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sense and simplicity

Classical light sources and their efficiency limitations

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Outline

- Types of light sources available today
- Incandescent and halogen lamps
- Physics and energy balance of fluorescent lamps
- Physics and energy balance of high-pressure lamps
- New concepts (besides LED)
- Overview of the best-in-class light sources of today

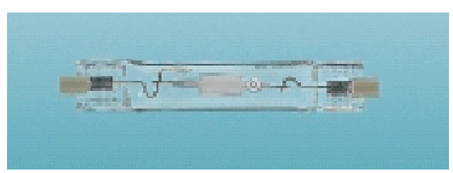
Artificial lighting

Overview of lamp types







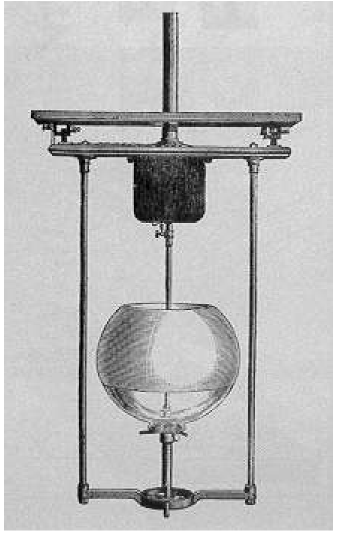



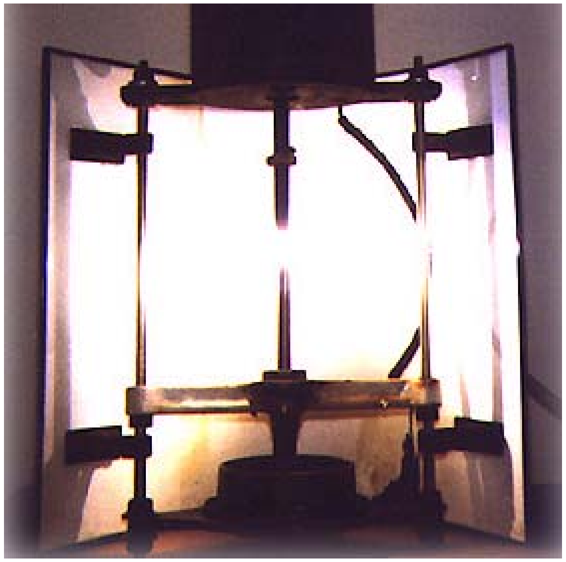
A little bit of history

Sir Humphry Davy

first electrical lamp:

the carbon arc lamp





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first incandescent bulb
(Warren de la Rue, ~1820

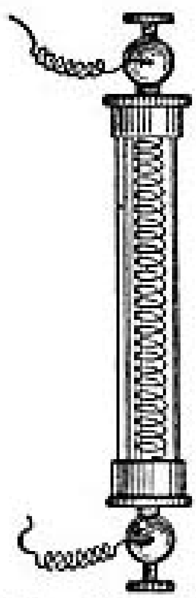
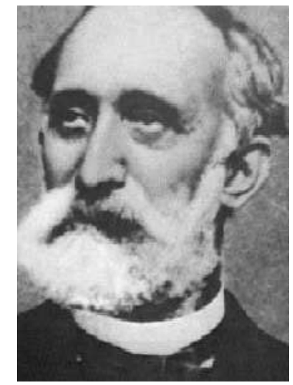
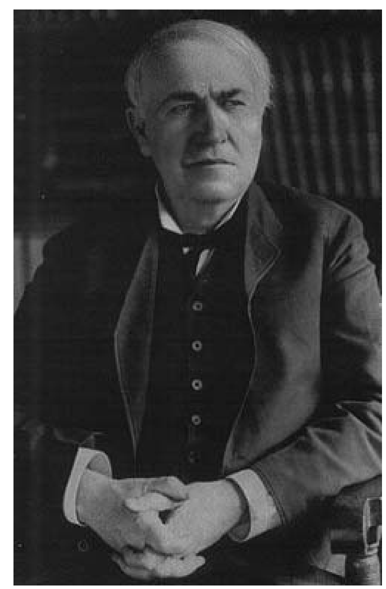


Fig. 138.—De la Rue's Enclosed Incandescing Metallic Wire. Note the fact that this form of incandescing metallic wire gave more light both because of its spiral form and from the fact of its being enclosed.

Joseph Swann



Heinrich Göbel

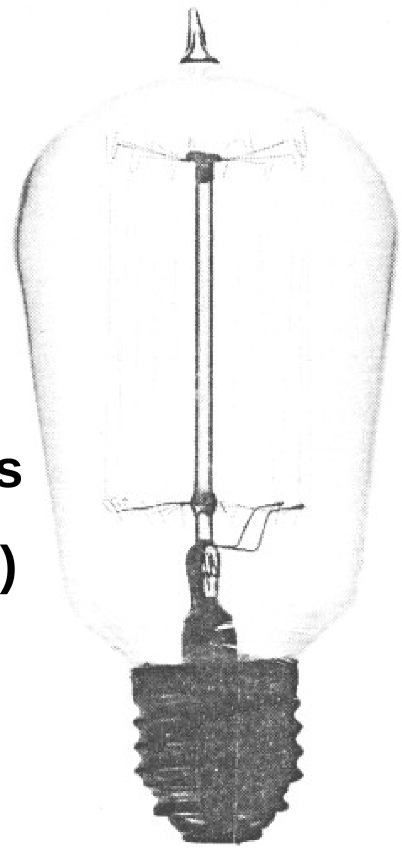


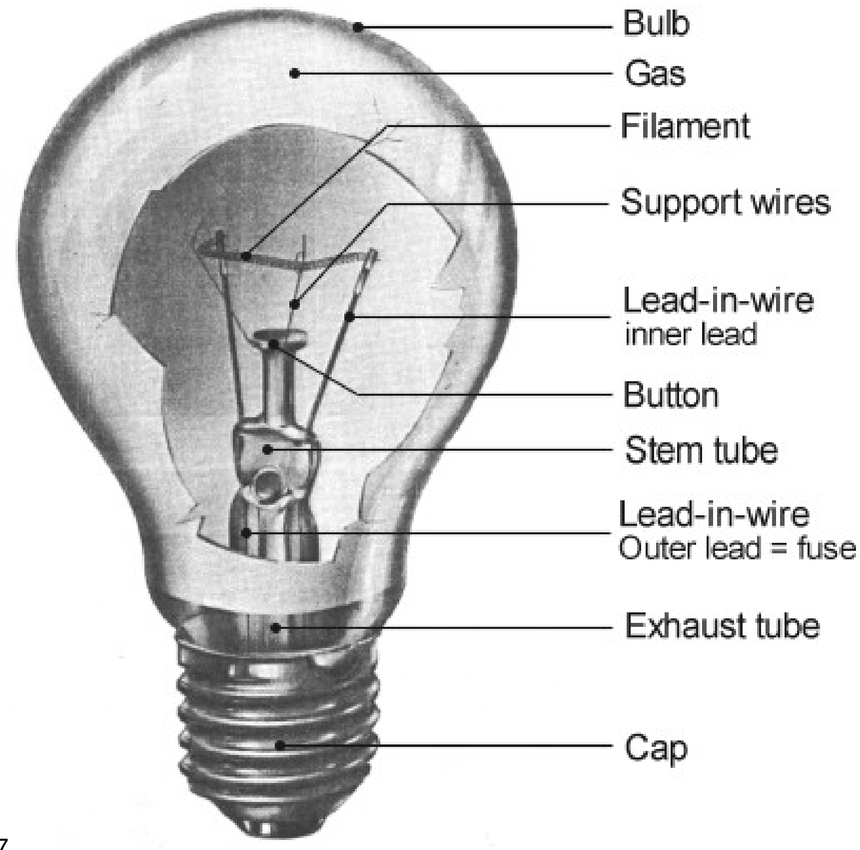
Thomas Edison

Incandescent and halogen lamps

Carbon filament lamps (Edison)

1-3 lm/W ; 100-400 h





Since 1935: no real innovation in GLS lamps

Status GLS-100W (230V) from 1935 – 2010:

14 lm/W ; 1000 hrs

7

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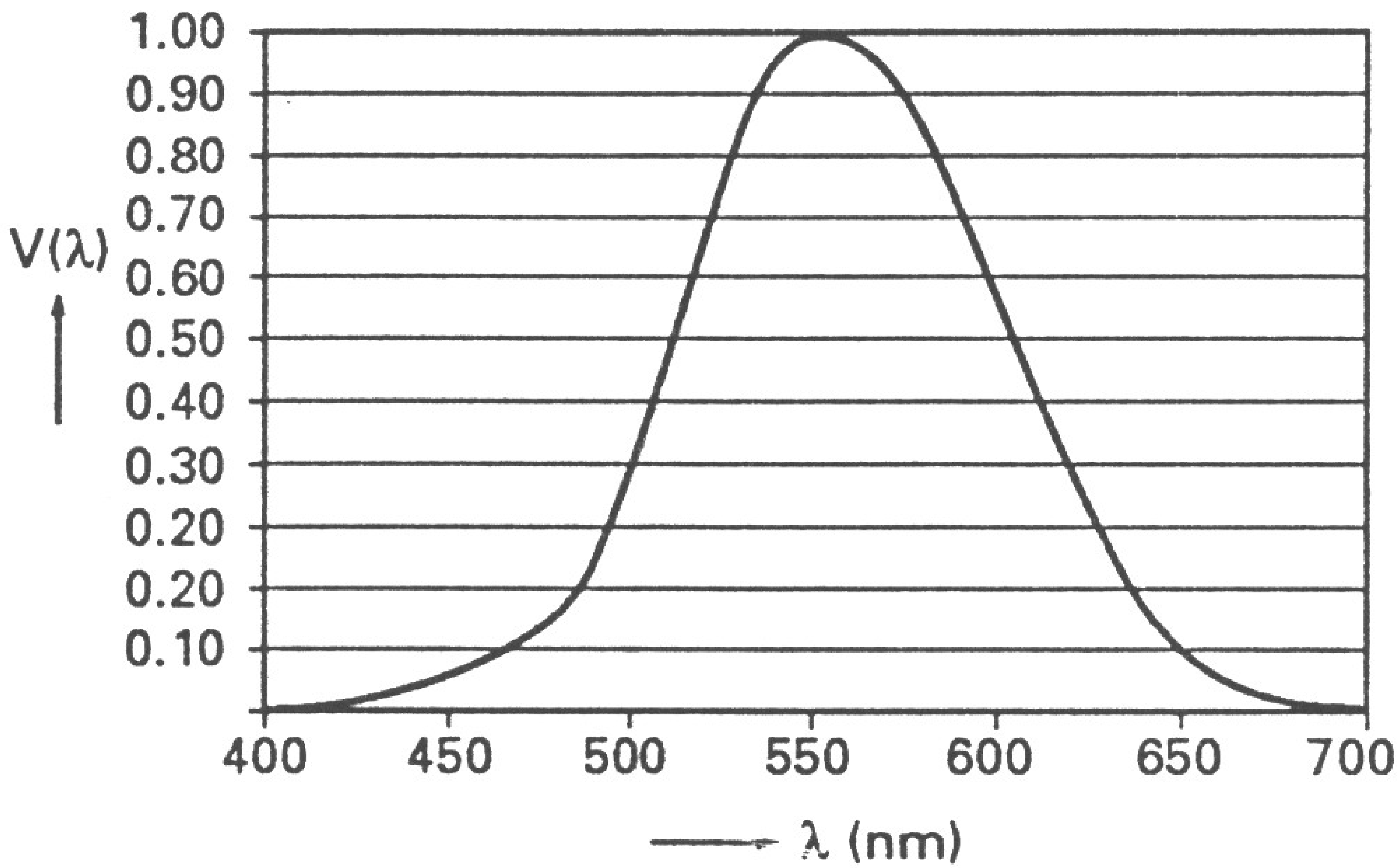
Eye sensitivity curve V(λ) as function of the wavelength λ

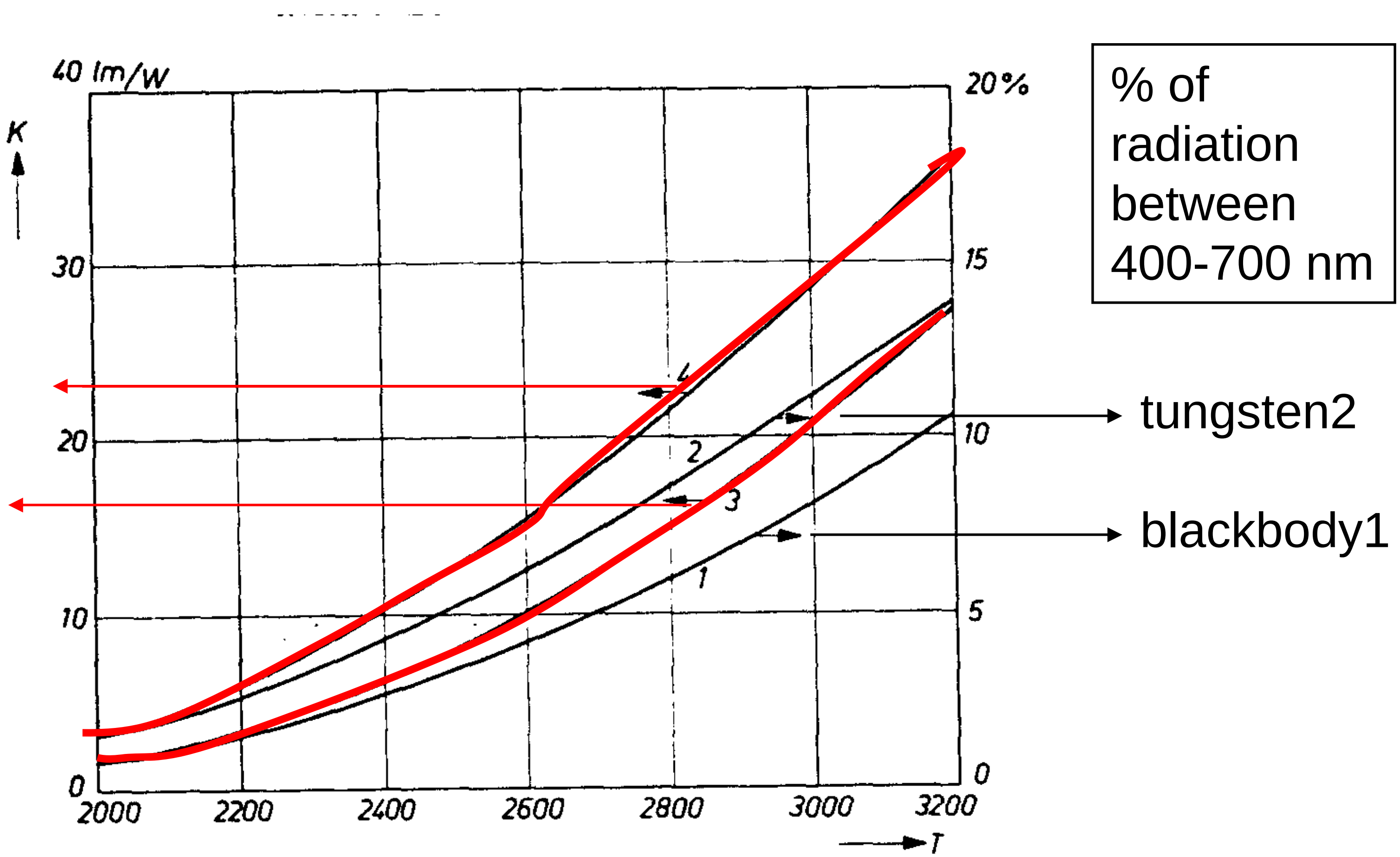


Efficiency of incandescent lamps as function of T

Efficacy lm/W

tungsten4

blackbody3

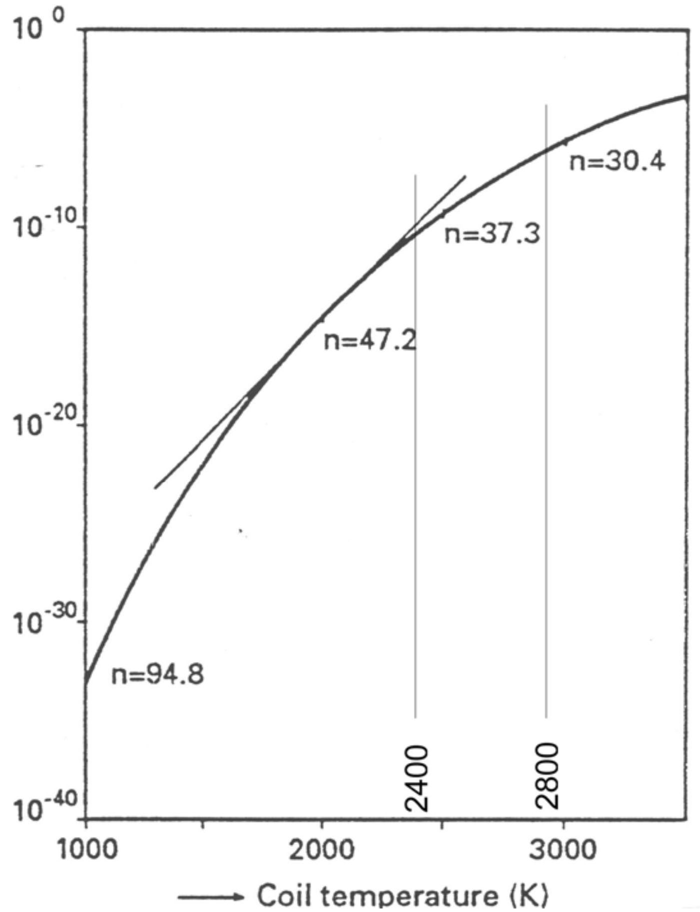


1,2 %radiation

3,4 lm/W (red line)

Higher temperatures : faster evaporation of coil

Evaporation Rate ($g \bullet cm^{-2} \bullet s^{-1}$)



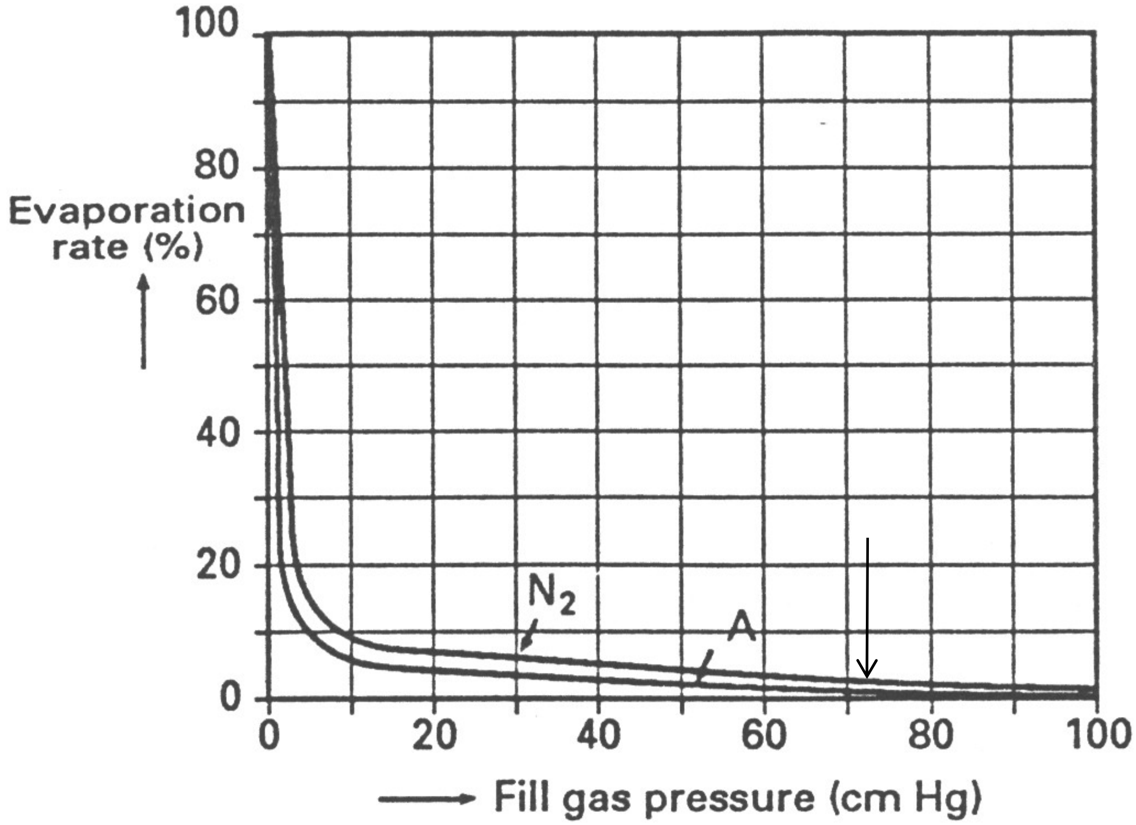
The zone between 2400 K and 2800 K indicates common incandescent lamp temperatures

$$J = c * T^n$$

Practical lamps: n = 36

Evaporation rate of W is relatively slow

Suppression of W evaporation by gas filling



- Practical limit in normal incandescent lamps ~ 1 Bar Ar
- In halogen lamps several Bar of Xe (possible due to smaller size ==> less convective losses) ==> even higher efficiencies

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New developments

Infrared reflecting coatings (~50-80 layers)
e.g. Ta_2O_5 / SiO_2
==>less power necessary to heat coil

dream?

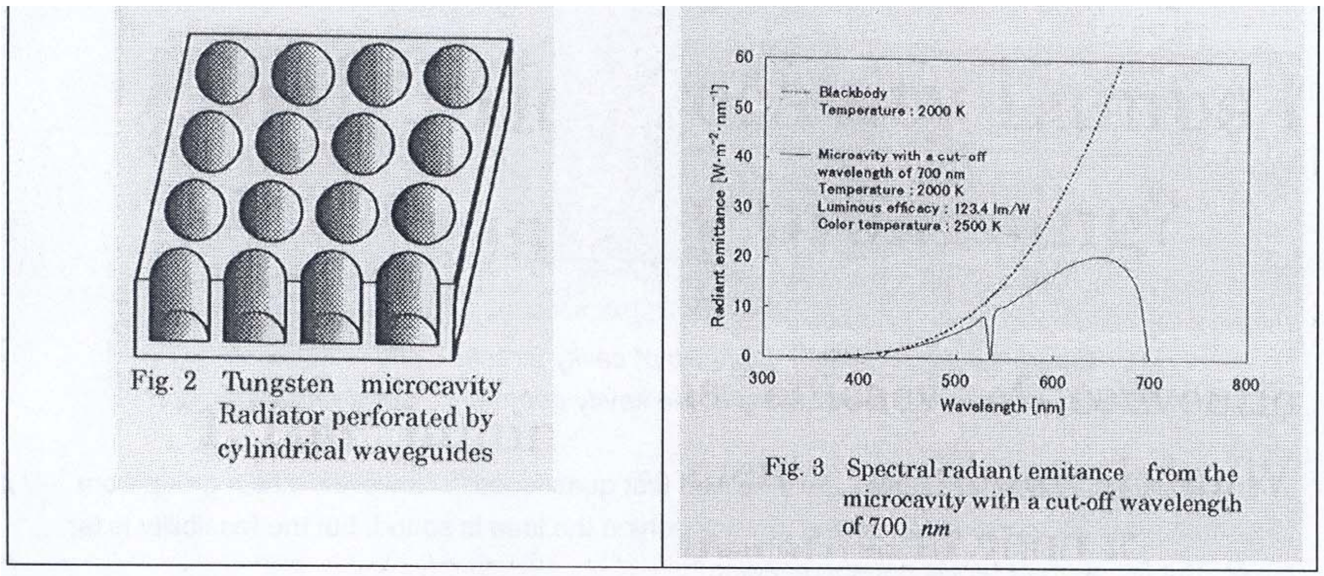


Figure 14 (from Sekine): The cavity structure (left) and the ideal emittance with cutoff

New developments

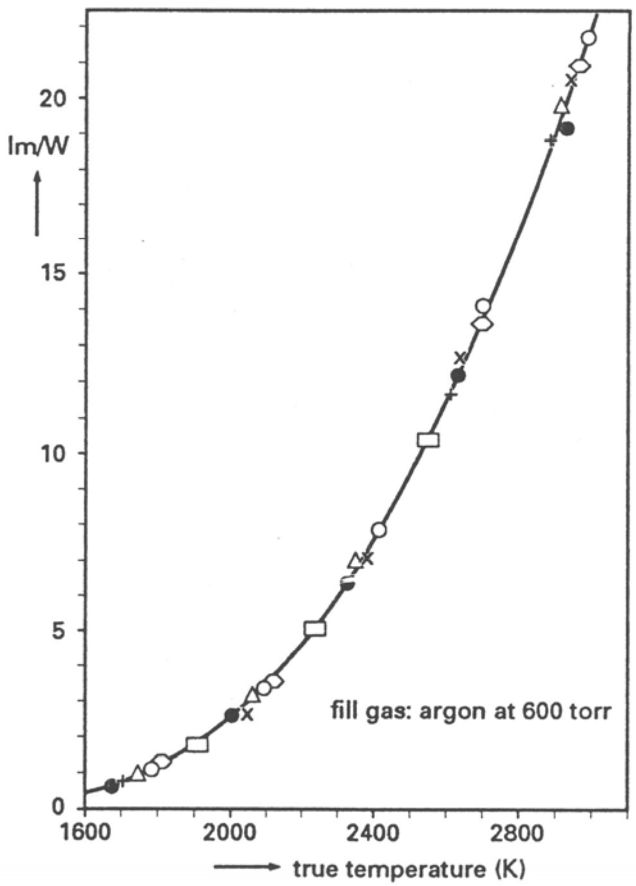
-30%
2-3 €

-50%
8-10 €

C-class ; allowed until 2016
17.1 lm/W

B-class ; allowed after 2016
(23.7 lm/W)

Current efficiency values for GLS/halogen lamps



230V 100 W GLS (T_{coil} = 2700 K) : 12 lm/W ; 1000 hr

230V Eco-30 lamps (T_{coil} = 2900 K) : 17.1 lm/W ; 2000 hr
(230V halogen bulb in GLS bulb, no electronics)

230V Eco-50 lamps (T_{coil} = 3000 K) : 23.7 lm/W ; 3000 hr
(12V bulb, incl. electronics losses, with IRC coating)

12V/60W capsule (T_{coil} = 3000 K) : 25.8 lm/W ; 5000 hr
(with IRC coating)

Even higher values in lab, but not always easy to make ...

Requirement of EU (after 2016) : min. 20 lm/W (B-class)

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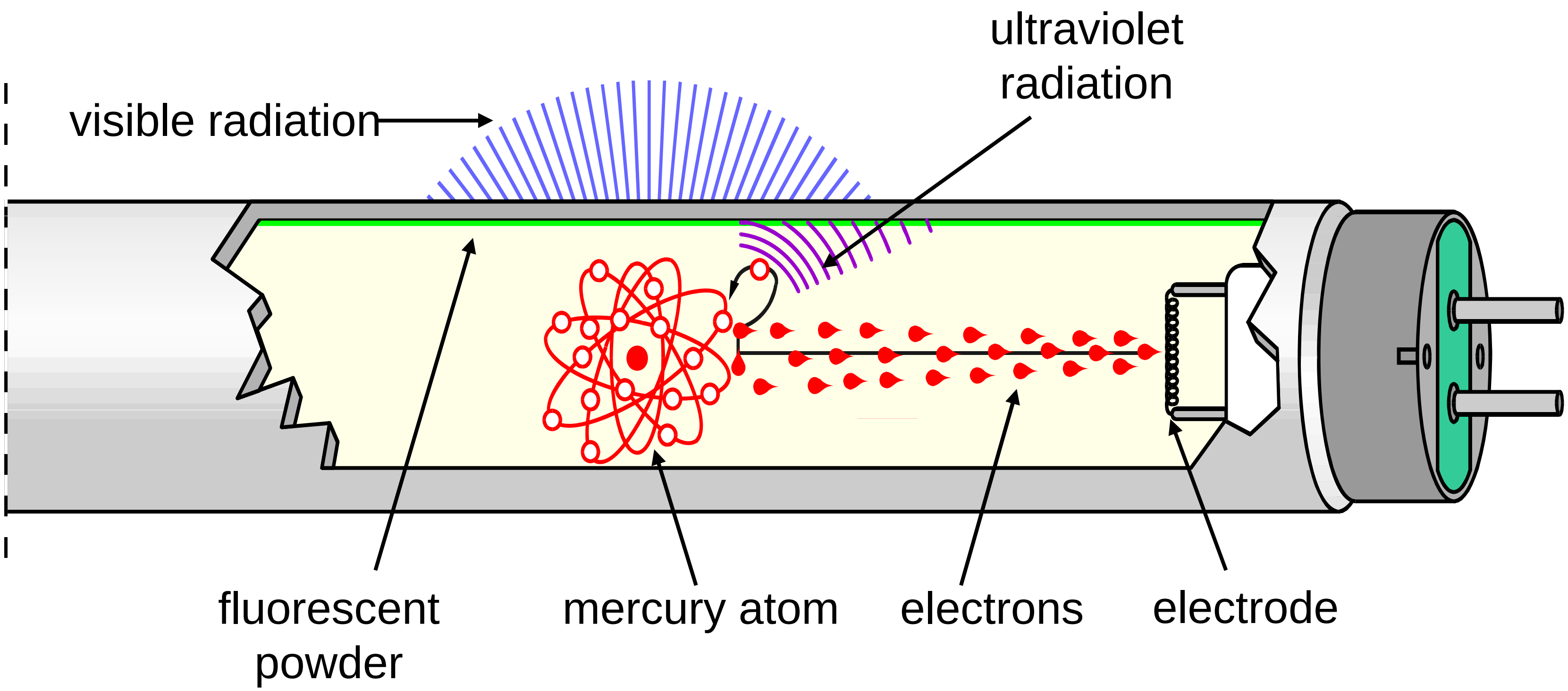
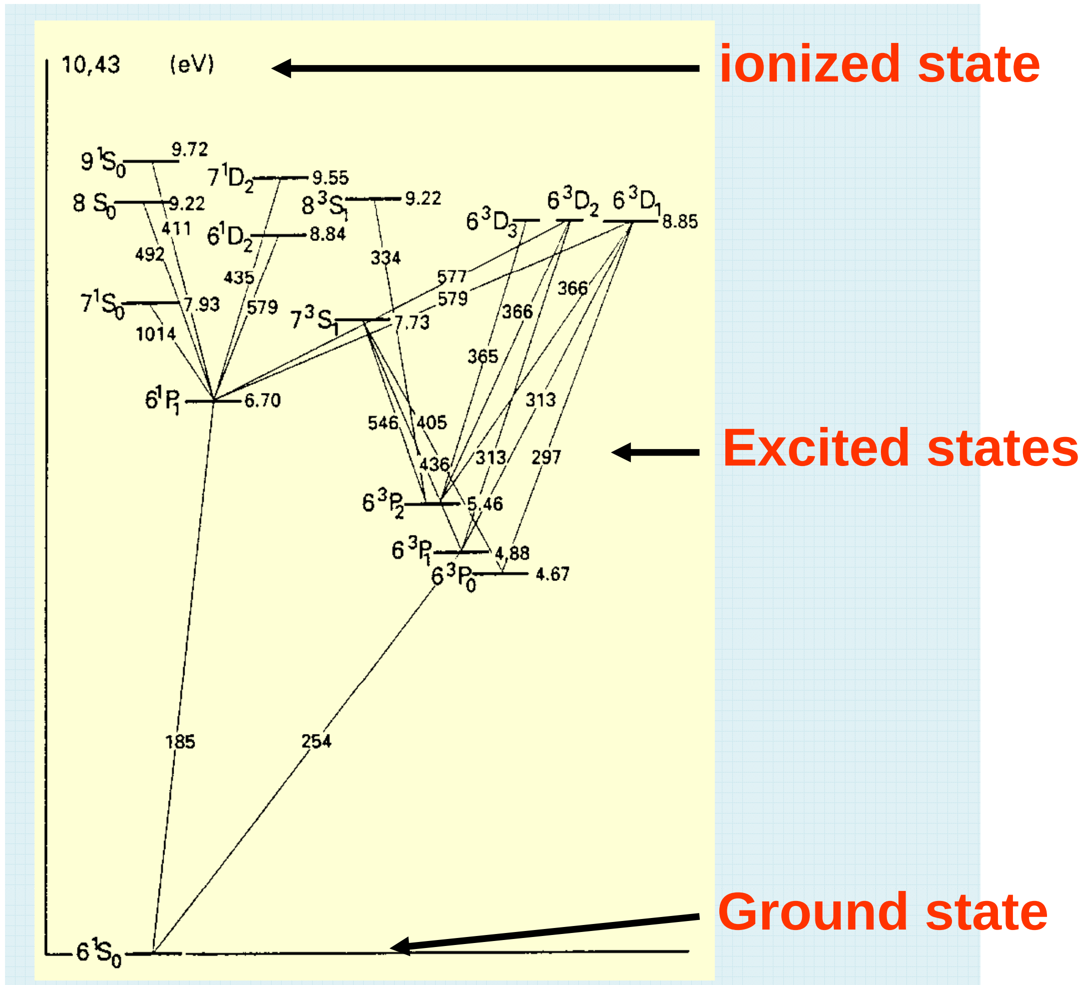
Fluorescent lamps



Emitting species in a fluorescent lamp : mercury

Energy level diagram - Mercury



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Energy balance of a fluorescent lamp

First: **40 W in lamp**

- 6 W in electrodes
  - through burner: current I_{lamp}
  - over burner: voltage V_{lamp}
  - between anode and positive column: anode fall (V_{anode})
  - between cathode and positive column: cathode fall (V_{cathode})
  - power dissipation: $(V_{\mathrm{anode}} + V_{\mathrm{cathode}}) \cdot I_{\mathrm{lamp}}$
  - this power does not enter the column
  - **electrode losses**

- 34 W in positive column

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Energy balance of a fluorescent lamp

Second: **34 W in positive column**

- 9 W **column losses**
  - volume losses
  - wall losses

- 1 W visible light from the discharge (mercury lines)

- 24 W is converted into UV radiation (185 nm / 254 nm)
  - UV efficiency lamp: 24 / 40 * 100% = 60%
  - UV efficiency column: 24 / 34 * 100% = 70%
  - UV generation very efficient

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Energy balance of a fluorescent lamp

Third: 24 W in UV

- 9 W converted into visible light via phosphor

- 15 W converted into heat
  - phosphor converts UV (5 eV) into visible light (2-3 eV)

    => Stokes shift losses
  - energy difference is converted into heat which is lost
  - **phosphor losses (scattering)**

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Energy balance of a fluorescent lamp

- **Total power converted into visible light: 10 W**
  - 9 W via phosphor
  - 1 W directly from column
  - efficiency: 10 / 40 * 100% = 25%
  - luminous efficacy: 85 lm/W

- **Total power lost: 30 W**
  - 12 W: infrared radiation
  - 18 W: convection and conduction
  - this power is applied to control the burner temperature (45 °C)

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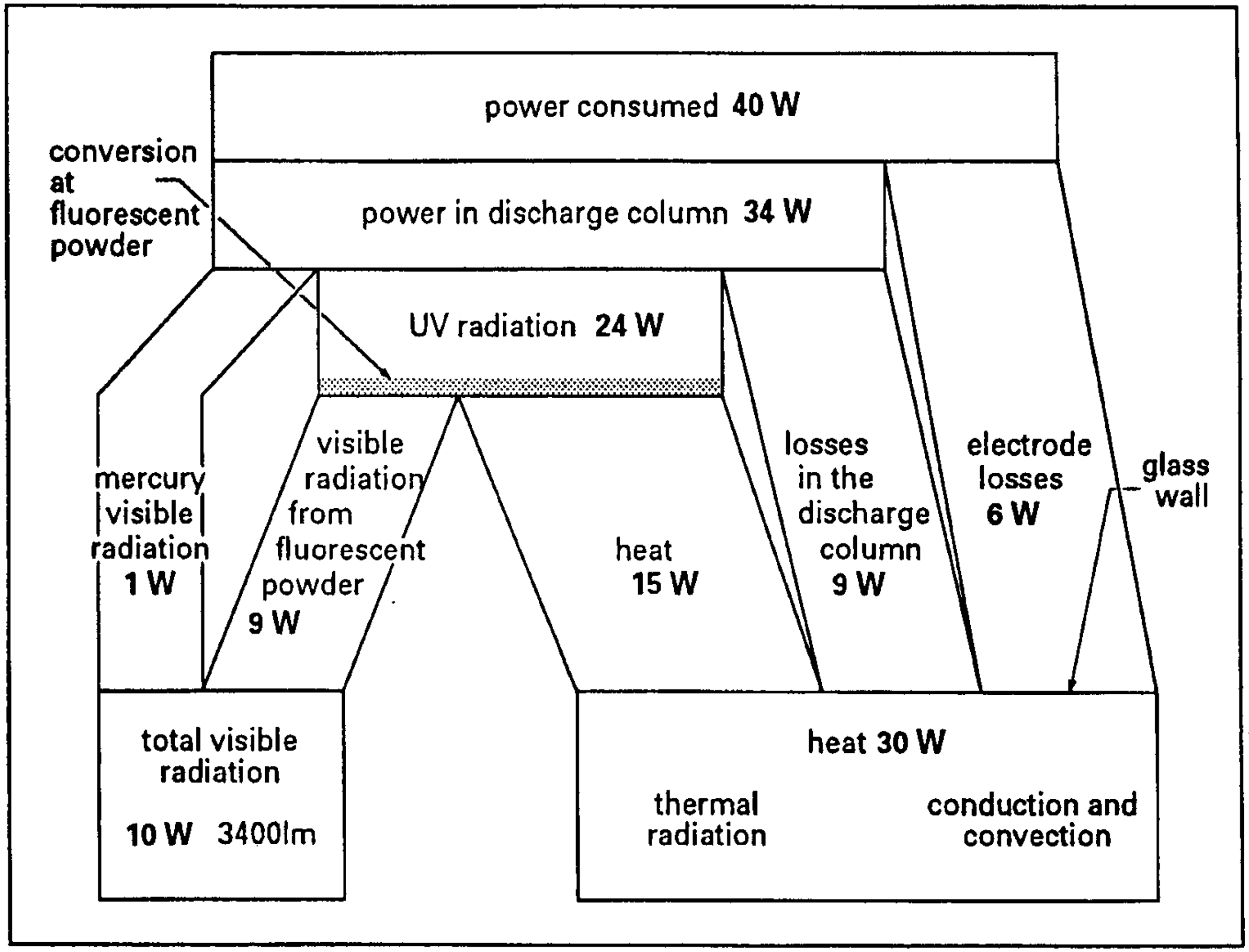
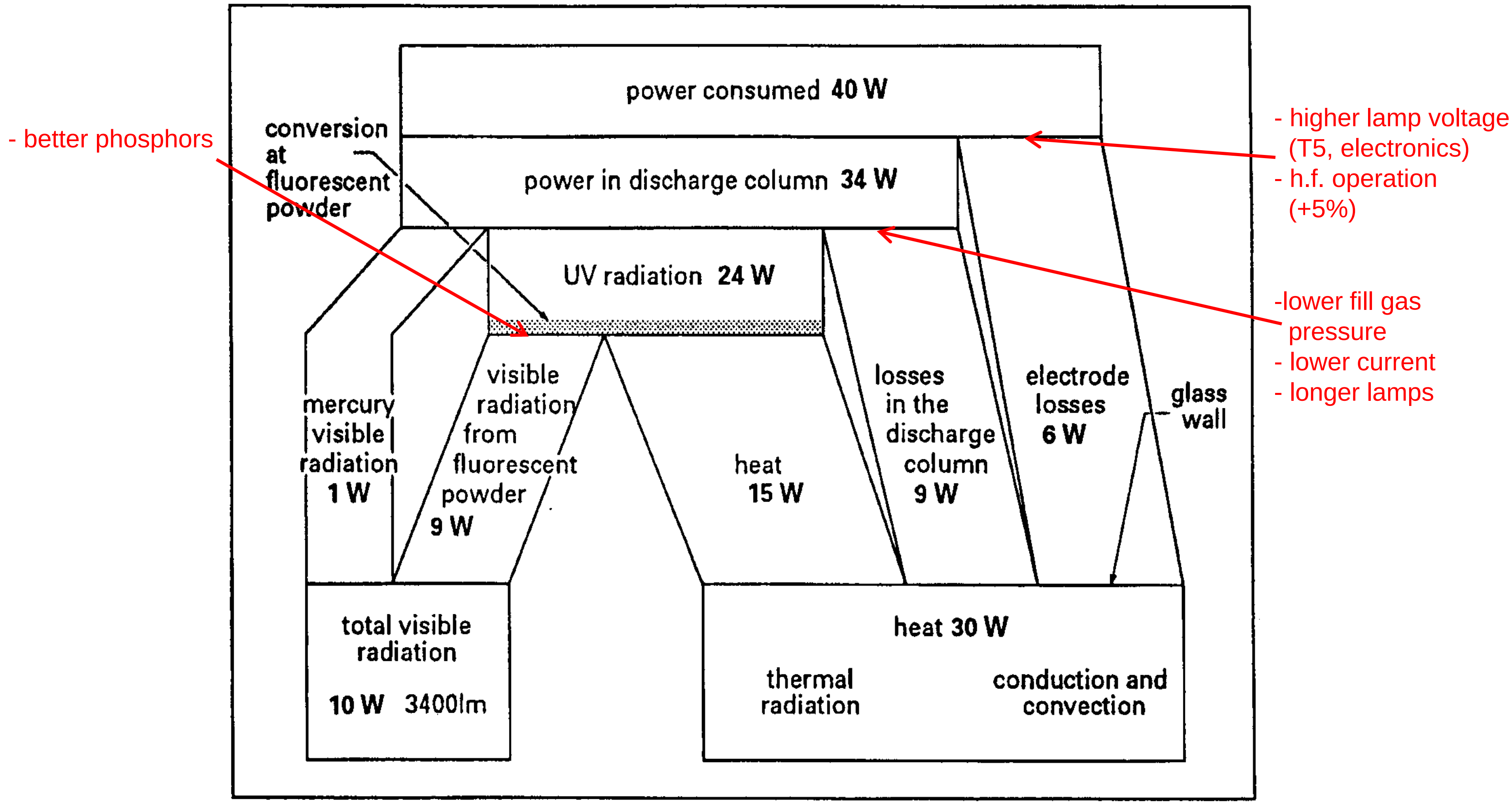
Energy balance of a fluorescent lamp in ~ 1960



Energy balance of a fluorescent lamp



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Room for improvement ?

- 40 W T12 lamp (38 mm diameter, halophosphate phosphors) : 58 lm/W
- 36 W T8 lamp (26 mm diameter, EM gear) : 79 lm/W
- 36 W T8 lamp (tri-band phosphors) : 93 lm/W
- 32 W T8 lamp (EL gear) : 100 lm/W
- 28W T5 lamp (16 mm, high voltage) : 105 lm/W
- 25 W T5 lamp (new phosphors, gas fill optimization) : 114 lm/W
- all with same lumen output and still not completely optimized ...

(Remark : real improvement is even higher as result of luminaire efficiency improvements, especially with T5)

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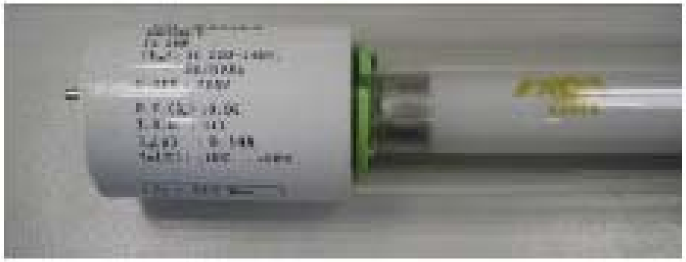
Opportunities for retrofit solutions

- Many installations in the world use old TL technologies (T12, T8 with standard halophosphate phosphors, inductive gear)
- many customers prefer a ‘plug-in’ solution (no changes in luminaire)
- with some additional electronics it is possible to maintain the same light level (with much better light quality...) and reduce system efficiency:

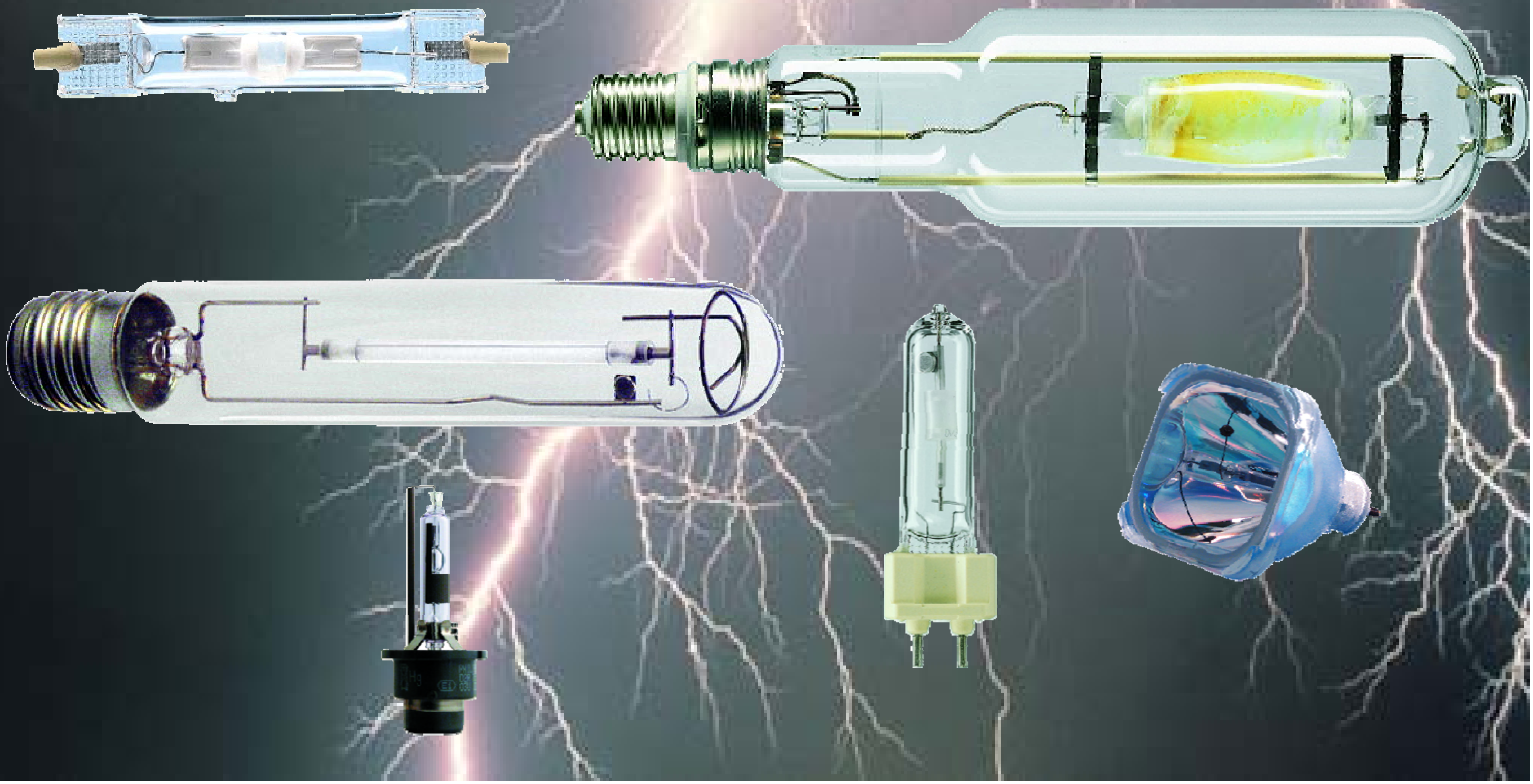
Standard TL tube (26 mm) with 36 W lamp and EM gear : 46 W

TL tube (26 mm) with a T5 ‘Eco’ lamp + EL gear inside : 22 W !

==> up to more than 50% power saving, longer lifetime and better light quality



High Intensity Discharge Lamps



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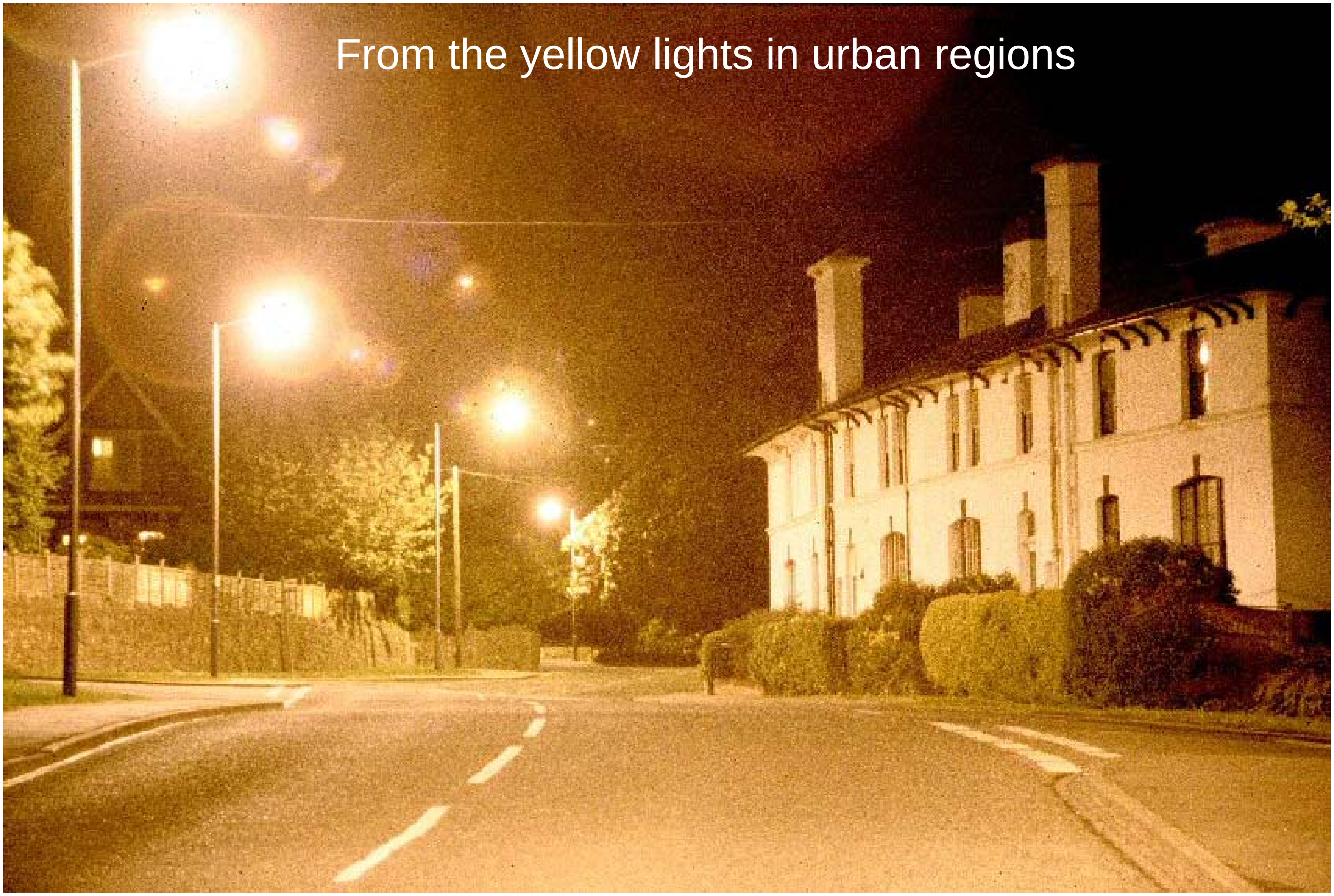
HID lamps are known from highways


From the yellow lights in urban regions


which are also used in green houses…

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HID lamps
are found in
a sports stadium

On construction sites


In fashion shops

In supermarkets

The Xenon headlights in your car

For tanning

In beamers

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What is a HID lamp?

Compact light source

A hot plasma gives the light

High temperature resistant burner

Outer bulb

Special gear is needed to operate the lamp

High luminance

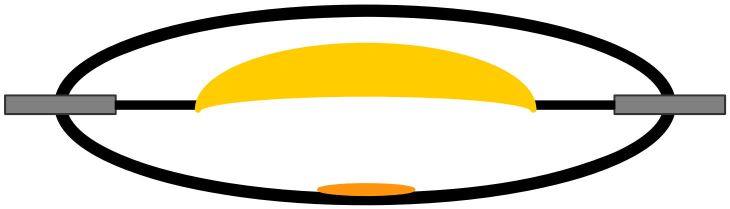
Long life

Efficiency from 50-150 lm/W

Professional installations

From 20 to 15000 W

General working principles of an HID lamp



- The W electrodes feed electrons in the plasma arc by thermal emission

- These are accelerated by the E-field and collide with the gas atoms and/or molecules (mostly mercury and rare gases)
  - Elastic collision
    - heat generation (temperature increase)
  - Inelastic collision
    - excitation (electromagnetic radiation)
    - Ionization (increases conductivity)

- In order to create the desired spectrum different elements are added in the form of a saturated vapour (Na, Sc, Tl, In, rare earth metals salts)

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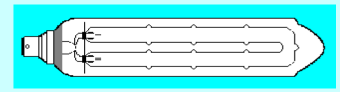
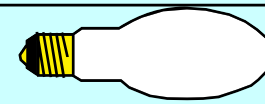
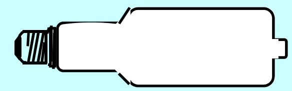
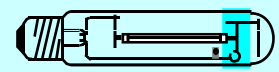
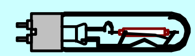
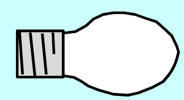
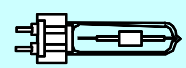
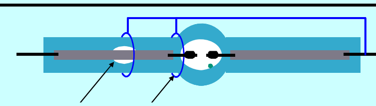
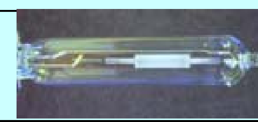
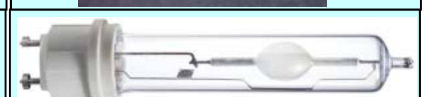
A number of HID lamp types

			max. efficacy (lm/W)
1931	low pressure sodium lamp		200
1935	high pressure mercury lamp		40
1964	Quartz high pressure metal halide lamp		75
1965	high pressure sodium lamp		150
1986	SDW-T white high pressure sodium lamp		50
1988	Quartz High Wattage Metal Halide Lamp		90
1991	QL Induction lamp Systems		75
1994	Ceramic metal halide lamp (CDM)		100
1995	Ultra High Pressure mercury lamp		70
2004	Cosmopolis ceramic MH Outdoor lamp		120
2008	CDM-Elite Medium Wattage		130

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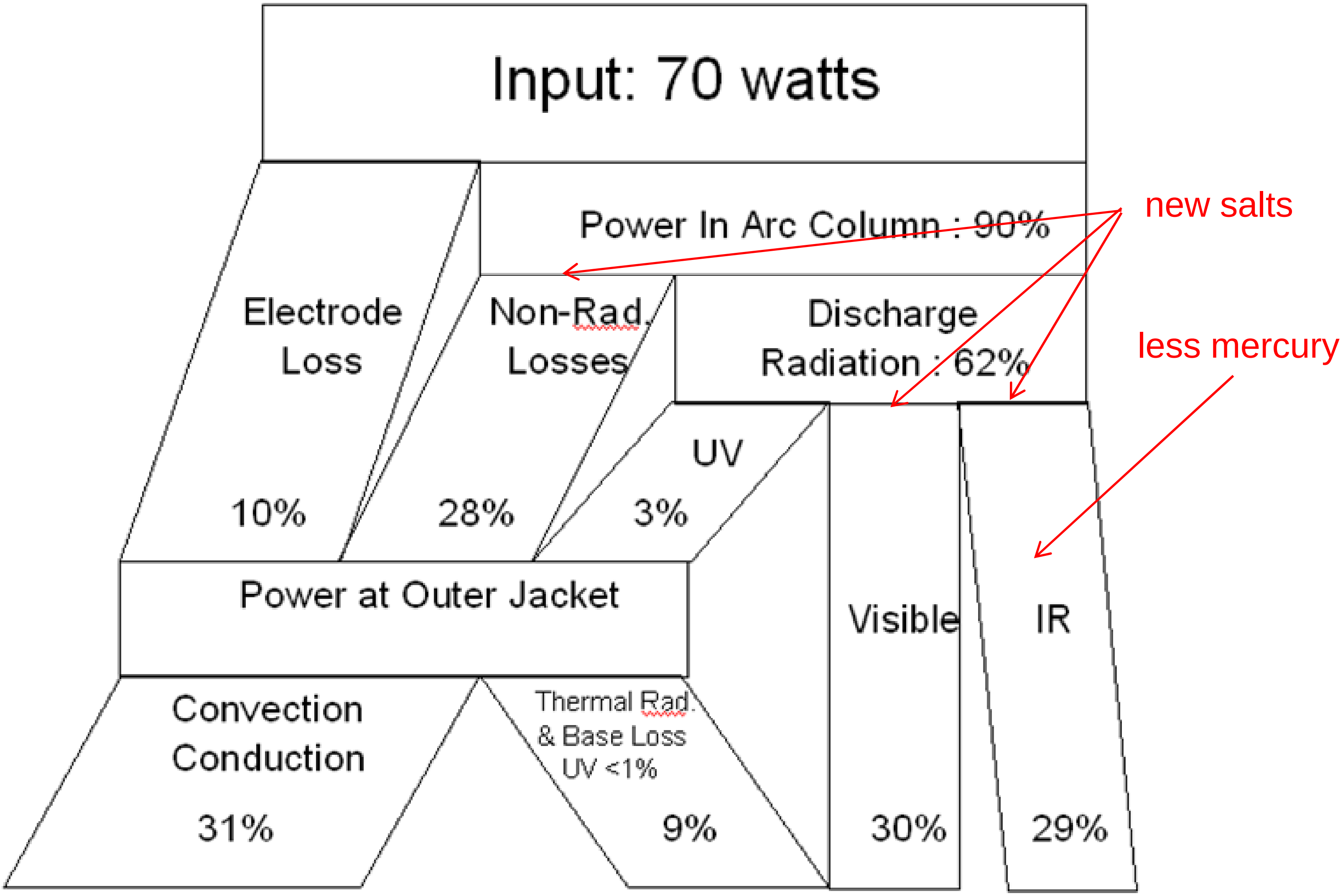
Energy balance of a 70 W CDM lamp (90 lm/W)



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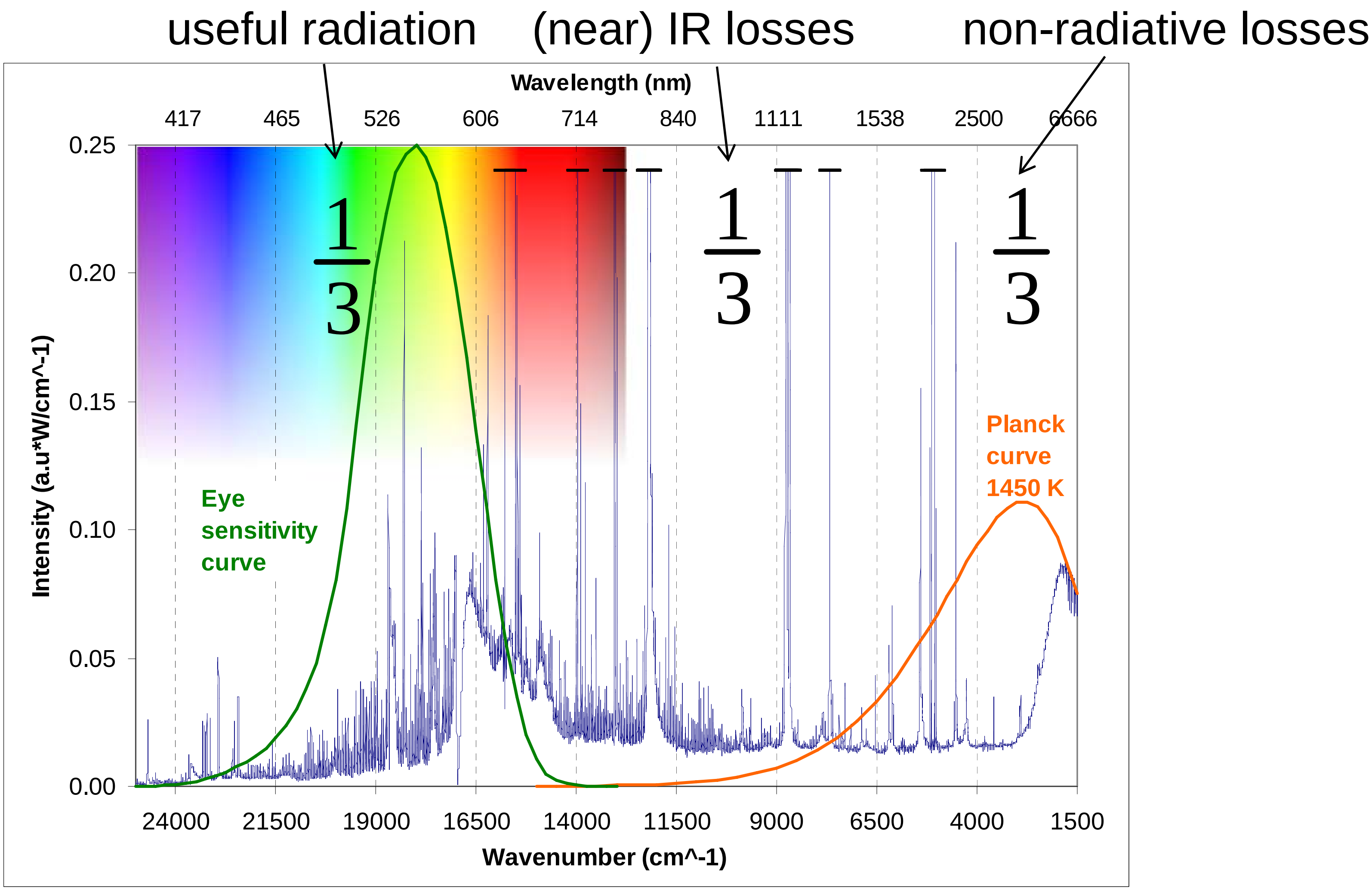
Energy balance of a typical HID lamp



measured in a ceramic metal halide lamp in vacuum without outer tube

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Recent developments

- New salt mixtures with increased cerium dose and stable colour point ==> increased efficiency (130 lm/W for high power lamps, 'CDM-Elite')
- Shaped ceramics : allows for higher vapour pressures of rare-earth species (better color rendering / less IR => higher efficiency) and reduced end-losses (thermal & optical)
- Miniaturization of burners ==> better optical control and (much) improved efficiency of the luminaire
- Practical limit ~ 150 lm/W on lamp level depending on a number of choices made (light quality, colour point, power)

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Will classical lamps soon be replaced by LEDs ?

- Many of them will indeed be replaced:
  - larger flexibility in application, and continuous efficiency improvement
  - enormous push in technology for applications outside lighting (LCD TV backlighting, mobile applications) ==> price erosion
  - lighting industry is making a massive transition to new LED systems

- However many existing lighting installations for which an LED replacement is not (yet) attractive, not (yet) available or still expensive:

€0,69
(25-100W)

€ 2,99-3,99
’25’-’100’W

(Q4 2009)

€ 29,99
(up to ’40’W only)

€ 3,30 (2800 lm, 90 lm/W)

€ 50-85 (~1800 lm,
70-100 lm/W)

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Long-term limits of SSL lamps based on LED energy balance and LTP requirements

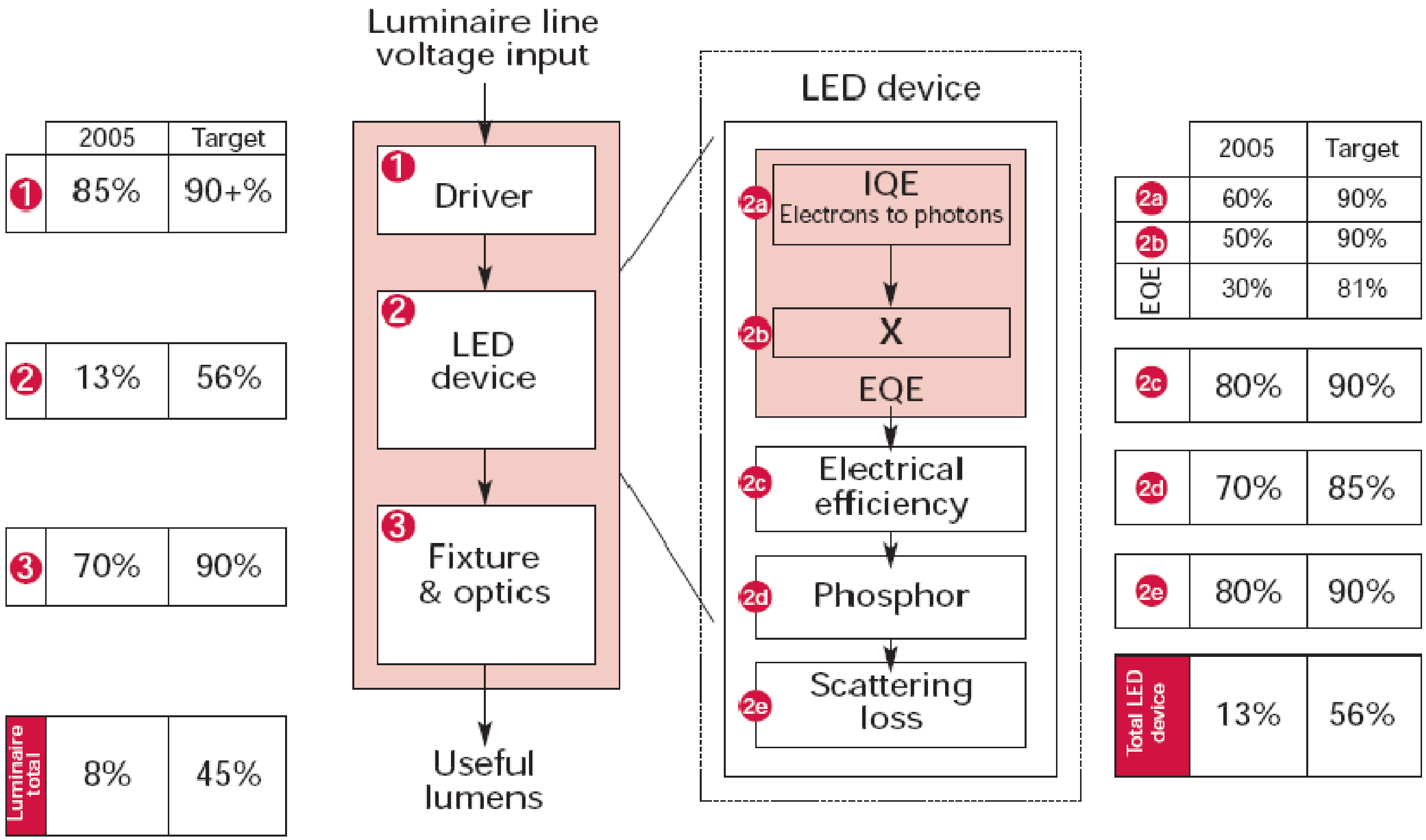

Exhibit 2.4 Current and target efficiencies – phosphor-converting LEDs

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LED limits in terms of efficiency ?

- Best lab result so far (Cree, feb. 2010) : 208 lm/W @ 350 mA / 25 C (cool-white)

- Practical efficiency limit for warm-white LEDs ~ 160 lm/W under operating conditions