A Protocol for Black Carbon Emissions

A Protocol for Measuring Emissions of Elemental Carbon and Organic Carbon
from Residential Wood Burning

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ISBN 978-92-893-4672-6 (PRINT)

ISBN 978-92-893-4673-3 (PDF)

ISBN 978-92-893-4674-0 (EPUB)

<http://dx.doi.org/10.6027/TN2016-541>

TemaNord 2016:541

ISSN 0908-6692

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Layout: Hanne Lebech

Cover photo: Jacquesverlaeken, *Hallstätter Gletscher in Austria. The dark surface on the ice, which could be black carbon or dust, increase the temperature of the ice and thereby increase the melting proces.*

Print: Rosendahls-Schultz Grafisk

Printed in Denmark

This publication has been published with financial support by the Nordic Council of Ministers. However, the contents of this publication do not necessarily reflect the views, policies or recommendations of the Nordic Council of Ministers.

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Nordic Council of Ministers

Ved Stranden 18

DK-1061 Copenhagen K

Phone (+45) 3396 0200

www.norden.org

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Summary of the Protocol for EC and OC emissions

This protocol was developed and subsequently tested in 2012–2015 by Nordic test and research institutes, with Danish Technological Institute as project manager. This protocol describes a potential standardized procedure for measurements of BC (Black Carbon) in terms of both EC (Elemental Carbon) and OC (Organic Carbon) from residential wood burning stoves. Such a standardized test can then be used for voluntary eco-labeling of wood stoves, specifically the Nordic Swan Ecolabel, “climate-friendly” stoves, and by manufacturers interested in testing and developing extremely low-emission, low-black carbon, “climate-friendly” stoves. The development of this testing protocol is part of a project supported by the Nordic Council of Ministers and the Climate and Clean Air Coalition (CCAC), and implemented by the International Cryosphere Climate Initiative (ICCI). This testing protocol could be used by multiple national laboratories interested in establishing a standardized baseline for stove comparison in terms of black carbon emissions.

1. Scope

This protocol describes a potential standardized procedure for measurements of BC (Black Carbon) in terms of both EC (Elemental Carbon) and OC (Organic Carbon) from residential wood burning stoves. The protocol is based on the Norwegian standard NS3058 for enclosed wood heaters' smoke emissions Part 1 (test facility and heating pattern), part 2 (determination of particulate emission) and NS3059 for enclosed wood heater's smoke emission – Requirements.

2. Preface

This protocol was developed and subsequently tested in 2012–2015 by Nordic test and research institutes, including SINTEF Energy, the University of Eastern Finland, SP-Technical Research Institute of Sweden and DTI – Danish Technological Institute. These experimental tests provided important feedback on the feasibility and replicability of this test protocol.

The goal of developing this testing protocol is to establish a standardized test for emissions of elemental carbon and organic carbon from residential wood combustion. Such a standardized test can then be used for voluntary eco-labeling of wood stoves, specifically the Nordic Swan Eco-label, “climate-friendly” stoves, and by manufacturers interested in testing and developing extremely low-emission, low-black carbon, “climate-friendly” stoves. The development of this testing protocol is part of a project supported by the Nordic Council of Ministers and the Climate and Clean Air Coalition (CCAC), and implemented by the International Cryosphere Climate Initiative (ICCI).

This protocol provides for a “piggyback test”, which would be conducted on top of the NS3058 Full Flow Dilution Tunnel test, or similar multiple burn rate testing procedures (such as those of the U.S.EPA) of EC and OC. , This testing protocol could also be used by multiple national laboratories interested in establishing a standardized baseline for stove comparison in terms of black carbon emissions.

Ongoing work will also ascertain the applicability of some of these procedures to so-called single burn rate or “hot gas” testing procedures currently used in many countries of the European Union.

This testing protocol test is suitable to wood burning appliances, which regulate the combustion air supply over a valve system, both manually and/or automatically controlled.

3. Highlights from NS3058

As mentioned previously, this testing protocol “piggybacks” on the Norwegian standard NS3058. It is recommended that users read and understand the NS3058, Parts 1 and 2 prior to application of this testing protocol. For more casual readers, highlights from the Norwegian testing standard are outlined here.

NS3058 only addresses particulate emissions; hence, no gaseous emissions are measured.

3.1 Fuel

3.1.1 *Dimensions*

The test fuel is described under paragraph 4.3 in NS3058 part 1. The test fuel shall consist of air-dried spruce and have a cross section of 49x49 mm, nailed together in a defined pattern, see Figure 1, with steel nails and wooden spacers with a cross section of 25x13 mm. The distance between each piece of wood is 10 mm. If more than one layer of wood is needed to achieve the mass needed for the test, the fuel is placed on top of each other.

Figure 1: Example of test charge – other composition may be applied

3.1.2 Moisture content

The moisture of the test fuel shall be between 16–20% wet basis, or 19–25% dry basis.

3.1.3 Mass of fuel

The mass of the fuel load is calculated as a function of the effective firebox volume. The effective volume of the firebox is determined accordingly to paragraph 4.2 in NS 3058-1. An interval of the fuel mass is allowed due to variable density of the spruce wood. This is calculated as described in the formula below, and means that the mass of the fuel has to be between the lower and higher value of mass.

$$mass_{lower\ value} = Volume[m^3] * 101 \frac{kg}{m^3}$$

$$mass_{high\ value} = Volume[m^3] * 123 \frac{kg}{m^3}$$

3.2 Heating patterns

The Norwegian standard uses four burn rate categories. The values are average burn rate in kg dry wood/hour. A stove must be tested at all applicable burn rate categories. The max output test, regardless of whether it yields burn rate 2, 3 or 4, must be carried out with any manual air controls kept fully open.

Up to 5 minutes after loading the stove, the operator is allowed to get the fire combustion started, using various means such as keeping the door ajar, having the air valve 100% open, or activating any ignition device. 5 minutes after loading the stove – at the latest – for manual controlled stoves, the valve(s) must be set in their final position. For automatically controlled stoves, no further manual manipulation of the air system is permitted.

For the purposes of this test, stoves are divided into 2 classes: Class 1 and Class 2.

Table 1: Burn rate categories for Class1 and Class2

	Burn rate category 1	Burn rate category 2	Burn rate category 3	Burn rate category 4	Units
Class 1	<0.80	0.80–1.25	1.26–1.90	>1.9	Kg dry wood/h
Class 2	<1.25	1.25–1.90	1.91–2.8	>2.8	Kg dry wood/h

Class 2 is by far the most common test class in NS3058. For a Class 2 stove, the nominal or rated heat output would typically be at 5–6 kW. Class 1 exclusively applies to stoves having fairly low heat output. In case Class 1 onwards is applied, the threshold limit of the low output test is changed from 1.25 to 0.80 kg dry matter burned per hour.

3.3 Measurement setup

The measurement setup should be built according to paragraph 4 NS3058 part 2. The Norwegian standard uses a full flow dilution tunnel.

Figure 2: Full flow dilution tunnel from NS3058 part 2 paragraph 4.2

The particulate measurement is conducted using a sampling collection train as described in paragraph 4.1 NS3058 part 2. The main parts of the collection train include a double filter holder with temperature monitoring system connected to a pump, and a gas meter. The measurement is conducted at isokinetic sampling conditions between the full flow dilution tunnel and the sampling collection train.

Figure 3: Sampling collection train from NS3058 part 2 paragraph 4.1

3.4 Calculation

Calculation of particulates in the flue gas is described in paragraph 6 in NS 3058-2. The results are only acceptable if isokinetic sampling has been accomplished – paragraph 6.6 in NS3058-2. If the results deviate too much from this norm, it is not possible to claim isokinetic sampling; and the measurement should be repeated.

4. Measurement Protocol for Elemental Carbon and Organic Carbon

This measurement protocol for black carbon from residential wood combustion builds on the measurement sections and procedures described in the Norwegian standard NS3058 and 3059 for measurement of particulate matter (PM). If the stove subjected to the test is brand new, it must be aged by at least 10 hours of burning use prior to any testing, in order to eliminate any volatile or other pollutants emitted by the stove, its components and its surface coating.

4.1 Deviations from NS3058

In order to reduce the risk of overloading black carbon onto the filters, a few modifications from NS3058 are needed;

4.1.1 Nozzle size – for sampling

The sampling nozzle size has been reduced to 5.9 mm. At the same time, the flow rate has been reduced in order to maintain the same nozzle speed, and thereby obtain isokinetic sampling between the full flow dilution tunnel and the sampling train. This means that a smaller volume of air is sucked through the filters and thereby, also a smaller amount of particles hence reducing the risk of overloading the filters. The 5.9 mm nozzle fits the emission levels of most modern clean-burning stoves; however, it is important that test lab staff observe the actual filter loading achieved. In the eventuality of almost white or pitch black filters, the diameter of the nozzle and the corresponding sampling line flow must be adjusted, as to secure filter shading preferable within a grey scale.

4.1.2 Burn rates

Measurements are only performed in two extreme burn rates, low output and maximum output: 1) one day with the air inlet control fully open to achieve a high burn rate (BR_{high}) and 2) one day of combustion in burn rate category 1 (below 1.25 kg/h – respectively 0.80 kg/h if Class 1 stove) (BR_{low}). The intermediate burn rates 2 (and 3) of NS 3058 are not performed as they are close to Nominal Heat Output, for which the air system has been designed.

4.1.3 Number of tests per burn rate

Three repeated tests per burn rate are required in order to secure robustness of the test. Prior to each test, an intermediate burn cycle is performed in order to harmonize the bed of embers. Depending on the air system of the stove, it may be necessary to remove a proportion of the poor quality (cold) embers from the spruce, prior to loading the intermediate charge. For the intermediate burn cycle, hard wood is used, and has to consist of 1.5 kg hard wood and the duration must be 50 ± 5 minutes in order to ensure the same quality fire bed each time. Fixed parameters for measurement are below:

Table 2: Data for flow and nozzle size

Parameter	Value	Unit
Flow in dilution tunnel	4.4	[m/s]
Nozzle size (sampling collection train)	5.9	[mm]
Flow rate (sampling collection train)	436	[l/h]

Note: The duct flow rate may vary between 4–5 meters/second as long as the suction flow rate is adjusted correspondingly, to maintain properly iso-kinetic sampling conditions.

4.2 Stove dependent parameters

Standard is in the case a right angular cube shaped firebox. Other firebox designs does apply. Regardless of the basic shape of the firebox, the effective firebox volume (from which the fuel mass is derived) can be determined as the largest right angular imaginary cube which could be entered into the firebox. See Figure 4, 5 and 6.

Figure 4: Paragraph for description: Height of fire-box

Note: The firebox height is measured from the bottom of the fire-box up to any Max Load indicator as specified by the manufacturer, or in the absence of such, further up to the junction between the flue baffle plate and the rear insulating brick.

Figure 5: Paragraph for description: Width of fire-box

Note: The width is the shortest horizontal firebox dimension that is parallel to the wall of the firebox.

Figure 6: Paragraph for description: Length of fire-box

Note: The length is the longest horizontal firebox dimension that is parallel to the wall of the firebox.

4.2.1 Amount of Fuel

The fuel load is determined from the volume of the largest right angular cube that could be entered into the firebox according to the measurements of height, width and length. The volume of this cube is the effective firebox volume, to go into the fuel load calculation of Norwegian Standard NS3059-1 4.3.3, and in this protocol at paragraph 3.1.3.

4.3 Measurements

Measurements are performed over two full days. The order of the tests is arbitrary, but as noted above should comprise one day with the inlet control fully open and one day at burn rate category 1.

The measurement period begins immediately after the test fuel has been loaded. The measurement is completed when the platform scale (weight) is back to the basic firebed (= scale reading just prior to loading the stove), indicating that the mass of the test charge has been combusted.

4.3.1 Maximum heat output test

Any air valve, which is subject to user control, must be set in a fully open position. It is permitted to adjust the air supply during the first five minutes of measurement. Pre-charge should consist of 1.5 kg hardwood and have a duration of 50 ± 5 minutes in order to ensure the same fire bed each time.

Table 3: Overview of the Maximum Heat Output test

Phase	Fuel	Amount	Measurement
Ignition & lightning	Hardwood	As defined by calculation x 1.2*	Sampling
Pre-charge	Hardwood	1.5 kg	-
1. Charge	Spruce	As defined by calculation	Sampling
Pre-charge	Hardwood	1.5 kg	-
2. Charge	Spruce	As defined by calculation	Sampling
Pre-charge	Hardwood	1.5 kg	-
3. charge	Spruce	As defined by calculation	Sampling

Note: *) The duration of the ignition & lighting period must be a minimum of 45 minutes.
If necessary, add extra firewood.

4.3.2 Low heat output test

The valve setting is adapted to fit a burn rate of maximum 1.25 kg dry matter per hour. It is permitted to adjust the air supply during the first five minutes of measurement. Pre-charge should consist of 1.5 kg hardwood and have a duration of 50 ± 5 minutes in order to ensure the same quality fire bed each time.

Table 4: Overview of the Low Heat Output Test

Phase	Fuel	Amount	Measurement
Ignition & lightning	Hardwood	As defined by calculation x 1.2*	Sampling
Pre-charge	Hardwood	1.5 kg	No sampling
1. charge	Spruce	As defined by calculation	Sampling
Pre-charge	Hardwood	1.5 kg	No sampling
2. charge	Spruce	As defined by calculation	Sampling
Pre-charge	Hardwood	1.5 kg	No sampling
3. charge	Spruce	As defined by calculation	Sampling

Note: *) The duration of the ignition & lighting period must be a minimum of 45 minutes.
If necessary, add extra firewood.

5. Filters

Filters for the collection of samples should be made of quartz to properly analyze for EC/OC, which is done at high temperature. The filters should be kept in glass petri dishes (covered). Use new petri dishes if possible. If re-used, wash them in pure water without any detergent, acid or organic compound.

5.1 Filter specification

Filters to be used for sampling of black carbon must fulfill the requirements in the table below.

The filters can be purchased from www.frisenette.dk/ or any other supplier with a product that matches the requirements, like Pallflex from www.pall.com. The temperature of maximum 900 °C is chosen because pre-treatment and analysis are done at above 800 °C.

Table 5: Filter data

Grade	Weight g/m ²	Retention efficiency, gas % 0.3 µm DOP	Binder	Max Temp °C
QF	85	99,998	NO	900

In addition, the diameter of the filter should be above 90 mm to minimize risk of overloading of the filters.

5.2 Pre-treatment of filters

Before sampling the filter is heated to 800 °C for 4 hours and then cooled in a desiccator cabinet overnight (for a minimum of 12 hours).

5.3 Handling of filters

After sampling, take a picture of the exposed filters for later correlation purpose. Then the filters must be placed in the glass petri dishes, weighed and sealed. The filters should be stored in the refrigerator until shipment for analysis. Consultation with SUNSET Laboratories refutes the need for shipment of the filters at sub-zero temperature conditions. The amount of condensables that might evaporate in-between minus 20 Celsius and ambient temperature is insignificant.

5.4 Filter analysis

The filter is analyzed for both OC and EC through thermal-optical procedures. In the case of this protocol, all the analyses were conducted by Sunset Laboratories Inc. The results are given in $\mu\text{g}/\text{cm}^2$ with separate results for EC and for OC, respectively. A sample is punched (1 cm x 1.5 cm) from the filter, which is then heated in an oxygen-free helium atmosphere at increasing temperatures to 700 °C. This removes all organic carbon, which is converted first to CO_2 and then to CH_4 and detected by an FID (Flame Ionization Detector), giving the OC value. During this first phase some organic compounds are pyrolytically converted to EC. This pyrolytic conversion is monitored by a laser. Afterwards the temperature is reduced to 525 °C and 2% oxygen is added in the helium stream. This enables oxidation of EC to CO_2 , which is then converted to CH_4 and detected by an FID, giving the EC value.

Problems with filters takes place when:

- The filter is so heavily loaded that the laser cannot penetrate the filter.
- Some EC (soot) is shaken off during shipment.
- The load of the filter is over the detection limit of the analyser ($400 \mu\text{g}/\text{cm}^2$).

If the filters are overloaded, it is not possible to measure the EC/OC values within acceptable boundaries for accuracy. If overloading occurs, further dilution is needed. This could be done by adding an extra secondary dilution stage after the full flow dilution tunnel and before the filter. Alternatively, for purposes of sampling for eco-labelling, an overloaded filter from a given stove might simply be deemed as failure by the stove to meet a given black carbon emissions standard.

Contact for Sunset Laboratories Inc.:

Pavlos Panteliadis
Research Scientist
Sunset Laboratory BV
Science Park 408
1098 XH, Amsterdam
The Netherlands
Tel: +31 20 70 52 300
email: pavlos@sunlab.com
<http://www.sunlab.com/>

Other labs with similar measuring equipment can perform the analysis as well.

5.5 PM determination

Because of the use of Quartz filters, this test is not suitable to simultaneous gravimetric determination of emissions of PM. Quartz filters are prone to mass loss during handling and use, which are likely to jeopardize the accuracy of any PM calculation. Further, minimizing the filter load in order to obtain accurate EC and OC is counterproductive to robust PM determination.

6. Calculation of EC and OC

The values of EC and OC are given in $\mu\text{g}/\text{cm}^2$ in order to calculate the value correlated to the mass of wood used. First, the value of EC and OC are multiplied by the area of the filter.

$$m_{EC}[\text{mg}] = \frac{EC \left[\frac{\mu\text{g}}{\text{cm}^2} \right] * \text{Area of filter}[\text{cm}^2]}{1000 \frac{\mu\text{g}}{\text{mg}}}$$
$$m_{OC}[\text{mg}] = \frac{OC \left[\frac{\mu\text{g}}{\text{cm}^2} \right] * \text{Area of filter}[\text{cm}^2]}{1000 \frac{\mu\text{g}}{\text{mg}}}$$

Then a mass is achieved. In the following formula, only calculation for EC is carried out, but the procedure is the same for OC. First the approach is to calculate the concentration of particulate matter (C_s) in the flue gas on a dry basis correlated to standard conditions (273K and 760 mmHg). $V_{m(\text{norm})}$ is the gas volume normalized to standard conditions, calculated by paragraph 6.1 in NS 3058-2 based on the measured gas volume at ambient conditions.

$$C_s \left[\frac{\text{g}}{\text{dm}^3} \right] = \frac{m_{EC}[\text{mg}]}{1000 \frac{\text{mg}}{\text{g}} * V_{m(\text{norm})}[\text{dm}^3]}$$

After calculation of the concentration of particulate matter C_s , the particulate emissions rate (E) is calculated. Q_{ad} is the average gas flow rate in the dilution tunnel.

$$E \left[\frac{\text{g}}{\text{h}} \right] = C_s \left[\frac{\text{g}}{\text{dm}^3} \right] * Q_{ad} \left[\frac{\text{dm}^3}{\text{h}} \right]$$

Due to particles being caught in the dilution tunnel, a value E_{ad} , that accounts for this phenomenon is calculated.

$$E_{ad} = 1,82 \times E^{0,83}$$

Finally, the emission factor (EF_{EC}) of EC can be calculated using the burn rate. This value is the final value. Emission factors are calculated for the two burn rates BR_{low} (below 1.25 kg/h) and BR_{high} (at maximum valve setting) and both for EC and OC. This example is only EC at BR_{low} .

$$EF_{EC} \left[\frac{g}{kg} \right] = \frac{E_{ad} \left[\frac{g}{h} \right]}{BR_1 \left[\frac{kg}{h} \right]}$$

Calculations are performed for the individual sampling periods.

7. Contact

Technical questions regarding this protocol may be directed to ICCI project coordinator Lars Nikolaisen. Email: bjerager@mail.tele.dk.

The Norwegian standard can be purchased at the web addresses below:

- NS 3058-1:1994 – <http://www.standard.no/en/webshop/ProductCatalog/ProductPresentation/?ProductID=133347>
- NS 3058-2:1994 - <http://www.standard.no/en/webshop/ProductCatalog/ProductPresentation/?ProductID=133348>
- NS 3059: <http://www.standard.no/en/webshop/ProductCatalog/ProductPresentation/?ProductID=133351>

Sammenfatning af Protokollen for EC og OC emissioner

Denne protokol er skrevet og efterfølgende testet i perioden 2012 til 2015 hos Nordiske forskningsinstitutter under ledelse af Teknologisk Institut i Danmark. Protokollen beskriver en standardiseret procedure for måling af rent kulstof eller sod (engelsk BC - Black Carbon) i form af elementar kulstof (engelsk: EC – Elemental Carbon) og organisk kulstof (engelsk: OC – Organic Carbon) der udsendes til atmosfæren ved forbrænding af træ i brændeovne. En sådan standardiseret afprøvning kan blive brugt til en frivillig miljømærkning af brændeovne, specielt til den Nordiske miljømærkning Svanen. Samtidig kan den bruges af fabrikanter der er interesseret i test og udvikling af brændeovne med meget lav emission, herunder emission af rent kulstof (BC). Udarbejdelsen af denne protokol er en del af et større projekt støttet af Nordisk Ministerråd og FN organisationen Climate and Clean Air Coalition (CCAC) og gennemført af miljøorganisationen International Cryosphere Climate Initiative (ICCI. Se også www.icci.org). Protokollen kan bruges af ethvert nationalt laboratorium der er interesseret i at gennemføre en standardiseret sammenligning af brændeovne med hensyn til emission af rent kulstof

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TemaNord 2016:541
ISBN 978-92-893-4672-6 (PRINT)
ISBN 978-92-893-4673-3 (PDF)
ISBN 978-92-893-4674-0 (EPUB)
ISSN 0908-6692

9 789289 346726