# 6. High Pressure Discharge Lamps

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### 6.1 Overview of Low- and High-Pressure Discharge Lamps

<table>
<thead>
<tr>
<th><strong>HID = High Intensity Discharge</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hg low-pressure (TL)</strong></td>
</tr>
<tr>
<td><img src="image1.png" alt="" /></td>
</tr>
<tr>
<td><strong>Hg high-pressure (HPMV = high pressure metal vapour)</strong></td>
</tr>
<tr>
<td><img src="image2.png" alt="" /></td>
</tr>
<tr>
<td><strong>Hg low-pressure (CFL, PL)</strong></td>
</tr>
<tr>
<td><img src="image3.png" alt="" /></td>
</tr>
<tr>
<td><strong>Na high-pressure (HPS = high pressure sod.)</strong></td>
</tr>
<tr>
<td><img src="image4.png" alt="" /></td>
</tr>
<tr>
<td><strong>Na low-pressure (SOX)</strong></td>
</tr>
<tr>
<td><img src="image5.png" alt="" /></td>
</tr>
<tr>
<td><strong>Metal-halide high-pressure (MH)</strong></td>
</tr>
<tr>
<td><img src="image6.png" alt="" /></td>
</tr>
</tbody>
</table>

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6.2 Spectrum of Hg Discharges

Energy level scheme of Hg

Ionization level (~ 10.4 eV)

Schematic emission spectrum of a Hg-discharge at a low pressure [~ mbar]

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6.2 Spectrum of Hg Discharges

Pressure dependence of the lumen output

60 lm/W ⇒ Why is this of interest for lamps?

Good imaging properties

High luminance

Pressure increase

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6.2 Spectrum of Hg Discharges

Measured spectra of water-cooled capillary mercury discharge lamps

Source: W. Elenbaas, Quecksilberdampf-Hochdrucklampen (1966)
6.3 The High-Pressure Mercury Lamp (HP)

Evacuated outer bulb
Melting
Electrode
Burner (Hg, noble gas = starting Gas, mostly Xe)

Ballast

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6.4 Phosphors for High-Pressure Mercury Lamps

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Blue-white light due to the lack of red radiation in the emission spectrum
Solution: Phosphor!

\[ \eta = 60 \text{ lm/W} \]
\[ R_a = 20 \]
Lifeime = 20,000 h
6.4 Phosphors for High-Pressure Mercury Lamps

Suitable phosphors
(Sr,Mg)$_3$(PO$_4$)$_2$:Sn 620 nm  Broadband emission
Mg$_4$GeO$_{5.5}$F:Mn 660 nm  Line emission
YVO$_4$:Eu 620 nm  Line emission
Y(V,P)O$_4$:Eu 620 nm  Line emission

$\eta = 60 \text{ lm/W}$
$R_a = 50$
Lifetime = 20,000 h
6.4 Phosphors for High-Pressure Mercury Lamps

Sn$^{2+}$ or Mn$^{4+}$ phosphors as UV → Red converter

Problem: Low lumen equivalent of these phosphors

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6.4 Phosphors for High-Pressure Mercury Lamps

YVO$_4$:Eu$^{3+}$ phosphors - Thermal behavior

The luminous efficacy under UV-A excitation increases up to about 300 °C
Cause: Increase in spectral overlap with Hg high-pressure discharge spectrum

Luminescence intensity as a function of temperature and excitation wavelength
6.5 The Electrode

**Hg low-pressure**

![Image of low-pressure electrode](image1.png)

- Power: 36 W
- Current: I = 0.36 A
- Materials: Tungsten + emitter
- Ions: BaO / SrO / CaO
- Temperature: T = 1350 K

**Hg high-pressure**

![Image of high-pressure electrode](image2.png)

- Power: 400 W
- Current: I = 4 A
- Materials: Tungsten + emitter
- Ions: BaO / SrO / Y$_2$O$_3$ / ThO$_2$
- Temperature: T = 2000 - 3000 K
6.6 The Electrode Feedthrough

Problem: Different thermal expansion coefficients

- SiO₂  \( \alpha = 0.5 \times 10^{-6} \text{ K}^{-1} \)
- W \( \alpha = 4.3 \times 10^{-6} \text{ K}^{-1} \)
- Mo \( \alpha = 2.8 \times 10^{-6} \text{ K}^{-1} \)

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6.7 Types of Reflectors

**Parabolic reflectors**

- Focal point (light source)
- Only possible if the light source is point like

**Elliptical reflectors**

- An ellipse has two focal points
- HID-lamps

Mathematical equation: $y = x^2$
6.8 Application of HP-Lamps

In street lighting (outdoor lighting)

\[ \eta = 60 \text{ lm/W} \]
\[ R_a = 50 \]
\[ \text{Lifetime} = 20,000 \text{ h} \]
\[ P = 100 \text{ W} - 2000 \text{ W} \]
6.9 The High-Pressure Sodium Lamp (HPS)

Pressure dependence of the lumen output

Na low-pressure Lamp (0.01 mbar)

Na high-pressure Lamp (100 mbar)

Pressure increase

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Problem: Na reacts at high temperatures with the quartz glass wall

\[ 4 \text{Na} + \text{SiO}_2 \rightarrow 2 \text{Na}_2\text{O} + \text{Si} \]

Solution: Transparent, high temperature resistant material, which does not react with Na

Al\(_2\)O\(_3\)-ceramics (corundum): MgO, CaO, B\(_2\)O\(_3\)-Additives (DSA = densely sintered alumina)

![Polycrystalline structure](image)
Widening of the Na-line and self-absorption leads to a spectral hole in the emission spectrum at around 589 nm
\[ p_{Na} = 150 \text{ mbar (saturated)} \]
\[ p_{Hg} = 1000 \text{ mbar (buffer gas)} \]
\[ p_{Xe} = 100 \text{ mbar (start gas)} \]
\[ \eta = 90 - 120 \text{ lm/W} \]
\[ R_a = 20 - 50 \text{ (pressure dependent)} \]
\[ T_c = 1930 \text{ K} \]
6.10 Application of HPS Lamps

Architectural and street lighting
6.11 Metal-Halide High-Pressure Lamps

**Filling:**
- NaI - TlI - InI
- SnBr₂ - SnI₂
- NaI - DyI₃ (SSTV)
- NaI - ScI₃ (automobile headlight)

**Goal:** High \( \eta \) & color rendering
6.11 Metal-Halide High-Pressure Lamps

HPI (High Pressure Iodide) lamps

Fig. 42 The CIE colour triangle, containing the spectrum locus, the system of chromaticity coordinates, the black-body locus and the lines of constant correlated colour temperature for values from 2000 K to 20 000 K.

- 451 nm (In)
- 535 nm (Tl)
- 589 nm (Na)

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6.11 Metal-Halide High-Pressure Lamps

Spectrum of a MH lamp

Hg / NaI / TlI / DyI₃ / Ar

P = 75 W

P_{rad} / P \approx 60 \%
P_{rad,vis} / P \approx 33 \%

atomic line and molecular radiation

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6.11 Metal-Halide High-Pressure Lamps

Filling of metal halide lamps

Lamp starting (starting gas)
Noble gases: Ar or Xe (xenon lamps) → Penning effect
Radioactive substances: $^85$Kr, $^{147}$Pm

Operating voltage
• Hg
• Trend towards the substitution of Hg (environmental aspect) → Zn

Light emission
• Hg
• Metal halides $\text{MeX}_n$ ($\text{Me} = \text{Na}, \text{In}, \text{Tl}, \text{Sc}, \text{Sn}, \text{Dy}, ...$)
### 6.12 Photometric Data in Comparison

<table>
<thead>
<tr>
<th>Improvement</th>
<th>$\eta$ (lm/W)</th>
<th>$R_a$</th>
<th>Color temperature $T_c$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure Hg</td>
<td>60</td>
<td>20</td>
<td>6000</td>
</tr>
<tr>
<td>+ phosphor</td>
<td>60</td>
<td>50</td>
<td>3800</td>
</tr>
<tr>
<td>High Pressure Na</td>
<td>60 - 130</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td>Xe-pressure↑</td>
<td>80 - 150</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td>Na-pressure↑</td>
<td>60 - 90</td>
<td>60</td>
<td>2200</td>
</tr>
<tr>
<td>Metal Halide</td>
<td>HPI (NaI-TlI-InI) 70 - 80</td>
<td>70</td>
<td>3800 - 4200</td>
</tr>
<tr>
<td>SnBr$_2$-SnI$_2$</td>
<td>70</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>NaI-DyI$_3$</td>
<td>75 - 80</td>
<td>90</td>
<td>3800 - 5600</td>
</tr>
<tr>
<td>NaI-ScI$_3$</td>
<td>80 - 90</td>
<td>75</td>
<td>3600 - 4200</td>
</tr>
</tbody>
</table>
### 6.13 Applications of MH Lamps

<table>
<thead>
<tr>
<th>Compound</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPI (NaI-TII-InI)</td>
<td>Street lighting</td>
</tr>
<tr>
<td></td>
<td>Architectural lighting</td>
</tr>
<tr>
<td></td>
<td>Sports field lighting</td>
</tr>
<tr>
<td>Tin</td>
<td>Older type of lamp is replaced by MH</td>
</tr>
<tr>
<td>NaI-DyI₃</td>
<td>Sports field lighting</td>
</tr>
<tr>
<td>NaI-ScI₃</td>
<td>Shop lighting</td>
</tr>
<tr>
<td></td>
<td>Studio-stage-TV (SSTV)</td>
</tr>
<tr>
<td></td>
<td>Automotive headlights</td>
</tr>
<tr>
<td>NaI-ScI₃ + Hg + Xe (blue)</td>
<td></td>
</tr>
</tbody>
</table>

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SSTV market = Stage-Studio-TV

6.13 Applications of MH Lamps

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6.13 Applications of MH Lamps

In the „beamer“

Warum Projektion?

- Vorteile:
  - sehr große Bilder
  - kleines Volumen und Gewicht

Rückwärts-Projektion

 Professionelle Präsentationen

Heimkino

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Construction of a beamer

A projector is actually a slide projector (diascope)!

In a beamer the slide is replaced by a small LCD screen or by a DMD (Digital Mirror Device)
6.13 Applications of MH Lamps

Operating principle of a LCD (Liquid Crystal Display)

LCDs are based on liquid crystals, which rotate the polarization plane of polarised light by a rotational angle $\alpha$.

- **Liquid crystal cell (with ITO)**
- **Analyzer foil (perpendicular to P)**
- **Polarizer-foil P**
- **Pixel on for $U = 0$**
- **Pixel off for $U > 0$**
6.14 UHP-Lamps

Requirements for light sources for projectors

- If possible punctual ⇒ A lot of light from a small volume
- High luminance (light density) ⇒ High Hg-pressure

UHP = **Ultra High Pressure** (Performance)
⇒ Approx. 200 bar Hg, electrode separation ~ 1 mm
⇒ Strong pressure-broadened lines of Hg
6.14 UHP-Lamps

Components of UHP-Lamps

- DGA Brenner (P = 70 W)
- Nb
- Schmelzglas
- Mo
- W Electrode

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6.14 UHP-Lamps

Description of UHP-lamp by

- Chemical equations
  - Vapor pressure of metal halides
  - Disintegration of the metal halides in the plasma

- Temperature distribution in the plasma
  - Energy balance
  - Loss via radiation
  - Loss due to chemical energy
  - Loss due to heat
    - Convection (flow)
    - Heat conduction

- Convection equation = Navier-Stokes-Equation

\[
\Rightarrow \frac{\partial^2 h}{\partial x'^2} + \frac{\partial^2 h}{\partial y'^2} = 0 \quad \text{Potential: } h = z + \frac{u}{\gamma w}
\]

- Energy balance of the electrodes and the wall
Temperaturbelastung des Quarzglases

Elektrodentemperatur und Belastung der Einschmelzung

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Sulfur lamp: In 1990 the first discharge lamp based on a molecular sulfur discharge ($\text{S}_4 - \text{S}_8$) was developed.

The energy coupling into the discharge takes place by means of a microwave generator (magnetron), because electrodes cannot be used.
6.15 New Developments

Sulfur lamp: To generate a very large luminous flux

<table>
<thead>
<tr>
<th>Typical operating parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input power: 1.400 W</td>
</tr>
<tr>
<td>Ball diameter: approx. 30 mm</td>
</tr>
<tr>
<td>Luminous flux: 135000 lm</td>
</tr>
<tr>
<td>Color temperature: 5700 K</td>
</tr>
<tr>
<td>Starting time: 25 s</td>
</tr>
<tr>
<td>Lifetime (lamp): 60.000 h</td>
</tr>
<tr>
<td>Lifetime (magnetron): 20.000 h</td>
</tr>
<tr>
<td>Light output: 95 lm/W</td>
</tr>
</tbody>
</table>

Light source with extremely high light output, about 140000 lm (~ 40 fluorescent tubes) and (almost) pure-white light (emission band of $S_8$, ..., $S_2$ molecules)

Efficiency: Similar to fluorescent lights (thus 90 - 100 lm/W)

Problems: EMC and lifetime of the microwave generator
6.15 New Developments

Sulfur lamp: Mechanism of light generation ⇒ Emission from molecules, e.g. $S_2$

### Energy Levels

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Energy [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_3$</td>
<td>10.6</td>
</tr>
<tr>
<td>$S_3^+$</td>
<td>2.1</td>
</tr>
<tr>
<td>$S_2^+$</td>
<td>0.8</td>
</tr>
<tr>
<td>$S_2$</td>
<td>9.36</td>
</tr>
<tr>
<td>$S_2^+$</td>
<td>1.67</td>
</tr>
<tr>
<td>$S_2$</td>
<td>4.46</td>
</tr>
<tr>
<td>$S^+$</td>
<td>10.36</td>
</tr>
<tr>
<td>$S^-$</td>
<td>2.1</td>
</tr>
</tbody>
</table>

### Reaction Products

<table>
<thead>
<tr>
<th>Reactants</th>
<th>Products</th>
<th>$\Delta E$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_2 + X$</td>
<td>$2S + X$</td>
<td>4.46</td>
</tr>
<tr>
<td>$S_2 + e$</td>
<td>$S_2^+ + e$</td>
<td>9.36</td>
</tr>
<tr>
<td>$S_2^-$</td>
<td>$S_2 + e$</td>
<td>1.8</td>
</tr>
<tr>
<td>$S + e$</td>
<td>$S^+ + e$</td>
<td>10.4</td>
</tr>
<tr>
<td>$S^-$</td>
<td>$S + e$</td>
<td>2.0</td>
</tr>
<tr>
<td>$Ar + e$</td>
<td>$Ar^+ + e$</td>
<td>15.76</td>
</tr>
</tbody>
</table>

6.15 New Developments

Substitution of Hg by Zn (e.g. in automotive headlamps)

Zn/Ar Discharge

- $W_{el} = 75\, \text{W}$
- $\text{LE} = 114 \, \text{lm/W}$
- $x = 0.228$, $y = 0.227$
- $T_c = 34000\, \text{K}$
- Efficacy = 20 lm/W
- $\epsilon = 0.174 \, \text{W}_{\text{opt}}/\text{W}_{\text{elek}}$
- $R_a = 0$

Ce$^{3+}$ Luminescence

Zn/Ar/metal halide Discharge

- $W_{el} = 75\, \text{W}$
- $\text{LE} = 280 \, \text{lm/W}$
- $x = 0.436$, $y = 0.387$
- $T_c = 3000\, \text{K}$
- Efficacy = 85 lm/W
- $\epsilon = 0.33 \, \text{W}_{\text{opt}}/\text{W}_{\text{elek}}$
- $R_a = 80$

Emission intensity [a.u.]

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
</tr>
<tr>
<td>0,0</td>
</tr>
</tbody>
</table>

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