# Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction

## Deliverable No. D6.7

## Final report on bulk tests in existing storage and handling facilities

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| **PP** | Restricted to other programme participants (including the Commission Services) | |
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# 1 Overall Summary of Deliverable 6.7

This deliverable reports the results of three sets of tonne-scale outdoor storage tests on torrefied pellets undertaken by E.ON, Vattenfall and Topell. These tests were designed to investigate the chemical and physical changes in the torrefied material during long-term (up to one year) storage of torrefied biomass in outdoor stockpiles. For reasons of supply limitations and practicalities of the testing, these stockpiles were limited to 1-4 tonnes of material per stockpile, so are still small in comparison to the quantities of material which would be stored at a power station site (hundreds of thousands of tonnes) and they did not undergo the compaction that is commonly employed on coal stockpiles. As part of the Vattenfall work, tests designed to evaluate the behaviour of the pellets in the handling systems of coal power plant were also undertaken. The three sets of test are discussed separately in this document, with overall conclusions drawn at the end. Other potential benefits of using torrefied biomass over untreated biomass, such as differences in milling and biodegradation behaviour are discussed in other deliverables from the SECTOR project.

The results of the stockpile tests indicate that the torrefied wood pellets supplied for these tests were not suitable for long-term storage outside, due to their propensity to absorb moisture and lose durability on exposure to rain. However, the rate at which this deterioration in quality occurred is slower than that of white wood pellet (pellets made from the compression of untreated wood, usually without addition of binders), which rapidly swell and disintegrate at their first exposure to moisture. In particular, for the first few weeks of the test, only the surface material showed significant deterioration. This suggests torrefied wood pellet could survive temporary storage outside to e.g. facilitate ship loading and discharge in a wider range of climatic conditions than is possible for white wood pellet.

Both the E.ON and Vattenfall tests showed similar pellet behaviour in the stockpile tests, with moisture contents, particularly in the centre of the piles, increasing steadily with time and exposure to rainfall. In the tests conducted by Topell, limited to two months of exposure, the moisture intake by pellets was limited to the surface of the stockpiles without reaching the core of the piles.

Development of the torrefaction and densification process is ongoing, with work undertaken within other work packages in the SECTOR project. No material produced from this optimisation work was available for testing, but production of a more robust pellet could allow these outdoor storage periods to be extended. The material used by Topell was produced at a later stage than the material used by E.ON and Vattenfall; these pellets were subjected to several handling operations and were stored for more than one year indoors, exposed to changing atmosphere conditions in the warehouse and to dust from manipulation of raw and torrefied materials.

During durability testing, it was identified that the mechanical durability standard EN 15210 does not include a drying step. This standard was developed for durability testing of untreated wood pellets, which are to be stored indoors. When exposing torrefied wood pellets to open air outdoor conditions, the moisture content in some sections of the piles increased to higher levels than the limit for sieving operations (~20 wt%), while still retaining its shape; this led to issues with the sifting of the wet fines from the pellet, potentially distorting the results. It is therefore recommended that EN15210 is reviewed for use with pellets with high moisture contents.

Although the quantities of material available were too small for full scale handling tests in coal plant, Vattenfall undertook additional testing to evaluate the handling properties of the torrefied pellet. Pellet breakage and fines generation were higher in the torrefied pellet than in a reference white wood pellet sample. This would suggest that material loss in the supply chain would be higher than with white wood pellet and dust management strategies within the plant would need to be reviewed. In particular, the level of dust generated in the sub-250 µm range, important for explosivity considerations, from the torrefied pellet was similar or higher than that of white wood pellet.

# 2 Introduction to Deliverable 6.7

One of the identified advantages of torrefied biomass over untreated biomass, and white wood pellet in particular, is the hydrophobic nature of the material, which should make it more suitable for outside storage, reducing the costs and difficulties associated with large-scale storage. Ideally, for large scale use, torrefied biomass should have storage and handling properties which enable it to be managed in a similar manner to coal. Coal stock management practices vary by country and power plant, but the fuel should be capable of being stored outside for long periods of time, under a wide variety of climatic conditions and in piles containing many thousands of tonnes. For example, in the UK it is not uncommon for power stations to have three months of fuel on stock, equivalent to over a million tonnes of coal for a 2000 MWe plant. In some countries, e.g. where transport links are likely to be severed for extended periods of time in winter, stocks may be an even higher percentage of total fuel consumption. Compaction of coal stocks using heavy machinery is also commonly practiced to exclude oxygen and reduce the risk of self-heating. Even when fuel management strategies revolve around smaller stocks with a rapid turnover, events such as unplanned outages can result in some material being stored for longer periods of time than planned. For torrefied pellet to be considered a suitable substitute for coal, it is therefore important that similar quantities (or even greater quantities, given the lower energy density) could be stored for extensive time periods while remaining stable, both in terms of its physical properties and chemically/biologically (for example, no fungal growth or self-heating).

While laboratory tests have demonstrated the hydrophobicity of some torrefied pellet, for example by demonstrating that pellet integrity is maintained after immersion in water (unlike for white (untreated) wood pellet (WWP)), these tests are not representative of the conditions that the torrefied pellet would be subject to in exposed stockpiles. For outdoor storage, the pellet must be resistant not only to a single immersion in water, but also to the effects of humidity and temperature as well as repeated wet-dry (or, in cooler climates, freeze-thaw) cycles.

The storage tests undertaken for this deliverable were designed to evaluate the overall weather resistance of torrefied pellet when stored for extended periods (up to one year). Separate tests have been conducted by E.ON (one pellet type, two stockpiles), Vattenfall (two pellet types in separate stockpiles) and Topell (one pellet type, two big bags of 1 $m^3$ volume). While practicality and material availability has necessitated the restriction of the size of these stockpiles to a few tonnes each, these tests are still considered more representative of medium to large scale storage than laboratory tests previously undertaken.

# 3 E.ON Tests

## 3.1 Introduction to E.ON Storage Tests

In May 2013, approximately 10 tonnes of torrefied spruce pellet, sourced from Andritz via Topell were received at a farm near Retford, UK. The farm's rural location minimised the possibility of disruption to the stockpile by outside interference (traffic, public etc.) A significant proportion of the UK coal-fired electricity generation fleet (over 10GWe capacity) is located within a 65km radius of this site, allowing its climate to be considered "typical" of that seen by UK coal plant stockpiles. The pellets were stored undercover in sealed tonne bags for around 3 weeks before the stockpiles were constructed. Two piles were set up, with different profiles, with regular monitoring, sampling and testing over a period of just over 1 year (June 2013 to June 2014). Details of this testing are given in section 3.3.1 below.

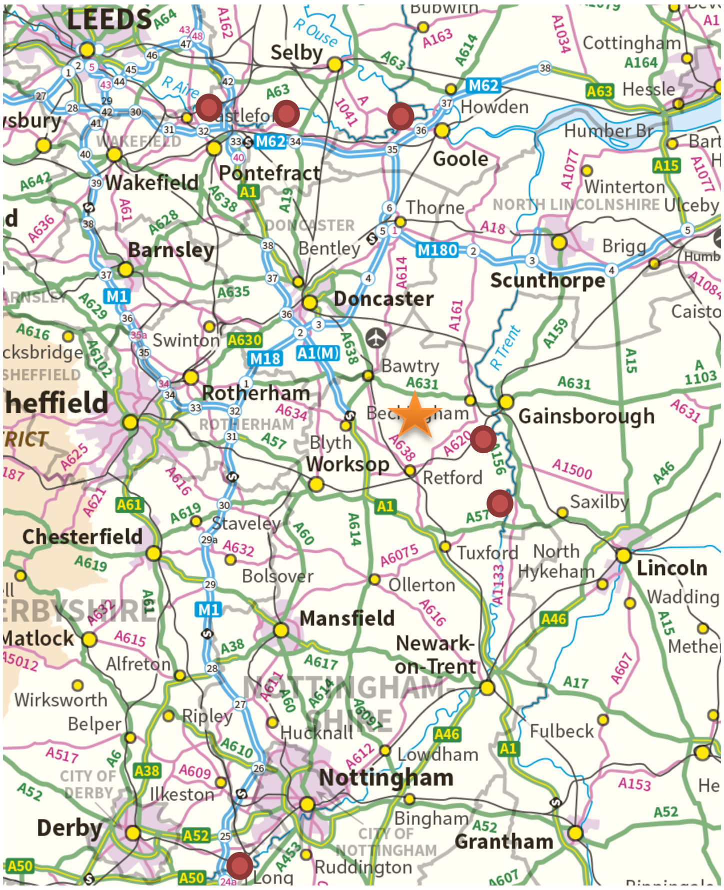

**Figure 1: Location of test site (yellow star) and nearby coal power stations (red markers). (Contains public sector information licensed under the Open Government Licence v1.0 obtained from www.emapsite.com).**

## 3.2 Deviations from the Description of Work document

In the original description of work document, the E.ON stockpile tests were supposed to consist of 10 ton tests of 1-3 different types of torrefied pellets. As only one type of pellet (10 tons of torrefied spruce pellet produced by Andritz) was received from the supplier, the decision was taken to undertake to set up two tests of this pellet with different pile profiles. Around 4 tonnes of pellet were used for each pile (constrained by the size of the mesh cages available).

## 3.3 Experimental method

### 3.3.1 Set-up

Due to the free flowing nature of the pellet, it was quickly determined that the sides of the test piles would have to be enclosed to contain the material. Metal mesh cages were constructed and placed upon pads formed from (unsealed) concrete slabs, with the sides of the cages lined with breathable plastic sacking. This set up contained the material whilst still allowing rain to flow from the pile.

For each pile, a thermocouple support was created which sited thermocouples at three different heights within the centre of each pile and a fourth at the base, approximately half-way between the centre and the edge (Figure 2). The wires were protected by plastic tubing and fed out of the bottom of the pile to the data loggers, which were held in a weatherproof box (Figure 3). Data was recorded using YCT 4 channel thermometer data loggers, set to type T. This gave a measurement range of -100°C to +400°C with an accuracy of ±0.1% reading 0.7°C. To ensure sufficient battery life between sampling visits, external battery packs were used. The temperature of each thermocouple was logged once per hour. Pellets were carefully poured from above around these thermocouples to ensure they remained centrally located. For one pile, the pellets were allowed to flow from the centre to form a peak ("peak pile", Figure 4), while for the other pile the top was levelled out at the top of the plastic barrier ("flat pile", Figure 5). No compression was applied to either pile, although following completion of pile building and during the sampling the flat pile the test team did walk on the surface; this is not considered to have a significant impact on the pile when compared to the mass of pellet used.

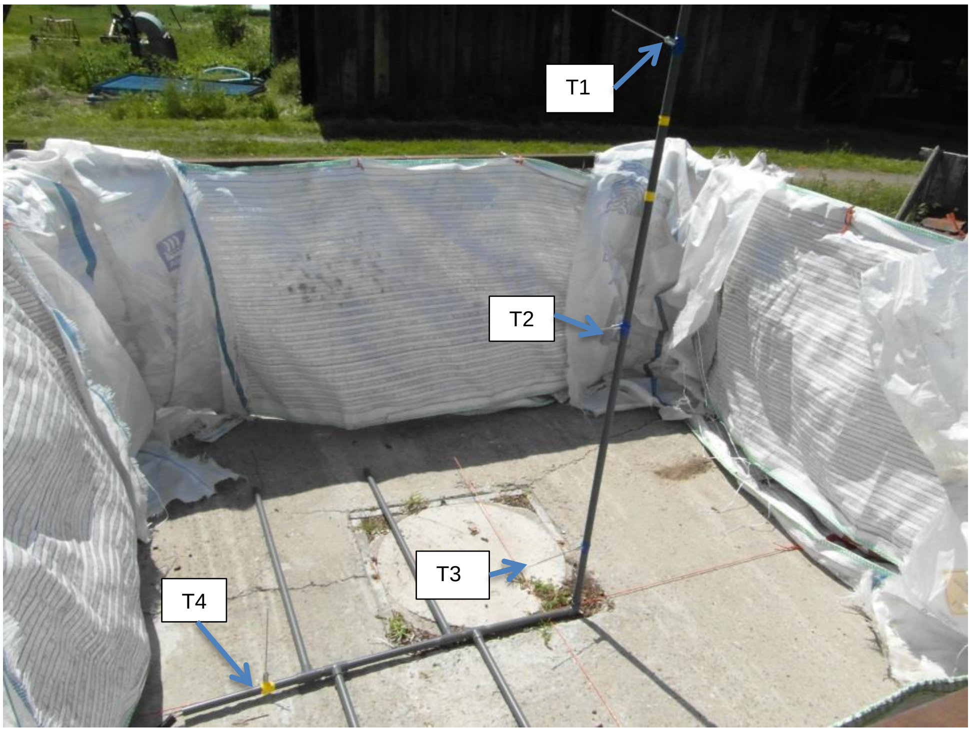

**Figure 2: Thermocouple set-up (both piles contained an equivalent set-up)**

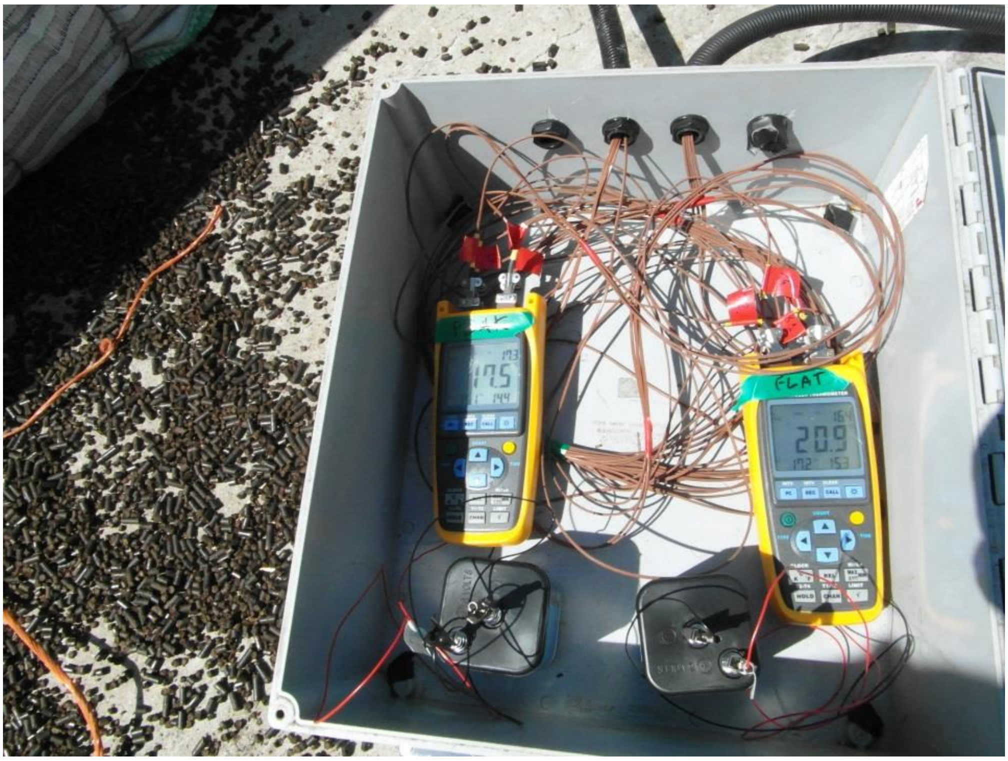

Figure 3: Thermocouple data loggers in weatherproof box

Figure 4: Completion of peak pile

**Figure 5: Completed flat pile**

A weather station, monitoring rainfall, humidity, wind speed and direction and air temperature, was set-up on site, with readings logged on an hourly basis (Figure 6). This is supplemented by data from an air monitoring station located approximately 12 km away from the test site. Unfortunately, restrictions on on-site power supply necessitated the locating of the weather station close to a building, with the result that wind direction and speed readings were not consistent with those expected from the general area conditions.

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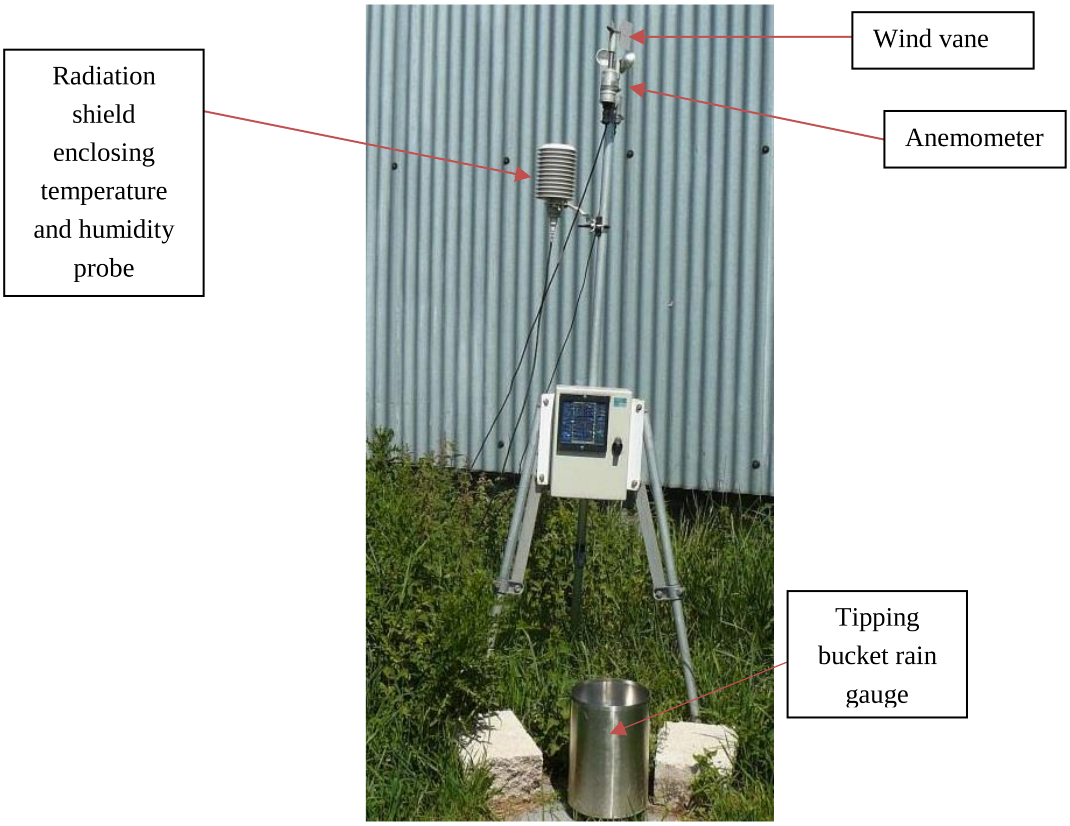


**Figure 6: Site weather station**

### 3.3.2 Sampling

As previously discussed, weather conditions and temperatures within the piles were monitored continuously during the tests. In addition, samples from the piles were taken regularly, with one sample taken from the surface of the pile (“edge”) and one from the interior of the pile (“middle”) to give a total of four samples for each visit. Each sample was approximately 6kg in size. While the edge samples were taken by hand, helping to ensure only surface material was taken, to obtain the samples from the middle, a sampling spear (Figure 7 & Figure 8) was used, which was pushed into the pile and a trapdoor opened up to take a sample without contamination from the surface material. The sampler is 2.18 m long with an external diameter of 10 cm and an internal diameter of 14 cm. The aperture dimensions are 14 x 6 x 5.5 cm allowing, for a volume of 462 cm$^3$ to be sampled. However, it was found that the penetration of this spear into the pile decreased as the piles became compacted with time, so for the final 6 months of visits, samples were taken from beneath the surface of the piles by digging pits up to ~50 cm deep (in a different location each visit) and taking the material from the bottom of the pit. The frequency of sampling visits decreased during the course of the storage tests; from weekly for the first two months then decreasing to approximately monthly.

**Figure 7: Sampling spear**

**Figure 8: Spike of sampling spear, showing rotating trapdoor (half open)**

### 3.3.3 Sample analysis

All samples were dried and analysed for moisture, ash, volatile matter, calorific value, sulphur and chlorine content in a laboratory accredited to ISO17025 for coal and biomass analysis. Mechanical durability was undertaken using the method of EN15210:2009-1, although the samples were pre-dried at 35°C to reduce the risk of the wet fines sticking to either the pellet or sieve and being included in the “intact” pellet mass.

### 3.3.4 Pile take down

After 1 year and 2 weeks, the piles were deconstructed by removal of the containing cages and stepwise removal of the material using a tractor equipped with a scoop. Photographs were taken at various points of the process, along with some additional samples to support observations.

## 3.4 Results

### 3.4.1 Weather data

As discussed in section 3.3.1, the necessity of locating the weather station close to a building means that the weather speed and direction data is unrepresentative. In addition, examination of the rainfall data and comparison to that from nearby locations suggests this is unreliable; being impacted by the time between visits to make sure the gauge was in working order. The air temperature and humidity data does however appear to be comparable to that obtained from the nearby air quality monitoring station (Figure 9 & Figure 10). Power to the site weather station logger was lost on two occasions – between days 299 and day 311 and from day 342 onwards; although this resulted in the loss of data during these times, as the T1 thermocouple of the peak pile was exposed during these time periods, temperature data from this thermocouple has been used as a proxy for these periods.

### 3.4.2 Stockpile Temperatures

Temperature logging from the stockpile thermocouples was around 89% complete for the flat pile and 88% for the peak pile, with the loss of data primarily due to battery failure, although for the peak pile there was a period where the logger was incorrectly set-up due to user error. In addition, for the flat top pile there was a short period on day 74 where the logged data was extremely variable, cycling between -18°C and +40°C within a few hours. It was decided that this data was probably erroneous, particularly as one period of power failure occurred just two days later, and so it has been excluded from the dataset. Data from the thermocouples embedded in the flat and peak piles are shown in Figure 11 & Figure 12 respectively, alongside the ambient air temperature data.

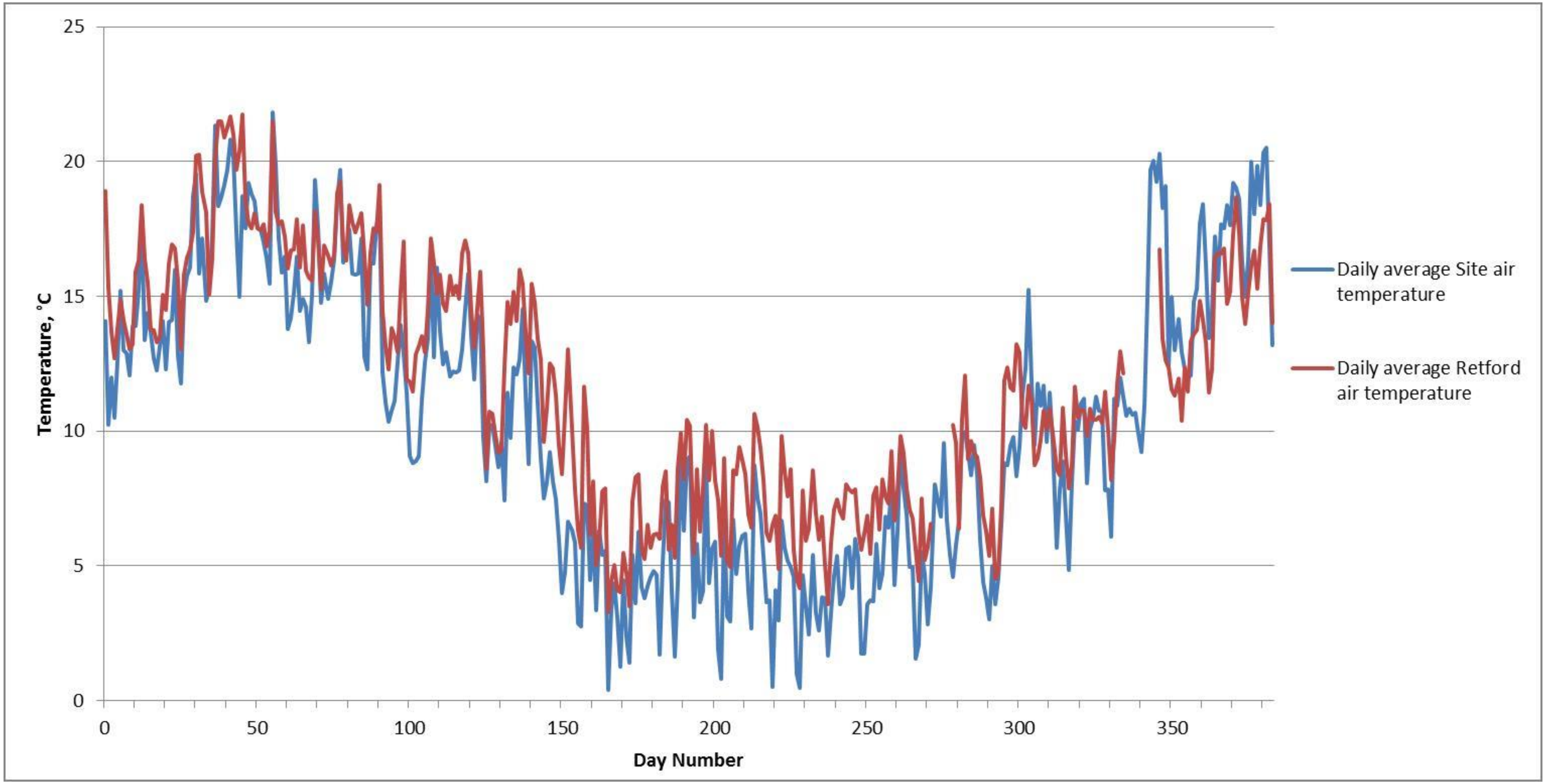


**Figure 9: Comparison between daily average air temperatures at test site and Retford Air Quality Monitoring Station**

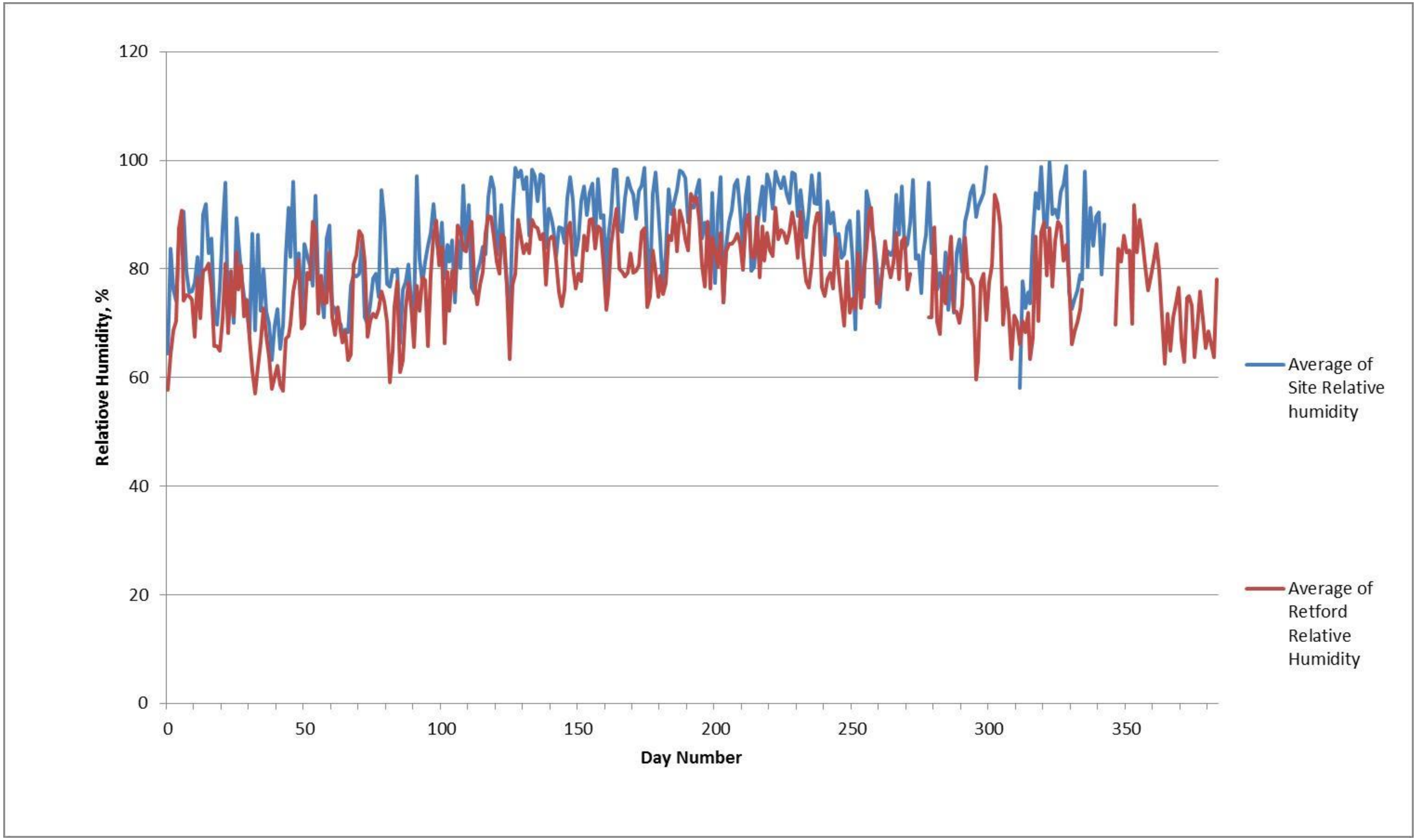


**Figure 10: Comparison of daily average relative humidity data from site and Retford air quality monitoring station**

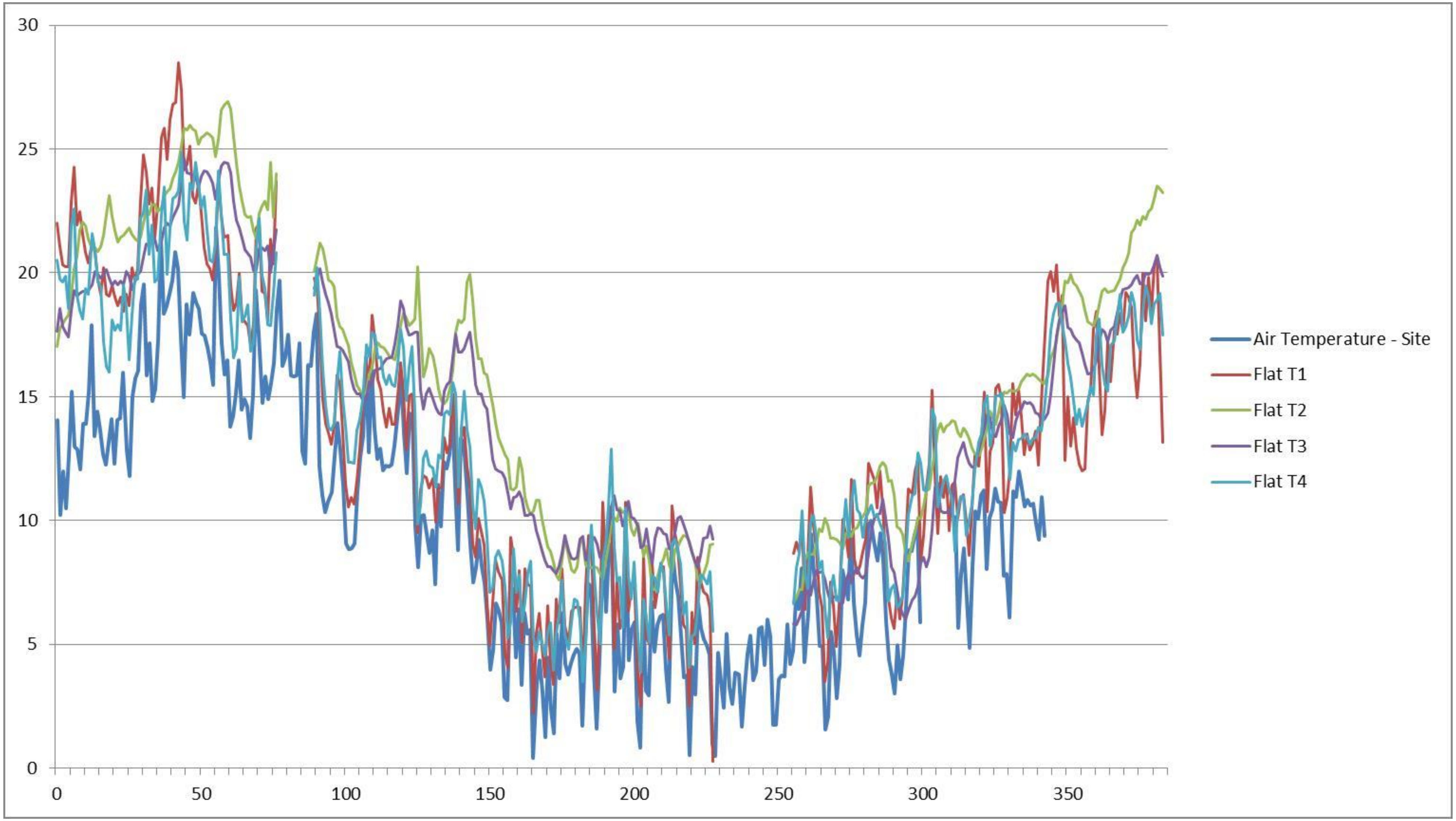


**Figure 11: Thermocouple data from flat pile, with comparison to site air temperature**

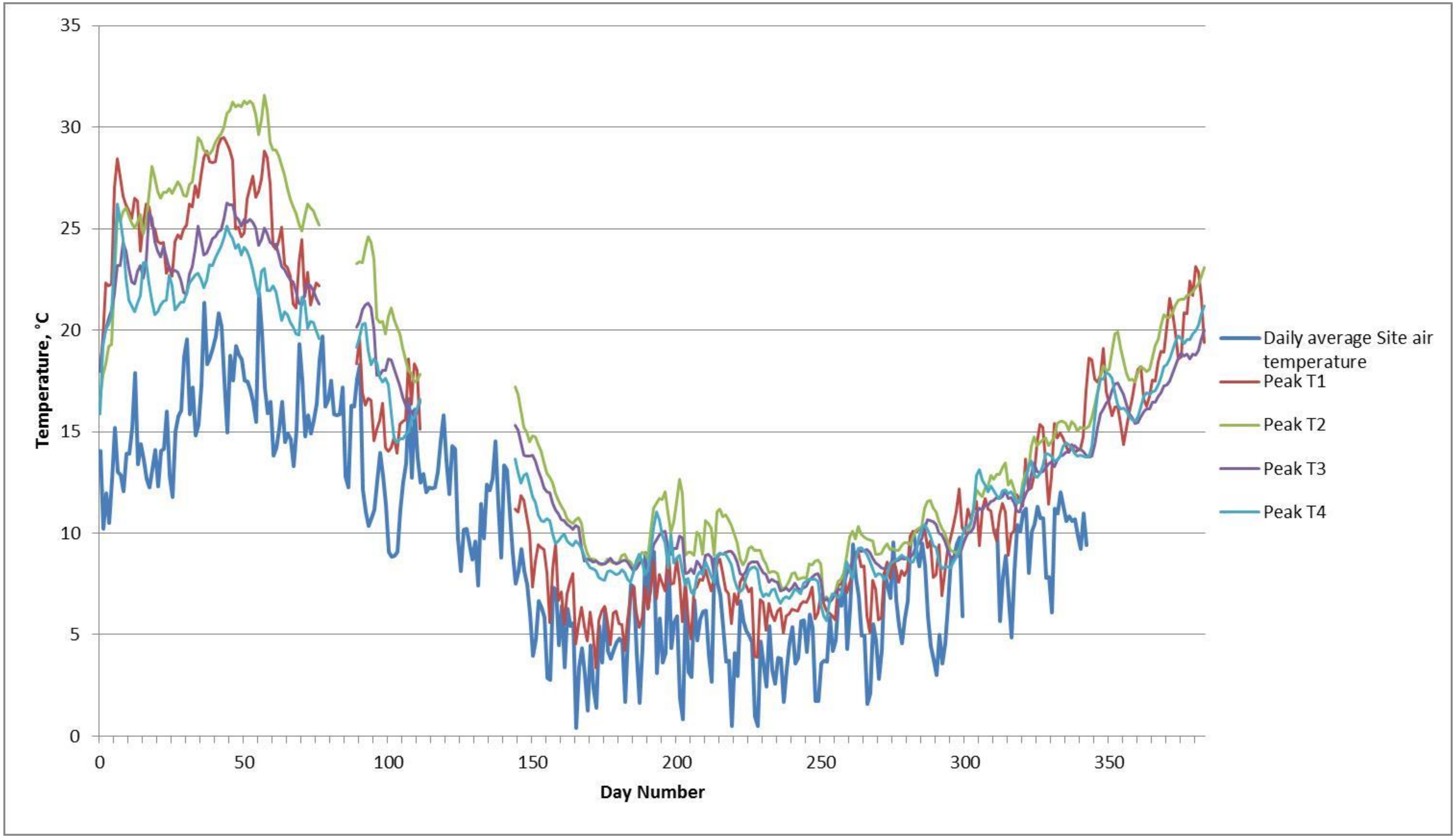


**Figure 12: Thermocouple data from peak pile, with comparison to site air temperature**

### 3.4.3 Chemical Analysis

Full analytical results of the samples taken during the tests are presented in Appendix 1 (Table 15 to Table 18); however the only significant difference between the samples across the year was the moisture content (which therefore impacted on the “as received” analyses of other fuel components). Analyses of the other fuel components remained very consistent when expressed on a dry or dry, ash-free basis.

**Table 1: Moisture content of stockpile samples**

| Day number | Flat Edge | Flat Middle | Peak Edge | Peak Middle |
|---|---|---|---|---|
| **0<br>(as received sample)** | 3.1 | 3.1 | 3.1 | 3.1 |
| **7** | 19.2 | 3.9 | 20.6 | 3.4 |
| **13** | 21.2 | 4.3 | 22.1 | 3.8 |
| **21** | 28.3 | 5 | 31.5 | 6.2 |
| **28** | 14.9 | 5.5 | 13.5 | 4.5 |
| **35** | 5.8 | 4.6 | 5.6 | 4.6 |
| **42** | 6.2 | 4.8 | 5.7 | 4.7 |
| **48** | 13.5 | 8.3 | 9.1 | 4.2 |
| **55** | 16.8 | 7.5 | 15.8 | 4.9 |
| **68** | 12.5 | 10.7 | 10.6 | 5.0 |
| **76** | 8.5 | 10.1 | 7.3 | 4.9 |
| **89** | 8.9 | 18.4 | 9.1 | 10.1 |
| **111** | 8.2 | 9.4 | 6.8 | 14.9 |
| **144** | 34.6 | 18.6 | 38.1 | 20.2 |
| **171** | 34.4 | 30.6 | 34.7 | 26.5 |
| **192** | 30.0 | 32.2 | 25.2 | 23.0 |
| **227** | 34.7 | 30.4 | 40.5 | 39.7 |
| **255** | 25.7 | 34.1 | 24.8 | 31.9 |
| **277** | 18.6 | 30.3 | 19.7 | 29.1 |
| **311** | 16.8 | 32.6 | 12.1 | 29.9 |
| **342** | 16.2 | 43.4 | 12.9 | 32.5 |
| **383** | 18.9 | 35.2 | 14.7 | 33.0 |

### 3.4.4 Physical analysis

Prior to mechanical durability testing, the pellets were dried at 35°C for a minimum of two days. Although standard EN15210:2009-1 specifies the test is undertaken on an “as received” sample, without this drying, the fines within the material clumped and blocked the sieve, resulting in unreliable results. Testing was undertaken in triplicate, with all samples showing good repeatability, and the averaged results are presented in Table 2.

**Table 2: Mechanical durability of stockpile samples**

| Day number | Flat Edge | Flat Middle | Peak Edge | Peak Middle |
|---|---|---|---|---|
| **0<br>(as received sample)** | 97.60 | 97.60 | 97.60 | 97.60 |
| **7** | 77.15 | 96.61 | 74.07 | 96.34 |
| **13** | 74.05 | 96.27 | 69.89 | 95.81 |
| **21** | 75.31 | 95.94 | 71.57 | 94.09 |
| **28** | 74.94 | 96.13 | 75.15 | 96.51 |
| **35** | 84.35 | 96.53 | 80.56 | 96.14 |
| **42** | 80.17 | 94.15 | | |
| **48** | 75.77 | 95.13 | 78.38 | 95.74 |
| **55** | 75.77 | 94.63 | 71.87 | 94.34 |
| **68** | 79.34 | 91.25 | 79.31 | 96.00 |
| **111** | 83.8 | 93.67 | 77.93 | 91.27 |
| **144** | 85.2 | 91.20 | 81.47 | 91.07 |
| **171** | 83.26 | 90.87 | 78.55 | 88.11 |
| **192** | 84.63 | 88.97 | 77.84 | 89.84 |
| **227** | 79.82 | 88.83 | 80.97 | 87.29 |
| **255** | 85.65 | 88.63 | 82.49 | 89.07 |
| **277** | 83.27 | 90.53 | 79.87 | 89.07 |
| **311** | 82.07 | 89.11 | 81.04 | 89.29 |
| **342** | 78.90 | 90.89 | 78.90 | 90.89 |
| **383** | 82.12 | 88.17 | 78.10 | 89.45 |

### 3.4.5 Stockpile Observations

With time, it was noticeable that both piles compacted, to the extent that by month 6 for the flat pile and month 9 for the peak pile, it was no longer possible to use the sampling spear to penetrate into the piles sufficiently to get a suitable “middle” sample and samples had to be taken by digging pits. Whereas during set-up the material was extremely free-flowing, the vertical walls of these pits generally held even down to 50-60cm below the surface of the pile (Figure 13). This compaction, combined with the removal of some of the material during sampling, resulted in the exposure of the topmost thermocouple (T1) in both piles – for the peak pile this occurred by around month 6 and for the flat around month 9, with the result that temperature data after these times reflects the local ambient temperatures rather than the pile temperature.

Dust blow from the stockpiles was not monitored, but there was no obvious dust accumulation around the piles (although note that they were quite exposed) and no visible dust release observed during sampling visits. Similarly, although leachate from the pile was not specifically collected, no evidence of leachate run-off was observed.

Figure 13: Sampling “pit” in flat pile

The loss of the free-flowing characteristic of the material was particularly noticeable during the take-down of the piles, where a central core of material remained after the surrounding cages were removed (see Figure 14 & Figure 15).

Figure 14: Peak pile after removal of supporting cage

**Figure 15: Flat pile immediately after removal of supporting walls**

By the time of the pile take-down, distinct layers of the stockpile were noticeable. The surface layer composed of visibly degraded pellets but with low levels of fines (defined as material which passes a 3.15mm round-hole sieve), whose moisture content varied according to the ambient weather conditions during the sampling (Figure 16). Just below was a layer of very wet material, with a high proportion of fines. This wet layer appeared to remain even when the site had been warm and sunny for a number of days prior to sampling. Underneath this the pellet was mainly very wet, although less degraded than the surface material. However, within this were pockets of pellet which appeared to be completely unchanged from the as received material, with low moisture content and a smooth, shiny surface. These pockets appeared randomly distributed with the pile, and during take-down no correlation was observed between the location of the pockets and either contact with the retaining membrane or with the locations of previous sampling.

**Figure 16: Pellets at the surface of the peak pile**

**Figure 17: Cross section of top of flat pile, showing high fines layer above wetter pellet**

During the pile takedown, these drier areas were particularly noticeable as paler brown bands between the black areas of wet pellets – there was no obvious transition zone between the two, with dry and wet pellets in direct contact (Figure 18 & Figure 19). During the routine collection of “middle” samples, no distinction was made between the wet and dry material so the recorded results will be for a mixture of the two, but during the take-down of the peak pile, a specific sample of the dry pellet was removed from near the centre of the pile. This was shown to have a free moisture content of 6.7%, i.e. significantly lower than that of the general “middle” samples. The durability of 94.7% was also closer to that of the original material than the durability of the other samples taken during stockpile dismantling. Some of the very wet pellets removed from both piles had a tendency to clump together, with a brown liquid held at the surface (Figure 20).

**Figure 18: Vertical face of flat pile during dismantling, showing areas of pellets with different moisture contents**

**Figure 19: Interior of peak pile during dismantling**

Figure 20: Clumping of the wet pellet

Figure 21: Base of peak pile

The concrete base of the peak pile was mainly dry, with no obvious sign of standing water which could indicate poor drainage of the pile (Figure 21). Immediately in contact with the concrete was a fine layer of dry pellet dust. In contrast, some areas of the concrete base to the flat pile were wet, although there was no sign of standing water and other areas were drier (Figure 22). Again, a layer of fines was present immediately in contact with the concrete, although this layer was wetter than for the peak pile.

At various points during the test, limited biological activity on the pile was observed, particularly the growth of plant seedlings on the surface of the peak pile (Figure 23). In general, these were removed by the test team. During removal of the flat pile, it was noticeable that at the bottom of the pile were a high number of earthworms, although these had not been noticeable within the rest of the material (Figure 22). Visible fungal growth was not however observed in either pile.

**Figure 22: Base of flat pile, showing high levels of wet fines and earthworms**

**Figure 23: Seedling growth on peak pile**

## 3.5 Discussion

### 3.5.1 Weather Data

The weather data during the test period, and in particular the rainfall and the number of frost-free days, has been compared with historical data from the UK Met Office for Waddington weather station (located around 40 km from the test site) (UK Met Office, 2014). As shown in Figure 24, the rainfall between July 2013 and June 2014 was close to the average value from 1970 to present, but the number of air frost days seen (15) in the winter of 2013-14 was the lowest seen in this period, indicating a generally mild winter. This is emphasised by the daily average air temperatures at the site, which are all above 0°C. As a result, it is unlikely that the pellets (even those on the surface) would have experienced significant freeze-thaw conditions which could contribute to the break-up of pellet. The data from the UK Met Office does not include information on the monthly average temperatures, but the monthly minimum and maximum temperatures from 1970-2014 have been used to generate an average temperature range through the year, which is compared with the average monthly temperature during testing in Figure 25. As can be seen, the temperatures during testing are generally within the “normal” range, with perhaps a slight bias towards the warmer end of the range, particularly from January 2014 onwards.

The wide year on year variation seen in the rainfall and air frost days in the Met Office data highlights the need for materials to be tested under a variety of climatic conditions, preferably through development of a simplified test rather than through long-term stockpile tests (as there is no way of knowing in advance how “typical” a year would be) before determining their suitability (or not) for long-term outdoors storage.

### 3.5.2 Stockpile temperatures

The interior temperature of both stockpiles was generally higher than the ambient air temperature, although there were no rapid increases in temperature which could indicate the onset of self-heating processes (Figure 11 & Figure 12). This difference between the stockpile temperature and the ambient air appeared to decrease with time (Figure 26). At the start of the tests, daytime absorption of heat by the dark-coloured pellets will create a large thermal inventory which will only fall slowly during the cooler nights, creating a large overall difference between the stockpile and the ambient air temperatures. As the moisture content of the pellets increases, the higher heat capacity of the water compared to the dry pellet would result in a smaller temperature increase for the same amount of heat absorption and so the temperature difference between the pile and the ambient air would be reduced. Thermocouples 2 and 3 in each pile appear to fluctuate least with ambient conditions, being closest to the centre of the pile, while T1, which was close to the surface (and became exposed partway through testing), reflected the changes in air temperature the most. T4 also showed more fluctuation, most likely due to heat transfer through the concrete base. While the winter of 2013-14 did not include any substantial cold periods, during the coolest period of winter (days 150-225), temperatures within the piles were consistently several degrees above the ambient conditions (Table 3).

**Table 3: Comparison of average temperatures within pile and ambient conditions between days 150 and 225.**

| Average Air temperature | 4.8°C | |
|---|---|---|
| Temperatures with test piles, °C | Flat pile | Peak pile |
| T1 | 6.63 | 6.89 |
| T2 | 9.52 | 10.26 |
| T3 | 9.61 | 9.36 |
| T4 | 6.93 | 8.77 |

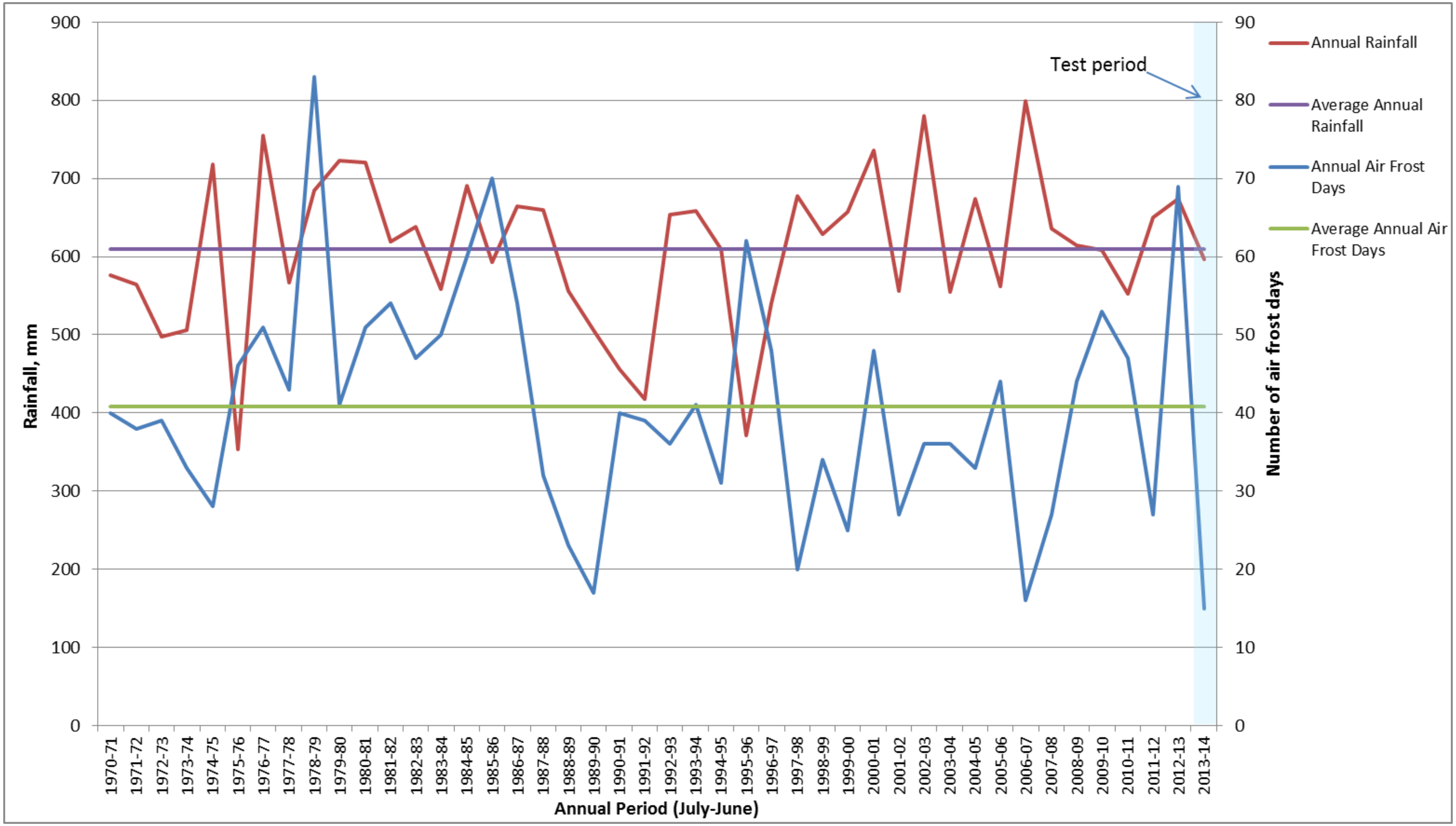


**Figure 24: Annualised rainfall total and number of air frost days from July 1970 to June 2014 at Waddington weather station (Data from UK Met Office, 2014)**

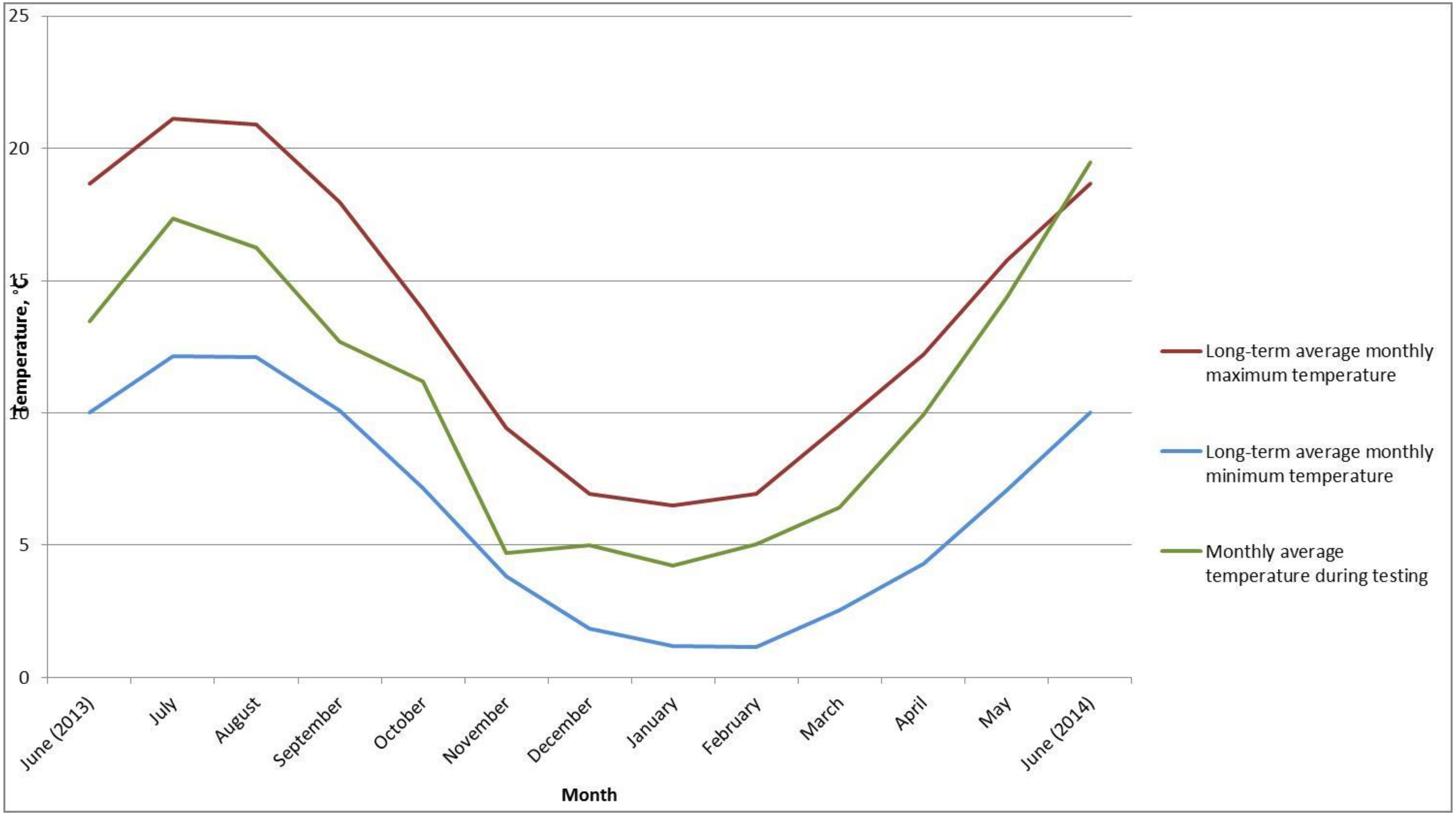


**Figure 25: Monthly average site air temperatures during testing compared with long term (1970-2014) monthly minimum and maximum temperatures at Waddington weather station (Waddington data from UK Met Office, 2014).**

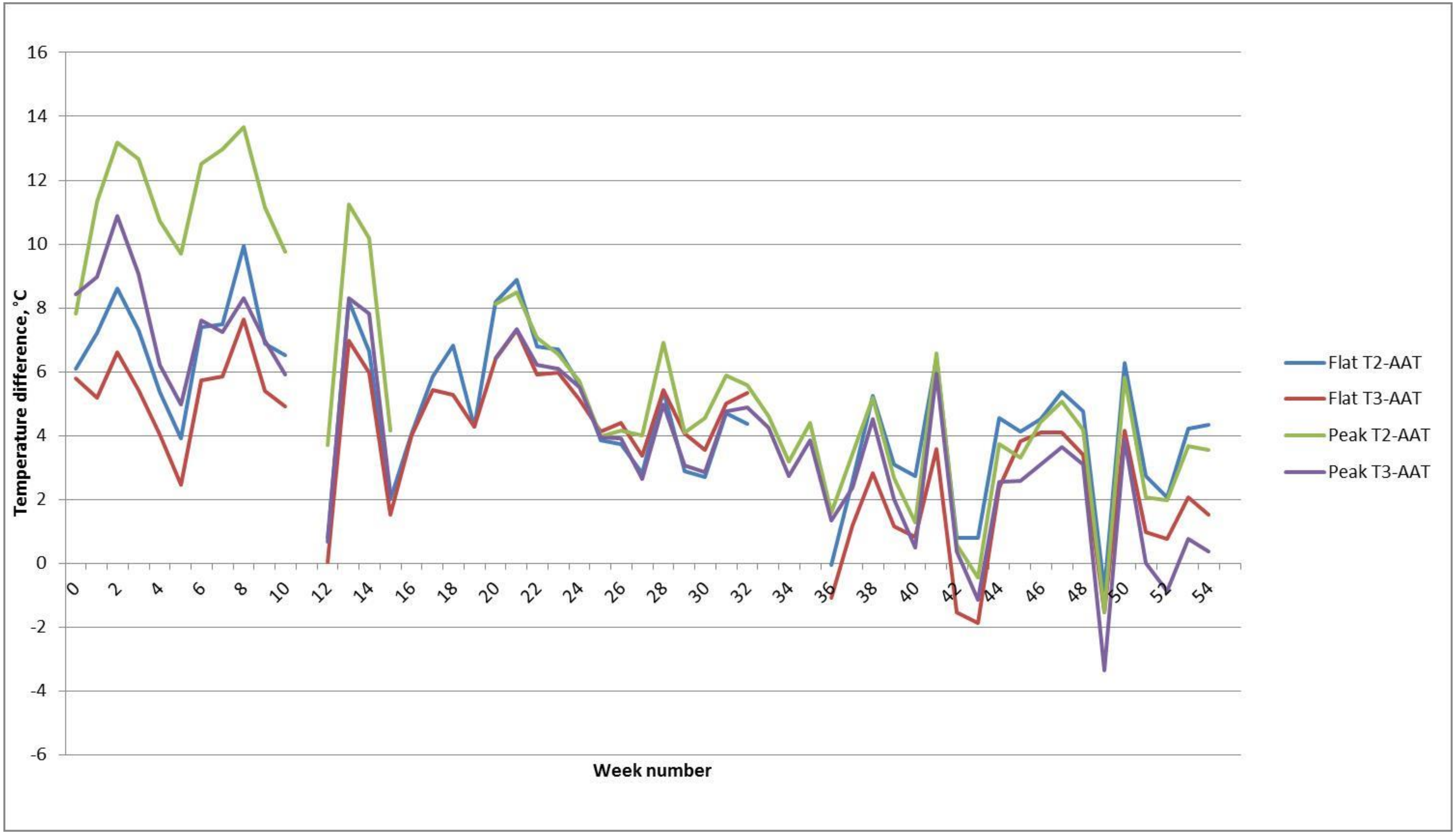


Figure 26: Weekly average differences between the pile thermocouple temperatures and the ambient air temperature (AAT)

### 3.5.3 Chemical Analysis

The variation in moisture content with time is shown in Figure 27, along with the cumulative monthly rainfall data from the Waddington weather station (note the rainfall total for June 2013 will include rainfall from 1-6th June 2013, i.e. before the stockpiles were established). Moisture contents in both peak and flat piles followed similar trends. Although torrefied pellets are commonly described as being hydrophobic, absorption of moisture by the pellet on the surface of both piles was extremely rapid, increasing from 3.1% in the “as received” pellet to around 20% by day 7. The subsequent variation in moisture content of the surface material is believed to reflect the weather conditions around the time of sampling, with the pellet rapidly drying out again in the sun and absorbing water during rainfall. The increase in moisture content of samples from the middle of the pile was slower, due to the delay in water infiltration into the centre of the pile, but showed less variation, following a general upwards trend until moisture contents of around 30-35% were reached. As discussed in Section 3.4.5, it was noted during the pile dismantling that the interior of the pile was not uniform, with visible patches of both very wet and very dry pellets (as well as pellets in between these two extremes). The “middle” samples taken for each pile will consist of a variable mixture of pellets of different moisture contents, so depending on whether the sampling probe reached a “dry” or “wet” pocket, variation in the moisture contents of these samples could be expected.

Although the Net Calorific Value (NCV) of the fuel appears to decrease in time (Figure 28), this is primarily due to the increase in fuel moisture content. Comparison of the dry, ash-free gross calorific values (DAF GCV) of the samples shows no discernible change with time (Figure 29), with the variability generally within that which could be expected from the analytical method. For comparison, the reproducibility limit on GCV for two laboratories analysing the same biomass sample under EN14918 is ±0.3 GJ/te; the majority of samples within the year are therefore within the reproducibility limit of the original “as received” material. Similarly, there is no discernible difference in ash, sulphur or chlorine levels throughout the testing (see Table 15 to Table 18); it should be noted that chlorine and sulphur levels were close to the method detection limit in any case.

The increase in moisture content, and the concurrent decrease in NCV, would have negative impacts on plant operation. One of the proposed advantages of torrefied material compared to white wood pellet, particularly when used in converted coal plant, is the higher as received NCV. Converted plant will have capacity constraints on various plant items, including mills, conveyors, air and flue gas systems, as they will have been designed for higher energy density fuel. The NCV of torrefied fuel lies between that of white wood pellet and coal, so any reduction in NCV would result in these capacity constraints becoming critical. The additional moisture introduced into the boiler would also require extra heat energy for evaporation, reducing plant efficiency.

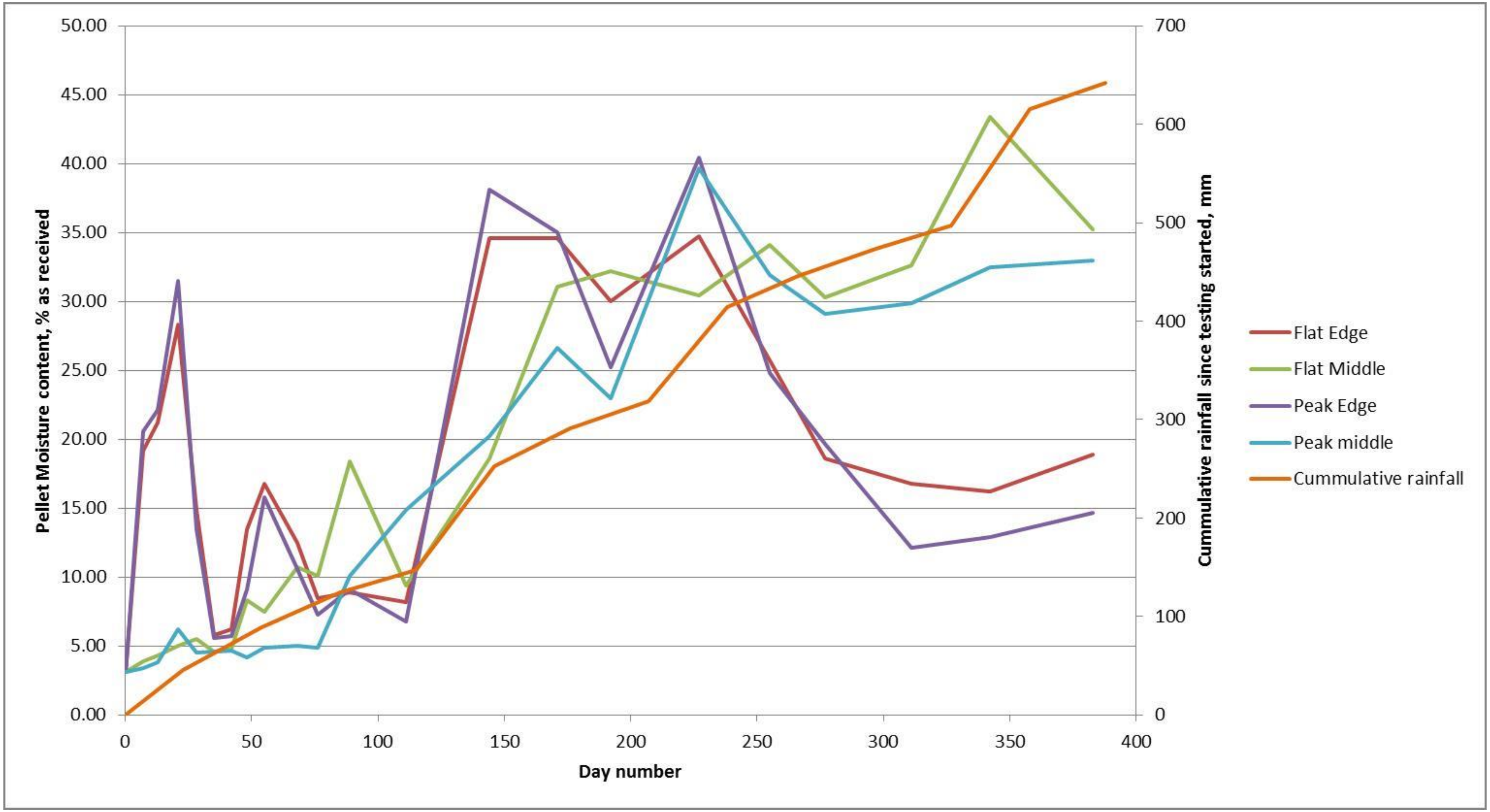


**Figure 27: Variation in pellet moisture content with time and comparison with rainfall data from Waddington weather station**

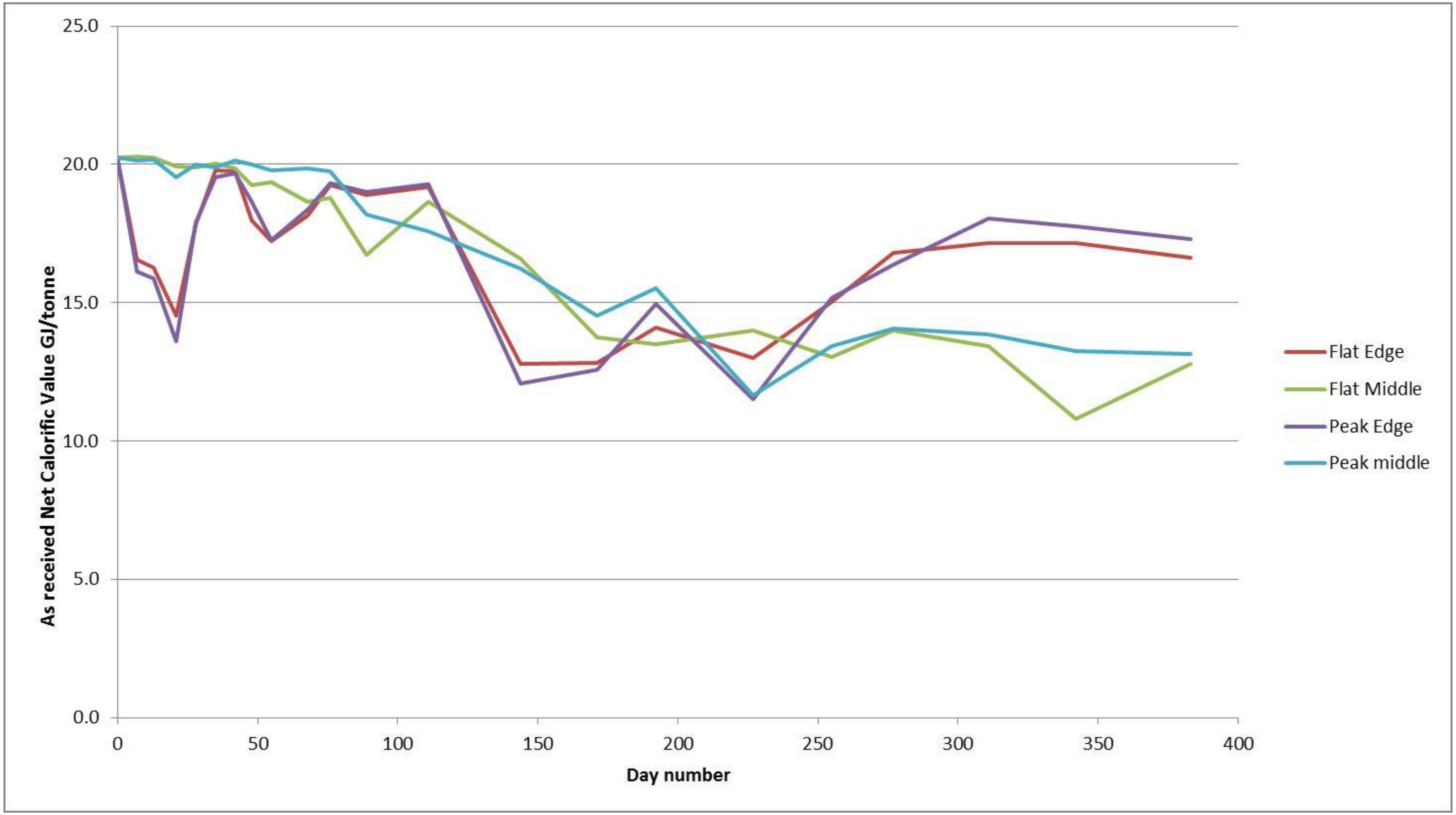


Figure 28: Variation of Net Calorific Value with time

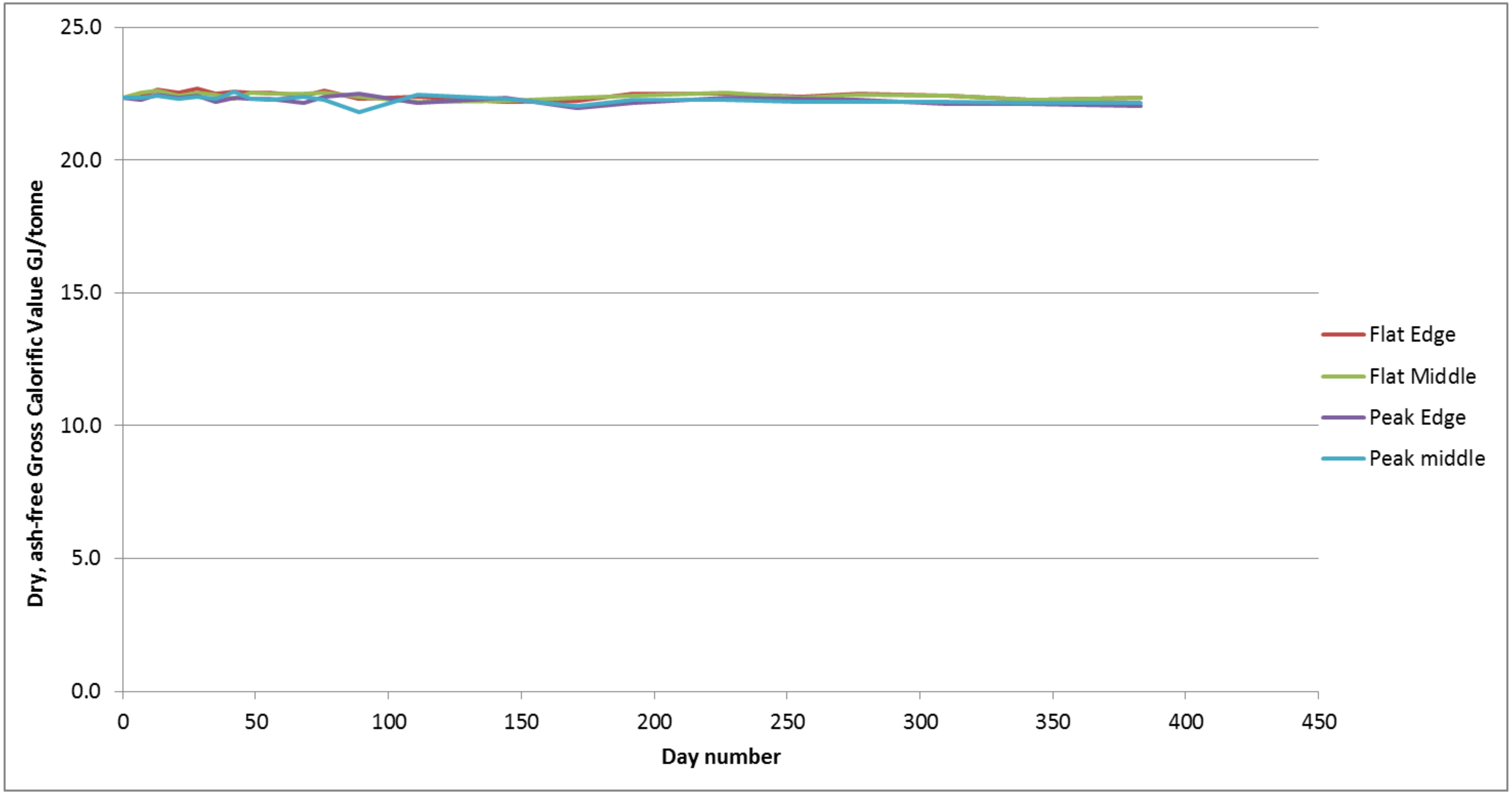


**Figure 29: Variation in dry, ash-free gross calorific value with time**

Should larger scale stockpiles follow the same pattern seen with these tonne-scale tests and contain areas of differing moisture contents, there may also be issues around combustion control as the moisture input to the boiler changes in accordance with the reclaim of different stock areas. This in turn could result in problems such as lower fuel burnout, higher carbon in ash and higher NOx and CO emissions.

### 3.5.4 Physical properties

The durability of the pellet on the surface of the pile decreased rapidly during the first few weeks then appeared to stabilise, and even increase, as shown in Figure 30. This may be due to the rapid loss of the least durable pellets resulting in a “selection” process in which only those pellets durable enough to survive the periods between testing periods remained to be sampled. The durability of the pellet (dried at 35°C before testing) against the total moisture content of the “as sampled” pellet is shown in Figure 31; for the samples taken from the surface of the test piles (edge) there does not appear to be a good correlation.

Within the pile, the deterioration in pellet durability was more gradual but consistent, stabilising reaching around 89% by day 200 but appearing to stabilise at this level for the rest of the testing. Unlike the surface pellet, superficially there does seem to be a correlation between moisture content and durability for the middle sample, but this may be misleading, as both parameters decreased steadily with time (i.e. these may both be effects rather than cause and effect). However, in the additional samples taken during the dismantling of the pile, the pellet durability does seem to decrease with increasing free moisture content (as determined by drying of the samples at 35°C), as shown in Table 4 for the peak pile and Table 5 for the flat.

**Table 4: Free moisture content and durability of peak pile pellets during takedown**

| Depth/sample | Free Moisture, % (dried at 35°C) | Durability |
|---|---|---|
| Surface (Edge sample) | 9.4 | 78.1 |
| 0.4m deep (middle sample) | 23.8 | 89.0 |
| 0.8m deep | 24.4 | 90.3 |
| Base | 19.5 | 90.9 |
| Dry area | 6.9 | 94.7 |

**Table 5: Free moisture content and durability of flat pile pellets during takedown**

| Depth/sample | Free Moisture, % (dried at 35°C) | Durability |
|---|---|---|
| Surface (Edge sample) | 11.5 | 82.1 |
| 0.4m deep (middle sample) | 37.5 | 88.2 |
| 0.65m deep | 24.4 | 89.5 |
| 0.93m deep | 26.8 | 87.3 |
| Base | 12.1 | 94.5 |

Although both piles contained a layer of fines at their base, it is unclear whether this is due to fines filtering down from the material above or breakage of pellet due to crushing within the stockpile.

## 3.6 Conclusions to E.ON Stockpile Testing

Two stockpiles of the same torrefied and pelletised material, each of 3-4 tonnes, were established at a rural test location. The location chosen is close to a number of UK coal-fired power plant and hence representative of the climatic conditions UK coal stockpiles are exposed to.

The results of the testing show that on exposure to outside conditions, the pellets on the surface of the test piles underwent rapid degradation in terms of both moisture content and durability. This surface material was however sensitive to the ambient conditions, drying quickly between rain periods. Below the surface layer of degraded pellets, a layer of very wet and fine material formed, up to around 20 cm thick. Below this layer, pellet degradation was slower but more consistent, with a gradual increase in the moisture content and a corresponding loss in mechanical durability. Large inconsistencies were observed within the piles, with bands of dry pellets which showed much less change from the original pellet than surrounding, wet material. The reasons for this variation within the pile is unclear, but may account for some of the variability in the analysis results, as these would have been affected by the proportion of dry to wet pellets in the samples collected.

Although no mechanical compaction of either stock occurred (as would be the case with long-term coal stocks), with time the piles did compact and agglomerate, making sampling of the middle of the pile more difficult. For the flat pile in particular, sampling via the digging of pits had to be undertaken a few months into the project. The loss of the free flowing characteristics of the pellet with time would be concern in the handling systems. Coal plants generally rely on the material in the bunkers to be free flowing in order to supply the mill feeders, with no mechanical reclamation systems. The agglomerated pellets would therefore be susceptible to causing hang-ups in the boiler and hence loss of the fuel feed.

Only limited evidence of biological activity within the piles was observed, with colonisation by plant seedlings but no visible fungi growth. No evidence of dust blow or leachate run-off from the stockpiles was observed.

While mechanical durability was determined for all samples and used as an indicator of degradation, it was found that the standard EN15210 method required modification (i.e. use of dried rather than as received material) to perform well, due to the tendency of wet fines to stick to the pellet material and the sieve. Following absorption of water, torrefied pellets maintain their pellet shape to a much greater degree than white wood pellet (which swell and disintegrate with moisture levels much above ~10%wt). As the current standard will have been developed using non-torrefied pellets, it is likely that insufficient consideration was given to the issues of pellet/fines mixtures with high moisture contents.

The winter of 2013/14 was milder than usual in this area of the UK, with very few days of air frost. This means that the pellets were not subjected to significant freeze-thaw action which would be expected to accelerate any disintegration. Rainfall levels were close to the long-term annual average. The year on year variation in weather patterns shows the necessity for rapid assessment tests to be developed which can replicate a wider range of climatic conditions to give confidence over the suitability of fuels for storage in different outdoor environments.

Overall, it is considered that these torrefied pellets would not be suitable for long-term outdoor storage, although for short periods they did show much better weather resistance than white wood pellet. They may therefore be advantageous in parts of the supply chain where it is costly to avoid short term exposure to rain, such as ship discharging.

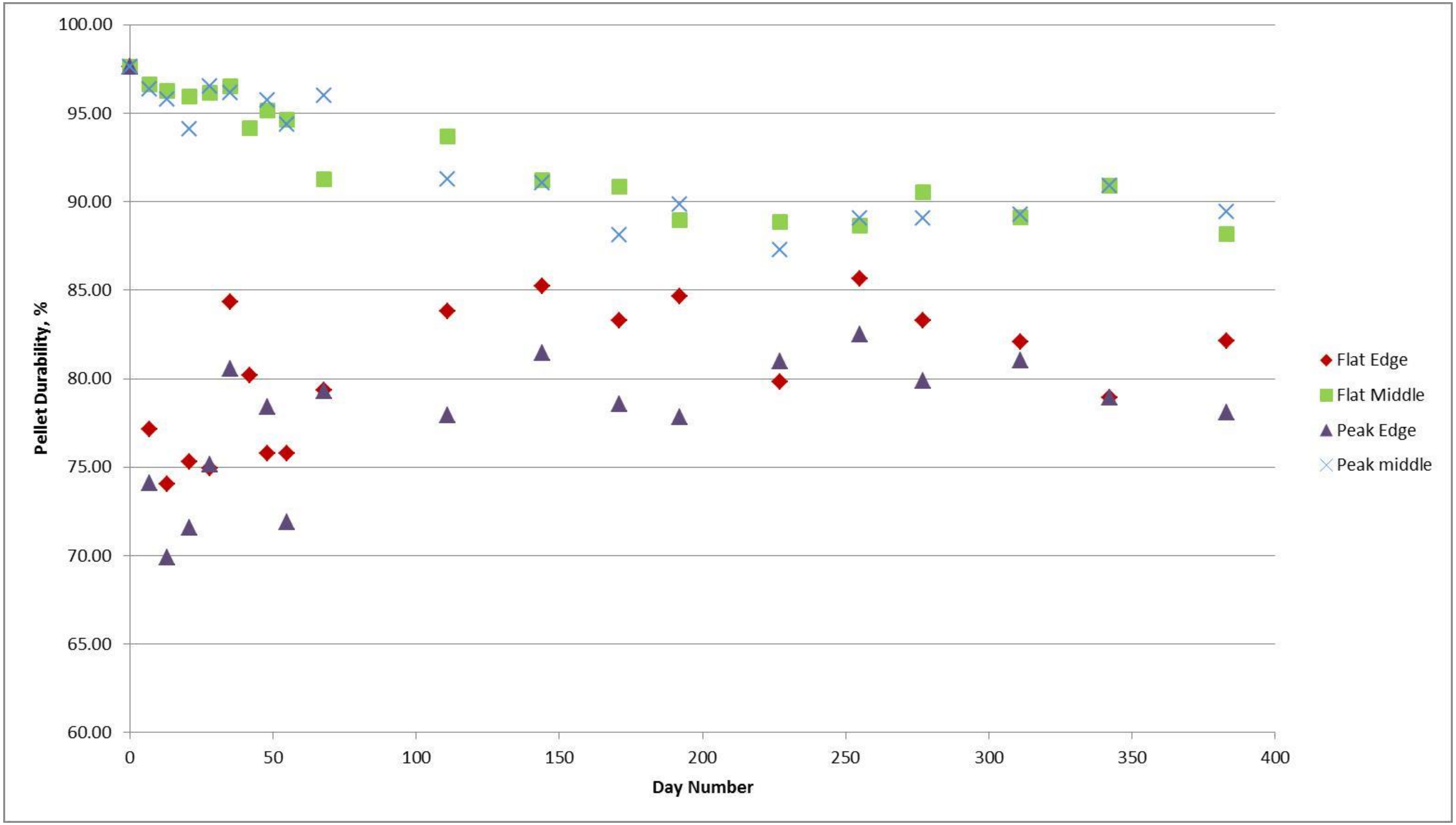


**Figure 30: Change in pellet durability with time**

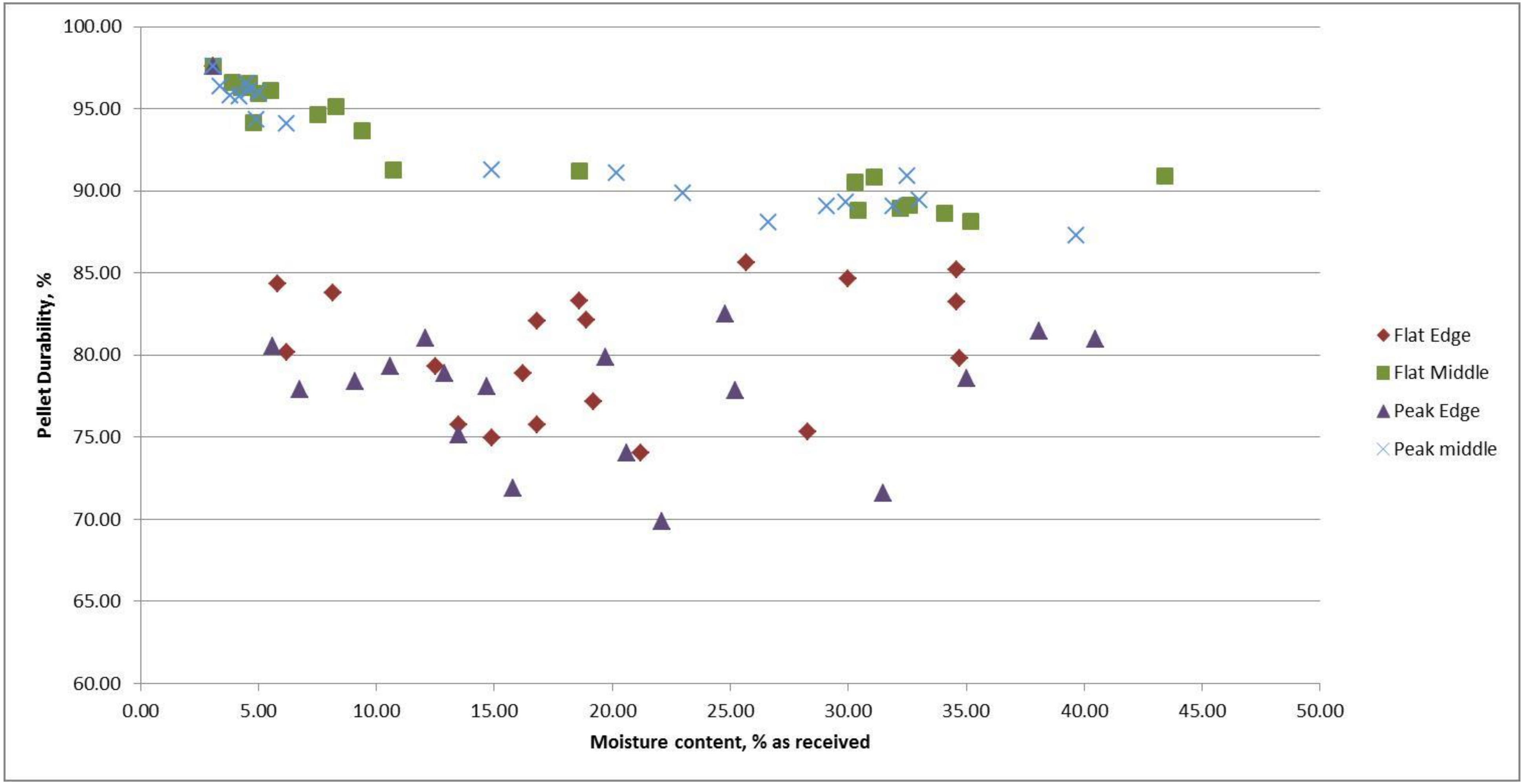


**Figure 31: Impact of moisture content on durability**

# 4 Vattenfall Testing

## 4.1 Introduction

### 4.1.1 Background & objective

This section summarizes the execution and results from Vattenfall's activities within Task 6.2 *Outdoor storage and handling tests*. The objective with the work has been two-fold:

- Small scale long term outdoor storage testing of two different types of torrefied pellets produced within the SECTOR project that should provide an indication if outdoor storage could be a viable option for large scale commercial applications
- Small scale handling tests to provide an indication of the expected handling properties and behaviour of torrefied pellets in existing coal handling lines

### 4.1.2 Deviations from Description of Work document

In the original Description of Work (DoW) document it was specified that Vattenfall's outdoor stockpile testing was supposed to be carried out on mixtures of coal and torrefied pellets. As it is highly unlikely that coal and torrefied pellets would be stored together at Vattenfall's (or any other power plant operator's) existing power stations this was considered irrelevant and it was jointly decided together with the work package leader to carry out the outdoor storage testing just on the torrefied pellets and not any mixtures.

According to the DoW document Vattenfall was also supposed to carry out tests and provide information regarding handling of 100-1000 kg torrefied material in one of the existing coal handling lines at a power plant to check the suitability of this line for handling of torrefied materials. During these tests, loss of material and formation of dust were supposed to be closely monitored. Considering that the majority of the Vattenfall plants that potentially could be candidates for co-combustion of torrefied pellets have a thermal capacity of > 600 $MW_{th}$ that would correspond a flow of torrefied pellets of > 30 kg/s it was not reasonable to believe that it would be possible to draw any useful conclusions based on the relatively small amounts of torrefied material made available to Vattenfall for handling tests within the frames of the SECTOR project (the amount of pellets provided within the project for this purpose would be consumed in less than 1 minute). Instead some experimental tests were carried out, that together with some conclusions from previous larger scale tests carried out by Vattenfall should provide an indication of how the torrefied material would behave in an existing plant in terms of dust formation and material loss.

## 4.2 Vattenfall Small Scale Outdoor Storage tests

### 4.2.1 Test Location

Both the outdoor stockpile testing and handling tests of the torrefied pellets have been carried out at Vattenfall's R&D centre in Älvkarleby (located ~150 km north of Stockholm, Sweden) (coordinates 60°34′N, 17°27′E) (Figure 32).

Selection of this site over an existing power plant site was primarily based on better practical conditions for supervision and monitoring of the pellets during the test duration. The site also provides the possibility to draw conclusions regarding impact of winter climate with prolonged times well below freezing degrees on the pellet properties.

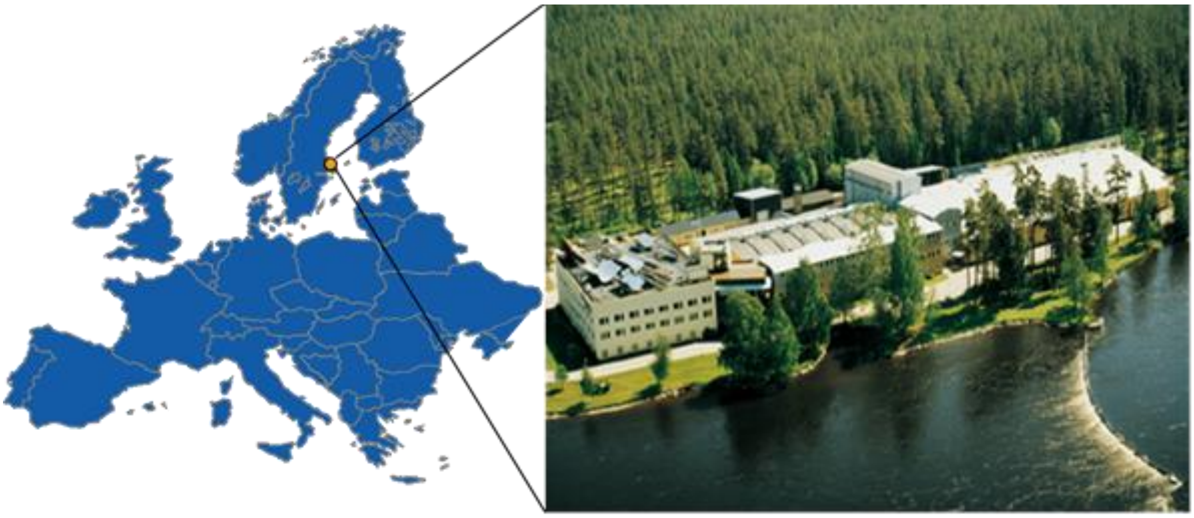


**Figure 32: Vattenfall's R&D centre in Älvkarleby, Sweden, used as location for the SECTOR outdoor storage and handling tests.**

### 4.2.2 Pellet grades

Within the SECTOR project Vattenfall was provided with two different pellet types according to:

- Poplar pellets – Torrefied by ECN in the Netherlands and pelletised at Andritz torrefaction pilot facility in Denmark. Total amount received ~4 tonnes.
- Spruce pellets – Torrefied and pelletised at Andritz torrefaction pilot facility in Denmark (sourced through Topell). Total amount received ~2 tonnes.

The pellets were transported from Andritz pilot facility in Denmark by means of truck. The pellets were packed in air tight big bags. The shipment arrived at Vattenfall's R&D centre the last week of May 2013 and the bags were stored outdoor but under roof and unopened until mid-June 2013 when the pellets were placed in the storage construction and the test period officially started.

Of the ~4 tonnes of poplar pellets received 2 tonnes were earmarked for handling tests.

### 4.2.3 Outdoor stockpile testing methodology

As the total volume of pellets available for the stockpile testing was relatively small, Vattenfall discussed and considered several different potential storage options/designs that could be applied in order to be able to simulate larger volumes of pellets, at least from a stock pile temperature perspective. The selection finally fell on a "Piece of Cake" solution as depicted in Figure 33. A more detailed drawing including the main dimensions of the storage construction is attached in appendix 2.

The storage construction was designed in water repellent plywood in order not to accumulate moisture in the construction itself that potentially could impact the results. Two hatches were added on the back to allow easy access for sampling of pellets (one hatch for each quality of pellets tested). The construction was also designed with a bottom with a slight angle of inclination in order to collect and lead any leach water produced during the test period to a pipe and subsequent leach water storage containers.

In order to keep the pellets in place during the test period the pellet piles were covered with a thin layer of "chicken wire".

During the trials the spruce pellets have been facing north-west while the poplar pellets have been facing south-west. The back of the storage construction has consequently been facing east.

**Figure 33: Outdoor storage construction used for testing of the SECTOR spruce and poplar pellets at Vattenfall's R&D centre in Älvkarleby, Sweden.**

### 4.2.4 Sampling plan and methodology

#### 4.2.4.1 Sampling plan

Table 6 summarises the main measurements as carried out during the test period. The tests were carried out from mid-June 2013 to end March 2014. Originally the plan was to test the pellets for a 6 month period in accordance with the DoW document, but this was extended in order to also be able to evaluate the effect of the winter conditions with months of snow and temperatures well below the freezing point.

All of the solid samples have been sent for analyses at an external accredited laboratory, Belab AB, which carries out the majority of the fuel analysis for Vattenfall's Nordic biomass fired plants.

The leach water analyses have been carried out by ALS Scandinavia, also an accredited laboratory in Sweden.

**Table 6: Sampling plan as applied for Vattenfall's outdoor storage and handling tests.**

| *Parameter* | *Standard* | *Frequency* | *Total nr. of samples* | *Comments* |
|---|---|---|---|---|
| Weather data<br>- *Ambient temperature*<br>- *Pressure*<br>- *Relative humidity*<br>- *Wind direction/speed*<br>- *Rain/snowfall*<br>- *Global irradiation* | - | Countinous | - | *Weather data provided by Swedish Metrological and Hydrological Institute SMHI). Daily averages (24h). Data based on a combination of data from actual local weather stations and the MESAN system.* |
| Ambient temperature | - | Countinous | - | *Local measurement logged countinously throughout the trials.* |
| Stockpile temprerature | - | Countinous | - | *Measured at three different positions in each pile, i.e. total of 6 measurements* |
| Sample preparation | *EN 14780:2011* | ~Monthly | 38 | - |
| Proximate analysis<br>- *Moisture*<br>- *Ash*<br>- *Volatiles*<br>- *Fixed C* | <br>*EN 14774:2009*<br>*EN 14775:2009*<br>*EN 15148:2009*<br>*Calculated* | ~Monthly | 38 | *All analyses carried out by accredited laboratory (Belab AB). Multiple paralell samples at start/end.* |
| Ultimate analysis<br>- *C, H, N*<br>- *O*<br>- *Cl, S* | <br>*EN 15104:2011*<br>*Calculated*<br>*EN 15289:2011* | Start/end | 8 | *All analyses carried out by accredited laboratory (Belab AB). Multiple paralell samples at start/end.* |
| Heating value<br>- *Calorific, effective* | <br>*EN 14918:2010* | ~Monthly | 38 | - |
| Ash melting | *EN 15370:2007* | Start/end | 4 | - |
| Bulk density | *EN 15103:2010* | Start/end | 14 | - |
| Mechanical Durability | *EN 15210:2010* | Start/end | 14 | - |
| Energy density | *Calculated* | Start/end | 14 | - |
| Sieve analysis | *EN 15149:2010* | Once | 1 | *One sieve analysis carried out and used for the "extended mechanical durability" test* |
| Leach water analysis | *EN 12457-4 to generate water analysed. See appendix 4 for specifics on component level.* | Once | 2 | *Not analysed continously. One lab induced test carried out on each of the pellet types. Analyses carried out by accredited laboratory (ALS Scandinavia)* |

#### 4.2.4.2 Sampling procedure

Pellet samples have been taken from the piles on a roughly monthly basis throughout the test period. Samples have been taken both from the surface layers of the piles as well as from the hatches at the back of the storage construction, believed to best represent the condition inside the piles.

Originally the plan was to take out the pellet samples about 20-30 cm into the piles from the hatch. However, due to the very free flowing nature of the pellets that quite easily start to pour out from the hatch as soon as it is opened, this proved to be difficult. In order to achieve as representative sampling as possible and to largest possible extent avoid pellets that could have been in direct in contact with the storage construction walls (that potentially could have higher moisture content due to water flowing down the walls), the initial pellets flowing out from the hatch at every sampling occasion was discarded. After that a sample of roughly 5 kg has been collected in a plastic bucket, very carefully mixed (in order not to damage any pellets) after which a final sample of ~1 kg has been collected and sent to the lab for analysis. The only difference was at the initial and final sampling occasions at which 5 kg of each sample was sent to the lab for analysis.

The surface samples have been extracted 5-10 cm into the piles in order to avoid possible contamination of objects blown onto the piles (for example leaves, etc. from nearby trees). Otherwise the same strategy as described above has been applied, i.e. larger sample extracted that has been carefully mixed and from which the final sample of ~1 kg has been taken and sent for analyses.

The samples sent to laboratory have been packed and transported in air tight plastic zip bags and the time from sampling to analysis at the lab has been ~2-3 days.

## 4.3 Analysis results

Table 7 provides a summary of the measured and analysed data for the poplar and spruce pellets at the start and end of the test period. As mentioned previously, the test period duration was mid June 2013 to end Mars 2014, roughly 9 months.

Originally the plan was only to sample and analyse the pellets from the hatch at the back of the storage constructions which is believed to best represent the inside conditions of the piles, but it was decided early on that it also would be of interest to test the pellets closer to the surface of the piles to establish the impact of the direct exposure to ambient conditions.

**Table 7: Main results from the analyses carried out at the poplar and spruce samples at the start and end of the ~9 month test period.**

| Parameter | Unit | Poplar | | | Spruce | | |
|---|---|---|---|---|---|---|---|
| Time | | June '13 | Mars '14 | Mars '14 | June '13 | Mars '14 | Mars '14 |
| Position | | Bags | Inside | Surface | Bags | Inside | Surface |
| **Ultimate analysis** | | | | | | | |
| Moisture | [%] | 3,90 | 32,03 | 33,90 | 3,93 | 34,03 | 37,10 |
| Ash | [%] | 0,67 | 0,43 | 0,40 | 0,43 | 0,20 | < 0.30 |
| Ash | [% (db)] | 0,70 | 0,67 | 0,70 | 0,45 | 0,31 | < 0.30 |
| Volatiles | [%] | 75,17 | 52,83 | 51,60 | 71,07 | 50,27 | 47,90 |
| Volatiles | [% (db)] | 78,23 | 77,73 | 78,00 | 73,97 | 76,20 | 76,10 |
| Fixed carbon | [%] | 20,26 | 14,70 | 14,10 | 24,57 | 15,50 | > 14.7 |
| Fixed carbon | [% (db)] | 21,06 | 21,60 | 21,30 | 25,58 | 23,49 | > 23.6 |
| **Proximate analysis** | | | | | | | |
| Carbon (C) | [%] | 51,03 | 36,90 | - | 53,13 | 36,20 | - |
| Carbon (C) | [% (db)] | 53,10 | 53,10 | - | 55,30 | 55,10 | - |
| Hydrogen (H) | [%] | 6,10 | 7,50 | - | 6,00 | 7,70 | - |
| Hydrogen (H) | [% (db)] | 5,90 | 6,10 | - | 5,80 | 6,07 | - |
| Nitrogen (N) | [%] | < 0.10 | < 0.10 | - | < 0.10 | 0,08 | - |
| Nitrogen (N) | [% (db)] | < 0.10 | < 0.10 | - | < 0.10 | 0,12 | - |
| Oxygen (O) | [%] | 42,13 | 42,20 | - | 40,33 | 55,90 | - |
| Oxygen (O) | [% (db)] | 40,23 | 40,30 | - | 38,33 | 38,60 | - |
| Chlorine (Cl) | [%] | < 0.02 | < 0.02 | - | < 0.02 | < 0.02 | - |
| Chlorine (Cl) | [% (db)] | < 0.02 | < 0.02 | - | < 0.02 | < 0.02 | - |
| Sulphur (S) | [%] | 0,012 | 0,012 | - | < 0.012 | < 0.012 | - |
| Sulphur (S) | [% (db)] | 0,012 | 0,012 | - | < 0.012 | < 0.012 | - |
| **Heating value** | | | | | | | |
| LHV | [MJ/kg] | 19,28 | 12,86 | 12,40 | 19,92 | 12,98 | 12,32 |
| LHV | [MJ/kg (db)] | 20,16 | 20,07 | 20,02 | 20,84 | 20,94 | 21,03 |
| LHV | [MWh/ton] | 5,35 | 3,57 | 3,45 | 5,53 | 3,60 | 3,42 |
| LHV | [MWh/ton (db)] | 5,60 | 5,57 | 5,56 | 5,79 | 5,81 | 5,84 |
| **Ash melting** | | | | | | | |
| Shrinking temp, ST | [C] | 825 | 730 | - | 815 | 830 | - |
| Deformation temp, DT | [C] | 1500 | 1260 | - | 1430 | 1390 | - |
| Hemisphere temp, HT | [C] | > 1500 | > 1500 | - | 1445 | 1420 | - |
| Flow temp, FT | [C] | > 1500 | > 1500 | - | 1485 | 1430 | - |
| **Physical properties** | | | | | | | |
| Mechanical durability | [%] | 97,5 | 89,0 | 94,0 | 96,4 | 93,8 | 95,4 |
| Bulk density | [kg/m3] | 700,7 | 710,0 | 706,0 | 708,0 | 711,0 | 710,0 |
| Energy density | [MJ/m3] | 13508 | 9130 | 8757 | 14105 | 9230 | 8750 |
| Energy density | [MWh/m3] | 3,75 | 2,54 | 2,43 | 3,92 | 2,56 | 2,43 |

At arrival both the poplar and spruce pellets had a low moisture content of less than 4% on average. In terms of heating value (LHV) on as received basis the poplar pellets had heating value of ~19,3 MJ/kg while the spruce pellets had a slightly higher heating value of 19,9 MJ/kg. As the exact torrefaction conditions applied during the production process of the two different pellet types is unknown it is difficult to pinpoint how much of the difference is related to the torrefaction process conditions applied and how much is related to the inherent differences between soft wood and hard wood. Normally soft woods have a slightly higher heating value than hard woods.

The heating values of both the poplar and spruce pellets, while within the indicative range of 18-22 MJ/kg used in the SECTOR project, are lower than the 21-23 MJ/kg that utilities were told as the possible expected range by some torrefaction technology vendors. Relatively high heating values in combination with high bulk densities are desired to reduce the transportation costs.

As a likely consequence of the lower heating values and the milder degree of torrefaction, both pellet types had a quite high mechanical durability at arrival. Although both pellet types just missed the target of 98% as is the wood pellet standard, this is still higher or in the range of the best quality torrefied pellets (in terms of mechanical durability) that Vattenfall has received and tested.

The following sections provide a more detailed discussion regarding the main results and how the most relevant parameters were developed over time during the trials.

### 4.3.1 Weather conditions during the trials

All the weather data (with exception of a local temperature measurement at the test site) has been provided by the Swedish Metrological and Hydrological Institute (SMHI). The data provided is a combination of measurement data from local weather stations as well as data from the so-called MESAN (MESoscale ANalysis system), which is a system taking many different types of observations into account such as multivariate observational data synoptic stations, automatic weather stations, satellites and weather radars to provide best possible estimates of specific parameters for any given coordinate. Data provided by the system is well validated and used in many commercial applications and is without any doubt accurate and representative enough for the purposes of the storage tests. Figure 34 shows for example the ambient temperature (daily averages) as logged locally at the piles during the trials compared to the temperature data as provided by SMHI. As can be seen there is a very good agreement between the results throughout the test period.

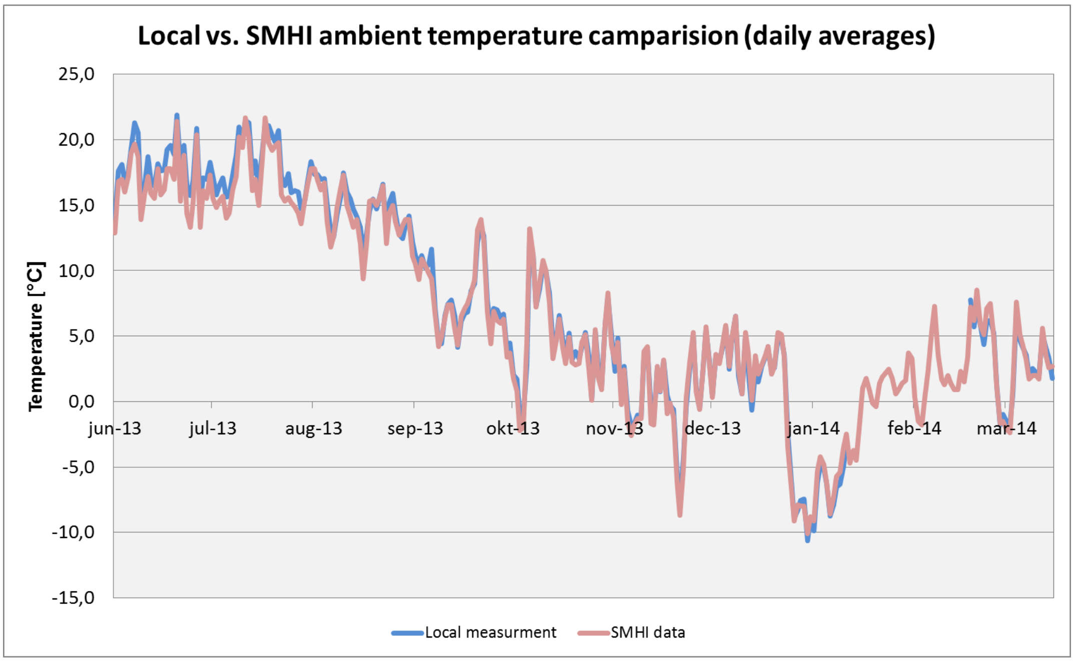


**Figure 34: Comparison of the ambient temperature as logged locally at the storage site and the data as received from SMHI during the test period. Values daily averages (24 hours).**

From Figure 34 it can be concluded that the pellets have been exposed to a relatively wide range of ambient temperatures during the trials. As the temperatures presented in the figure are daily averages, the temperature have momentarily been higher as well as lower than presented in the figure. The highest observed temperature during the trials (hourly average) was +33.1°C registered in July 2013 while the lowest observed temperature was -19.8°C registered in January 2014.

Due to some unfortunate failures in the local temperature logging, as further explained in the next section, data for the local on-site temperature measurement is missing for a period from the end January until the beginning of March 2014.

Figure 35 shows the accumulated rain/snowfall during the trial period. The figure also provide the times at which solid samples were taken from the piles. Generally, no sampling was done at days with heavy rainfall.

As can be seen the pellet piles have been exposed to roughly 375 mm rain/snowfall during the test period, meaning that each of the piles have been exposed to roughly 1.8 $m^3$ of water during the trial period.

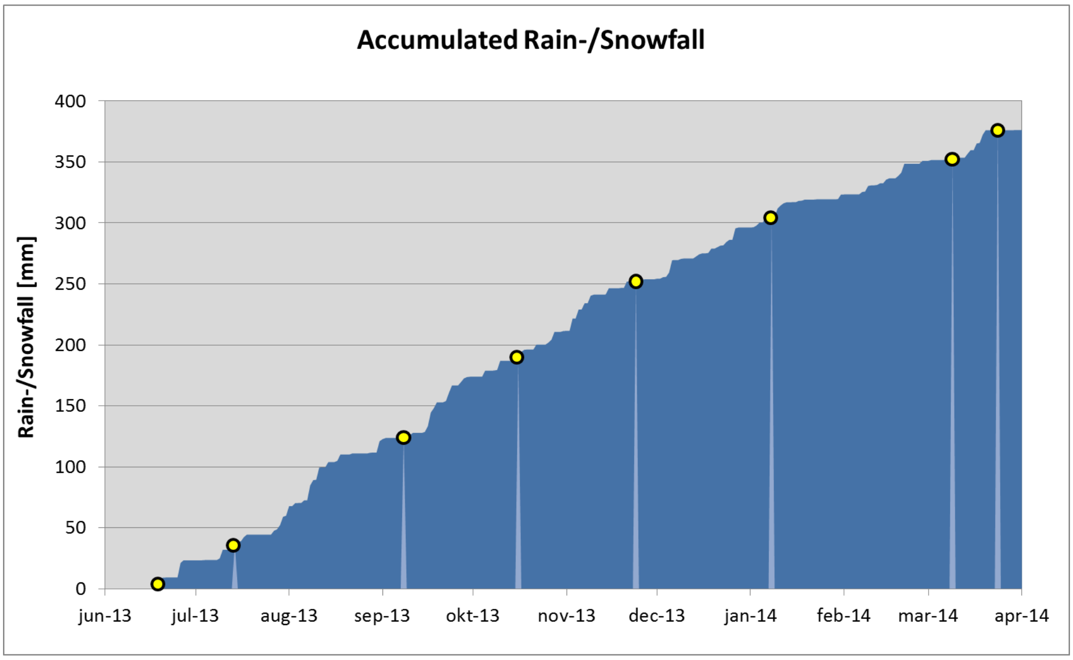


**Figure 35: The accumulated rain-/snowfall during the test period. The yellow dots mark the dates at which samples were taken out from the piles.**

### 4.3.2 Temperature in stock piles

During the test period, the temperature in the piles was measured and logged at 3 different positions in each pile according to Table 8. A separate ambient temperature measurement was also placed at the back of the pellet piles (facing east and placed protected from direct exposure to sunshine) to continuously log the local on-site ambient temperature during the test period.

In general the difference between the individual temperature measurements within the piles have been relatively small and roughly been following the same trends, as can be seen in Figure 36. Some measurements deviate a little more than others during certain periods, but follow in general the same trends. No significant differences between the poplar and spruce pellets can be observed.

**Table 8: Position of the temperature measurements in the stockpiles.**

| Stockpile temperature measurements | | | |
|---|---|---|---|
| | From centre wall [mm] | From back wall [mm] | From bottom [mm] |
| **Spruce position 1** | 300 | 300 | 1000 |
| **Spruce position 2** | 300 | 300 | 300 |
| **Spruce position 3** | 1000 | 1000 | 300 |
| **Poplar position 1** | 300 | 300 | 1000 |
| **Poplar position 2** | 300 | 300 | 300 |
| **Poplar position 3** | 1000 | 1000 | 300 |

Figure 37 shows how the temperature in the most centre measurement in the two piles (corresponding to Spruce/Poplar position 2 in Table 3) compared to the local on-site measured ambient temperature during the entire test period. Due to some technical problems with the temperature logger and a period with failure of the logger power supply, data is unfortunately missing from a period of 2 weeks in December 2013 as well as the majority of February 2014.

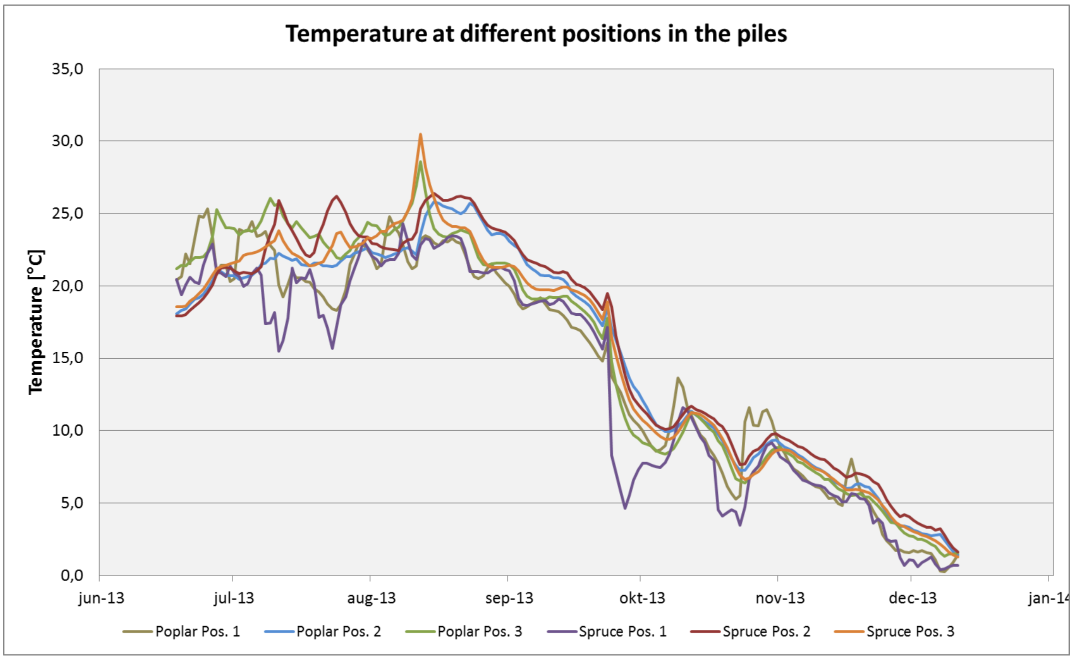


**Figure 36: Temperature at the different measurement positions in the stockpiles during the first 6 months of testing.**

From Figure 37 it can be concluded that the stock pile temperatures follow the outside temperature relatively closely. There is a short period in august during which the stock pile temperatures have been at a constant or slightly increasing level despite a declining trend in ambient temperature.

However, this is very likely due to the fact that daytime temperature and global irradiation has been quite high during this period and this in combination with the quite dark colour of the pellets have resulted in that the “thermal inventory” built up in the piles during the summer months has continued during daytime despite a lower daily average ambient temperature (primarily due to lower temperatures during night time).

The main conclusion from the stockpile temperature measurements is that there have not been clear indications of self-heating taking place in the stockpiles during the test period and that the stock pile temperatures have followed the ambient temperature relatively closely for the majority of the test period.

If this is due to the properties of the torrefied pellets or if the size of the piles (amount of pellets) simply has been too small to generate any representative effects regarding self-heating is difficult to conclude from these tests, but it is very likely that the volume of the piles have been too small to result in any tendencies of self-heating.

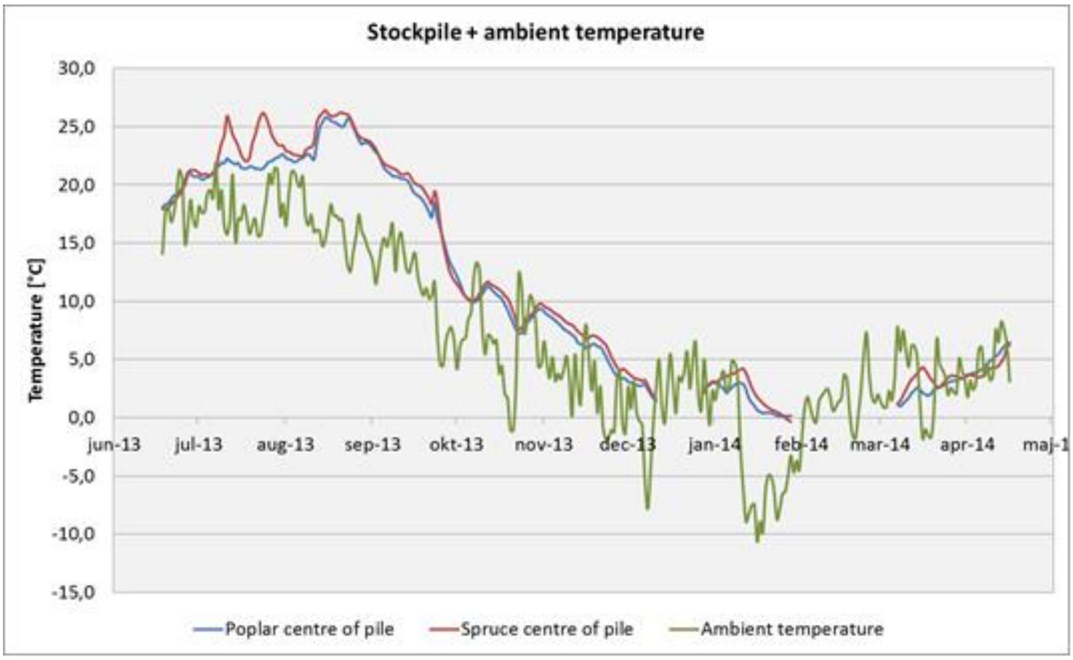


**Figure 37: Temperature in the centre of the piles compared to the ambient temperature during the test period.**

### 4.3.3 Pellet moisture content

Figure 38 summarise the results from the pellet moisture content analyses throughout the test period. Generally it can be seen that the moisture content has increased quite drastically during the test period, inside as well as close to the surface of the piles. From the initial moisture content of ~4% the moisture content at the end of the test period is close to ~35% both inside as well as on the surface of the piles. Both the poplar and spruce pellets seems to behave relatively similar in terms of moisture uptake although the spruce pellets seems to have absorbed moisture at a slightly higher rate than the poplar pellets.

Logically, the moisture content have increased faster at the surface layer that has been directly exposed to ambient conditions indicating that the pellets absorb moisture up to a certain level, after which the moisture gradually migrates further into the pile. That this has been the case is further confirmed by the fact it took several months before any leach water was collected from the piles (the first leach water was observed in beginning of September, roughly 2.5 months from the start of the trials).

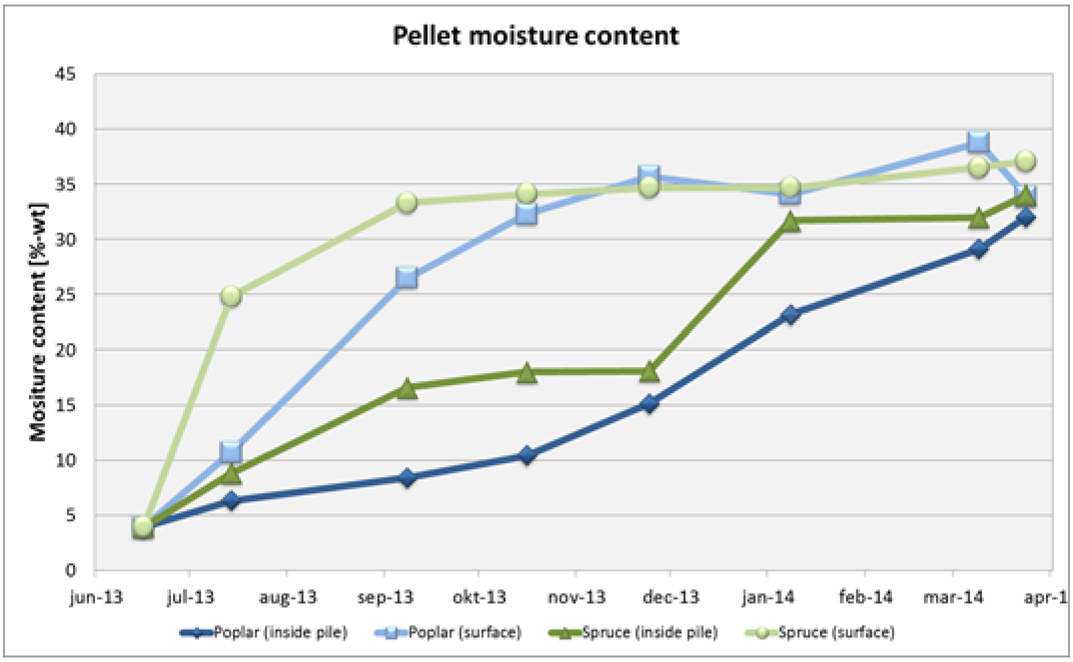


**Figure 38: Pellet moisture content inside as well as surface of the stockpiles during the test period.**

This significant increase in moisture content is obviously an area of concern and will have several implications as discussed in subsequent sections.

### 4.3.4 Pellet heating value

Figure 39 shows how the lower heating value (LHV) of the pellets on as received (ar) basis has developed during the test period. As the LHV(ar) is a direct function of the moisture content, a significant decrease can be observed during the test period. From an initial LHV(ar) of 19.3-19.9 MJ/kg the heating value decreases to ~12-13 MJ/kg for both the spruce and poplar pellets.

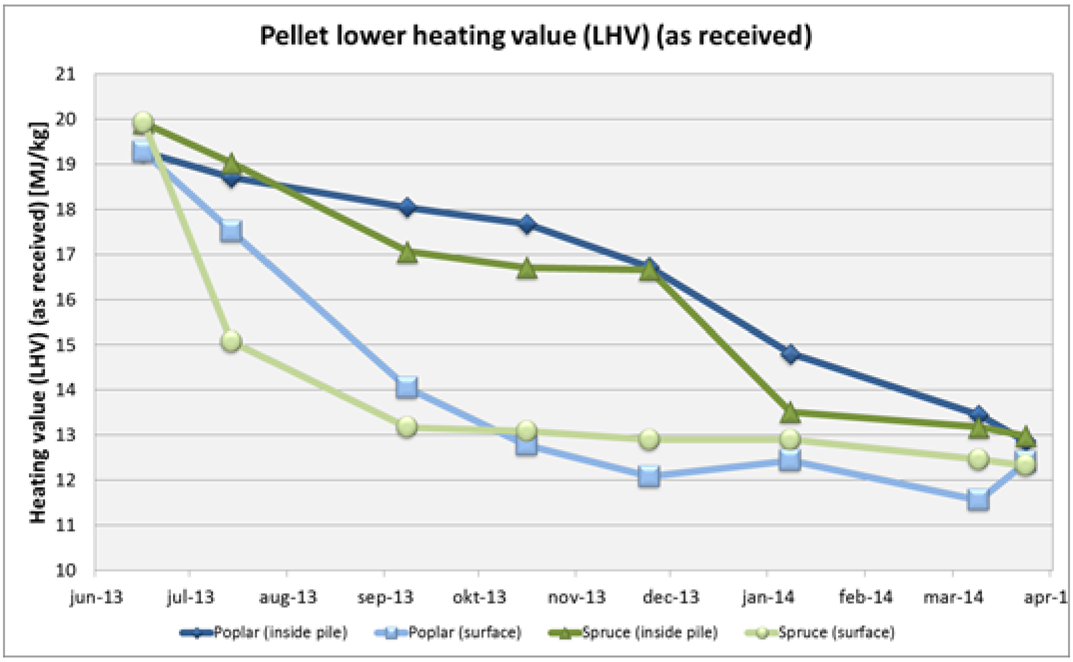


**Figure 39: Lower heating value (LHV) on as received basis during the test period.**

This drastic decrease of the LHV is naturally an area of concern that could impose several implications and negative consequences for example related to the fuel transport at the plants (especially at high co-firing rates) as significantly larger mass flows has to be transported to the mills for the same overall energy input to the boiler. It is also expected that the overall power plant efficiency will be affected negatively as more energy will be required to dry the material in connection with the milling process.

It is also of interest to plot the LHV on dry basis to exclude the impact of the increasing moisture content and to investigate if there is any energy loss in the material due to biological activity, chemical oxidation or with the leach water.

As can be seen in the figure the LHV on dry basis is quite constant throughout the test period, for both the poplar/spruce pellets as well as on the surface and inside the piles. Thus it can be concluded that there are no indications of any significant loss in energy content of the pellets due to any biological, physical or chemical reactions taking place in the piles.

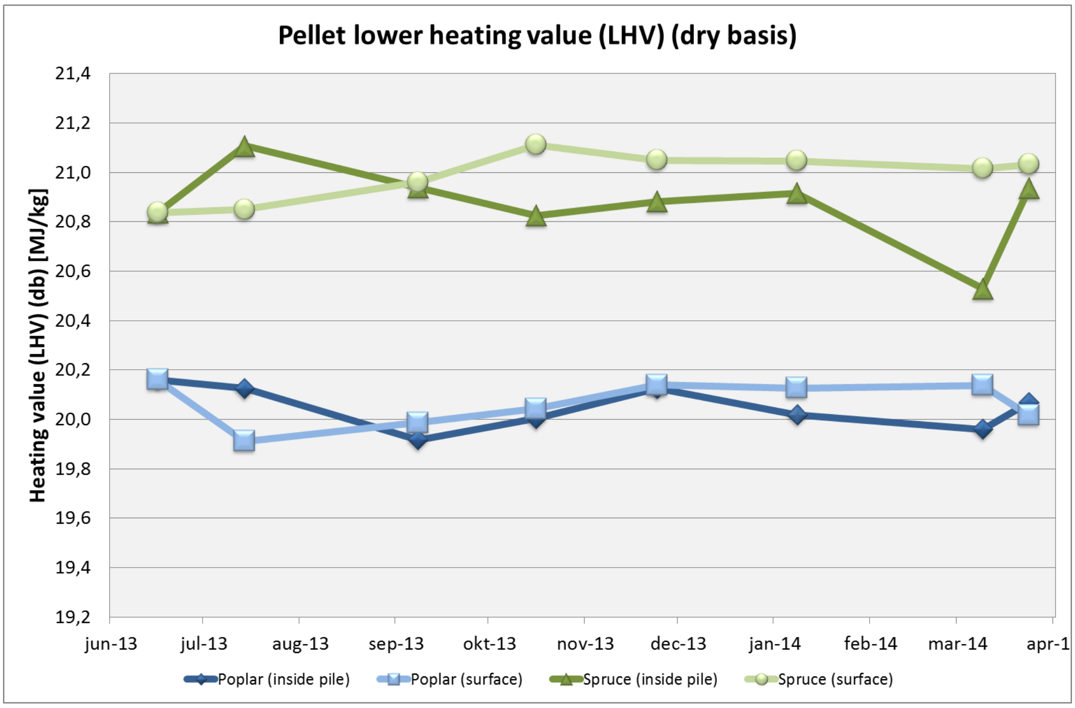


**Figure 40: Lower heating value (LHV) on dry basis during the test period.**

### 4.3.5 Ultimate and proximate analysis

During the trials ultimate analysis (moisture, ash, volatile matter and fixed carbon) was analysed for all solid samples taken. Figure 41 plots the volatile matter and ash content during the test period (all values on dry basis to exclude the effect of the varying moisture content during the test period).

Although the results should be interpreted with certain caution due to the relatively few samples taken it can be seen that for the poplar pellets both volatile matter and ash content seem to be relatively constant throughout the test period and within the level of measurement uncertainty as stated by the lab.

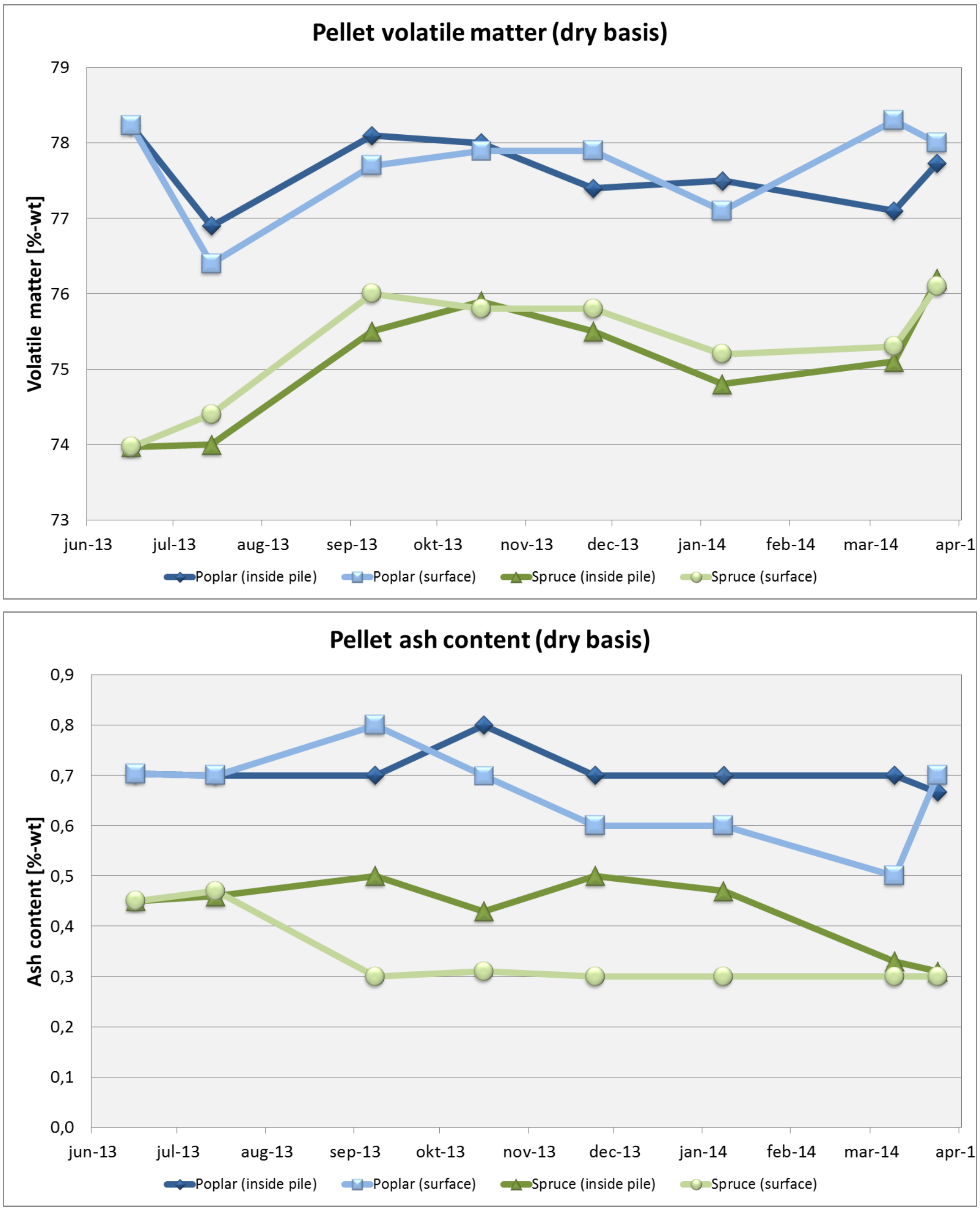


**Figure 41: The pellet volatile matter and ash content as analysed during the test period.**

For the spruce samples on the other hand there seems to be a weak trend towards increasing volatile matter content and slightly decreasing ash content. The ash content numbers should be used with care as all values are within the level of measurement uncertainty. Also the results from several of the analysed samples states an ash content <0.30 % rather than an explicit value (see appendix 3 & 4) and thus it is not possible to plot the exact values.

The proximate analysis was done at the start and the end of the test period. The results are summarised in Table 9 below on dry basis to exclude the impact of the increased moisture.

At the start, 3 parallel samples were analysed and the standard deviation for these samples are included in the table as well.

Generally it can be concluded that in terms of proximate analysis there is very little difference between the results at the start and end of the test period and the outdoor storage does not seem to affect the proximate analysis to any larger extent.

**Table 9: Proximate analysis for the SECTOR poplar and spruce pellet samples as analysed at the start and end of the 9 month test period. The end samples are based on samples from inside the piles.**

| Proximate analysis | | Poplar | | Spruce | |
|---|---|---|---|---|---|
| | | Start[1] | End[2] | Start[1] | End[2] |
| Carbon (C) | [% (db)] | 53,10 | 53,10 | 55,30 | 55,10 |
| Hydrogen (H) | [% (db)] | 5,90 | 5,90 | 5,80 | 5,80 |
| Nitrogen (N) | [% (db)] | < 0.10 | < 0.10 | < 0.10 | 0,12 |
| Oxygen (O) | [% (db)] | 40,23 | 40,20 | 38,33 | 38,60 |
| Clorine (Cl) | [% (db)] | < 0.02 | <0.02 | < 0.02 | < 0.02 |
| Sulphur (S) | [% (db)] | 0,012 | 0,018 | < 0.012 | < 0.012 |

[1] *Average of 3 samples from within the stock piles*

[2] *One sample from within the stock piles*

### 4.3.6 Ash melting temperature

Ash melting temperature was just tested for one sample per pellet type at the start and at the end of the test period, the results summarised in Table 10.

**Table 10: Ash melting behavior for the SECTOR poplar and spruce pellet samples as analysed at the start and end of the 9 month test period. The end samples are based on samples from inside the piles.**

| Ash melting | | Poplar | | Spruce | |
|---|---|---|---|---|---|
| | | Start | End | Start | End |
| Shrinking temp., ST | [°C] | 825 | 730 | 815 | 830 |
| Deformation temp., DT | [°C] | 1500 | 1260 | 1430 | 1390 |
| Hemisphere temp., HT | [°C] | > 1500 | > 1500 | 1445 | 1420 |
| Flow temp., FT | [°C] | > 1500 | > 1500 | 1485 | 1430 |

Based on the analyses it seems that the ash melting characteristics for the spruce samples are relatively similar at the start and end of the test period, while for the poplar samples there seems to be a decrease in shrinking and deformation temperature. Due to the lack of multiple parallel samples the results should be interpreted with great care.

### 4.3.7 Mechanical durability

Mechanical durability of the pellets was tested at start and end of the test period. The main results summarised in Figure 42.

Three parallel samples representing the conditions were analysed at both the start and end of the trials to establish the standard deviation. In addition, one sample from the surface layer of each pile was analysed at the end of the trials to establish potential differences.

At the beginning of the trials and as received from Andritz, the spruce and poplar samples had mechanical durabilities of 96.4 to 97.5 % respectively. The initial parallel samples also show very little variation between them, indicating a relatively uniform product quality in this respect.

As can be seen from the figure there is a decrease in mechanical durability during the test period, but not as severe as expected. The poplar pellets seem to exhibit the largest decrease in mechanical durability with roughly 8.5% (from ~97.5% down to 89%), while the spruce pellets only exhibit a minor reduction of ~2.6% (From ~96.4 down to 93.8%).

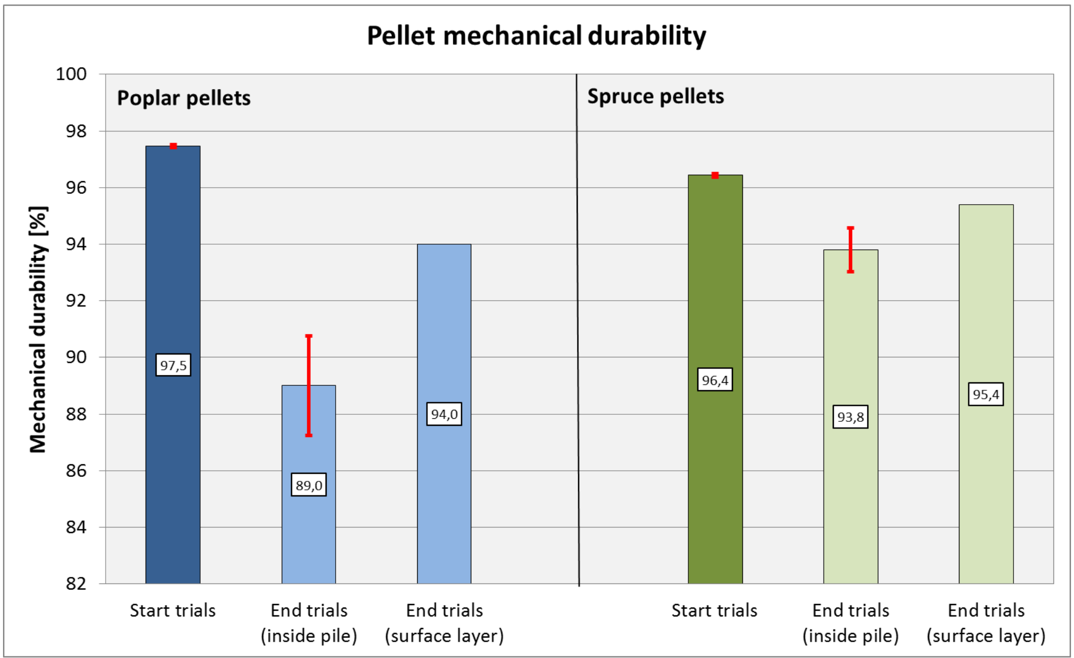


**Figure 42: Mechanical durability of the SECTOR pellets samples at the start and end of the ~9 month test period.**

Even more surprising are the results from the surface layer that for both the poplar and spruce pellet samples exhibit higher mechanical durability than the respective samples taken from inside the piles. Considering the clear visual degradation of the pellets at the surface layer as discussed and depicted in section 4.3.10, this is somewhat unexpected. One possible explanation is that the pellets have been exposed to “natural wear & tear” by wind, rain/snowfall as well as freezing conditions during the trials and that a lot of the material loss that would occur during the tumbling process in the mechanical durability testing already had been removed naturally during the storage period resulting in pellets with relatively high mechanical durability characteristics.

The high moisture content of the pellets is also something that possibly could influence the results of the mechanical durability testing as the analysis according to the EN 15210:2010 standard is carried out on as received basis. Due to the high moisture content it could be so that smaller particles that under dry circumstances would come loose from the pellets during the mechanical durability testing still sticks to the pellets resulting in the relatively high mechanical durability values.

### 4.3.8 Bulk- and energy density

Table 11 summarises the bulk density and energy density of the poplar and spruce pellets at the start and end of the storage period. The initial bulk density of both the torrefied poplar and spruce pellets were around 700 kg/m$^3$ which is slightly higher than corresponding values for conventional wood pellets and within the range of 650-800 kg/m$^3$ considered within the SECTOR project.

As can be seen in the table, the bulk density of the torrefied pellets has only increased slightly during the test period, despite the fact that the moisture content is significantly higher than the starting conditions, indicating that some swelling of the pellets must have taken place. There were no significant differences between the samples from inside the piles and the surface layer.

**Table 11: Bulk- and energy density of the poplar and spruce pellets at the start and end of the ~9 month test period.**

| | | Poplar | | | Spruce | | |
|---|---|---|---|---|---|---|---|
| | | Start[1] | End (inside)[1] | End (surface)[2] | Start[1] | End (inside)[1] | End (surface)[2] |
| Bulk density | [kg/m3] | 701 | 710 | 706 | 708 | 711 | 710 |
| Energy density | [GJ/m3] | 13,5 | 9,1 | 8,8 | 14,1 | 9,2 | 8,8 |
| Energy density | [MWh/m3] | 3,75 | 2,54 | 2,43 | 3,92 | 2,56 | 2,43 |

[1] *Average of 3 samples from within stock piles*

[2] *One sample from the surface layer*

The energy density determines the transport and storage volume for a defined amount of energy and is a relevant value for conveying and storage. The energy density of the pellets has been calculated from the bulk density figures and the heating values on as received basis. Since energy density is directly proportional to the LHV on as received basis there is a significant decrease in energy density of both the poplar and spruce pellets at the end of the outdoor storage period. This could have negative consequences for the fuel transport systems within the plant fence (especially at high co-firing rates) as significantly larger volumes has to be transported to the mills for the same overall energy input to the boiler. The lower energy densities also mean that a significantly larger storage volume will be required for a certain energy amount of energy.

### 4.3.9 Leach water

Table 12 summarises the main results from the leach water analyses. The analyses were carried out by an accredited laboratory, ALS Scandinavia AB.

As leach water analyses are quite expensive, Vattenfall decided to carry out one leach water analysis on each pellet type. To be able to compare the results with work carried out within other parts of the SECTOR project and to avoid effects of possible local contamination by the construction material used for the storage or by contaminants from rainwater, the leach water was induced in the lab through shake test in accordance to EN 12457-4.

**Table 12: Main results from the leach water analyses carried out on the poplar and spruce pellets. The leach water was generated by means of shake test in accordance to EN 12457-4. The pellets used for the leach water analyses was "fresh" pellets taken from the bags as received from Andritz.**

| SECTOR - Leach water analyses | | | |
|---|---|---|---|
| **General** | | **Poplar** | **Spruce** |
| Colour | [mg Pt/l] | 750 | 330 |
| Turbidity | [NTU] | >1000 | >1000 |
| Smell (at 20°C) | [-] | Strong | Clear |
| Smell (characteristic)(at 20°C) | [-] | | Smoke |
| pH | [-] | 5,41 | 4,55 |
| Conductivity | [mS/cm] | 0,409 | 0,329 |
| Hardness (total) | [°dH] | 6,72 | 5,74 |
| **COD, BOD, Carbon** | | | |
| Chemical Oxygen Demand (COD) | [mg/l] | 3860 | 5740 |
| Biological Oxygen Demand (BOD) | [mg/l] | 853 | 1800 |
| Total Organic Carbon (TOC) | [mg/l] | 512 | 974 |
| Total Inorganic Carbon (TIC) | [mg/l] | 16,3 | 13,3 |
| **Various** | | | |
| Alkalinity | [mg HCO3/l] | 27 | < 1.0 |
| Sulfate (SO4) | [mg/l] | 8,19 | 8,44 |
| Chloride (Cl) | [mg/l] | 1,6 | 6,42 |
| Flouride (F) | [mg/l] | 24,9 | 57 |
| Ammonium (NH4) | [mg/l] | 0,395 | 0,792 |
| Nitrite (NO2) | [mg/l] | < 0.01 | < 0.01 |
| Nitrate (NO3) | [mg/l] | < 2.00 | < 2.00 |
| Phosphate (PO4) | [mg/l] | 21,6 | 19,1 |
| Sulphur (S) | [mg/l] | 2,96 | 2,66 |
| Phenol index | [mg/l] | 0,324 | 0,451 |
| **PAH** | | | |
| PAH, Sum 16 | [µg/l] | 0,021 | 0,027 |
| **BTEX** | | | |
| benzene | [µg/l] | < 2.00 | < 0.20 |
| toluene | [µg/l] | < 10.0 | < 1.00 |
| ethylbenzene | [µg/l] | < 1.0 | < 0.10 |
| sum of xylenes | [µg/l] | < 1.5 | < 0.15 |
| **Metals** | | | |
| Calcium (Ca) | [mg/l] | 30,5 | 27,6 |
| Iron (Fe) | [mg/l] | 0,158 | 0,829 |
| Potassium (K) | [mg/l] | 104 | 64,6 |
| Magnesium (Mg) | [mg/l] | 10,6 | 8,12 |
| Sodium (Na) | [mg/l] | 11,2 | 7,19 |
| Aluminum (Al) | [µg/l] | 49,6 | 79,1 |
| Arsenic (As) | [µg/l] | 1,42 | < 1 |
| Barium (Ba) | [µg/l] | 54,6 | 179 |
| Cadmium (Cd) | [µg/l] | 1,04 | 0,896 |
| Cobalt (Co) | [µg/l] | 0,337 | 0,851 |
| Chromium (Cr) | [µg/l] | 7,84 | 16,1 |
| Copper (Cu) | [µg/l] | 10,7 | 23,9 |
| Mercury (Hg) | [µg/l] | < 0.02 | < 0.02 |
| Manganese (Mn) | [µg/l] | 439 | 3880 |
| Nickel (Ni) | [µg/l] | 2,95 | 5,28 |
| Lead (Pb) | [µg/l] | 0,402 | 0,242 |
| Zinc (Zn) | [µg/l] | 269 | 195 |

The pellets used for the leach water testing was “fresh” pellets taken directly from the bags as received from Andritz.

Studying the results of the leach water analyses for the SECTOR pellets it can be concluded that the slightly acidic nature of the leach water combined with the elevated BOD and COD levels compared to coal, most likely will require a treatment before it can be released to the plant sewer system. However as the environmental regulations might differ both on national and in case of water effluents on a local level, it is not possible to provide a clear recommendation regarding the needed purification degree of the various effluents before the leach water is released to the sewer systems.

The BOD to COD ratio of ~0.2-0.3 indicates a high content of components which are difficult to biodegrade and thus some type of chemical treatment might be required.

### 4.3.10 Other observations of interest during the trials

Smell has not been measured in any scientific way during the test period, but has continuously been monitored on a personal indicative level. This has been done by persons that has experience from and been involved in Vattenfall’s previous R&D efforts related to thermally treated biomass and thus have previous experience form both torrefied and steam treated pellets as well as conventional white pellets.

Generally the conclusion is that, although there is a mild “slightly sticky acidic” odour from the pellets, smell is not expected to be a limiting factor for outdoor storage. Any smell connected to the pile is almost unnoticeable at a few metres distance away from the piles. The personnel who have followed the tests are of the opinion that the “slightly sticky” smell has declined throughout the test period. It has not been possible to make any distinctions between the spruce and poplar pellets in terms of smell. The smell from the torrefied SECTOR pellets is for example also considered to be considerably milder than for example steam treated pellets.

Biological activity in terms of mould or fungi formation in the piles has been monitored visually throughout the test period. Vattenfall has on a few occasions experienced mould formation in connection to both torrefied and steam treated pellets, something that has been an area of concern from a HSE perspective. During the test period no indications whatsoever regarding mould or fungi formation has been observed in connection with the SECTOR pellets.

What however has been observed is a continuous degradation of the pellet quality at the surface of the piles. Figure 43 shows a comparison of pellets appearance at start/end of the test period. The pellets closest to the surface have a considerably “rougher” appearance compared to the original condition at start of the test period and has also a slightly lighter colour, most likely a result of a bleaching effect due to long term direct exposure to the sunlight. There has also been a significant amount of visible fines resulting from disintegrated pellets at the surface of both piles.

The appearance of the pellets inside of the piles is relatively close to the original condition, despite the higher moisture content.

Although no compression strength tests or similar scientific tests have been carried out on the pellets, it is clear that the compression strength of the pellets closest to the surface of the piles would be significantly worse as a majority of these pellets can be crushed between two fingers, something that definitely not was possible when the pellets arrived. Once again, the pellets inside the piles seem to fare slightly better in this regard.

**Figure 43: The poplar and spruce pellets at start and end of the 9 month outdoor storage period. The pellets close to the surface have a considerably rougher appearance compared to the original conditions. There is also a significant amount of fines from disintegrated pellets close to the surface.**

## 4.4 Handling tests

As mentioned in section 4.1.2, carrying out any handling tests at an existing power plant with the very small amount of pellets made available to Vattenfall within the SECTOR project was not considered to be a practically applicable idea and would provide very little in terms of representative results. Therefore, based on the review of scientific literature survey, a number of small scale tests were carried out. These tests together with experiences from previous large scale tests at Vattenfall should provide some indication on how the torrefied pellets as received within the SECTOR project would behave in real existing power plant conditions.

### 4.4.1 Drop tests

#### 4.4.1.1 Background

During transport and after arrival at the plant, pellets will be subject to elevation and drops a number of times before reaching the fuel mills and burners of the boiler. This will for example include unloading the pellets from ocean vessels, loading/unloading of the pellets into rail cars or trucks, loading/unloading in silos as well as at transition points on belt conveyors in the fuel feeding system at the power plants. Every time pellets are elevated and dropped they break and consequently produce small particles and dust. This is problematic both from an HSE perspective (explosion, fire, inhaling of fine particles, etc.) as well as from an economical point of view as the material losses increase.

In order to provide an indication of the breakage behaviour as well as particle and dust formation during handling of pellets, drop tests have been carried out. The pellets used in these drop tests have been the poplar pellets torrefied by ECN and pelletised by Andritz, earmarked for handling tests. As no standard protocol for drop test of pellets exists, inspiration for the tests has been taken from the work published by Oveisi et. al. (2013).

As a comparison and reference, commercial Swedish wood pellets with the same diameter as the SECTOR pellets (6mm) were also tested.

#### 4.4.1.2 Methodology

During the tests torrefied and white pellets were placed in bags and dropped from a height of 7.52 m down on a concrete floor. Each bag was dropped 10 times corresponding to a total height of 75.2 m. Drop tests were carried out on 300 g as well as 2000 g samples to investigate the impact of sample weight. Five duplicate samples were included to establish the standard deviation and increase certainty in the results. In total 20 different bags dropped 10 times each resulting in a total of 200 drops. The test matrix is summarised in Table 13.

**Table 13: Summary of the test plan for the drop tests.**

| Test plan - SECTOR pellet drop tests | | | | | |
|---|---|---|---|---|---|
| | | White | | Torrefied | |
| Weight of each bag | [g] | 300 | 2000 | 300 | 2000 |
| Nr. of duplicate bags | [-] | 5 | 5 | 5 | 5 |
| Drop height | [m] | 7,52 | 7,52 | 7,52 | 7,52 |
| Number of drops | [-] | 10 | 10 | 10 | 10 |
| Total drop height | [m] | 75,2 | 75,2 | 75,2 | 75,2 |

Prior to filling the bags the pellets were sieved manually over a 3.36 mm sieve to remove any fine particles. The pellets were also carefully examined in order to identify and exclude already damaged or broken pellets from the tests. The reason for using a 3.36 mm sieve instead of a 3.15 mm sieve as recommended in accordance with standards is as simple as that only a 3.36 mm sieve was available at the lab.

The pellets were filled in ordinary plastic zip-bags that can be bought in any conventional grocery store. The bags were filled quite loosely and for the 300 g samples 2 litre bags were used while 5 litre bags were used for the 2000 g samples. Double bags were used (i.e. the first bag was put in a second bag) in order to minimise the potential impact in case of bag breakage during the tests.

After ten drops the pellets in the bags were sieved over a 3.36 mm sieve and both the amount of collected fine particles and the weight of the pellets left on the 3.36 mm sieve were recorded and the mass loss calculated.

### 4.4.1.3 Results & conclusions

The results from the drop tests are summarised in Figure 44. From the figure it can be concluded that the torrefied pellet samples clearly exhibit a higher degree of pellet breakage and fine particle loss (< 3.36 mm) than the white pellet reference samples. The white pellet samples have a fine particle loss of ~3.7-3.8 % compared to the torrefied samples that that have a fine particle loss of ~11.5-11.8 %. From the standard deviation figures it can also be concluded that the results from all tests are relatively consistent and that no significant spread in the results can be observed.

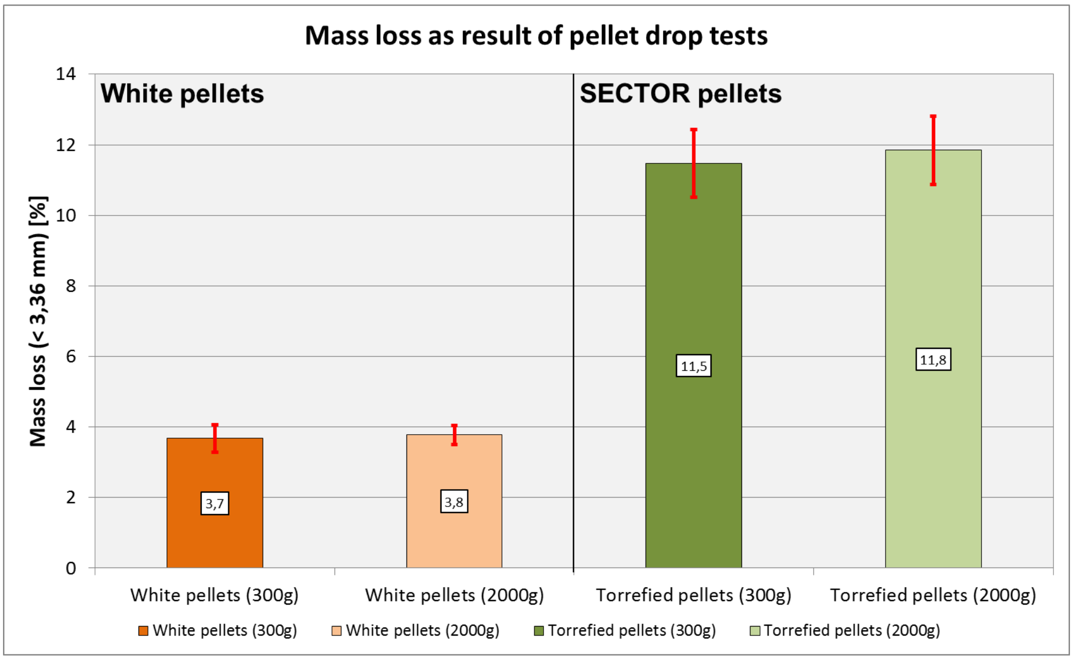


**Figure 44: Summary of the results from the drop tests. From the test it can be clearly concluded that the torrefied pellets have a significantly higher degree of fine particle loss compared to the reference white pellet samples.**

From the tests it can also be concluded that increased sample size will result in a slightly higher fine particle formation although the difference is relatively small.

## 4.4.2 Extended mechanical durability

Dusting is an extremely important aspect from a HSE (Health, Safety and Environment) perspective. Especially the self-ignition/explosion aspects of wood dust, especially that of torrefied pellets, is an area of concern as this is considerably more reactive than coal dust. Although the mechanical durability testing according to EN 15210 gives a good indication regarding the expected total dust formation from the pellets it does not really provide much information regarding the properties of the formed dust and the potentially related issues. In order to provide a better indication of the dusting tendency of wood pellets, an “extended mechanical durability” method has been proposed/developed and used by Vattenfall R&D

which makes it possible to quantify different fractions of the resulting dust fraction for different fuels.

The method, which is relatively simple, involves the following steps:

1. Mechanical durability test according to EN standard for wood pellets (EN 15210). The fine fraction passing the sieve (< 3.15 mm) must be collected for further analyses
2. The fine fraction (< 3.15 mm) retained from the initial mechanical durability test is further tested and analysed for particle size distribution by using the following sieving steps (mm): 2.5, 1.0, 0.63, 0.425, 0.250, 0.125, 0.063 and 0.045.
3. Moisture content is to be determined according to EN standard method (EN 14774) prior further sieving test for fractions <0.250 mm, <0.125 mm and <0.063 mm.
4. As a basis for reference and comparison, the same sieve analysis (as above) of material passing the 3.15 mm sieve in the mechanical durability test should be performed on white wood pellets, and hard coal after performing identical mechanical durability testing.

The motivation for the choice of fractions (especially the lower ones) and moisture content analyses are primarily that these normally are used in ATEX classification work to establish fire and explosion risks; particles <0.063 mm for evaluation of airborne dust, <0.125 mm for evaluation of “glowing” temperature of a dust layer, and <0.250 mm for evaluation of self-ignition temperature.

The results from an extended mechanical durability test carried out on the SECTOR pellets compared to the results from conventional white pellets and a hard coal sample are summarised in Figure 45 and Figure 46. The figure also includes some results from previous Vattenfall tests carried out on both torrefied and steam treated material.

One conclusion that can be drawn from the figure is that the dust formation from the SECTOR poplar pellets is expected to be lower compared to previous torrefied samples as tested by Vattenfall. With that said, most of the previously tested torrefied samples have had a higher heating value than the SECTOR pellets, thus indicating a higher degree of torrefaction and consequently are more problematic from a dusting perspective.

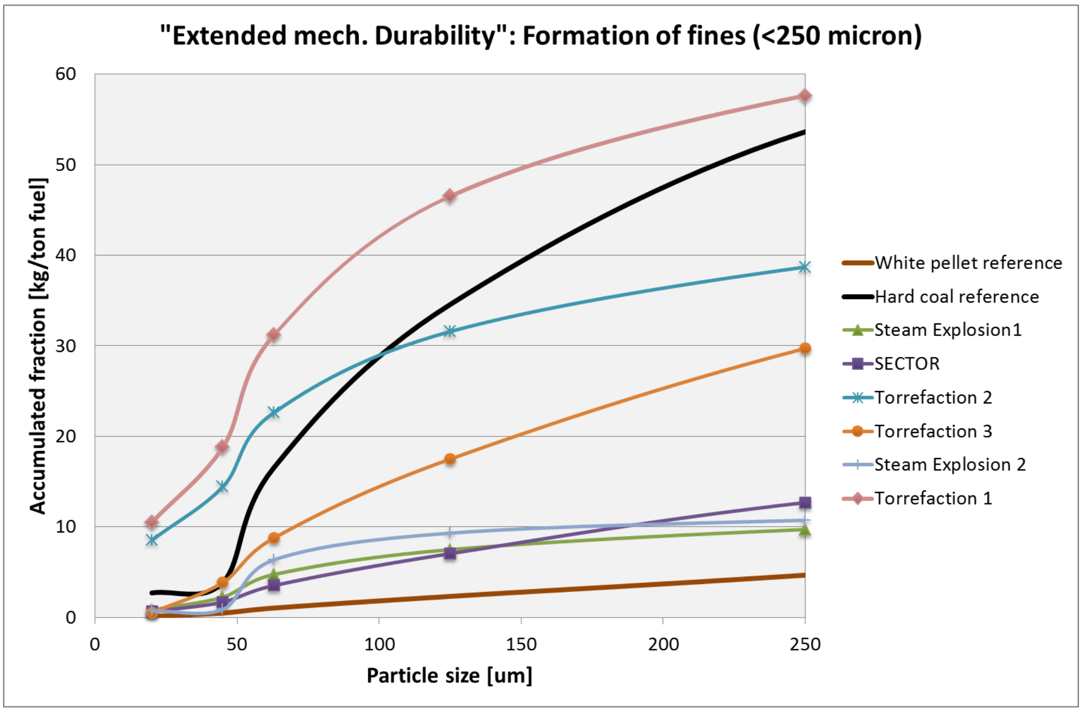


**Figure 45: Summary of the expected fine dust formation (< 250 µm) according to the extended mechanical durability test. Please note that comparison between the coal and biomass samples should be done with certain care as dust formation from coal normally is established according to different standards.**

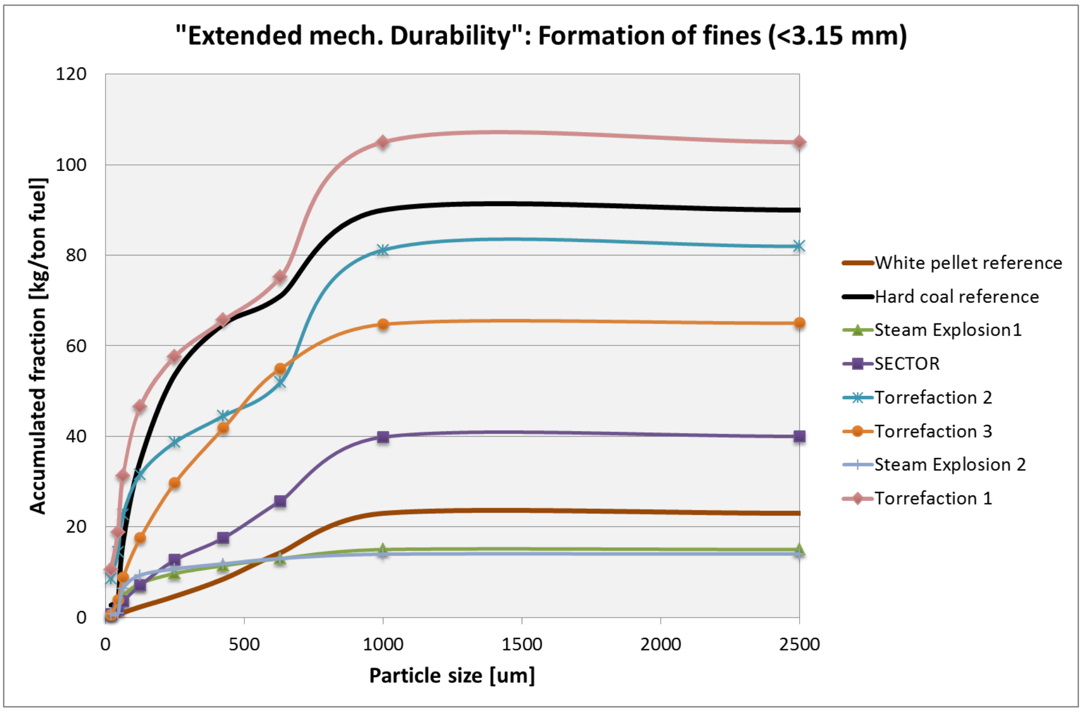


**Figure 46: Summary of the expected fine dust formation (< 3.15 mm) according to the extended mechanical durability test. Please note that comparison between the coal and biomass samples should be done with certain care as dust formation from coal normally is established according to different standards.**

### 4.4.3 Angle of repose

The angle of repose measured for both the poplar and spruce pellets are in the range of 30-33°C, which is clearly lower than coal. This will result in that the storage area required for torrefied pellets will be larger than for coal.

Another aspect that has been experienced in connection to previous large scale tests carried out at existing Vattenfall plants is that the flow properties of thermally treated biomass pellets prevents driving into higher pellets layers with wheel loaders, as is normally done to compact stockpiles of coal.

### 4.4.4 Conveying and critical angel of inclination

Previous large scale tests at existing Vattenfall plants have concluded that thermally treated and densified biomass pellets can be conveyed with problem free operation using existing coal conveying belt systems, under condition that sufficient dust suppression and absorption systems are installed. Conveying with a maximum angle of inclination of 15-16° has been tested with only very few isolated cases of pellets rolling backwards observed.

There have been instances of pellets falling of the conveyor belts, ending up at the inspection routes next to the conveyor belts. Pellets have also slipped through rubber fittings at transfer points and fallen to the ground. As this represent an increased safety hazard for personnel working in these areas, some minor adaptations to existing equipment will likely be required such as for example mounting of mesh grids on the pathways, etc.

The SECTOR pellets are not believed to behave any different from a conveying perspective and the conclusions and observations above are believed to be fully valid for the SECTOR pellets as well.

## 4.5 Summary and conclusions of Vattenfall tests

The outdoor storage properties of two torrefied pellet types based on poplar and spruce feedstock respectively have been tested during a 9 month period. The pellets have been stored in a “piece of cake” storage construction in an attempt to simulate larger volume of pellets.

At arrival, both pellet qualities were characterised by a low moisture content and a high mechanical durability around ~98%. The heating values of both pellet types, 19.3 and 19.9 MJ/kg respectively, indicate that a moderate degree of torrefaction has been applied; most probably in order to achieve acceptable mechanical integrity and dusting properties of the final pellet product and optimise raw material use. The spruce pellets had a slightly higher heating value than the poplar pellets, most likely related to the inherent differences between softwood and hard wood.

During the test period the pellets have been exposed to varying weather conditions. Each pile has been exposed to ~1.8 $m^3$ of water/snowfall and the temperature range has varied between +33°C to -20°C. During the test period the temperatures have been logged continuously in 3 different positions in each pile. Generally the stock pile temperatures have followed the ambient temperature very closely and the volumes of pellets tested have most likely been too small to result in any significant self-heating.

During the test period solid samples have been taken from both the surface of the piles as well as inside the piles. Both the poplar and spruce pellets exhibited a significant increase in moisture content when exposed to rain/snowfall. At the end of the test period the moisture content of the pellets throughout the whole piles (surface as well as inside) was ~35 %-wt. As a consequence both the heating value (ar) and energy density had decreased drastically, which is negative both from a fuel transport perspective at the power plant site (larger capacity required) as well as from a power plant efficiency perspective as more heat will be required to dry the fuel in the mills (especially problematic at higher co-firing ratios or 100% torrefied pellet operation).

Leach water tests carried out for both pellet qualities indicated elevated levels of both COD and BOD compared to coal, which together with pH levels in the range of 4.6 to 5.4 most likely will require further treatment prior to discharged to plant sewer system. As the requirements can differ on national and local degree of treatment should be studied on a case by case basis.

Mechanical durability of the pellets was analysed at the start and end of the trials. Although the mechanical durability decreased for both pellet types, the decrease was lower than expected.

The main conclusion from the outdoor storage tests are that neither of the pellet qualities tested are really suitable for outdoor storage, at least not for any prolonged periods of time, due to the high moisture absorption when exposed to rain-/snowfall.

In terms of handling properties the extended mechanical durability testing of the SECTOR pellets indicates dusting behaviour similar or slightly higher than that of white pellets in the range < 250 µm, which is the most critical range from an ATEX and HSE perspective.

However, in the same time both the extended mechanical durability test and drop tests indicates that the total fine formation (< 3.15 mm) is likely to be higher compared with white pellets and looking at the whole chain, from the production site to the mills at the power plant site, most likely a higher loss of material will be observed in case of torrefied pellets.

Conveying of thermally treated biomass pellets have previously been tested in connection to large scale tests at existing Vattenfall plants and has been proven to be possible without any problems (angle of inclination of 15-16° has been tested). The SECTOR pellets are not believed to behave any differently.

In conclusion, conveying and handling of torrefied pellets (with properties in accordance to what has been tested for the SECTOR pellets) in existing coal lines should be possible provided sufficient dust suppression/collection systems are in place or added and that sufficient provisions are made to prevent the falling of pellets from conveyor belts and transition points. Exact level of modifications and associated costs needs to be studied and established on a plant specific basis.

# 5 Topell Tests

## 5.1 Introduction

### 5.1.1 Background & objective

This chapter summarizes the methodology and results on outdoor storage tests conducted by Topell Energy under Task 6.2 of SECTOR project.

The main aim of this test is to discuss the possibility of storing torrefied wood pellets in a similar manner as coal - that is in stockpiles outdoors in the open air, but also on changing fuel handling practices needed that should not pose new challenges for power plants.

### 5.1.2 Deviations from the Description of Work document

According to the original project plan, Topell had to conduct a one tonne open air storage test with torrefied wood pellets under Task 6.2. Learning from the previous tests presented in this report and trying to answer some of the open questions remaining, Topell decided to conduct the test with two separated stockpiles with one ton of pellets each. The main aim for this change was to have different piles for different sampling periods, avoiding influence of sampling when working only with one pile during all the testing period.

## 5.2 Experimental method

### 5.2.1 Test location

Topell conducted a two tonnes outdoor storage test in a farm located in Callantsoog, in the north west of The Netherlands (Figure 47). This location provided full exposure to representative weather conditions in the country while isolating it from public disruption and minimising other polluting sources. The test lasted for two months, starting in February 2015, sampling one different bag at the end of each testing month.

**Figure 47: Location of test site in NW of The Netherlands (source: Map data © OpenStreetMap.org contributors licences under the Creative Commons Attribution-ShareAlike 2.0 licence).**

### 5.2.2 Set-up

The test has been conducted with two big bags filled with torrefied forestry residue pellets, one ton each, as big bags allow transpiration between their interior and the surroundings while keeping the pellets in the desired pile shape. Free falling was used to fill both bags. As the first bag was to be dismantled and sampled after one month of test, four thermocouples recording the temperature at different depths were placed in the second pile, which were connected to a data logger in a waterproofed box (Figure 48). The data obtained is considered representative for both piles. The data logger was set to record all temperatures every hour.

Typical plastic garden nets with a hole size of 5 mm were used to divide the pile in five different sections, 10, 30, 50, 70 and 90 cm of depth. These nets were placed to facilitate collecting proper samples of each section when dismantling the piles while allowing eventual percolation of water and fines from the top to the bottom.

**Figure 48: Test set up with thermocouples in pile 2**

The data, current and historical, on general weather conditions in the area were taken by the Dutch weather observatory “De Kooy” situated 13 km north from the test location. This data is freely available in internet (http://www.knmi.nl/klimatologie/uurgegevens/#no).

### 5.2.3 Sampling

As already explained above, one bag was completely dismantled after each testing month, following the different sections defined with the nets installed. Representative samples of approximately 15 kg were taken from each depth, which were 0, 10, 20, 40, 60, 80 and 100 cm from the top of the pile. Special care was taken not to mix pellets from different sections during sampling.

### 5.2.4 Sample analysis

Each sample taken was divided in two equal parts in order to conduct two sets of analysis in different institutions. While ECN conducted minimum ignition energy determinations with a self-developed method, which is based on the existing standard, Topell Energy measured moisture content, ash content, calorific value and mechanical durability following the existing European standards for biomass analysis. For samples with higher moisture content than 20 wt%, it was needed to dry them before conducting the mechanical durability tests. This is related to sieving practices defined in standard BS EN 15149-2:2010, which indicates that for sieving operations (part of durability test) the samples cannot exceed 20 wt% in moisture content.

## 5.3 Results

### 5.3.1 Weather conditions during test period

The data obtained from the Dutch weather observatory mentioned above is taken as the ambient temperature due to the fact that it was not possible to log continuously the ambient temperature in the testing site. However, discrete measurements when visiting the testing site showed good agreement between both measurements.

As shown in Figure 49, the first pile (first month) was exposed to a maximum temperature of 11.5°C while the second pile faced 13.7°C. The minimum temperature during the whole testing period was achieved during the first month with -3.7°C, despite several days achieving temperatures below 0°C during both months, with also frost conditions.

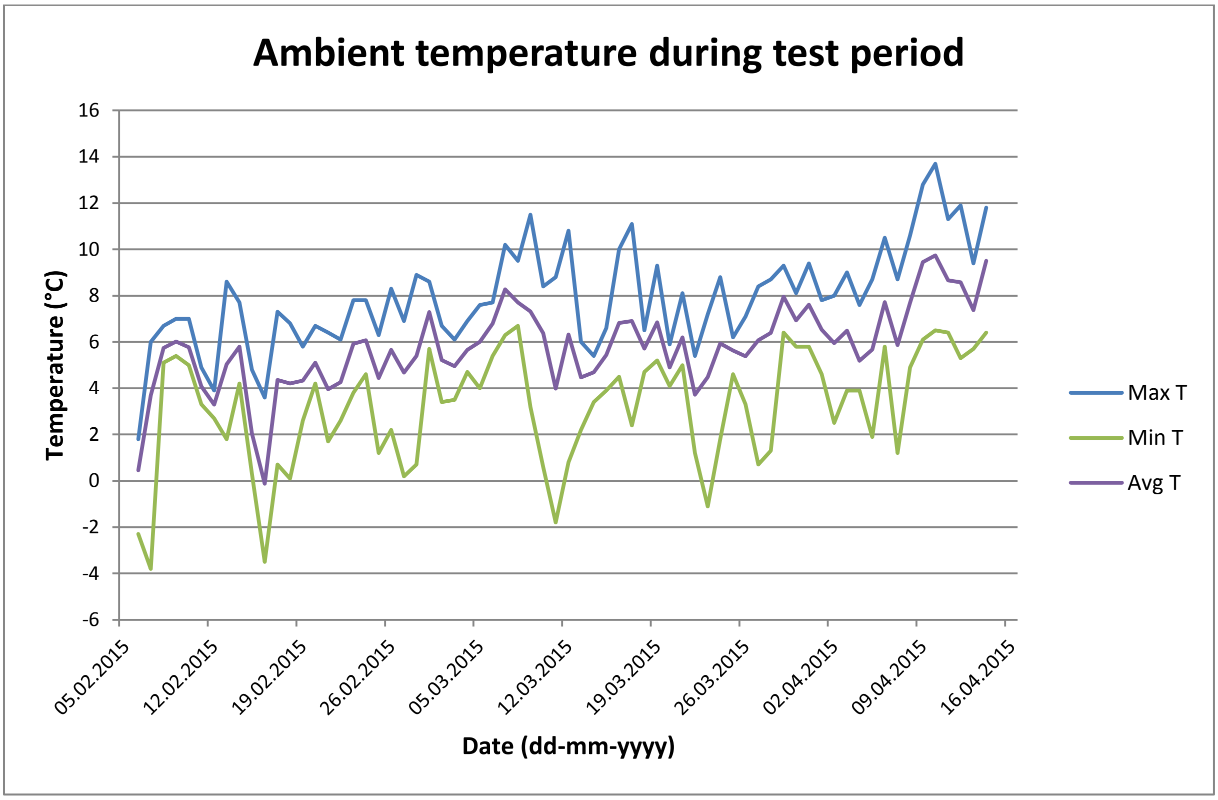


Figure 49: Temperature profile in testing area (daily averages)

Figure 50 illustrates the cumulative rainfall and the relative humidity during the total testing period. Pile 1 was exposed to 50 mm rainfall after one month and pile 2 to almost 90 mm rainfall over the two months of testing, while the relative humidity remained mostly above 75%, achieving daily peaks close to 100%. Both rainfall and humidity slightly decreased during the second test month.

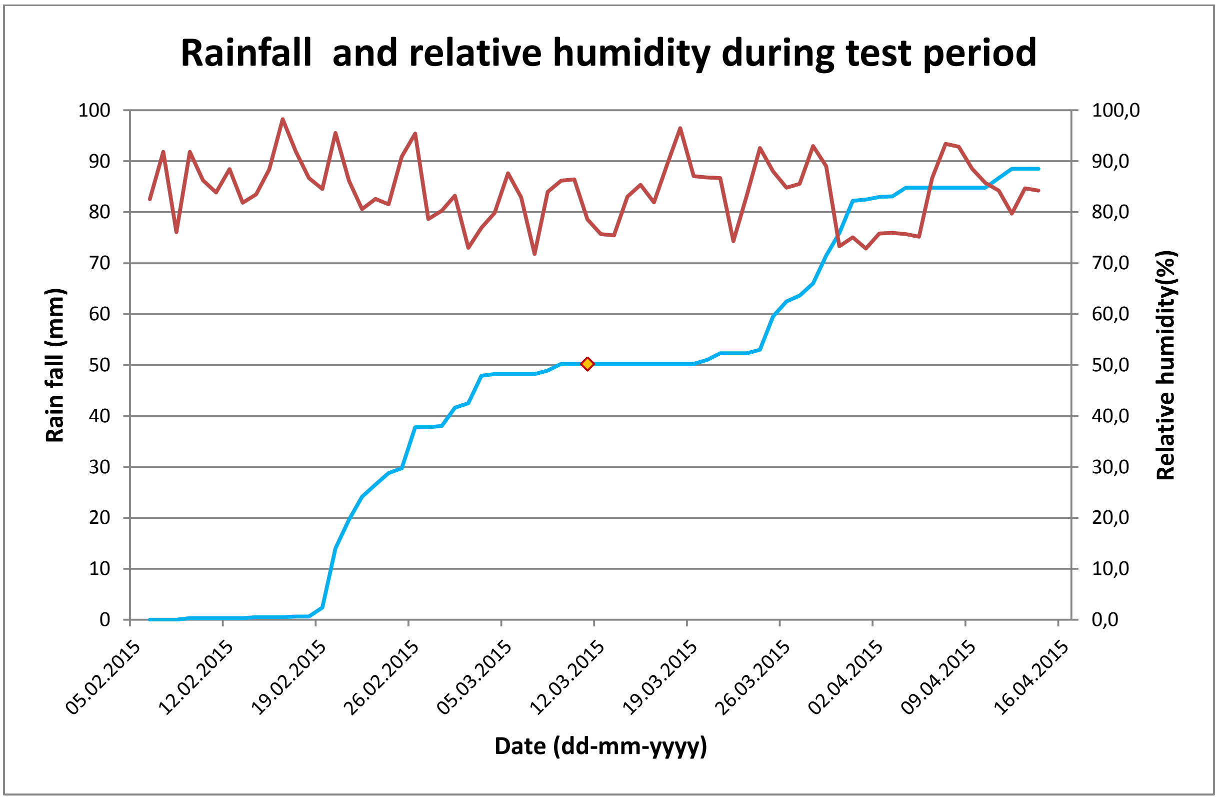


**Figure 50: Cumulative rainfall (blue) and relative humidity (red) during the testing period. The dot marks the sampling date of pile 1 (11th March). Pile 2 was sampled on 14th April.**

### 5.3.2 Temperature measurements in the stockpile

Four thermocouples were vertically inserted in pile 2 in order to monitor and record the temperature trends at four different depths that were 10, 40, 60 and 90 cm from the top. Unfortunately due to recording failure of the data logger and overwriting of data most of the measurements could not be recorded continuously until the last test week. For the rest of the test period discrete measurements were manually saved during the weekly checks at the test site.

Temperature profiles inside the stock pile and ambient temperature are displayed in Figure 51. As can be observed there has been no relevant difference between temperatures within and outside the pile recorded during the whole test period. This shows that there has been no self-heating due to chemical oxidation or biological degradation of the pellet over this period. As white wood pellet cannot be stored outside without disintegration, direct comparison of white wood pellet and torrefied pellet in outdoor storage is not possible, however the climate chamber work undertaken in SECTOR deliverable 6.6 demonstrates that the torrefied material is much more resistant to biological degradation and dry matter losses than white wood pellet. Self-heating of white wood pellet in bulk (indoor) storage is a known issue, while exothermic reactions and self-ignition are also of concern in open air stockpiles for some coal types.

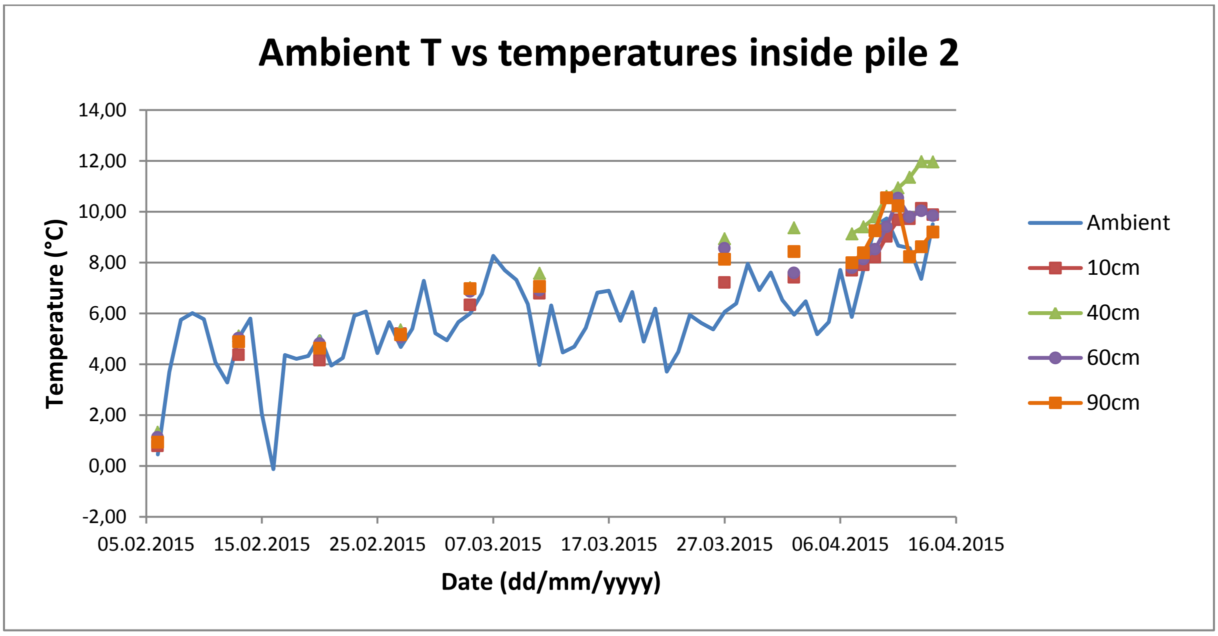


**Figure 51: Profile of ambient temperature versus temperatures measured inside pile 2**

### 5.3.3 Moisture content of pellets

The original pellets used for this test had been stored for more than one year in Topell's warehouse in Duiven, which is covered but not closed so the stockpiles were subjected to changing relative humidity (48 to 100%) and temperature conditions (-10 to 38°C). During this period, no representative increase in moisture content was observed, which demonstrates the hydrophobic properties when the material is not directly exposed to rain.

The results on moisture content of pellets from both piles are shown in Figure 52. While the original pellets had a moisture content of around 9.5 wt%, the top (exposed) layers show fast absorption of rain water. The higher temperatures, the higher sun exposure, the lower relative humidity and the lower quantity of rain, although the differences are not large, before sampling pile 2 explain the decrease in moisture content for the sample directly exposed (0cm) after 2 months when compared with the sample from the same depth after 1 month.

A larger increase in moisture can be observed with the samples taken at 10 cm from the top (26.5-27.5 wt% respectively). This is due to the layer of fines found around 10 cm below the pellets that were directly exposed, in both piles, which isolates the lower pellets. Before the formation of this layer of fines (due to the degradation of the top pellets), water seems to percolate until pellets at 20 cm (12.7-13.6 wt%) from the top, while after this layer of fines is formed, it appears to isolate the pellets below so moisture remained high in pellets at 10 cm but it did not affect the pellets below (Figure 53-Figure 56). In these pictures it is also shown that pellets in top layers still preserved their pellet shape instead of decomposing and falling apart as fines as it would happen with white wood pellets when exposed to the open air. Pellets deeper in the pile did not suffer any visual degradation.

Therefore, these results demonstrate the strong enhancement in hydrophobicity of torrefied pellets compared to normal white wood pellets; the latter would swell and disintegrate immediately upon exposure to rain.

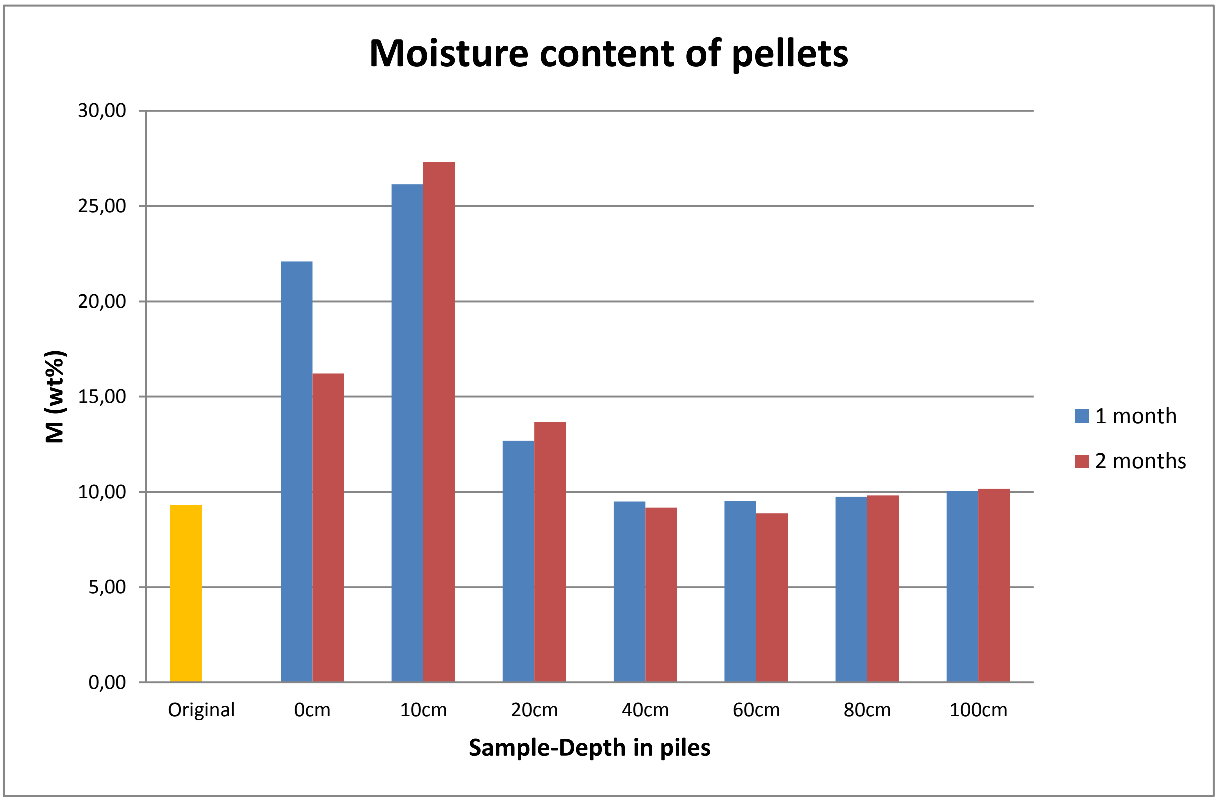


**Figure 52: Moisture content of pellets from both piles at the different sampling depths**

**Figure 53: Slow degradation of top layer**

**Figure 54: Layer of fines at 10cm depth**

**Figure 55: Pellets at 20cm depth**

**Figure 56: Pellet at 80cm depth**

### 5.3.4 Calorific value of pellets

Figure 57 summarises the results of the analysis of net calorific value conducted with samples from all sampling depths of both testing piles. The direct relation between moisture content and calorific value as received explains the different trends shown by the pellets directly exposed and the pellets in the piles. Thus, the net calorific value as received of the pellets directly exposed to rain water (top layers) decreases to 13.4 GJ/ton for the sample with higher moisture content (10 cm, 2 months) while the values for pellets inside the pile are constant during the whole testing period.

Isolating the effect of moisture in the calorific value, the net calorific value on dry basis was also calculated. Torrefied pellets show no biological degradation when stored open air and the results of the pellets tested show a steady value of 19.3 GJ/ton (d.b.) (note that the heating value of the Topell pellets is lower than that of the pellets used in the E.ON and Vattenfall tests due to the use of forestry residues rather than stem wood as the raw material for the torrefaction process)

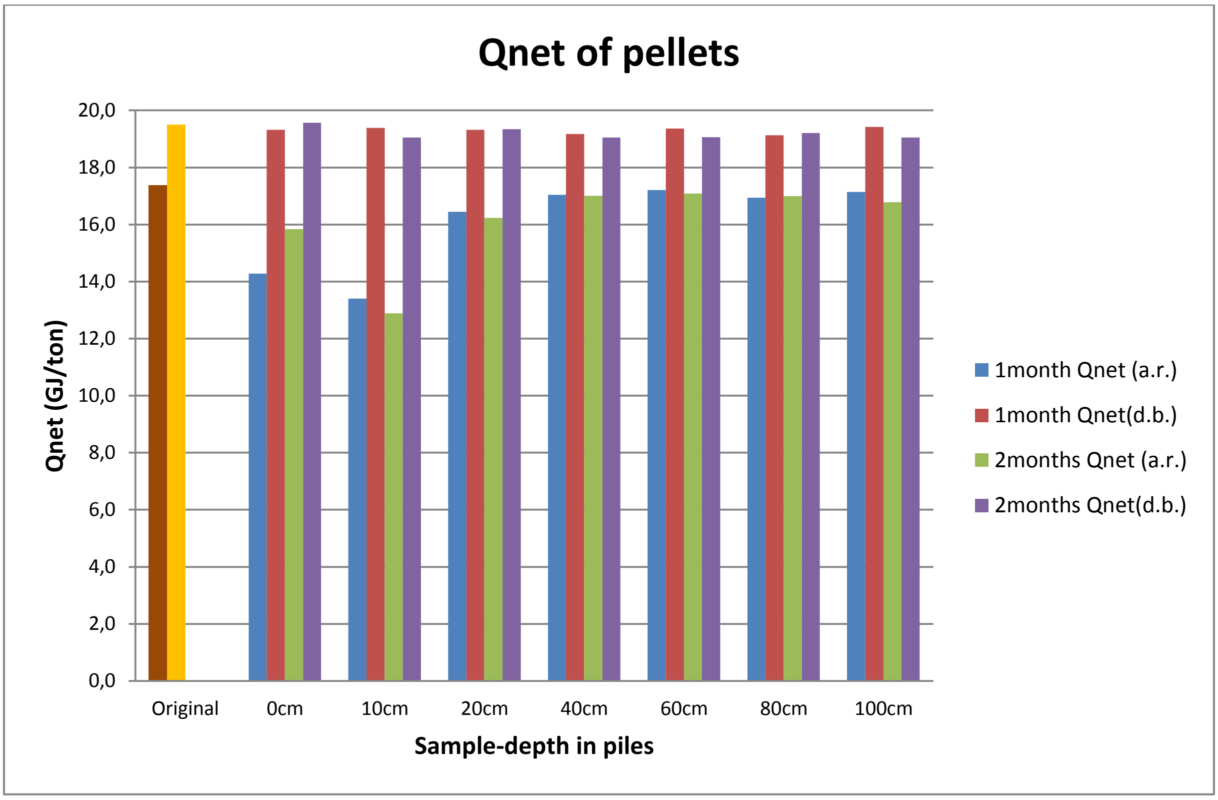


**Figure 57: Net calorific value in both, as received and dry basis for all the samples collected. For the original sample brown represents as received and yellow is for dry basis.**

Although the scope of this deliverable is discussing storage and transport issues on outdoor stored torrefied pellets, the effect of net calorific value on boiler efficiency as a result of water intake is also addressed. The extent of this influence is directly related to weather conditions in the storing yard of the power plant and to the length of the storage period. From the results above, low percolation rates and moisture intake resistance indicate limited losses when considering the whole volume of a normal stockpile. When using the angle of repose and the density of pellets previously reported in this deliverable, it is found that in the first two months, less than 5% of the pile would be affected by direct rain and frost exposure. Thus, for storage periods within this time frame the effect on boiler efficiency would be limited. Where longer storage periods are required (for example for coal stations which maintain stockpiles for several months), covered storage may be required, but it is not thought that this will need to be fully enclosed as is the case for white pellet. Testing reported in Deliverable 6.3 showed that torrefied pellets protected from direct rain exposure (but not temperature or humidity changes) did not suffer losses in mechanical durability, suggesting that a roof (or even the sheeting used in some plants to prevent dust blow from coal stockpiles) may provide sufficient protection for longer term storage of torrefied materials.

### 5.3.5 Ash content of pellets

Ash content analyses were conducted in all the samples from both piles in order to study eventual leaching of inorganic matter from the pellets. As can be seen in Figure 58, there has been hardly any change in ash content through the testing period. The original pellets had an ash content of 2.91 wt% (d.b.) and only in the top layers it is observed a slight decrease of 0.15 wt% while for the rest of samples values range from 2.81-2.94 wt% (d.b.). Although the loss in ash content of the top layers could be attributed to leaching of alkalis, there is no data on ash chemical composition to support this and the differences in results fall still in the reproducibility limit of the analysis method. Therefore, there is no clear evidence of any relationship between changes in ash content and outdoor storage.

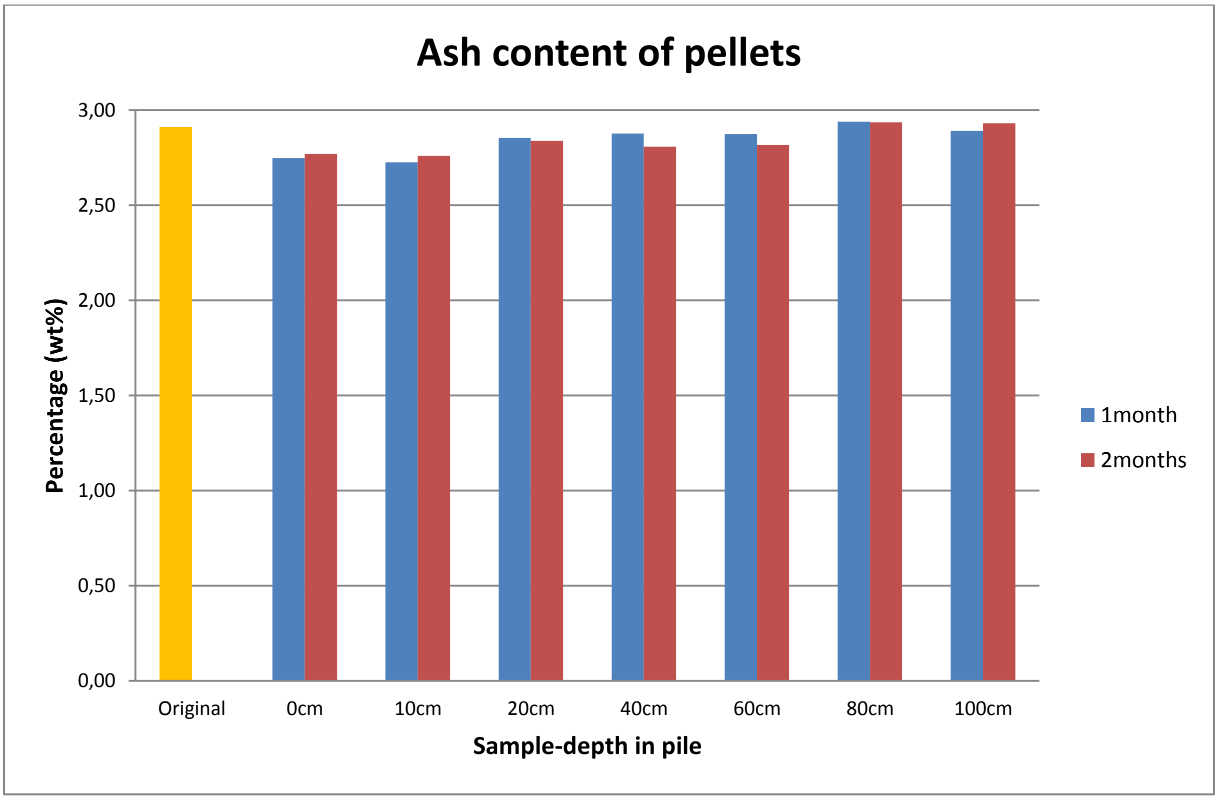


**Figure 58: Ash content analysis results of all samples on dry basis.**

### 5.3.6 Mechanical durability of pellets

Mechanical durability of pellets is an important parameter when discussing resistance to degradation during handling and transport operations and the formation of fines and dust. The results on mechanical durability of all the samples are presented in Figure 59.

Samples with moisture content higher than 20 wt% had to be dried as discussed in Section 3.3.3. As it was not possible to dry the samples to the initial moisture content of the pellets, these samples had to be dried completely (at 80°C), thereby losing the original binding properties from water, which is one of the key parameters for pellet production and quality. Thus the results for 0 and 10 cm underestimate the mechanical durability of the pellets in these zones up to a certain extent.

The original pellets, produced more than a year before these tests were conducted, had a low mechanical durability (94.4%) due to several handling and transport operations they were subjected to previously. Immediately after production the same pellets had durabilities between 96-98%, as reported in other research programs. Thus, the degradation suffered by the layers exposed to rain water is found to be more severe than in the previous tests reported in this deliverable.

With a direct relationship with increase in moisture content, top layers show a clear degradation in mechanical durability, presenting losses up to 28% in their values. For pellets deeper in the pile, there is no consistent change observed, as water did not percolate inside the pile. Other degrading effects such as biological activity were not observed in the pile or in the top layers.

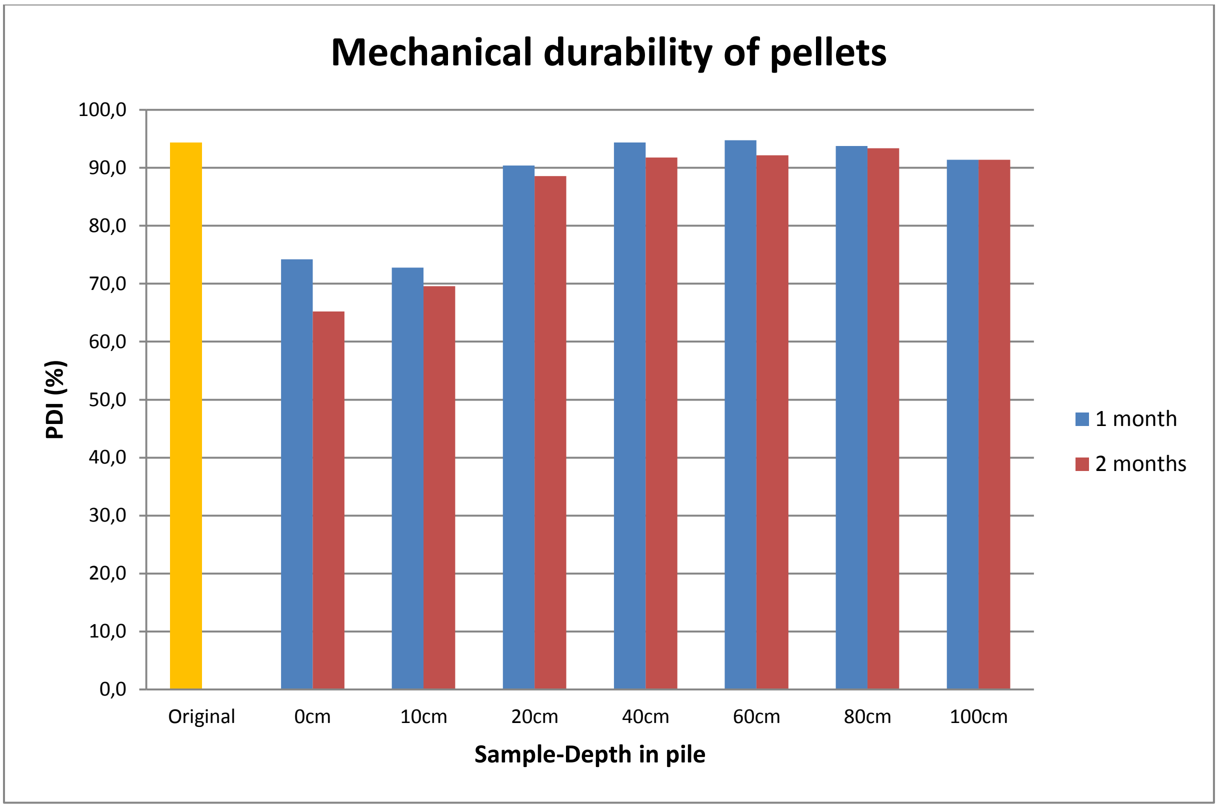


**Figure 59: Mechanical durability results of all samples**

Formation of fines and dust is normally associated with explosion hazards in coal and biomass facilities. However, pellet degradation occurs due to the moisture intake by the pellets so the fines and dust generated will be also wet, reducing the risk of dust explosions in the fuel handling system. Where fines are lost from handling systems and allowed to accumulate on plant surfaces there is a risk of them drying and presenting a dust explosion risk, as with other biomass fuels, but this will be dependent on the individual plant equipment and procedures.

Spontaneous combustion of an open air stockpile of coal is not uncommon due to the voids in the pile and to the free air flowing. In order to reduce this hazard, loaders drive on the pile to compact it. This hazard is more severe when increasing the moisture content of coal. In these tests, there was no evidence of self-heating or spontaneous combustion, so compaction of the pellets (which risks mechanical damage to the pellets) may not be required.

### 5.3.7 Explosivity of dust formed during handling of exposed pellets

ECN has conducted measurements to determine the Minimum Ignition Energy of the Topell torrefied forest residue pellet samples that were exposed for a period of one month, in the Hartmann tube in accordance with European Standard EN 13821:2002. Normally the MIE would be determined by pulverising the Topell torrefied forest residue pellets and subjecting the fraction below 63 µm to MIE measurements. However, to specifically investigate the effect of pellet weathering, the exposed pellets were dried and subsequently subjected to the mechanical durability determination in accordance with EN15210:2009-1. The obtained dust samples were sieved, and the fraction below 63 µm was dried overnight at 85 °C and subjected to MIE measurements. A sample of commercially available white wood pellets was subjected to the same measurements as a reference, although it should be noted that this sample was not subjected to any outdoor storage experiment. The results of the durability assessment and associated MIE, both with induction switched off and on, are presented in Table 14.

**Table 14 Minimum Ignition Energy of tumbling dusts < 63 µm obtained from open air exposed Topell torrefied pellets and reference non-exposed white wood pellets**

| Sample depth in pile [cm] | Mechanical durability [%] | MIE (Induction Off/On) [mJ] |
|---:|---:|---:|
| 0 | 74.1 | 144/82 |
| 20 | 91.1 | 82/82 |
| 100 | 90.2 | 120/144 |
| White wood pellets (reference) | 96.3 | 14/Not determined |

The results demonstrate that despite of the fact that the Topell torrefied forest residue pellets were less durable and that the overall dust formation could be higher than for white wood pellets, the dust that is formed below 63 µm during handling of white wood pellets has a required minimum ignition energy that is approximately an order of magnitude smaller than for dust obtained from exposed Topell torrefied forest residue pellets. The MIE determination tests were performed both with an inductance where the spark is protracted, simulating the conditions during milling of the torrefied pellets; and once without an inductance simulating the conditions during dust formation during handling and logistics. Normally the MIE with inductance switched off results in comparable or slightly higher values, compared to inductance switched on. Since the determination of the MIE is a statistical method that consists of numerous measurements at different energy levels and ignition delay times, slightly different trends can be observed, for instance for the sample obtained from a depth of 100 cm. However, the observed difference of almost an order of magnitude is considered significant. While explosivity tests on other torrefied materials show a wider range of MIE values, including some that are very low, as reported in Deliverable 6.5, care needs to be taken when comparing the data. The work in Deliverable 6.5 was undertaken on fresh pellet, not material which had been weather exposed, in most cases the fine dust was generated by milling, not tumbling and where testing was carried out on dusts from tumbling, the size fraction used was <500 µm, not <63 µm. These differences demonstrate the need to both assess the explosivity of different torrefied materials individually and to identify the most appropriate test methodology to use for a given situation.

## 5.4 Conclusions of Topell tests

Topell Energy has conducted an outdoor storage test with two big bags filled with torrefied pellets exposing them open air for two months. One bag was sampled and dismantled after the first test month while the second pile was only sampled and manipulated at the end of the test in order to mitigate the different piles from any disturbances that could result from sampling.

The tested torrefied pellets were produced from local forest residues, a feedstock with significant lower calorific value than clean wood chips while also having higher ash content. The material produced in the torrefaction plant of Topell achieved a net calorific value of 19.3 GJ/ton, which corresponds to a good torrefied product when compared with the calorific value of the original feedstock. In terms of mechanical durability, the pellets presented lower values than when originally produced as they were previously stored for more than one year and they were subjected to several handling and transport operations during this period.

The results of this test show that the top layer of pellets directly exposed to rain water and eventual frost and snow fall (although snow fall did not occur during the 2014/2015 winter in The Netherlands), suffered degradation in terms of moisture intake and decrease of durability. This degradation generated a layer of fines at 10 cm depth that prevented percolation of water further deeper in the piles but also blocked transpiration from pellets directly below this layer that absorbed minor quantities of moisture before the formation of the mentioned layer. Thus, only 15 cm of pellets were affected by water intake with significant negative effects on calorific value and durability while the rest of the pellets did not show any change compared to the original. When extrapolating these results to larger stockpiles, the percentage of pellets negatively affected by water intake would be lower than 5%. In any case this is a major advantage of torrefied pellets compared to wood pellets, which will quickly disintegrate during open air exposure to rain.

In terms of mechanical durability, degraded top layers generate fines and dust that accumulate in inner parts of the pile. While dust generation is regarded as a negative safety issue, it has to be considered that the same moisture that degrades the pellets and generates dust is also contained in the dust and fines, inhibiting any deflagration or explosion to occur. Based on these tests, torrefied fuels do not appear to present the same self-ignition and spontaneous combustion risks as untreated biomass or reactive coals, but a thorough evaluation of the risks of any new torrefied material would still be recommended.

The dust fractions below 63 µm that were obtained during mechanical durability assessments of exposed torrefied forest residue pellets from the storage tests demonstrated a minimum ignition energy that was approximately an order of magnitude higher than for reference (unexposed) white wood pellets. The observed mechanical durability for the torrefied forest residue pellets was lower than white wood pellets and as such the overall dust formation was higher. However based on these findings it cannot be stated whether the dust formed during handling of exposed torrefied forest residue pellets results in increased explosivity risks compared to dust formed during handling of white wood pellets.

Despite the advantages and disadvantages of torrefied pellets towards coal described above, some common practices in some of the existing coal fired power plants could be adapted to use torrefied pellets efficiently without major disturbances and in some cases with limited extra investments required. Modifications required to existing coal handling practices may include:

- Avoid pilling up new material on already stored material. This would require removal of pellets from storage in a “piece of cake” manner and not scraping layers of the stockpile.
- Construction of simple covered storage structures, as it is already done in some facilities with coal. These structures do not need to be completely closed as for white pellets (which will disintegrate in contact, not only with rain water or snow but with ambient moisture).

It is expected that these changes would be lower cost than those required for the use of white wood pellet (such as covered conveyors and storage domes/silos).

# 6 Overall Conclusions from Stockpile testing

In total, six stockpiles were established during these tests and monitored for storage behaviour. The two stockpiles by E.ON in the UK, used the same torrefied spruce pellets sourced from Andritz (through Topell) but with different pile profiles, while of the two piles set up by Vattenfall in Sweden, one used the same Andritz torrefied spruce and the other Poplar torrefied by ECN. These stockpiles were stored outdoors uncovered for a duration of up to one year, while pellets were sampled for analysis during regular intervals. Topell established two stockpiles with torrefied forest residue pellets in the Netherlands, the latter stockpiles were also stored outdoors uncovered albeit for shorter durations of one and two months. After these timeframes the entire stockpile was sampled at once.

The stockpile test revealed that torrefied pellets appear to be unsuitable to be stored outdoors uncovered for long durations of up to one year. During this timeframe, the moisture content in the piles increased gradually, hence lowering the net calorific value of the material. This decrease in net calorific value could have several plant impacts, including:

- Higher fuel input for the same thermal output
- Possible reduced maximum loads due to equipment constraints (e.g. conveyors, fans), particularly on converted coal plant
- Higher moisture contents require more energy in fuel pre-heating to evaporate the moisture and hence reduce plant efficiency.

On some occasions, pellet agglomeration was observed which could inhibit the free flowing nature that fuel pellets usually display.

The observed decrease in pellet durability will result in more pellet breakage and dust formation during handling operations. The impact of this on plant operations will be site specific, but a potential concern may include the accumulation of potentially explosive dusts released during handling operations on plant surfaces and hence a requirement for additional dust controls. These risks may be mitigated by the high moisture content of the fines. Dust blow from the stockpile may also be a concern, although the presence of a layer of wet fines just below the surface in all of the test piles would suggest that a significant proportion of the fines generated due to pellet breakage are retained within the pile rather than being blown away.

In addition, the Vattenfall tests demonstrated that a relatively low pH leachate, with high biological and chemical oxygen demand, was formed by the interaction of the pellet with rain water, which would require the run-off from the stock pile to be treated before discharge. Excluding the impact of the increased moisture content, the basic chemical analysis of the fuels throughout testing did not show any significant differences. Temperature monitoring within all the piles did not give any evidence of self-heating, with temperatures generally tracking those of the ambient air, although temperatures in the centre of the piles were usually somewhat higher. However, these stockpiles were limited in size and so may have been too small to show self-heating effects.

The dust obtained from the degraded surface layer of torrefied pellets displayed a minimum ignition energy that was approximately an order of magnitude higher than for dust generated from white wood pellets, implying that the dust generated during handling of these degraded torrefied pellets is less prone to explode. However, work undertaken elsewhere in the SECTOR project (such as deliverable 6.5) has shown a variety of different results for minimum ignition energy, albeit under different conditions. It is therefore probable that explosivity testing would be required as part of the initial evaluation of a potential torrefied fuel.

The torrefied pellets displayed increased water resistance compared to white wood pellets. White wood pellets are well-known to swell and disintegrate on any exposure to rain, to the extent that transport ships will cease discharging at the first drop of rain. For the first few weeks of the testing, only the surface layer of the pellets showed large increases in moisture content or corresponding decreases in mechanical durability. For the large quantities of material needed by power plant, this surface layer would be a low percentage of the total delivery. It is therefore possible to envisage a situation where degradation of this portion of the fuel could be acceptable in return for the greater logistical flexibility of being able to establish temporary (e.g. <1 month) stocks outside or to allow discharge & movement of biomass materials in more inclement weather conditions. The excavation of the stockpile may however need to take place in a different manner than with coal, i.e. the entire height of the stockpile should be scooped up at once to prevent the formation of another surface layer. Evaluation of the necessity of this short-term flexibility and whether it provided a sufficient value case to justify the use of torrefied material as opposed to white wood pellet would have to be undertaken on a plant by plant basis. It may be possible to extend storage periods through the use of sheeting or simple covers to prevent direct rain exposure – these systems would be lower cost than the fully enclosed storage required for white wood pellet.

Development of the torrefaction and densification process is ongoing, with work undertaken within other work packages in the SECTOR project. The material produced from this optimisation work was not available for testing, but it may prove more robust and allow these storage periods to be extended. The standard to assess the mechanical durability of untreated biomass, EN15210:2009-1, should be reviewed to ensure that it is appropriate for testing pellet/fines mixtures with high moisture contents. This standard was developed based on untreated biomass pellets (e.g. white wood pellet), which generally have low moisture content and are never exposed to moisture during transport & storage. Wet fines could stick to the pellets, rather than being removed by sieving, and so artificially increased the apparent durability. This effect could be easily circumvented by drying at 35°C, before undertaking the durability testing, with the result that all the fines were sieved from the pellet.

# 7 References

UK Met Office 2014. Historic station data: Waddington, accessed from http://www.metoffice.gov.uk/pub/data/weather/uk/climate/stationdata/waddingtondata.txt on 20th September 2014. Contains public sector information licensed under the Open Government Licence v1.0.

Oveisi, E.; Lau, A.; Sokhansanj, S.; Lim, C.; Bi, X.; Larsson, S.; Melin, S.; *“Breakage behaviour from wood pellets due to free fall”*, Powder Technology 235 (2013) 493-499.

# 8 List of abbreviations

ar = *as received*

ATEX = *ATmosphere EXplosibles*

BOD = *Biological Oxygen Demand*

COD = *Chemical Oxygen Demand*

daf = *dry, ash-free basis*

db = *dry basis*

DoW = *Description of Work*

GCV = *Gross Calorific value*

HHV = *Higher Heating Value*

HSE = *Health Safety Environment*

LHV = *Lower Heating Value*

*MESAN = MESoscale ANalysis system*

NCV = *Net calorific value*

R&D = *Research & Development*

*SMHI = Swedish Metrological & Hydrological Institute*

## Appendix 1: Chemical analysis of E.ON Stockpile samples

**Table 15: Chemical Analysis of Peak Middle samples**

| | As Received Analysis | | | | | | | | Dry Ash Free Analysis | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Day number** | Total Moisture % | Volatile matter % | Ash % | GCV kJ/kg | Sulphur % | Chlorine % | H (calculated) % | Net CV kJ/kg | Volatile matter % | GCV kJ/kg |
| **0** | 3.1 | 73.9 | 0.6 | 21,510 | 0.01 | 0.01 | 5.50 | 20,236 | 76.7 | 22,340 |
| **7** | 3.4 | 73.3 | 0.7 | 21,410 | 0.01 | 0.01 | 5.58 | 20,140 | 76.4 | 22,330 |
| **13** | 3.8 | 73.3 | 0.4 | 21,470 | 0.01 | 0.01 | 5.59 | 20,180 | 76.5 | 22,410 |
| **21** | 6.2 | 71.7 | 0.3 | 20,850 | 0.01 | 0.01 | 5.45 | 19,540 | 76.7 | 22,300 |
| **28** | 4.5 | 72.2 | 0.5 | 21,270 | 0.01 | 0.01 | 5.51 | 19,980 | 76.0 | 22,390 |
| **35** | 4.6 | 72.7 | 0.4 | 21,190 | 0.01 | 0.01 | 5.53 | 19,900 | 76.5 | 22,310 |
| **42** | 4.7 | 72.0 | 0.4 | 21,440 | 0.01 | 0.01 | 5.53 | 20,150 | 75.9 | 22,590 |
| **48** | 4.2 | 73.1 | 0.5 | 21,270 | 0.01 | 0.01 | 5.56 | 19,980 | 76.7 | 22,320 |
| **55** | 4.9 | 72.1 | 0.4 | 21,090 | 0.01 | 0.01 | 5.48 | 19,800 | 76.1 | 22,270 |
| **68** | 5.0 | 72.1 | 0.5 | 21,160 | 0.01 | 0.01 | 5.50 | 19,860 | 76.3 | 22,390 |
| **76** | 4.9 | 72.6 | 0.5 | 21,050 | 0.01 | 0.01 | 5.51 | 19,760 | 76.7 | 22,250 |
| **89** | 10.1 | 68.5 | 0.4 | 19,530 | 0.01 | 0.01 | 5.13 | 18,190 | 76.5 | 21,820 |
| **111** | 14.9 | 64.0 | 0.4 | 18,994 | 0.01 | 0.01 | 4.89 | 17,586 | 75.6 | 22,450 |
| **144** | 20.2 | 60.3 | 0.4 | 17,700 | 0.01 | 0.01 | 4.58 | 16,230 | 75.9 | 22,290 |
| **171** | 26.6 | 55.8 | 0.3 | 16,094 | 0.00 | 0.00 | 4.20 | 14,545 | 76.5 | 22,046 |
| **192** | 23.0 | 58.3 | 0.5 | 17,040 | 0.01 | 0.01 | 4.42 | 15,530 | 76.2 | 22,270 |
| **227** | 39.7 | 45.9 | 0.3 | 13,345 | 0.01 | 0.01 | 3.47 | 11,634 | 76.5 | 22,250 |
| **255** | 31.9 | 51.9 | 0.3 | 15,050 | 0.01 | 0.01 | 3.93 | 13,430 | 76.5 | 22,200 |
| **277** | 29.1 | 54.2 | 0.4 | 15,650 | 0.01 | 0.01 | 4.10 | 14,060 | 76.9 | 22,200 |
| **311** | 29.9 | 53.4 | 0.5 | 15,462 | 0.01 | 0.01 | 4.03 | 13,870 | 76.6 | 22,191 |
| **342** | 32.5 | 51.4 | 0.4 | 14,861 | <0.01 | 0.01 | 3.88 | 13,238 | 76.6 | 22,145 |
| **383** | 33.0 | 50.8 | 0.3 | 14,754 | <0.01 | <0.01 | 3.84 | 13,128 | 76.2 | 22,140 |

**Table 16: Chemical analysis of Peak Edge samples**

| | As Received Analysis | | | | | | | | Dry Ash Free Analysis | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Day number** | Total Moisture % | Volatile matter % | Ash % | GCV kJ/kg | Sulphur % | Chlorine % | H (calculated) % | Net CV kJ/kg | Volatile matter % | GCV kJ/kg |
| **0** | 3.1 | 73.9 | 0.6 | 21,510 | 0.01 | 0.01 | 5.50 | 20,236 | 76.7 | 22,340 |
| **7** | 20.6 | 60.6 | 0.3 | 17,620 | 0.01 | 0.01 | 4.60 | 16,130 | 76.6 | 22,280 |
| **13** | 22.1 | 59.8 | 0.4 | 17,390 | 0.01 | 0.01 | 4.55 | 15,880 | 77.2 | 22,440 |
| **21** | 31.5 | 52.9 | 0.2 | 15,250 | 0.01 | 0.01 | 4.01 | 13,620 | 77.5 | 22,330 |
| **28** | 13.5 | 67.0 | 0.3 | 19,320 | 0.01 | 0.01 | 5.09 | 17,900 | 77.7 | 22,410 |
| **35** | 5.6 | 72.1 | 0.4 | 20,850 | 0.01 | 0.01 | 5.46 | 19,550 | 76.7 | 22,180 |
| **42** | 5.7 | 72.5 | 0.4 | 20,990 | 0.01 | 0.01 | 5.51 | 19,680 | 77.2 | 22,350 |
| **48** | 9.1 | 69.6 | 1.3 | 19,990 | 0.01 | 0.01 | 5.28 | 18,640 | 77.7 | 22,310 |
| **55** | 15.8 | 64.9 | 0.3 | 18,720 | 0.01 | 0.01 | 4.92 | 17,280 | 77.4 | 22,310 |
| **68** | 10.6 | 68.4 | 0.4 | 19,710 | 0.01 | 0.01 | 5.17 | 18,350 | 76.9 | 22,150 |
| **76** | 7.3 | 71.5 | 0.4 | 20,660 | 0.01 | 0.01 | 5.43 | 19,320 | 77.5 | 22,380 |
| **89** | 9.1 | 69.2 | 0.4 | 20,370 | 0.01 | 0.01 | 5.29 | 19,020 | 76.5 | 22,510 |
| **111** | 6.8 | 72.0 | 0.3 | 20,614 | 0.01 | 0.01 | 5.45 | 19,287 | 77.4 | 22,160 |
| **144** | 38.1 | 47.2 | 0.3 | 13,770 | 0.01 | 0.01 | 3.58 | 12,070 | 76.6 | 22,350 |
| **171** | 35.0 | 50.3 | 0.2 | 14,234 | 0.00 | 0.00 | 3.77 | 12,574 | 77.6 | 21974 |
| **192** | 25.2 | 57.4 | 0.3 | 16,500 | 0.01 | 0.01 | 4.33 | 14,960 | 77.0 | 22,150 |
| **227** | 40.5 | 45.6 | 0.2 | 13,251 | 0.01 | 0.01 | 3.46 | 11,524 | 76.9 | 22,350 |
| **255** | 24.8 | 56.8 | 0.3 | 16,710 | 0.01 | 0.01 | 4.32 | 15,180 | 75.8 | 22,310 |
| **277** | 19.7 | 61.7 | 0.2 | 17,840 | 0.01 | 0.01 | 4.68 | 16,360 | 77.0 | 22,270 |
| **311** | 12.1 | 67.4 | 0.2 | 19,408 | 0.01 | <0.01 | 5.09 | 18,027 | 76.9 | 22,127 |
| **342** | 12.9 | 67.0 | 0.5 | 19,152 | <0.01 | <0.01 | 5.05 | 17,758 | 77.4 | 22,110 |
| **383** | 14.7 | 66.0 | 0.2 | 18,728 | <0.01 | <0.01 | 4.96 | 17,311 | 77.6 | 22,024 |

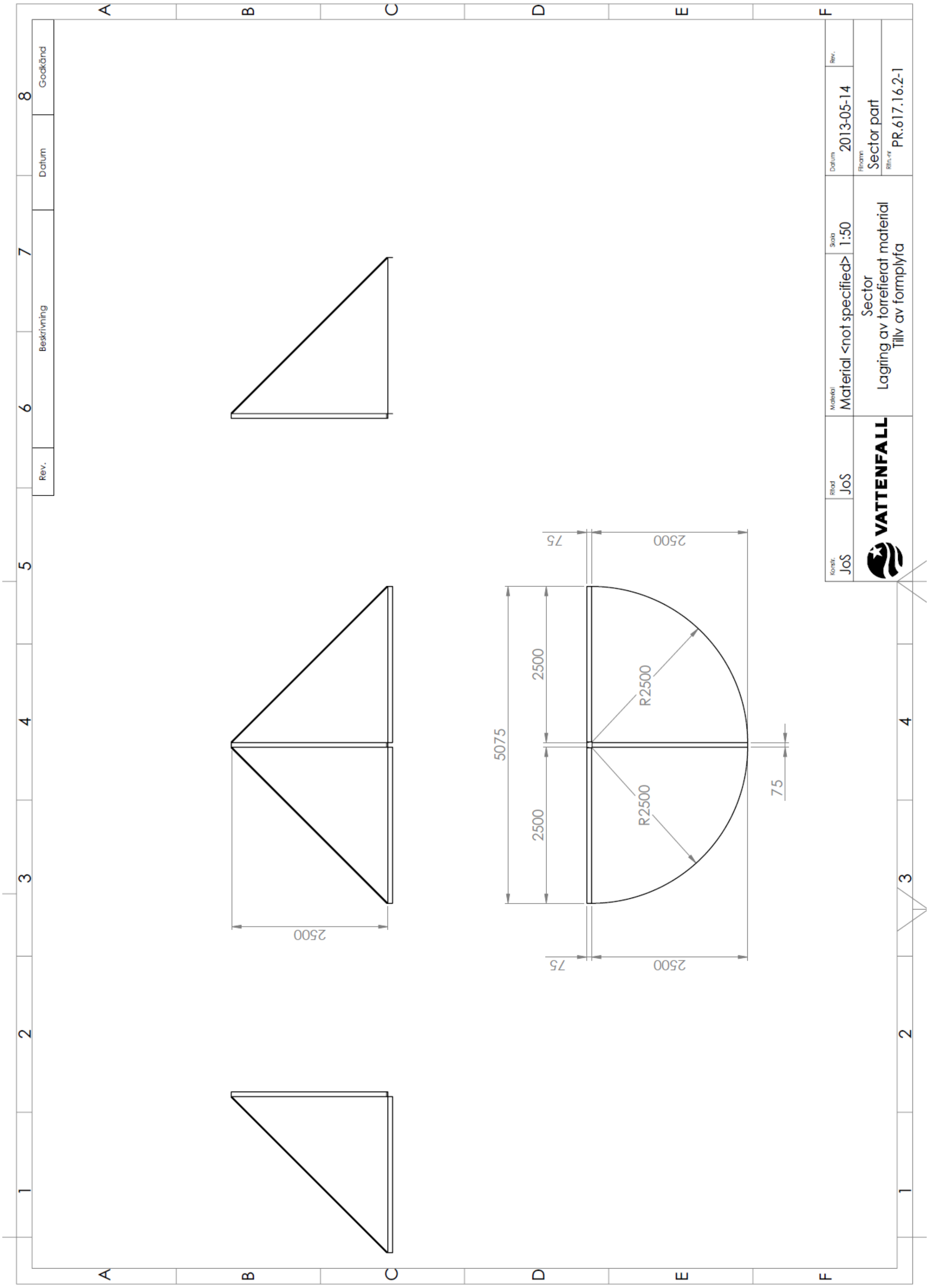
**Table 17: Chemical analysis of Flat Middle samples**

| | As Received Analysis | | | | | | | | Dry Ash Free Analysis | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Day number** | Total Moisture % | Volatile matter % | Ash % | GCV kJ/kg | Sulphur % | Chlorine % | H (calculated) % | Net CV kJ/kg | Volatile matter % | GCV kJ/kg |
| **0** | 3.1 | 73.9 | 0.6 | 21,510 | 0.01 | 0.01 | 5.50 | 20,236 | 76.7 | 22,340 |
| **7** | 3.9 | 72.7 | 0.5 | 21,550 | 0.01 | 0.02 | 5.57 | 20,270 | 76.0 | 22,540 |
| **13** | 4.3 | 71.9 | 0.5 | 21,520 | 0.01 | 0.01 | 5.52 | 20,240 | 75.5 | 22,610 |
| **21** | 5.0 | 71.7 | 0.4 | 21,210 | 0.01 | 0.01 | 5.48 | 19,920 | 75.8 | 22,420 |
| **28** | 5.5 | 71.3 | 0.4 | 21,200 | 0.01 | 0.01 | 5.46 | 19,900 | 75.8 | 22,530 |
| **35** | 4.6 | 72.1 | 0.4 | 21,330 | 0.01 | 0.01 | 5.51 | 20,040 | 75.9 | 22,450 |
| **42** | 4.8 | 72.9 | 0.4 | 21,160 | 0.01 | 0.01 | 5.54 | 19,860 | 76.9 | 22,320 |
| **48** | 8.3 | 68.9 | 0.5 | 20,570 | 0.01 | 0.01 | 5.28 | 19,240 | 75.5 | 22,550 |
| **55** | 7.5 | 69.5 | 0.5 | 20,680 | 0.01 | 0.01 | 5.31 | 19,360 | 75.5 | 22,480 |
| **68** | 10.7 | 67.3 | 0.4 | 19,990 | 0.01 | 0.01 | 5.15 | 18,630 | 75.7 | 22,490 |
| **76** | 10.1 | 67.5 | 0.5 | 20,150 | 0.01 | 0.01 | 5.17 | 18,800 | 75.5 | 22,540 |
| **89** | 18.4 | 61.5 | 0.4 | 18,180 | 0.01 | 0.01 | 4.69 | 16,730 | 75.7 | 22,390 |
| **111** | 9.4 | 69.0 | 0.5 | 19,999 | 0.01 | 0.01 | 5.23 | 18,653 | 76.6 | 22,180 |
| **144** | 18.6 | 62.3 | 0.3 | 18,030 | 0.01 | 0.01 | 4.72 | 16,570 | 76.8 | 22,230 |
| **171** | 31.1 | 51.7 | 0.3 | 15,330 | 0.00 | 0.00 | 3.94 | 13,731 | 75.4 | 22,333 |
| **192** | 32.2 | 51.1 | 0.3 | 15,130 | 0.01 | 0.01 | 3.90 | 13,510 | 75.7 | 22,410 |
| **227** | 30.4 | 52.1 | 0.4 | 15,587 | 0.01 | 0.01 | 3.99 | 13,991 | 75.4 | 22,520 |
| **255** | 34.1 | 49.9 | 0.2 | 14,680 | 0.01 | 0.01 | 3.80 | 13,030 | 76.0 | 22,340 |
| **277** | 30.3 | 52.5 | 0.3 | 15,570 | 0.01 | 0.01 | 4.01 | 13,980 | 75.6 | 22,440 |
| **311** | 32.6 | 50.7 | 0.2 | 15,065 | 0.01 | <0.01 | 3.87 | 13,443 | 75.5 | 22,415 |
| **342** | 43.4 | 42.7 | 0.3 | 12,545 | <0.01 | 0.01 | 3.24 | 10,794 | 75.8 | 22,275 |
| **383** | 35.2 | 48.6 | 0.3 | 14,433 | <0.01 | <0.01 | 3.70 | 12,784 | 75.3 | 22,345 |

**Table 18: Chemical analysis of Flat Edge samples**

| | As Received Analysis | | | | | | | | Dry Ash Free Analysis | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Day number** | Total Moisture % | Volatile matter % | Ash % | GCV kJ/kg | Sulphur % | Chlorine % | H (calculated) % | Net CV kJ/kg | Volatile matter % | GCV kJ/kg |
| **0** | 3.1 | 73.9 | 0.6 | 21,510 | 0.01 | 0.01 | 5.50 | 20,236 | 76.7 | 22,340 |
| **7** | 19.2 | 61.3 | 0.3 | 18,010 | 0.01 | 0.01 | 4.67 | 16,550 | 76.1 | 22,370 |
| **13** | 21.2 | 59.3 | 0.4 | 17,750 | 0.01 | 0.01 | 4.55 | 16,260 | 75.6 | 22,640 |
| **21** | 28.3 | 54.6 | 0.2 | 16,110 | 0.01 | 0.01 | 4.17 | 14,530 | 76.4 | 22,530 |
| **28** | 14.9 | 65.2 | 0.3 | 19,250 | 0.01 | 0.01 | 5.00 | 17,820 | 76.9 | 22,700 |
| **35** | 5.8 | 71.4 | 0.4 | 21,110 | 0.01 | 0.01 | 5.46 | 19,800 | 76.1 | 22,510 |
| **42** | 6.2 | 71.0 | 0.4 | 21,070 | 0.01 | 0.01 | 5.44 | 19,760 | 76.0 | 22,560 |
| **48** | 13.5 | 65.8 | 0.4 | 19,390 | 0.01 | 0.01 | 5.03 | 17,990 | 76.4 | 22,520 |
| **55** | 16.8 | 63.2 | 0.3 | 18,680 | 0.01 | 0.01 | 4.83 | 17,240 | 76.2 | 22,530 |
| **68** | 12.5 | 66.4 | 0.3 | 19,550 | 0.01 | 0.01 | 5.07 | 18,160 | 76.1 | 22,420 |
| **76** | 8.5 | 69.5 | 0.4 | 20,590 | 0.01 | 0.01 | 5.33 | 19,250 | 76.3 | 22,600 |
| **89** | 8.9 | 70.7 | 0.3 | 20,270 | 0.01 | 0.01 | 5.36 | 18,910 | 77.9 | 22,320 |
| **111** | 8.2 | 70.0 | 0.3 | 20,520 | 0.01 | 0.01 | 5.34 | 19,182 | 76.4 | 22,400 |
| **144** | 34.6 | 49.6 | 0.3 | 14,430 | 0.01 | 0.01 | 3.75 | 12,780 | 76.2 | 22,170 |
| **171** | 34.6 | 49.7 | 0.2 | 14,485 | 0.00 | 0.00 | 3.76 | 12,836 | 76.2 | 22,216 |
| **192** | 30.0 | 52.9 | 0.3 | 15,690 | 0.01 | 0.01 | 4.04 | 14,090 | 75.9 | 22,510 |
| **227** | 34.7 | 49.6 | 0.2 | 14,639 | 0.01 | 0.01 | 3.78 | 12,983 | 76.1 | 22,490 |
| **255** | 25.7 | 56.3 | 0.2 | 16,580 | 0.01 | 0.01 | 4.29 | 15,030 | 76.0 | 22,380 |
| **277** | 18.6 | 61.8 | 0.2 | 18,270 | 0.01 | 0.01 | 4.73 | 16,810 | 76.1 | 22,500 |
| **311** | 16.8 | 63.0 | 0.3 | 18,583 | 0.01 | <0.01 | 4.81 | 17,148 | 76.0 | 22,414 |
| **342** | 16.2 | 63.8 | 0.3 | 18,600 | 0.01 | 0.01 | 4.84 | 17,172 | 76.4 | 22,265 |
| **383** | 18.9 | 61.7 | 0.2 | 18,090 | <0.01 | <0.01 | 4.70 | 16,627 | 76.3 | 22,359 |

# Appendix 2: Vattenfall Storage construction drawing



# Appendix 3: Summary of Vattenfall poplar pellet analyses

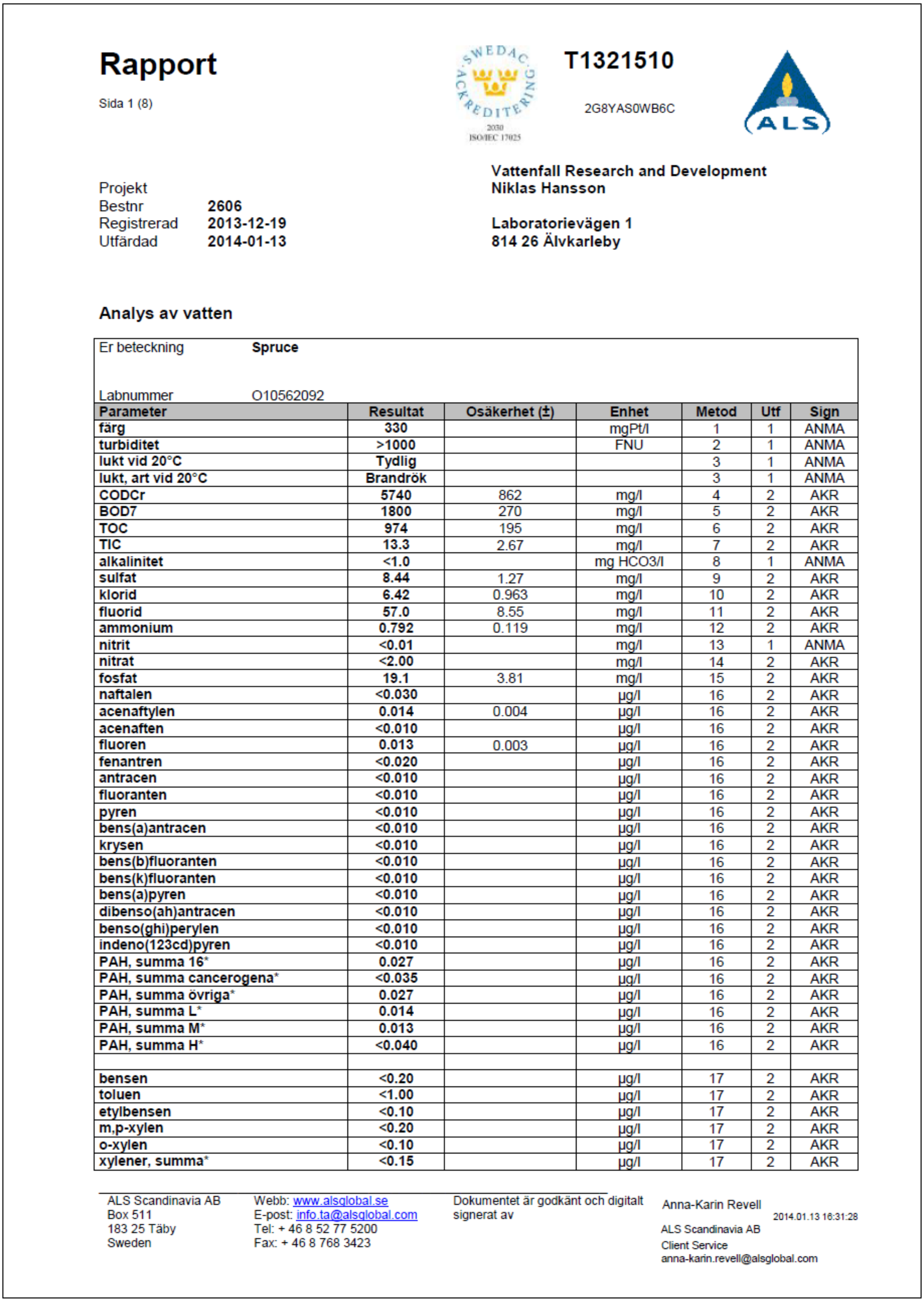
| Poplar pellet samples | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sample name** | | 1,1 | 1,2 | 1,3 | 2,1 | 2,2 | 3,1 | 3,2 | 4,1 | 4,2 | 5,1 | 5,2 | 6,1 | 6,2 | 7,1 | 7,2 | 8,1 | 8,2 | 8,3 | 8,4 |
| Sampling location at pile | [-] | Sacks as delivered | Sacks as delivered | Sacks as delivered | Inside | Surface | Inside | Surface | Inside | Surface | Inside | Surface | Inside | Surface | Inside | Surface | Inside | Inside | Inside | Surface |
| Sampling date | [-] | 13-06-16 | 13-06-16 | 13-06-16 | 13-07-14 | 13-07-14 | 13-09-08 | 13-09-08 | 13-10-16 | 13-10-16 | 13-11-24 | 13-11-24 | 14-01-08 | 14-01-08 | 14-03-09 | 14-03-09 | 14-03-24 | 14-03-24 | 14-03-24 | 14-03-24 |
| Arrival date at lab | [-] | 13-06-18 | 13-06-18 | 13-06-18 | 13-07-15 | 13-07-15 | 13-09-09 | 13-09-09 | 13-10-18 | 13-10-18 | 13-11-26 | 13-11-26 | 14-01-09 | 14-01-09 | 14-03-10 | 14-03-10 | 14-03-26 | 14-03-26 | 14-03-26 | 14-03-26 |
| Report date at lab | [-] | 13-06-26 | 13-06-26 | 13-06-26 | 13-07-22 | 13-07-22 | 13-09-16 | 13-09-16 | 13-10-23 | 13-10-23 | 13-12-03 | 13-12-03 | 14-01-16 | 14-01-16 | 14-03-17 | 14-03-17 | 14-04-03 | 14-04-03 | 14-04-03 | 14-04-03 |
| **Analysed parameters** | | | | | | | | | | | | | | | | | | | | |
| Moisture, 105C | [%] | 3,9 | 3,9 | 3,9 | 6,3 | 10,7 | 8,4 | 26,5 | 10,4 | 32,3 | 15,1 | 35,7 | 23,2 | 34,1 | 29,1 | 38,8 | 32,5 | 30,5 | 33,1 | 33,9 |
| Ash, 550C | [% db] | 0,69 | 0,7 | 0,72 | 0,7 | 0,7 | 0,7 | 0,8 | 0,8 | 0,7 | 0,7 | 0,6 | 0,7 | 0,6 | 0,7 | 0,5 | 0,6 | 0,7 | 0,7 | 0,7 |
| Ash, 550C ar | [%] | 0,66 | 0,67 | 0,69 | 0,7 | 0,6 | 0,6 | 0,6 | 0,7 | 0,5 | 0,6 | 0,4 | 0,5 | 0,4 | 0,5 | 0,3 | 0,4 | 0,5 | 0,4 | 0,4 |
| Volatile | [% db] | 77,4 | 78,9 | 78,4 | 76,9 | 76,4 | 78,1 | 77,7 | 78 | 77,9 | 77,4 | 77,9 | 77,5 | 77,1 | 77,1 | 78,3 | 78,1 | 77,7 | 77,4 | 78 |
| Volatile | [%] | 74,4 | 75,8 | 75,3 | 72,1 | 68,2 | 71,5 | 57,1 | 69,9 | 52,7 | 65,7 | 50,1 | 59,5 | 50,8 | 54,7 | 48,5 | 52,7 | 54 | 51,8 | 51,6 |
| Fixed Carbon | [% db] | 21,91 | 20,4 | 20,88 | 22,4 | 22,9 | 21,2 | 21,5 | 21,2 | 21,4 | 21,9 | 21,5 | 21,8 | 22,3 | 22,2 | 21,2 | 21,3 | 21,6 | 21,9 | 21,3 |
| Fixed Carbon | [%] | 21,01 | 19,6 | 20,08 | 20,9 | 20,4 | 19,4 | 15,6 | 18,9 | 14,3 | 18,5 | 13,6 | 16,6 | 14,5 | 15,5 | 12,2 | 14,2 | 14,8 | 14,4 | 13,8 |
| Carbon (C) ar | [%] | 51,1 | 51 | 51 | - | - | - | - | - | - | - | - | - | - | - | - | | 36,9 | | |
| Carbon (C) db | [% db] | 53,2 | 53,1 | 53 | - | - | - | - | - | - | - | - | - | - | - | - | | 53,1 | | |
| Hydrogen (H) ar | [%] | 6,1 | 6,1 | 6,1 | - | - | - | - | - | - | - | - | - | - | - | - | | 7,5 | | |
| Hydrogen (H) db | [% db] | 5,9 | 5,9 | 5,9 | 5,9 | 5,9 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 5,9 | 6,2 | 6,2 |
| Nitrogen (N) ar | [%] | < 0.10 | < 0.10 | < 0.10 | - | - | - | - | - | - | - | - | - | - | - | - | | < 0.10 | | |
| Nitrogen (N) db | [% db] | < 0.10 | < 0.10 | < 0.10 | - | - | - | - | - | - | - | - | - | - | - | - | | < 0.10 | | |
| Oxygen (O) ar | [%] | 42 | 42,2 | 42,2 | - | - | - | - | - | - | - | - | - | - | - | - | | 55 | | |
| Oxygen (O) db | [% db] | 40,1 | 40,3 | 40,3 | - | - | - | - | - | - | - | - | - | - | - | - | | 40,2 | | |
| Chlorine (Cl) ar | [%] | < 0.02 | < 0.02 | < 0.02 | - | - | - | - | - | - | - | - | - | - | - | - | | < 0.02 | | |
| Chlorine (Cl) db | [% db] | < 0.02 | < 0.02 | < 0.02 | - | - | - | - | - | - | - | - | - | - | - | - | | <0.02 | | |
| Sulphur (S) ar | [%] | 0,012 | 0,012 | 0,012 | - | - | - | - | - | - | - | - | - | - | - | - | | 0,012 | | |
| Sulphur (S) db | [% db] | 0,012 | 0,012 | 0,012 | - | - | - | - | - | - | - | - | - | - | - | - | | 0,018 | | |
| Gross cal. value Const volume ar | [MJ/kg] | 20,539 | 20,635 | 20,649 | 20,06 | 18,927 | 19,479 | 15,681 | 19,132 | 14,482 | 18,231 | 13,817 | 16,41 | 14,152 | 15,108 | 13,322 | 14,419 | 14,897 | 14,309 | 14,122 |
| Net cal. value Const press ar | [MJ/kg] | 19,208 | 19,307 | 19,322 | 18,704 | 17,519 | 18,039 | 14,044 | 17,67 | 12,781 | 16,718 | 12,078 | 14,808 | 12,432 | 13,442 | 11,559 | 12,715 | 13,262 | 12,599 | 12,404 |
| Net cal. value Const press db | [MJ/kg] | 20,086 | 20,189 | 20,205 | 20,125 | 19,911 | 19,917 | 19,987 | 20,004 | 20,043 | 20,125 | 20,139 | 20,019 | 20,127 | 19,96 | 20,138 | 20,012 | 20,154 | 20,04 | 20,016 |
| Net cal. value Const press db ashfree | [MJ/kg] | 20,225 | 20,33 | 20,351 | 20,272 | 20,056 | 20,056 | 20,146 | 20,164 | 20,184 | 20,27 | 20,258 | 20,162 | 20,258 | 20,109 | 20,249 | 20,138 | 20,302 | 20,175 | 20,151 |
| Gross cal. value Const volume ar | [Kcal/kg] | 4905 | 4928 | 4931 | 4790 | 4520 | 4652 | 3745 | 4569 | 3458 | 4354 | 3299 | 3919 | 3380 | 3608 | 3181 | 3443 | 3557 | 3417 | 3372 |
| Net cal. value Const press ar | [Kcal/kg] | 4587 | 4610 | 4614 | 4466 | 4184 | 4308 | 3354 | 4220 | 3052 | 3992 | 2884 | 3536 | 2969 | 3210 | 2760 | 3036 | 3167 | 3009 | 2962 |
| Net cal. value Const press db | [Kcal/kg] | 4797 | 4821 | 4825 | 4806 | 4755 | 4756 | 4773 | 4777 | 4786 | 4806 | 4809 | 4781 | 4806 | 4766 | 4809 | 4779 | 4813 | 4786 | 4780 |
| Net cal. value Const press db ashfree | [Kcal/kg] | 4830 | 4855 | 4860 | 4841 | 4789 | 4789 | 4811 | 4815 | 4820 | 4841 | 4838 | 4815 | 4838 | 4802 | 4835 | 4809 | 4848 | 4818 | 4812 |
| Gross cal. value Const volume ar | [MWh/tonne] | 5,704 | 5,73 | 5,734 | 5,571 | 5,256 | 5,409 | 4,355 | 5,313 | 4,022 | 5,063 | 3,837 | 4,557 | 3,93 | 4,195 | 3,7 | 4,004 | 4,137 | 3,974 | 3,922 |
| Net cal. value Const press ar | [MWh/tonne] | 5,334 | 5,361 | 5,366 | 5,194 | 4,865 | 5,009 | 3,9 | 4,907 | 3,549 | 4,643 | 3,354 | 4,112 | 3,452 | 3,733 | 3,21 | 3,531 | 3,683 | 3,499 | 3,445 |
| Net cal. value Const press db | [MWh/tonne] | 5,578 | 5,607 | 5,611 | 5,589 | 5,529 | 5,531 | 5,55 | 5,555 | 5,566 | 5,589 | 5,593 | 5,559 | 5,589 | 5,543 | 5,592 | 5,557 | 5,597 | 5,565 | 5,559 |
| Net cal. value Const press db ashfree | [MWh/tonne] | 5,616 | 5,646 | 5,652 | 5,63 | 5,57 | 5,569 | 5,595 | 5,6 | 5,605 | 5,629 | 5,626 | 5,599 | 5,626 | 5,584 | 5,623 | 5,592 | 5,638 | 5,603 | 5,596 |
| AF - Shrinking temp, ST | [C] | - | 825 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 730 | | - |
| AF - Deformation temp. , DT | [C] | - | 1500 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1260 | | - |
| AF - Hemisphere temp., HT | [C] | - | > 1500 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | > 1500 | | - |
| AF - Flow temp., FT | [C] | - | > 1500 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | > 1500 | | - |
| Bulk density | [kg/m3] | 701 | 700 | 701 | - | - | - | - | - | - | - | - | - | - | - | - | 712 | 712 | 706 | 706 |
| Mechanical durability | [%] | 97,4 | 97,5 | 97,5 | - | - | - | - | - | - | - | - | - | - | - | - | 87,4 | 88,7 | 90,9 | 94 |
| Energy density | [MJ/m3] | 13465 | 13515 | 13545 | | | | | | | | | | | | | 9053 | 9443 | 8895 | 8757 |
| Energy density | [MWh/m3] | 3,74 | 3,75 | 3,76 | | | | | | | | | | | | | 2,51 | 2,62 | 2,47 | 2,43 |

# Appendix 4: Summary of spruce pellet analyses

***Spruce pellet samples***

| ***Sample name*** | | ***1,1*** | ***1,2*** | ***1,3*** | ***2,1*** | ***2,2*** | ***3,1*** | ***3,2*** | ***4,1*** | ***4,2*** | ***5,1*** | ***5,2*** | ***6,1*** | ***6,2*** | ***7,1*** | ***7,2*** | ***8,1*** | ***8,2*** | ***8,3*** | ***8,4*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sampling location at pile | [-] | Sacks as delivered | Sacks as delivered | Sacks as delivered | Inside | Surface | Inside | Surface | Inside | Surface | Inside | Surface | Inside | Surface | Inside | Surface | Inside | Inside | Inside | Surface |
| Sampling date | [-] | 13-06-16 | 13-06-16 | 13-06-16 | 13-07-14 | 13-07-14 | 13-09-08 | 13-09-08 | 13-10-16 | 13-10-16 | 13-11-24 | 13-11-24 | 14-01-08 | 14-01-08 | 14-03-09 | 14-03-09 | 14-03-24 | 14-03-24 | 14-03-24 | 14-03-24 |
| Arrival date at lab | [-] | 13-06-18 | 13-06-18 | 13-06-18 | 13-07-15 | 13-07-15 | 13-09-09 | 13-09-09 | 13-10-18 | 13-10-18 | 13-11-26 | 13-11-26 | 14-01-09 | 14-01-09 | 14-03-10 | 14-03-10 | 14-03-26 | 14-03-26 | 14-03-26 | 14-03-26 |
| Report date at lab | [-] | 13-06-26 | 13-06-26 | 13-06-26 | 13-07-22 | 13-07-22 | 13-09-16 | 13-09-16 | 13-10-23 | 13-10-23 | 13-12-03 | 13-12-03 | 14-01-16 | 14-01-16 | 14-03-17 | 14-03-17 | 14-04-03 | 14-04-03 | 14-04-03 | 14-04-03 |
| ***Anlaysed parameters*** | | | | | | | | | | | | | | | | | | | | |
| Moisture, 105C | [%] | 4 | 4,1 | 3,7 | 8,8 | 24,8 | 16,6 | 33,3 | 18 | 34,1 | 18,1 | 34,7 | 31,7 | 34,7 | 32 | 36,5 | 34 | 34,4 | 33,7 | 37,1 |
| Ash, 550C | [% db] | 0,47 | 0,43 | 0,45 | 0,46 | 0,47 | 0,5 | < 0.30 | 0,43 | 0,31 | 0,5 | < 0.3 | 0,47 | < 0.30 | 0,33 | < 0.30 | < 0.30 | 0,31 | < 0.30 | < 0.30 |
| Ash, 550C ar | [%] | 0,45 | 0,41 | 0,43 | 0,42 | 0,35 | 0,42 | < 0.30 | 0,3526 | 0,2 | 0,4 | 0,2 | 0,32 | < 0.30 | 0,22 | < 0.30 | < 0.30 | 0,2 | < 0.30 | < 0.30 |
| Volatile | [% db] | 73,9 | 74 | 74 | 74 | 74,4 | 75,5 | 76 | 75,9 | 75,8 | 75,5 | 75,8 | 74,8 | 75,2 | 75,1 | 75,3 | 76,4 | 76,2 | 76 | 76,1 |
| Volatile | [%] | 71 | 70,9 | 71,3 | 67,5 | 56 | 62,9 | 50,7 | 62,238 | 49,9 | 61,8 | 49,5 | 51,1 | 49,1 | 51,1 | 47,8 | 50,4 | 50 | 50,4 | 47,9 |
| Fixed Carbon | [% db] | 25,63 | 25,57 | 25,55 | 25,54 | 25,13 | 24 | > 23,7 | 23,67 | 23,89 | 24 | > 23,9 | 24,73 | > 24,5 | 24,57 | > 24,4 | > 23,3 | 23,49 | > 23,7 | > 23,6 |
| Fixed Carbon | [%] | 24,55 | 24,59 | 24,57 | 23,28 | 18,85 | 20,08 | > 15,7 | 19,4094 | 15,8 | 19,7 | 15,6 | 16,88 | > 15,9 | 16,68 | > 15,4 | > 15,3 | 15,29 | > 15,6 | > 14,7 |
| Carbon (C) ar | [%] | 53,1 | 53 | 53,3 | - | - | - | - | - | - | - | - | - | - | - | - | - | 36,2 | - | |
| Carbon (C) db | [% db] | 55,3 | 55,3 | 55,3 | - | - | - | - | - | - | - | - | - | - | - | - | - | 55,1 | - | |
| Hydrogen (H) ar | [%] | 6 | 6 | 6 | - | - | - | - | - | - | - | - | - | - | - | - | - | 7,7 | - | |
| Hydrogen (H) db | [% db] | 5,8 | 5,8 | 5,8 | 5,8 | 5,8 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 6,2 | 5,8 | 6,2 | 6,2 |
| Nitrogen (N) ar | [%] | < 0.10 | < 0.10 | < 0.10 | - | - | - | - | - | - | - | - | - | - | - | - | - | 0,08 | | |
| Nitrogen (N) db | [% db] | < 0.10 | < 0.10 | < 0.10 | - | - | - | - | - | - | - | - | - | - | - | - | - | 0,12 | | |
| Oxygen (O) ar | [%] | 40,4 | 40,4 | 40,2 | - | - | - | - | - | - | - | - | - | - | - | - | - | 55,9 | | |
| Oxygen (O) db | [% db] | 38,3 | 38,4 | 38,3 | - | - | - | - | - | - | - | - | - | - | - | - | - | 38,6 | | |
| Chlorine (Cl) ar | [%] | < 0.02 | < 0.02 | < 0.02 | - | - | - | - | - | - | - | - | - | - | - | - | - | < 0.02 | | |
| Chlorine (Cl) db | [% db] | < 0.02 | < 0.02 | < 0.02 | - | - | - | - | - | - | - | - | - | - | - | - | - | < 0.02 | | |
| Sulphur (S) ar | [%] | < 0.012 | < 0.012 | < 0.012 | - | - | - | - | - | - | - | - | - | - | - | - | - | < 0.012 | | |
| Sulphur (S) db | [% db] | < 0.012 | < 0.012 | < 0.012 | - | - | - | - | - | - | - | - | - | - | - | - | - | < 0.012 | | |
| Gross cal. value Const volume ar | [MJ/kg] | 21,248 | 21,212 | 21,243 | 20,4 | 16,627 | 18,588 | 14,88 | 18,183 | 14,801 | 18,208 | 14,627 | 15,207 | 14,624 | 14,877 | 14,201 | 14,692 | 14,646 | 14,71 | 14,078 |
| Net cal. value Const press ar | [MJ/kg] | 19,937 | 19,897 | 19,932 | 19,036 | 15,074 | 17,058 | 13,168 | 16,712 | 13,08 | 16,662 | 12,899 | 13,512 | 12,896 | 13,179 | 12,454 | 12,972 | 12,979 | 12,994 | 12,324 |
| Net cal. value Const press db | [MJ/kg] | 20,869 | 20,852 | 20,791 | 21,108 | 20,85 | 20,939 | 20,96 | 20,826 | 21,111 | 20,883 | 21,05 | 20,916 | 21,046 | 20,53 | 21,015 | 20,911 | 21,064 | 20,838 | 21,032 |
| Net cal. value Const press db ashfree | [MJ/kg] | 20,967 | 20,942 | 20,884 | 21,205 | 20,948 | 21,044 | 21,012 | 20,916 | 21,176 | 20,996 | 21,109 | 21,015 | 21,099 | 20,598 | 21,059 | 20,968 | 21,129 | 20,898 | 21,092 |
| Gross cal. value Const volume ar | [Kcal/kg] | 5074 | 5065 | 5073 | 4872 | 3971 | 4439 | 3553 | 4342,178 | 3534 | 4348 | 3493 | 3631 | 3492 | 3553 | 3391 | 3508 | 3498 | 3513 | 3362 |
| Net cal. value Const press ar | [Kcal/kg] | 4761 | 4751 | 4760 | 4546 | 3600 | 4073 | 3144 | 3990,721 | 3124 | 3979 | 3080 | 3227 | 3080 | 3147 | 2974 | 3098 | 3099 | 3103 | 2943 |
| Net cal. value Const press db | [Kcal/kg] | 4984 | 4979 | 4965 | 5041 | 4979 | 5000 | 5005 | 4973,249 | 5041 | 4987 | 5027 | 4995 | 5026 | 4902 | 5018 | 4994 | 5030 | 4976 | 5023 |
| Net cal. value Const press db ashfree | [Kcal/kg] | 5007 | 5001 | 4987 | 5064 | 5002 | 5025 | 5018 | 4994,741 | 5057 | 5014 | 5041 | 5018 | 5038 | 4919 | 5029 | 5007 | 5046 | 4990 | 5037 |
| Gross cal. value Const volume ar | [MWh/tonne] | 5,901 | 5,891 | 5,899 | 5,665 | 4,617 | 5,162 | 4,132 | 5,051 | 4,11 | 5,056 | 4,062 | 4,223 | 4,061 | 4,131 | 3,944 | 4,08 | 4,067 | 4,085 | 3,909 |
| Net cal. value Const press ar | [MWh/tonne] | 5,536 | 5,525 | 5,535 | 5,286 | 4,186 | 4,737 | 3,657 | 4,642 | 3,632 | 4,627 | 3,582 | 3,752 | 3,581 | 3,66 | 3,459 | 3,602 | 3,604 | 3,608 | 3,422 |
| Net cal. value Const press db | [MWh/tonne] | 5,795 | 5,791 | 5,774 | 5,862 | 5,79 | 5,815 | 5,821 | 5,785 | 5,862 | 5,799 | 5,846 | 5,808 | 5,844 | 5,701 | 5,836 | 5,807 | 5,849 | 5,787 | 5,841 |
| Net cal. value Const press db ashfree | [MWh/tonne] | 5,822 | 5,816 | 5,8 | 5,889 | 5,817 | 5,844 | 5,835 | 5,810 | 5,881 | 5,831 | 5,862 | 5,836 | 5,859 | 5,72 | 5,848 | 5,823 | 5,868 | 5,803 | 5,857 |
| | | | | | | | | | | | | | | | | | | | | |
| AF - Shrinking temp, ST | [C] | - | 815 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 830 | - | - |
| AF - Deformation temp. , DT | [C] | - | 1430 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1390 | - | - |
| AF - Hemisphere temp., HT | [C] | - | 1445 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1420 | - | - |
| AF - Flow temp., FT | [C] | - | 1485 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1430 | - | - |
| | | | | | | | | | | | | | | | | | | | | |
| Bulk density | [kg/m3] | 708 | 709 | 707 | - | - | - | - | - | - | - | - | - | - | - | - | 710 | 714 | 709 | 710 |
| Mechanical durability | [%] | 96,4 | 96,5 | 96,4 | - | - | - | - | - | - | - | - | - | - | - | - | 94,2 | 92,9 | 94,3 | 95,4 |
| Energy density | [MJ/m3] | 14115 | 14107 | 14092 | | | | | | | | | | | | | 9210 | 9267 | 9213 | 8750 |
| Energy density | [MWh/m3] | 3,92 | 3,92 | 3,91 | | | | | | | | | | | | | 2,56 | 2,57 | 2,56 | 2,43 |

# Appendix 5: Leach water analyses – ALS report



## Rapport

Sida 1 (8)

T1321510

2G8YAS0WB6C

2030
ISO/IEC 17025

**Vattenfall Research and Development**
**Niklas Hansson**

**Laboratorievägen 1**
**814 26 Älvkarleby**

Projekt
Bestnr **2606**
Registrerad **2013-12-19**
Utfärdad **2014-01-13**

### Analys av vatten

Er beteckning **Spruce**

Labnummer O10562092

| Parameter | Resultat | Osäkerhet (±) | Enhet | Metod | Utf | Sign |
|---|---|---|---|---|---|---|
| **färg** | **330** | | mgPt/l | 1 | 1 | ANMA |
| **turbiditet** | **>1000** | | FNU | 2 | 1 | ANMA |
| **lukt vid 20°C** | **Tydlig** | | | 3 | 1 | ANMA |
| **lukt, art vid 20°C** | **Brandrök** | | | 3 | 1 | ANMA |
| **CODCr** | **5740** | 862 | mg/l | 4 | 2 | AKR |
| **BOD7** | **1800** | 270 | mg/l | 5 | 2 | AKR |
| **TOC** | **974** | 195 | mg/l | 6 | 2 | AKR |
| **TIC** | **13.3** | 2.67 | mg/l | 7 | 2 | AKR |
| **alkalinitet** | **<1.0** | | mg HCO3/l | 8 | 1 | ANMA |
| **sulfat** | **8.44** | 1.27 | mg/l | 9 | 2 | AKR |
| **klorid** | **6.42** | 0.963 | mg/l | 10 | 2 | AKR |
| **fluorid** | **57.0** | 8.55 | mg/l | 11 | 2 | AKR |
| **ammonium** | **0.792** | 0.119 | mg/l | 12 | 2 | AKR |
| **nitrit** | **<0.01** | | mg/l | 13 | 1 | ANMA |
| **nitrat** | **<2.00** | | mg/l | 14 | 2 | AKR |
| **fosfat** | **19.1** | 3.81 | mg/l | 15 | 2 | AKR |
| **naftalen** | **<0.030** | | µg/l | 16 | 2 | AKR |
| **acenaftylen** | **0.014** | 0.004 | µg/l | 16 | 2 | AKR |
| **acenaften** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **fluoren** | **0.013** | 0.003 | µg/l | 16 | 2 | AKR |
| **fenantren** | **<0.020** | | µg/l | 16 | 2 | AKR |
| **antracen** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **fluoranten** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **pyren** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **bens(a)antracen** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **krysen** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **bens(b)fluoranten** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **bens(k)fluoranten** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **bens(a)pyren** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **dibenso(ah)antracen** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **benso(ghi)perylen** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **indeno(123cd)pyren** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **PAH, summa 16*** | **0.027** | | µg/l | 16 | 2 | AKR |
| **PAH, summa cancerogena*** | **<0.035** | | µg/l | 16 | 2 | AKR |
| **PAH, summa övriga*** | **0.027** | | µg/l | 16 | 2 | AKR |
| **PAH, summa L*** | **0.014** | | µg/l | 16 | 2 | AKR |
| **PAH, summa M*** | **0.013** | | µg/l | 16 | 2 | AKR |
| **PAH, summa H*** | **<0.040** | | µg/l | 16 | 2 | AKR |
| | | | | | | |
| **bensen** | **<0.20** | | µg/l | 17 | 2 | AKR |
| **toluen** | **<1.00** | | µg/l | 17 | 2 | AKR |
| **etylbensen** | **<0.10** | | µg/l | 17 | 2 | AKR |
| **m,p-xylen** | **<0.20** | | µg/l | 17 | 2 | AKR |
| **o-xylen** | **<0.10** | | µg/l | 17 | 2 | AKR |
| **xylener, summa*** | **<0.15** | | µg/l | 17 | 2 | AKR |

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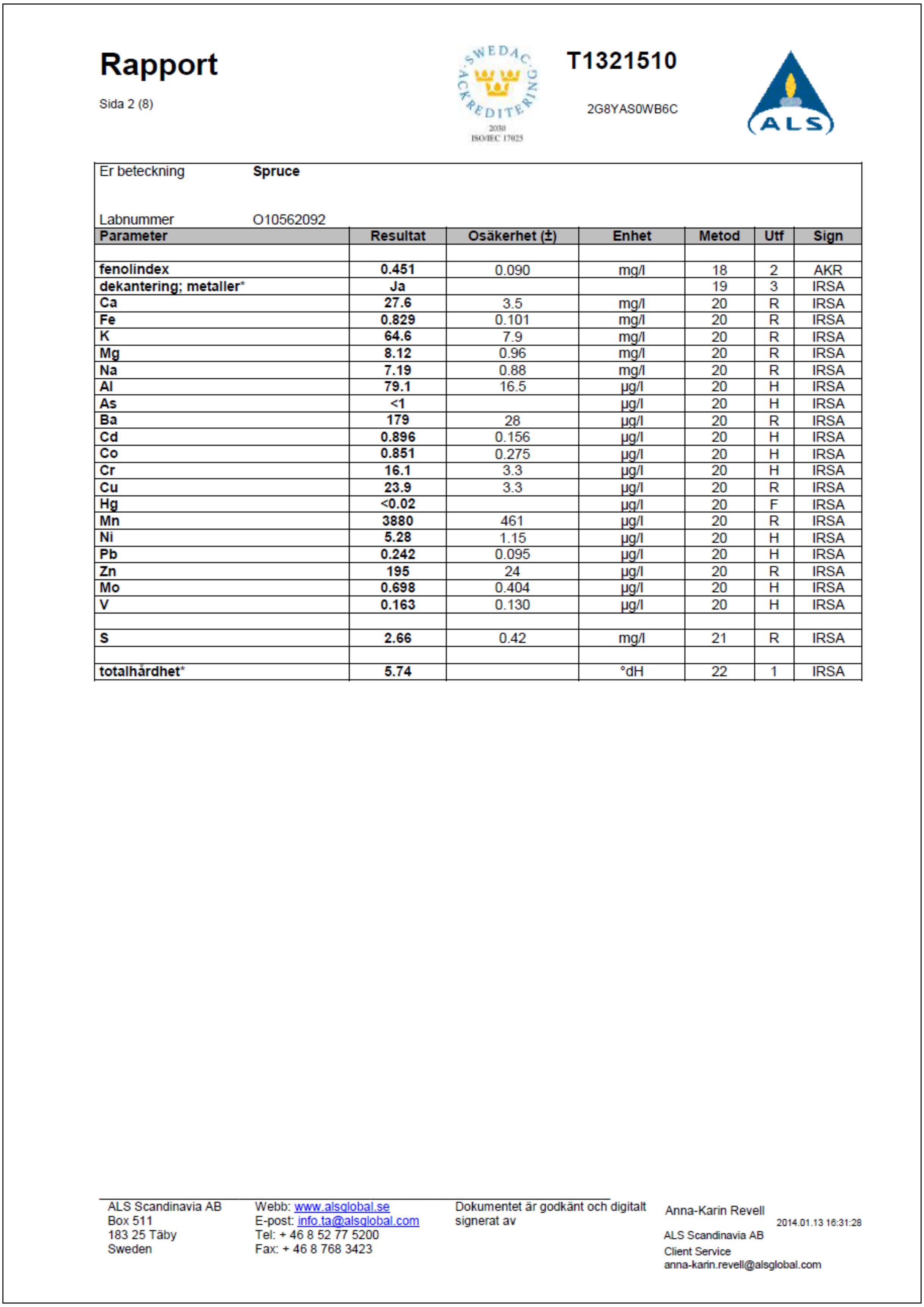

# Rapport

Sida 2 (8)

2030
ISO/IEC 17025

**T1321510**

2G8YAS0WB6C

Er beteckning **Spruce**

Labnummer O10562092

| Parameter | Resultat | Osäkerhet (±) | Enhet | Metod | Utf | Sign |
|---|---|---|---|---|---|---|
| | | | | | | |
| **fenolindex** | **0.451** | 0.090 | mg/l | 18 | 2 | AKR |
| **dekantering; metaller*** | **Ja** | | | 19 | 3 | IRSA |
| **Ca** | **27.6** | 3.5 | mg/l | 20 | R | IRSA |
| **Fe** | **0.829** | 0.101 | mg/l | 20 | R | IRSA |
| **K** | **64.6** | 7.9 | mg/l | 20 | R | IRSA |
| **Mg** | **8.12** | 0.96 | mg/l | 20 | R | IRSA |
| **Na** | **7.19** | 0.88 | mg/l | 20 | R | IRSA |
| **Al** | **79.1** | 16.5 | µg/l | 20 | H | IRSA |
| **As** | **<1** | | µg/l | 20 | H | IRSA |
| **Ba** | **179** | 28 | µg/l | 20 | R | IRSA |
| **Cd** | **0.896** | 0.156 | µg/l | 20 | H | IRSA |
| **Co** | **0.851** | 0.275 | µg/l | 20 | H | IRSA |
| **Cr** | **16.1** | 3.3 | µg/l | 20 | H | IRSA |
| **Cu** | **23.9** | 3.3 | µg/l | 20 | R | IRSA |
| **Hg** | **<0.02** | | µg/l | 20 | F | IRSA |
| **Mn** | **3880** | 461 | µg/l | 20 | R | IRSA |
| **Ni** | **5.28** | 1.15 | µg/l | 20 | H | IRSA |
| **Pb** | **0.242** | 0.095 | µg/l | 20 | H | IRSA |
| **Zn** | **195** | 24 | µg/l | 20 | R | IRSA |
| **Mo** | **0.698** | 0.404 | µg/l | 20 | H | IRSA |
| **V** | **0.163** | 0.130 | µg/l | 20 | H | IRSA |
| | | | | | | |
| **S** | **2.66** | 0.42 | mg/l | 21 | R | IRSA |
| | | | | | | |
| **totalhårdhet*** | **5.74** | | °dH | 22 | 1 | IRSA |

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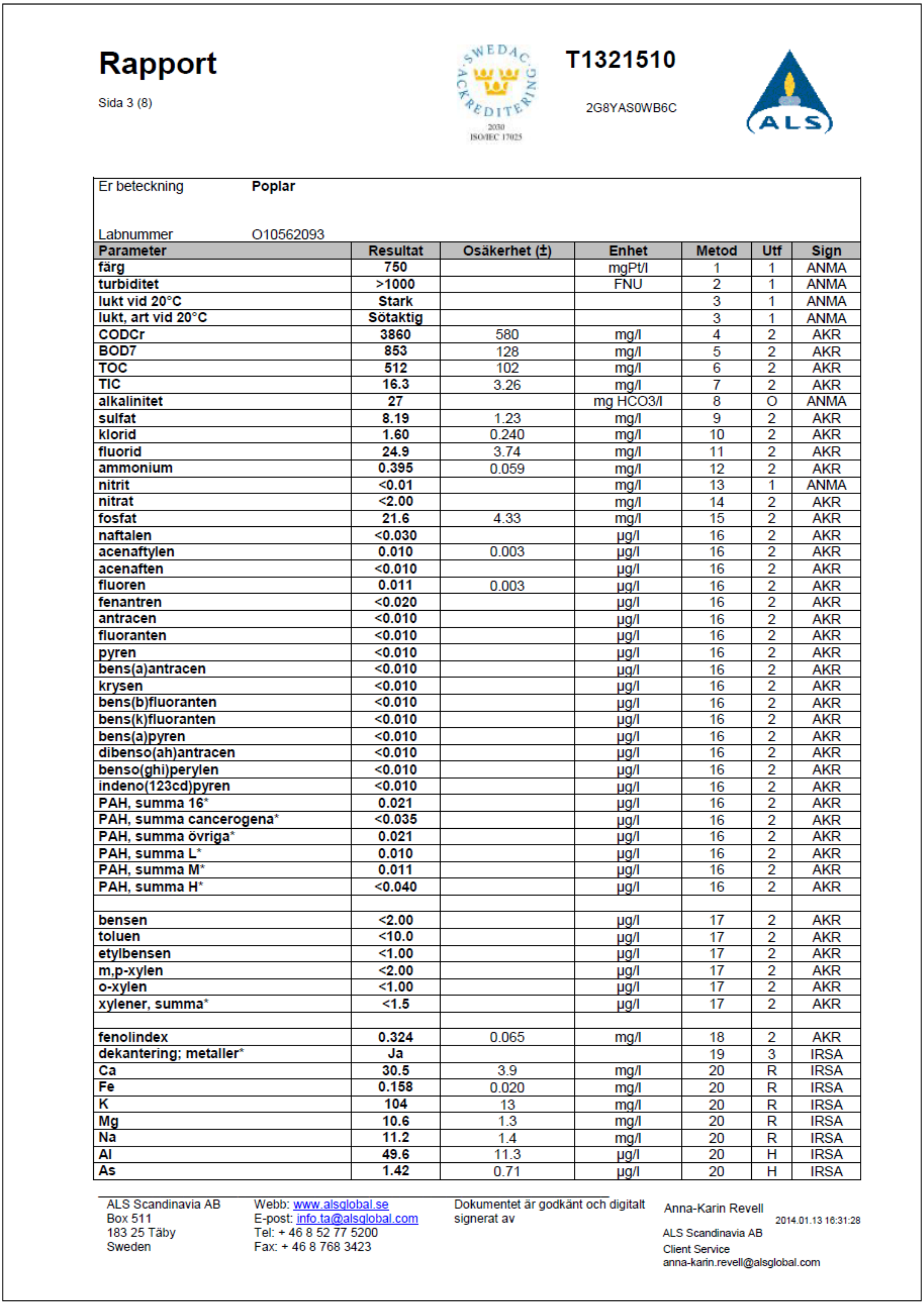

# Rapport

Sida 3 (8)

2030

**T1321510**

2G8YAS0WB6C

Er beteckning **Poplar**

Labnummer O10562093

| Parameter | Resultat | Osäkerhet (±) | Enhet | Metod | Utf | Sign |
|---|---|---|---|---|---|---|
| **färg** | **750** | | mgPt/l | 1 | 1 | ANMA |
| **turbiditet** | **>1000** | | FNU | 2 | 1 | ANMA |
| **lukt vid 20°C** | **Stark** | | | 3 | 1 | ANMA |
| **lukt, art vid 20°C** | **Sötaktig** | | | 3 | 1 | ANMA |
| **CODCr** | **3860** | 580 | mg/l | 4 | 2 | AKR |
| **BOD7** | **853** | 128 | mg/l | 5 | 2 | AKR |
| **TOC** | **512** | 102 | mg/l | 6 | 2 | AKR |
| **TIC** | **16.3** | 3.26 | mg/l | 7 | 2 | AKR |
| **alkalinitet** | **27** | | mg HCO3/l | 8 | O | ANMA |
| **sulfat** | **8.19** | 1.23 | mg/l | 9 | 2 | AKR |
| **klorid** | **1.60** | 0.240 | mg/l | 10 | 2 | AKR |
| **fluorid** | **24.9** | 3.74 | mg/l | 11 | 2 | AKR |
| **ammonium** | **0.395** | 0.059 | mg/l | 12 | 2 | AKR |
| **nitrit** | **<0.01** | | mg/l | 13 | 1 | ANMA |
| **nitrat** | **<2.00** | | mg/l | 14 | 2 | AKR |
| **fosfat** | **21.6** | 4.33 | mg/l | 15 | 2 | AKR |
| **naftalen** | **<0.030** | | µg/l | 16 | 2 | AKR |
| **acenaftylen** | **0.010** | 0.003 | µg/l | 16 | 2 | AKR |
| **acenaften** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **fluoren** | **0.011** | 0.003 | µg/l | 16 | 2 | AKR |
| **fenantren** | **<0.020** | | µg/l | 16 | 2 | AKR |
| **antracen** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **fluoranten** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **pyren** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **bens(a)antracen** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **krysen** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **bens(b)fluoranten** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **bens(k)fluoranten** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **bens(a)pyren** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **dibenso(ah)antracen** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **benso(ghi)perylen** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **indeno(123cd)pyren** | **<0.010** | | µg/l | 16 | 2 | AKR |
| **PAH, summa 16*** | **0.021** | | µg/l | 16 | 2 | AKR |
| **PAH, summa cancerogena*** | **<0.035** | | µg/l | 16 | 2 | AKR |
| **PAH, summa övriga*** | **0.021** | | µg/l | 16 | 2 | AKR |
| **PAH, summa L*** | **0.010** | | µg/l | 16 | 2 | AKR |
| **PAH, summa M*** | **0.011** | | µg/l | 16 | 2 | AKR |
| **PAH, summa H*** | **<0.040** | | µg/l | 16 | 2 | AKR |
| | | | | | | |
| **bensen** | **<2.00** | | µg/l | 17 | 2 | AKR |
| **toluen** | **<10.0** | | µg/l | 17 | 2 | AKR |
| **etylbensen** | **<1.00** | | µg/l | 17 | 2 | AKR |
| **m,p-xylen** | **<2.00** | | µg/l | 17 | 2 | AKR |
| **o-xylen** | **<1.00** | | µg/l | 17 | 2 | AKR |
| **xylener, summa*** | **<1.5** | | µg/l | 17 | 2 | AKR |
| | | | | | | |
| **fenolindex** | **0.324** | 0.065 | mg/l | 18 | 2 | AKR |
| **dekantering; metaller*** | **Ja** | | | 19 | 3 | IRSA |
| **Ca** | **30.5** | 3.9 | mg/l | 20 | R | IRSA |
| **Fe** | **0.158** | 0.020 | mg/l | 20 | R | IRSA |
| **K** | **104** | 13 | mg/l | 20 | R | IRSA |
| **Mg** | **10.6** | 1.3 | mg/l | 20 | R | IRSA |
| **Na** | **11.2** | 1.4 | mg/l | 20 | R | IRSA |
| **Al** | **49.6** | 11.3 | µg/l | 20 | H | IRSA |
| **As** | **1.42** | 0.71 | µg/l | 20 | H | IRSA |

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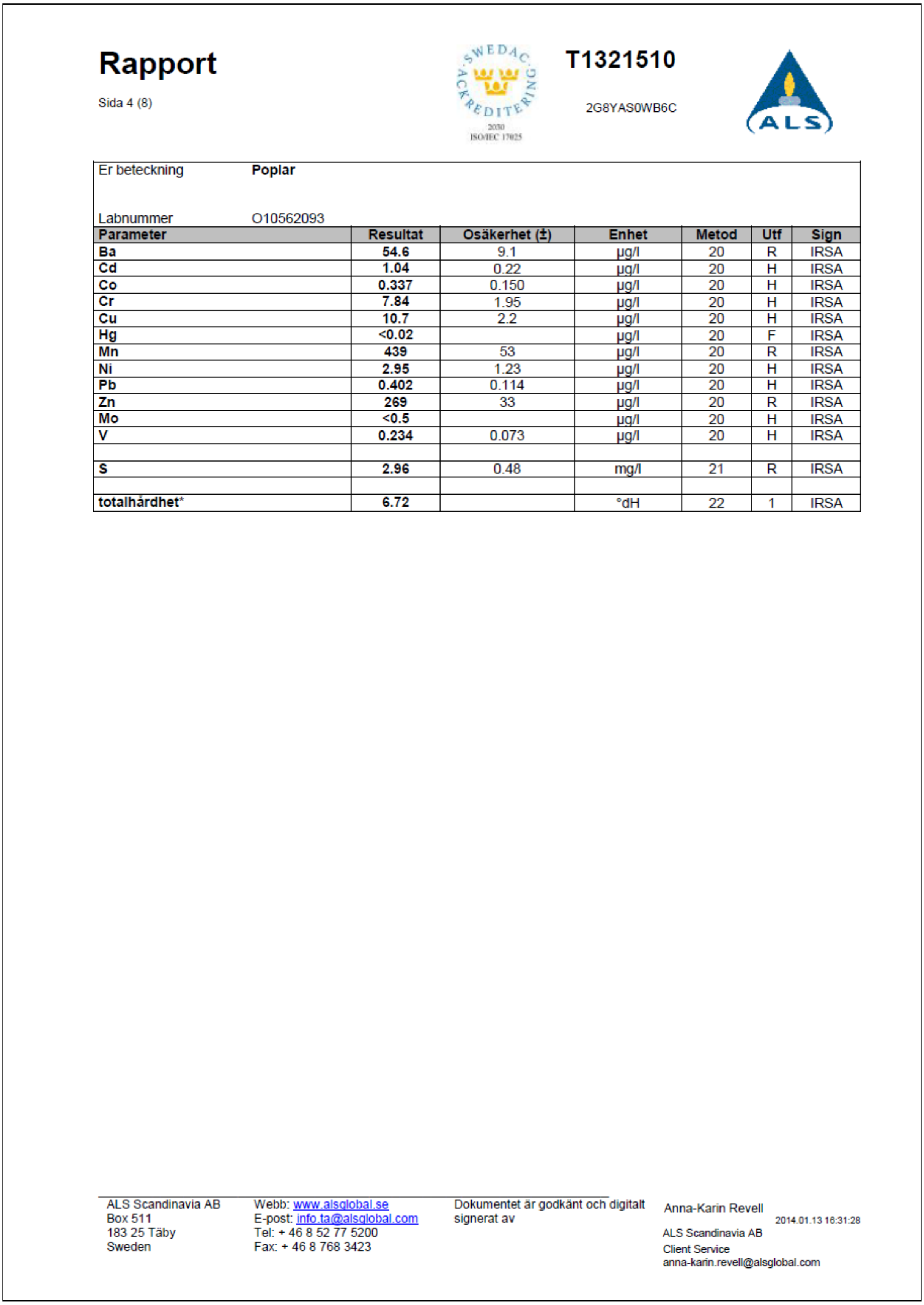

# Rapport

Sida 4 (8)

2030
ISO/IEC 17025

**T1321510**

2G8YAS0WB6C

| | |
|---|---|
| Er beteckning | **Poplar** |
| Labnummer | O10562093 |

| Parameter | Resultat | Osäkerhet (±) | Enhet | Metod | Utf | Sign |
|---|---|---|---|---|---|---|
| **Ba** | **54.6** | 9.1 | µg/l | 20 | R | IRSA |
| **Cd** | **1.04** | 0.22 | µg/l | 20 | H | IRSA |
| **Co** | **0.337** | 0.150 | µg/l | 20 | H | IRSA |
| **Cr** | **7.84** | 1.95 | µg/l | 20 | H | IRSA |
| **Cu** | **10.7** | 2.2 | µg/l | 20 | H | IRSA |
| **Hg** | **<0.02** | | µg/l | 20 | F | IRSA |
| **Mn** | **439** | 53 | µg/l | 20 | R | IRSA |
| **Ni** | **2.95** | 1.23 | µg/l | 20 | H | IRSA |
| **Pb** | **0.402** | 0.114 | µg/l | 20 | H | IRSA |
| **Zn** | **269** | 33 | µg/l | 20 | R | IRSA |
| **Mo** | **<0.5** | | µg/l | 20 | H | IRSA |
| **V** | **0.234** | 0.073 | µg/l | 20 | H | IRSA |
| | | | | | | |
| **S** | **2.96** | 0.48 | mg/l | 21 | R | IRSA |
| | | | | | | |
| **totalhårdhet*** | **6.72** | | °dH | 22 | 1 | IRSA |

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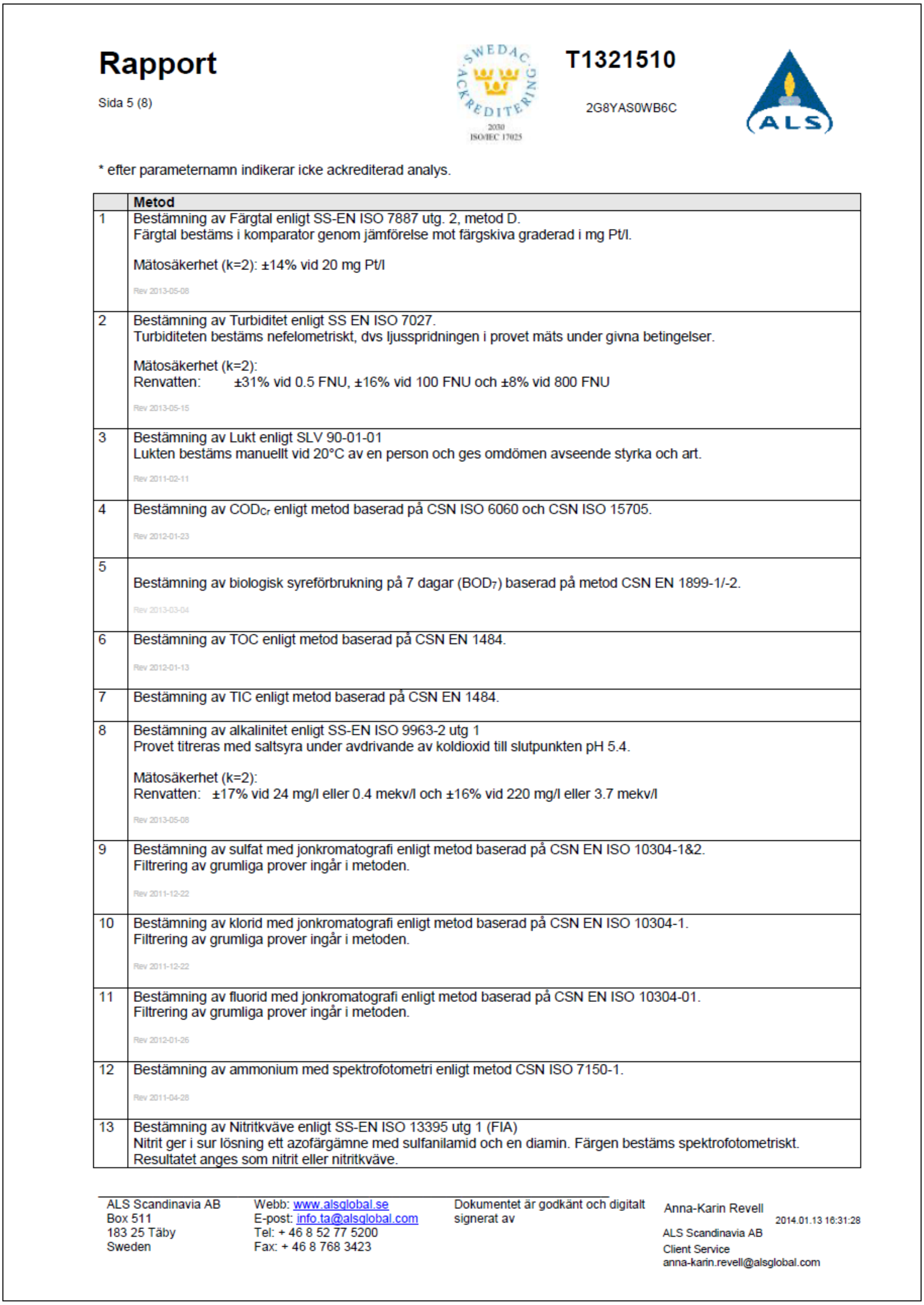

# Rapport

Sida 5 (8)

2030
ISO/IEC 17025

**T1321510**

2G8YAS0WB6C

* efter parameternamn indikerar icke ackrediterad analys.

| | **Metod** |
|---|---|
| 1 | Bestämning av Färgtal enligt SS-EN ISO 7887 utg. 2, metod D.<br>Färgtal bestäms i komparator genom jämförelse mot färgskiva graderad i mg Pt/l.<br>Mätosäkerhet (k=2): ±14% vid 20 mg Pt/l<br>Rev 2013-05-08 |
| 2 | Bestämning av Turbiditet enligt SS EN ISO 7027.<br>Turbiditeten bestäms nefelometriskt, dvs ljusspridningen i provet mäts under givna betingelser.<br>Mätosäkerhet (k=2):<br>Renvatten: ±31% vid 0.5 FNU, ±16% vid 100 FNU och ±8% vid 800 FNU<br>Rev 2013-05-15 |
| 3 | Bestämning av Lukt enligt SLV 90-01-01<br>Lukten bestäms manuellt vid 20°C av en person och ges omdömen avseende styrka och art.<br>Rev 2011-02-11 |
| 4 | Bestämning av $COD_{Cr}$ enligt metod baserad på CSN ISO 6060 och CSN ISO 15705.<br>Rev 2012-01-23 |
| 5 | Bestämning av biologisk syreförbrukning på 7 dagar ($BOD_7$) baserad på metod CSN EN 1899-1/-2.<br>Rev 2013-03-04 |
| 6 | Bestämning av TOC enligt metod baserad på CSN EN 1484.<br>Rev 2012-01-13 |
| 7 | Bestämning av TIC enligt metod baserad på CSN EN 1484. |
| 8 | Bestämning av alkalinitet enligt SS-EN ISO 9963-2 utg 1<br>Provet titreras med saltsyra under avdrivande av koldioxid till slutpunkten pH 5.4.<br>Mätosäkerhet (k=2):<br>Renvatten: ±17% vid 24 mg/l eller 0.4 mekv/l och ±16% vid 220 mg/l eller 3.7 mekv/l<br>Rev 2013-05-08 |
| 9 | Bestämning av sulfat med jonkromatografi enligt metod baserad på CSN EN ISO 10304-1&2.<br>Filtrering av grumliga prover ingår i metoden.<br>Rev 2011-12-22 |
| 10 | Bestämning av klorid med jonkromatografi enligt metod baserad på CSN EN ISO 10304-1.<br>Filtrering av grumliga prover ingår i metoden.<br>Rev 2011-12-22 |
| 11 | Bestämning av fluorid med jonkromatografi enligt metod baserad på CSN EN ISO 10304-01.<br>Filtrering av grumliga prover ingår i metoden.<br>Rev 2012-01-26 |
| 12 | Bestämning av ammonium med spektrofotometri enligt metod CSN ISO 7150-1.<br>Rev 2011-04-28 |
| 13 | Bestämning av Nitritkväve enligt SS-EN ISO 13395 utg 1 (FIA)<br>Nitrit ger i sur lösning ett azofärgämne med sulfanilamid och en diamin. Färgen bestäms spektrofotometriskt.<br>Resultatet anges som nitrit eller nitritkväve. |

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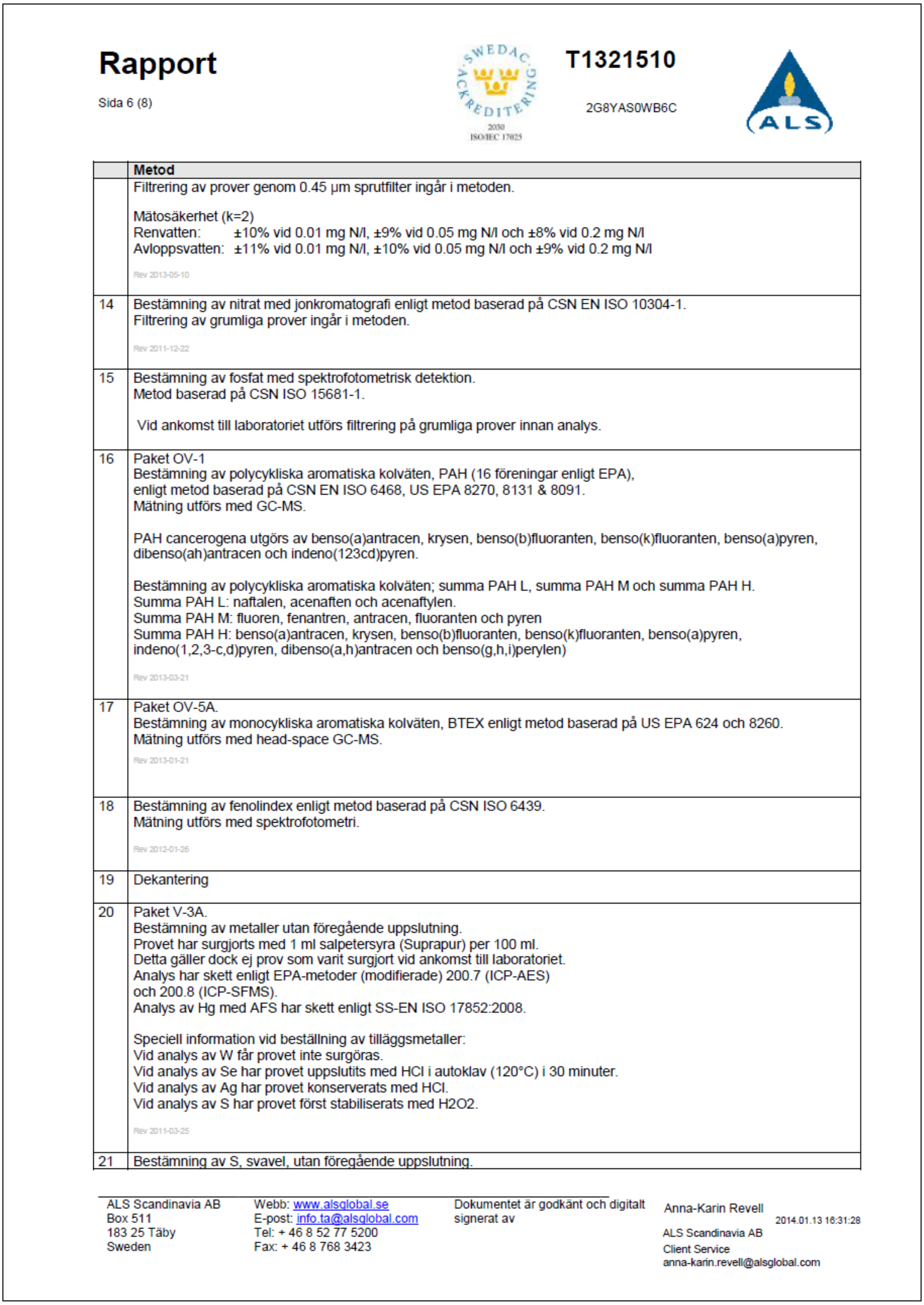

**Rapport**

Sida 6 (8)

2030
ISO/IEC 17025

**T1321510**

2G8YAS0WB6C

| | **Metod** |
|---|---|
| | Filtrering av prover genom 0.45 µm sprutfilter ingår i metoden.<br>Mätosäkerhet (k=2)<br>Renvatten: ±10% vid 0.01 mg N/l, ±9% vid 0.05 mg N/l och ±8% vid 0.2 mg N/l<br>Avloppsvatten: ±11% vid 0.01 mg N/l, ±10% vid 0.05 mg N/l och ±9% vid 0.2 mg N/l<br>Rev 2013-05-10 |
| 14 | Bestämning av nitrat med jonkromatografi enligt metod baserad på CSN EN ISO 10304-1.<br>Filtrering av grumliga prover ingår i metoden.<br>Rev 2011-12-22 |
| 15 | Bestämning av fosfat med spektrofotometrisk detektion.<br>Metod baserad på CSN ISO 15681-1.<br>Vid ankomst till laboratoriet utförs filtrering på grumliga prover innan analys. |
| 16 | Paket OV-1<br>Bestämning av polycykliska aromatiska kolväten, PAH (16 föreningar enligt EPA), enligt metod baserad på CSN EN ISO 6468, US EPA 8270, 8131 & 8091.<br>Mätning utförs med GC-MS.<br>PAH cancerogena utgörs av benso(a)antracen, krysen, benso(b)fluoranten, benso(k)fluoranten, benso(a)pyren, dibenso(ah)antracen och indeno(123cd)pyren.<br>Bestämning av polycykliska aromatiska kolväten; summa PAH L, summa PAH M och summa PAH H.<br>Summa PAH L: naftalen, acenaften och acenaftylen.<br>Summa PAH M: fluoren, fenantren, antracen, fluoranten och pyren<br>Summa PAH H: benso(a)antracen, krysen, benso(b)fluoranten, benso(k)fluoranten, benso(a)pyren, indeno(1,2,3-c,d)pyren, dibenso(a,h)antracen och benso(g,h,i)perylen)<br>Rev 2013-03-21 |
| 17 | Paket OV-5A.<br>Bestämning av monocykliska aromatiska kolväten, BTEX enligt metod baserad på US EPA 624 och 8260.<br>Mätning utförs med head-space GC-MS.<br>Rev 2013-01-21 |
| 18 | Bestämning av fenolindex enligt metod baserad på CSN ISO 6439.<br>Mätning utförs med spektrofotometri.<br>Rev 2012-01-26 |
| 19 | Dekantering |
| 20 | Paket V-3A.<br>Bestämning av metaller utan föregående uppslutning.<br>Provet har surgjorts med 1 ml salpetersyra (Suprapur) per 100 ml.<br>Detta gäller dock ej prov som varit surgjort vid ankomst till laboratoriet.<br>Analys har skett enligt EPA-metoder (modifierade) 200.7 (ICP-AES) och 200.8 (ICP-SFMS).<br>Analys av Hg med AFS har skett enligt SS-EN ISO 17852:2008.<br>Speciell information vid beställning av tilläggsmetaller:<br>Vid analys av W får provet inte surgöras.<br>Vid analys av Se har provet uppslutits med HCl i autoklav (120°C) i 30 minuter.<br>Vid analys av Ag har provet konserverats med HCl.<br>Vid analys av S har provet först stabiliserats med $H_2O_2$.<br>Rev 2011-03-25 |
| 21 | Bestämning av S, svavel, utan föregående uppslutning. |

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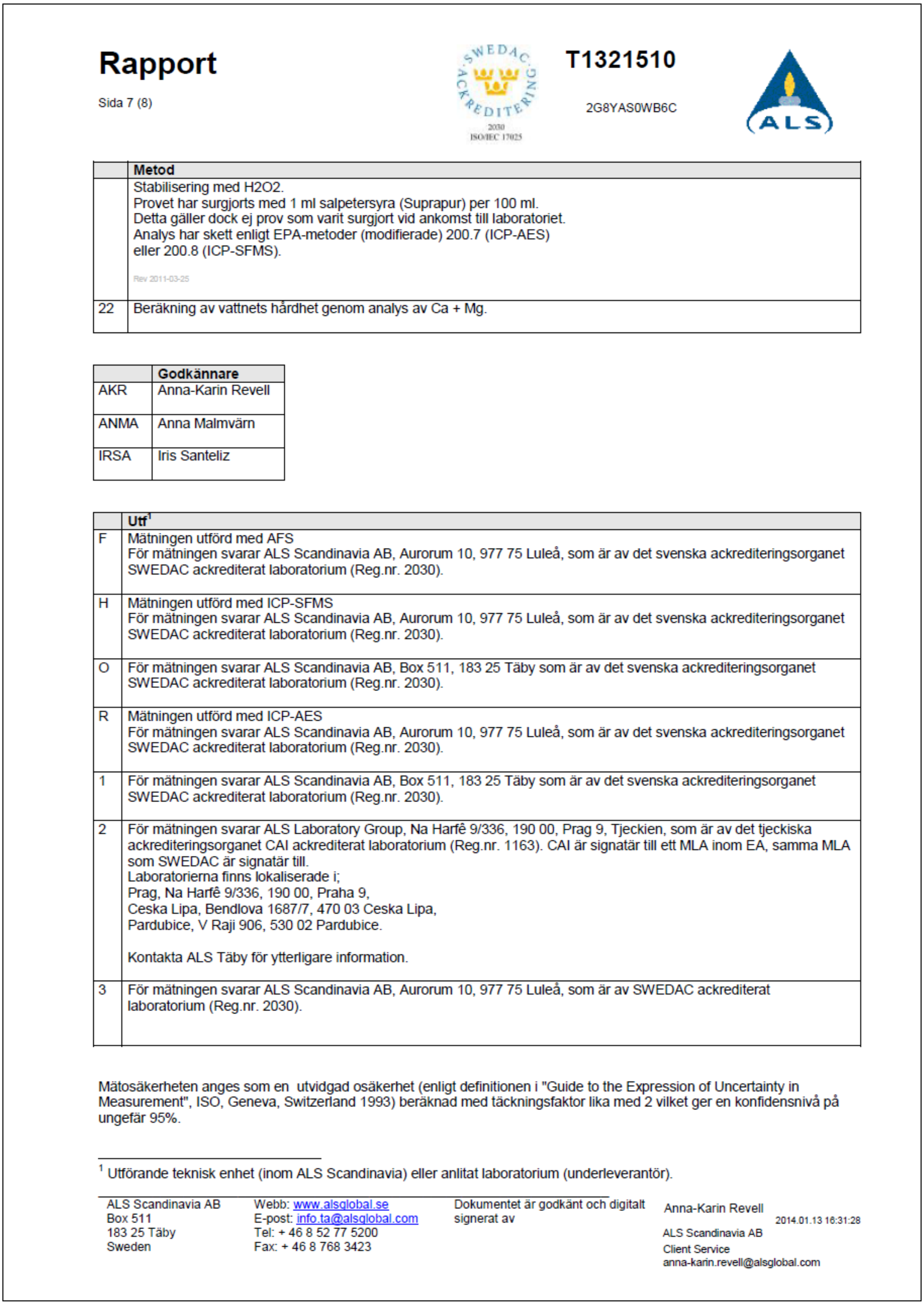

# Rapport

Sida 7 (8)

T1321510

2G8YAS0WB6C

| | Metod |
|---|---|
| | Stabilisering med H2O2.<br>Provet har surgjorts med 1 ml salpetersyra (Suprapur) per 100 ml.<br>Detta gäller dock ej prov som varit surgjort vid ankomst till laboratoriet.<br>Analys har skett enligt EPA-metoder (modifierade) 200.7 (ICP-AES)<br>eller 200.8 (ICP-SFMS).<br>Rev 2011-03-25 |
| 22 | Beräkning av vattnets hårdhet genom analys av Ca + Mg. |

| | Godkännare |
|---|---|
| AKR | Anna-Karin Revell |
| ANMA | Anna Malmvärn |
| IRSA | Iris Santeliz |

| | Utf[1] |
|---|---|
| F | Mätningen utförd med AFS<br>För mätningen svarar ALS Scandinavia AB, Aurorum 10, 977 75 Luleå, som är av det svenska ackrediteringsorganet SWEDAC ackrediterat laboratorium (Reg.nr. 2030). |
| H | Mätningen utförd med ICP-SFMS<br>För mätningen svarar ALS Scandinavia AB, Aurorum 10, 977 75 Luleå, som är av det svenska ackrediteringsorganet SWEDAC ackrediterat laboratorium (Reg.nr. 2030). |
| O | För mätningen svarar ALS Scandinavia AB, Box 511, 183 25 Täby som är av det svenska ackrediteringsorganet SWEDAC ackrediterat laboratorium (Reg.nr. 2030). |
| R | Mätningen utförd med ICP-AES<br>För mätningen svarar ALS Scandinavia AB, Aurorum 10, 977 75 Luleå, som är av det svenska ackrediteringsorganet SWEDAC ackrediterat laboratorium (Reg.nr. 2030). |
| 1 | För mätningen svarar ALS Scandinavia AB, Box 511, 183 25 Täby som är av det svenska ackrediteringsorganet SWEDAC ackrediterat laboratorium (Reg.nr. 2030). |
| 2 | För mätningen svarar ALS Laboratory Group, Na Harfê 9/336, 190 00, Prag 9, Tjeckien, som är av det tjeckiska ackrediteringsorganet CAI ackrediterat laboratorium (Reg.nr. 1163). CAI är signatär till ett MLA inom EA, samma MLA som SWEDAC är signatär till.<br>Laboratorierna finns lokaliserade i;<br>Prag, Na Harfê 9/336, 190 00, Praha 9,<br>Ceska Lipa, Bendlova 1687/7, 470 03 Ceska Lipa,<br>Pardubice, V Raji 906, 530 02 Pardubice.<br>Kontakta ALS Täby för ytterligare information. |
| 3 | För mätningen svarar ALS Scandinavia AB, Aurorum 10, 977 75 Luleå, som är av SWEDAC ackrediterat laboratorium (Reg.nr. 2030). |

Mätosäkerheten anges som en utvidgad osäkerhet (enligt definitionen i "Guide to the Expression of Uncertainty in Measurement", ISO, Geneva, Switzerland 1993) beräknad med täckningsfaktor lika med 2 vilket ger en konfidensnivå på ungefär 95%.

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[1] Utförande teknisk enhet (inom ALS Scandinavia) eller anlitat laboratorium (underleverantör).

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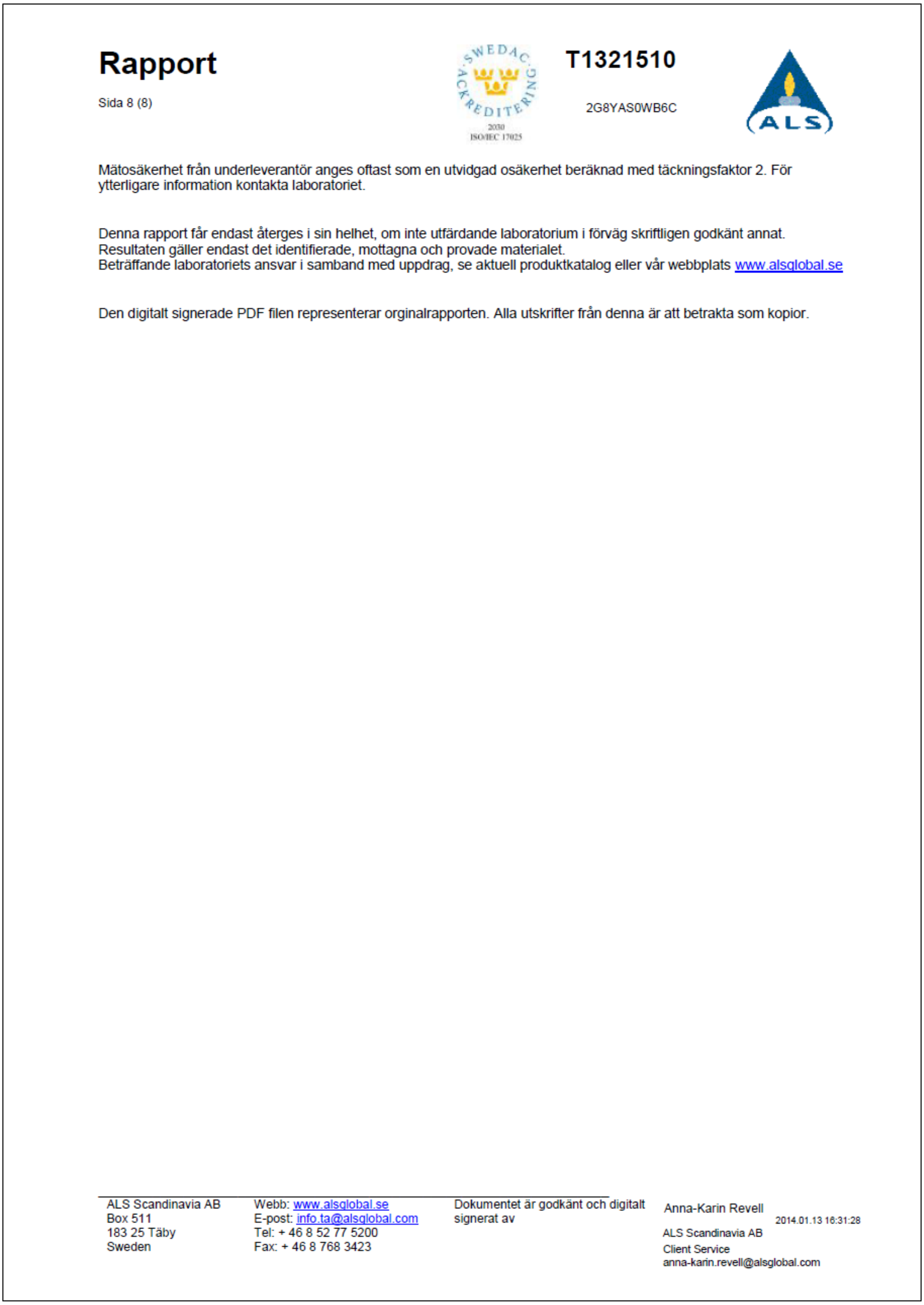

# Rapport

Sida 8 (8)

2030
ISO/IEC 17025

**T1321510**

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Mätosäkerhet från underleverantör anges oftast som en utvidgad osäkerhet beräknad med täckningsfaktor 2. För ytterligare information kontakta laboratoriet.

Denna rapport får endast återges i sin helhet, om inte utfärdande laboratorium i förväg skriftligen godkänt annat.
Resultaten gäller endast det identifierade, mottagna och provade materialet.
Beträffande laboratoriets ansvar i samband med uppdrag, se aktuell produktkatalog eller vår webbplats www.alsglobal.se

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