Mineral and Heavy Metal Composition of Oil Shale Ash from Oxyfuel Combustion

Alar Konist,* Dmitri Neshumayev, Zachariah S. Baird, Edward J. Anthony,* Marek Maasikmets, and Oliver Järvik

1. INTRODUCTION

To avoid negative climatic effects caused by global warming, the amount of anthropogenic CO₂ emitted to the atmosphere must be reduced.¹,² However, currently the majority of the world’s energy needs are still supplied by fossil fuels. In Estonia, for instance, most of its electricity is produced by oil shale-fired power plants.³ One way to reduce CO₂ emissions from such power plants is to use pure oxygen along with recirculated flue gas in the combustion instead of air. This type of combustion produces flue gas with a high concentration of CO₂, which can then be more easily captured and stored to reduce emissions.⁴

Additional advantages of such technology are that it offers the possibility of cofiring biomass if circulating fluidized bed combustion (CFBC) technology is used, further reducing anthropogenic CO₂ production, without adversely affecting heavy metal emissions⁵ or even the possibility of net reductions of anthropogenic CO₂ via the so-called bioenergy with carbon capture and storage.⁶ However, for oxyfuel combustion to be used industrially, its feasibility must be demonstrated. Many of the current obstacles are economic. For example, the price of CO₂ (specifically European CO₂ emission allowances) is too low and there is a lack of government support and investment.⁶,⁷ This paper focuses on the various technological and environmental challenges that must first be addressed.

Earlier research has already investigated many aspects of oxyfuel combustion with oil shale.⁸⁻¹⁰ Thermogravimetric analysis experiment has also been performed to better understand the kinetics of oil shale combustion in the CO₂-rich oxyfuel atmosphere.¹¹ Small laboratory reactor experiments have also been performed,¹²⁻¹⁴ and in some of these experiments, it was observed that oxyfuel combustion reduces the amount of free lime in the ash.¹² Yörükl et al.¹⁵ have also used a process simulator to model an oxyfuel combustion process with oil shale. In addition, our research group has performed oxyfuel combustion experiments with a larger 60 kWth CFB combustor,¹⁶ and here, we present new data from these CFB experiments to investigate the effect of oxyfuel combustion on the resulting ash composition.

Oil shale contains an organic material, called kerogen, dispersed in a mineral matrix,¹⁻¹⁰ and thus, oil shale produces large amounts of ash upon combustion. For instance, Estonian kukersite oil shale contains around 65−70% inorganic matter and also contains various trace elements (Table 1). The carbonates in the oil shale generally decompose on combustion, but at least 50 wt % of the oil shale remains as ash (see analysis in the Methods section). Oil shale ash was considered for a long time to be a hazardous waste; therefore, almost all of the produced ash was deposited in nearby ash fields.¹⁶,¹⁷ Some fly ash is also emitted to the atmosphere with the flue gas.¹⁸

Oil shale ash can potentially produce toxic effects. Blinova et al.¹² noted that aqueous eluates from fly ash were toxic to any aquatic species. They further noted that the toxicity was mainly related to the high alkalinity caused by the ash high free lime content (which hydrates in aqueous solution and is then
neutralized by atmospheric CO$_2$); however, “the toxic impact of trace elements such as As and Pb cannot be excluded”.

The fly ash emitted to the atmosphere can increase the concentration of heavy metals in the soil where it settles. However, Blinova et al.$^{22}$ did not observe any long-term soil contamination in the region near the power plants, at least not for As, Cd, Cu, Pb, or Zn. Additionally, Velts et al.$^{23}$ concluded that heavy metals in the oil shale ash have low leachability, and experimental results from Blinova et al.$^{22}$ showed that some trace elements were not bioavailable. Finally, it is worth noting that the concentration of most of the trace elements is still of the same order of magnitude as Estonian soil. Nevertheless, the ash does have a potential environmental impact, and if oxyfuel combustion affects the composition of the ash, the resulting environmental effects would weigh on the decision of whether or not to use the technology industrially.

An example of this can be seen when the power plants in Estonia started to replace older pulverized combustion (PC) boilers with newer CFBC boilers.$^{24,25}$ Both Blinova et al.$^{22}$ and Reinik et al.$^{26}$ compared ashes from the two current combustion technologies and concluded that fly ash from the CFBC boilers was less toxic than PC fly ash. Moreover, CFBC ash had lower concentrations of heavy metals, on average presumably because of the fact that the carbonate content was higher. Here, we investigate what effect oxyfuel combustion in a CFBC boiler has on the composition of the ash, with emphasis on the content of heavy metals in the ash.

2. RESULTS AND DISCUSSION

2.1. Changes in Composition. From the chemical composition data in Table 2 we can conclude that the amount of calcium and magnesium found in overhead zones decreased in the ash, and the amount of sulfate in the ash correspondingly decreased. However, the concentration of other elements, such as silicon, and metals, such as iron, aluminum, and titanium, increased. In addition, ashes from the overhead zones in the boiler had lower losses on ignition (LOIs).

Ash minerals were also determined from the X-ray diffraction (XRD) data, and the results are given in Table 3. The oxyfuel ashes still contain large quantities of calcite. At higher temperatures, such as those in the boiler, calcite generally decomposes to form CO$_2$ and lime. However, because oxyfuel combustion takes place in a CO$_2$ atmosphere, the reaction equilibrium is shifted, and decomposition occurs at a higher temperature.$^{12}$ This explains the high concentrations of calcite in the oxyfuel ash. Our earlier experiments in a batch reactor showed a similar difference between oxyfuel and normal combustion ashes.$^{12}$ Dolomite generally decomposes into periclase and lime and reacts to form other Ca–Mg silicate phases.$^{12}$ However, interestingly, unlike the batch experiments, the CFBC oxyfuel ashes still contained some

### Table 1. Typical Heavy Metal Content of Oil Shale and Comparison with Coal and Limits Given in Estonian Law for Residential Soil$^{a,b}$

| Element | kukersite oil shale | kukersite oil shale | kukersite oil shale (OS1) | coal (average) | coal (range) | suggested conc. limits$^{c}$ | permitted conc. limits$^{c}$ |
|---------|---------------------|---------------------|---------------------------|---------------|-------------|-----------------------------|-----------------------------|
| As      | 7.6–21              | 21                  | 6.5                       | 10            | 0.5–80      | 20                          | 75                          |
| Ba      | 1150–1500           |                     |                           | 200           | 20–1000     | 500                         | 750                         |
| Be      |                     |                     |                           |               |             |                             |                             |
| Cd      | 0.4–4               |                     |                           |               |             |                             |                             |
| Co      | 2.9–3.0             | 3                   | 3.1                       | 5             | 0.5–30      | 20                          | 50                          |
| Cr      | 17–38               | 17                  | 22.1                      | 20            | 0.5–60      | 100                         | 300                         |
| Cu      | 17–55               | 7.5                 | 10.6                      | 15            | 0.5–50      | 100                         | 150                         |
| Hg      | 0.08–0.3            | 0.22                |                           | 0.1           | 0.02–1      |                             |                             |
| Mn      | 310–387             | 340                 | 368.4                     | 70            | 5–300       |                             |                             |
| Mo      | 3                   |                     |                           | 3             | 0.1–10      |                             |                             |
| Ni      | 12–21               | 15                  | 15.4                      | 20            | 0.5–50      | 50                          | 150                         |
| Pb      | 20–30               | 30                  | 31.1                      | 40            | 2–80        | 50                          | 300                         |
| Sb      | 0.5–0.6             | <0.4                |                           | 1             | 0.05–10     | 10                          | 20                          |
| Se      |                     |                     |                           | ND            |             |                             |                             |
| Sr      |                     |                     |                           | 160.4         |             |                             |                             |
| Th      | 2.3–3.4             |                     |                           | 4             | 0.5–10      |                             |                             |
| Ti      |                     |                     |                           | 1162.5        |             |                             |                             |
| Tl      |                     | 0.5                 | <0.5                      |               |             |                             |                             |
| U       | 3                   |                     |                           | 2             | 0.5–10      | 1                           | 5                           |
| V       | 24                  | 20.5                |                           |               |             |                             |                             |
| Zn      | 49.4                |                     |                           |               |             |                             |                             |

$^{a}$Unit: $\mu$g g$^{-1}$. $^{b}$ND = not detected. $^{c}$Limits for residential soil prescribed in Estonian law.

### Table 2. Chemical Composition of the Ashes from the Oxyfuel Experiments$^{c}$

| Element | BA | EHE | C1 | C2 | FA |
|---------|----|-----|----|----|----|
| SiO$_2$ | 10.61 | 20.79 | 31.09 | 30.76 | 36.21 |
| Al$_2$O$_3$ | 2.50 | 4.92 | 7.48 | 7.41 | 9.38 |
| TiO$_2$ | 0.13 | 0.28 | 0.45 | 0.45 | 0.58 |
| Fe$_2$O$_3$ | 2.23 | 3.75 | 4.68 | 4.72 | 5.53 |
| MnO | 0.069 | 0.073 | 0.052 | 0.053 | 0.046 |
| CaO | 39.00 | 36.77 | 27.39 | 27.98 | 24.86 |
| MgO | 10.37 | 9.56 | 6.74 | 6.82 | 5.53 |
| Na$_2$O | 0.03 | 0.05 | 0.17 | 0.20 | 0.65 |
| K$_2$O | 0.64 | 1.70 | 3.18 | 3.02 | 3.42 |
| P$_2$O$_5$ | 0.093 | 0.121 | 0.130 | 0.137 | 0.158 |
| SO$_3$ | 8.71 | 7.29 | 6.00 | 5.12 | 4.69 |
| LOI | 25.59 | 14.65 | 12.59 | 13.28 | 8.87 |

$^{c}$Unit: wt %.
Table 3. Mineral Composition of the Ashes from the 20 April 2017 Oxyfuel Experiment

| Mineral       | BA    | EHE   | C1    | C2    | FA    |
|---------------|-------|-------|-------|-------|-------|
| quartz        | 8.4   | 16.0  | 25.4  | 25.3  | 28.6  |
| K-feldspar    | 3.0   | 7.9   | 18.6  | 18.7  | 21.9  |
| K-mica        | 0.5   | 0.8   | 0.7   | 0.6   | 0.7   |
| calcite       | 44.2  | 24.6  | 20.1  | 20.4  | 16.6  |
| dolomite      | 9.8   | 10.0  | 2.9   | 2.2   | 1.0   |
| lime          | 4.7   | 8.1   | 4.3   | 4.6   | 4.9   |
| periclase     | 6.4   | 6.8   | 5.2   | 5.1   | 4.3   |
| anhydrite     | 11.5  | 11.0  | 8.6   | 7.4   | 7.2   |
| C2S β         | 4.3   | 4.2   | 4.6   | 4.9   | 3.9   |
| merrwinite    | 3.2   | 4.0   | 3.6   | 4.0   | 4.3   |
| akermanite    | 2.6   | 4.4   | 2.5   | 3.0   | 2.0   |
| hematite      | 1.3   | 1.8   | 2.9   | 3.0   | 3.6   |
| wollastonite  | trace | 0.5   | 0.7   | 0.9   |

Unit: wt %.

Table 4. Mineral Composition of Ashes from the Industrial Auvere Power Plant

| Mineral       | BA     | EHE     | C1     | C2     | FA     |
|---------------|--------|---------|--------|--------|--------|
| quartz        | 3.4    | 5.1     | 14.9   | 12.4   | 12.3   |
| K-feldspar    | 2.0    | 5.4     | 18.2   | 11.4   | 16.9   |
| K-mica        | 2.8    | 5.8     | 5.8    | 2.9    | 6.2    |
| calcite       | 26.9   | 0.8     | 12.6   | 10.4   | 8.5    |
| dolomite      | 6.7    | 0.5     |        |        |        |
| lime          | 23.5   | 32.0    | 17.4   | 21.3   | 20.4   |
| periclase     | 8.5    | 8.4     | 6.0    | 8.5    | 6.8    |
| anhydrite     | 12.2   | 22.7    | 7.3    | 12.2   | 7.7    |
| C2S β         | 5.0    | 11.6    | 7.0    | 8.1    | 8.6    |
| merrwinite    | 4.1    | 5.7     | 6.2    | 6.1    | 7.1    |
| akermanite    | 4.4    | 7.4     | 2.7    | 4.7    | 3.7    |
| hematite      | 0.5    | 0.5     | 1.5    | 1.1    | 1.3    |

Unit: wt %.
concentration was actually lower in the filter ash than in the bottom ash.

Because the concentration of heavy metals generally increases in ashes further from the boiler, we also measured the concentrations in the fly ash. The fly ash samples were collected from the flue gas after the fabric filter. Two samples were collected during the 20 April 2017 experiments: one during normal combustion with air and a second during oxyfuel combustion. However, only a few milligrams of the ash could be obtained during the course of the experiments, and hence, our inductively coupled plasma mass spectrometry (ICP-MS) method could not provide reliable results. We were, however, able to measure the size distributions of the same fly ashes. These data were presented earlier, but here, we show the size distribution again for convenience in Figure 3. Figure 3 shows that the oxyfuel fly ash had a distribution that was shifted toward larger particle sizes. The median particle diameter for air combustion was 34 nm, and for oxyfuel, it was 42 nm. However, perhaps even more importantly, the oxyfuel experiment produced less fly ash in the flue gas: 1.0 mg m\(^{-3}\) (dry basis) compared to 1.6 mg m\(^{-3}\) during normal combustion. Even if the concentration of heavy metals in the oxyfuel fly ash is around the same as with normal combustion, if the amount of fly ash emitted is lower overall, then the environmental impact would most likely be lower.

3. CONCLUSIONS

Oxyfuel combustion conditions did not produce a noticeable effect on the concentrations of heavy metals in the ash. As the concentrations of heavy metals in our ash samples aligned with those of ashes from industrial boilers, we expect that switching to an oxyfuel atmosphere would not significantly affect the concentrations of heavy metals in ashes from industrial power plants. Additionally, in our experiments, flue gas during oxyfuel combustion contained fewer and larger ash particles. If a similar reduction occurs in an industrial boiler, then this would decrease the health impact of the plant.

The high concentration of CO\(_2\) in the oxyfuel atmosphere reduced the extent of decomposition of calcite and dolomite. As a result, ashes from oxyfuel combustion can be expected to have less free lime and this will reduce expansive behavior in landfills. The reduction in free lime will help lower the pH of ash leachate, which in turn ensures that the oxyfuel ash will have a lower environmental impact.

4. METHODS

4.1. Oil Shale Samples. Kukersite oil shale from Estonia was used as the fuel. The fuel was dried, crushed, and separated to obtain oil shale with a size less than 3 mm. Table 7 gives the proximate and ultimate analysis of the oil shale samples used. Proximate analysis was performed on the sample as it was received, and the ultimate analysis is given in terms of the dry sample. The data for sample OS3 was published earlier by Loo et al.\(^5\)

4.2. CFBC Experiments. The ashes were obtained from combustion experiments in a 60 kW\(_{th}\) CFB combustor. Several experiments were carried out using either normal air-fired combustion or oxyfuel combustion with a mixture of CO\(_2\) and O\(_2\). The CO\(_2\) and O\(_2\) were taken from commercially available gas cylinders. The experimental CFB setup is shown in Figure 4. Table 8 gives an overview of the experiments performed, and Figure 4 shows the locations from which ash samples were
obtained. Here, Table 9 gives the distribution of the ash by mass fraction at different locations in the CFB. The experimental CFB and the combustion experiments are described in more detail elsewhere.  

4.3. ICP−MS Measurements. Trace elements were quantified using Thermo iCAP Qc Quadrupole ICP−MS. Digestion of the samples (along with the filters) was done using concentrated HNO₃ and HF. The samples were digested in sealable Teflon containers in a microwave oven. The analysis was run in kinetic energy discrimination mode with high-purity helium in order to eliminate any interferences.

4.4. XRF−XRD Measurements. The mineral composition of some of the oxyfuel ashes was investigated using XRD. For comparison, some oil shale ashes from the industrial Auvere power plant were examined using the same technique. A Bruker D8 diffractometer was used, which was fitted with a Lynx-Eye linear detector. Experiments were performed using Cu Kα radiation in the 2θ range of 3−72°, with a step size of 0.02° 2θ and a counting time of 0.1 s per step. The X-ray tube was operated at 40 kV and 40 mA. For analysis, the Siroquant 3.0 code was used, which is based on the Rietveld algorithm. The presence of portlandite indicates that the samples had come into contact with moisture in the atmosphere, which caused hydration of some of the lime. Therefore, the compositions were recalculated to include the portlandite in the lime concentration.

X-ray fluorescence (XRF) spectrometry was used to measure the chemical composition of these ashes. Here, a Rigaku Primus II XRF spectrometer was used.

4.5. Size Distribution Measurements. The particle size measurements are already described in our earlier work, but we describe the method here as well because we rely on some of these results in the discussion section. The fly ash analyzed...
| ash type           | plants | refs | As | Ba  | Cd  | Co  | Cr  | Cu  | Hg  | Mn  | Mo  | Ni  | Pb  | Rb  | Sb  | Sn  | Sr  | Th  | Tl  | U   | V   | Zn |
|-------------------|--------|------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| fly ash           | Eesti--PC | 22   | 48.9 | 0.94 | 51  | 20.18 | 19379 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| fly ash           | Eesti--CFBC | 22   | 25.8 | 0.13 | 48  | 18.56 | 6723  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| fly ash           | Balti--PC | 22   | 28.2 | 0.26 | 42  | 12.37 | 11262 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| fly ash           | Balti--CFBC | 22   | 17.2 | 0.17 | 49  | 15.29 | 7549  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| bottom ash        | Eesti--PC | 20   | 16   | 4.5  | 19  | 9.9  | 700   | 27 | 24 | <0.4 |     |     |     |     |     |     |     |     |     |     |     |     |
| superheater       | Eesti--PC | 20   | 18   | 4.9  | 23  | 11   | 700   | 29 | 44 | <0.8 |     |     |     |     |     |     |     |     |     |     |     |     |
| economizer        | Eesti--PC | 20   | 14   | 4.5  | 19  | 9.5  | 690   | 26 | 34 | <0.6 |     |     |     |     |     |     |     |     |     |     |     |     |
| cyclone           | Eesti--PC | 20   | 16   | 4.5  | 21  | 9.3  | 650   | 26 | 45 | 0.6  |     |     |     |     |     |     |     |     |     |     |     |     |
| ESP I and II      | Eesti--PC | 20   | 42   | 5.3  | 33  | 9.6  | 470   | 31 | 130| 1.3  |     |     |     |     |     |     |     |     |     |     |     |     |
| ESP III and IV    | Eesti--PC | 20   | 59   | 6.6  | 49  | 12   | 440   | 38 | 210| 1.1  |     |     |     |     |     |     |     |     |     |     |     |     |
| fly ash > 4−6 μm  | Eesti--PC | 20   | 68   | 6.6  | 58  | 13   | 0.1   | 350| 380| 2   |     |     |     |     |     |     |     |     |     |     |     |     |
| fly ash < 4−6 μm  | Eesti--PC | 20   | 92   | 7.4  | 48  | 18   | 0.3   | 340| 450| 2.4  |     |     |     |     |     |     |     |     |     |     |     |     |
| bottom ash        | Balti--PC | 26   | 107  | 0.1  | 3   | 17   | 7.9   | 0.02| 573| 2.7  | 17  | <0.04| <0.2| 252| 2.8 | 2.5 | 24 | 63  |     |     |     |
| super-heater      | Balti--PC | 26   | 143  | 0.05 | 3.5 | 21   | 9.8   | 0.02| 463| 3.1  | 18  | <0.04| <0.2| 228| 3.3 | 2.7 | 29 | 56  |     |     |     |
| pre-heater        | Balti--PC | 26   | 132  | 0.08 | 5.6 | 38   | 9.2   | 0.02| 373| 2.3  | 28  | <0.04| <0.2| 245| 4.8 | 3   | 45 | 38  |     |     |     |
| cyclone           | Balti--PC | 26   | 154  | 0.2  | 3.5 | 19   | 36    | 0.02| 545| 2.7  | 20  | <0.04| <0.2| 265| 3.1 | 2.9 | 29 | 46  |     |     |     |
| ESP I             | Balti--PC | 26   | 179  | 0.2  | 3.7 | 37   | 7.8   | 0.02| 373| 6.4  | 22  | <0.04| <0.2| 208| 3.2 | 3.1 | 38 | 82  |     |     |     |
| ESP II            | Balti--PC | 26   | 280  | 0.6  | 5.8 | 59   | 15    | 0.02| 420| 8.4  | 33  | <0.04| <0.2| 204| 5.2 | 4.4 | 60 | 142 |     |     |     |
| ESP III           | Balti--PC | 26   | 242  | 0.9  | 5   | 51   | 12    | 0.03| 310| 8.3  | 28  | <0.04| <0.3| 168| 4.2 | 4.6 | 80 | 143 |     |     |     |
| bottom ash        | Balti--CFBC | 26   | 59   | 0.06 | 3.7 | 20   | 8     | 0.02| 826| 3.5  | 21  | <0.04| <0.2| 346| 3.6 | 2.4 | 24 | 41  |     |     |     |
| INTREX            | Balti--CFBC | 26   | 87   | 0.07 | 4.3 | 29   | 7.4   | 0.02| 875| 3.6  | 25  | <0.04| <0.2| 279| 5.3 | 2.8 | 32 | 51  |     |     |     |
| ESP I             | Balti--CFBC | 26   | 199  | 0.07 | 8   | 54   | 12    | 0.08| 524| 3.3  | 40  | <0.04| <0.2| 354| 6.5 | 4.3 | 67 | 56  |     |     |     |
| ESP II            | Balti--CFBC | 26   | 125  | 0.06 | 3.4 | 20   | 7.7   | 0.02| 606| 2.8  | 20  | <0.04| <0.2| 270| 3.2 | 3   | 28 | 38  |     |     |     |
| ESP III           | Balti--CFBC | 26   | 207  | 0.07 | 8.9 | 60   | 14    | 0.15| 521| 3.3  | 44  | <0.04| <0.2| 401| 7.4 | 4.9 | 71 | 55  |     |     |     |
| ESP IV            | Balti--CFBC | 26   | 180  | 0.06 | 7.5 | 52   | 14    | 0.12| 429| 3.6  | 41  | <0.04| <0.2| 371| 6.1 | 4.3 | 62 | 53  |     |     |     |
| bottom ash        | 2nd block--PC | 23   | 25   | 25  | 545 | 13    | 20 | 155 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| mix               | PC     | 23   | 35   | 600 | 38  | 30  | 120 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| ESP I             | 8th block--CFBC | 23   | 45   | 385 | 30  | 38  | 30  | ~30 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| mix               | CFBC   | 23   | 40   | 445 | 20  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

*Unit: ppm.*
experiments conducted on 20 April 2017 (Figure 5). Particle sizes were measured using an electrical low-pressure impactor (ELPI+) which was produced by Dekati. The ELPI measurement technique was developed by Keskinen et al., and it measures the number concentration as a function of the aerodynamic particle diameter. In the device, the aerosol particles are first charged with a corona charger and then, they enter a low-pressure cascade impactor. The electric current produced by the charge carried by the impacted particles is measured by electrometers as the particles impact electrically isolated collection stages, and this signal can then be used to calculate the number of particles with different sizes. The measurements were carried out during the combustion experiments, so the ELPI provided near-real time data.

The sampling location for the ELPI device was after the fabric filter. A portion of the flue gas was removed and sent to a diluter. This gas was then sent to both the CO₂ analyzer and the ELPI+ device. The measurement setup is shown in Figure 2.

![Graph showing distribution of particles by size in the fly ash during normal and oxyfuel combustion.](image)

**Figure 3.** Distribution of particles by size in the fly ash during normal and oxyfuel combustion.

**Table 7.** Proximate and Ultimate Analysis of the Oil Shale Samples Used

|     | OS1   | OS2   | OS3   |
|-----|-------|-------|-------|
| LHV (MJ kg⁻¹) | 8.82  | 9.83  | 8.56  |
| moisture     | 9.0   | 0.2   | 0.5   |
| volatile matter | 49.2  | 47.5  | 47.5  |
| fixed carbon  | 1.6   | 1.3   |       |
| ash           | 50.7  | 49.0  | 50.7  |
| C             | 27.3  | 28.6  | 27.4  |
| N             | 0.07  | 0.07  | 0.07  |
| S             | 1.7   | 1.6   | 1.6   |
| H             | 2.7   | 2.8   | 2.7   |
| total organic carbon | 21.3  | 23.0  | 21.8  |
| CO₂ (mineral) | 21.7  | 20.2  | 20.6  |

"Lower heating value.

**Table 9.** Distribution of Ash among the Different Locations in the Experimental CFBC (See Figure 1)

| description of ash | mass fraction of total ash |
|--------------------|----------------------------|
| BA                 | 37                         |
| EHE                | 7                          |
| C1                 | 2                          |
| C2                 | 47                         |
| FA                 | 7                          |

![Diagram showing the 60 kW circulating fluidized bed combustor used for the experiments.](image)

**Figure 4.** Schematic of the 60 kW circulating fluidized bed combustor used for the experiments.

by the ELPI device came from both air and oxyfuel experiments conducted on 20 April 2017 (Figure 5).

Particle sizes were measured using an electrical low-pressure impactor (ELPI+) which was produced by Dekati. The ELPI measurement technique was developed by Keskinen et al., and it measures the number concentration as a function of the aerodynamic particle diameter. In the device, the aerosol particles are first charged with a corona charger and then, they

![Diagram showing the setup used for the ELPI measurements.](image)

**Figure 5.** Setup used for the ELPI measurements.

**Table 8.** Overview of the CFBC Experiments Performed

| date       | atmosphere | oil shale |
|------------|------------|-----------|
| 12 July 2016 | oxyfuel    | OS1       |
| 12 July 2016 | air        | OS1       |
| 11 January 2017 | air     | OS2       |
| 12 January 2017 | air      | OS2       |
| 20 April 2017 | oxyfuel   | OS3       |
| 20 April 2017 | air        | OS3       |
AUTHOR INFORMATION

Corresponding Authors
Alar Konist – Tallinn University of Technology, Tallinn 19086, Estonia; orcid.org/0000-0001-5492-248X; Email: alar.konist@taltech.ee
Edward J. Anthony – University of Ottawa, Ottawa K1N 6NS, Canada; orcid.org/0000-0001-6822-2417; Email: b.j.anthony@cranfield.ac.uk

Authors
Dmitri Neshumayev – Tallinn University of Technology, Tallinn 19086, Estonia
Zachariah S. Baird – Tallinn University of Technology, Tallinn 19086, Estonia
Marek Maasikmets – Estonian Environmental Research Centre, Tallinn 10617, Estonia
Oliver Järvi – Tallinn University of Technology, Tallinn 19086, Estonia

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c04466

Notes
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