Two Centuries of Electric Light Source Innovations

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Light, and ways of producing it, undoubtedly belongs to the most fascinating and exciting kind of science man has ever tried to master. To be more exact, light sources do not belong to one kind of science but embody most of them. This is the development of vacuum techniques, of particular glasses, the purification of gases, the refinement of metals, the elaboration of fluorescent substances, and other countless engineering feats that allowed the making and improvement of all lamps we depend on today. Of course, many of these breakthroughs were precisely driven by the need for better light sources, having longer lifetimes, higher efficiency and better color properties. Yet, no one suspects that two centuries of scientific research, discoveries, developments and refinements stare upon us every time we flip a switch to give birth to light.

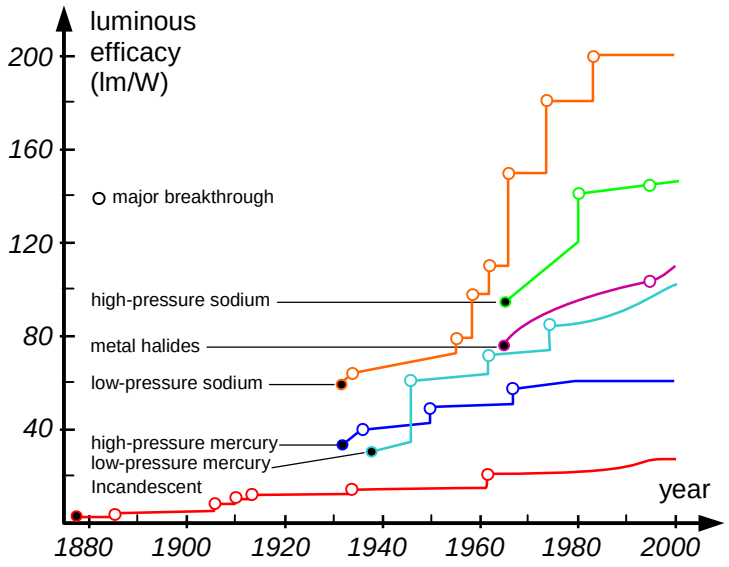

Figure 1: Luminous efficacy evolution of light sources.

It was exactly two hundred and one year ago that Humphry Davy set the foundations of the lighting industry with his simultaneous discoveries of light emission from incandescent metal wires and from electrical arcs (also by W. Petrov). Until 1802, and since 400,000 BC, man had relied solely on fire for his lighting needs. The invention of the electric pile by Alessandro Volta in 1800 opened a brand new era of perspectives. His stacks of copper, zinc and saltwater-soaked cardboards allowed the circulation of steady flows of electric currents that would eventually spark the lighting revolution. A revolution that was indeed slow to start.

The early years

The discoveries of Davy and Petrov had to wait five decades, the development of steam-powered dynamos and the refinement of Volta's battery, before becoming a practical reality. By 1850, Léon Foucault built the first carbon arc lamp that was subsequently used for theatrical lighting, while four years later Einrich Goebel, a German emigrant in the USA, made the first practical incandescent lamps. His sources were made of carbonized bamboo filaments enclosed in evacuated perfume bottles, and were intended to illuminate the shop window of his watch shop in New York city.

A third way of electric lighting emerged in 1856 from the discovery by Michael Faraday (England) of the electric glow discharge in rarefied gasses (1831-35). This year, Julius Plücker and glass blower Enrich Geissler started some systematic investigations of electrical discharges in evacuated glass tubes provided with electrodes at each end. Subsequent experiments from Hittorf, Crookes and Golstein revealed that the light color of the discharge changed upon the addition of other gases and vapors. This phenomenon was

finally understood in 1859, when Robert Bunsen and Gustav Kirchoff showed that each chemical element emits a specific set of light colors, or spectral lines. This discovery eventually set the foundations of spectroscopy. However, the inner working principles of these tubes were not understood until the 1920s, when General Electric (GE, USA) scientist Irving Langmuir studied and made the first accounts of the physics of ionized gases, and coined the term *plasma* to describe them. Then for this reason and others, "Geissler" and "Crookes" tubes were relegated to the rank of lab curiosities until the beginning of the twentieth century.

Figure 2: Various ways of light production.

On the side of carbon arcs, many improvements followed the lamp of Foucault. From the work of Foucault and Dubosc, Serrin designed in 1859 a mechanical system to keep the arc at a given position despite the unequal burning rate of the cathode and the anode. Later, Crompton in England and Wallace-Farmer in the USA made an arc lamp that was regulated in voltage, thus permitting its use in series circuits. A further major step followed in 1870, when Russian engineer Paul Jablochoff invented a self-regulating arc lamp made of two close graphite rods separated by a layer of plaster of Paris. These lamps had a lifetime of 90 minutes, and a set of electrodes could not be re-ignited once it has been used. Despite its many drawbacks, this kind of source led in 1878 to the first practical electric arc street lighting in Paris. Two years later, Compton and Pochin in England and Friedrich von Hefner-Alteneck in Germany invented the differential carbon arc lamp, which was power-regulated by monitoring both arc current and voltage. This system eventually superseded Jablochoff's lamp in street and industrial lighting.

Carbon arc systems were pretty crude, cumbersome, noisy, dirty and drew a lot of electrical power. Beside this, its bright harsh light did not make it suitable for home lighting. The consequence is that many persons looked for a better and softer way of producing light, and it was already of common knowledge that a piece of carbon or metal heated by a current would do the job. However, things sound far simpler than they are, and most of the attempts went up in smoke as all materials eventually caught fire. The culprit was not so much the filament material than the poor quality of vacuum in early lamp prototypes.

Emergence and development of practical incandescent lamps

The development of incandescent filament lamps owes a lot to that of vacuum pumps. In 1838 it was discovered that carbon brought to incandescent does not consume in a air-free environment. From this knowledge the enclosed arc lamp was born in 1893 (Jandus and Mark) and had a lifetime of 150 hours, or three to five times that of lamps burning in free air.

Although it was known that platinum wires could be brought to incandescence in open air for a long time (de la Rue, 1802), the need for lamps with higher filament temperatures was felt. Carbon rods were studied and used by J.W. Starr and M.J. Roberts between 1840 and 1854. The former made in 1845 a lamp partially evacuated with a mercury column from Torricelli's barometer. Lodyguine, a Russian scientist, circumvented in 1856 the problem of poor vacuum by using an atmosphere of nitrogen instead. Two hundred of his carbon rod lamps were successfully used for lighting the harbor of St Petersburg. These first lamps, although successful in their own right, did not show a good lifetime due to the presence of residual impurity gases either in nitrogen or in vacuum.

Figure 3: Goebel's lamps. (ca. 1854, [1])

Two major breakthroughs speeded up the development toward a commercially viable lamp. First, in 1865 Sprengel invented the mercury-drop vacuum pump, which was much better than von Guericke's pump developed around two hundred years before. This new device could evacuate a vessel down to at least a ten thousandth of the atmospheric pressure (10 Pa), a factor hundred lower that previously achieved. L. Boem then improved this pump in 1878, and reached a millionth of atmospheric pressure (10 mPa).

However, no matter how good lamps were pumped down, their lifetime was still too short (several hours at best). The reason for this was discovered in 1879 by Francis Jehl and Thomas Edison (USA), who found that gases occluded in lamp materials are released in vacuum over time. They then patented an effective outgassing method, which consisted of heating the lamp during the pump-down process. In February of this same year, Joseph Swan demonstrated a working incandescent graphite rod lamp before the Royal Institution in Newcastle, England. This was eight months before Edison made his successful low-resistance carbon filament lamp.

Historically, Swan was the first to achieve a working carbon incandescent lamp. However, the lamp lifetime was reportedly too short to be commercially viable, which was not the case of Edison's lamp. Edison primarily used a U-shaped carbonized cotton thread for the filament, later replaced by a carbonized bamboo fiber which boasted a luminous efficacy of 2 lm/W (ten times lower that today's standard filament lamps) and a lifetime of 45 hours.

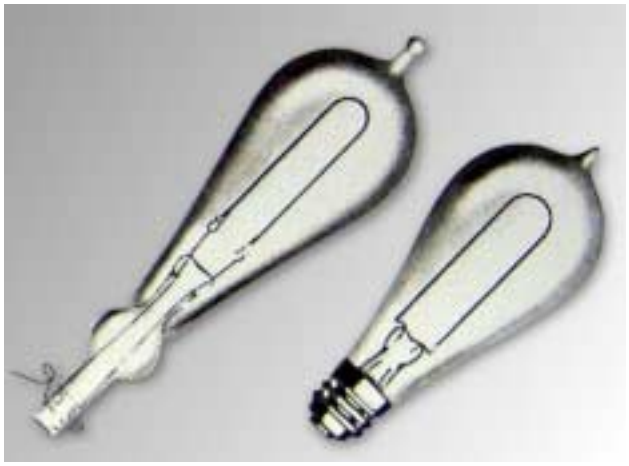

Figure 4: Carbon filament lamps made by AEG from Edison's patents. (ca. 1900, [1])

By the end of the 1870's, the principles for making a good incandescent lamp were established, and it was then agreed that a low-resistance filament was needed for its use in parallel circuits. This set the requirements for thinner filament, which are prone to burn out quickly in poor vacuum. A better lamp thus called for stringent improvements of the making procedures and the quality of the materials. Then from 1880 to 1883 many inventors worked at improving the quality of the carbon filament. Swan came up with a novel process that consisted of squirting reconstituted cotton into threads, which were carbonized into very fine carbon filaments of constant diameters. In 1894, A. Malignani introduced the use of red phosphorus as a chemical getter, which maintains an excellent level of vacuum in the bulb throughout the lamp life.

The search for higher luminous efficacies and color temperatures pushed the research toward higher filament temperature. Besides a shortening of their lifetime, this led to the severe blackening of lamp bulbs as carbon has a high vapor pressure. Then, more refractory filament materials were needed in order to reach more than 1200ºC. In 1893, Lodyguine investigated several metals, which included tungsten, while four years later Carl Auer von Welsbach succeeded at making an osmium filament lamp that was put on market in 1902. Followed in 1905, Dr Hans Kuzel made the first (brittle) tungsten filaments, which were used in new lamps marketed the year after. This novel source pushed the lifetime up to 1000 hours and had an efficacy of 8 lm/W (two times that of carbon filament lamps), which eventually put an end to the osmium lamp of Auer von Welsbach. In 1907, these lamps were also made to operate on 110V mains and were available up to the 500W size.

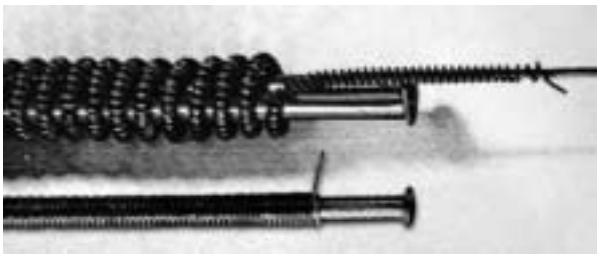

Figure 5: Coiled-coil (top, 1933) and simple coil (bottom, 1913) filaments. ([1])

The next major breakthroughs happened from the work of William Coolidge (General Electric, USA), who in 1910 succeeded at making ductile tungsten filaments (as opposed to those made until then). Because of its higher mechanical strength, this filament could be operated at a higher temperature, thus boosting the

lamp efficacy to 10 lm/W. Two years later, Langmuir discovered the benefits of coiled tungsten filaments operating in inert atmospheres (nitrogen, then argon-nitrogen mixture). The winding permitted a reduction of the filament thermal losses, while the surrounding gas lowered its evaporation rate. Both combined, this gave a lamp efficacy of 12 lm/W (first marketed by GE in 1913 in 500, 700 and 1000W sizes) and spelled the end of all carbon and other straight filament lamps.

From this point on, the development of incandescent sources slowed down. In 1933, the first coiled-coil tungsten filament lamp was made available for general lighting, although it was already in use since 1913 for projection purposes. The following years saw the introduction of krypton and xenon-filled lamps having higher filament temperatures owing to reduced evaporation rates. The impact of these later lamps was limited because the use of heavier gases did no lead to an efficacy increase higher than ten percents.

Figure 6: Original 500W tungsten-halogen incandescent lamp. (GE, 1959, [2])

The last major advance in this domain happened at the end of the 1950's with the making by Zuber and Mosby (GE) of the first viable tungsten lamp having a filling of halogens. The presence of this class of elements allows a chemical cycle to return evaporated tungsten atoms back to its source. This permitted the use of ultra-compact packages with 100% lumen maintenance throughout lamp life (no bulb blackening). Also, its efficacy was raised to 20 lm/W an later to 26 lm/W, thus making the most efficient incandescent lamp yet.

These sources were first marketed in 1962 and triggered an explosive development of compact lamps for general, studio, automotive, flood lighting and movie projection. In the 1980's the first low voltage capsule lamps integrated or not in compact reflectors were put on the market, while infrared-reflecting coatings were tried at the beginning of the 1990's in an attempt to further decrease the thermal losses of the filaments.

Their pathetic efficacies make incandescent lamps more suitable for heating purpose than lighting. However, low production costs and simplicity of use (no current-limiting ballast required) ensures them several decades of strong use at home and for commercial lighting. If the future see the development of stable up-converting phosphors transforming infrared into visible light, or that of proper tungsten optical band-gap crystals, then incandescent sources will be able to compete with vapor discharge lamps.

The rise of electric discharge and arc lighting

The only practical light sources worked out until 1860 where of incandescent nature. Even the brilliant carbon arc emits its light mainly from the white-hot anode; the contribution from the arc being relatively negligible. This year, on September 3rd, the Hungerford suspension bridge in London was lighted with the first mercury arc lamps ever made. This invention from J.T. Way was a carbon arc enclosed in an atmosphere of air and mercury vapor. This was the first time the arc itself was the source of light.

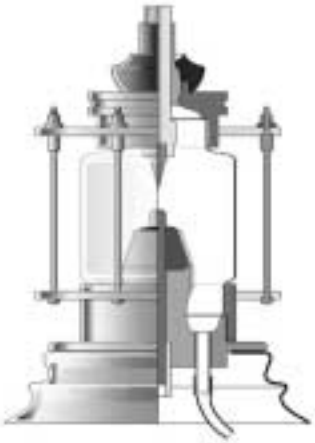
Figure 7: J.T. Way's mercury arc lamp. (1860)

Mercury in light sources poses today an environmental threat and work are carried out to suppress it. By then it made a lot of sense to use it, as this is the only metal with an appreciable vapor pressure at room temperature and can emit a large proportion of visible light when energized in electrical discharges. This known fact led to the invention of the low-pressure mercury lamp by Peter Cooper-Hewitt (USA) in 1901, followed by a quartz atmospheric-pressure version by R. Küch and T. Retschinsky (Germany) in 1906 (marketed in 1908 by Westinghouse).

These lamps performed stunningly well by 1900 standards, they had efficiencies many times that of carbon filament lamps. The reason for this resides in the light emission mechanisms that are different in these two

kinds of lamps. Incandescence arises from high thermal energy (i.e. lattice vibrations in the filament material) that allows the emission of visible light. Consequently, a large portion of the emitted radiation is in the infrared (95% of input energy in standard filament lamps). As opposed to this, an electric discharges and arcs emit their light upon excitation and relaxation of gas or vapor atoms and molecules from electron impacts. Thus more input energy can be radiated into useful visible light, leading to much higher efficiencies (e.g. 35% visible light for low-pressure sodium vapor). However, the difference between the two kinds of light sources lies also in their emission spectra. If incandescent lamps give excellent light color renditions, electric discharge lamps at this time did not.

Figure 8: Küch and Retschinsky's quartz mercury arc lamp. (1906, [3])

It was recognized that Cooper-Hewitt and Küch-Retschinsky lamps emitted a bluish light deficient in red, thus having poor color rendering properties. This limited their use to streets, warehouses and industries. This particular problem was addressed with series-connected filament lamps that provided the additional red light and stabilized the electrical discharge.

The extensive use of both types of mercury lamps started when proper electrodes were developed. Until the 1930's, the original lamps had electrodes made of mercury pools, which waste a lot of electrical energy for the supply of electrons to the discharge.

High-pressure mercury lamps – the forerunners

The lamp from Küch and Retschinsky had a limited success due to many unsolved problems, like proper electrodes, no tight quartz-to-metal seals and strong UV emissions leading to skin injuries. In the beginning of the 1930's, many lighting companies worked to address these problems and aimed at presenting an atmospheric-pressure mercury lamp on the market.

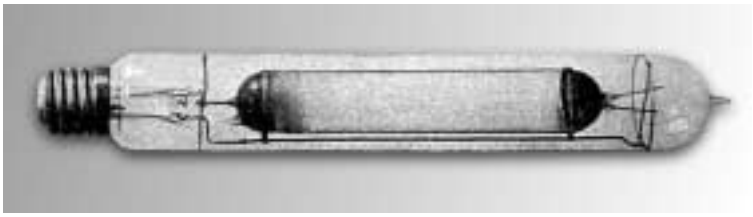

Figure 9: The "Osira" mercury lamp. (GEC, 1932, [4])

In 1932, General Electric Company of England (GEC) was the first to present such a lamp under the tradename "Osira". Because no satisfactory sealing technique between quartz and tungsten was found, this lamp used a discharge tube made of aluminosilicate hard glass. The relatively low softening temperature of this material limited the power loading of the electric arc to 10-100 W/cm and restricted its use to the vertical position. This later problem was eventually solved by the use of an electromagnet that kept the arc straight when the lamp was horizontally operated. The efficacy of such lamp was 30 to 40 lm/W, with a lifetime of a couple of thousands hours. The low power loading of the arc and the subsequent electrode power losses did not allow the making of efficient low-power mercury lamps. Only the 400 and 250W sizes were made available in this configuration. Also worth of interest, these original lamps did not integrate any starting aid, like an auxiliary probe. Thus GEC fitted each luminary with a small Tesla coil in order to ignite the lamp. This was certainly the first time that an igniter was used.

Figure 10: The first high-pressure mercury lamp. (Philips HP300, 1936, [5])

By the end of the 1930's, Willem Elenbaas (Philips, the Netherlands) theoretically predicted a rise of mercury lamp efficacy with the increase of the arc power loading. This was effectively verified after the invention of quartz-to-tungsten graded seals in 1935

(Cornelis Bol - Philips). The next year, Philips was then able to market the first low-power high-pressure (20 atmosphere) lamp, the HP300 (75W). This was followed by a breakthrough source: the water-cooled SP500W working at 80 atmospheres (Philips). Not only these lamps had a better efficacy (40 and 60 lm/W respectively), they also showed improved color rendering properties owing to the higher operating pressure.

Figure 11: One of the first fluorescent high-pressure mercury lamps. (Philips, 1950, [6])

The SP500W lamp was primarily designed and used for film projection and floodlighting applications, while the HP300 remained favored for street and industrial lighting due to its still insufficient emission of red light. This problem of color rendering pushed the research toward color-improved lamps that used an integrated incandescent filament (acting also as a ballast - 1941) and/or a phosphor coating on the inner surface of the outer bulb to transform useless ultra violets into red light, thus filling the gap in the mercury spectrum.

In 1934, cadmium sulfide was found to be a suitable fluorescent material, although it provided only a mild color correction. The introduction of the color-corrected mercury lamp was made possible with the elaboration of manganese-activated magnesium germanate and fluorogermanate in 1950, which improved greatly the color rendering index and had a beneficial effect of the lamp efficacy. Three years later, tin-activated orthophosphate was introduced, and in an attempt to have proportionally more red emission, “deluxe” lamps with a rosy glaze on the outer bulb were marketed for a short while by a number of manufacturers (1956). Then in 1967, the hugely successful europium-activated vanadate and phospho-vanadate phosphors inherited from color TV technology were introduced and are still in use today. These modern color-improved mercury lamps have a color rendering index (CRI) of 65 against 15 for clear lamps and a luminous efficacy of 60 lm/W.

Figure 12: Super-high pressure mercury lamps, then and now.

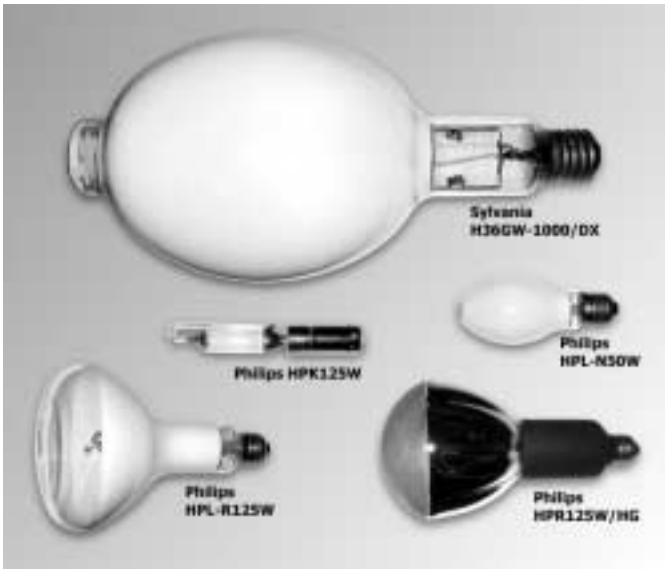

Figure 13: Various modern high-pressure mercury lamps.

The present design results from a large number of improvements in the lamp structure that occurred in the 1950’s and 1960’s. Among them are new kinds of quartz-to-metal seals using 20 micron-thick molybdenum foils pressed in quartz. Also, the changeover from thorium to alkali oxide electrodes (Osram, Germany) permitted a better lumen maintenance throughout lamp life.

The last major innovation concerning these lamps occurred in 1998 with the invention of UHP (Ultra High

Performance/Pressure) lamps by Hanns Fischer (Philips) for LCD projection purposes. These new sources operate with an internal pressure of about 200 atmospheres, thus leading to a strong continuum in the emission spectrum and a high arc power loading. These make this kind of lamp efficient (60 lm/W) and optically small (0.7 mm arc gap), thus allowing for an excellent optical control.

Standard high-pressure mercury lamps (not UHP) are today on the brink of extinction because of the environmental threat posed by mercury, and their relatively poor performances compared to metal halide and high-pressure sodium sources.

Metal halide lamps – the legacy of mercury sources

It was recognized since the earliest days of mercury lamps that the lack of red light in their emission spectrum impeded heavily on their widespread use. In 1906, Guercke already suggested to add some red-emitting metals to the lamp of Küch and Retschinsky in order to improve its color properties. M. Wolke followed this procedure in 1912 and used cadmium and zinc. This turned out to be unsuccessful due to a low lamp cold-spot temperature (600ºC), which led to an insufficient zinc and cadmium vapor pressures. Also, these metals readily attacked the quartz envelope, thus rendering the lamp useless after a couple of tens of hours of operation.

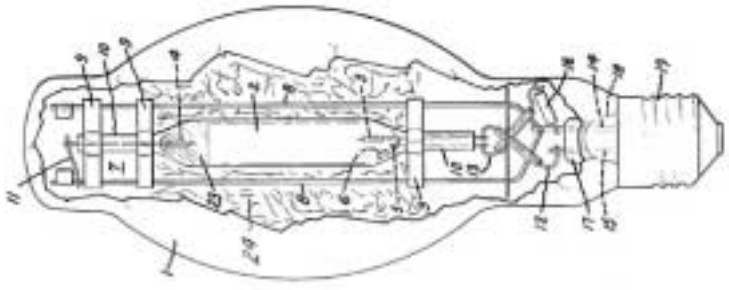

Figure 14: Reiling's metal halide lamp. (GE, 1961, [7])

The development of suitable fluorescent materials and ballasting filaments dampened the need for color-improved mercury arcs. However, studies were still going on possible additives for the mercury lamp in order to increase its luminous efficacy, regardless of color properties. In 1941, Schnetzler made a mercury-thallium lamp having an efficiency of 70 lm/W, almost twice as high as its mercury counterpart. The desired thallium vapor pressure was reached by operating the arc tube at thrice its normal power loading, with the consequence we can imagine on the life expectancy.

In the next decade, studies turned toward metal-halogen compounds that have higher vapor pressures than metals at a given temperature. Gilbert Reiling (GE) patented the first metal halide lamp in 1961, which was intended to replace high-pressure mercury lamps in their sockets. It had a filling primarily of mercury, thallium and sodium iodide that showed a sizeable increase of lamp efficacy (up to 100 lm/W) and color properties, and made it more suitable for commercial, street and industrial lighting. Eventually GE marketed this lamp in 1964 with additives of sodium and scandium iodides instead. Most major manufacturers followed shortly thereafter, with varied compositions in order to meet different lighting needs and to circumvent competitors' patents. Today the most popular additives are sodium-scandium iodides, lithium-sodium-thallium-indium halides and several mixtures of rare-earth halides.

Figure 15: Self-ballasted metal halide lamp. (ca. 1980, GE MaxiLight 55W)

The sixties and seventies witnessed a furious development of metal-halide lamps in different geometries from tubular to reflector, and in power range between 175W and 5000W in order to meet the soaring demands in the many applications it found. One of the last strongholds this kind of source did not invade was at home. At the end of the 1970's GE, Sylvania (USA) and Philips designed prototypes of self-ballasted

metal-halide lamps intended to replace standard filament lamps for domestic applications. This was ultimately proven unsuccessful due to some lethal drawbacks such as the lack of hot re-strike capabilities and the prohibitive cost of the lamps.

Two major breakthroughs followed at the beginning of the 1980's. In 1981, Thorn Lighting (England) presented the first metal halide lamp with a sintered alumina ceramic discharge tube, which resulted from ten years of research and development. Unfortunately, this revolutionary source did not reach the market due to a lamp voltage/current characteristic that did not match any available ballast. Around the same year, and with more success, Osram introduced its compact double-ended HQI-TS lamps that found an application in shop-window and commercial lighting.

Figure 16: Various compact metal halide lamps.

In 1991, Osram, Philips, Valeo and many other car equipment manufacturers engaged themselves in the '*vedilis'* project, which led to the xenon-metal halide lamps (D1 and D2) for automotive headlights. Philips then revived metal halide lamps with ceramic discharge tubes in 1995, when it launched its range of CDM lamps. Osram and GE soon followed. These lamps present today an alternative to high-pressure sodium sources for downtown street lighting. The use of this particular design allows for a better lamp-to-lamp color matching, higher efficacies and better color rendering. Even more so, the bluish light of metal halide performs better than the orange hue of high-pressure sodium when scotopic vision prevails in low illumination levels at night.

Low-pressure mercury fluorescent lamps – toward domestic applications

The origin of fluorescent tubes goes back to the invention in 1901 of the low-pressure mercury lamp by Cooper-Hewitt. For the same reasons as its high-pressure counterpart, its use was restricted to places where color rendering was not an issue. Right from the start, Cooper-Hewitt worked to improve his lamp by applying some fluorescent dyes (primarily Rhodamine B) on the bulb surface and later on luminary reflectors in order to compensate for the lack of red emission. The idea of using fluorescence to convert invisible light into useful radiation was not new, and already in 1859 E. Becquerel tried to use Geissler tubes filled with fluorescent materials in order to get a practical light source. His trials were not successful as the efficacy was too low. Later in 1896, one year after the discovery of X-rays by W. Röntgen, T. Edison made a X-ray lamp internally coated with calcium tungstate which radiated a bluish white light. This source was three times as efficient as carbon filament lamps, and had X-rays not caused severe injuries, this lamp would have certainly been the first commercial fluorescent source.

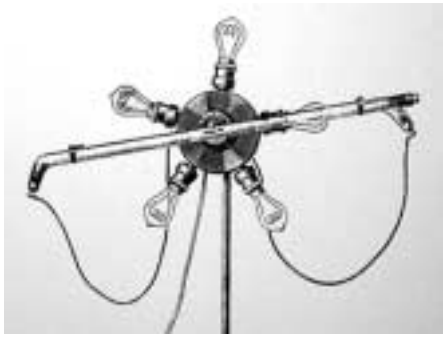
Figure 17: Cooper-Hewitt tube connected in series with carbon filament lamps, which act as a ballast. (ca. 1910, [8])

Back to the twentieth century, it was discovered in 1920 that an electrical discharge in a proper mixture of argon and mercury at low pressure could radiate efficiently (60% of power input) ultraviolet light at 253.7nm and 184.9 nm. Six years later, Meyer, Spanner and Germer from Osram (Germany) published a landmark report where they described a low-pressure mercury vapor lamp provided with externally-heated oxide-coated electrodes, and an internally phosphor-coated bulb to convert UV radiation into visible light. This document set what would become the first successful fluorescent tubes. However, its marketing had to wait for the development of efficient electron-emitting electrodes by M.

Pirani and A. Rüttenauer (Osram) in 1932, and the elaboration of the calcium tungstate - zinc silicate phosphor. Then in September of 1935, the first tubular fluorescent lamp was demonstrated before the Illuminating Engineering Society in Cincinnati, North America. This was presumably from General Electric, who had taken over the patent of André Claude on a similar fluorescent tube in 1932. Osram followed in 1936, and displayed its 'L' lamp at the World Exhibition held in Paris. Between 1936 and 1938, most major lamp manufacturers made fluorescent tubes available both in Europe and in the US for general lighting applications. These lamps had a tube diameter of 38mm, an efficiency of about 30 lm/W and a moderate color-rendering index, yet good enough for its use at home.

Figure 18: Philips TL100 and ballasting device from 1939. ([5])

In 1942, A.H. McKeag from GEC (England) made a giant leap with the discovery of calcium and strontium-activated halophosphates. Lamps using this phosphor formulation were introduced in 1946 and had twice the efficacy of former tubes, while the color rendering was much improved. Philips made the next step with the introduction in 1973 of the three-band phosphors. This boosted the efficacy up to 90 lm/W with excellent color rendition (IRC 80-90). This new formulation also allowed the increase of the lamp wall power loading and led to the reduction of the tube diameter from 38mm (T12) to 26mm (T8), and then to 16mm (T5) at the beginning of the 1980s. A decade later, Osram shrunk things further and put a 7mm-diameter (T2) fluorescent tube on the market (Lumilux-FM).

Figure 19: First successful compact fluorescent lamp. (Philips, 1976)

The reduction of lamp size permitted the design of compact fluorescent lamps with integrated ballast. The first of this kind was presented by Philips at a world technical conference held in Eindhoven in 1976. In 1980, this company introduced successfully its SL*18, followed by an electronic version in 1982. Competitors were quick to catch up and by the end of the 1980's compact fluorescent lamps were widely available at a reduced cost and package size. The success of these lamps was partly due to the energy crisis that raised the cost of electric consumption, thus calling for more efficient and cost-effective light sources.

Figure 20: Electrodeless mercury fluorescent lamp. (Philips QL55)

At last and not least, from the eighties until the mid-nineties several lamp makers introduced electrodeless versions of fluorescent lamps. In these sources the discharge originates from an electromagnetic field generated by an induction coil antenna. The suppression of the electrodes increases the lamp lifetime up to sixty to a hundred thousands of hours.

Fluorescent lamps were the first and only discharge lamps to reach the level of domestic lighting. Today, they provide a wide range of color temperature with excellent color rendition and high efficacies. This explains why they account for seventy percent of all lamps used in commercial illuminations. Development still continues today, and priorities are set to size and efficiency. To this respect, the use of

surface-mounted electronic components permitted the making of smaller CFL lamps to fit in low-power luminaries, therefore claiming more ground to its incandescent counterpart.

Low-pressure sodium lamps – reaching summits in efficacy

Extensive experiments with electrical discharges in alkali vapors could have started only in 1920 when A.H. Compton formulated a borate glass resistant to sodium. Alkalis, being strong reducers, require special glasses as normal materials like soda-lime silicates are readily attacked and lead to the formation of a brown light-absorbing film. Two years later, in 1922, M. Pirani and E. Lax from Osram experimented sodium discharges for lighting applications. The following year, Compton and C.C. van Voorhis in the USA attained an efficacy of 340 lm/W with a lamp externally heated by an oven. Naturally, the calculation of the efficacy did not take into account the energy provided to keep the lamp at its optimum working temperature of 260°C.

Figure 21: The first low-pressure sodium discharge lamp. (Philips, 1932, [9])

Then, in 1931, both Philips and Osram made the first viable low-pressure sodium lamps, and the following year a stretch of road between Beek and Geleen, in the Netherlands was lighted with Philips lamps. These sources were DC-operated via an externally heated cathode and had an efficacy of about 50 lm/W. A Dewar flask surrounded the discharge tube in order to limit the thermal losses. In 1933 followed the AC-driven positive column type of lamp, which had a higher efficacy partly due to a more favorable current density in the discharge.

From 1933 until 1958, lamps were composed of a separate discharge tube and a double-walled vacuum flask. In 1958, Philips marketed an integral lamp, which included the discharge tube within an evacuated bulb thus preventing the former from getting dirty, as it was the case in the previous design. Subsequent work was done on increasing the lamp efficacy by improving its thermal insulation. A first solution consisted of enclosing the discharge tube in several infrared-absorbing glass sleeves. Then infrared mirrors made of gold or bismuth thin films were employed. Philips made a leap forward in 1965 with the introduction of the tin oxide semiconductor mirror, and later the better tin-doped indium oxide film. These materials exhibit a strong infrared reflectivity while being highly transparent to sodium light. This led in 1983 to a lamp reaching the symbolic barrier of 200 lm/W (SOX-E, by Philips), which is the highest efficacy reached yet.

Figure 22: Sodium lamp with bamboo-shaped discharge tube and detachable Dewar outer jacket. (Philips SO/H60W, 1955)

The reason why low-pressure sodium is so efficient at producing visible light is that this element, under the right conditions, radiates an almost-monochromatic yellow light almost coinciding with the peak sensitivity of the human eye in photopic vision. Also, this yellow light emission corresponds to transitions from the two lowest (resonant) energy levels of sodium, thus allowing an efficient transfer of energy from the electric discharge to the excitation of sodium atoms.

In the 1980s, several low-power lamps were experimented for replacing filament lamps in security lighting. Technically these sources were successful but their prohibitive cost and the need for specific

ballasts prevented their widespread use. Interestingly, Philips designed a LPS lamp that had electrical characteristics closely matching that of existing fluorescent tubes, so the ballasting equipment was already standard.

Today, low-pressure sodium lamps remain unchallenged in terms of luminous efficacy. Its bi-chromatic orange spectrum is the key to its efficiency, but is also the limitation factor that restrains its use for street and industrial lighting. In return, its light leads to excellent seeing contrasts, particularly in foggy weather. Further developments of these sources concern its high-frequency operation and improvement of thermal insulation, which will certainly bring the efficacy up to 230 lm/W in a more or less distant future. Also worth of interest is the development of electrodeless versions that obviate the need for life-limiting parts such as the electrodes. These sources are however not likely to reach the market due to difficulties in the making of a proper discharge vessel.

Figure 23: Two special low-pressure sodium lamps for security lighting. (1980's)

High-pressure sodium lamps – a compromise between color and efficacy

It was known that increasing the pressure of a sodium discharge would lead to a lower efficacy, but also to a broader and richer spectrum having better color-rendering properties. The borate glass originally developed by Compton and the other materials used in low-pressure sodium lamps are not suitable for high-pressure operation. As the power loading and the temperature of the discharge increase, the reactivity of sodium toward the wall increases and lamps degrades themselves within minutes of operation. Then, the development of the high-pressure sodium (HPS) lamp had to wait for the work of Cahoon and Christensen in 1955-57, and that in 1955 of R.L. Coble on tubes made of sintered translucent alumina. This material was found to be resistant and impermeable to alkalis, thus making it suitable for high-pressure sodium lamps.

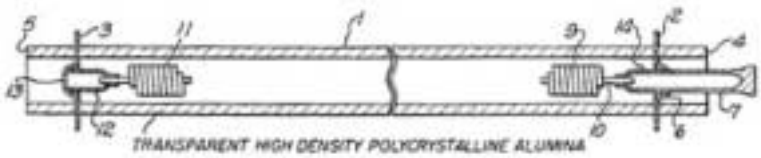

Figure 24: The first high-pressure alkali vapor ceramic discharge tube. (GE, 1961, [10])

During the following years, systematic studies were carried out on high-pressure alkali discharges. Among them, cesium looked promising due to its relatively white spectrum. However, the final choice was sodium because of its good compromise between efficacy and color rendering. The development of suitable sealing and manufacturing techniques allowed William Louden and Kurt Schmidt (GE) to make the first practicable high-pressure sodium lamps in 1964. The next year, GE launched an industrial full-scale production and a 400W lamp was made available in 1966 under the 'Lucalox' brand name. A 250W version followed three years later. Their efficacies ranged between 90 and 100 lm/W with a life expectancy of 6000 hours. Refinements in the 1980's extended the lifetime to 24,000 hours and the efficacy between 100 and 140 lm/W with a color-rendering index of 20-25.

The design of this lamp was radically different than that of metal halide and the mercury

Figure 25: Early range of sodium lamps from GE. (1966, [11])

lamps. It also called for different types of ballasts. While metal halide and mercury sources were and still are powered in the USA with step-up leakage transformers, high-pressure sodium lamps required a choke and an external igniter. Then followed several versions of lamps with built-in internal switches that use the inductance of the choke to kick-start the discharge tube.

Most of these sources have a filling of mercury, xenon and sodium. The role of xenon is to allow the lamp to start, while mercury sets the electric field in the lamp discharge (positive column) and does not contribute to the emission spectrum. Without it, the lamp voltage drop would be too low and the current too high, thus requiring an inefficient and bulky ballast and impairing the luminous efficacy. The environmental problems caused by mercury forces its suppression, and mercury-free HPS lamps were made available by mid 1990's. These lamps have a higher xenon pressure and some starting aid like sintered metal strips on the discharge tube surface (Philips).

The 1980's saw also the development of the so-called *white HPS* lamps by Thorn, Philips and Iwasaki (Japan), which provide an incandescent-like color at four times the efficacy of tungsten filament lamps. These sources are still popular today even with the advent of ceramic metal halide lamps. The advantages of white HPS lies in the large portion of red light in its emission spectrum, leading to a color temperature as low as 2500K. Metal halide lamps cannot reach such war white tone. Also worth of notice is a lamp developed in the mid-1990s by Osram (DSX-T), which has its color temperature that can be changed from 2700K (standard tungsten white) to 2900K (tungsten halogen white) by a flick of a switch.

Bright perspectives

The field of lighting had many changes since the revolution in lifestyle and lightstyle Davys's discoveries induced! So affected has been and still is the field of lamp manufacturing. The eighteenth century witnessed the slow emergence of precursors that led to the exponential development of myriads of sources in the next hundred years. By the dawn of the twentieth century, thousands of lamp makers were struggling on a boiling market, and to say the truth, it was not far from easy to jump in this business since techniques and physics involved at this time were not as developed as today. A century later, only three major (general) manufacturers have survived: Philips, Osram and GE, who count more than 3500 references in their product catalogs. A couple of hundred of medium-sized, minor or specialized manufacturers surround them. They are now facing new challenges that will change our lifestyle and lightstyle through the 21st century: the development and extensive use of white LEDs, and the abandon of harmful materials in all vapor discharge lamps while still pushing upward their luminous efficacies and color rendering properties.

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More technical and historical details are available at: http://www.geocities.com/mfgendre

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