Sust. Fuels TOC

Proceedings of FBC2003
17TH International Fluidized Bed Combustion Conference
May 18-21, 2003, Jacksonville, Florida USA

FBC2003-098

CO-COMBUSTION OF MUNICIPAL SLUDGE WITH WOOD/COAL IN CFB – ENRICHMENT OF PHOSPHOROUS AND CADMIUM IN ASHES

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ABSTRACT

Municipal sludge, originating from two wastewater treatment plants in Sweden, has been burned together with wood pellets or bituminous coal in a circulating fluidised bed (CFB) boiler equipped with a secondary cyclone and bag filter for fly ash removal. Such co-combustion is an alternative to mono-combustion of sludge. The sludge is burned in either mechanically dewatered or pre-dried form. The mechanically dewatered sludge was fed with a pump, but pre-dried sludge could be fed by the fuel feed system normally used for coal. Both types of sludge were burned with either wood-pellets or coal as main fuel under identical operating conditions, typical for a CFB boiler. The focus was on ash balances and on analysis of fuels and ashes to obtain concentrations of relevant species. The presence of phosphorous (P) is of special interest in relation to trace elements, such as mercury (Hg), cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), nickel (Ni) and zinc (Zn). For this reason a comparison has been made between these trace elements and phosphorous in the various ashes and the original sludge as well as other sources of phosphorous that could be used for agricultural purposes. The results show that sewage sludge and fly ash, after combustion of sludge, contain similar amounts of phosphorous as other phosphorous sources for agricultural use, but the levels of trace elements in relation to phosphorous (Hg, Cd, Pb, Cr, Cu) are higher than in animal manure and artificial fertilizer and higher than the present limits in Sweden.

INTRODUCTION

Sludge from municipal waste-water treatment pants can be incinerated in dedicated plants like the fluidised bed combustor located in Hamburg [1]. In a specialized plant like this one, organic pollutants and pathogens are destroyed, and inorganic trace elements like chlorine and sulphur are trapped in the flue gas treatment process. Low combustion temperature and staging of the air supply lead to low emissions of nitrogen oxides (NOx) despite the high content of nitrogen in the sludge. The drawback of this concept is that, if an auxiliary fuel is not used, drying of the sludge prior to the incineration is required in order to sustain combustion at a proper temperature of 850 °C. This, in conjunction with the flue gas treatment process, makes the unit fairly complex and only possible to justify in connection to large wastewater treatment plants. Co-combustion of sludge with coal or other primary fuels like wood offers an alternative to mono-combustion. The idea is to burn sludge in conventional solid fuel boilers like fluidised beds, normally used for power and/or heat production. This increases the number of possible facilities and decreases the need for transportation of sludge from small wastewater treatment plants. The energy content of the sludge can be recovered, either in connection to pre-drying or, if low-temperature heat can be utilised, in a flue gas condenser. With coal as a base fuel this leads to an effective reduction of the CO_2 emission. Within the European Union the regulations of emissions from mono-combustion of wastes like sludge have been adapted to include co-combustion in conventional boilers, making the procedure for acceptance and approval easier [2]. The alternative to incineration of sewage sludge is to use the sludge directly as a fertilizer for agricultural growth of food.

Especially the fertilizing agent phosphorous (P) is regarded as a limited resource that should be taken care of. Therefore, demands on re-circulation of the phosphorous to the agriculture sector could be expected in the future. The limitation of this alternative is the pollution of the sludge by various species originating from human activities, and special attention has to be paid to trace elements like mercury (Hg), cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), nickel (Ni) and zinc (Zn) that could contaminate the soil in the long run (decades). Incineration of the sewage sludge would avoid this contamination if these trace elements could be separated from the phosphorous in the ashes. The question of whether such a separation is needed is the subject of the present paper. Focus is on the fate of the phosphorous and some harmful trace elements when co-combusting sewage sludges from two waste water treatment plants in Sweden with wood and coal as base fuels in a fluidised bed combustor equipped with a secondary cyclone and bag filter for fly ash removal. A comparison is also carried out with other sources of P-fertilisers with respect to contamination by the selected trace elements.

EXPERIMENTAL BACKGROUND

The Boiler

The 12MWth circulating fluidised bed (CFB) boiler, located at Chalmers Technical University was used for the tests, Figure 1. The combustion chamber (1) has a square cross-section of about 2.25 m2 and a height of 13.6 m. Fuel is fed from fuel hoppers (20) to the bottom of the combustion chamber through a fuel chute (2). Make-up bed material or limestone for sulphur capture is fed from (17) and (18). The circulating solids are separated in the primary cyclone (9) and transported through the particle return leg (10), the loop seal (11), and in the case of pure coal combustion also through the external heat exchanger (12), back into the combustion chamber. Primary combustion air is supplied to the wind box (3) below the gas distributor, whereas secondary air may be added either into the combustion chamber (4), normal staging, or downstream of the cyclone (7), advanced staging, see [3], [4]. After passing of the exit duct from the cyclone (8), which acts as an afterburner chamber, the flue gas is cooled to 150 °C in the convection path and fly ash is separated from the flue gas, first in a secondary cyclone (13) and then in a bag filter (14). This is a two-step particle separation process. Normally a bag filter or an electrostatic precipitator captures the fly ash without any cyclone upstream in the flue gas path. The various alternatives for fly ash removal influence the potential of trapping trace elements [5].

The Fuels

Bituminous coal or wood pellets were used as base fuels. The coal originated from the Katowice district in Poland, while the wood pellets were produced from domestic trees like pine and birch in a factory located in the city of Ulricehamn by “AB Svensk Brikettenergi”. The additional fuels were two different municipal sewage sludges. In the first test series pre-dried sludge from the wastewater treatment plant “Himmerfjärds-verket” was used. This plant treats wastewater from 245 000 inhabitants of the city of Södertälje and the southeast part of Stockholm. The second test series involved mechanically dewatered sludge from the plant “Ryaverket”, the second largest wastewater treatment plant in Sweden, taking care of wastewater from 580 000 inhabitants of the city of Göteborg and surroundings.

In order to feed the wet sludge cake into the boiler, a sludge pump (a development of a piston pump normally used for cement) was installed in connection to the research facility, (21) in Figure 1. The properties of the fuels investigated are given in Table 1. Both treatment plants produce digested sludge and employ precipitation with ferrous iron for phosphorous removal from the wastewater.

Experimental Procedure

The operating conditions of the tests are given in Table 2. The ranges of variation in Table 2 are those from test to test. The ambition was to keep the operation conditions as similar as possible between the tests, only changing amount of sludge added and type of sludge. It is possible to feed higher fractions of pre-dried sludge than mechanically dewatered sludge. This is reflected in the test programme. Higher sludge ratio leads to higher calcium (Ca) feed with the sludge, and this makes it difficult to freeze the total calcium to sulphur ratio (Ca/S), since the exact Ca and S contents of the sludge were not known at the time of the experiments. As seen from Table 2, the operating condition was quite stable despite the large differences between the fuels. The research boiler is equipped with a control system that maintains the air flows constant when the load is set. The fuel flow is then controlled by the oxygen concentration in the stack and the pressure fluctuation on the waterside of the boiler is balanced by a heat exchanger. This control system makes it possible to maintain a very stable condition for several hours, which is important when trace elements and phosphorous are to be tracked. All tests were run between 10 and 24 hours prior to collection of solid samples for analysis. This strategy improves the ash balance, since equilibrium in trace element concentration has to be established before the ash samples can be taken. In each test the following samples were taken: a) base fuel and sludge; b) solids representing the content in the combustion chamber where taken in sample hole H2 in the bottom of the furnace and in the cyclone leg (10) shown in Figure 1; c) fly ash from the secondary cyclone (13) and bag filter (14). These samples were then sent for proximate, ultimate, ash and trace elements analysis in various accredited external laboratories.

RESULTS

Relative increase of ash components.

The differences in the feed rate of trace elements when substituting coal or wood with sludge are particularly important in the present tests. There are three consequences of the substitution of coal or wood with sludge. First, the heating values are different, second, the ash content of the sludge is higher, and third, the trace element concentrations of the sludge are also higher, as seen in Table 1 (ash content, heating value) and Table 3 (trace element concentrations, phosphorous). A comparison of the supply of ash, trace elements and phosphorous between the reference cases with pure coal and wood and the test cases with sludge addition is seen in Figure 2. The comparison is limited to the trace elements Hg, Cd, Pb, Cr, Cu, Ni, Zn. For these elements there are limits in Sweden, below which the material may be used as a source of phosphorous for agricultural purposes, as seen in Table 3, [6]. Figure 2 shows the obvious result that the increase of trace elements, ash and phosphorous is much higher using wood as reference fuel than using coal. Dry sludge allows higher feed rates than wet sludge, but it also leads to much higher feed rates of trace elements and phosphorous.

Ash balance and distribution of ash.

Mass balances illustrate the accuracy of the measurements. Under equilibrium operating conditions the total mass balance of solid material over a fluidised bed combustor can be expressed as:

Mass flows of fuel ash, lime and silica sand fed=exiting mass flows of bottom ash and fly ash

Here conversion of lime and unburned char in the exit flows are taken into account, but release of volatiles from the ashes is neglected. Silica sand was fed in some cases to regenerate the bottom bed as a compensation for the low ash flow when operating with wood only. The total mass balances shown in Figure 3 a-d verify that the closure has been good. Only in the case of pure wood the balance is not closed in a satisfactory way because of the very small ash flow that could not be accurately recorded. The distribution of ash between bottom and fly ash is seen in Figure 4 a-d. The solids flows leaving the unit (expressed in actual kg/h) show a typical situation for a CFB unit: the amount of bottom ash (bed ash) is determined by the fuel ash, the lime supply and the fragmentation behaviour of these inert materials. The fraction of bottom ash is highest (41 %) in the second test series with coal as base fuel, where the bottom bed material was continuously regenerated in all three tests to remove coarse ash material originating from the coal. The bottom ash fraction is lowest in the corresponding tests with wood as base fuel (6%), where no bed regeneration was needed and also the lime flows were kept low. In the first test series, the bottom ash fraction was dominated by the ash of the pre-dried sludge and of the higher lime flow, resulting in an average bottom ash fraction of 27%. The distribution of fly ash between secondary cyclone and bag filter in Figure 4 a-d reveals that the secondary cyclone dominates the collection of fly ash; in average 87 % of the total fly ash is captured by the secondary cyclone.

Concentrations of Phosphorous.

The average P-concentrations of the two sludges tested are given in Table 3: 3.6 and 2.9%, respectively. This can be compared with the average value of 2.7% obtained from analysis of sludge samples from 47 wastewater treatment plants in Sweden, [6]. The individual values (3.6% and 2.9%) of the sludges originating from the two wastewater treatment plants engaged in this study (they are part of the 47 plant study) are also given in Table 1. It is evident that the sludges used in the present study well represent the general Swedish sludges with respect to concentration of phosphorous and that the concentration is high enough for direct agricultural utilization. The question is where the P is found after combustion. Figure 5 gives a first idea of the fate of P; it ends up in the ashes, more in the two fly ashes than in the bottom ashes, since the P concentrations are higher in these samples than in the furnace and bottom ash. The absolute P concentrations depend on the ash content of the base fuel. The coal ash dilutes the P-content greatly compared to the low-ash wood pellets. Lime supply also acts as a diluter, and the lime flows are higher using coal as base fuel because of the higher sulphur content compared to wood. Altogether, this means that the highest P-concentrations are found in the fly ashes produced with wood as base fuel. The reference cases with pure base fuels in the first test series with pre-dried sludge are exceptions from this picture. The two tests with pure wood and coal, Figure 5a,b, were run too close (after 10h) to the tests with maximum sludge feeds. (The corresponding data points at zero waste fraction are therefore not connected to the remaining curves in the diagram). The reference cases in the second test series, Figure 5c,d are identical with respect to operating conditions, but they were run avoiding influence from previous tests with sludge supply and hence represent the correct values. The P concentration in the ashes then reflects the very low P content of the base fuels, Figure 5c,d. The P concentration in the fly ashes when adding sludge to wood as base fuel is higher than in the original sludge. This makes sense, since the organic part of the sludge has been removed by combustion.

From a P concentration point of view the fly ashes could be used directly as a source of phosphorus in the agriculture. Two factors determine if this is a good idea or not. The first one is related to the form of phosphorus in the ashes compared to the original compound in the sludge and the second concerns the contamination of the material by trace elements. The original form is mainly ferric phosphate ($FePO_4$), since the precipitation species is ferrous iron. $FePO_4$ performs well as a fertilizer when sludge is directly used on the soil. When the sludge is burned, the iron is oxidized to iron oxide (Fe_2O_3) and the phosphate could combine with other species like calcium or aluminium, for example. Lime added to the furnace for sulphur capture could react with phosphorous to form calcium phosphate. This is avoided if hydrated lime $Ca(OH)_2$ is supplied to the inlet of the bag filter for removal of both chlorine and sulphur from the flue gas. Then the secondary cyclone ash is kept clean from an external source of calcium. Now, the inorganic part of the sludge, the ash and, for example, the relation between aluminium and calcium in the ash determine how the phosphate will be bound in the end product and how suitable this product is for the uptake of the phosphorous for growing plants. This alternative with hydrated lime addition is indicated in Figure 1, (no. 19), but it was not used in the present tests.

Mass balances and emissions of each trace element from the first test series can be found in [4], and for the second test series similar data will be reported elsewhere. In both test series no emissions of trace elements, not even mercury, were recorded within the limits of sensitivity of the analysers during the measurements in the stack. The ash balances were closed in a satisfactory way in all cases with the exception mentioned above. This means that the ash flows are well controlled. For the trace elements reported below there was a good closure of the species balance in the first test series [4]. This indicates a high accuracy of the analyses of trace elements in the fuels and ashes. For the second test series the same accredited laboratory was used, so these analyses should be reliable as well.

Trace Elements - Absolute Concentrations.

The concentration of phosphorous is important for the usefulness of P for agricultural purposes, but equally important is the trace element concentration, given for all ash samples in Appendix 1. The result can be sorted out in the following way: The bottom ash is different from the fly ash. It is built up by the bed solids that circulate between the furnace, primary cyclone, cyclone leg, particle seal and back to the furnace again. In a pure wood combustion case the bed material is sand, which dominates the bottom ash removed. Co-combustion of sludge should be characterised by an increase of the main components P and Fe and the trace elements Cu and Zn. Lime needs to be added as well, and this increases the Ca content of the bottom ash. These general trends are seen in Table A1:a and A1:b for Zn, Cu and P but not for Ca. As discussed previously, the two reference cases in the first test series with pure base fuel were contaminated by earlier tests where sludge was used. Also the second reference case with wood as base fuel was not performed with sufficient time between an earlier run with pure coal combustion and with lime supplied. This explains the high content of Ca in the bottom ash. In the case of pure coal combustion the re-circulating solids are built up by silica sand, coal ash and lime. If the second reference case is used instead as a representative base case it is clearly seen in Table A1:a and A1:b that the addition of sludge increases the concentrations of Zn, Cu, P and Fe. However, due to the dilution of the bottom ash by silica sand and the relatively coarse size of the material, the ash balances show small amounts and low concentrations of phosphorous at moderate sludge feeds. Consequently, bottom ash is not suggested for use as a P-source in agriculture. The ash fraction of largest interest for re-use is that from the secondary cyclone, the dominant one according to the ash balance, Figure 4. The particle size is a fine powder similar to an artificial fertilizer. From a trace element point of view the situation is less favourable, Table A1:c and A1:d. Cu, Zn and Fe increase considerably in the ash, apart from the valuable phosphorus. The heavy metals Hg and Cd also accumulate in the secondary cyclone ash. Hg is a special case due to its volatile nature. No Hg is present in the bottom ash. The highest concentrations are in the bag filter samples, Figure 6 and Table A1:e and A1:f. Cd is somewhat different. Cd is found in the bottom ash to some extent, Figure 7 and Table A1:a, A1:b. The concentrations of the filter ash samples are about the same as in the secondary cyclone ash. An exception is the second reference case with wood as base fuel, where a number of trace elements show high concentrations in the filter ash. The accumulation of Hg in the filter ash, the relatively small amount and the contamination with hydrated lime, if injected for sulphur and chlorine capture, leads to the conclusion that bag-filter ash is not suitable as a P-source for plant growth.

Comparison of trace element concentrations in relation to P-content.

For the estimate of the significance of trace elements in relation to phosphorous, the ratio of trace elements to phosphorous is helpful. This approach is demonstrated in Figures 6 and 7 for Hg and Cd as examples. The full account for the selected trace elements Hg, Cd, Pb, Cr, Cu, Ni and Zn is given in Appendix 2 where also a comparison is presented with sludges and other P sources available for use in the agricultural sector, such as animal manure and artificial fertilizer (see Table A2:d). In general, the trace element concentrations from sludge are several times higher than those from the other sources. The fertilizer selected for comparison has a Cd guarantee, with a Cd content of less than 5 mg Cd/kg P and other trace elements are also low. The difference from sludge is great. The ash samples (Table A2:a-c) are less favourable with respect to Hg and Cd than other P-sources, Figure 6 and 7. For Hg, the enrichment in the filter is as high as 180 mg Hg/kgP (Figure 6c) in comparison to levels of only 0.4-0.9 in animal manure and 0.04 in artificial fertilizer (Table A2:d). For Cd the difference is not that high; the concentrations are more equal in the ashes from the secondary cyclone and from the filter, and some Cd is found in animal manure as well. Nevertheless, the Cd/P levels are 300 times higher in the fly ash from wet sludge combustion than in the artificial fertilizer.

Accumulation of trace elements on the soil for food production.

In Sweden there is a limit for the absolute concentrations of some trace elements for direct use of sludge as a P-source. This limit is set assuming that the organic part is still present in the sludge. There is also a limit for the maximum trace element concentration, calculated as amount supplied with the P-source on a certain area of soil used for food production during one year. For Hg the limit is 1.5 mgHg/(acre,year). These limits are appropriate for judgement of the usefulness of sludge utilisation, since they are set to prevent long time contamination of the soil. In order to illustrate the potential risk of long time contamination by different P-sources, a calculation based on an addition of 22 kg of P to one acre/year is presented. The quantity 22 kg was chosen because it corresponds to a normal addition of fertilizer (in Sweden) [6]. The values of Tables A2:b-c are used to produce average data for the fuels and ash flows of each test series. The results are shown in Figure 8a-g, where the limits are also indicated. Figure 8a shows that unburned sludge or ashes after combustion will cause higher levels of Hg contamination than animal manure or artificial fertilizer. The enrichment of Hg in the bag filter ash leads to higher levels than the limit, while ash from the secondary cyclone is comparable to direct use of sludge as a P-source. For Cd the case is even less favourable, Figure 8b. Only one of the fly ashes is acceptable with Cd levels below the limit. As a matter of fact, the average sludge produced from the 48 wastewater treatment plants in Sweden ends up with too high concentrations of Cd in the soil if 22 kg of P is to be supplied. Animal manure or artificial fertilizer (with a Cd guarantee) would avoid this problem. For the other trace elements on the list, (Pb, Cr, Cu, Ni, Zn) the picture is similar, Figures 8c-g. There is always a higher risk of contamination of the soil when using sludge or ashes from combustion of sludge as a P-source than from animal manure or artificial fertilizer. The only exception is Zn, Figure 8g, where the liquid and solid manure from pigs result in levels above the limit, in the same range as sludge and fly ashes.

CONCLUSIONS

The following conclusions can be made:

- Co-firing of sludge with coal or wood is an important option instead of mono combustion of sludge.
- The substitution of coal or wood with sewage sludge as fuel will always increase the net flow of minerals, P, Hg, Cd, Pb, Cr, Cu, Ni and Zn into the boiler. The largest increase from the level of the base fuel is obtained with the combination of wood and pre-dried sewage sludge.
- Most of the inert material leaving the boiler is fly ash. As an average, 87 % of the total amount of fly ash consisted of secondary cyclone ash. If phosphorous is to be recovered from the ash, then the secondary cyclone ash would be the most suitable one. Bottom ash is less suitable because of low concentration of phosphorous and the bag filter ash may be diluted by calcium if calcium hydroxide injection is employed.
- Sewage sludge and fly ash after combustion of sludge contain similar levels of phosphorous as other P-sources for agricultural use, but the levels of trace elements in relation to phosphorous (Hg, Cd, Pb, Cr, Cu) are much higher in sewage sludge than in animal manure and artificial fertilizer.
- Agricultural utilisation of sewage sludge or fly ash after combustion with the purpose of supplying phosphorous leads in many cases to too high levels of trace elements in the soil (on a yearly basis) than acceptable according to existing limits in Sweden. Agricultural utilisation of sewage sludge or fly ash from combustion as a source of phosphorous is only justified after some removal of the trace elements.
    - An alternative to removal of trace elements is to use sewage sludge or fly ash from combustion as a source for production of a pure phosphorous fraction with similar trace element concentrations as in artificial fertilizers.

ACKNOWLEDGMENTS

This work was performed with financial support from VärmeForsk Service AB, the Swedish Energy Administration (STEM) and VA Forsk. The practical performance of the tests were carried out with heavy support from the operating staff of Akademiska Hus AB and researcher belonging to the department of energy conversion and is gratefully acknowledged.

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TABLES

TABLE 1. Fuel analysis.

	Coal Series 1	Wood Series 1	Sludge Series 1	Coal Series 2	Wood Series 2	Sludge Series 2
Proximate analysis						
Water (wt-%, raw)	9.2±0.8	9.3±0.23	19.0±5.4	9.0±0.2	8.1±0.2	73.0±0.4
Ash (wt-%, dry)	17.3±2.1	0.8±0.2	37.9±1.0	17.5±1.0	0.4±0.1	46.0±1.3
Combustibles (wt-%, dry)	82.8±2.1	99.2±0.2	62.1±1.0	82.5±1.0	99.6±0.1	54.0±1.3
Volatiles (wt-%, daf)	35.0±0.1	81.2±0.4	90.6±0.7	32.7±0.1	81.7±0.3	90.3±3.1
Ultimate analysis (wt-%, daf)						
C	82.5	50.5	53.2	84.9	50.2	52.1
H	5.0	6.0	7.1	5.0	6.1	7.1
O	9.9	43.4	30.6	7.7	43.6	33.2
S	0.86	0.02	1.95	0.73	0.01	1.60
N	1.70	0.14	7.11	1.57	0.12	6.05
Cl	0.07	0.01	0.05	0.08	0.002	0.09
Lower heating value (MJ/kg)						
Hu, daf	32.49	18.91	20.92	33.35	18.80	19.88
Hu, raw	24.03±0.9	17.00±0.05	9.76±0.9	24.65±0.4	17.20±0.03	2.59±0.1
Ash analysis (g/kg dry ash)						
K	3.2±0.15	54±13	4.3±0.43	11±0.22	100±6.2	8.6±0.30
Na	0.80±0.19	11±3.3	1.4±0.13	1.9±0.22	6.2±2.6	1.8±0.26
Al	15±1.7	22±3.7	46±3.7	84.±2.0	5.1±2.0	67±0.86
Si	310±25	94±19	125±6.8	290±4.0	72±8.8	200±10
Fe	43±7.2	74±37	180±12	47±1.4	15±3.7	110±11
Ca	29±6.4	160±25	64±5.0	30±1.9	230±12.8	43±2.4
Mg	14±2.2	24±3.9	10±0.85	18±0.28	36±16	10±0.21
P	5.3±4.0	41±17	91±7.6	1.0±0.61	13±1.0	61±8.2
Ti	1.9±0.43	0.38±0.24	1.3±0.16	0.69±0.021	0.52±0.45	1.7±0.30

daf= dry and ash free, raw=as received

TABLE 2. Operating conditions

	Coal/Sludge 1 Series 1	Wood/Sludge 1 Series 1	Coal/Sludge 2 Series 2	Wood/Sludge 2 Series 2
load, MW_{th}	5.9±0.2	5.8±0.1	6.0±0.1	5.7±0.2
bed temp., °C (bottom)	841±0.04	841±0.6	843±2	843±1
bed temp., °C (top)	855±0.6	856±3	860±1	852±6
exit temp. of after burning chamber, °C	772±5	793±7	783±10	823±14
total riser pressure drop, kPa	6.8±0.3	6.8±0.4	6.5±0.03	6.2±0.1
Calcium addition molar ratio Ca/S	2.3±0.1	1.9±0.1 (0) (1)	3.0±0.2	3.0±1.2 (0) (1)
Ca/S with Ca in fuel included	3.2±0.4	2.9±0.8	3.9±0.1	5.2±1.4
excess air ratio	1.23±0.01	1.24±0.001	1.22±0.001	1.22±0.01
combustor air ratio	1.05±0.01	1.03±0.003	1.03±0.002	1.05±0.01
superficial flue gas velocity at top of riser U_{top}, m/s	5.2±0.5	4.5±0.3	4.8±0.1	4.5±0.1

(1) without sludge

TABLE 3. Fuel analysis. Trace elements and main inorganic components calculated on dry fuel.

	Coal Series 1	Wood Series 1	Sludge 1 Series 1	Coal Series 2	Wood Series 2	Sludge 2 Series 2	Sludge 1 ref. 4	Sludge 2 ref. 4	Sludge* average	Sludge** average	Limit***
Trace elements (mg/kg dry fuel)											
Hg	0.06±0.02	0.03±0	0.72±0.05	0.06±0.006	0.01±0.01	1.1±0.2	1.13	1.31	1.1	1.2	2.5
Cd	0.11±0.01	0.16±0.03	0.93±0.03	0.1±0	0.17±0	1.5±0.2	1.10	1.57	1.2	1.4	2
Pb	21±3	5±0	30±0.79	21±0	1.0±0	50±2	28	52	33	42	100
Cr	13±3	5±0	110±11	9.2±3	0.46±0.08	43±3	83	44	33	39	100
Cu	35±9	5.8±2	340±18	28±0.7	2.4±0.14	500±60	329	506	390	430	600
Mn	120±18	140±6	220±11	170±10	160±7	450±40	161	405	280	280	n.l.
Co	5.9±1.0	3±0	7.4±0.6	3.3±0.07	0.2±0	9.7±1	5.7	9.3	6.2	8.3	n.l.
Ni	19±2	2±0	26±1.5	1.5±2	0.27±0.04	23±0.8	22	22	20	22	50
As	1.4±0.4	0.3±0	3.8±0.5	1.3±0.2	0.75±0.4	6.2±0.3	2.7	4.8	4.7	5.5	n.l.
Sb	0.40±0.1	0.3±0	1.4±0.3	1±0	1.0±0	4.8±0.4	2.6	3.4	2.4	3.4	n.l.
V	36±5	0.25±0.3	28±3	9.1±0.4	0.45±0.2	29±2	13	22	18	18	n.l.
Tl	0.09±0.01	0.02±0	0.08±0.01	0.05±0	0.03±0	0.13±0.01	0.12	0.26	0.15	0.16	n.l.
Zn	n.a.	n.a.	n.a.	37±2	15.5±0.7	730±40	788	760	550	680	800
Se	n.a.	n.a.	n.a.	1.4±0.6	0.085±0.08	2.0±0.1	1.81	1.39	1.3	1.6	n.l.
Main elements g/kg dry fuel											
K	0.52±0.1	0.45±0.01	1.7±0.2	2.0±0.06	0.4±0.03	4.1±0.18	2.8	6.2	n.r	n.r	n.l
Na	0.13±0.01	0.09±0.02	0.57±0.04	0.34±0.23	0.24±0.01	0.87±0.11	2.0	2.8	n.r	n.r	n.l
Al	2.5±0.6	0.19±0.06	18±1.4	15±0.35	0.02±0.01	32±0.61	24	38	n.r	n.r	n.l
Si	51±10	0.82±0.31	49±4	52±3.2	0.27±0.05	97±6.1	35	65	n.r	n.r	n.l
Fe	7.1±2	0.66±0.41	70±4	8.4±0.65	0.058±0.02	55±4.9	47	87	n.r	n.r	n.l
Ca	4.6±1.0	1.3±0.10	26±2	5.3±0.08	0.91±0.09	21±0.92	30	21	n.r	n.r	n.l
Mg	2.3±0.3	0.2±0.02	4.0±0.3	3.2±0.10	0.14±0.06	4.9±0.10	4.7	4.4	n.r	n.r	n.l
P	0.9±0.8	0.36±0.19	36±3	0.19±0.10	0.05±0.01	29±3.7	36	30	27	33	n.l
Ti	0.3±0	0.003±0.003	0.52±0.06	0.12±0.002	0.002±0.002	0.82±0.14	n.r.	n.r.	1.8	1.8	n.l

* Average of analysis of sludge from 48 different waste water treatment plants in Sweden (ref. 6).

** Weighted average of trace elements in sludge with respect to amount of sludge produced at each waste water treatment plant (average of sludge produced in Sweden, ref. 1).

***Limit for agricultural use of sewage sludge as phosphorous fertilizer in Sweden (ref. 6).

n.l.=no limit

n.a.=not analysed

n.r.=not reported

FIGURES

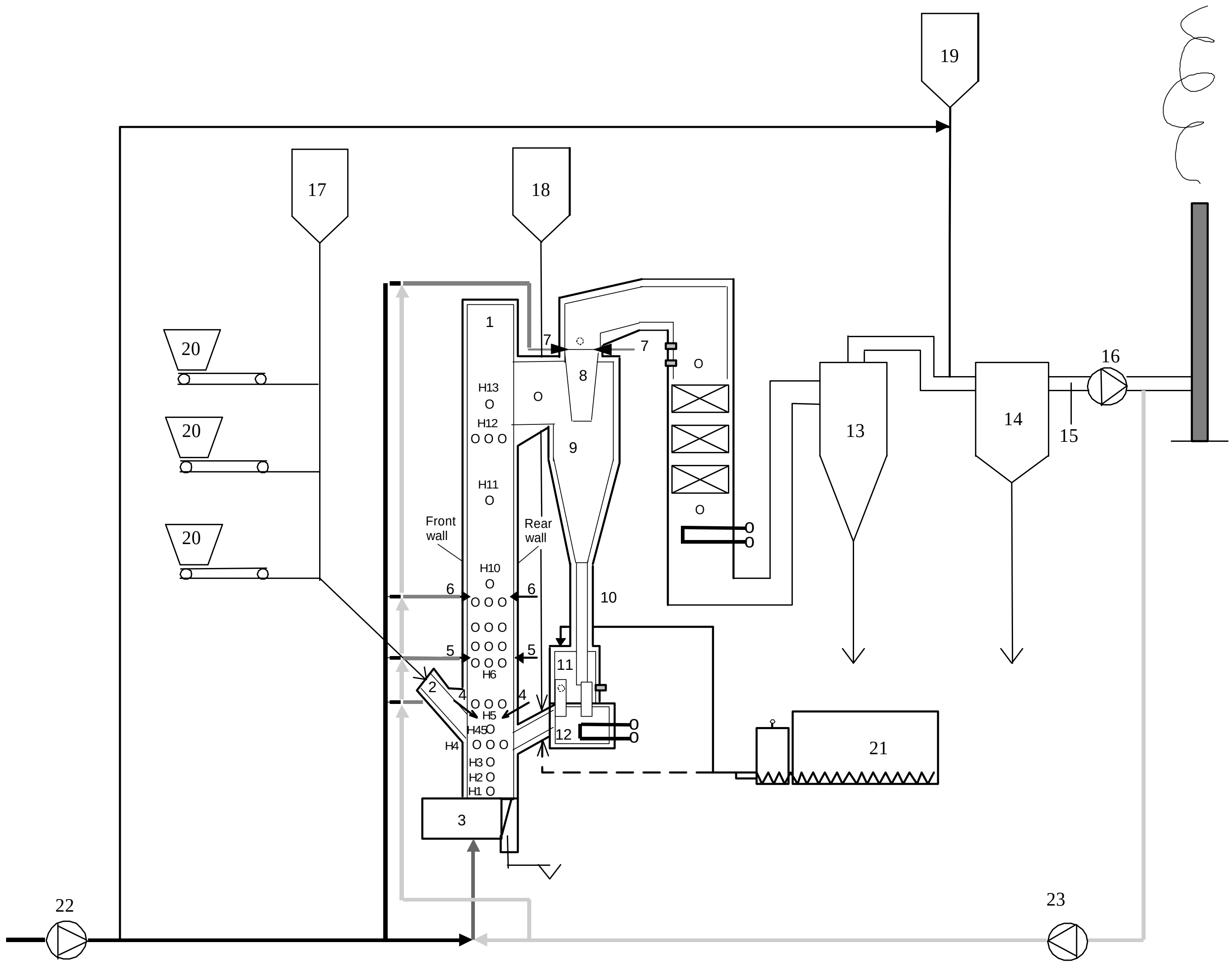


Figure 1. The 12-MW$_{th}$ CFB boiler at Chalmers University of Technology. (1) combustion chamber, (2) cyclone, (3) particle return leg, (4) particle seal, (5) heat exchanger, (6) windbox, (7) fuel feed chute, (8) primary air supply, (9) secondary air to 2.1meter, (10) secondary air to 3.7 meter, (11) secondary air to 5.4 meter, (12) secondary air addition after cyclone, (13) exit duct cyclone.

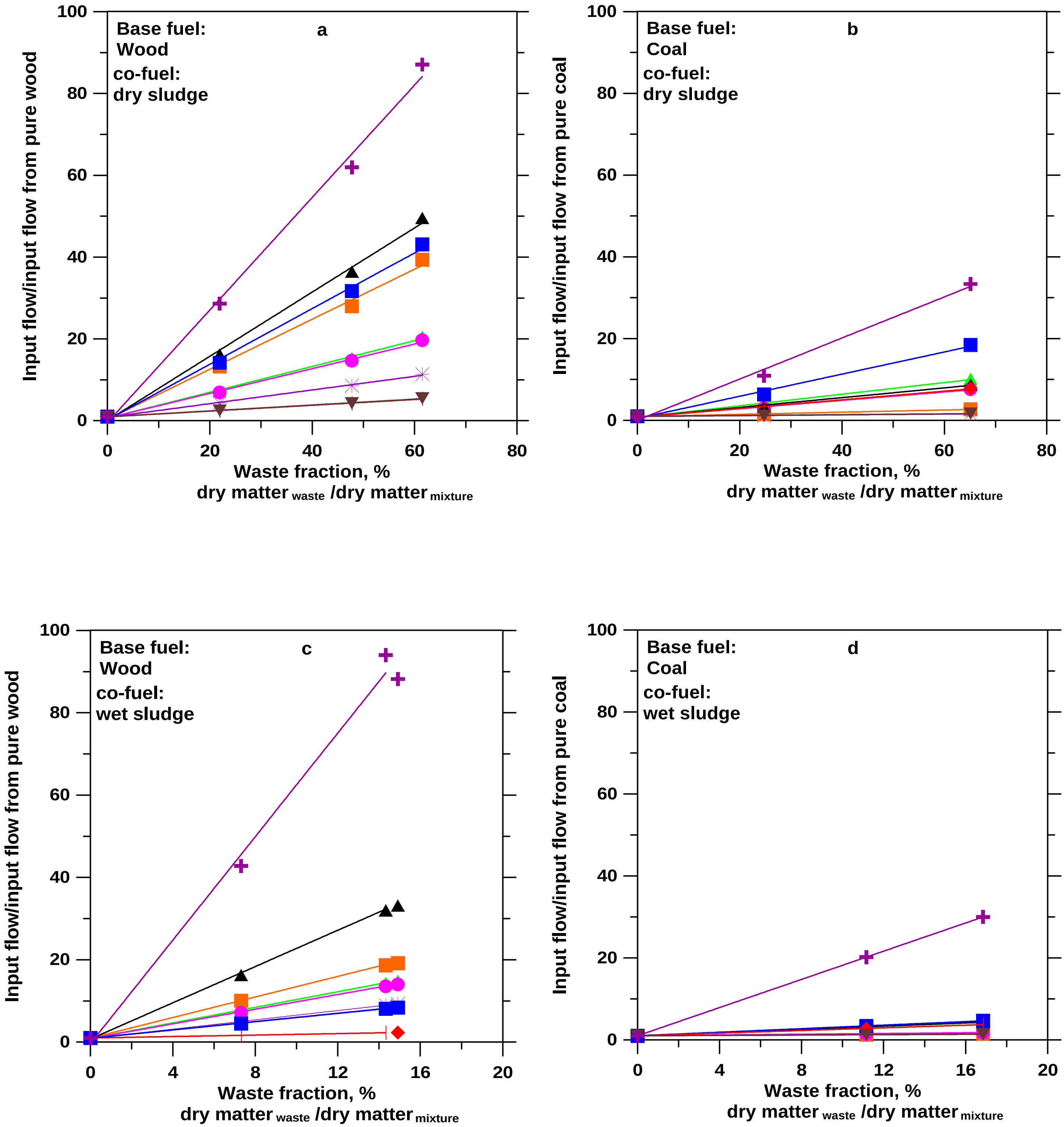


Figure 2 a-d. Relative increase of the input flow to the boiler of ash components as function of sludge addition. First test series with pre-dried sludge as co-fuel, Figure a,b. Second test series with mechanical dewatered sludge as co-fuel, Figure c,d. Wood as base fuel in Figure a,c. Coal as base fuel in Figure b,d.
Ash Hg Cd Pb Cr Cu Ni Zn P

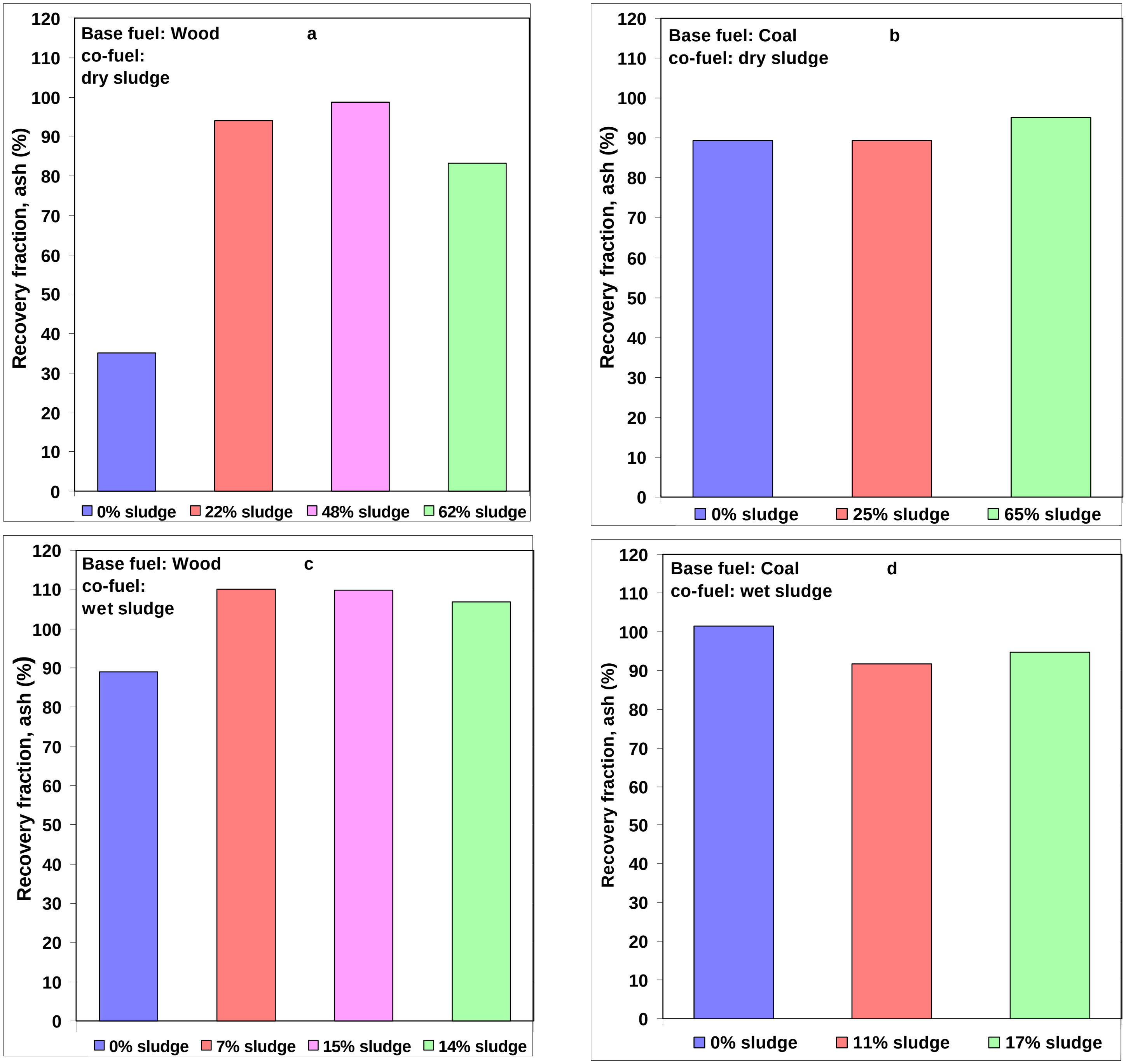


Figure 3 a-d. Ash recovery fraction (out/in*100). First test series with pre-dried sludge as co-fuel, Figure a,b. Second test series with mechanical dewatered sludge as co-fuel, Figure c,d. Wood as base fuel in Figure a,c. Coal as base fuel in Figure b,d.

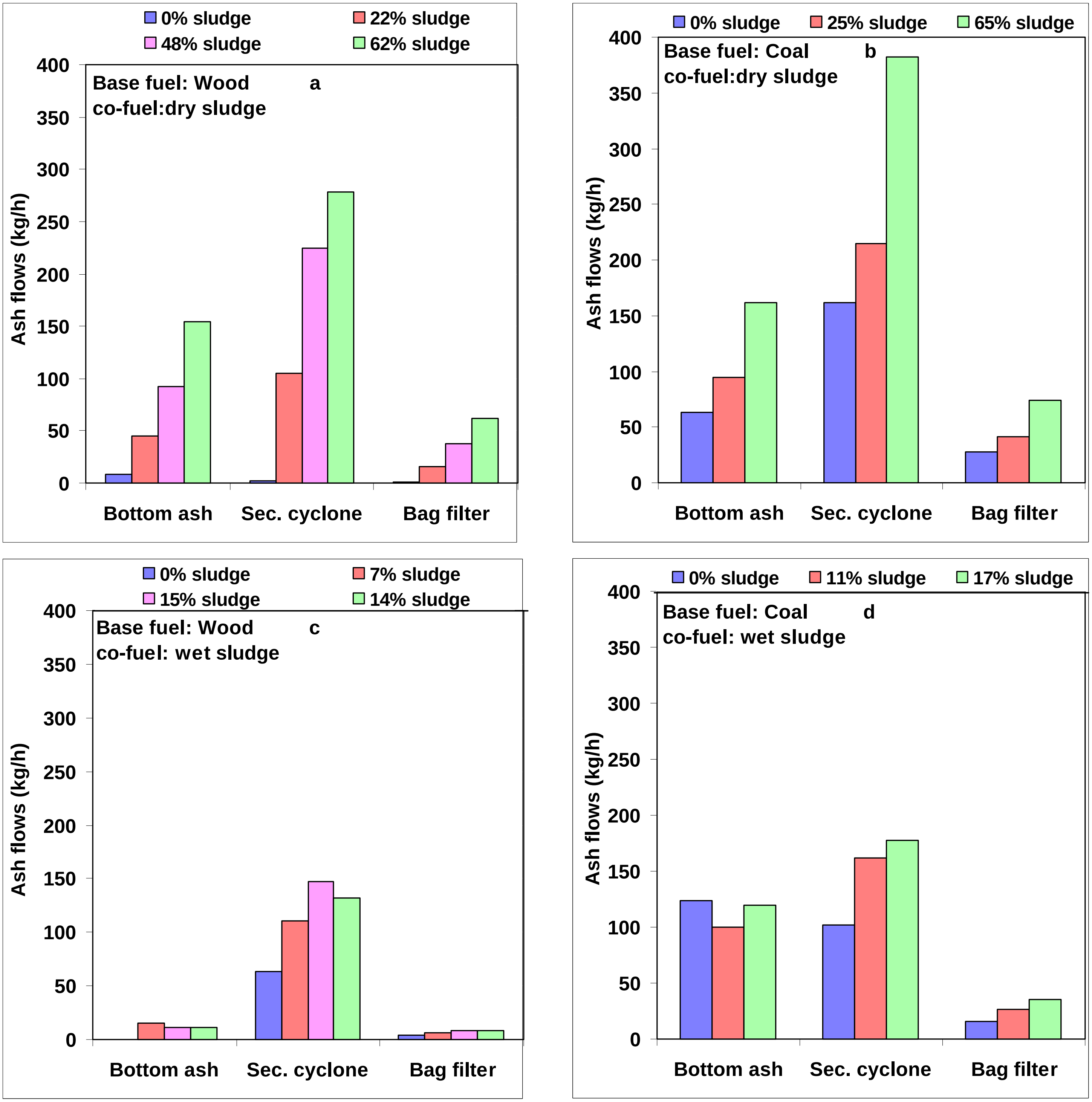


Figure 4 a-d. The flows of solids through the boiler. First test series with pre-dried sludge as co-fuel, Figure a,b. Second test series with mechanical dewatered sludge as co-fuel, Figure c,d. Wood as base fuel in Figure a,c. Coal as base fuel in Figure b,d.

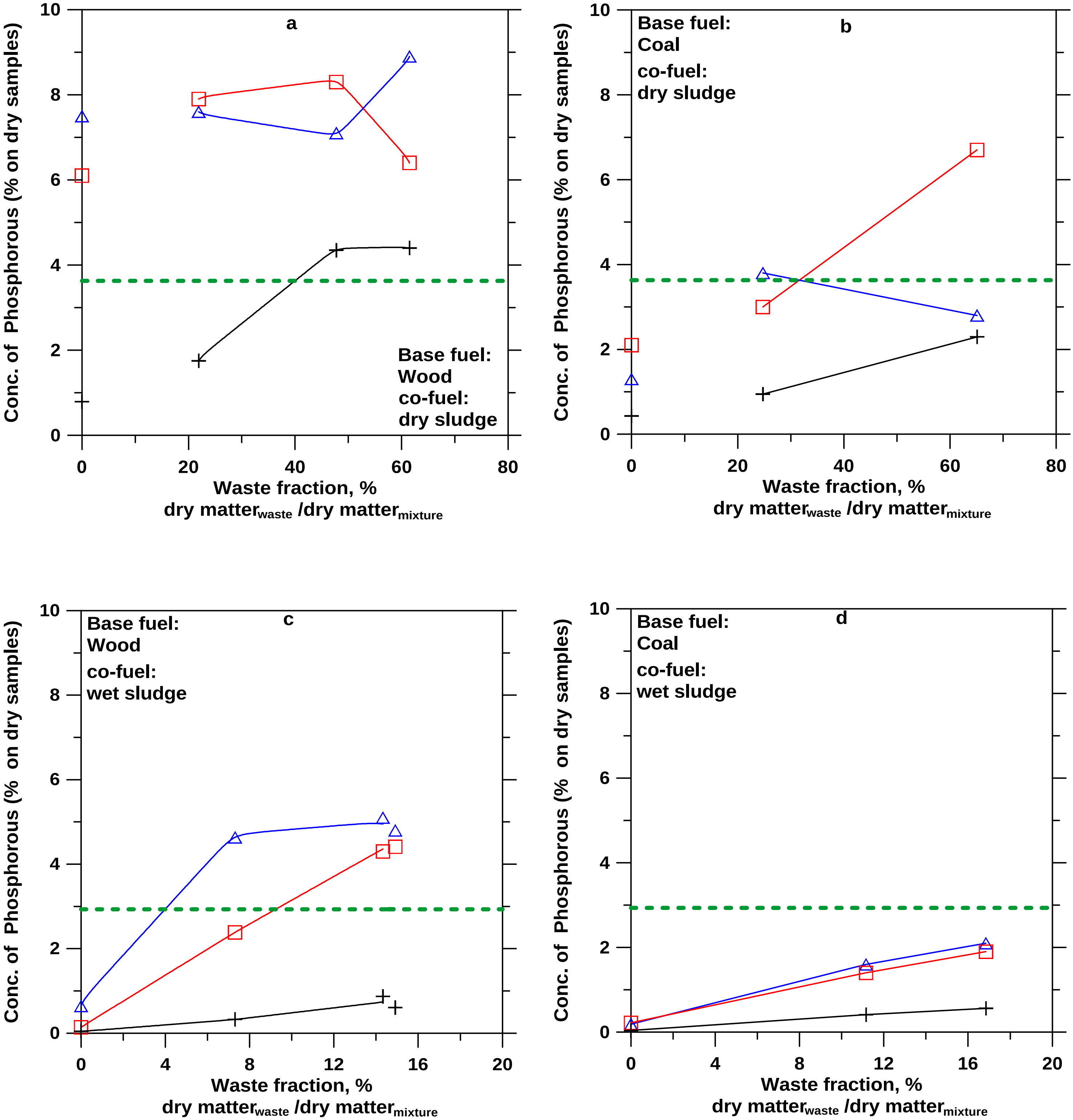


Figure 5 a-d. Comparison of the concentration of phosphorous in municipal sewage sludge and ash samples taken from the bag filter, secondary cyclone and bottom ash. First test series with pre-dried sludge as co-fuel, Figure a,b. Second test series with mechanical dewatered sludge as co-fuel, Figure c,d. Wood as base fuel in Figure a,c. Coal as base fuel in Figure b,d.

△ **Bag filter ash** □ **Sec. cyclone ash** + **Bottom ash** - - - - **Sewage Sludge**

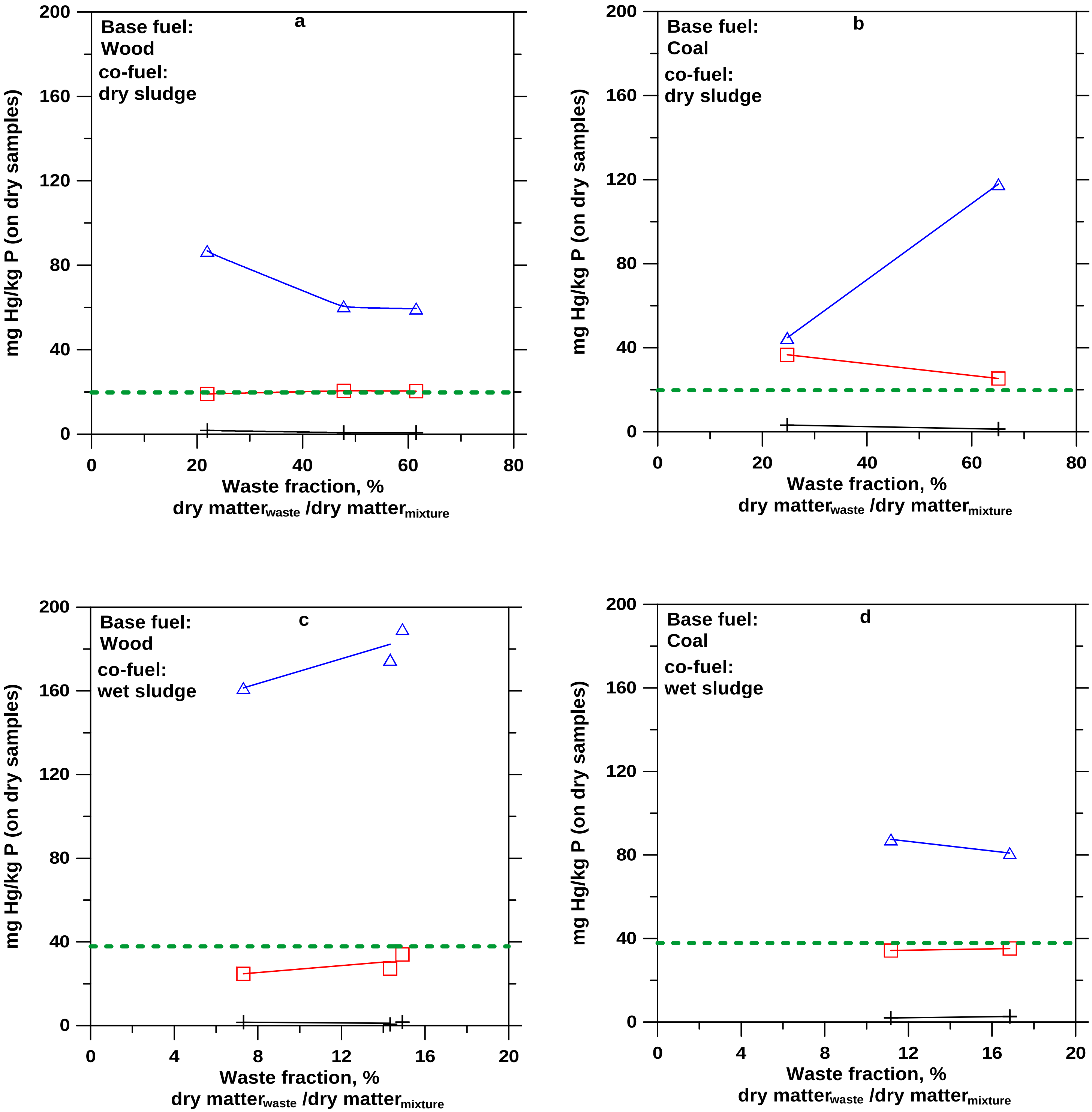


Figure 6 a-d. Comparison of the ratio of Hg/P in municipal sewage sludge and ash samples taken from the bag filter, secondary cyclone and bottom ash. First test series with pre-dried sludge as co-fuel, Figure a,b. Second test series with mechanical dewatered sludge as co-fuel, Figure c,d. Wood as base fuel in Figure a,c. Coal as base fuel in Figure b,d.

△ Bag filter ash □ Sec. cyclone ash + Bottom ash - - - - Sewage Sludge

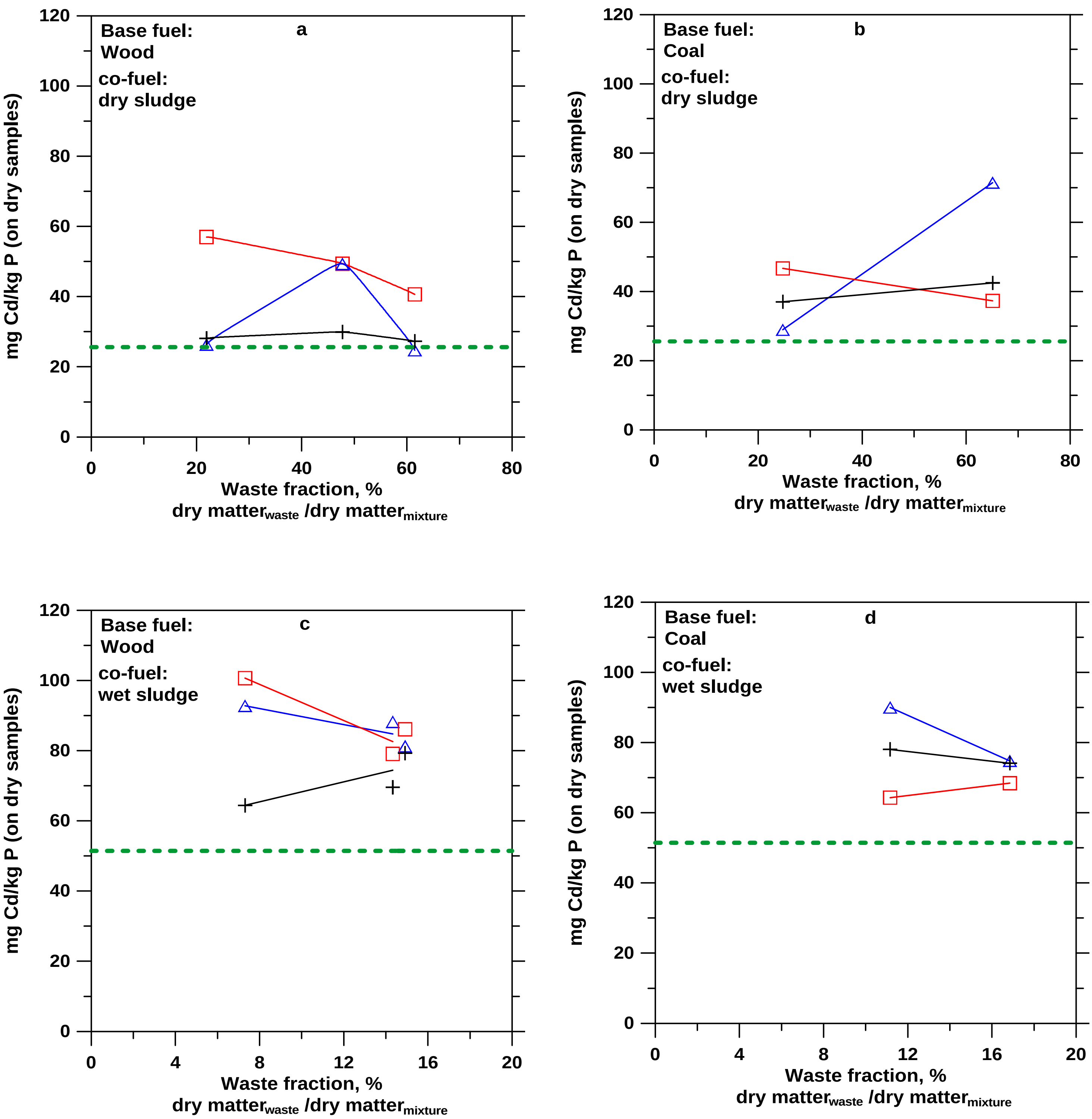
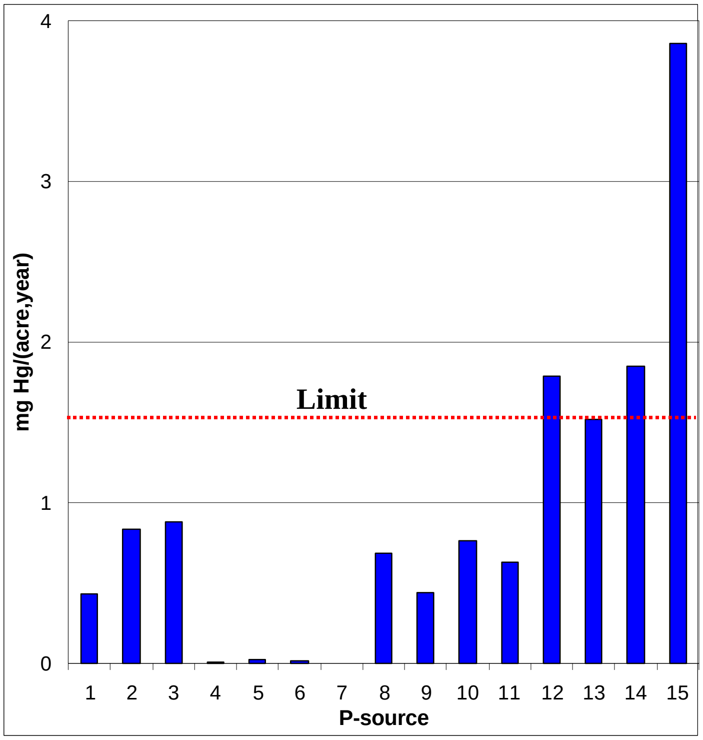


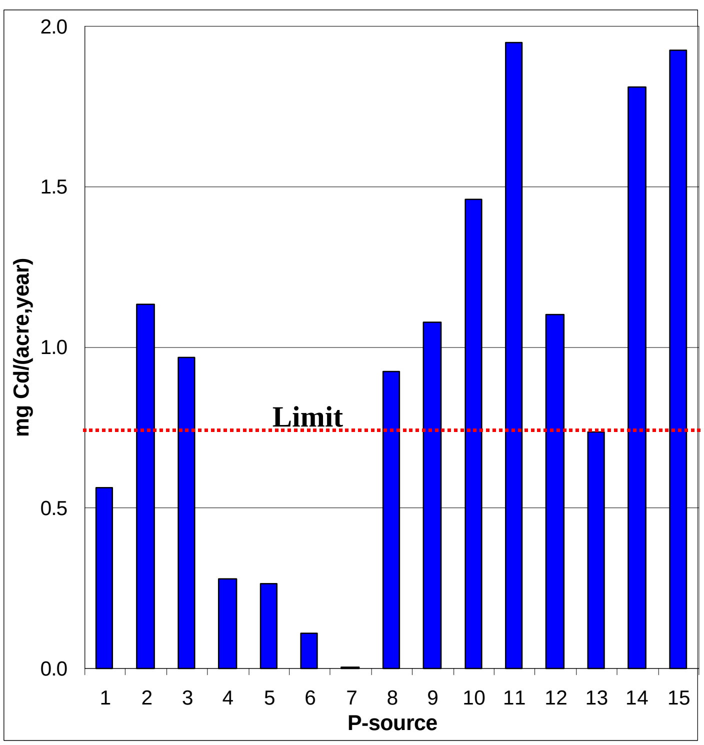
Figure 7 a-d. Comparison of the ratio of Cd/P in municipal sewage sludge and ash samples taken from the bag filter, secondary cyclone and bottom ash. First test series with pre-dried sludge as co-fuel, Figure a,b. Second test series with mechanical dewatered sludge as co-fuel, Figure c,d. Wood as base fuel in Figure a,c. Coal as base fuel in Figure b,d.

△ **Bag filter ash** □ **Sec. cyclone ash** + **Bottom ash** - - - **Sewage Sludge**



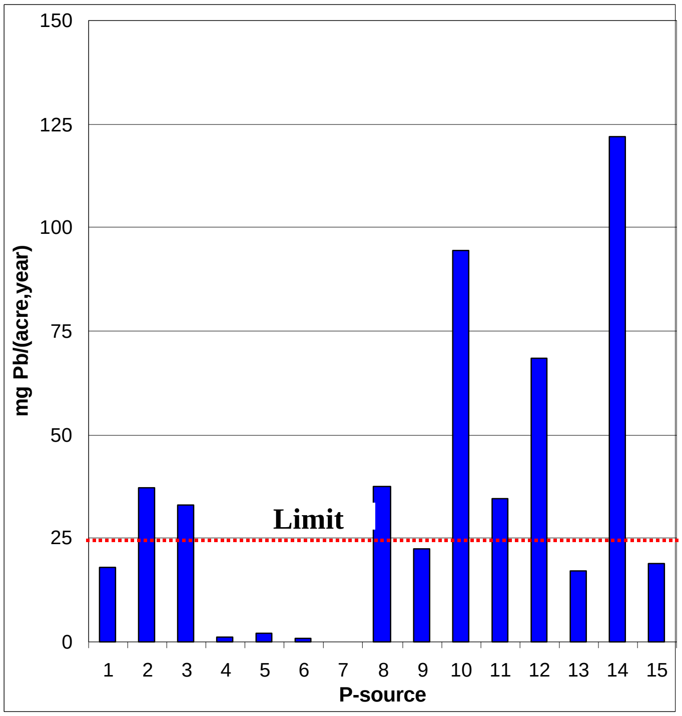
1 sewage sludge series 1
2 sewage sludge series 2
3 sewage sludge average
4 liquid manure from pigs
5 solid manure from pigs
6 liquid manure from cows
7 artificial fertilizer
8 secondary cyclone ash, coal, dry sludge
9 secondary cyclone ash, wood, dry sludge
10 secondary cyclone ash , coal, wet sludge
11 secondary cyclone ash, wood, wet sludge
12 bag filter ash, coal, dry sludge
13 bag filter ash, wood, dry sludge
14 bag filter ash, coal, wet sludge
15 bag filter ash, wood, wet sludge

Figure 8a. Contamination of mercury when 22 kg phosphorous is supplied to one acre during one year. Comparison of various P-sources. 1-3 sewage sludge, 4-6 animal manure, 7 artificial fertilizer, 10-15 fly ash.



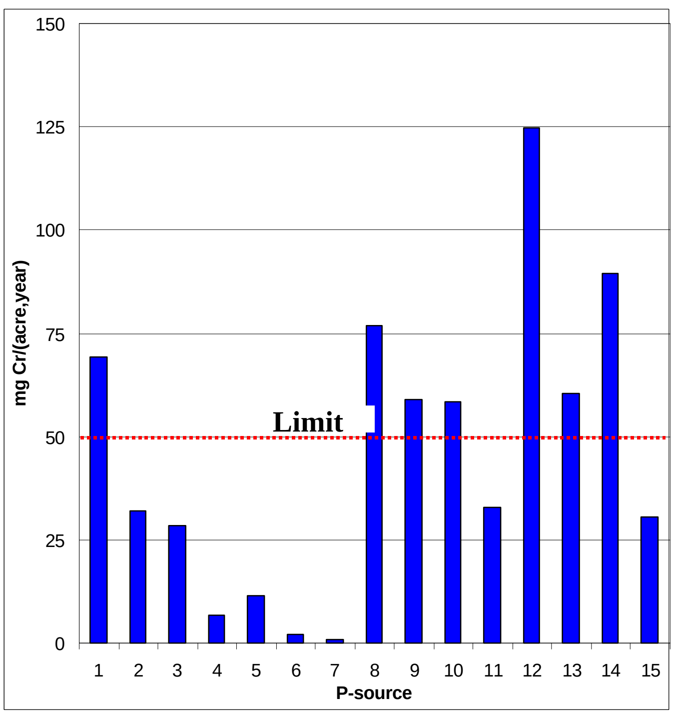
1 sewage sludge series 1
2 sewage sludge series 2
3 sewage sludge average
4 liquid manure from pigs
5 solid manure from pigs
6 liquid manure from cows
7 artificial fertilizer
8 secondary cyclone ash, coal, dry sludge
9 secondary cyclone ash, wood, dry sludge
10 secondary cyclone ash , coal, wet sludge
11 secondary cyclone ash, wood, wet sludge
12 bag filter ash, coal, dry sludge
13 bag filter ash, wood, dry sludge
14 bag filter ash, coal, wet sludge
15 bag filter ash, wood, wet sludge

Figure 8b. Contamination of cadmium when 22 kg phosphorous is supplied to one acre during one year. Comparison of various P-sources. 1-3 sewage sludge, 4-6 animal manure, 7 artificial fertilizer, 10-15 fly ash.



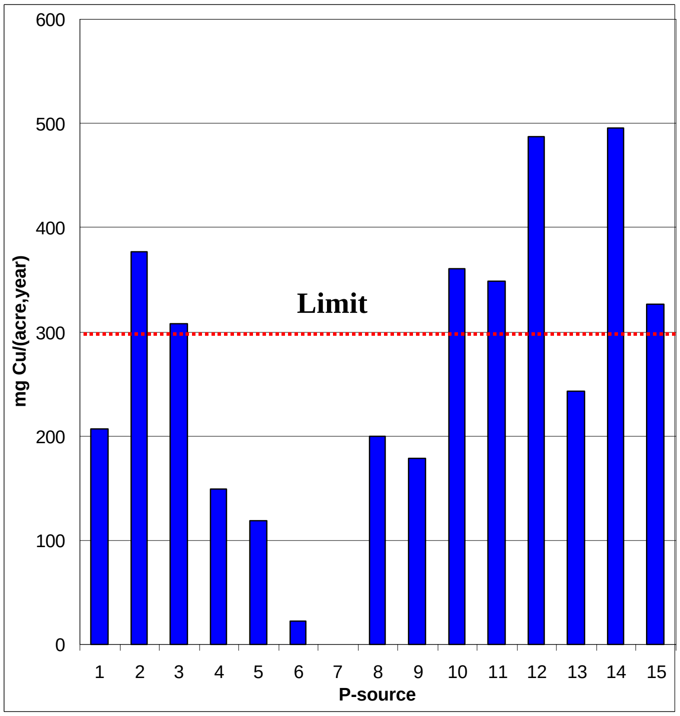
1 sewage sludge series 1
2 sewage sludge series 2
3 sewage sludge average
4 liquid manure from pigs
5 solid manure from pigs
6 liquid manure from cows
7 artificial fertilizer
8 secondary cyclone ash, coal, dry sludge
9 secondary cyclone ash, wood, dry sludge
10 secondary cyclone ash , coal, wet sludge
11 secondary cyclone ash, wood, wet sludge
12 bag filter ash, coal, dry sludge
13 bag filter ash, wood, dry sludge
14 bag filter ash, coal, wet sludge
15 bag filter ash, wood, wet sludge

Figure 8c. Contamination of lead when 22 kg phosphorous is supplied to one acre during one year. Comparison of various P-sources. 1-3 sewage sludge, 4-6 animal manure, 7 artificial fertilizer, 10-15 fly ash.



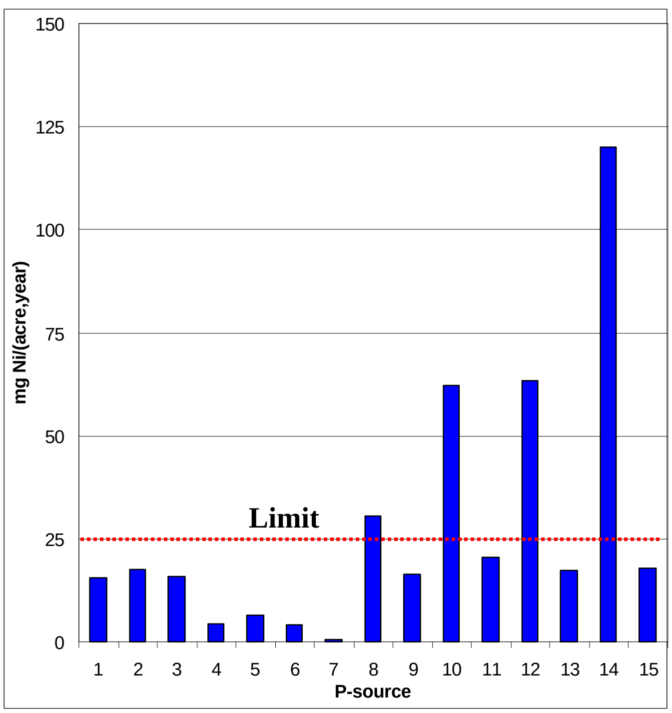
1 sewage sludge series 1
2 sewage sludge series 2
3 sewage sludge average
4 liquid manure from pigs
5 solid manure from pigs
6 liquid manure from cows
7 artificial fertilizer
8 secondary cyclone ash, coal, dry sludge
9 secondary cyclone ash, wood, dry sludge
10 secondary cyclone ash , coal, wet sludge
11 secondary cyclone ash, wood, wet sludge
12 bag filter ash, coal, dry sludge
13 bag filter ash, wood, dry sludge
14 bag filter ash, coal, wet sludge
15 bag filter ash, wood, wet sludge

Figure 8d. Contamination of chromium when 22 kg phosphorous is supplied to one acre during one year. Comparison of various P-sources. 1-3 sewage sludge, 4-6 animal manure, 7 artificial fertilizer, 10-15 fly ash.



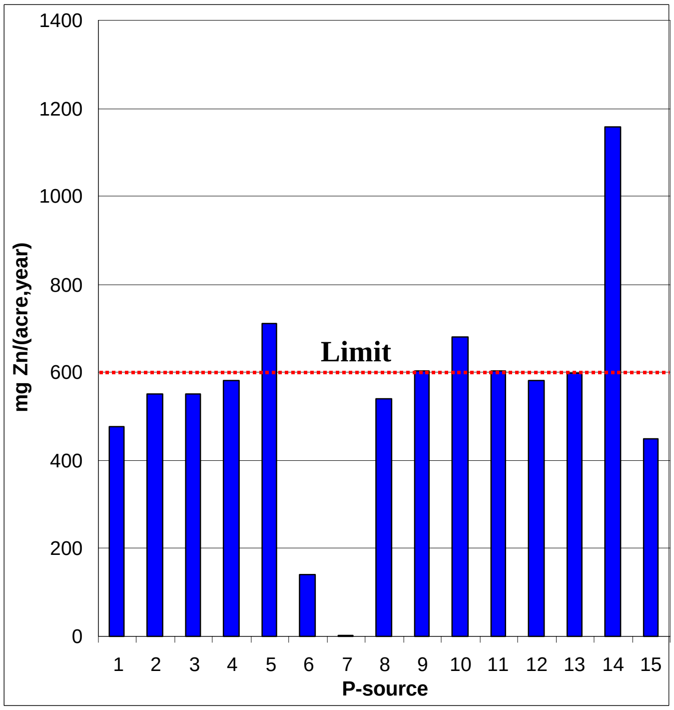
1 sewage sludge series 1
2 sewage sludge series 2
3 sewage sludge average
4 liquid manure from pigs
5 solid manure from pigs
6 liquid manure from cows
7 artificial fertilizer
8 secondary cyclone ash, coal, dry sludge
9 secondary cyclone ash, wood, dry sludge
10 secondary cyclone ash , coal, wet sludge
11 secondary cyclone ash, wood, wet sludge
12 bag filter ash, coal, dry sludge
13 bag filter ash, wood, dry sludge
14 bag filter ash, coal, wet sludge
15 bag filter ash, wood, wet sludge

Figure 8e. Contamination of copper when 22 kg phosphorous is supplied to one acre during one year. Comparison of various P-sources. 1-3 sewage sludge, 4-6 animal manure, 7 artificial fertilizer, 10-15 fly ash.



1 sewage sludge series 1
2 sewage sludge series 2
3 sewage sludge average
4 liquid manure from pigs
5 solid manure from pigs
6 liquid manure from cows
7 artificial fertilizer
8 secondary cyclone ash, coal, dry sludge
9 secondary cyclone ash, wood, dry sludge
10 secondary cyclone ash , coal, wet sludge
11 secondary cyclone ash, wood, wet sludge
12 bag filter ash, coal, dry sludge
13 bag filter ash, wood, dry sludge
14 bag filter ash, coal, wet sludge
15 bag filter ash, wood, wet sludge

Figure 8f. Contamination of nickel when 22 kg phosphorous is supplied to one acre during one year. Comparison of various P-sources. 1-3 sewage sludge, 4-6 animal manure, 7 artificial fertilizer, 10-15 fly ash.



1 sewage sludge series 1
2 sewage sludge series 2
3 sewage sludge average
4 liquid manure from pigs
5 solid manure from pigs
6 liquid manure from cows
7 artificial fertilizer
8 secondary cyclone ash, coal, dry sludge
9 secondary cyclone ash, wood, dry sludge
10 secondary cyclone ash , coal, wet sludge
11 secondary cyclone ash, wood, wet sludge
12 bag filter ash, coal, dry sludge
13 bag filter ash, wood, dry sludge
14 bag filter ash, coal, wet sludge
15 bag filter ash, wood, wet sludge

Figure 8g. Contamination of zinc when 22 kg phosphorous is supplied to one acre during one year. Comparison of various P-sources. 1-3 sewage sludge, 4-6 animal manure, 7 artificial fertilizer, 10-15 fly ash.

APPENDIX 1

TABLE A1:a. Trace elements and inorganic components calculated on dry ash. Bottom ash samples from first test series.

Base fuel	coal**	coal	coal	wood**	wood	wood	wood
Co-fuel	none	dry sludge	dry sludge	none	dry sludge	dry sludge	dry sludge
Waste fraction*	0	25	65	0	22	48	62
Ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash
Trace elements (mg/kg dry ash)							
Hg	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Cd	0.35	0.35	0.98	0.59	0.49	1.3	1.2
Pb	27	25	32	5.0	12	29	28
Cr	51	59	158	41	66	105	115
Cu	60	125	296	139	245	415	395
Mn	470	485	481	1350	1048	605	600
Co	17	13	10	6.7	7.9	7.8	8.9
Ni	51	46	40	28	30	32	33
As	9.0	7.6	9.2	6.2	8.2	8.2	8.2
Sb	0.7	0.8	1.9	0.7	1.4	2.5	2.4
V	155	110	100	49	67	54	69
Tl	0.16	0.17	0.15	0.004	0.03	0.07	0.08
Zn	215	360	870	350	525	1250	1250
Main elements g/kg dry ash							
K	10	9.4	9.5	8.3	7.8	7.5	7.8
Na	1.7	1.9	3.1	2.3	2.1	3.4	3.4
Al	59	55	54	19	25	32	36
Si	181	176	148	316	262	160	120
Fe	27	35	58	19	39	78	88
Ca	157	173	170	99	101	158	177
Mg	7.5	8.1	8.0	5.1	5.9	7.7	8
P	4.3	9.5	23	7.9	18	44	44
Ti	3.2	3.2	4.0	1.9	2.6	4.9	4.8
Combustibles wt-% on dry ash	3.1	0.5	1.1	0.10	0.10	0.13	0.10

*dry matter(waste)/dry matter (mixture),%

** Test performed to close a test with sludge supply

TABLE A1:b. Trace elements and inorganic components calculated on dry ash. Bottom ash samples from second test series.

Base fuel	coal	coal	coal	wood**	wood	wood	wood
Co-fuel	none	wet sludge	wet sludge	none	wet sludge	wet sludge	wet sludge
Waste fraction*	0	11	17	0	7	15	14
Ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash
Trace elements (mg/kg dry ash)							
Hg	0.02	0.01	0.02	0.01	0.01	0.01	0.01
Cd	0.37	0.32	0.42	0.08	0.21	0.48	0.61
Pb	26	18	22	5.5	5.0	11	14
Cr	37	25	26	20	13	21	20
Cu	37	83	114	15	50	93	143
Mn	572	442	467	510	868	605	873
Co	19	13	12	6.7	2.1	4.9	4.0
Ni	46	33	31	18	11	30	14
As	7.2	5.8	6.6	1.7	1.8	2.0	3.2
Sb	4.9	4.4	4.5	2.0	2.3	2.1	2.6
V	74	50	51	25	6.9	16	12
Tl	0.09	0.11	0.13	0.02	0.03	0.05	0.05
Zn	94	131	173	68	97	196	229
Se	0.46	0.35	0.39	0.12	0.07	0.09	0.18
Main elements g/kg dry ash							
K	10	12	12	15	6.0	9.6	7.8
Na	1.3	2.7	2.3	1.9	1.0	1.7	2.3
Al	48	62	61	76	6.9	38	14
Si	300	180	203	259	402	374	385
Fe	18	29	31	24	9.4	20	20
Ca	89	171	153	96.7	53	30	69
Mg	5.5	8.4	8.1	8.4	3.0	3.8	4.3
P	0.4	4.1	5.6	0.4	3.3	6.1	8.7
Ti	2.4	3.1	2.9	3.8	0.5	2.0	0.8
Combustibles wt-% on dry ash	2.0	0.5	3.0	0.25	0.00	0.20	0.00

*dry matter(waste)/dry matter (mixture),%

** Test performed to close a test with pure coal and lime supply

TABLE A1:c. Trace elements and inorganic components calculated on dry ash. Secondary cyclone ash samples from first test series.

Base fuel **Co-fuel** **Waste fraction*** **Ash**	coal** none 0 sec. cyclone ash	coal dry sludge 25 sec. cyclone ash	coal dry sludge 65 sec. cyclone ash	wood** none 0 sec. cyclone ash	wood dry sludge 22 sec. cyclone ash	wood dry sludge 48 sec. cyclone ash	wood dry sludge 62 sec. cyclone ash
Trace elements (mg/kg dry ash)							
Hg	1.1	1.1	1.7	0.89	1.5	1.7	1.3
Cd	1.4	1.4	2.5	5.7	4.5	4.1	2.6
Pb	80	70	72	76	79	75	73
Cr	110	120	200	160	200	210	190
Cu	300	290	570	500	600	690	540
Mn	450	490	550	2500	1200	1100	680
Co	17	16	18	15	15	15	16
Ni	60	55	63	55	55	58	54
As	7.1	5.7	5.7	9.5	5.1	6.4	5.6
Sb	1.1	0.8	2.8	2.1	3.1	3.6	2.3
V	150	130	99	110	74	83	95
Tl	0.86	0.66	0.45	0.80	0.54	0.46	0.47
Zn	580	760	1600	2300	2200	2300	1700
Main elements g/kg dry ash							
K	10	9.0	10	25	14	13	12
Na	2.7	2.8	4.3	7.5	5	5.5	4.6
Al	63	63	63	49	54	56	57
Si	90	85	86	107	84	88	87
Fe	62	79	149	128	170	164	143
Ca	65	73	78	115	95	93	80
Mg	10	10	11	12	12	12	11
P	21	30	67	61	79	83	64
Ti	4.4	5.0	8.0	6.8	8.3	9.0	7.4
Combustibles wt-% on dry ash	15.9	17.9	9.4	2.9	2.2	1.9	4.0

*dry matter(waste)/dry matter (mixture),%

** Test performed to close a test with sludge supply

TABLE A1:d. Trace elements and inorganic components calculated on dry ash. Secondary cyclone ash samples from second test series.

Base fuel	coal	coal	coal	wood**	wood	wood	wood
Co-fuel	none	wet sludge	wet sludge	none	wet sludge	wet sludge	wet sludge
Waste fraction*	0	11	17	0	7	15	14
Ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash
Trace elements (mg/kg dry ash)							
Hg	0.21	0.48	0.67	0.01	0.59	1.5	1.17
Cd	0.34	0.90	1.3	0.81	2.4	3.8	3.4
Pb	64	68	71	12	38	66	70
Cr	36	42	44	17	37	54	73
Cu	61	245	291	20	389	591	766
Mn	509	609	632	1130	1370	1480	1560
Co	16	19	19	5.9	9.7	14	17
Ni	38	46	45	17	27	34	39
As	3.7	5.2	6.1	1.7	4.0	5.2	6
Sb	2.5	4.2	4.3	2.0	3.4	5.4	5.4
V	71	77	69	23	23	47	41
Tl	0.26	0.35	0.28	0.09	0.15	0.25	0.28
Zn	91	419	503	73	685	1070	1180
Sn	3.7	3.3	3.3	0.27	1.1	2.8	2.2
Main elements g/kg dry ash							
K	7.8	10	11	8.3	13	14	16
Na	2.1	3.1	3.6	1.2	3.5	5.5	5.5
Al	52	63	64	22	31	58	56
Si	79	98	102	367	302	212	199
Fe	31	48	57	16	51	85	89
Ca	65	70	64	45	61	66	79
Mg	11	11	11	5.0	6.2	8.8	8.9
P	2.2	14	19	1.4	24	44	43
Ti	2.6	3.2	3.1	1.5	2.0	3.2	3.1
Combustibles wt-% on dry ash	49	39	34	3.0	0.6	2.1	0.7

*dry matter(waste)/dry matter (mixture),%

** Test performed to close with pure coal and lime supply

TABLE A1:e. Trace elements and inorganic components calculated on dry ash. Bag house filter ash samples from first test series.

Co-fuel	none	dry sludge	dry sludge	none	dry sludge	dry sludge	dry sludge
Waste fraction*	0	25	65	0	22	48	62
Ash	Bag house filter ash	Bag house filter ash	Bag house filter ash	Bag house filter ash	Bag house filter ash	Bag house filter ash	Bag house filter ash
Trace elements (mg/kg dry ash)							
Hg	1.3	1.7	3.3	4.9	6.6	4.3	5.3
Cd	1.2	1.1	2.0	3.2	2.0	3.5	2.2
Pb	120	120	86	68	55	63	66
Cr	110	160	200	210	220	180	250
Cu	290	530	850	810	910	730	970
Mn	530	550	580	5000	3700	5800	1200
Co	44	38	25	18	17	17	17
Ni	110	110	80	64	60	60	64
As	13	15.0	20.0	14	14	13	21
Sb	0.6	1.3	3.9	4.6	4.2	4.2	5.5
V	360	310	160	130	97	120	100
Tl	0.94	0.88	0.66	2.4	2.0	2.4	0.74
Zn	1900	1000	1900	2100	2000	2100	2300
Main elements g/kg dry ash							
K	15	13.0	8	18	17	22	11
Na	3.3	3.3	3.1	5.5	5	6.2	4.5
Al	101	91	44	53	54	50	57
Si	136	116	98	68	68	67	70
Fe	55	100	63	153	163	142	187
Ca	81	89	218	124	118	130	101
Mg	11	11	8	16	15	17	13
P	13	38	28	75	76	71	89
Ti	6.6	8.0	3.8	8.3	8.7	7.7	10
Combustibles wt-% on dry ash	14.7	10.5	3.8	4.0	4.8	4.3	1.6

*dry matter(waste)/dry matter (mixture),%

** Test perfomed to close a test with sludge supply

TABLE A1:f. Trace elements and inorganic components calculated on dry ash. Bag house filter ash samples from second test series.

Base fuel	coal*	coal	coal	wood**	wood	wood	wood
Co-fuel	none	wet sludge	wet sludge	none	wet sludge	wet sludge	wet sludge
Waste fraction*	0	11	17	0	7	15	14
Ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash
Trace elements (mg/kg dry ash)							
Hg	0.64	1.4	1.7	0.54	7.5	9.1	8.9
Cd	1.3	1.4	1.6	18	4.3	3.9	4.5
Pb	122	102	99	138	37	42	47
Cr	84	71	78	96	68	63	70
Cu	154	387	437	167	717	654	784
Mn	727	728	768	12800	8480	6820	6140
Co	51	46	46	42	17	20	19
Ni	99	100	98	96	35	47	37
As	10	14	17	16	25	35	26
Sb	4.9	7.3	7.7	5.4	5.8	7.8	7.2
V	205	175	180	150	62	87	70
Tl	0.51	0.42	0.35	1.5	0.69	0.40	0.7
Zn	185	506	628	55	889	1010	1050
Sn	7.7	6.5	6.5	8.3	8.1	8.0	8.2
Main elements g/kg dry ash							
K	14	14	13	18	27	21	27
Na	3.1	3.7	4.0	2.0	4.5	4.4	4.8
Al	94	94	92	57	50	62	56
Si	130	132	131	90	91	100	92
Fe	37	58	66	31	89	95	102
Ca	80	97	97	196	176	128	159
Mg	12	12	12	27.2	21	16	18
P	1.9	16	21	6.5	46	48	51
Ti	5.5	5.4	5.3	3.7	2.9	3.3	3.2
Combustibles wt-% on dry ash	24	15	14	12	3.3	5.6	2.6

*dry matter(waste)/dry matter (mixture),%

** Test performed to close a test pure coal and lime supply

APPENDIX 2

TABLE A2:a. Concentration of Hg, Cd, Pb, Cr, Cu, Ni and Zn in relation to the P content (on dry samples) for the bottom ash samples. Test series 1 and 2.

Base fuel	coal	coal	coal	wood	wood	wood	wood
Co-fuel	none	dry sludge	dry sludge	none	dry sludge	dry sludge	dry sludge
Waste fraction*	0	25	65	0	22	48	62
Ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash
Trace elements (mg/kg P)							
Hg	7.0	3.2	1.3	3.8	1.7	0.69	0.68
Cd	81	37	42	75	28	30	27
Pb	6221	2593	1378	633	700	667	625
Cr	11919	6190	6885	5127	3771	2414	2602
Cu	13953	13228	12908	17532	14000	9540	8977
Ni	11919	4815	1754	6962	1714	736	750
Zn	50000	38095	28105	44304	30000	28736	28409
Base fuel	coal	coal	coal	wood	wood	wood	wood
Co-fuel	none	wet sludge	wet sludge	none	wet sludge	wet sludge	wet sludge
Waste fraction*	0	11	17	0	7	15	14
Ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash	bottom ash
Trace elements (mg/kg P)							
Hg	41	2.0	2.7	22	1.5	1.7	0.6
Cd	1000	78	74	180	64	79	70
Pb	69863	4268	3839	12360	1534	1792	1609
Cr	101370	5976	4554	44944	4049	3386	2322
Cu	101370	20122	20268	33708	15184	15277	16437
Ni	124658	7927	5446	40449	3482	4872	1586
Zn	356164	54878	46429	451910	71933	42403	45977

*dry matter(waste)/dry matter (mixture),%

TABLE A2:b. Concentration of Hg, Cd, Pb, Cr, Cu, Ni and Zn in relation to the P content (on dry samples) for the secondary cyclone ash samples. Test series 1 and 2.

Base fuel	coal	coal	coal	wood	wood	wood	wood
Co-fuel	none	dry sludge	dry sludge	none	dry sludge	dry sludge	dry sludge
Waste fraction*	0	25	65	0	22	48	62
Ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash
Trace elements (mg/kg P)							
Hg	52	37	25	15	19	20	20
Cd	67	47	37	93	57	49	41
Pb	3810	2333	1075	1246	1000	904	1141
Cr	5238	4000	2985	2623	2532	2530	2969
Cu	14286	9667	8507	8197	7595	8313	8438
Ni	2857	1833	940	902	696	699	844
Zn	27619	25333	23881	93	27848	27711	26563
Base fuel	coal	coal	coal	wood	wood	wood	wood
Co-fuel	none	wet sludge	wet sludge	none	wet sludge	wet sludge	wet sludge
Waste fraction*	0	11	17	0	7	15	14
Ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash	sec. cyclone ash
Trace elements (mg/kg P)							
Hg	95	34	35	7.2	25	34	27
Cd	155	64	68	587	101	86	79
Pb	29091	4857	3737	8696	1594	1496	1628
Cr	16364	3000	2316	12319	1552	1224	1698
Cu	27727	17500	15316	14493	16317	13392	17814
Ni	17273	3286	2368	12319	1133	770	907
Zn	68182	32857	28947	110000	31091	25620	25581

*dry matter(waste)/dry matter (mixture),%

TABLE A2:c. Concentration of Hg, Cd, Pb, Cr, Cu, Ni and Zn in relation to the P content (on dry samples) for the bag house filter ash samples. Test series 1 and 2.

Base fuel	coal	coal	coal	wood	wood	wood	wood
Co-fuel	none	dry sludge	dry sludge	none	dry sludge	dry sludge	dry sludge
Waste fraction*	0	25	65	0	22	48	62
Ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash
Trace elements (mg/kg P)							
Hg	100	45	118	65	87	61	60
Cd	92	29	71	43	26	49	25
Pb	9231	3158	3071	907	724	887	742
Cr	8462	4211	7143	2800	2895	2535	2809
Cu	22308	13947	30357	10800	11974	10282	10899
Ni	8462	2895	2857	853	789	845	719
Zn	35385	26316	26429	28000	26316	29577	25843
Base fuel	coal	coal	coal	wood	wood	wood	wood
Co-fuel	none	wet sludge	wet sludge	none	wet sludge	wet sludge	wet sludge
Waste fraction*	0	11	17	0	7	15	14
Ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash	bag house filter ash
Trace elements (mg/kg P)							
Hg	337	88	81	84	161	190	175
Cd	700	90	75	2791	93	81	88
Pb	64211	6375	4714	21395	798	875	922
Cr	44211	4438	3714	14884	1467	1313	1373
Cu	81053	24188	20810	25891	15473	13625	15373
Ni	52105	6250	4667	14884	755	979	725
Zn	78947	78947	26190	23535	15995	23554	21569

*dry matter(waste)/dry matter (mixture),%

TABLE A2:d. Concentration of Hg, Cd, Pb, Cr, Cu, Ni and Zn in relation to the P content (on dry samples) for sewage sludge, manure from pigs and cattle and artificial fertilizer

P-source	sewage sludge series 1	sewage sludge series 2	sewage sludge average*	liquid manure from pigs	solid manure from pigs	liquid manure from cattle**	artificial fertilizer***
P-concentration (g/kg)	36	29	27	22	21	24	40
Trace elements (mg/kg P)							
Hg	20	38	40	0.41	0.90	0.58	0.04
Cd	26	51	44	13	12	5.0	0.24
Pb	815	1693	1500	54	95	41	2.0
Cr	3150	1449	1300	309	524	96	37
Cu	9409	17153	14000	6773	5381	1000	6.9
Ni	713	795	720	205	290	192	22
Zn	21717	25011	25000	26455	32381	6417	76

* Average of analysis of sludge from 48 different waste water treatment plants in Sweden (ref. 6)

** milk producing cows (ref. 6)

*** NPK-S 21-4-7 from Hydro Agri (ref. 6)