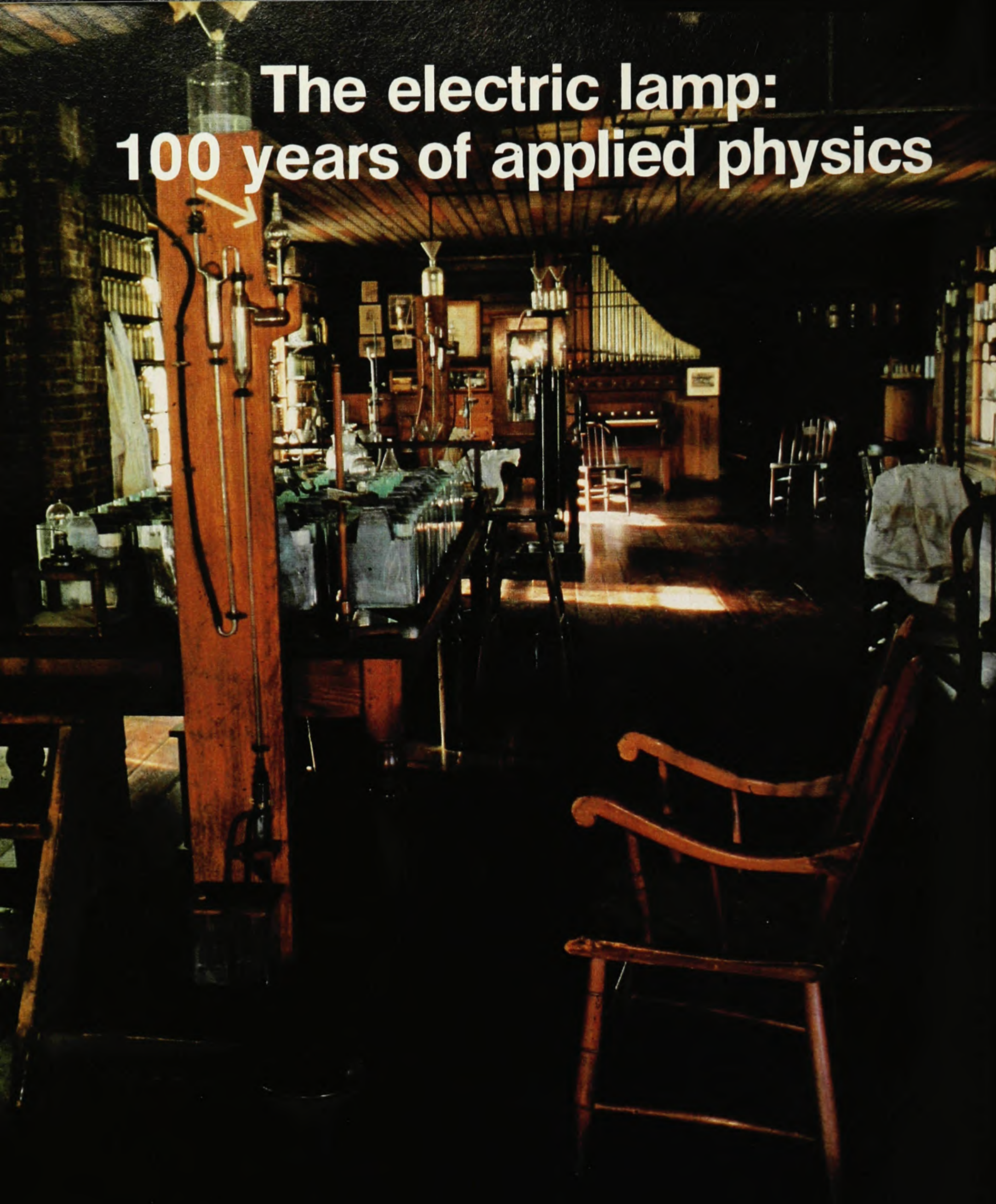
The electric lamp: 100 years of applied physics



Since Edison's success, progress in physics and in materials science has produced much more efficient and powerful incandescent sources as well as lamps based on gas discharges and luminescence.

John M. Anderson and John S. Saby

Night-time in 1879, but a scant 100 years ago, was considerably darker than the nocturnal world of today. Artificial illumination was limited to kerosene lamps, illuminating gas, the just-emerging arc lamp for street lighting and a few lingering candles.

Illuminating gas manufacture and distribution had become a well established fact by 1870, having grown rapidly from its commercial origins in about 1800. Even though there was the ever-present danger from explosion and asphyxiation, the gas industry, content only to generate and distribute gas, was lethargic toward research to find better light sources. Efforts in this direction had to come from other quarters. Arc lighting was one such, growing steadily in interest from the first demonstration about 1810 of an electrical arc between charcoal electrodes by Sir Humphrey Davy to the Royal Institution in London. However, a sustained electrical source at high power for commercial arc lighting was not available until the 1870's. It came in the form of dynamos based, in principle, upon a half century of electromagnetic discoveries by Michael Faraday, Joseph Henry, André Ampère, and many others. The arc-lighting industry grew rapidly from the first commercial installations in about 1880, and prospered for 40 years, until better light sources forced its demise.

Another challenge to the illuminating gas industry came in the form of solids made incandescent by electrical current. For their origin we can also go back to Davy who heated platinum to incandescence in 1802. Although the potentialities were apparent, and a number of persons worked in the period up to about 1870 to place platinum, iridium, and carbon rods in vacuum or inert atmospheres, all fell short of a lamp that would burn for an extended period. Probably the biggest problem was attainment of a good vacuum. Another factor, just as for arcs, was the lack of a powerful sustained electrical source.

In 1878 Thomas Edison joined the ranks of those striving for a practical incandescent lamp: Joseph Swan and St. George Lane-Fox in England; William Sawyer, Albon Man, Hiram Maxim and Moses Farmer in the United States. The controversy over who in fact invented the incandescent lamp still rages today, especially the choice between Edison and Swan. Both made contributions—for instance, Swan insisted that carbon was the answer—but we do find it without question that Edison devised both a practical lamp of reasonable size and a complete electrical system, with both generation and distribution, to exploit his lamp. Because his first carbonized thread lamp ran 40 hours before intentional overvolting destroyed it, and because this happened on 21 October 1879, we take this as the starting point for a century of active lamp research and development, a century rich in interplay between physics and technology.

Edison's laboratory at Menlo Park, New Jersey. This is a reconstruction (built by Henry Ford in the 1920's) at Greenfield Village, Michigan of the laboratory the way it was at the time of Edison's work on the light bulb. It is now part of a museum. (Courtesy of General Electric Co.)

The understanding of light production in lamps follows from physical principles. By 1879 light was well established as a transverse wave motion, its velocity about 3×10^8 m/s, its spectrum observed, including both ultraviolet and infrared. Kirchoff's cavity radiation defined its laws of total emission and absorption. Radiation from incandescing solids was called "temperature" radiation. To this, Paul Drude (*Theory of Optics*, 1902) further defined "luminescent" radiation resulting from a *change* in the radiating body. What was really meant by this had to await explanation based upon the quantum theory. Luminescence is now universally defined as radiation in excess of thermal, and further defined by the manner of excitation—for example, cathodoluminescence by cathode rays, photoluminescence, and so on.

As the physics of light production became better understood, the level of lamp technology improved. And those in search of better lamps have occasionally discovered new science, including for example, thermionic emission, plasma phenomena and chemical transport theory.

In this article we will follow the historical sequence of lamp development, in incandescent and various kinds of discharge lamps, to the present day. We will give special attention to the efficiency of the different lighting techniques and look to see what improvements in efficiency we might expect in the future.

"Subdividing" light

The arc lamps of the 19th century were noisy; they flickered and gave off noxious gases. Although they were producible in sizes down to 500 candle power, about 6000 lumens, or equivalent to two 40-watt fluorescent lamps, they were hardly usable in the home. The need was clearly recognized for some means to "subdivide" light. Also, arc lamps were operated in series, so that when one was extinguished, all went out unless proper bypass circuits were used. Edison, following the gas-industry practice, imagined a parallel-wire distribution, wherein voltage would be held constant and lamps could be added or dropped at will. To do this he required a high-resistance incandescent conductor in the lamp, starting initially with about 130 ohms. On this point he stood very nearly alone, and it is this vital concept, was well as his practical lamp, that earned him worldwide recognition. Edison, in fact, coined the term "filament" for the incandescent conductor, which is universally used today. Most workers in the field of electric lighting, including Swan, preferred a low resistance, analogous to the series arc system. Some, like Lord Kelvin and John Tyndall, totally rejected the idea that light could be "subdivided."

Thermal radiation had been well defined experimentally before Max Planck determined the theory in 1900. Scientists therefore recognized that the incandescent wire must have a high temperature to be efficient, that is, to have appreciable radiation in the visible spectrum. The first successful incandescent material was carbon because of its very high sublimation temperature. In practice it operated at about 1700° C, and the life of lamps was limited by evaporation to about 300 hours. Platinum was dangerously close to melting (the melting point is 1773° C) before it gave similar efficiency. On page 36 we show electron micrographs of some early filaments.

After a practical lamp had been secured, work began to measure its characteristics. Following the many experiments of James Joule to find the mechanical equivalent of heat, it seemed natural to find the mechanical equivalent of light, which ultimately was taken to mean the power input required to produce a unit of photometric light—in other words, what we now call the watts per lumen. By 1900 scientists recognized the eye's sensitivity curve, and they had defined a candle as a light source emitting 4π lumens. Herbert Ives[1] measured, in 1910, the emission at the peak of the eye's sensitivity curve, at a wavelength $\lambda = 550$ nm, and found that the emission was equivalent to 0.0012 watts per lumen or about 830 lumens per watt. Today we take this number to be 683 lumens per watt.

Edison's early incandescent lamp was far from ideal. On the lamp's 50th anniversary in 1929, scientists made photometric measurements on a replica of Edison's first carbonized sewing-thread lamp. The lamp gave 1.4 lumens of visible light per watt of total electrical input. By comparison, (see the graph on page 38) a modern incandescent lamp has 17.4 lumens per watt, a figure that is considered "lossy." Lumens per watt, defined as the lamp's "efficacy" (formerly "efficiency"), is a measure of the lamp's efficiency as a light source.

The incandescent lamp industry grew explosively. Edison formed a number of companies to manufacture lamps, dynamos, wire and components. The Pearl Street power station in lower Manhattan was opened in September 1882, and its

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complete success proved to any lingering doubter that the incandescent lamp was ready to provide a needed service.

Edison continued to experiment with lamps, producing continually improved designs. In 1883 he discovered an effect—the "Edison effect"—that was a precursor of the thermionic tube.

Improving the filament

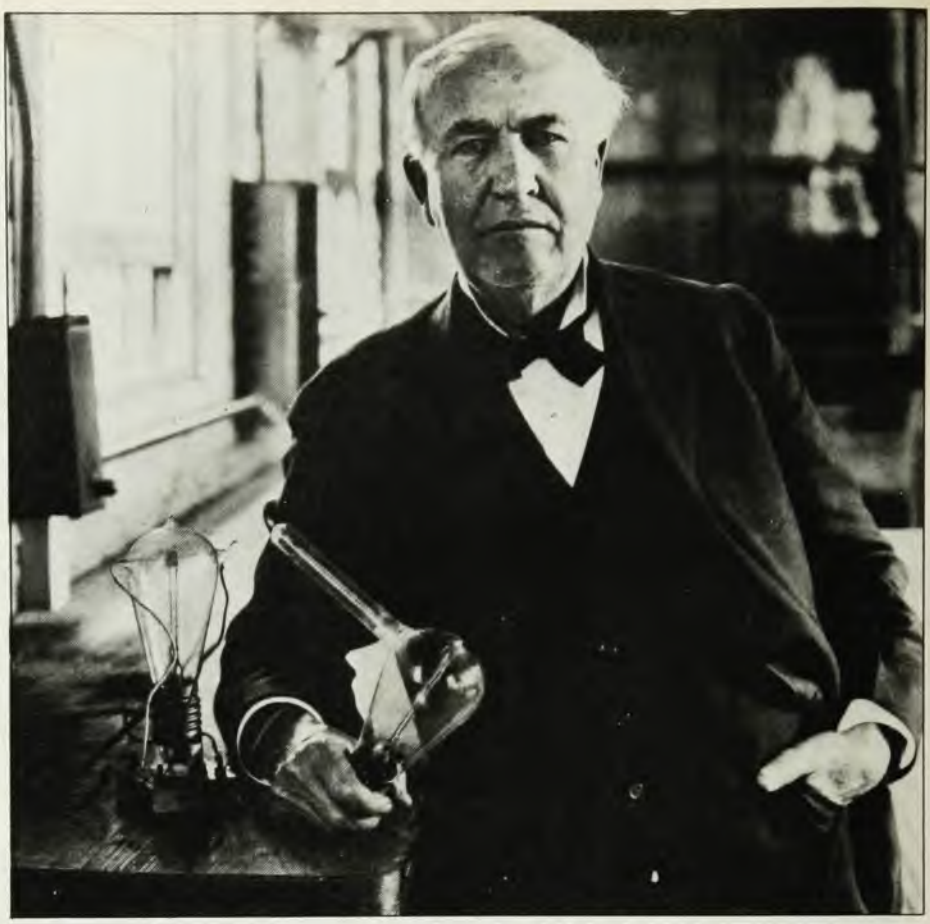
By 1900 Edison believed there could be no further advancement in the carbon incandescent lamp. In a way he was right. Carbon lamps were mature, but Edison did not anticipate one further development, Willis Whitney's "metallizing" of a flashed filament. This was done by heating the filament to over 3000° C in a carbon resistance furnace; the flashed appearance and temperature coefficient of resistance resembles that of a metal.

In 1897, Walter Nernst, professor of chemistry at Göttingen, devised the "Nernst glower," a variation on the incandescent lamp. The glower was a slender rod of refractory oxides, mostly zirconia (about 85 percent), with yttria and erbia (about 15 percent). Other trace oxides were also included. When indirectly preheated, the rod became an "electrolytic" conductor, typically operating at 0.25 amperes and 200 volts to give 32 candle power. The Nernst lamp was a selective radiator, which accounts in part for its relatively good efficacy. The exact mechanism of conduction was unclear until 1954 when Joseph Weininger and Paul Zemany found that oxide ions were the mobile charge carriers in the rod.[2]

As refractory metals began to appear commercially, it became clear that the days of the carbon lamp were numbered. Osmium, with a melting point of 2700° C, was developed in 1898 by Auer von Welsbach and marketed to a very limited extent, being brittle and quite scarce. Tantalum with a melting point of 2850° C, was not so brittle, more plentiful, and enjoyed considerable popularity from 1905 to 1910.

Tantalum filaments became prone to a failure that later also plagued tungsten filaments: After some hours of being heated, the metal recrystallizes, sometimes with boundaries normal to the wire axis. As these crystals offset, the area of contact between them becomes smaller, and that leads to failure of the lamp.

Tungsten, with a melting point of 3380° C, was the next metal to come, and it remains on the scene to this day. Early processes reduced and sintered the tungsten into filaments. Alexander Just and Franz Hanaman reported, in 1904, the first practical process: they heated tungsten powder in an organic binder under a moist hydrogen and nitrogen atmosphere to remove all carbon, leaving substantially pure tungsten in a matrix (see the electron micrographs on page 36).



Edison. In this photo from around 1883 he is shown with bulbs demonstrating the "Edison effect," which was later shown to be thermionic emission. His other activities kept him from following up on the discovered effect, but he did send sample tubes to other investigators. John Ambrose Fleming, in England, was the first to use the effect to make a diode in 1905. (General Electric Co.)

The efficacy of the tungsten lamp, even at its initial value of 7.8 lumens per watt, was enough to displace all previous incandescent lamps in about ten years, as shown in the graph.

However, the tungsten filament was brittle, and the prevailing wisdom was that it could not be made ductile. William Coolidge, after many years of work, solved the problem by hot working below the annealing temperature. His technique draws out the tungsten crystals into fibers along the wire. But when the filament burns above the annealing temperature in a lamp, it recrystallizes and tends to offset, as we mentioned above for tantalum, as shown in the electron micrographs on page 37. To prevent this problem, Coolidge at first added thoria to inhibit grain growth, so preventing the offset but created another problem: thoriated filaments sag during burning. Later, potassium was added to promote fibrous structure, minimizing transverse grain boundaries, and, consequently, the sagging.

Until 1910, all lamps with oxidizable filaments were operated in vacuum. They all suffered from the evaporation of the filament material, which darkened the glass envelope and progressively reduced the light output.

Perhaps the last major advancement for improvement of efficacy in the common tungsten incandescent lamp was Irving Langmuir's introduction of an inert gas, first nitrogen, and then in 1918, argon, after it became available in volume. This technique retarded evaporation. Langmuir's work in this area led to many other contributions by him—space-charge laws and plasma sheath work, to name but two.

The tungsten lamp story is by no means complete at this point. Elmer Fridrich and Emmett Wiley found, in 1958, that lamps with one or more of the halogens can achieve more lumens per watt than conventional lamps of the same life.[3] This improvement is brought about by a regenerative cycle: Tungsten on the glass (or quartz) envelope reacts with free iodine or bromine and a trace of oxygen to form volatile halides and oxyhalides. These materials are in turn decomposed near the hot tungsten. Thus, in the ideal case, tungsten is kept off the glass wall. One may then use a smaller envelope, to permit a higher pressure of rare gas, and in turn, slower evaporation of the tungsten. One can operate the filament above 3000 K, instead of the usual 2800 K. This raises the efficacy above 20 lumens per watt. Although they are not yet used in the mass home market, these lamps are finding increasing application where their

Replica of the first electric lamp. Its filament is a carbonized sewing thread. Edison himself made the replica in 1929, at a celebration of the fiftieth anniversary of his original achievement organized by Henry Ford in Dearborn, Michigan. Edison's lab was moved to a nearby site and restored for the occasion. (Photo courtesy of US National Park Service, Edison National Historic Site.)

benefits justify their higher cost; examples are film projectors and automobile headlights.

The evolving electric-discharge lamp

Even though Davy demonstrated an electrical arc in air in 1810, the first practical arcs for lighting did not appear until about 1880. For lack of any real scientific understanding about them, electrical arcs were little more than phenomena, albeit with practical application, until at least the beginning of the 20th century. The major discoveries in physics in the last years of the 19th century and up into the 1920's permitted an explanation of the many previous empirical observations both for low- and high-pressure discharges.

Faraday, about 1835, evacuated glass tubes to 3–4 torr and observed the major regions of glow in a low-pressure discharge. Heinrich Geissler, a physicist at Bonn and a skilled glass blower, made discharge tubes and invented a mercury vapor pump that generated a much better vacuum. Geissler's tubes were extensively used in research laboratories throughout Europe. At lower pressures the glowing gas seemed to disappear leaving only a fluorescing of the glass envelope. Julius Plücker (1859) deflected "rays" from the cathode with a magnet; Johann Hittorf and and Sir William Crookes discovered, in 1869 and 1879, shadow effects due to "cathode rays," and Eugen Goldstein discovered "canal rays" behind holes in the cathode in 1886. In time scientists suspected that the rays were particles and J. J. Thomson undertook, in 1897, to measure their charge and mass. At first he could not believe his results, namely that the ratio e/m was exceedingly large, but soon the concept of an "electron" could not be avoided. The indivisibility of the atom, held generally throughout the 19th century, was shattered. Wilhelm Wien (1889) capped the century by showing that the canal rays were positively charged atoms from the gas in which the discharge took place. The concept of electron ionization of the gas, coupled with the already well-developed kinetic theory of gases, then permitted a serious study of gas-discharge phenomena.

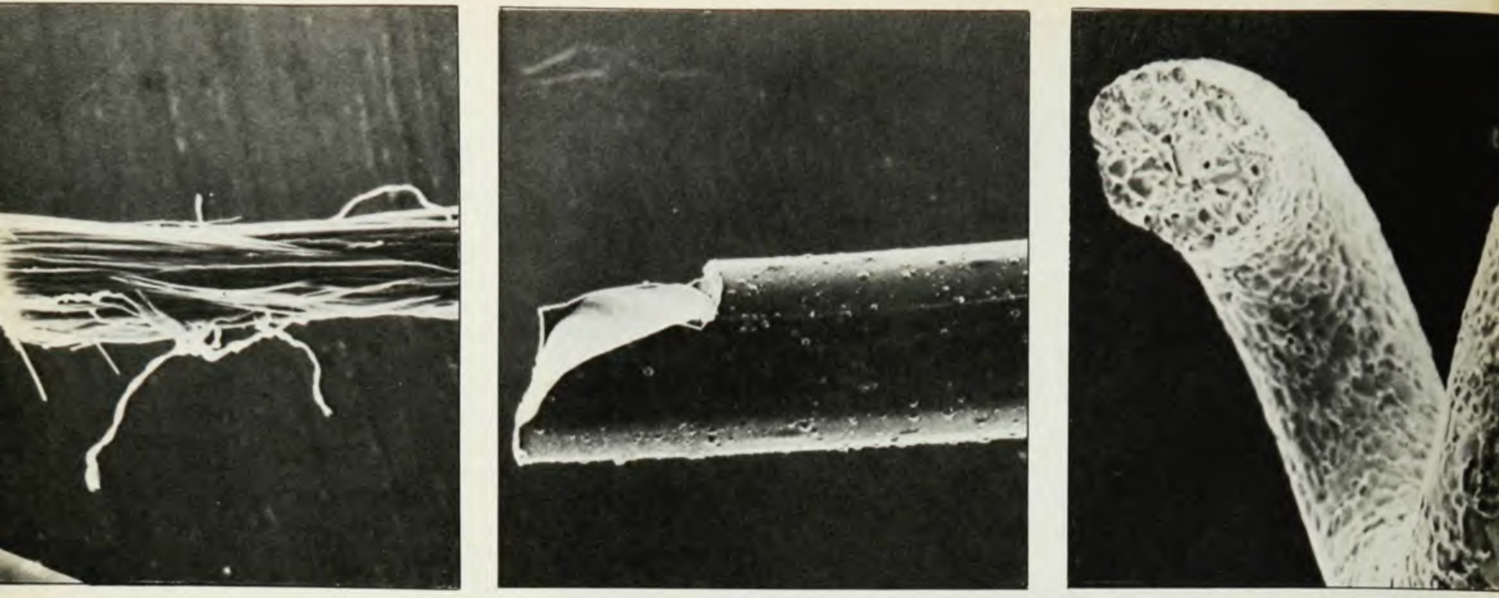
Even though arcs burning in air gave efficacies up to 25 lumens per watt, another promising development was taking place. Geissler tubes were early recognized as good light sources—in essence they are our neon signs today—but their life was short because of gas clean-up. The first practical low-pressure discharge lamp was, in 1895, that of D. McFarlane Moore. He established discharges in air, nitrogen, or carbon dioxide at a pressure of 0.1 torr. The discharges, at more than 10 kV between cathode and anode, took place in glass tubes up to 60 meters long. The tubes enjoyed some popularity, mostly because of the good color, but by 1912, the technique was on the way out. The Cooper–Hewitt lamp that had become known in 1901 was a more convenient and less expensive lamp with an efficacy up to about 15 lumens per watt. It was a low-pressure discharge in mercury from a liquid cathode to an iron anode. There were many lamps sold for applications where color was not important, for as Maurice Solomon in his book *Electric Lamps*, in 1912, tells us, " . . . the almost complete absence of red and yellow lines in the spectrum causes all colored objects illuminated by mercury vapor lamps to lose their natural colors, and people present the appearance of the dead."

Discharges in gases at the turn of the century were probably more important for helping to establish the evolving quantum physics than for light sources. Line spectra from discharges could now be explained as discrete energy changes in the atom according to Niels Bohr's model of 1913. In the same year, James Franck and Gustav Hertz observed step-wise retardation of electrons by gas atoms. That observation provided direct evidence that there are discrete atomic energy levels and that atoms can be raised to excited levels by collisions with electrons. Einstein's theory of spontaneous emission, absorption, and stimulated emission in 1917 gave a quantitative basis to emission intensity and density of states. Even the more subtle observations of spectroscopy were explained by the wave mechanics of the mid 1920's. A firm theoretical basis now existed for further lamp development.

As material science developed, the many discharge lamps that had been envisioned, some even before 1900, became possible. A major step, for example, was the quartz–molybdenum seal, which became available after World War II. This technique, coupled with the oxide cathode, made a high-pressure mercury lamp with efficacy above 50 lumens per watt practical for widespread use. Today a variety of discharge lamps, both high and low pressure, is used in general lighting.[4]

The low-pressure sodium lamp, one of today's discharge lamps, is useful where geometrical light control is unimportant and where monochromatic illumination is acceptable. First introduced in Europe by the Philips Company in the 1930's, it utilizes a sodium-rare-gas discharge that channels about one third of the total input energy into the yellow sodium resonance "D" lines. Physically, it consists of a long arc tube similar to that of a fluorescent lamp, but lined with sodium resistant glass.

It also shares with the fluorescent lamp



Early lamp filaments. These scanning electron micrographs show (left to right) carbonized thread from a reproduction of Edison's lamp (#8 mercerized cotton); a GEM carbon filament, made by squirting cellulose through a die to make a uniform filament that was then covered with a graphite layer; and a sintered tungsten filament from Langmuir's first successful gas-filled lamp. (SEM photos by H. F. Webster.)

a high efficiency of generation of resonance radiation. Because the vapor pressure for optimum efficiency requires that the arc tube operate above 200°C, there are energy losses even though the lamp has an elaborate thermal insulation. The primary loss mechanism in this discharge is heat conduction to the walls of the arc tube (see the table on this page). Refinements of this heat-conserving structure are credited with most of the improvements to the present efficacy, which in the larger size lamps (the 180 watt low-pressure sodium lamp is more than a meter long) exceeds 180 lumens per watt.

Discharge lamps require electrical circuitry called "ballasts" to maintain the required voltage and current. Because of ballast losses the overall efficiency of the lamp-ballast system is lower than that of the lamp alone. Technology exists however, to keep ballast losses below 10 percent in most cases.

Exciting phosphors to fluoresce

At 80 lumens per watt, the fluorescent lamp is one of the most efficient lamps in general use (see table). Introduced in 1938, it consists of a long, phosphor-coated glass envelope, commonly 38 mm in diameter, filled with 1–2 torr of a noble gas plus a small quantity of mercury. Applying a voltage creates an ionized conduction region between the lamp's electrodes. At normal operating temperature, slightly above room temperature, only a few millitorr of mercury are present; yet mercury with its first resonant line at 254 nm dominates the spectrum. This ultraviolet radiation excites the phosphor coating. In turn, the phosphor creates nearly all the visible light produced by the lamp; only a few percent of the total light comes from visible lines in the mercury spectrum.

Willem Elenbaas studied the mercury–rare-gas discharge and reported his results in the early 1930's. Later, in 1950, Carl Kenty made a careful study of energy-state density in, and radiation from, the fluorescent-lamp discharge.[5] Still later, in 1956–57, John Waymouth and his colleagues showed the way to improve efficacy in lamps with higher loading (watts per unit length).[6] He proposed adding neon to the argon gas.

The ionized conduction region in the fluorescent lamp was the target of a recent study, in 1972, by P. C. Drop and Jan Polman.[7] They calculated the response of the discharge column to signals at up to megahertz frequencies and found that while the behavior in the conduction region at intermediate frequencies deviated in energy states and electron densities from dc behavior, at high frequencies it again approached that under dc fields.

Today, fluorescent lamps produce about two thirds of all the electrically generated light in the world—twice as much as all other lamps combined.

Generating high-intensity discharges

The high-pressure mercury lamp, the first member of a growing family of high-intensity discharge lamps, emerged in the 1930's.[8] It has an inner quartz arc tube surrounded by an envelope that protects its leads from oxidation. The inner tube contains sufficient mercury to produce about 1.5–2 atmospheres when fully vaporized. It also has approximately 20 torr of argon starting gas.

High-pressure mercury lamps waste about 33 percent of their energy as ultraviolet radiation, primarily at 185, 254 and 365 nm (see table).

Power Balance of Existing Lamps

	Power	Efficacy	Part of input power, percent			
			Radiated		Not radiated	
Type	W	L/W	Visible	Not used	Conduction	Ends
Incandescent, general service	100	17.5	7	80	13	
High-pressure mercury	400	52	15	33	42	10
Low-pressure sodium	180	183	36	4	50	10
Fluorescent	40	80	23	40*	17	20
Metal Halide	400	100	34	20	36	10
High-pressure sodium	400	120	30	20	40	10

*32% lost in the phosphor

Coiled-coil tungsten filament. On the left is a scanning-electron micrograph of a filament from a conventional 100-W lamp, fresh from the factory. On the right is similar filament from a bulb that had burned for about 500 hours. Note the growth of crystal structures, outlined by thermal etching, and the start of a few offset fractures; some of the crystals extend over several coils. (SEM photos by H. F. Webster.)

Scientists have been trying to suppress the ultraviolet radiation and improve the visible light output by adding to the inner tube elements with visible atomic spectra. Unfortunately metals, the most desirable additives, are not sufficiently volatile to attain the required concentration in the vapor. Also, many metals form mercury amalgams, which reduce the metal vapor pressure even further. In 1960 Gilbert Reiling discovered that metal halides added to mercury lamps can produce the desired concentration of metal atoms in the vapor. The metal halide lamps that emerged as a result of this discovery are more efficient than high-pressure mercury lamps (see table) but they have somewhat shorter lives. The chemically active species inside attack metal parts and even the quartz tube itself.

High-pressure sodium

In the past few years city streets have been seeing a rapid shift from high-pressure mercury to high-pressure sodium lighting. High-pressure sodium lamps radiate over much of the visible spectrum, giving a golden-white light. The discharge mechanism of high-pressure sodium, whereby resonance "D" lines are broadened and reversed by self absorption, is mostly responsible for the very broad spectrum.

The key to the achievement of this useful discharge was the development of a special arc-tube material, translucent polycrystalline alumina. This material is cheaper than single-crystal alumina, which would also be chemically suitable and translucent. Not only is polycrystalline alumina chemically resistant to sodium but it is also capable of operating when the temperature at the center of the arc tube reaches 1200° C. At this central temperature the cooler ends are hot enough to maintain adequate sodium pressure for optimum light generation.

High-pressure sodium lamps are small—a 400-W arc tube is 10 cm long and it has a diameter of 8 mm, an advantage in some applications. One can also trade off the relatively high efficacy (see table) for improved color rendition. This tradeoff entails a higher pressure of sodium vapor over the Na–Hg amalgam and consequently a higher temperature within the arc tube and increased infrared losses.

Lamps as indicators

During an electric discharge in gas at low pressure a region near the cathode glows. This phenomenon has been known since Faraday's time. But in 1928 modern neon-glow indicator lamps became possible when Theodore Foulke combined argon and neon to form a Penning mixture. In such a mixture metastable atoms of the majority gas ionize the minority gas atoms, which leads to a lower starting voltage. This technique allows reliable starting of the glow at voltages below 120 V.

In some fluorescent materials—semiconductor phosphors—one can produce light by radiative recombination of hole–electron pairs. Although these phosphors have not been in general illumination use, they have facilitated a variety of widely used special-purpose electric light sources.

A good example is the television screen. Used today only for information display, the screen employs excitation of a phosphor layer by an electron beam. Given sufficient future improvement in phosphors and electron sources, the technique could potentially be applied to general illumination.

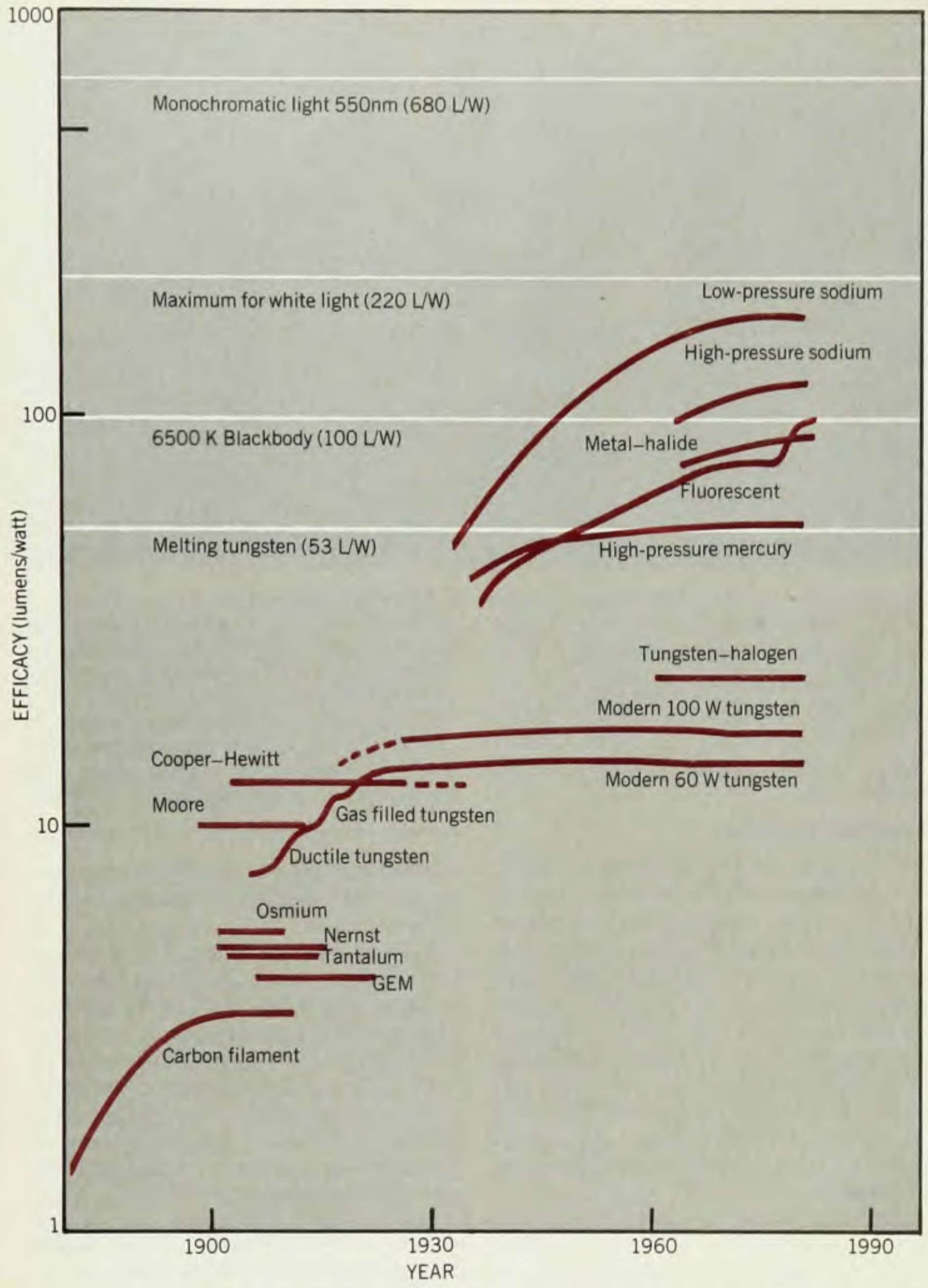
One can also excite electrons within luminescent materials by applying external electric fields. Discovered in 1937 by Georges Destriau, this technique made possible one highly specialized application: the thin fire-safe electroluminescent-illuminated instrument panels used some years ago on all the NASA Apollo command spacecraft and Lunar Excursion Modules. Unfortunately, due to the low efficiency of the electron-impact excitation mechanism, the Destriau effect has limited potential for general illumination.

A very efficient way of generating hole–electron pairs is by carrier injection across rectifying junctions. Oleg Loessev discovered light production by this phenomenon in silicon carbide as early as 1923. Efficient light generation here requires high injection ratios, a high proportion of radiative recombinations of hole–electron pairs, and rectifying structures that enable escape of light. Electroluminescent light-emitting diodes embody such structures. These diodes pervade the displays in electronic wristwatches and pocket calculators.

Though not cheap or efficient enough for general illumination, light-emitting diodes have adequate quantum efficiencies for use in indicator lights and in injection lasers in gallium arsenide and similar materials. (Quantum efficiency is the ratio of the number of photons emitted by a material to the number of electrons or ultraviolet photons incident on that material.) Another type of indicator lamp combines phosphors that convert infrared radiation into visible light with gallium-arsenside light-emitting diodes. These devices convert 0.9 micron radiation in the infrared into visible light.

Increasing the efficiency

What are the large challenges for the next century of electric light? The most important shortcoming of electric illumination is its low efficiency. Even the most efficient electric lamps require about



Approximate efficacies of various light sources. We plot efficacies as a function of time for different kinds of electric lamps, showing the evolution within each technology as well as progress from one technology to another. We also indicate efficacies of several standard sources.

three watts of electric power for every watt of visible light.

Consider the tungsten incandescent lamp, the lamp with the lowest efficiency among all widely used electric lamps (see table). About 80 percent of the tungsten incandescent lamp's energy input is radiated at non-visible wavelengths, primarily in the infrared. The nonradiated losses are primarily due to heat conduction, partly via the electrical leads, but mostly by the inert-gas filling. Even with gas-conduction losses reduced as much as possible by use of heavier and more expensive inert gases, the efficiency of incandescent lamps can be improved by only a few percent.

Thus any significant improvement in the incandescent lamp must be obtained by reduction of the infrared losses.

One technique under study is to use infrared reflection toward the filament, which could help maintain the high filament temperature at a fraction of the electric energy input of present designs. This technique could double the efficacy. Ironically, this and similar ideas have been occupying researchers' minds during a good part of this century. Approximately 50 US patents on various means of increasing incandescent lamp efficacy by infrared reflection have been issued since 1912.

Reducing the infrared-reflection technique into a practical incandescent lamp design is quite tricky. The energy saving depends critically on the spectral characteristics of the sensitive reflection arrangement. This includes absorption of visible light, as well as the effective emissivity of the coil. Tungsten coils are difficult to design with effective emissivity much greater than 0.5. Geometrical perfection of the reflector, and reasonable accuracy of placement of the coil within the reflector are also important. The Duro Test Corporation has recently announced the development of such a selective-reflector lamp.

Another technique for improving incandescent-lamp efficacy is also available, at least in principle. One can add phosphors to the lamp to absorb radiated infrared and emit visible light. One can excite such phosphors into intermediate energy levels through successive absorption of infrared photons. When the phosphor has absorbed sufficient energy, it radiates a visible photon. Although such phosphors have been used in light-emitting diodes, their efficiency has not been high enough to warrant their use in lamps, especially when absorption of visible light is taken into account. This technique, however, warrants further exploration.

One may ask what would the characteristics of a superior lamp look like? Such a lamp should be compact; it should also be compatible with existing sockets for incandescent lamps; its efficacy should be higher than 40 lumens per watt, and its cost should be low enough to justify adoption by the public. *A priori*, gas-discharge light sources appear to have the best chance of filling these needs. The main hurdle would be the ballast; historically ballasts have added cost and complexity of installation to discharge lamps. However, technology exists today to make sufficiently small electronic ballasts that could conceivably be integrated into the lamp and permit screw-in installation. The General Electric Company recently announced development of such a lamp, the "Electronic Halarc."

Turning to the low-pressure sodium lamp, we find only modest promise for improving this lamp. Attempts to improve its color by additives have extracted energy from the D-lines, decreasing the lamp's efficacy. Improved color without significant penalty in efficacy appears unlikely. Most efficacy improvements to date may be credited to heat conservation by selective infrared reflecting coatings on the glass envelope. The coatings transmit visible light. Improvements in efficacy either by reduction of the loss of heat conduction of the arc tube walls, or by elevating the sodium vapor pressure, are expected to be incremental.

Directions for future improvement of the fluorescent lamp are suggested by the table. Twenty percent of the total input energy goes into so-called "end losses." These include dissipation in the plasma at and near the electrodes, as well as external power used to heat the electrodes. Anode losses can be almost eliminated by

Test vehicle for lamps. This 1920 Reo touring car was one of General Electric's "laboratories on wheels" for testing headlamps as well as other lights for automobiles. (General Electric Co.)

operation at high frequency. Recent developments in electronics technology broaden the choice of operating conditions. This should facilitate greatly improved lamp–ballast systems. Reduction of cathode losses requires cathodes that can supply electron emission with less heating.

Fluorescent-lamp phosphors in common use have quantum efficiencies of about 90 percent; yet, in principle, phosphor improvement provides the best opportunity for a truly significant improvement in the fluorescent lamp. One remedy is to put less energy into the ultraviolet photons that are absorbed by the phosphor than the present 5 eV.

One candidate for lower-energy ultraviolet photons is cadmium. Bentley Barnes and Robert Springer have measured low-pressure cadmium discharges.[9] They found that the ultraviolet efficiency of cadmium is comparable to that of mercury. But cadmium has its first resonance line at 326 nm compared to 254 nm for mercury, so that cadmium has 22 percent less energy per quantum. Also, cadmium has nearly 30 percent more visible spectrum than mercury. All in all, up to 28 percent more lumens per watt might be possible with cadmium. But cadmium is toxic. The cadmium lamps require elaborate thermal insulation to permit operation at a high enough wall temperature for optimum discharge conditions. One must also develop phosphors capable of operation at 300° C, in chemical contact with cadmium vapor.

Another remedy for quantum loss lies in developing phosphors that emit two visible photons per excitation. Such phosphors would have two sequential radiative transitions after excitation—the first one to an intermediate energy state, the second one to the ground state. Mercury resonance radiation has sufficient energy to achieve two visible photons per excitation and phosphors with two-step de-excitation do exist. The known two-quantum phosphors, however, generally have very low efficiency.

Can fluorescent lamps be made smaller? Studying this question scientists have been faced with the disadvantages of end losses in short arcs. Anderson showed in 1970 that one can overcome the end-loss problem by ferrite-excited electrodeless discharges.[10] The most severe physical limit to small size is degradation of the phosphors at high intensity.

Turning to high-intensity discharge lamps, we observe that, like fluorescent lamps, they can also be electronically ballasted and they already have the necessary compact form. Because of end effects, however, small high-intensity lamps have traditionally been far less efficient. Also, they warm up slowly after starting, and they are difficult to restart after momentary power interruption. These problems, however, can be overcome by stretching today's technology.

As to metal–halide discharge lamps, researchers expect to arrive at a better understanding of the role of additives, particularly to broaden the choice of suitable additive metals. In turn, this will bring about higher efficacy and more ideal spectra. Mastery of halogen-transport chemistry will facilitate the balancing of the effect of different halides, a key to longer life and better electrical characteristics.

A logical further development of the high-pressure sodium lamp is toward increasing the efficacy by further reducing the conduction losses. Such increases, however, are expected to be small.

Physicists are challenged to generate new ideas for light production. Most of the really major past improvements came by exploiting new combinations of phenomena or technologies. For example, the fluorescent lamp combined the gas discharge with fluorescence, and the high-pressure sodium lamp requires a newly available material.

Gas discharges can be thought of as selective incandescent radiators: How selective can they be made? Several light sources now make use of spectrally selective reflective coatings. How efficient could an incandescent lamp become if its filament were thermally insulated from a reflector? Could a practical arrangement be found whereby the entire radiation outside the visible is reflected onto the filament and the visible radiation is entirely transmitted?

One hundred years ago Thomas Edison would have predicted a number of features of today's incandescent lamps but he would not have foreseen most of the wide variety of electric lamps we take for granted today. Our crystal balls tend to the cloudy beyond the point of estimating improvements of today's lamps. However, we predict with confidence that the innovations of the second century of electric light will require as much applied physics as the first century.

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