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1993
ISO 9835:1993

Methods for

Measurement of air pollution —

Part 11: Determination of a black smoke index in ambient air

UDC 614.715:543.275.3:531.082.531

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the Environment and Pollution Standards Policy Committee (EPC/-) to Technical Committee EPC/35, upon which the following bodies were represented:

Association of Consulting Scientists
BCIRA
British Cement Association
British Coal Corporation
British Gas plc
Combustion Engineering Association
Department of the Environment (Her Majesty's Inspectorate of Pollution)
Department of Health
Department of Trade and Industry (Laboratory of the Government Chemist)
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National Society for Clean Air
Royal Society of Chemistry

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Contents

National foreword

This Part of BS 1747 has been prepared under the direction of the Environment and Pollution Standards Policy Committee. It is identical with ISO 9835:1993 *Ambient air — Determination of black smoke index*, published by the International Organization for Standardization (ISO) with the active participation and approval of the UK.

This Part of BS 1747 is one of a series relating to air quality arising from UK participation in the work of ISO/TC 146. Methods for the determination of particular constituents of ambient air will be published as further Parts of this British Standard. Topics relating to air quality characteristics will be published as Parts of BS 6069 *Characterization of air quality*.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 8 and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

1 Scope

This International Standard specifies a method for measuring the black smoke index of an ambient air sample. The method is based on the staining effect of particles which is produced when a sample of air is drawn through a filter paper.

The method is intended for the measurement of a black smoke index in the range 6 to 375 in the ambient atmosphere. It is based on the measurement of reflectance. The method does not measure the mass concentration of particles directly.

2 Definition

For the purposes of this International Standard, the following definition applies.

2.1
black smoke

strongly light-absorbing, particulate material suspended in the ambient atmosphere

NOTE 1 The major contributor to black smoke is soot particles; i.e. particles containing carbon in its elemental form.

3 Principle and theory

Air is drawn through a filter paper and the reflectance of the stain produced is measured. If it is assumed that reflected light from the surface of the filter paper has passed through the layer of light absorbent particles twice, reflectance from the filter surface is analogous to the absorption of light by particles suspended in air in accordance with the equation

$$R = R_0 \exp\left(\frac{-2aV}{A}\right) \quad \ldots (1)$$

where

R is the intensity of reflected light from the surface of a stained paper;

R_0 is the intensity of reflected light from the surface of a clean paper;

A is the area of the stain on the filter paper, in square metres;

V is the volume sampled, in cubic metres;

a is the absorption coefficient, in reciprocal metres.

Thus, rearranging equation (1):

$$a = \frac{A}{2V} \times \mathrm{In}\left(\frac{R_0}{R}\right) \quad \ldots (2)$$

The method specified in this International Standard can be used to measure the absorption coefficient on any filter material, but the conversion of absorption coefficient or extinction coefficient to what is, by convention, known as the black smoke index, is purely an arbitrary operation which is carried out by reference to tables or graphs. For further explanations, see Annex A.

4 Apparatus

4.1 *Sampling equipment.* The sampler shall be designed for daily operation, or it shall be of an automatic type for continuous operation. Flow diagrams of alternative arrangements of sampling equipment are shown in Figure 1. Details of the sampling equipment are given in **4.1.1** to **4.1.6**.

4.1.1 *Air intake*, a conical funnel of 30 mm to 50 mm diameter that is constructed of polyvinylchloride. The funnel shall be mounted vertically with the mouth downwards at a height of not less than 2,5 m and not greater than 5 m above the ground. The inlet shall be located at least 1 m horizontally from any external walls.

4.1.2 *Connection tubing*, constructed of polyvinylchloride, of internal diameter 8 mm ± 1 mm and not greater than 6 m in length. Bends shall be avoided if possible but, if unavoidable, shall have a radius greater than 50 mm.

4.1.3 *Filter unit.* The filter holder shall be constructed of an electrically conducting and chemically inert material (with respect to the atmosphere likely to be encountered). The area of the aperture shall be 5 cm^2 + 5 %. The leakage across the filter and valves (if used) shall not exceed 2 % of the total flow rate. The filter holder should be of a design which will provide a homogeneous particle layer on the surface of the filter medium.

The homogeneity of the particle layer can be checked by measuring the reflectance at several points across the diameter of the stain produced by sampling particles using the filter holder. The variation in reflectance across the stain shall not exceed 1 percentage unit of reflectance.

4.1.4 *Filter material.* The filter membrane shall have a collection efficiency of as close to 100 % as possible in the 0,1 micron to 5 micron particle size range. Variations in reflectance across the whole surface area shall not exceed 1 reflectance unit. In addition, the filter material shall be suitable for a flow rate of 2 m^3/d.

NOTE 2 The reflectance of unused filters may vary from batch to batch, and it is therefore necessary to check and adjust for the variability of the filters before use.

4.1.5 *Sampling pump*, capable of delivering up to 2,0 l/min of air with the filter in line. If a membrane pump is used, a 0,2 litre ballast shall be incorporated to minimize pressure fluctuations. The pump is placed before the flow or volume meter (see Figure 1).

4.1.6 *Volume measurement and flow rate control*, consisting of a sampler equipped with a flow controller capable of keeping the flow rate constant to within ± 5 % of the measured flow. Measure the volume sampled by either

a) recording the elapsed time and calculating the volume sampled under the control of the flow controller; or

b) reading the volume directly from a dry gasmeter having an accuracy of at least 5 % of the measured volume (the sampling flow rate shall be 2 $m^3/d \pm 0{,}2\ m^3/d$).

4.2 *Reflectometer*, consisting of a light source and detector and having either an analogue or digital readout of either the percentage reflectance (linear scale; 0 to 100 % reflectance) or the extinction coefficient (logarithmic scale; 0 to infinity) type.

The points on the density chart[1] shall be within the limits shown in Figure 2.

Instruments designed according to the requirements mentioned in this subclause shall be capable of measuring the absorption coefficient with a precision of better than 5 % at absorption coefficients greater than $1 \times 10^{-5} m^{-1}$.

5 Procedure

5.1 Sampling

Assemble the sampling train in the order illustrated in Figure 1 using the specified connection tubing (**4.1.2**) for all connections. Place a clean sheet of filter paper (**4.1.4**) in the filter unit. If the two faces of the paper do not have the same texture, place the paper so that the suspended particulate matter is collected on the smoother surface.

Assemble the filter unit (**4.1.3**) according to the manufacturer's instructions. Check the assembled equipment for leakage.

Record the initial reading of the gasmeter (if fitted).

Start the sampling pump (**4.1.5**), adjust the sampling rate to 1,4 l/min (2 m^3/d) and note the starting time. Sample for 24 h.

At the end of the sampling period, record the flow rate and time, switch off the sampling pump and record the final reading of the dry gasmeter (if fitted) and the sampling period to the nearest hour and minute.

Calculate the volume sampled, in cubic metres, using the flow rate and the sample duration or using the readings of the dry gasmeter. (See also **4.1.6**.)

5.2 Calibration of the reflectometer

Calibrate the reflectometer according to the manufacturers' instructions.

5.3 Measurement of the reflectance of smoke stains

5.3.1 Calibrate the reflectometer at least once per month using the procedure described in **5.2**.

5.3.2 Set the reflectometer to 100 % reflectance (zero absorbance) on a clean filter paper according to the reflectometer manufacturer's instructions.

5.3.3 Replace the clean filter paper by an exposed one (see **5.1**), measure the reflectance according to the manufacturer's instructions and record the reflectometer reading (which will be less than 100 % reflectance or more than zero absorbance).

The measured reflectances shall lie in the range 35 % to 95 % reflectance, corresponding to a range of 0,64 to $13{,}13 \times 10^{-5}$ for the absorption coefficient.

5.3.4 Check the 100 % adjustment of the reflectometer on a clean filter paper at frequent intervals, for example at least after every 10 smoke stains, and readjust if necessary.

6 Expression of results

6.1 Calculation

Calculate the absorption coefficient a, in reciprocal metres, using equation (2)

$$a = \frac{A}{2V} ¥ \ln\left(\frac{R_0}{R}\right) \qquad \ldots (3)$$

where

R is the reflectance of the stained paper, in percentage of R_0;

R_0 is the reflectance of the clean reference paper (100 by definition);

V is the volume sampled, in cubic metres;

A is the area of the stain on the filter paper, in square metres.

Report the absorption coefficient to the first decimal place.

NOTE 3 Table A.1 may be used to convert the absorption coefficient, a, to the black smoke index, in line with the OECD or EEC reference methods.

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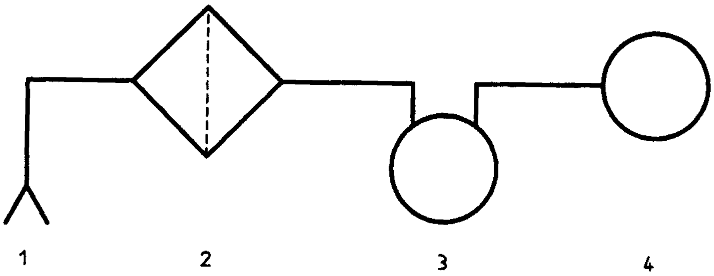
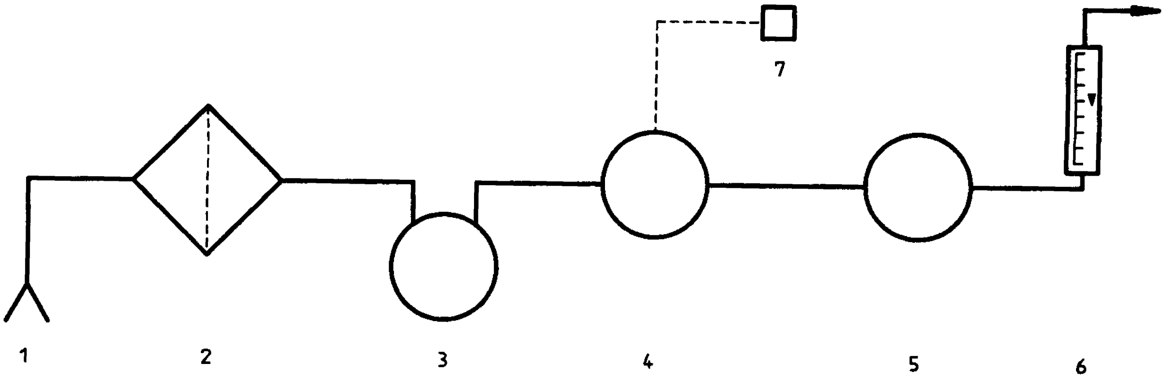
[1] Kodak Publication No. Q-16.



a) Alternative 1



b) Alternative 2

Key
1 Air intake
2 Filter clamp
3 Sampling pump
4 Dry gasmeter
5 Flow controller
6 Variable area flowmeter
7 Elapsed time meter

Figure 1 — Alternative sampling arrangements for black smoke measurement

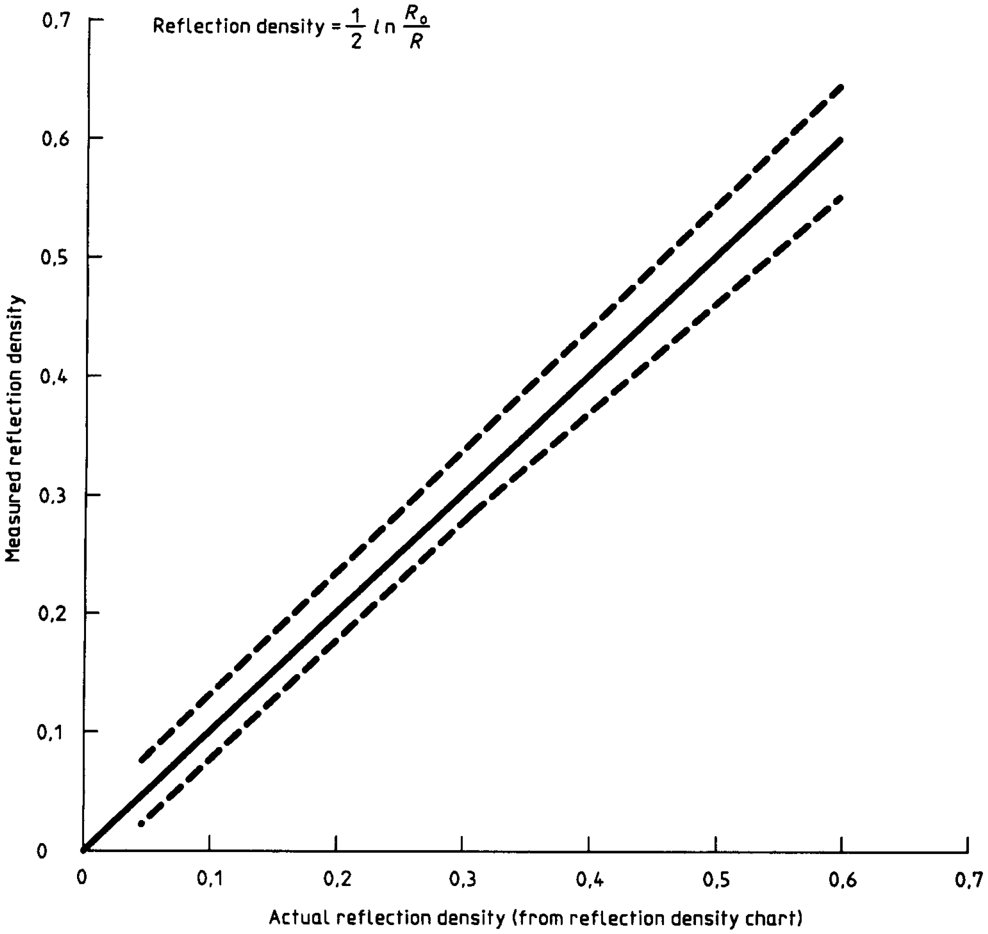


Figure 2 — Reflectometer response

6.2 Precision and accuracy

The reflectance of filter stains can be read to 1 reflectance unit with 95 % confidence. The resulting confidence limits for the absorption coefficient, a, are given in Table 1.

Table 1 — Confidence limits for absorption coefficients

Reflectance, R	a^{a}	Confidence limits	
%	$\times 10^{-5}$	Δb	% b
95	0,65	0,13	20,3
80	2,83	0,16	5,8
70	4,52	0,18	4,0
60	6,47	0,21	3,3
50	8,78	0,25	2,9
40	11,61	0,31	2,7
36	12,94	0,35	2,7

[a] For $A = 5{,}07 \times 10^{-4}$ m^2 and $V = 2$ m^3

7 Test report

The test report shall include the following information:

a) a reference to this International Standard;

b) a complete identification of the air sample, including date, time and location;

c) the type of filter paper and reflectometer used;

d) the results obtained, including the volume sampled, the sample duration, the flow rate and the measured reflectance (or absorbance);

e) any unusual features noted during the determination;

f) any operation carried out that is not specified in this International Standard;

g) the location of any sources of black smoke close to the sampler which may have contributed to the results;

h) any other information relevant to the method.

Annex A (informative)
Conversion of absorption coefficient to traditional black smoke units

A.1 Basic theory

For pure substances, the relationship between the extent of light absorption and the depth or thickness of the absorbing material is given by Lambert's Law, which states that equal fractions of the incident radiation are absorbed by successive layers of equal thickness of the light absorbing substance. This is represented mathematically by the equation

$$I = I_0 \exp(-al) \qquad \text{. . . (A.1)}$$

where

I_0 is the intensity of incident light;

I is the intensity, after passage through 1 cm of the given material;

a is the absorption coefficient, which is characteristic of the particular material;

l is the thickness of the absorbing material.

The absorption coefficient, a, refers to light of a particular wavelength and its value varies with the wavelength of the absorbed radiation. Thus, equation (A.1) represents the transmission and absorption of monochromatic radiation in a particular medium.

A.2 The theory of reflectance measurement

During sampling, air is drawn through a filter medium and the collected particles produce a stain on the surface of the filter paper. It is clear that most filter materials present a barrier to the radiation, therefore there can be no transmission of light and it is necessary to measure reflectance. Thus, to employ Lambert's Law (see equation A.1) it is necessary to assume that the surface of the filter material underlying the deposit acts as a perfect mirror and therefore the radiation passes through the absorbing layer twice. The staining power of the particulates on the surface is measured by comparing the stained surface with a blank, unexposed surface. The intensity of the incident radiation, I_0, and of the transmitted radiation, I, can be replaced by R_0 and R, assuming that the reflectance, R_0, of the unexposed filter material is analogous with the incident radiation, which is not actually measured. In fact, the difference between the incident radiation and the reflected radiation is due to scatter, which can be assumed to be the same for both blank and exposed filter papers and therefore ignored in terms of reflectance measurement.

The thickness, l, of the absorbing layer can be calculated using the equation

$$l = \frac{V}{A} \qquad \text{. . . (A.2)}$$

where

V is the volume of air sampled, in cubic metres;

A is the area of the stain, in square metres, on the filter medium.

Thus, Lambert's Law can be adapted for reflectance measurement as follows:

$$R = R_0 \exp\left(\frac{-2aV}{A}\right) \qquad \text{. . . (A.3)}$$

where a is the absorption coefficient, in reciprocal metres.

Thus, rearranging equation A.3:

$$a = \frac{A}{2V} \times \mathrm{In}\left(\frac{R_0}{R}\right) \qquad \text{. . . (A.4)}$$

This principle makes it possible to measure reflectance under certain carefully controlled conditions.

A.3 Reflectance and black smoke measurement

The concept of black smoke has been in use for many years as a result of the "standard" method published by the Organization for Economic Co-operation and Development (OECD) in 1963. A "calibration curve" was provided to convert reflectance measurements to micrograms per square centimetre of black smoke which could then be converted to a black smoke concentration. Since the relationship between reflectance and gravimetric concentration units can change from place to place and with time at any one place, it is clear that no meaningful universal relationship can be derived. Furthermore, the use of gravimetric units has led to considerable confusion of black smoke measurements with the results from gravimetric methods which measure the mass of suspended particulate material in a unit volume of air.

A black smoke index is therefore a measure of the dirtiness or staining power of the atmosphere.

The EEC Black Smoke Reference Method and the OECD method from which it was derived employ Whatman No. 1 filter papers[2] and the EEL smokestain reflectometer[2]. The EEL reflectometer employs white light and the efficiency of the Whatman No. 1 filter papers is quite low. Thus, the relationship between reflectance and absorption coefficient deviates from the ideal situation represented by equation A.4.

The ideal situation only exists when

a) monochromatic light is used; and

b) the particulate material collects on the surface of the filter medium.

When Whatman No. 1 filter papers are used, the particles penetrate deeply into the paper and some pass right through it. Under these conditions, it has been shown that equation (A.4) approximates to

$$a_1 = \frac{A}{V} \times \text{In}\left(\frac{R_0}{R}\right) \qquad \text{. . . (A.5)}$$

Thus, the theoretical absorption coefficient a (equation A.4) as determined in the standard method is related to the modified absorption coefficient a_1 (equation A.5) as follows:

$$a_1 = 2\text{a} \qquad \text{. . . (A.6)}$$

The conversion of the absorption coefficient to what is, by convention, known as the black smoke index, is a purely arbitrary operation which is carried out by reference to tables or graphs. The absorption coefficient itself is an adequate index of black smoke and conversion to the traditional “black smoke concentration” can be carried out by reference to the calibration curve in Figure A.1, and detailed data for the conversion is given in Table A.1. The data relate to measurements made using Whatman No. 1 filter papers[2] and the EEL type 43 smokestain reflectometer[2]. Measurements may be made using other combinations of filter paper and reflectometer, but it is not possible to relate these directly to the OECD and EC data using the calibration curve in Figure A.1.

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[2] Whatman No. 1 filter papers and the EEL type 43 smokestain reflectometer are examples of suitable products available commercially. This information is given for the convenience of users of this International Standard and does not constitute an endorsement by ISO of these products.

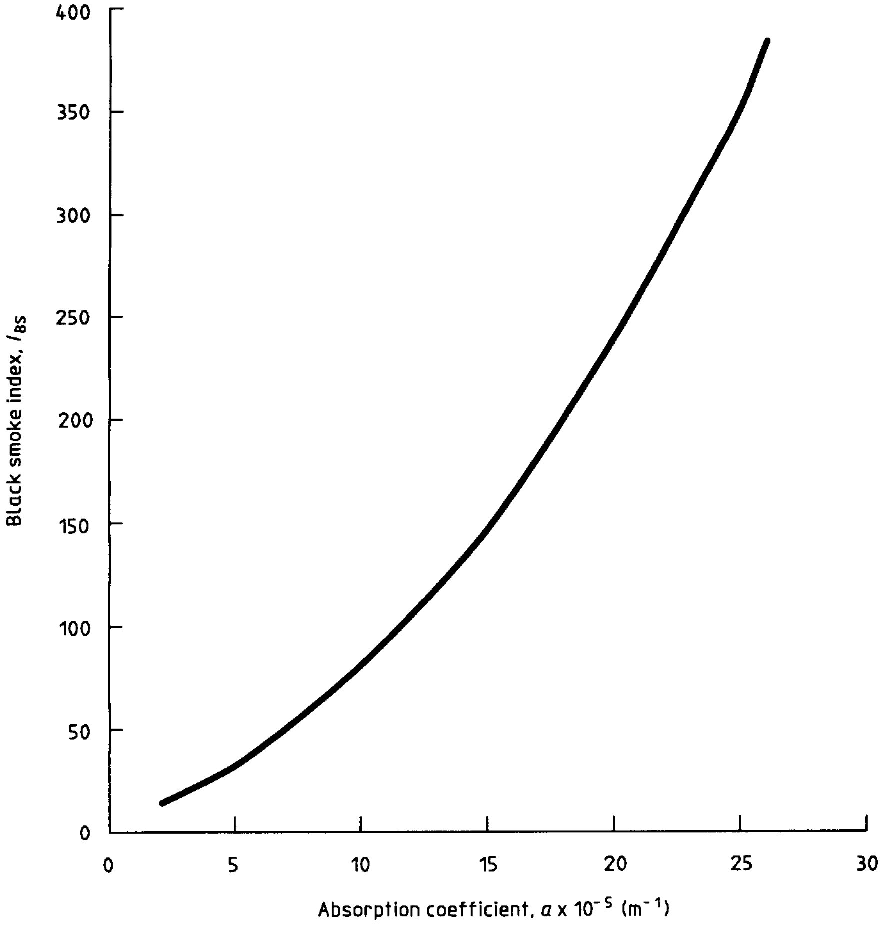

Figure A.1 — Black smoke calibration curve

Table A.1 — Absorption coefficient and black smoke index

$a \times 10^{-5}$ [a]	I [b]
1,28	6,2
1,41	6,9
1,55	7,6
1,68	8,4
1,81	9,2
1,95	10,0
2,08	10,8
2,22	11,7
2,36	12,5
2,50	13,4
2,63	14,3
2,77	15,2
2,91	16,1
3,05	17,1
3,20	18,0
3,34	19,0
3,48	20,0
3,63	21,0
3,77	22,0
3,92	23,1
4,06	24,2
4,21	25,3
4,36	26,4
4,51	27,5
4,66	28,6
4,81	29,8
4,96	31,0
5,11	32,2
5,27	33,4
5,42	34,7
5,58	36,0
5,74	37,3
5,89	38,6
6,05	39,9
6,21	41,3
6,37	42,7
6,53	44,1
6,70	45,5
6,86	47,0
7,03	48,5
7,19	50,0
7,36	51,5
7,53	53,1
7,70	54,7
7,87	56,4
8,04	58,0
8,21	59,7
8,39	61,5
8,56	63,2
8,74	65,0
8,92	66,9
9,10	68,7
9,28	70,6
9,46	72,6
9,64	74,6
9,83	76,6
10,00	78,7
10,20	80,8
10,39	82,9
10,58	85,1
10,77	87,4
10,96	89,7
11,16	92,0
11,35	94,4
11,55	96,8
11,75	99,3
11,95	101,9
12,15	104,5
12,36	107,1
12,56	109,8
12,77	112,6
12,98	115,5
13,19	118,3
13,40	121,3
13,62	124,3
13,83	127,4
14,05	130,6
14,27	133,8
14,50	137,1
14,72	140,5
14,95	143,9
15,17	147,4
15,40	150,1
15,64	154,7
15,87	158,5
16,11	162,3
16,35	166,2
16,59	170,2
16,83	174,3
17,08	178,5
17,33	182,8
17,58	187,2
17,83	191,6
18,09	196,2
18,35	200,9
18,61	205,6
18,88	210,5
19,14	215,5
19,41	220,6
19,69	225,8
19,96	231,1
20,24	236,5
20,52	242,0
20,81	247,7
21,10	253,5
21,39	259,4
21,69	265,4
21,99	271,5
22,29	277,8
22,60	284,2
22,91	290,8
23,22	297,5
23,54	304,2
23,86	311,7
24,19	319,2
24,52	327,0
24,86	335,3
25,20	344,0
25,54	353,0
25,89	362,3
26,25	372,1

[a] a, is the absorption coefficient in reciprocal metres.

[b] I_{BS} is the black smoke index.

blank

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