for electric power generation. Economically, they are now preferred for large, central-station power generation schemes.

Photovoltaic conversion of solar radiation directly to electric power can occur in a thin layer of appropriate material—silicon, for example. Although other materials can also be used for photovoltaic conversion (see main article), silicon is particularly attractive due to its great abundance, the high conversion efficiency (10–15 percent) obtained with silicon devices, and the high level of development of silicon manufacturing technology. During photovoltaic conversion, electric charges are freed when light falls on the photovoltaic device, and these charges flow as current through an external load. Most photovoltaic devices are responsive to a broad range of wavelengths, and the wavelength range can be tailored to encompass the major part of the solar spectrum.

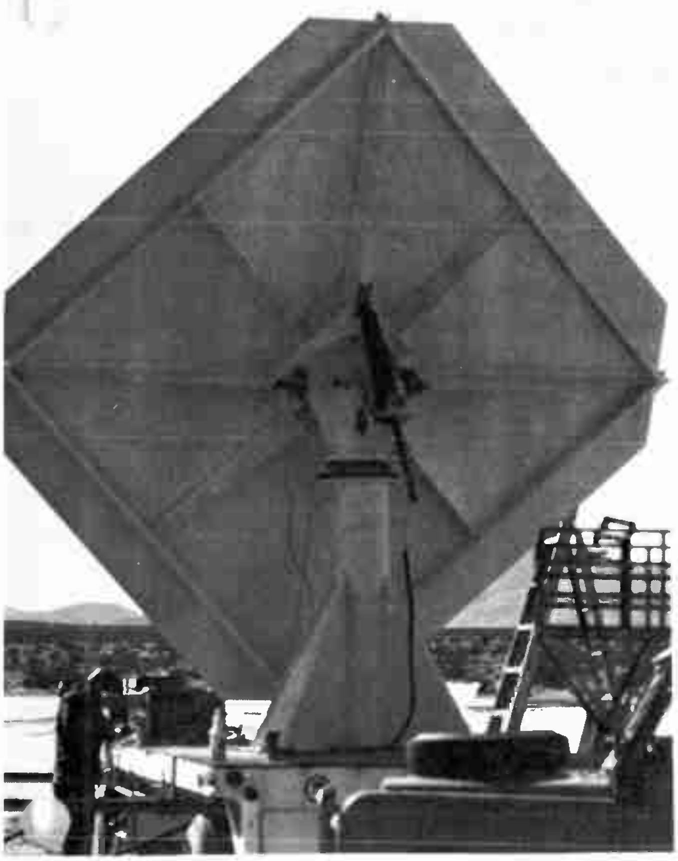
What makes a good photovoltaic conversion device? The most important characteristic is carrier (free charge) lifetime, which depends on the quality of the crystal. The purer it is, the longer the carrier lifetime and the higher the conversion efficiency. There is a tradeoff, however, between purity requirements and manufacturing cost. The former may sometimes be relaxed resulting in reduced costs with no observable deterioration in performance. For large-scale production of high-purity silicon, required for large-scale photovoltaic conversion power plants, a new technique for making long, continuous silicon crystal—silicon ribbon (sometimes referred to as "silicon sheet")—is being developed. It is quite different from the con-



ventional Czochralski single crystal growth technique used at present. The biggest problem to be overcome in this technique is the forming of "grain boundaries," which shorten the carrier lifetime considerably, reducing the conversion efficiency.

The major advantage of photovoltaics over other solar electric technologies is flexibility in size. The exposed surface area of photovoltaic converter arrays can range from one square meter to many square kilometers, making them potentially much less sensitive to the rigid economies of scale, that inevitably force conventional fossil and nuclear power plants and solar thermal systems to become very large. The possibility of colocation of photovoltaic converters with their load is another potential advantage, since it could eliminate much of the capital cost and power loss cost associated with power distribution equipment. Thus, photovoltaic arrays can be used in a variety of applications such as a single family residence, a commercial or public building, and an industrial plant, as well as in a central station power plant.

One way of converting solar energy into thermal energy (which is subsequently used for the generation of electricity in a more or less conventional way) is through the use of the central receiver ("power tower") concept, portrayed here. According to this concept, solar energy is transmitted optically from heliostats (mirrors mounted on bidirectional tracking systems, as shown in the photograph directly below) to a tower-top receiver (boiler) mounted near the turbogenerator. A modular central receiver system, consisting of a collector net area of 0.5 km^2 per module (with a total land area of 1.3 km^2/module), and with a tower height of 260 m, is shown. A single 100-MW (electric) generator would be driven by one, two, or three modules combined with 3-, 6- or 12-hour thermal energy storage capacity for peaking, intermediate, or baseload operations, respectively. A collector area of 1 km^2/100 MW (electric) of rated plant capacity and a thermal storage capacity of six hours have been estimated to yield near minimal busbar energy costs.



To reach the goal of a U.S. photovoltaic energy production rate in the year 2020 of 10^{12} kWh/year (about 65 percent of the electric energy generation in the year 1970, but only about 5.5 percent of the total electric energy generation projected for the year 2020), the required array area would be 0.7×10^{10} meters^2; *about 0.1 percent of the total land area of the U.S.* (For perspective, the total road and highway area in the U.S. today is 1.5 percent of the entire land area). This calculation assumes a 10-percent efficiency of the solar arrays and an average daily insolation (the rate at which solar energy is received on a horizontal surface) of 4 kWh/m^2. The average production rate of silicon sheets needed for replacement, assuming a 20-year lifetime for the systems, would be 3.5×10^8 m^2/year!

A *wind power* system consists of a rotor, a rotor direction controller, a mechanical transmission and electrical generator, an ac fequency controller, a support tower, and either an energy storage device or equipment for tying into a utility power grid. With regard to rotors, the best developed and understood rotors (as well as the most efficient, aerodynamically) to date are the two- or three-bladed, propeller-type, horizontal axis rotors. However, newer designs are being developed, and will have to be evaluated.

A major structural element in the wind power station is the tower, which supports and elevates the rotor to reach high-velocity winds. There is a tradeoff between the added cost of making the tower taller and the added energy output achieved. Also, for each single tower there is an optimum number and size of rotors. In addition to withstanding constant winds velocities at up to 180 km/h, the wind tower must also stand fast at sudden forces created by gusting winds. And it must be designed to withstand vibrations caused by unsteadiness in the wind and by changes in the wind flow around the tower, as well as vibratory forces transmitted to it by the rotor.

One productive area in wind power where technical efforts are channeled is the search for improved efficiency. A vertical rotor with blades that change their position during their rotation to extract the maximum wind power represents one significant development. Another design, under development by Grumman Corporation, Bethpage, N.Y., called "sail wing," incorporates flexible rotor blades like sails with a fairly large area as a "leading" edge and a rope as a "trailing" edge. Low cost is a big asset of this design, which is recommended for developing countries. Another improvement in wind power conversion systems is suggested in a vortex generator that prespins the air prior to the rotor itself, enabling the rotor to operate in much weaker winds than were necessary prior to the introduction of this installation.

Technical feasibility for wind power systems is well established (the history of electrical windmills goes back about 80 years), but there has been little experience with plant sizes over 10 kW. As far as the economic aspects are concerned, only a few economically successful medium- and large-size (over 100-kW) wind-electric plants have been built, and, in most cases, they have been experimental, one-of-a-kind units that were not cost-effective. Little or no follow-up effort was made to reduce costs.

In one published assessment of the status of wind-electric power generation, it is mentioned that the cost goal should be to make the total power delivery costs, which comprise fixed charges (interest, depreciation, insurance, and taxes) plus operation and maintenance of wind plants competitive with the *true* power delivery costs of other conventional technologies, including pollution control and land reclamation for fossil-fueled plants and waste disposal for nuclear power plants.

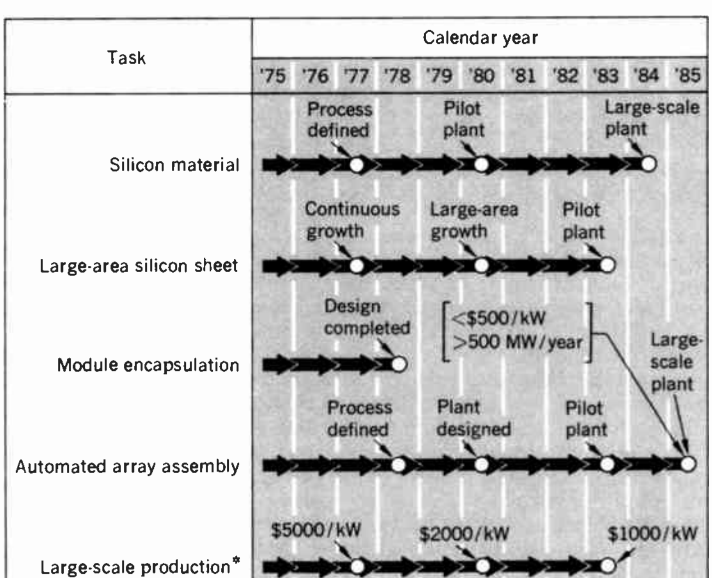
(*Continued from p. 47*)
systems is higher than that for the capital-intensive power generation techniques. However, if investments in facilities for mining and processing of fossil and nuclear fuels, as well as in transportation equipment, were included in their capital investment costs, the picture might shift in favor of solar energy systems. But further development of solar energy for generation of electricity has so far been hampered by a lack of economic incentives to potential developers and users of solar energy systems.

On-site, total energy systems

One concept for a solar energy system—the "on-site" system—does show promise of being economically competitive. Intended to supply both electric and thermal power for small-scale or even medium-scale use—as in a private residence, a small industrial complex, or a community of up to 100 000 persons—the on-site concept includes the use of waste heat from the energy conversion process (implemented either by photovoltaics or by a solar thermal method) for heating and cooling on the site where the conversion takes place. Waste heat use is considered very important by Ronal Larson of the Georgia Institute of Technology in Atlanta, Ga. Having worked in Congress on solar legislation as IEEE's first Congressional Fellow, Prof. Larson feels that declining oil and natural gas resourcees will dictate a more efficient use of waste heat from power generation. (At least two thirds of the energy consumed in the U.S. each year ends up as waste heat.)

The overall efficiency of conventional power generation is in the range of 35 percent. In comparison, a 15-percent efficiency may be obtainable in the photovoltaic conversion itself. But an on-site, "total energy" system, using this photovoltaic conversion system, along with its waste heat, is expected to have an overall efficiency of 50 percent and higher. Whether or not, from a total economics viewpoint, on-site systems are advantageous is more difficult to determine. Factors like capital investment, the size of the power system, its construction time and operating costs, and the expense of transmission and distribution systems make a detailed cost/benefit analysis an extremely complex task.

The milestone plan for the low-cost silicon solar array project, managed by Jet Propulsion Laboratory (JPL), Pasadena, Calif., for the Energy Research and Development Administration, calls for automated array assembly at a cost of less than \$500/kW and at a rate higher than 500 MW/year (solar to electric power conversion capacity), in 10 years time. JPL subcontracts parts of the program to industry.



*Delivery of 200-kW power producing capacity

Energy storage, integration with power grids

One disadvantage of most solar electric power generation methods, both in their direct (photovoltaics, solar thermal) or indirect (wind) applications, is that energy storage would be required to permit a continuous supply independent of the weather. In the U.S., for instance, the average available sun power is only about 20 percent of the peak value. In addition, backup power from other, conventional power generating methods (fossil, nuclear) would have to be made available in case of prolonged cloudiness (or lack of wind).

For short-period storage for single residential homes, available lead-acid batteries are considered adequate, but a much higher storage capability will be required for large-scale solar electric power stations. Various storage methods are being investigated, including electrical, thermal, mechanical, hydraulic, and chemical storage. Efforts in these areas are now concentrated on advanced electrical batteries; on heat storage in water or rocks, or in a medium in a status of phase change (for example, using the latent heat of melting); on huge flywheels revolving at very high speeds; on water pumping to higher levels from which hydroelectric turbines can be driven; and on generation of hydrogen, which can later be burned at will. Other, more exotic methods for storage of energy include air compression and energy storage in superconducting magnets. The most important factor in considering any storage method is the cost per kWh.

Backup power may be a real problem, at least from the utilities' point of view, in particular, in the absence of adequate storage. Imagine a large community that is based on solar electric power gradually hooking up to a local power grid (that provides backup power) after a prolonged time of cloudy weather, when all the stored energy has been used up. This would result in continuous load buildup on the local utility. That utility must therefore maintain a peak load capacity for exactly such occurrences, although the average load could be much lower—in other words, additional power generating and/or transmission capacity that would entail much more investment capital and maintenance cost.

Closely related to the above question is the problem of integration of solar power plants with existing power grids. In the case of photovoltaic conversion, to assure compatibility between the solar power plant and the power grid, *power conditioning* equipment is needed for converting the dc voltage obtained from the solar array into ac for transmission. Further requirements would include equipment for rectification of voltage from the power grid for storage, and electrical regulation and control equipment, to handle the varying output power of the solar array and its load demands. Equipment similar to the kinds mentioned, although on a much smaller scale, is now available and operational in aircraft. The problem of integration of future solar power plants with existing utility grids is now being investigated in a study sponsored by The Energy Research and Development Administration (ERDA) and EPRI at Southern California Edison Company, Rosemead, Calif.

Technical development needed

Apart from integration with existing utility grids, technical problems exist in all solar electric power generation schemes which will need solutions before commercial, large-scale applications can be carried out. In photovoltaics, the key objective is cost reduction by a factor of about forty, to 50¢/W (peak) for silicon solar cell arrays. (The goal for advanced solar cells for terrestial use, using thin-film approaches, is about 25¢/W.) And this objective must be achieved at no sacrifice in conversion efficiency (up to about 15-percent efficiency is believed to be obtainable with present technology). To accomplish this, arrays of solar cells would have to be mass-produced, and for this purpose, present manufacturing techniques of solar arrays would have to be examined. For example, reduction in the number of process steps, development of a continuous flow process, selection of high-speed processes, integration of array assembly with device fabrication, and reduction in energy use during the process would have to be carefully considered. Every approach will have to be pursued to the point where a clear decision can be made as to the merits of each.

Another problem is life expectancy of the solar arrays. While the silicon, in terrestial use, could maintain its properties indefinitely (in space it deteriorates due to radiation damage), the encapsulation material, which plays the dual role of transmitting the sun rays and protecting the array metal contacts, degrades with time. And what the specifications of "solar grade" silicon should be is another open question.

A study is now underway at Texas Instruments to determine the answer to this question, and, in the meantime, other materials offering cheaper manufacturing processes than those associated with silicon arrays are being examined. Thin-film cadmium sulfide (CdS) and copper sulfide (CuS) is one combination. Although generally known to have severe degradation problems, some CdS–Cus cells have performed satisfactorily for a relatively long time. Success has been reported by a French group in developing stable CdS cells. However, this subject is still a matter of great debate within the research and development community. Also, a question has been raised as to safety during manufacture and to poisonous gas hazards in case of cadmium fires.

Another potentially attractive possibility is the use of gallium arsenide (GaAs), which shows promise of eventual higher efficiency than that obtainable with photovoltaic cells from other materials. Also, gallium arsenide can tolerate more heat than silicon, a desirable characteristic for combined thermal-electric applications. Experimental and relatively expensive GaAs cells are made in the U.S. by Varian, Jet Propulsion Laboratory, IBM, and perhaps others. Reduction in size, and consequently in the cost, of arrays of GaAs cells is enabled through the use of plastic lenses—concentrators—a technique which is also used with silicon cells.

Technical challenges also exist in other solar energy applications for electric power generation. In the solar-thermal, central receiver concept, although all the elements of such a plant are within the capability of existing technology, extensive developments will be required to reduce capital equipment and construction costs. Developmental problems associated with the distributed collector power plant are somewhat different from those associated with the central receiver plant due to the need for efficiently transferring collected, thermal energy from a large area to a central point.

More advanced is the status of wind energy conversion systems (WECSs). Some wind power units are already being tested in utility grids. However, some problems still remain to be solved. The key problem is the intermittent nature of wind and its wide geographical and seasonal variations, necessitating storage and backup power discussed earlier. Also, insufficient experience in operational dynamics is causing uncertainties in estimates of costs and lifetimes of large-scale WECS units. Another difficulty is inadequate design data for large-scale systems (particularly those including many units). In addition, more information is needed on appropriate storage systems, user interfaces, and operational requirements.

In contrast to the intermittent availability of the sun's radiation or winds, temperature differences between ocean layers exist 24 hours a day and the oceans themselves constitute a huge natural solar collection and storage system—an apparent advantage of ocean-thermal energy conversion (OTEC) systems (see *Spectrum,* Oct. 1973, pp. 22–27) over other solar power technologies. However, technological efforts are required in OTEC systems, too, before they become commercially attractive.

The biggest technological challenge in OTEC is the design of heat exchangers, not only because of their relatively big size but, primarily, because high heat transfer efficiency is required at small temperature differences. In addition, the problems of "biofouling" by sea organisms that flourish in warm water and the potentially high corrosion rate due to sea water will have to be dealt with. And there is the potential mechanical problem of large drag forces from external currents on the relatively long pipe that will have to be used to bring cold water to the upper layers.

Impact on U.S. energy use

With the host of technical problems facing solar energy efforts, the immediate questions that come to mind are: what is the projected contribution of solar electric technology to the energy requirement in the U.S., and when will the impact of the various technologies be noticeable? Interpretation of an ERDA assessment, which is based on the assumption of reduced costs of solar electric applications to the point where they will become competitive with other electric power generation methods, shows an almost insignificant near-term impact—by the year 1985, only about 0.07 percent of the total projected U.S. energy demand is expected to be supplied from solar electric power plants. Even much later, in the year 2020, the projected impact of solar power is only 8.5 percent—less than direct solar thermal applications (heating and cooling, and agricultural and process heat applications, not discussed in this article) which might surpass 10 percent.

(For perspective, though, it should be kept in mind that *electric* energy now comprises about 10 percent of the *total* energy consumed in the U.S.) The most immediate impact of solar electric power is expected to be that of the solar thermal central receiver—power tower technology— and wind power. Demonstration of the latter is planned for the late 1970s and prototype units are in operation today. As far as photovoltaic systems are concerned, demonstration of units up to about 10 MW (electric) is projected to take place by 1983. Most other solar electric technologies will probably reach demonstration (precommercialization) stages in the mid-1980s.

But even before demonstrations take place, an important question, that of energy payback of the various solar power technologies, will have to be addressed. This question, which has been raised mainly in connection with nuclear power plants (see *Spectrum*, Aug. 1975, p. 53) asks how long it takes for a power plant to generate electrical energy equal to that consumed in the construction of the plant and in processing its fuels. The shorter this payback period, the less wasteful in energy that plant is. With solar electric technologies, there is hardly any data on manufacturing processes of many solar components and the answer about solar power plants can, therefore, only be estimated. According to Lloyd O. Herwig, scientific advisor in ERDA's Solar Energy Division, the feeling is that one plant can return its invested energy in a few months to one year.

Meager funding; institutional inertia

Many would probably agree that what is needed, more than anything else, is more financial help to solar programs. In spite of a growing Federal allocation each year for solar R&D, questions have been raised as to the adequacy of this funding. For ERDA, the total revised solar energy budget requested for fiscal year (FY) 1976 is $89 million, only about 4.5 percent of the total revised energy research and development budget that was requested by the agency for FY '76.

Public pressure, however, to increase the solar energy budget is high, and this is reflected in Congress. As this article goes to press, the U.S. Congress is reported to be near agreement on a number close to $150 million for solar energy, for FY '76. But even if this proposed increase is enacted into law, the heavy emphasis in ERDA's budget request for FY '76 will still be on nuclear fission and fusion. (Similarly, on the private front, the proposed 1975 solar energy budget in EPRI was only about 2.3 percent of the entire yearly proposed budget of the institute.)

Critical of this situation, Jerry Grey, administrator of public policy in the American Institute of Aeronautics and Astronautics, New York, N.Y., and private consultant in solar energy, whose background is both in nuclear and solar energy research, maintains that the technology for satellite solar power stations, for example (not explicity mentioned in ERDA's revised FY '76 budget request), could mature earlier than that of nuclear fusion (a budget of $264 million was requested by ERDA for FY '76 for fusion), and that the former should be pursued more vigorously, and, accordingly, it deserves at least a tiny slice of ERDA's budget. Even in the budget of the National Aeronautics and Space Administration, the amounts allotted for satellite solar power station research and development were unimpressive—$1.2 million in FY '74 and $1.1 million in '75—and these figures are not expected to increase radically (that is, by a factor of ten or more) in FY '76.

For further reading

An assessment of seven classes of solar-powered systems for generating energy (electric or otherwise) for terrestial consumption is presented in "Solar energy for earth," a publication of the *American Institute of Aeronautics and Astronautics*, New York, N.Y., dated April 21, 1975. (Much of the technological information included in this *Spectrum* article came from the AIAA publication.) An implementation schedule for a solar-electric applications program is included in the publication ERDA-48, vol. 2, of the Energy Research and Development Administration, called "Creating energy choices for the future," pp. 33–39. Another publication by this agency, ERDA-49, dated June 1975, includes the national solar energy research, development, and demonstration program in the U.S.

Environmental advantages

With difficulties on the economic, technical, and institutional levels, environmentally, at least, the picture is more encouraging. Future solar-electric power plants, based on solar-thermal or photovoltaic conversion may have local environmental effects—local waste heat may have to be disposed of, and albedo (that is, the reflection characteristics of the earth that, in turn, affect the temperature and convection pattern of air and generate local winds) may be affected. In addition, esthetic or visual effects will have to be considered. All of these are currently under study, and will be quantitatively and objectively evaluated. It is believed, however, that these effects will be insignificant compared to the effects of air pollution from fossil-fueled power plants (see *Spectrum*, Oct. 1965, pp. 56–69, Nov. 1970, pp. 40–50, and Dec. 1970, pp. 65–75), or to the effects of potential radioactive releases from nuclear power plants and the various stages of the nuclear fuel cycle during accidents (see *Spectrum*, Aug. 1975, pp. 46–55, and Sept. 1975, pp. 56–64).

Furthermore, solar power plants require no mines or wells, nor do they need mills, refineries, and elaborate transportation systems. And the problem of disposal of waste is practically nonexistent with solar power plants. Even the problem of the extensive acreage that will be required for solar power generation due to the diffused nature of the sun's radiation might sometimes be handled very constructively, as in the following illustrative example, given by a solar proponent: A large coal-generated power plant is operating in Four Corners, New Mexico. The generated power is intended for Los Angeles, and has to be transmitted some 700 miles away. During the plant's expected lifetime, some 100 square kilometers will have to be strip-mined for coal. Although a 1000-MW (electric) solar power plant using solar cells at 10-percent conversion efficiency might require a similar area, if it were to be constructed instead, the land itself could be reused or returned to its original use when the plant had completed its life, and no land reclamation programs would be required. ◆

Captain Eddy: the man who 'launched a thousand EEs'

His genius in getting things done meant success in training electronics technicians for the U.S. Navy in WW II

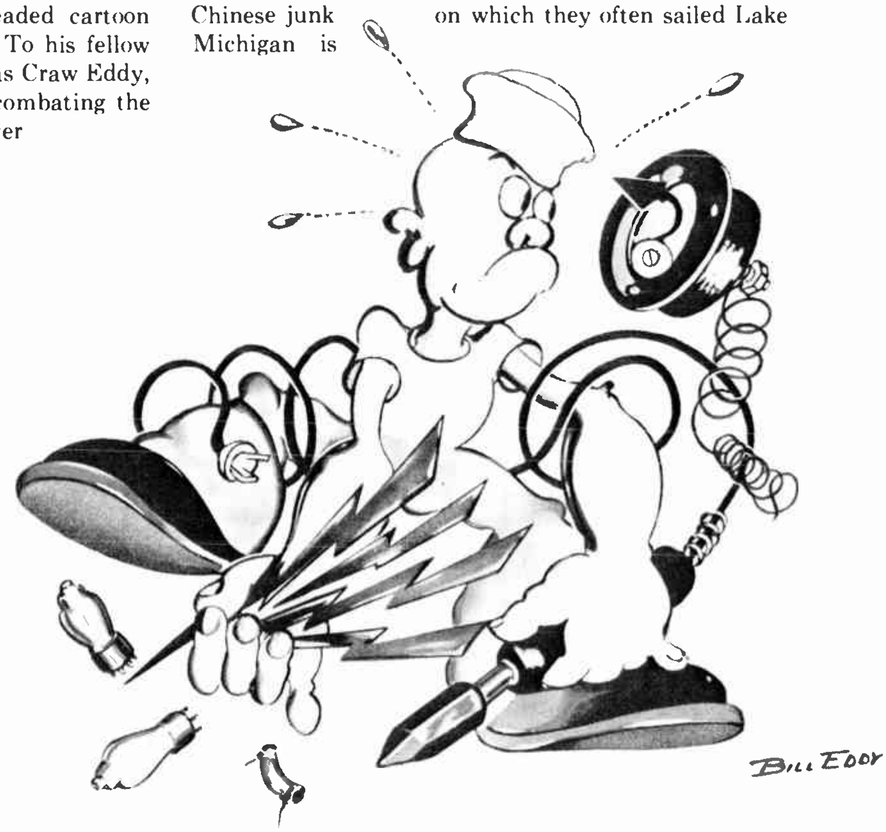
In early September of this year in Michigan City, Indiana, I met, for the first time, William Crawford Eddy, a man known to me previously only by reputation. Who is William Crawford Eddy? To me, and to thousands of others like me who were trained as electronics technicians in the U.S. Navy during World War II under the Eddy programs, he will always be Captain Eddy. To thousands of others who, over a span of 33 years, eagerly awaited each year the arrival of the new Honeywell calendar with its balding, egg-headed cartoon characters, he is Bill Eddy, cartoonist. To his fellow cadets at Annapolis, he is remembered as Craw Eddy, a student with unique capabilities for combating the establishment. And to his associates over the years in the television industry, he is known as Bill Eddy, inventive genius.

This year, in celebrating the 200th anniversary of the U.S. Navy, it seems appropriate to reflect both on Capt. Eddy—a brilliant, versatile, resourceful, and often unconventional man—and on the Eddy training programs that had a turning-point effect on the careers of many who are practicing EEs today.

Today, Capt. Eddy and his wife, Chris, live in a home located on a corner of a busy intersection in Michigan City, Indiana. In a telephone conversation prior to my visit, he had cautioned me that, in spite of its central location, the house was almost invisible from the street because of the dense trees and shrubbery. As I drove up the driveway to what I hoped was the right house, Capt. Eddy strode briskly forth and welcomed me. Inside, we spent an hour or two discussing the Navy electronics technicians' training programs as well as other facets of Capt. Eddy's career. Later we toured the several acres of land surrounding the house, which is now a unique game preserve of sorts.

Many years ago, the Eddys started taking in disabled or abandoned animals and birds, nursing back to health those that needed it, and simply providing food and shelter for the healthier ones. Today, there are about 100 birds and animals on the property. Capt. Eddy's ingenuity enabled him to get a special permit from the U.S. government allowing him to operate the sanctuary legally. Among the many creatures that are lovingly cared for are a blind raccoon, birds that cannot fly, and normal animals of all kinds who appreciate kind treatment and a good home.

Capt. and Mrs. Eddy spend most of their time these days at their Michigan City home, so the custom-made Chinese junk on which they often sailed Lake Michigan is



now in dry dock on the property. As a matter of fact, Capt. Eddy is readying it for sale. It seems that the birds and animals leave little time for boating.

Back inside the house once again, I saw some of the numerous examples of the works of William Eddy, artist. In addition to his cartoons, he has also worked in oils, creating beautiful paintings; made ceramic sculptures of fish and other animals; done intricate

Ronald K. Jurgen Managing Editor

wood carvings; and, at any time, is apt to take up a new, challenging art form.

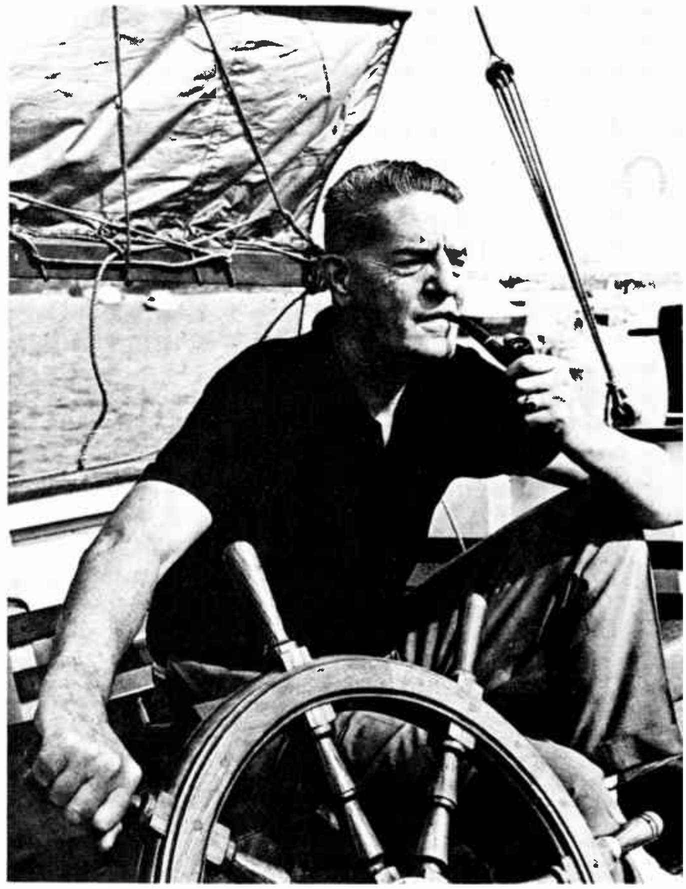
But what about the other careers of Capt. Eddy?

Within hours of the Japanese attack on Pearl Harbor in 1941, Capt. Eddy, then medically retired from the U.S. Navy, was on his way from Chicago to Washington. His objective was to be placed back on active duty. By the time his train reached Washington the following morning, he had a plan for the Bureau of Naval Personnel that would solve one of its most pressing problems: where to get the technicians desperately needed to maintain the new search and fire-control radars just beginning to reach the fleet. The Navy accepted the plan almost immediately—reinstatement to active duty took a little longer—and thus began the phenomenally successful Radio Technician and Aviation Radio Technician training programs. In 1945, the ratings became Electronics Technician's Mate (ETM) and Aviation Electronics Technician's Mate (AETM).

When Capt. Eddy proposed to the Navy that he set up a technicians' training program, both he and the Bureau of Naval Personnel envisioned a need for about 135 men to be trained. As it turned out, more than 185 000 men ultimately went through the program.

Capt. Eddy told the Bureau that in the Chicago television studio that he then directed for Balaban and Katz, a subsidiary of Paramount Pictures, there were men and facilities for teaching the needed high-frequency technology to the technicians. When the Navy gave its approval, civilian Bill Eddy returned to Chicago and told John Balaban, president of the firm, about the Washington trip, omitting mention of the fact that already promised to the Navy at no cost was the complete Balaban and Katz TV facility, including some $400 000 worth of equipment. When both John Balaban and his brother, the president of Paramount, gave the go ahead, Capt. Eddy and his engineers began enlisting men right off the street. Early students attended classes for a month without uniforms.

At first, Capt. Eddy interviewed personally all prospects for the program. When this became unwieldy and recruiters in the field were finding it difficult to determine the suitability of prospects, he worked up a written test that proved to be 90-percent effective in selecting candidates for the program. As Capt. Eddy readily admits today, the famous Eddy Test was not the type of aptitude test a psychologist would have devised. But it worked. Through probing questions,



the Eddy Test determined whether or not a prospect had the inborn mechanical ability to be taught the use of simple tools (see box, page 56) and the mental prowess to understand the complex electronics used in the Navy equipment.

Applicants for the Eddy Test were especially encouraged from two disparate age groups: 17-year olds for easy molding and enthusiasm and those 38 and older for maturity and responsibility. The younger ETM, Capt. Eddy felt, could fill the type of billet at sea where a group of ETMs would be present. The more mature and responsible man was usually assigned to duty where only one ETM was on board, such as on a picket or submarine.

Having passed the Eddy Test, the enlistee vaulted

Two years of college in ten months

At Radio Chicago, Capt. Eddy and his engineers devised an intensive, ten-month course to train electronics technicians for the Navy. They even wrote their own textbooks and trained their own instructors when necessary. One of the outstanding examples was a mathematics refresher book of 24 one-hour lessons. It took a new approach, at that time, by containing problems worked out in full so that puzzled students could see exactly how proper solutions were obtained. The ten-month course was broken up into three segments called Pre-Radio, Primary (Elementary Electricity and Radio Materiel), and Secondary (Advanced).

After the mandatory boot-camp training, Pre-Radio schooling took place in the Chicago area (at Wright Junior College, Hugh Manley School, Theodore Herzl School, and the Naval Armory at Michigan City, Indiana). Testimony to Capt. Eddy's ability to get things done, and to his uncompromising insistence on performance in the RT program, is provided by the fact that he convinced Mayor Kelly of Chicago to turn over to the Navy, the Chicago Board of Education Schools (Wright, Manley, and Herzl). But, later, Capt. Eddy routinely transferred Kelly's son out of the RT program.

Pre-Radio training was designed to bring to men of widely varying backgrounds a common level of technical knowledge in $3\frac{1}{2}$ weeks. A comprehensive review of high-school algebra was part of Pre-Radio training and the elements of electricity and the fundamentals of shop practice were taught in both lecture and laboratory classes. Eddy's students remember with nostalgia the super-size slide rule that was intro-

"Now You Guys Be Sure To Let Me Know If I Approach Overload Conditions"

over the otherwise mandatory grades of Apprentice Seaman and Seaman Second Class, becoming Seaman First Class directly. The Eddy program was open to all Navy inductees who had passed their preinduction physicals and had also passed the Eddy Test.

When I talked with Capt. Eddy in Michigan City, he stressed the fact that the RT program was successful only because of the dedication of the students, who more often than not put in ten hours a day of classroom and laboratory work; the enthusiasm of the instructors; and the total cooperation of the Navy and of individuals such as Chicago mayor Kelly (see box below). In retrospect, Capt. Eddy looks upon his days at Radio Chicago, the name for the program's headquarters, as just one phase of his career. And well he might, for a truly remarkable career it has been.

The inventiveness that would later lead to his obtaining 35 patents in such fields as optics, sound, light waves, and mechanics, manifested itself earlier in a somewhat different manner at Annapolis. By the beginning of his senior year, Midshipman Eddy's unique money-making schemes had earned him 148 demerits out of the 150 permitted before expulsion became mandatory. He set up a miniature roller-skating rink on the fourth floor of the dormitory hall and charged admission—until he was ordered to "cease and desist." He improvised a rifle range from his dormitory window, using campus figureheads of Benjamin Franklin, Nathan Hale, and Admiral Perry as targets. Midshipman Eddy knew that wind swirling in the courtyard be-

duced in Pre-Radio as a valuable classroom aid to the solution of practical problems.

Successful completion of Pre-Radio opened the door to Primary, a three-month program of advanced mathematics, alternating current theory, and an introduction to radio circuits. (Primary schools were in such locations as Chicago at the State-Lake building and in Del Monte, California; Great Lakes, Illinois; Gulfport, Mississippi; and Dearborn, Michigan.) Through a careful blending of theory and laboratory practice, and liberal use of visual aids such as giant meter displays, a vast amount of material was covered in a relatively short time.

An early assignment in Primary was the complete con- tion of a one-tube radio receiver. In the mechanical practice laboratory, the student began to develop his skills in soldering, wiring, drilling metal, and in reading and working with simple schematics. In the last month of Primary, each student built a five-tube superheterodyne receiver.

The final six-month phase of the program, Secondary (at locations such as Navy Pier, Chicago; Washington, D.C.; Treasure Island, California; and Corpus Christi, Texas), placed great emphasis on the need for a thorough understanding of the theory and practice of all Navy electronic equipment including radio receivers and transmitters, direction finders, and underwater sound gear. Laboratories were equipped with all of the latest models of such equipment and each student had the opportunity to perform experiments on, and correct simulated problems with, the same equipment that he would later maintain at sea.

Graduation from the Radio Technician or Aircraft Radio Technician program brought an RT 3/c or ART 3/c rating, the next step up from Seaman 1/c.

A typical question on the Eddy Test

Q. You have been filing a soft copper rod and find that your file has loaded up with copper filings. How would you correct this problem?

1. Heat file to cherry red and immerse it in cold water.
2. Use a precision scriber to pick out the copper particles.
3. Use a file card.
4. Immerse file in a saturated solution of HCl and agitate briskly to dissolve copper.
5. Discard file and requisition a new one.

Answer #3 is obviously the correct answer and, since "file card" is a name for a stiff metal brush common to machine shops, it would isolate the applicant with knowledge of shop techniques. Answer #2 would indicate a careless approach and answer #5 would indicate a "give up" attitude. Answers #1 and #4 indicate little knowledge of the problem and probably little mechanical background.

A former SecNav reminisces

What success I have had in life is in large measure due to the training and discipline provided by the U.S. Navy during my formative ages of 17, 18, and 19. In the fall of 1944, I was drifting somewhat aimlessly through high school and desiring to join the armed forces. By stroke of good fortune—through the encouragement and foresight of a typically outstanding high-school science teacher—I took the famous Eddy Test; by a greater stroke of fortune, passed. Promptly I became a high-school dropout and entered the Navy ETM program.

By luck, I was one of the few who landed in the school on State Street in Chicago where Capt. Eddy had his office. I can see him to this day, pipe jutting from a stern jaw, cruising through the classrooms and the laboratories, giving a Navy "well done" here and there, with a follow-up, "but you can do better."

Upon entering college in the fall of 1946, I was accorded immediate credit for the work done in this program and was able to complete engineering school in three years rather than four. The learning techniques taught in the program enabled me to effect a smooth transition from military to academic life.

For 5½ years, beginning in February 1969, I was privileged to serve the U.S. Navy and my country in the posts of Under Secretary and Secretary of the Navy. Once again, the technical training, the discipline, and the inspiration of the Eddy Program was put to good use—I even found my old slide rule which, although a little worse for wear, served to calculate the multimillion dollar contracts. Still on active duty were a few who had likewise profited from the Eddy Program and, be they admirals, or chiefs, or a service secretary, all were grateful to Capt. Bill Eddy.

John W. Warner, Administrator
American Revolution Bicentennial Administration
Washington, D.C.

low his window made marksmanship extremely difficult. At ten cents a round, he reaped profits while seldom having to pay off for accurate shooting—until he was ordered to quit.

On the Severn River near the Academy, he kept a motorboat he called "Opportunity" because he said it knocked once and then stopped. He used the boat to tow canoe loads of lazy cadets upstream. When Academy officials banned the boat from the river harbor, not-to-be-daunted Midshipman Eddy cleverly attempted to have his boat incorporated into the Annapolis fleet by sending a request to the then Secretary of the Navy, Curtis Wilbur. The letter was stamped "NO" and promptly returned.

After his commission, Ensign Eddy became a specialist in gunnery, naval radio, and sound detection. When he was transferred to the Asiatic submarine fleet, he was the youngest naval officer ever qualified to command an undersea craft without having attended the regular submarine school. Later, at the Navy's submarine school at New London, Connecticut, he invented devices still in use today for submarine warfare.

When Capt. Eddy retired from the Navy in 1934, he steered his career toward television. At the Farnsworth Television Laboratory, his inventive genius began to blossom and he obtained patents for superimposition of optical images and improvements in cold-cathode oscillating circuits. His work brought him to the attention of NBC in New York City. There, he added to his list of patents. Later, at Balaban and Katz in Chicago, another facet of his career opened up.

In 1938, J. F. Sullivan, advertising manager of Honeywell's Brown Instruments Division (now the Process Control Division) was on the same train with Capt. Eddy and happened to notice a cartoon he was drawing. It was "cartoon love" at first sight and Mr. Sullivan, who at the time was in the process of trying to come up with a non-pinup-type calendar to send to the division's customers, asked for cartoon samples for the calendar. He was so pleased with the results that he signed Bill Eddy to a lifetime contract to create cartoons exclusively for the Honeywell calendar, an association that continued through 1971. The end of the Eddy cartoon calendars was a great loss to the thousands of Eddy fans, who over the years had pinned his sympathetic characters to shop and laboratory walls, appreciative of his unique ability to translate into humorous drawings, man's inability to cope with the machines he builds.

Shortly after the close of World War II, Capt. Eddy formed Television Associates of Indiana, a manufacturing and engineering service organization. While heading this company, he developed a new method for obtaining accurate profiles of the earth using radar in low-flying planes. An airborne Honeywell recorder produced a true graph of the earth's profile along the flight path. (Along with his corporate and cartooning activities, he still found time for a monthly trip around the world to inspect his company's eight field offices.)

Capt. Eddy retired a few years ago but today, at 73, is as active as he has ever been in his multifaceted career. After years of extensive traveling throughout the world, he says that he and Mrs. Eddy are content to stay put in Michigan City. But you can be certain that, to Capt. William C. Eddy, staying put will never mean being idle. ◆

Special thanks are due Gene Murphy of Honeywell, Inc., who worked with Capt. Eddy on the Honeywell calendars, for providing background material and for permitting us to reproduce one of the Honeywell copyrighted Eddy cartoons, and to the U.S. Navy for the drawing of Capt. Eddy's sea-going "electroniker."