# Optical smoke units and smoke potential of different products

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# 1 Introduction

The amount of smoke, which is generated in a fire, can be determined in different ways as illustrated below.

Either it can be linked directly to the optical measure and the flow of smoke or it can be linked to the burning objects. The typical unit for the first option is [ob $m^3/s$] or if it is a linked to the object the values are given in yield. E.g. how much smoke is generated compared to the amount of burned fuel. The unit is in this case [g/g], so that a soot yield of 0.012 g/g, means that for every kg fuel there is burned 12 g of soot is generated.

For use in a zone model, the first method is the most useful, because the figures do not need to be converted. Here you measure the light attenuation, where you do not need the extinction coefficient to convert from concentration of soot to attenuation of light.

If you measure the amount of smoke, this amount has in some way to be correlated to an optical density. This is done via an extinction coefficient. The extinction coefficient for flaming combustion is 8700.

## 1.1 Nomenclature

The term [ob] is identically to [dB/m]

| | | |
|---|---|---|
| CO | [l/s] | Carbon monooxide generation at NTP |
| $D_0$ | [$m^2/g$] | Smoke potential (natural logarithm) |
| $D_{0,10log}$ | [ob $m^3/g$] | Smoke potential, linked to amount of burned fuel |
| $\Delta H_{ch}$ | [kJ/kg] | Heat of combustion |
| $\Delta H_{eff}$ | [kJ/kg] | Effective heat of combustion, same as $\Delta H_{mat}$ |
| $I_o$ | [-] | Intensity of light ray, no smoke |
| I | [-] | Intensity of light ray after passing the distance L through smoke |
| $\dot{m}$ | [kg/s] | Mass loss |
| S | [ob $m^3/s$] | Measured smoke production |
| $S_0$ | [ob] | Smoke potential used in Argos, linked to RHR |
| RHR | [kW] | Rate of heat release |

Smoke density for a given room is also a bit confussion, as this can be started in 3 different ways. Either based on natural logarithm, 10-based logarithm or 10 times 10-based logarithm.

| | | |
|---|---|---|
| $D_e$ | [-] | Optical density (natural logarithm) |
| $D_L$ | [$m^{-1}$] | Optical density pr. meter(natural logarithm) |
| $D_{log}$ | [Bel] | Optical density (10-based logarithm) |
| $D_{L, log}$ | [Bel/m] | Optical density pr. meter (10-based logarithm) |
| $D_{10log}$ | [dB] | Optical density (10X 10-based logarithm) |
| $D_{L, 10log}$ | [dB/m] | Optical density pr. meter (10X 10-based logarithm) |

The optical density given with is called $D_e$, this is a dimensionless quantity.

$$D_e = -\ln \frac{I}{I_0} \quad \textbf{(1)}$$

The optical density per metre is called $D_L$. There is a close relationsship between $D_L$ and visibility $m^{-1}$. The optical density per metre is from the formula:

$$D_L = -\frac{1}{L} \cdot \ln \frac{I}{I_0} \quad \textbf{(2)}$$

The optical density can also be based on 10-log. As this make the conversion between visibility and optical density easier

Optical density [Bel]

$$D_{\log} = -\log \frac{I}{I_0} \quad \textbf{(3)}$$

Optical density per metre [Bel/m]

$$D_{L,\log} = -\frac{1}{L} \cdot \log \frac{I}{I_0} \quad \textbf{(4)}$$

Furthermore in Argos the unit dB is used. This is 10 times bel.

Optical density [dB]

$$D_{10\log} = -10 \cdot \log \frac{I}{I_0} \quad (5)$$

Optical density per metre [dB/m]

$$D_{L,10\log} = -\frac{1}{L} \cdot 10 \cdot \log \frac{I}{I_0} \quad (6)$$

## 2 Conversion between the different units

By isolating $I/I_0$ the conversions factors between the different units can easily be found:

$$D_e = \ln(10) \cdot D_{\log} = 2.303 \cdot D_{\log} \quad (7)$$

$$D_e = \frac{\ln(10)}{10} \cdot D_{10\log} = 0.2303 \cdot D_{10\log} \quad (8)$$

$$D_L = \ln(10) \cdot D_{L,\log} = 2.303 \cdot D_{L,\log} \quad (9)$$

$$D_L = \frac{\ln(10)}{10} \cdot D_{L,10\log} = 0.2303 \cdot D_{L,10\log} \quad (10)$$

Visibility illuminated objects (signs with illuminated with external light).

$$Visibility[m] = \frac{\ln(10)}{D_L} = \frac{1}{D_{L,\log}} = \frac{10}{D_{L,10\log}} \quad (11)$$

Visibility illuminated from objects (signs illuminated form within)

$$Visibility[m] = \frac{2.5 \cdot \ln(10)}{D_L} = \frac{2.5}{D_{L,\log}} = \frac{25}{D_{L,10\log}} \quad (12)$$

Calculation of mass loss in a fire:
Mass loss is in [kg/s], RHR [kw], H [kJ/kg]

$$\dot{m} = \frac{RHR}{\Delta H_{eff}} = \frac{RHR}{\Delta H_{ch} \cdot \chi} \quad (13)$$

Smoke potential is defined by

$$D_{0,10\log} = D_{L,10\log} \cdot \frac{\dot{V}}{\dot{m}} = -\frac{1}{L} \cdot 10 \cdot \log_{10}\left(\frac{I}{I_0}\right) \cdot \frac{\dot{V}}{\dot{m}} = \frac{S}{\dot{m}} = \frac{S \cdot \Delta H_{eff}}{RHR} \quad \textbf{(14)}$$

This is the formula from the Argos theory manual, noting that $\Delta H_{mat}$ is the same as $\Delta H_{eff}$

$$S_0 = D_{0,10\log} \cdot \frac{\Delta H_{air}}{\Delta H_{mat}} \cdot \rho_0 \quad \textbf{(15)}$$

Substituting $D_{0,10\log}$ from equation 14 into equation 15 gives

$$S_0 = \frac{S}{RHR} \cdot \Delta H_{air} \cdot \rho_0 \quad \textbf{(16)}$$

This formula should be used when calculating $S_0$ on the basis of a known smoke production and heat release rate. This is the formula to use to convert Stefan Särdqvist "Initial fires" to be used in Argos.

A practical formulation of equation 15 to find $S_0$, if the smoke potential from Rasbash and Phillips is known, is given below. Note the $D_{0,10\log}$ has the unit [ob m$^3$/g]. $S_0$ has the unit [ob] or [dB/m].

$$S_0 = D_{0,10\log} \cdot \frac{3000\,\frac{kJ}{kg}}{\Delta H_{mat}} \cdot 1200\,\frac{g}{m^3} \quad \textbf{(17)}$$

$$\Delta H_{air} = 3000\,\frac{kJ}{kg} \quad \textbf{(18)}$$

$$\rho_0 = 1.2\,\frac{kg}{m^3} = 1200\,\frac{g}{m^3}$$

Equation (15) is the definition of the smoke potential $S_0$, which is used in Argos. By combining equation (14) and equation (15) a relationship between smoke production measured in the fire and the optical smoke potential used in Argos can be found, equation (16).

Likewise it should be possible to arrive at a CO potential for use in Argos based on the same principles as the smoke potential used in the program.

## 3 Practical considerations

To give a feeling of the size of smoke potentials for different fires in Argos formula 17 has been used to calculate smoke potentials for the data given by Rasbash and Phillips, 1978.

| **Name of material** | Lower heat of combustion (effective heat of combustion) ***note 1** | Smoke potential, Flaming ***note 2** $D_{0,10\log}$ | Smoke potential, Non-flaming ***note 2** $D_{0,10\log}$ | Smoke potential, **Argos (flaming)** $S_0$ | Smoke potential, **Argos (non-flaming)** $S_0$ |
|---|---|---|---|---|---|
| | [kJ/kg] | [ob m^3/g] | [ob m^3/g] | [ob] | [ob] |
| Fibre insulation board | | 0.6 | 1.8 | | |
| Chipboard | | 0.37 | 1.9 | | |
| Hardboard | 14000 | 0.35 | 1.7 | 90 | 437 |
| Birch Plywood | 14000 | 0.17 | 1.7 | 44 | 437 |
| External plywood | 14000 | 0.18 | 1.5 | 46 | 386 |
| alfa-Cellulose | | 0.22 | 2.4 | | |
| Rigid PVC | 5700 | 1.7 | 1.8 | 1074 | 1137 |
| Extruded ABS | 30000 | 3.3 | 4.2 | 396 | 504 |
| Rigid polyurethane foam | 16300 | 4.2 | 1.7 | 928 | 375 |
| Flexible polyurethane foam | 17500 | 0.96 | 5.1 | 197 | 1049 |
| Plasterboard | | 0.042 | 0.39 | | |

**Source**

***note 1*** *Tabel 3-4.11 page 3-78 in SPFE Handbook 2.nd edition*

***note 2*** *From tabel 11.5 (page 384) in An introduction to Fire Dynamics*

***note 3** The unit [ob] is short for [dB/m]

Table 1

It can be seen from the table that for flaming combustion, which is the typical in a zone model, except for a smouldering fire. The smoke potential varies between 44 dB/m to 1074 dB/m. It is also clear that smoke potential for non-flaming combustion is higher than for flaming, which could be expected.

Argos currently set a default value of 100 dB/m, when a new fire is entered into the database. This may be correct for wood, but for plastic material the smoke potential should be higher. Perhaps around 400 dB/m.

# 4 Smoke potential calculated on the basis of yield

Yield can be expressed as

$$y_s = \frac{m_s}{m} \quad \Rightarrow \quad m_s = m \cdot y_s$$

It is also given that

$$D_0 = D_L \cdot \frac{V}{m} \quad \Rightarrow \quad D_L = D_0 \cdot \frac{m}{V}$$

And

$$D_L = POD \cdot masskoncentration \quad \Rightarrow \quad D_0 \cdot \frac{m}{V} = POD \cdot y_s \cdot \frac{m}{V}$$

m and V disappear on both sides and

$$D_0 = POD \cdot y_s$$

For the optical potential (dB/m) the above equation becomes

$$D_{0,10\log} = POD \cdot y_s \cdot \frac{10}{\ln(10)} = POD \cdot y_s \cdot \frac{1}{0.2303}$$

Example with diesel oil, which have a soot yield of 0.1g/g.

POD (same as extinction coefficient) is 8.7 $m^2$/g.

This gives

$$D_{0,10\log} = 8.7 \cdot 0.1 \cdot \frac{1}{0.2303} = 3.78 \, \frac{ob\, m^3}{g}$$

Assuming an effective heat of combustion of 40000 kJ/kg a smoke potential for use in Argos can be calculated

$$S_0 = D_{0,10\log} \cdot \frac{3000 \frac{kJ}{kg}}{\Delta H_{mat}} \cdot 1200 \frac{g}{m^3} = 3.78 \cdot \frac{3000}{40000} \cdot 1200 = 340 \, \frac{dB}{m}$$

This is a smoke potential, which is above wood, but below some types of plastics.

# 5 Testing of the smoke calculation in Argos

A test was carried out in Argos, where a calculation was done with a given smoke input. This calculation was verified against the same calculation done by hand. It gave exact the same result – see below.

## 5.1 Visibility calculations

Below is derived, how a hand calculation can be done of the OD – density in a room.

$$\frac{dS_{tot}}{dt} = \frac{q_{fire}}{\Delta H_{air} \cdot \rho_0} \cdot S_0$$

$$\Downarrow$$

$$S_{tot} = \int \frac{q_{fire}}{\Delta H_{air} \cdot \rho_0} \cdot S_0 \; dt$$

$$\Downarrow$$

$$S_{tot} = \frac{S_0}{\Delta H_{air} \cdot \rho_0} \int q_{fire} \; dt$$

$$\Downarrow \text{ if constant heat release}$$

$$S_{tot} = \frac{S_0 \cdot q_{fire}}{\Delta H_{air} \cdot \rho_0} \cdot \Delta t$$

The term $q_{fire}$*Δt is the same as energy released (ΔE).

$$OD = \frac{S_{tot}}{V} = \frac{\frac{S_0 \cdot q_{fire}}{\Delta H_{air} \cdot \rho_0} \cdot \Delta t}{V} = \frac{S_0 \cdot q_{fire}}{\Delta H_{air} \cdot \rho_0} \cdot \frac{\Delta t}{V}$$

$$\Downarrow$$

$$OD = \frac{S_0 \cdot q_{fire}}{3000 \frac{kJ}{kg} \cdot 1.2 \frac{kg}{m^3}} \cdot \frac{\Delta t}{V} = \frac{1}{3600 \frac{kJ}{m^3}} \cdot \frac{S_0 \cdot q_{fire} \cdot \Delta t}{V}$$

### 5.2 Example (constant fire)

A fire of 1 MW (1000 kW=1000 kJ/s) is burning in a room, which has a volume of 300 m$^3$ (10 m x 10 m x 3 m). The material burning is wood (optical smoke potential=50dB/m). What is the optical density after 146 seconds, if the smoke produced is distributed throughout the room (no smoke layer formed)?

$$OD = \frac{1}{3600\frac{kJ}{m^3}} \cdot \frac{S_0 \cdot q_{fire} \cdot \Delta t}{V} = \frac{1}{3600\frac{kJ}{m^3}} \cdot \frac{50\frac{dB}{m} \cdot 1000\frac{kJ}{S} \cdot 146s}{300m^3} \approx 6.76\frac{dB}{m}$$

To calculate the visibility:

$$Visibility = \frac{10\,db}{OD} = \frac{10\,db}{6.76\frac{dB}{m}} \approx 1.5\,m$$

### 5.3 Example (Non-constant fire - $\alpha t^2$-fire)

If the fire is not constant $q_{fire}$ has to be integrated with respect to time. This happens also for the constant fire, but here it is a bit more simple as the energy released is just $\Delta E = q_{fire} * \Delta t$.

For the non-constant fire, the energy release is

$$\Delta E = \int q_{fire}\ dt = \int \alpha \cdot t^2\ dt = \frac{\alpha}{3}(\Delta t)^3$$

This means that the formula for optical density becomes

$$OD = \frac{1}{3600\frac{kJ}{m^3}} \cdot \frac{S_0 \cdot \frac{\alpha}{3} \cdot (\Delta t)^3}{V} = \frac{1}{10800\frac{kJ}{m^3}} \cdot \frac{S_0 \cdot \alpha \cdot (\Delta t)^3}{V}$$

This time, the fire grows as a “fast” fire with $\alpha$=0.047 kW/s$^2$, which means that the fire will reach 1 MW after 146 s. What is the OD in the room at that time?

$$OD = \frac{1}{10800\frac{kJ}{m^3}} \cdot \frac{S_0 \cdot \alpha \cdot (\Delta t)^3}{V} = \frac{1}{10800\frac{kJ}{m^3}} \cdot \frac{50 \cdot 0.047 \cdot (146)^3}{300m^3} \approx 2.26\frac{dB}{m}$$

To calculate the visibility:

$$Visibility = \frac{10\,db}{OD} = \frac{10\,db}{2.26\,\frac{dB}{m}} \approx 4.4\,m$$

## 6 What value for optical smoke potential is reasonable to use

On basis of the data from Initial Fires the smoke potential for use in Argos was calculated - see Appendix A. The average smoke potentials were calculated for 98 fires by the methods described above, formula 16. The mean value for all those fires is 151 dB/m and the median is 115 dB/m. See Appendix A for more statistic on the measurements.

The smoke potential varies between 1.5 and 712 db/m for the measurements. Comparing these data to Rasbash and Phillips data for 7 fires (Table 1), is seems reasonable to set the lower limit to 50 dB/m. This is the value for wood, which is one of the least sooty solid fuels.

Looking at the data in Appendix A about 4 experiments gave a smoke potential higher than 400 dB/m. In table 1 two of the fires have a value above 400 dB/m. Bearing in mind that diesel oil, which is fairly sooty, have a smoke potential about 400 dB/m it seems reasonable to set a upper limit to 400 dB/m.

Normally a fire is a combination of different materials, each having different smoke potentials. So even if one of the materials has a high smoke potential this will be levelled out by some of the other materials. So the smoke potential should be between 50 and 400 dB/m. A reasonable value to be used is 200 dB/m, which is above the average value found in the experiments.

An exception for this rule is, if a storage contains only one material, which produces a lot of smoke. Eg. rigid PVC (table 1), which has a smoke potential of 1074 dB/m. This value should then be used in the simulations.

# 7 References

*Argos Theory Manual*
Edited by Bjarne P. Husted and Thomas W. Sødring
Danish Institute of Fire and Security Technology
Hvidovre
Denmark, December 2003

Daniel Nilsson
*Aktiva 2002* (In Swedish)
Department of Fire Safety Engineering
Lund University,
Sweden 2002

Dougal Drysdale
*An introduction to Fire Dynamics, 2. edition*
John Wiley and Sons, Ltd.
England April 2000

Rasbash, D.J. and Phillips, R.P.
*Quantification of smoke produced at fires. Test methods for smoke and methods of expressing smoke evolution.*
Fire and Materials, vol 2, page 102-109, 1978

Stefan Särdqvist
*Initial Fires - RHR, Smoke production and CO Generation from single Items and Room Fire Tests*
Department of Fire Safety Engineering
Lund University, Sweden
Lund, April 1993

*The SFPE Handbook of Fire Protection Engineering*
DiNenno et Al.
Second Edition
National Fire Protection Association, Inc,
USA 1995

# Appendix A Initial fires and average smoke potential (Argos)

Time averaged smoke potential for all fires from Initial fires, where smoke potential was measured (98 items), is given below. The mean value of all the time averaged smoke potentials is 151 dB/m. The median is 115 dB/m. The standard deviation is 137 dB/m. The 99% confidence interval for the mean value is between 151+/- 36. This means that with 99% confidence the mean value lies between 115 dB/m and 187 dB/m assuming it is a normal distribution.

For all the rest of the items (101 fires in total) the smoke potential was set on the conservative side to 200 as this is above the mean value of 151 dB/m and on the safe side of the confidence interval.

The unit of smoke potential in Argos is [dB/m], which is the same as the unit [ob].

| **Name** | **Average optical smoke potential (dB/m)** |
|---|---:|
| Boards, Gypsum plaster O1-13 | 1.65 |
| Boards, Gypsum plaster O1-12 | 2.52 |
| Boards, Expanded plastics O6-21 | 10.29 |
| Curtains Y7-13 | 10.29 |
| Curtains Y7-10 | 13.98 |
| Christmas trees, expt.no. 17, Y8-21 | 15.54 |
| Pipe insulation K4-18 | 15.56 |
| Boards, Laminate faced panels O6-12 | 16.46 |
| Boards, Gypsum plaster O1-14 | 25.15 |
| Boards, Gypsum plaster O1-15 | 25.29 |
| Chairs, 2-cushion mock-up chairs Y52-77 | 25.68 |
| Pipe insulation K4-10 | 25.87 |
| Boards, Mineral wool O5-11 | 27.47 |
| Curtains Y7-14 | 27.59 |
| Boards, Particle boards O4-21 | 30.64 |
| Pipe insulation K4-17 | 31.8 |
| Boards, Particle boards O4-23 | 33.62 |
| Boards, Plywood O3-20 | 35.03 |
| Boards, Plywood O3-21 | 35.03 |
| Boards, Expanded plastics O6-22 | 35.5 |
| Curtains Y7-11 | 37.76 |
| Chairs, 2-cushion mock-up chairs Y52-78 | 40.24 |
| Boards, Fibre boards O4-10 | 42 |
| Pipe insulation K4-11 | 46.99 |
| Boards, Fibre boards O4-11 | 47.25 |
| Chairs, 2-cushion mock-up chairs Y52-76 | 47.56 |
| Boards, Particle boards O4-22 | 48.24 |
| Sofa Y54-10 | 48.56 |
| Chairs, 2-cushion mock-up chairs Y52-55 | 49.5 |

| | |
|---|---|
| Sofa Y54-13 | 53.36 |
| Boards, Laminate faced panels O6-11 | 54.99 |
| Sofa Y54-18 | 55.24 |
| Boards, Gypsum plaster O1-11 | 55.71 |
| Chairs, 2-cushion mock-up chairs Y52-56 | 60.75 |
| Chairs, 2-cushion mock-up chairs Y52-88 | 70.01 |
| Boards, Particle boards O4-20 | 74.38 |
| Boards, Particle boards O4-24 | 74.58 |
| Boards, Stell sheets O2-11 | 80.38 |
| Bed, foam mattresses Y6-12 | 85.53 |
| Chairs, Stackable Y50-12 | 91.65 |
| Boards, Wood panels O3-10 | 94.64 |
| Curtains Y7-15 | 100.31 |
| Boards, Laminate faced panels O6-13 | 100.38 |
| Sofa Y54-12 | 102.8 |
| Boards, Particle boards O4-25 | 103.72 |
| Boards, Particle boards O4-26 | 106.39 |
| Christmas trees, expt.no. 18, Y8-22 | 107.39 |
| Large vehicles, train seats Z3-12 | 109.22 |
| Television set Y1-20 | 112.79 |
| Chairs, Stackable Y50-11 | 117.09 |
| Television set Y1-21 | 119.62 |
| Bed, Complete Y6-24 | 121.73 |
| Chairs, 2-cushion mock-up chairs Y52-73 | 124.62 |
| Chairs, 2-cushion mock-up chairs Y52-79 | 126.61 |
| Sofa Y54-19 | 127.06 |
| Boards, Stell sheets O2-10 | 127.37 |
| Chairs, Stackable Y50-14 | 131.17 |
| Chairs, Stackable Y50-13 | 132.29 |
| Boards, Expanded plastics O6-20 | 143.76 |
| Bed, foam mattresses Y6-10 | 144.73 |
| Boards, Gypsum plaster O1-16 | 145.06 |
| Chairs, Stackable Y50-10 | 161.51 |
| Chairs, 2-cushion mock-up chairs Y52-90 | 166.71 |
| Chairs, 2-cushion mock-up chairs Y52-86 | 166.83 |
| Sofa Y54-16 | 169.98 |
| Chairs, 2-cushion mock-up chairs Y52-58 | 171.11 |
| Sofa Y54-15 | 172.37 |
| Large vehicles, bus seats Z3-11 | 178.27 |
| Chairs, 2-cushion mock-up chairs Y52-68 | 182.36 |
| Sofa Y54-20 | 204.48 |
| Bed, foam mattresses Y6-11 | 214.32 |
| Bed, Mattress Y6-22 | 221.4 |
| Curtains Y7-16 | 225.16 |
| Chairs, 2-cushion mock-up chairs Y52-85 | 227.78 |
| Chairs, 2-cushion mock-up chairs Y52-67 | 243.57 |
| Sofa Y54-14 | 244.98 |
| Boards, Laminate faced panels O6-10 | 248.98 |
| Chairs, 2-cushion mock-up chairs Y52-72 | 253.19 |
| Pipe insulation K4-12 | 253.57 |

| | |
|---|---|
| Chairs, 2-cushion mock-up chairs Y52-57 | 254.23 |
| Chairs, 2-cushion mock-up chairs Y52-66 | 258.86 |
| Chairs, 2-cushion mock-up chairs Y52-80 | 276.69 |
| Curtains Y7-12 | 278.62 |
| Pipe insulation K4-16 | 280.77 |
| Chairs, 2-cushion mock-up chairs Y52-83 | 291.33 |
| Chairs, 2-cushion mock-up chairs Y52-84 | 291.98 |
| Bed, Mattress Y6-23 | 297.97 |
| Chairs, 2-cushion mock-up chairs Y52-61 | 318.45 |
| Sofa Y54-17 | 320.13 |
| Chairs, 2-cushion mock-up chairs Y52-81 | 321.44 |
| Sofa Y54-11 | 323.15 |
| Chairs, 2-cushion mock-up chairs Y52-59 | 352.68 |
| Chairs, 2-cushion mock-up chairs Y52-75 | 378.24 |
| Pipe insulation K4-14 | 401.82 |
| Pipe insulation K4-15 | 508.04 |
| Pipe insulation K4-13 | 535.29 |
| Boards, Mineral wool O5-10 | 602.25 |
| Chairs, 2-cushion mock-up chairs Y52-65 | 712.79 |
| **Mean Value** | **151.2213265** |