IEA Bioenergy, Expert workshop

Highly Efficient and Clean Wood Log Stoves,
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Black carbon emissions from wood stoves

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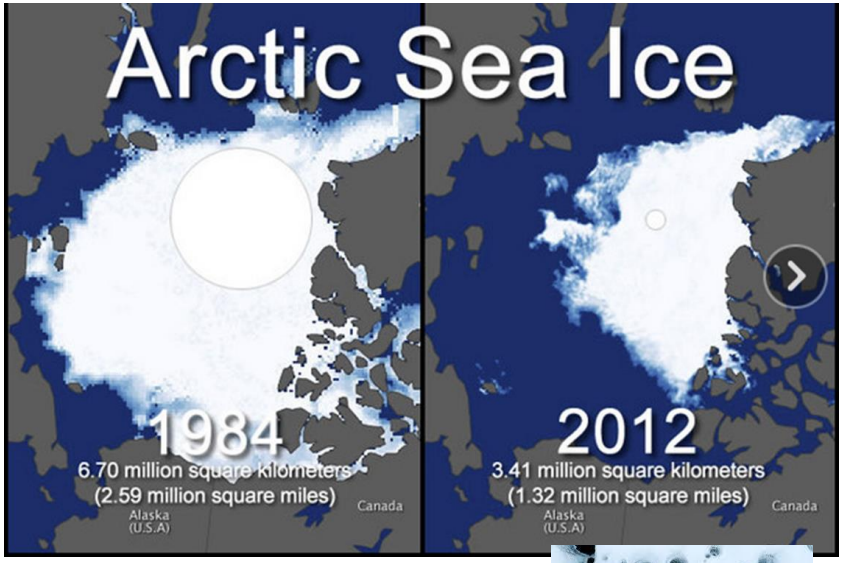
Overview

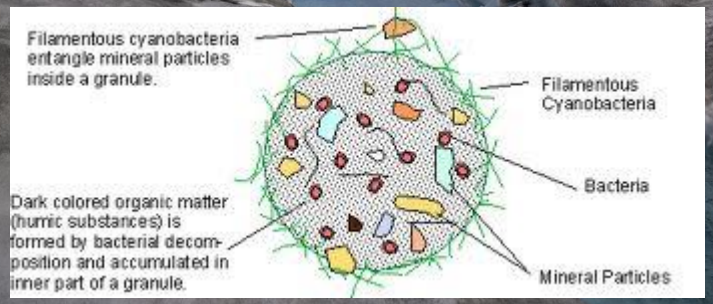
- What's all the mess about Black Carbon?
- Measurement procedures and methods attempted at SINTEF Energy, mixed with results from some recent and ongoing projects
- Summary

WHY REDUCE BC EMISSIONS?

- 2010-2011 -> The SLCF theory gets a revival and results in a sudden interest in BC/OC emissions on a high political level
- Political pressure to get quick results
- The effect of SLCF is controversial

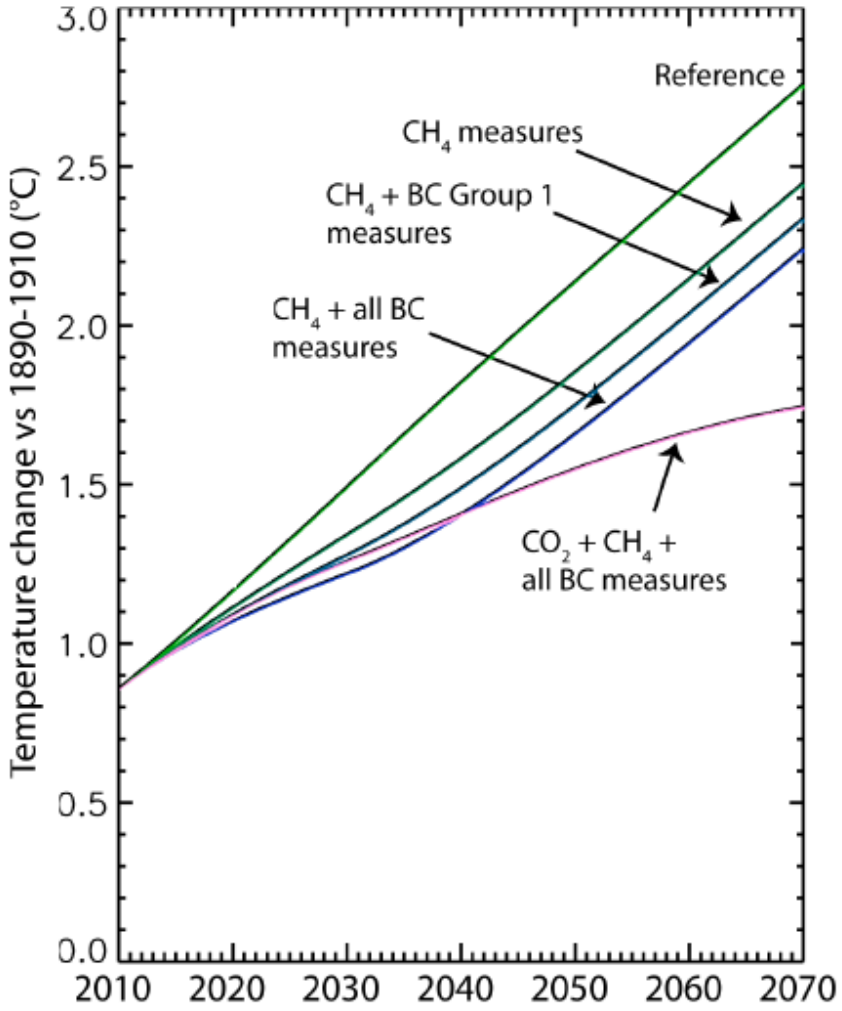


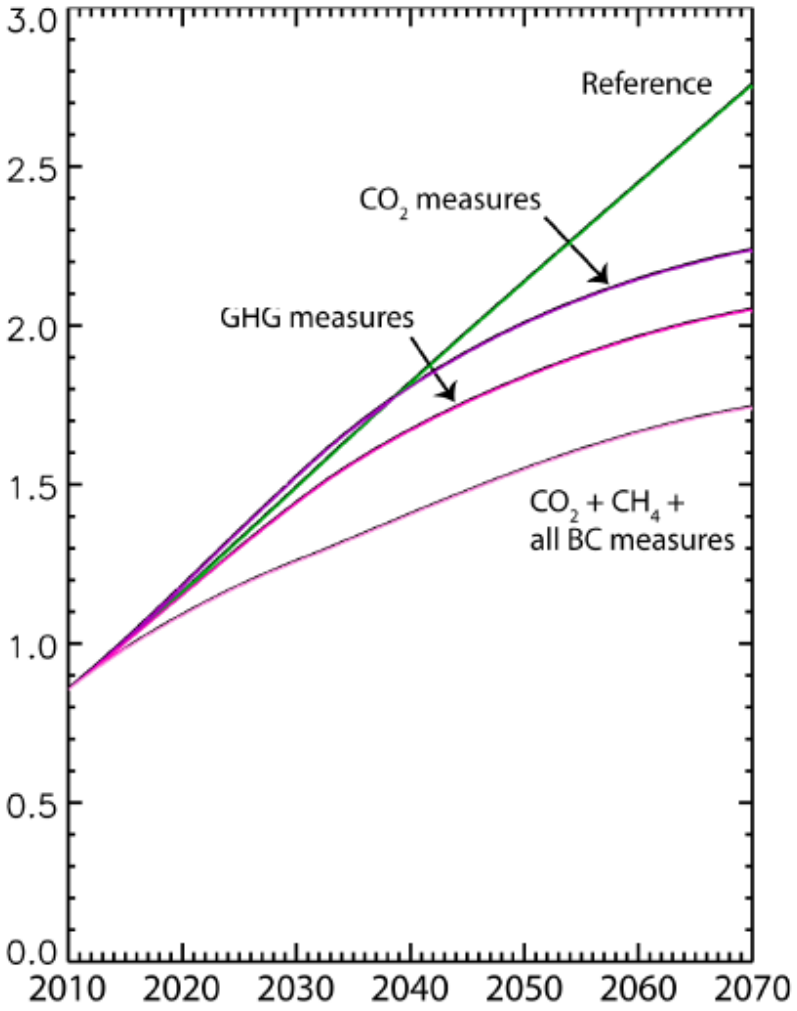
- Cryoconite, 0.1-10 mm
  - Mineral particles
  - Soot, EC/OC/BC? 0.4-2%?
  - Bacteria, algae

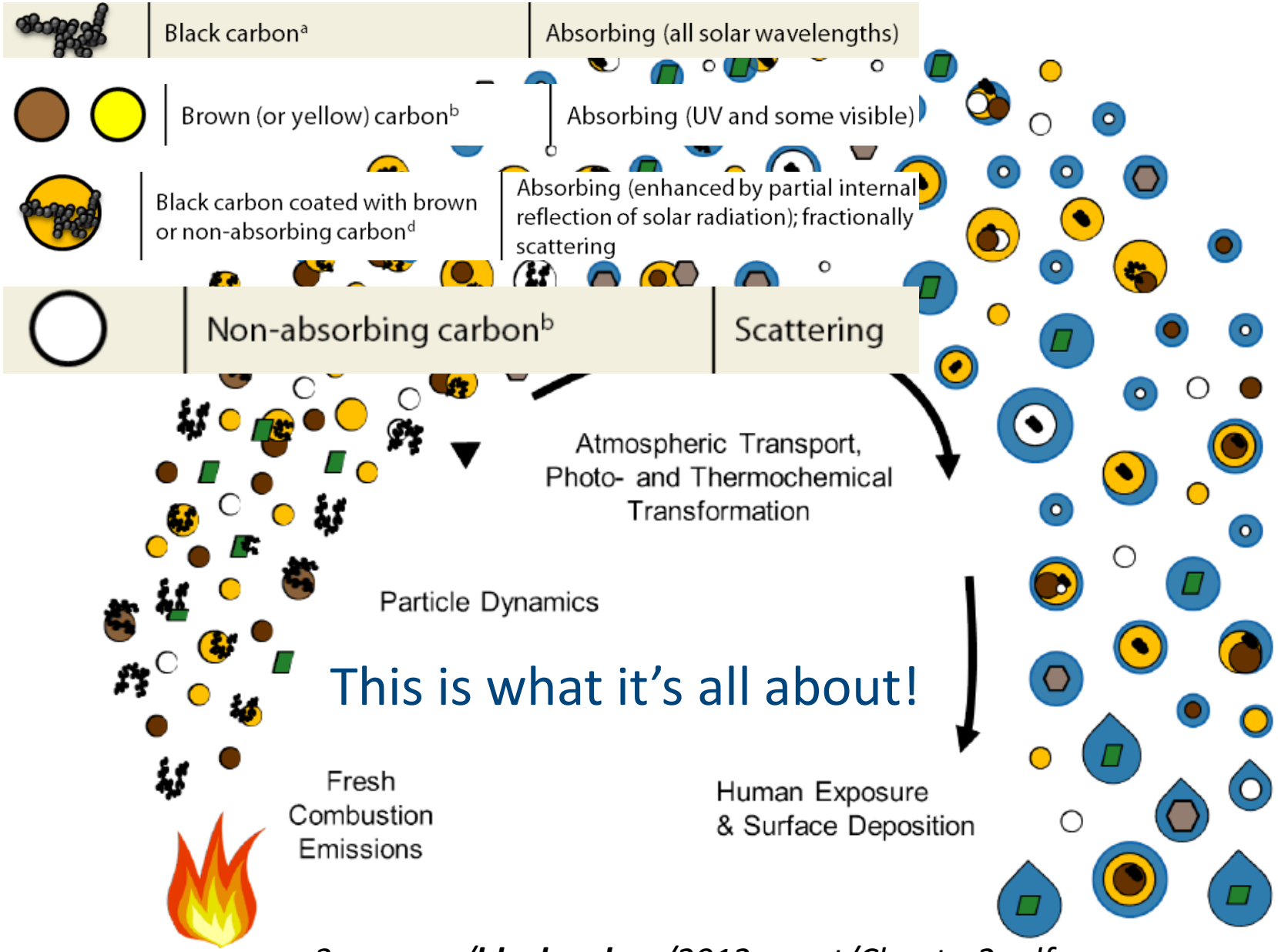


This is what it's all about!

(SLCF) Short-lived climate forcers







*www3.epa.gov/**blackcarbon**/2012report/Chapter2.pdf*

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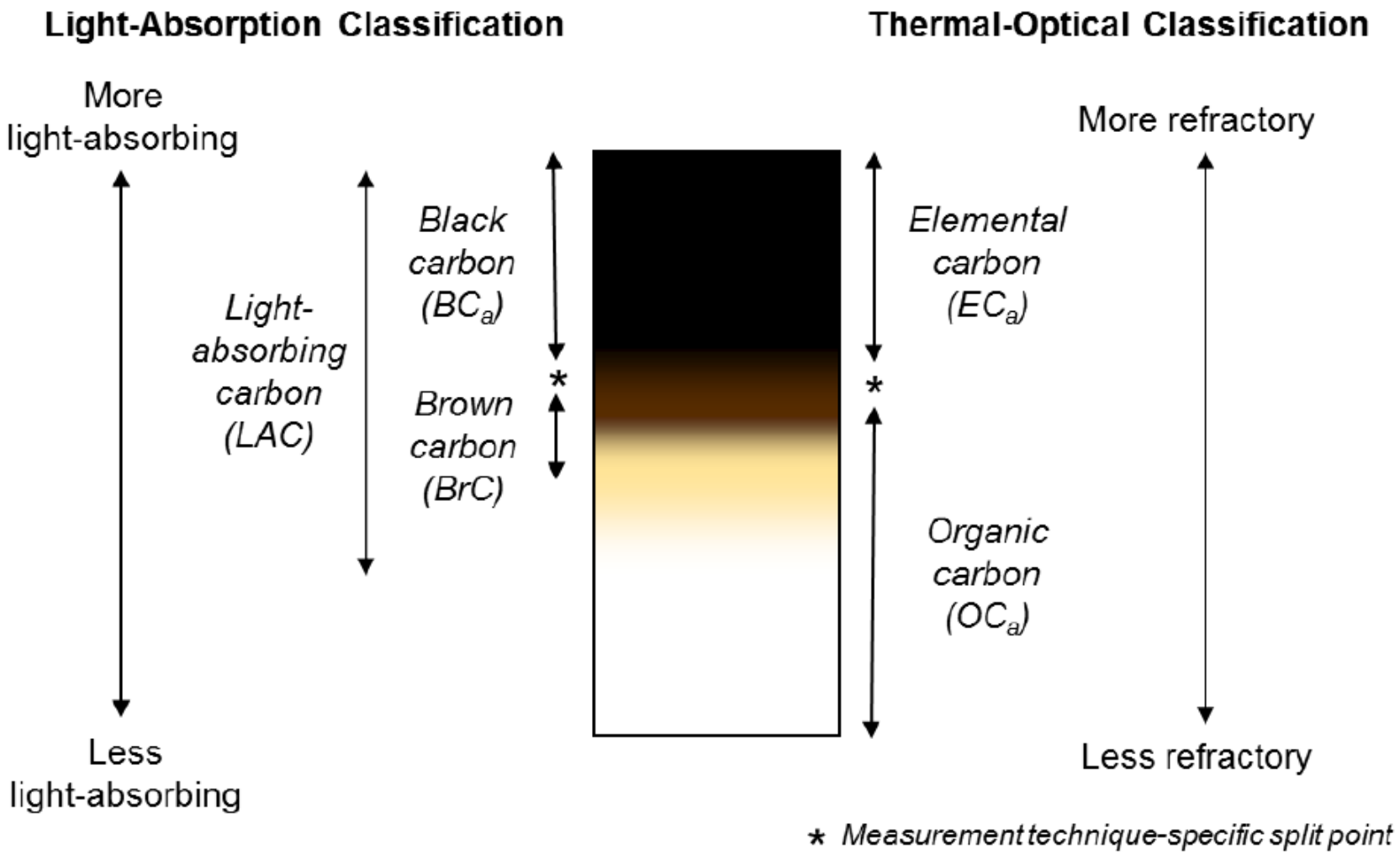
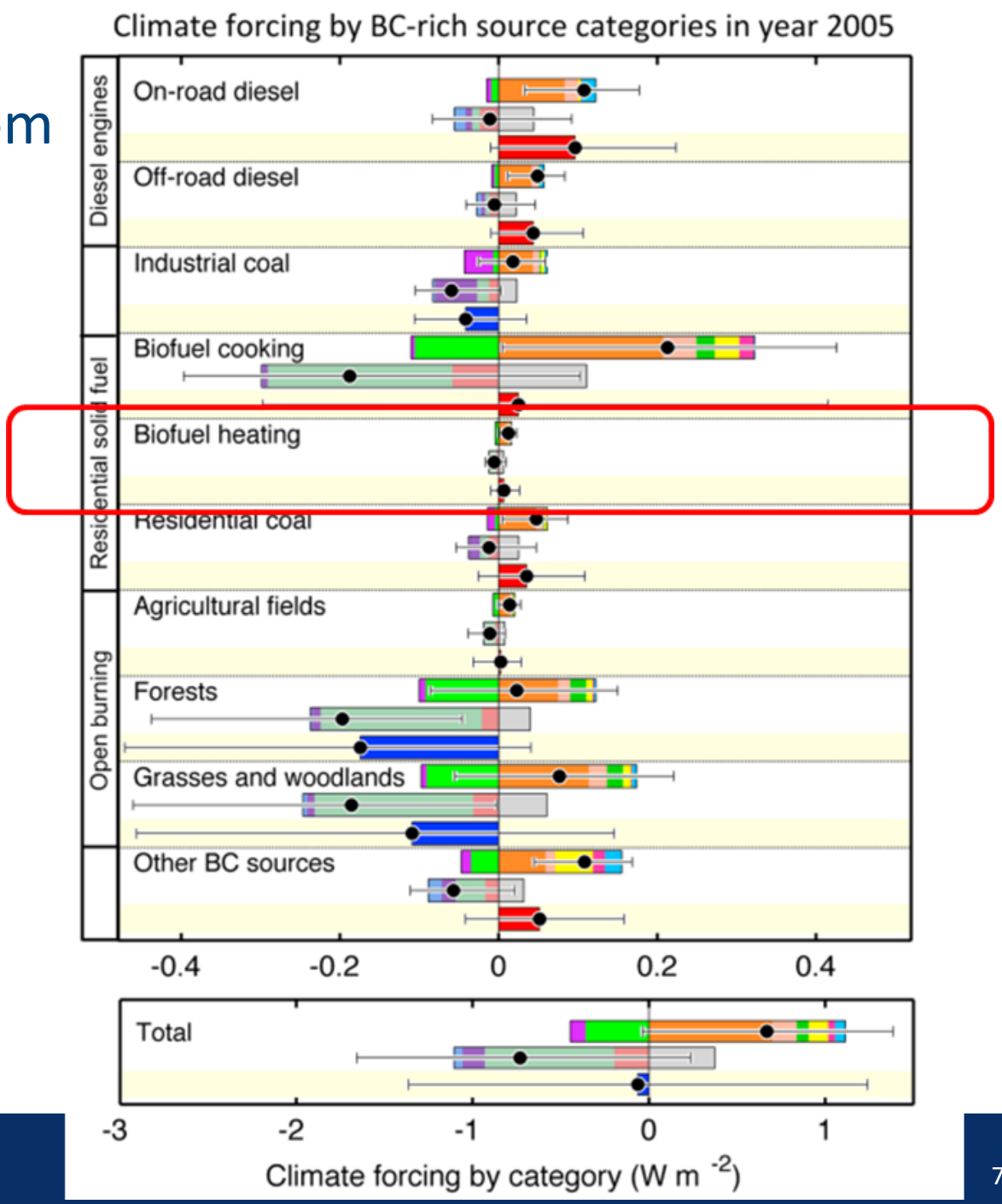


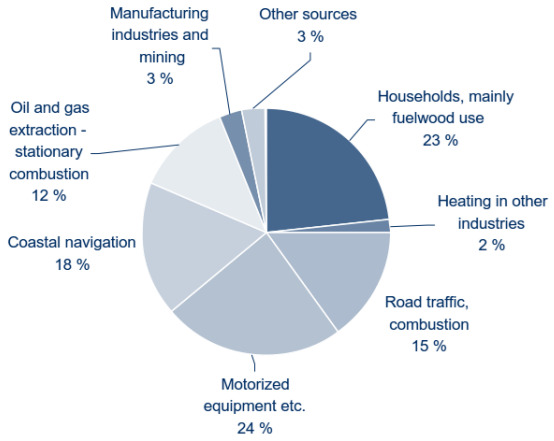
The contribution from Biofuel heating?



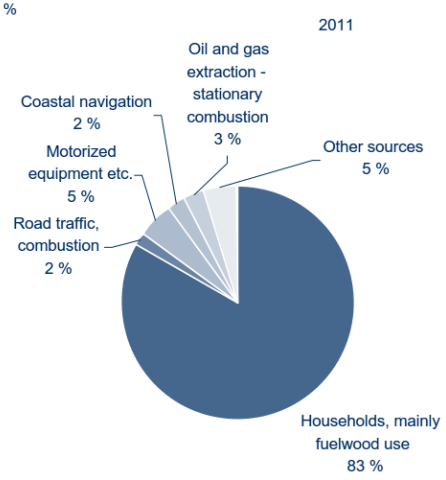
Total climate forcing for BC Rich source categories continuously meeting matched to 2005 observations (Bond et al., 2013)

Emissions of Black carbon and Organic carbon in Norway 1990-2011, WOOD STOVES

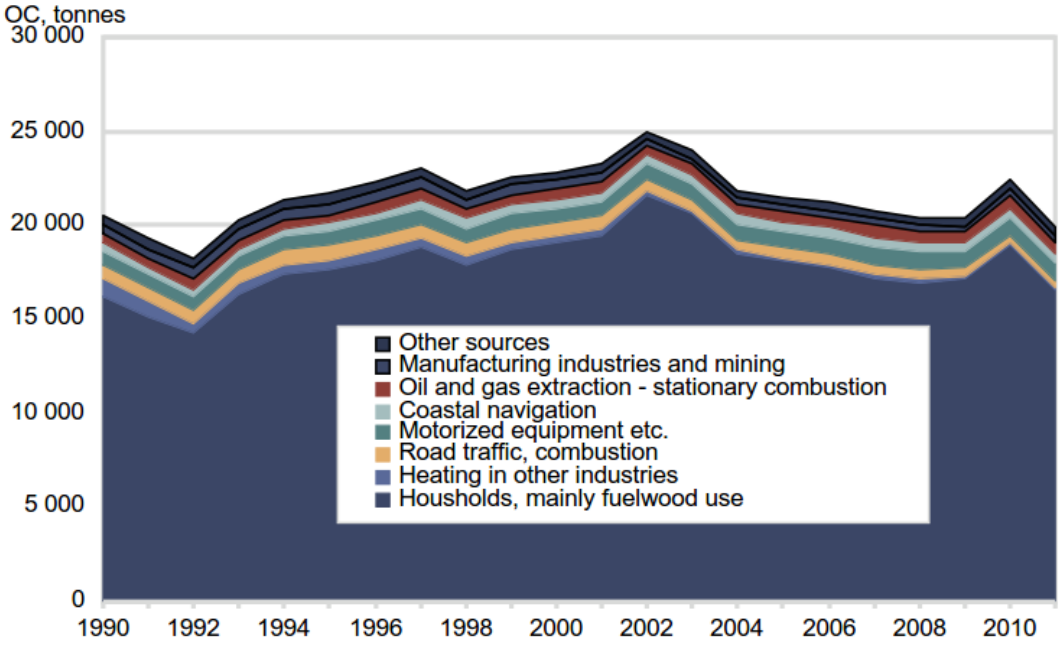
Distribution of BC emissions between sectors, 2011. Per cent



Distribution of OC sectors. 2011. Per cent



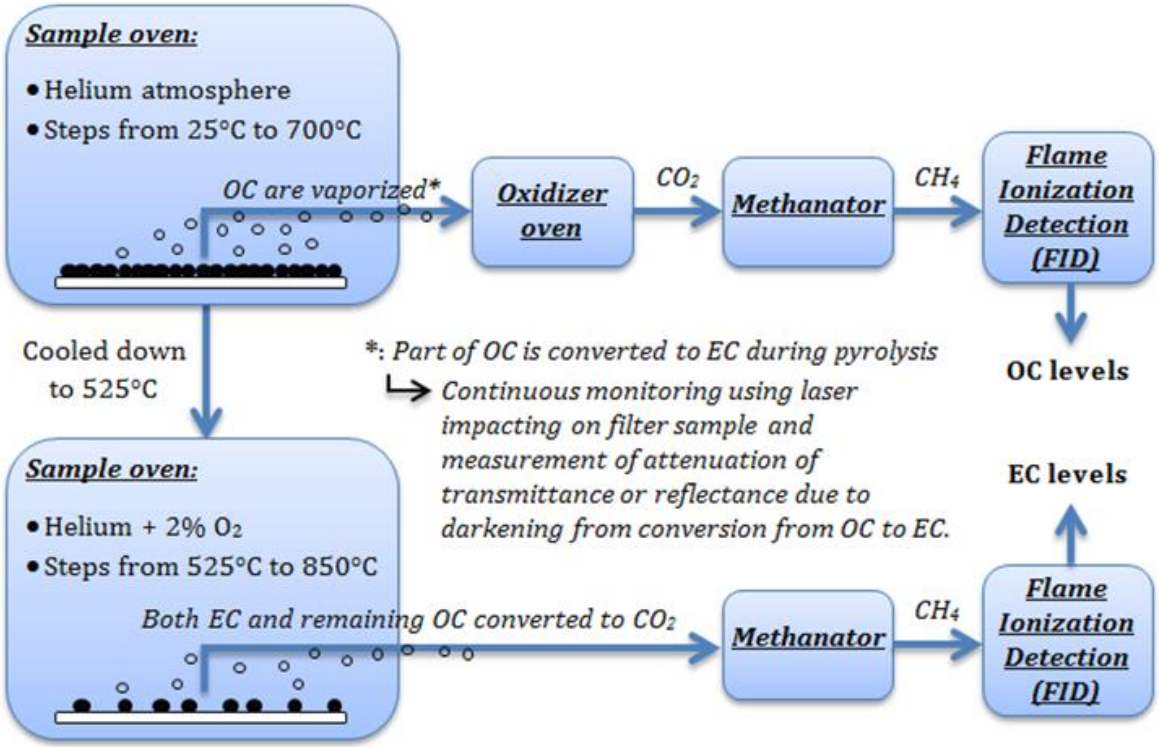
Emissions of Organic Carbon (OC) to air by source in Norway. 1990-2011. Tonnes

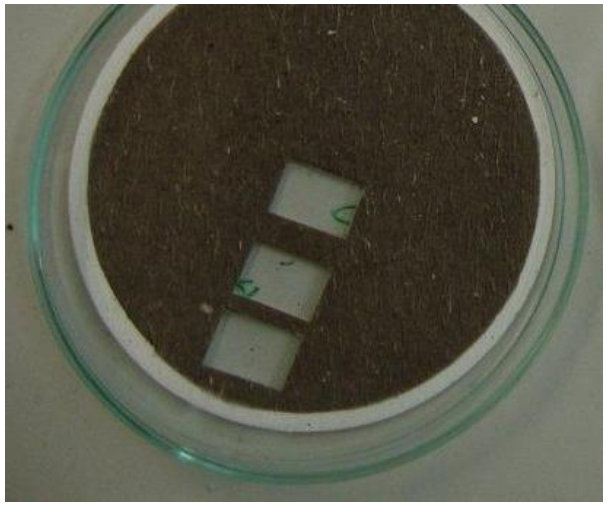


Source: Statistics Norway 2014

Recent and current projects - The OC/EC analysis procedure used in all current projects

- The analysis of elemental carbon (EC) and organic carbon (OC) were performed with an OC/EC analyzer manufactured by Sunset Laboratory Inc.
- The analyzer is uses a thermal-optical measurement principle





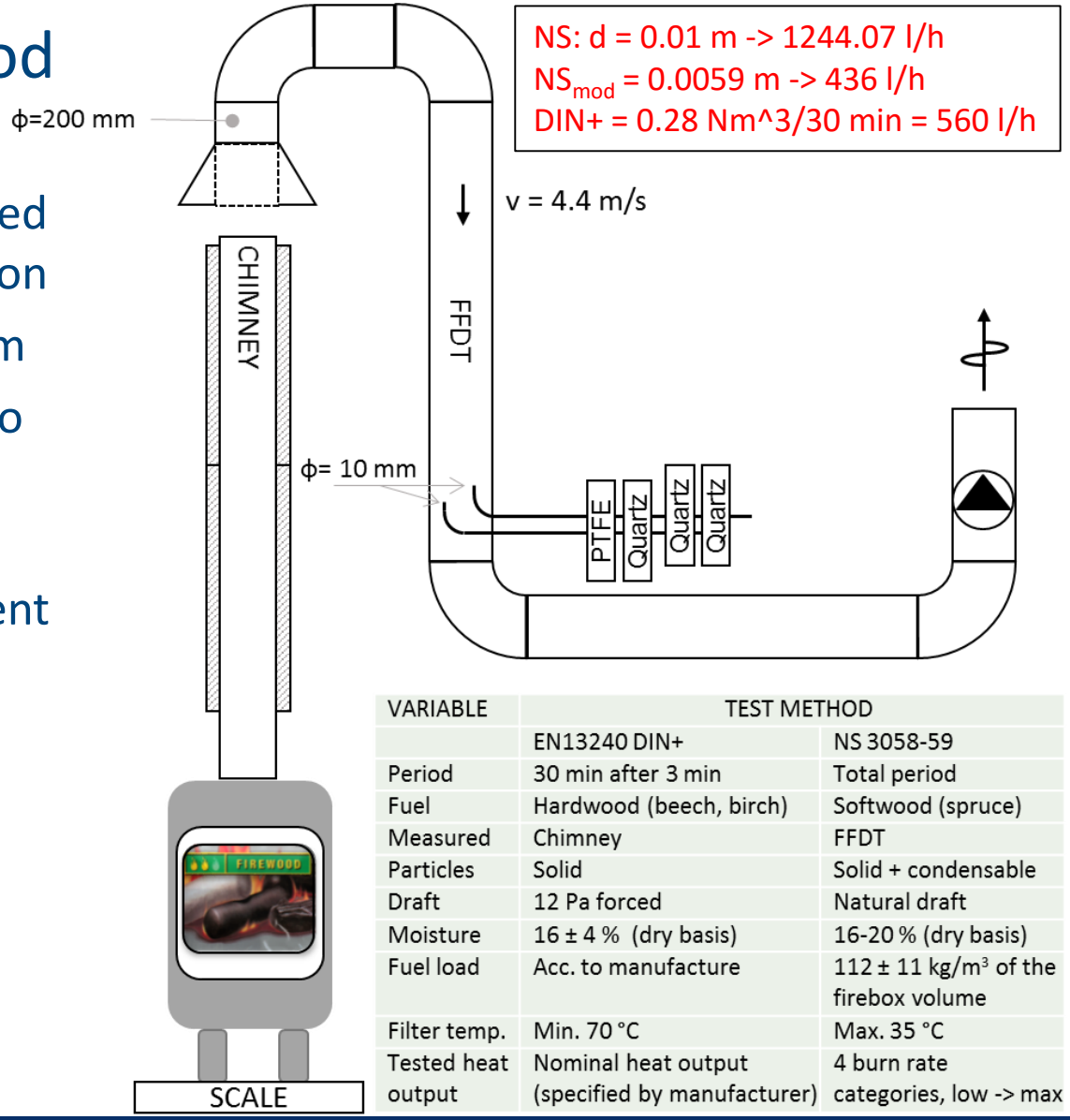
Recent and current projects

BlackOut 2013

- The first project in which emissions of elemental carbon (EC) and organic carbon (OC) from domestic wood burning have been measured in Norway.
- Obtained what we believe are more realistic estimates for total suspended particulate (TSP or PM_t) concentrations emitted from domestic Norwegian wood burning.
- Proposes a new tripartite classification of wood-burning stoves based on the year of manufacture; (1) very old (1940 to 1970-80), old (1970-80 to 1998) and new (1998 to present).
- One of the project's principal challenges has been to obtain accurate measurements of EC due to high particle filter load during sampling using a full flow dilution tunnel, especially at low burn rates, as required by the Norwegian Standard for measurement of PM_t."

Initial sampling method

- A double filter train was used with a T/Q Q/Q configuration
- Nozzle diameter was 10 mm
- Filters were kept below zero degrees at any time, also during shipment
- Dry-ice used during shipment



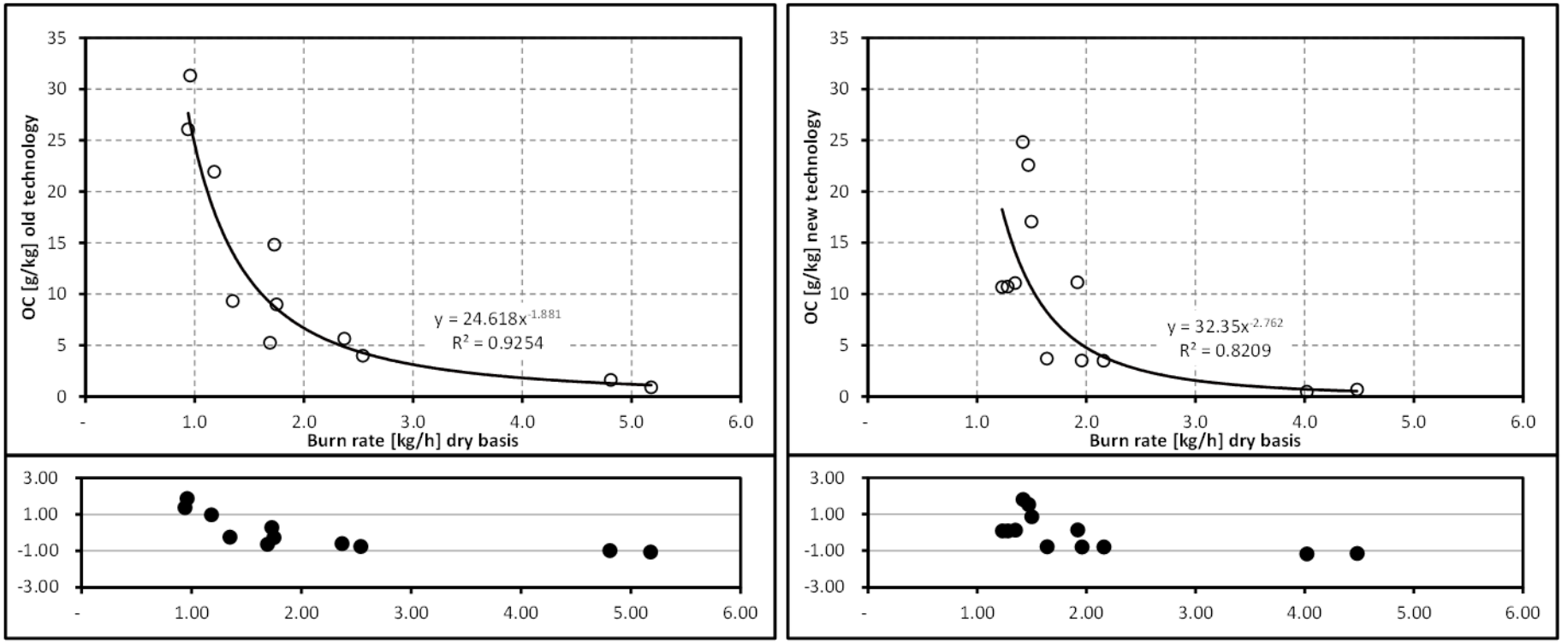
VARIABLE	TEST METHOD	
	EN13240 DIN+	NS 3058-59
Period	30 min after 3 min	Total period
Fuel	Hardwood (beech, birch)	Softwood (spruce)
Measured	Chimney	FFDT
Particles	Solid	Solid + condensable
Draft	12 Pa forced	Natural draft
Moisture	16 ± 4 % (dry basis)	16-20 % (dry basis)
Fuel load	Acc. to manufacture	112 ± 11 kg/m^3 of the firebox volume
Filter temp.	Min. 70 °C	Max. 35 °C
Tested heat output	Nominal heat output (specified by manufacturer)	4 burn rate categories, low -> max

BlackOut 2013

Medium firing (without night firing)= 1.6 kg/h as median			
Emission factor / Stove type	[g PM_t/kg wood] (g/GJ)	[g EC/kg wood] (g/GJ)	[g OC/kg wood] (g/GJ)
Wood stove – old technology	17.4 (860)	1.01 (50)	12.89 (640)
Wood stove – new technology	12.2 (600)	0.90 (44)	9.26 (460)

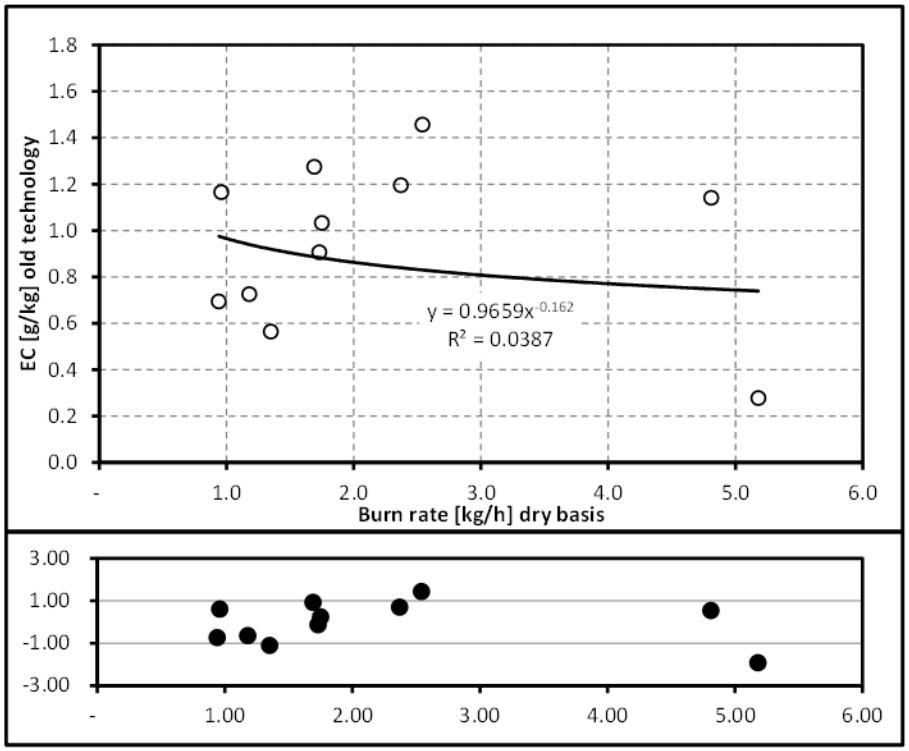
Normal firing (with night firing) = 1.25 kg/h as median			
Emission factor / Stove type	[g PM_t/kg wood] (g/GJ)	[g EC/kg wood] (g/GJ)	[g OC/kg wood] (g/GJ)
Wood stove – old technology	22.7 (1120)	0.96 (47)	16.7 (830)
Wood stove – new technology	13.4 (660)	0.86 (42)	10.47 (520)

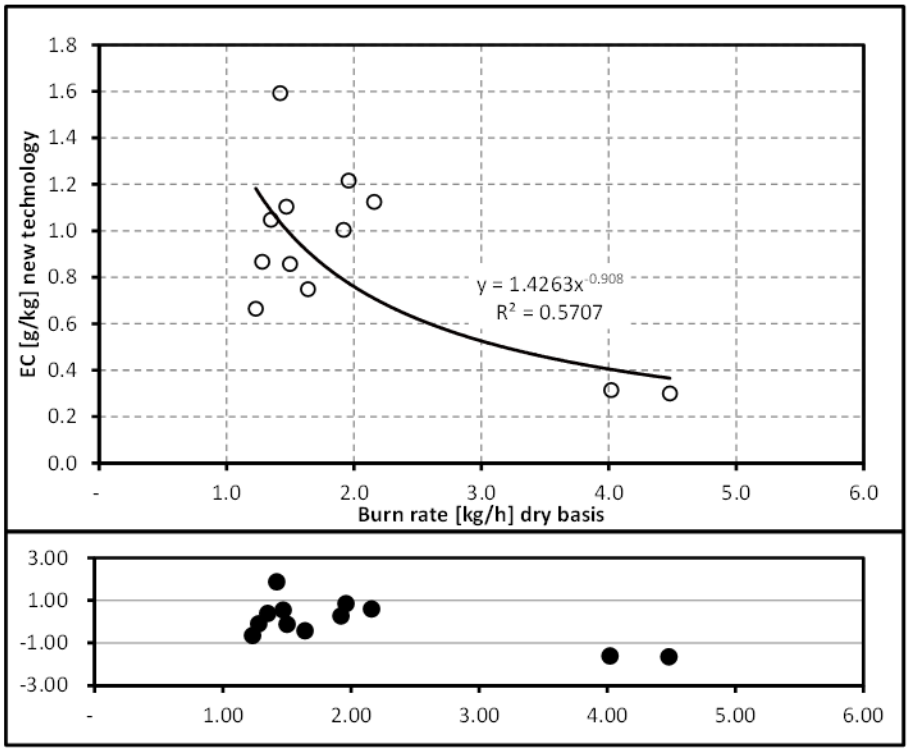
BlackOut 2013



OC in [g/kg] vs. dry basis burn rate of wood [kg/h] with associated plots of z= measured value-average value)/standard deviation. Old technology stove to the left. New technology stove to the right.

BlackOut 2013



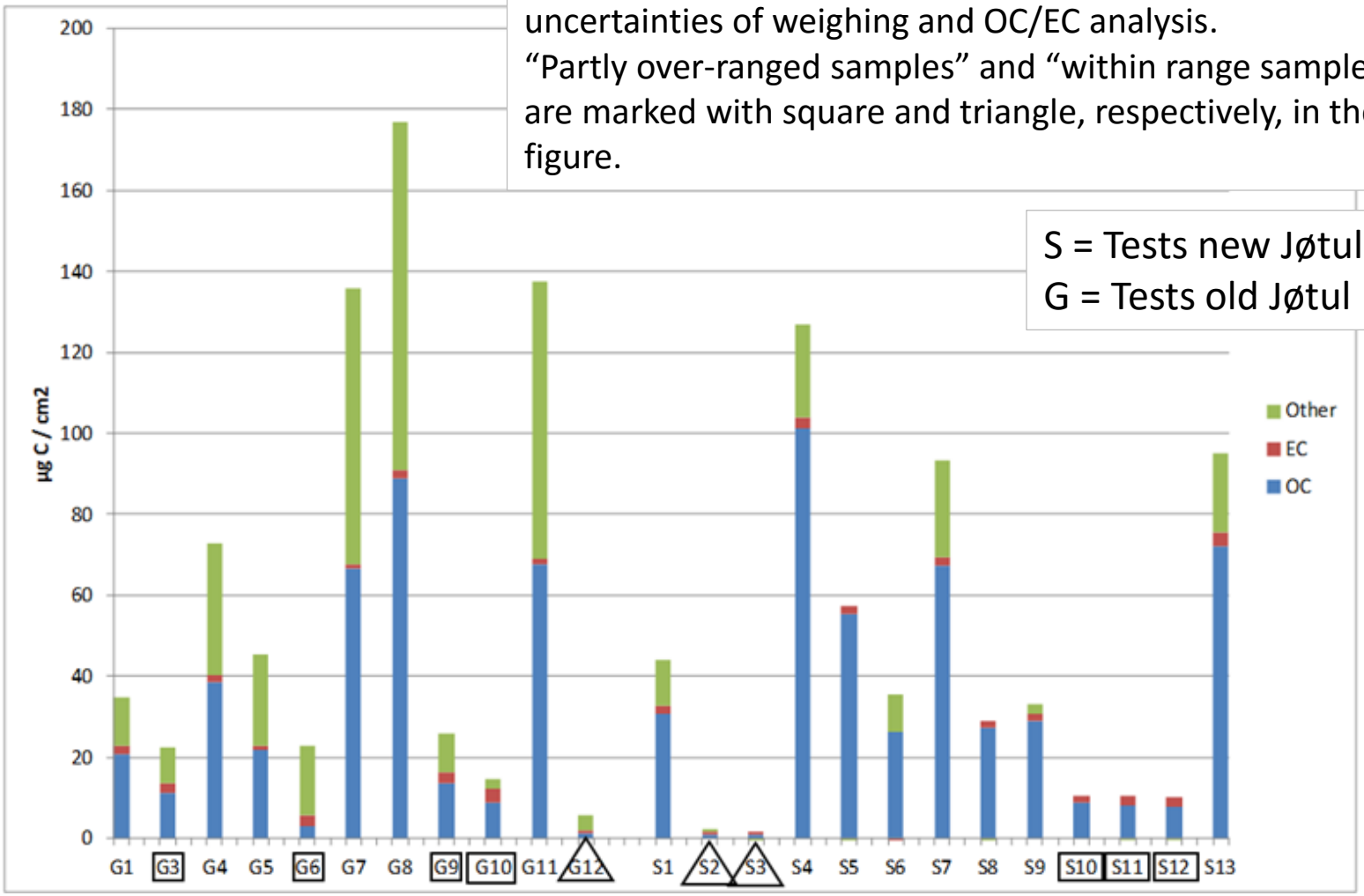


EC in [g/kg] vs. dry basis burn rate of wood [kg/h] with associated plots of z= measured value-average value)/standard deviation. Old technology stove to the left. New technology stove to the right.

BlackOut 2013

EC and OC in different combustion tests
"Other" represents the fraction of weighed PM, which was not analysed in carbon analysis. It contains particle mass other than carbon, and it is affected by the uncertainties of weighing and OC/EC analysis.
"Partly over-ranged samples" and "within range samples", are marked with square and triangle, respectively, in the figure.

S = Tests new Jøtul F3
G = Tests old Jøtul F3



Challenges

- Sunlab (manufacturer of the analyser) recommends a mass of 5 to 400 µg/cm^2 for OC and 1 to 15 µg/cm^2 for EC on the filter to guarantee accurate analysis
- Earlier tests showed problems with mass loading on the filter when tested in accordance to NS3058
- The high mass resulted in high uncertainties to of especially EC
- Particulate matter is not evenly distributed over the filter, in the centre of the filter larger particles can be found with higher EC concentrations

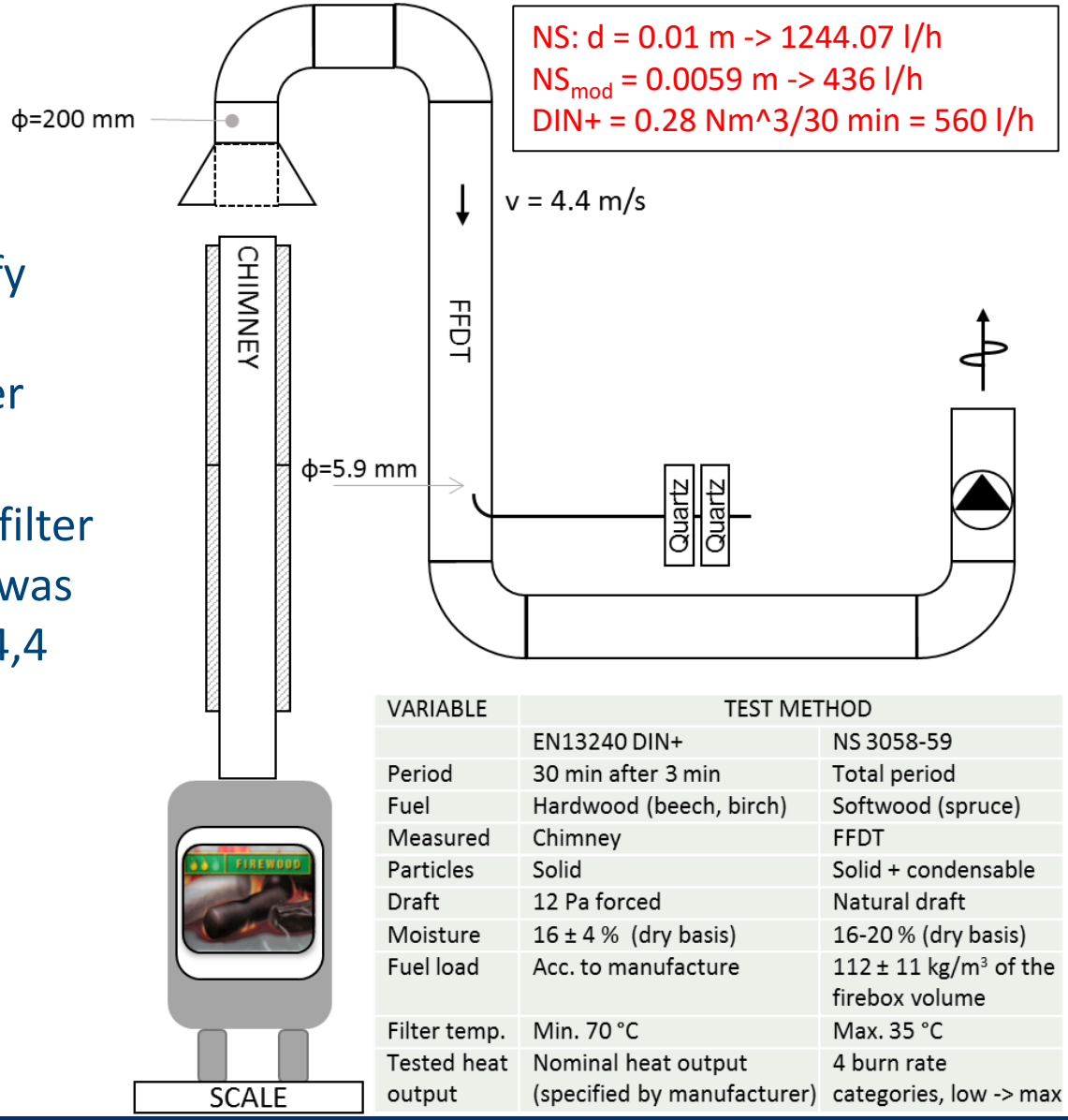
Recent and current projects

- **ICCI 2013-2015** (International Cryosphere Climate Initiative)

  Two successive projects were undertaken to establish a common procedure to conduct BC/OC measurements, further verified through a round robin test in Norway (SP Fire Research Norway), Sweden (SP Fire Research Sweden) and Denmark (Technological Institute, TI Denmark) on selected stoves. The projects were financed entirely through ICCI . Ref . Pam Pearson pam@iccinet.org , Director , International Cryosphere Climate Initiative (ICCI)

Second try

- To reduce the costs (Teflon filter are costly) and simplify the sampling just one filter holder with two quartz filter were used
- To reduce the mass on the filter the velocity in the dilution was increased from 3,3 m/s to 4,4 m/s
- Nozzle diameter decreased from 10 mm to 5,9 mm
- Filters kept at ambient temperature at all times



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Filter temp.	Min. 70 °C	Max. 35 °C
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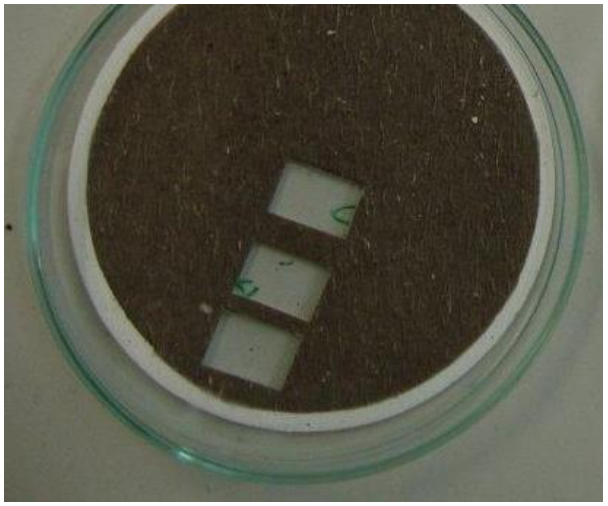
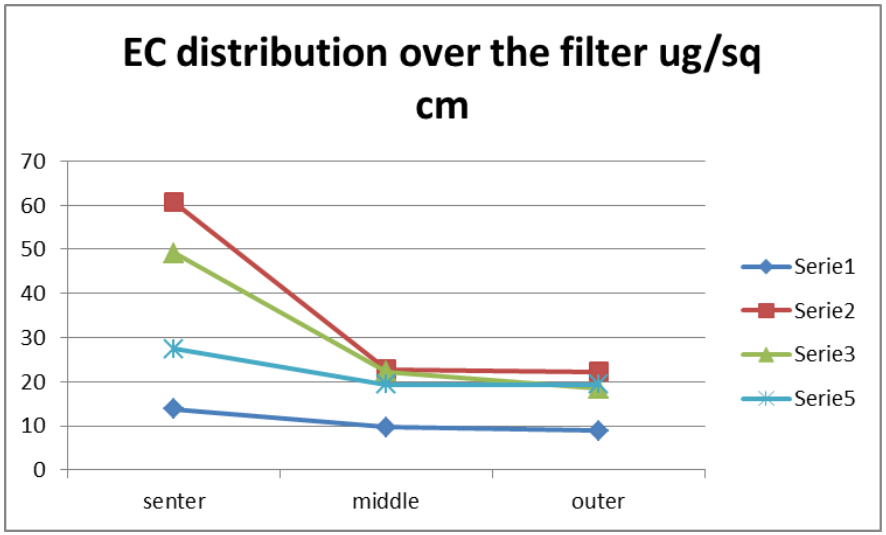
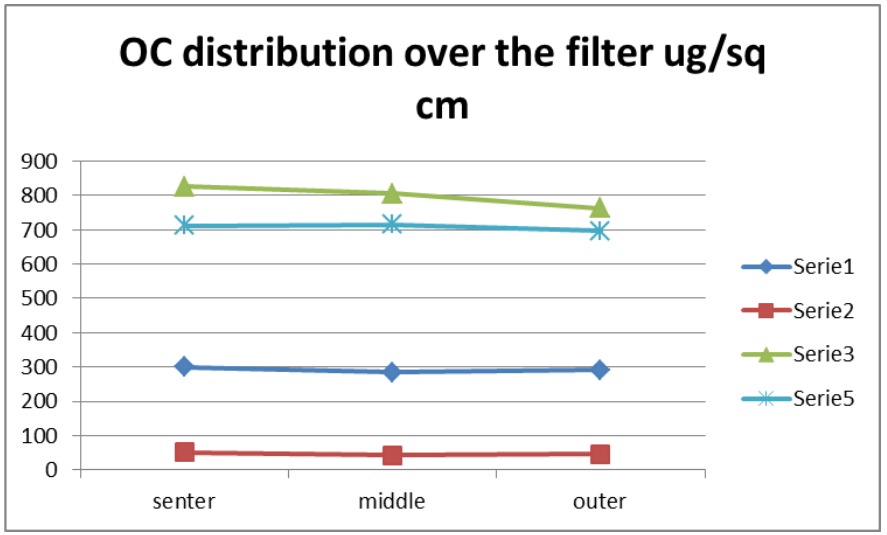
Results - distribution over the filter area

- EC higher concentration in the middle of the filter
- OC evenly distributed







Results

	Nozzle	Category	Test	kg/h dry	PM g/kg dry Quartz	PM mg/MJ	PM mg Quartz filter	EC mg	EC g/kg dry	EC mg/MJ	OC mg	OC g/kg dry	OC mg/MJ	EC/PM	OC/PM
modern stove	5,9	1	4	1,04	**22,7**	**1237,1**	24,5	**0,16**	**0,38**	**20,7**	**14,00**	**15,4**	**839,24**	2 %	**68 %**
	5,9	2	5	1,38	3,0	164,0	2	0,29	0,61	33,2	0,89	1,54	83,92	20 %	51 %
	10	3	1	1,93	2,7	146,6	6,17	1,22	0,65	35,4	1,45	0,81	44,14	24 %	30 %
	10	4	2	3,95	2,9	158,6	6,6	**4,69**	**2,05**	**111,7**	0,67	0,51	27,79	**70 %**	18 %
basic stove	5,9	1	6	1,12	14,1	768,4	14,1	0,21	0,34	18,5	7,44	6,65	362,40	2 %	47 %
	5,9	2	7	1,66	4,0	218,0	6,7	0,13	0,74	40,3	1,50	2,16	117,71	19 %	54 %
	5,9	3	10	2,83	1,9	105,2	4,3	0,22	0,3	16,3	0,31	0,41	22,34	16 %	21 %
	5,9	4	9	3,32	3,6	195,1	2	0,11	0,17	9,3	2,03	1,94	105,72	5 %	54 %

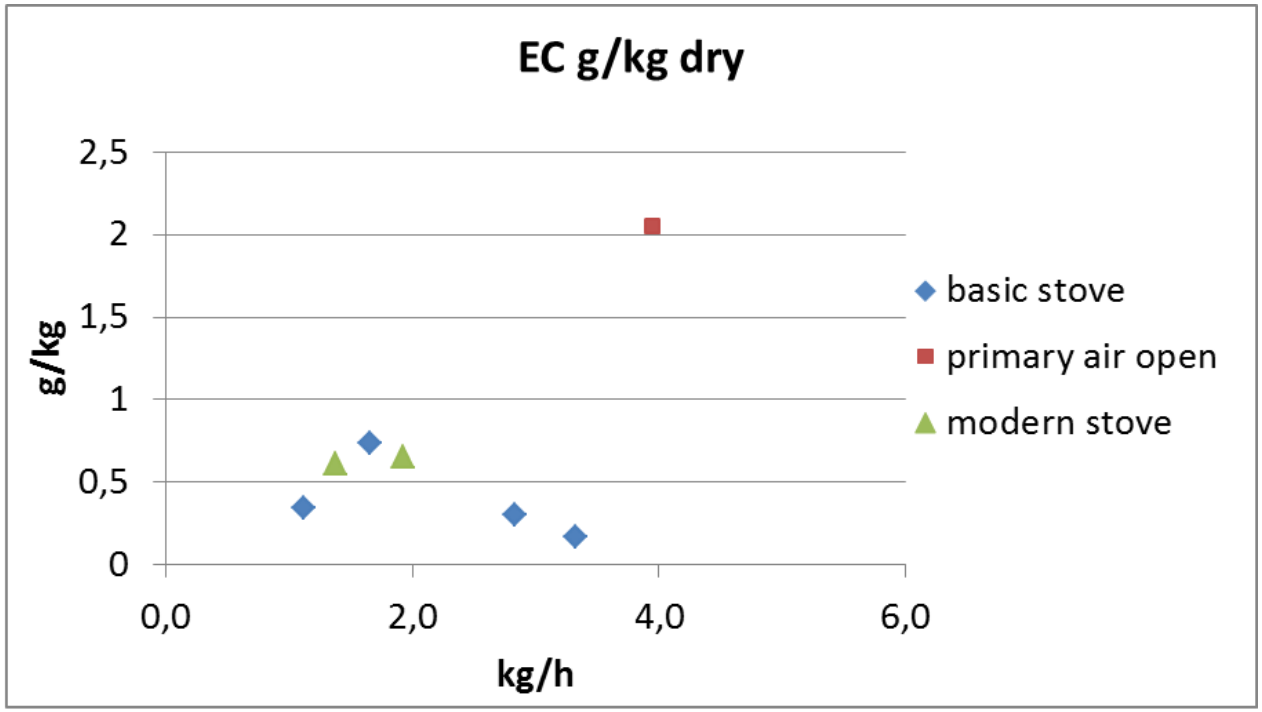
Results in the vicinity of operational limits / possible error

Results above operational limits / highly uncertain results

- Test 4 high uncertainty of OC, Test 2 high uncertainty of EC and, Test 6 increased uncertainty of OC due to high loadings

Results

- The modern stove could not be operated in burn rate category 4
- Primary air open during firing resulted in the highest amount of EC
- Trends between type of stove, PM concentration or burn rate category and EC? – not clearly



Results DTI

Stove	Burn rate (kg/h)	EC (mg)	OC (mg)	EC emi (g/kg)	OC emi (g/kg)	Filter #	TC (mg)	EC/TC ratio
Traditional	1,23	0,16	1,06	0,36	1,61	28	1,22	0,13
Traditional	1,42	0,21	0,90	0,41	1,31	26	1,11	0,19
Traditional	1,51	0,36	0,84	0,66	1,30	2	1,20	0,30
Traditional	1,94	0,68	1,33	1,08	1,86	29	2,01	0,34
Lamda auto control	1,14	0,26	0,60	0,57	1,10	24	0,86	0,30
Lamda auto control	1,30	0,20	0,68	0,46	1,21	22	0,88	0,23
Lamda auto control	1,34	0,24	0,65	0,53	1,16	16	0,89	0,27
Lamda auto control	1,49	0,28	0,31	0,58	0,63	14	0,59	0,47
Dual downdraft + auto	1,22	0,00	0,12	0,01	0,28	12	0,12	0,00
Dual downdraft + auto	1,29	0,06	0,30	0,19	0,66	10	0,36	0,17
Dual downdraft + auto	1,36	0,06	0,11	0,18	0,28	6	0,17	0,35

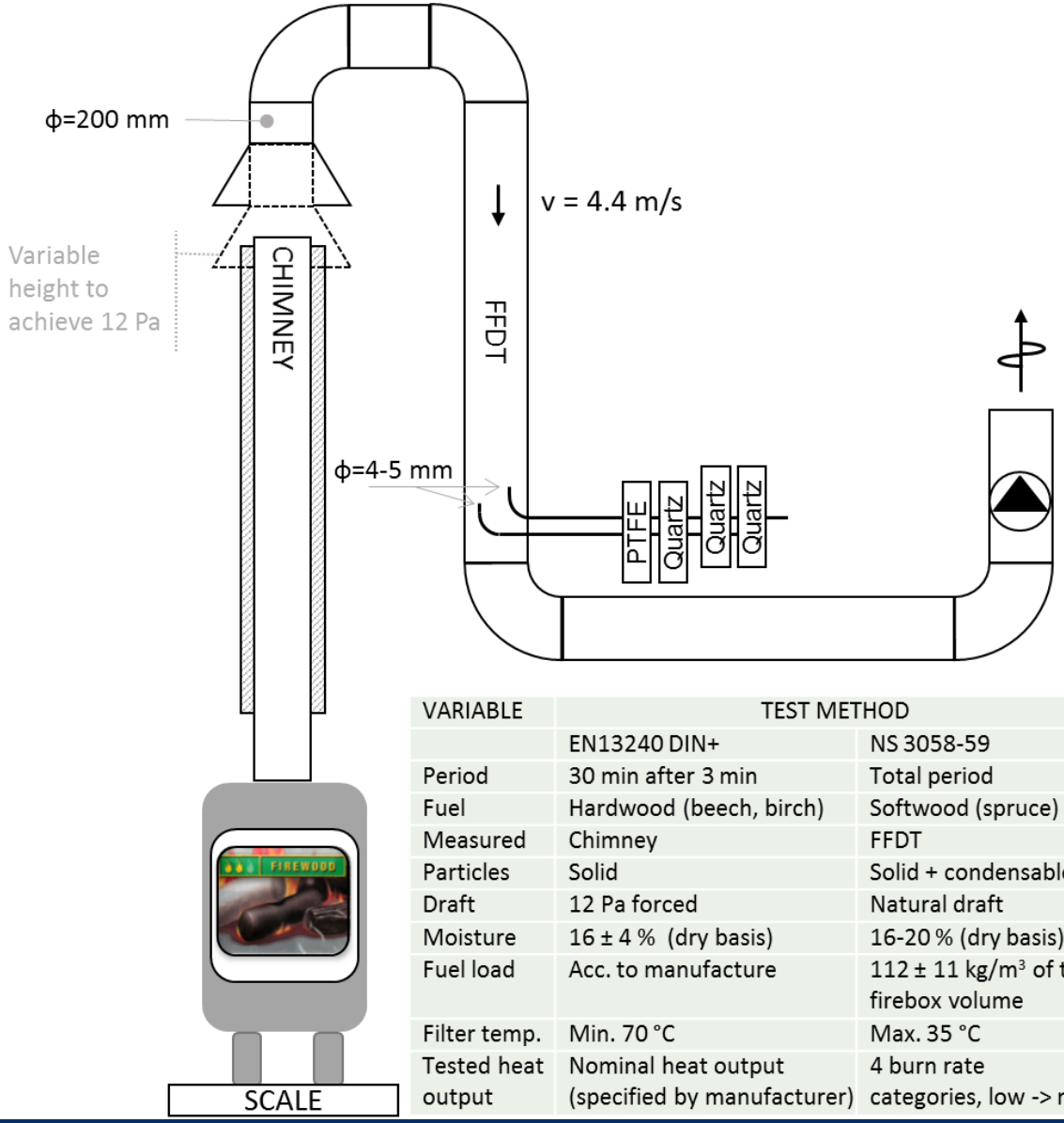
Recent and current projects

- **BC emission control through regular stove maintenance - 2015**

  The effect of leakage on the EC emissions

Recent attempt

- Back to using double filter train with T/Q Q/Q configuration
- Velocity in the FFDT is kept at 4,4 m/s
- Nozzle diameter is 5,9 mm



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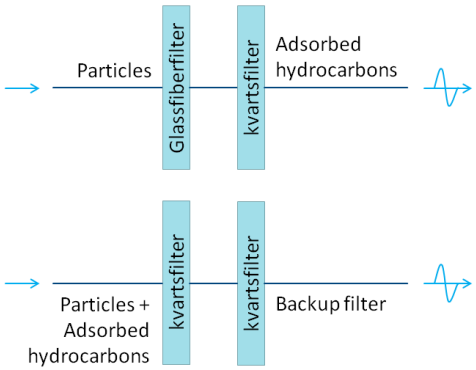
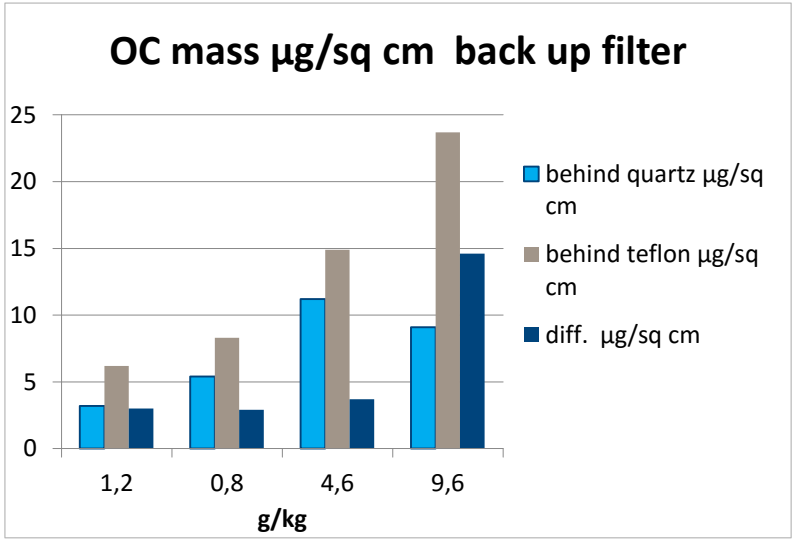
Recommended EC/OC sampling

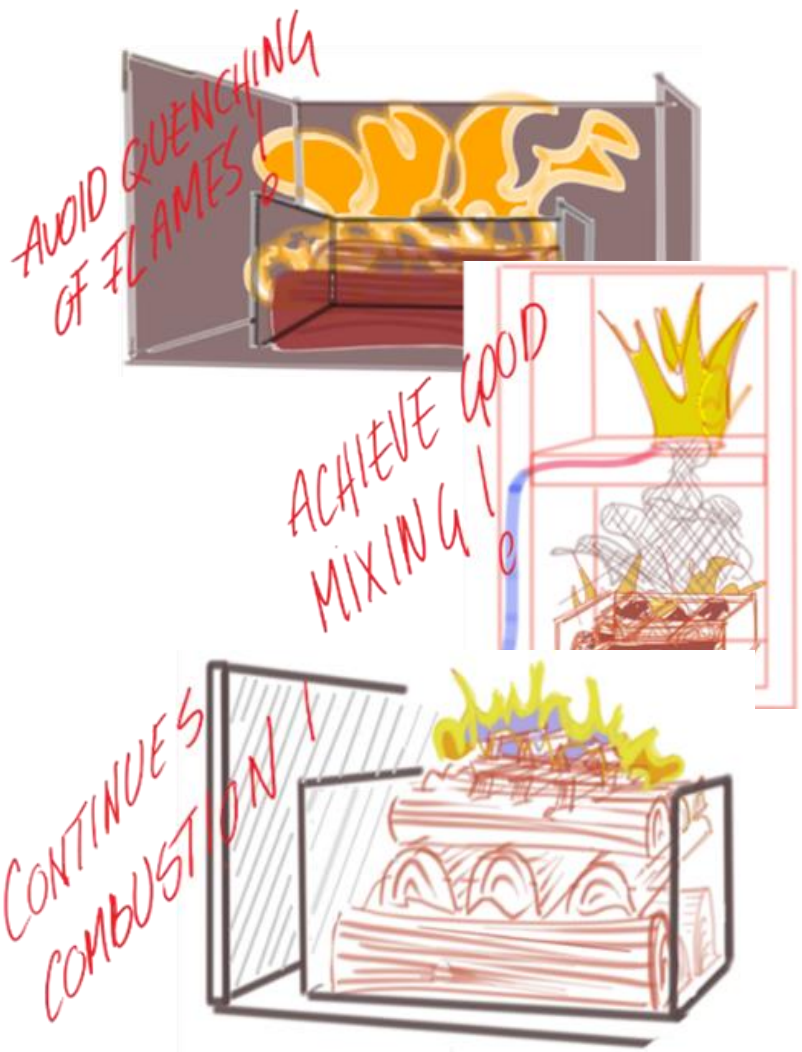
- Quartz filter are required since high temperatures are applied during the analysis
- Two double filter holders should be used in parallel so as adsorbed OC on the quartz filter can be corrected
- Filter holder 1: **quartz (EC/OC analysis + adsorbed OC)** + backup
- Filter holder 2: Teflon (inert) + **quartz (adsorbed OC)**

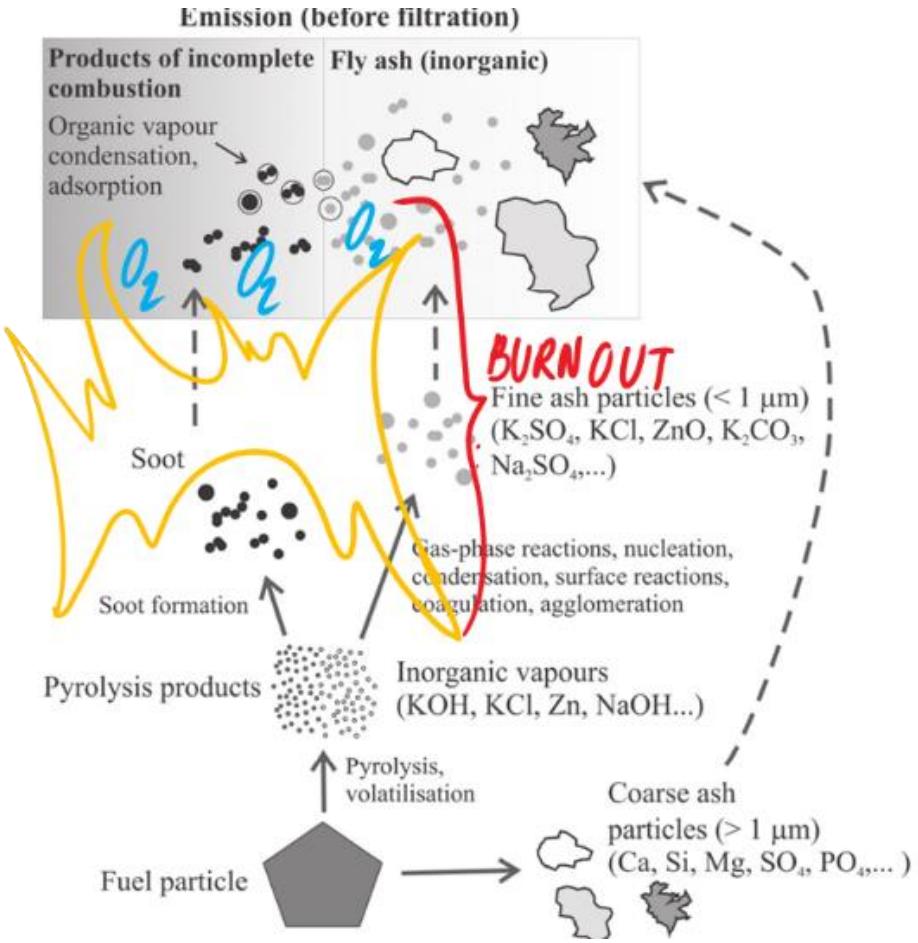




Without OC correction for the gaseous adsorbed OC the OC concentration can be over-estimated with up to 70% for low PM concentrations

ASPECTS TO CONSIDER WHEN DESIGNING NEW STOVES





SUMMARY

- What is covering the Artic snowman?
- Particle aging, atmospheric chemistry
- What is BC/EC
- What is Brown Carbon?
- BC measurement standards
- What's the real contribution from small-scale appliances

Cryoconite covered arctic snowman