ENERGINET.DK

# Index - Final Report

# 1. Final report

## 1.1 Project details

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|---|---|
| **Project title** | ECOSORT – Sorting of industrial waste |
| **Project identification** | 2010-1-10448 |
| **Name of the programme which has funded the project**<br><br>(ForskVE, ForskNG or ForskEL) | ForskEL |
| **Name and address of the enterprises/institution responsible for the project** | Force Technology<br><br>Park Allé 345<br><br>DK-2605 Brøndby |
| **CVR** (central business register) | 55 11 73 14 |
| **Date for submission** | 18-12-2012 |

## 1.2 Executive summary

The present report constitutes the final report of the Ecosort project, a project aimed at reducing the release of harmful substances such as chlorine using sensor based sorting of combustible waste and thereby making the final RDF product suitable for co-firing in coal fired power plants in Denmark.

The project is partly financed by the PSO F&U programme ForskEL and by funds from the European Agency for Competitiveness and Innovation (EACI) under the Eco-Innovation programme. A part of the project is financed by each of the project participants.

The project partners are nomi i/s, located in Holstebro, Denmark, which processes combustible waste and FORCE Technology, located in Brøndby, Denmark, which has specialized in producing NDT systems for the industry using X-ray or radioactive isotopes.

In the agreement between FORCE Technology and PSO F&U programme ForskEL (project no. 2010-1-10448) the following main objectives were stated:

The main objective of the project is to document the environmental and economical advantages of a novel and very flexible sensor-based sorting of industrial waste for production of high quality fuel for co-combustion at central power plants instead of waste incineration plants or landfill.

The sorting system will be a full scale first generation system. Further objectives are:

- to demonstrate that the environmental impact of using the sorting technology is a higher quality in the recycling processes – e.g. higher value of products and less emissions, higher recycle rates,

- to demonstrate that implementation of the new sensor technology is profitable for project partner using the technology, and future users of the technology and for FORCE,
- to demonstrate the flexibility of sensor based sorting systems promoting the technology to sorting or characterisation of other types of waste,
- to disseminate knowledge of the technology and the results of the project through conferences, papers, the internet, personal contacts, etc.,
- to introduce productive technologies to and enhance the qualifications of the EU waste business,
- to demonstrate successful co-operation between public and private companies.

The major outputs of the project are:

- One well documented full scale first generation sorting machine.
- One report including technical, environmental, economic evaluations of the sorting technology.
- Targeted spreading of information about the technology, the project and its results.

The direct environmental impact of this project is that sorted industrial waste can partially replace coal as fuel at Danish central power plants eliminating emission of 39.000 t $CO_2$ per year. The application has a high replication potential. The result indicators of the application are:

- Successful installation, commissioning and documentation of the sensor and sorting system.
- Higher quality/value of the sorted waste streams/products – resulting in higher recycles rates and less emission.
- Sorting accuracy and speed of the industrial applications.
- Profitability of the new technology – for end-users and FORCE.

To reach the goals outlined the project has been divided into 5 different work packages.

WP1 Managament
WP2 Sorting of waste for co-combustion
(WP3 NiCd battery sorting)
WP4 Exploitation and dissemination during the project
WP5 Common dissemination activities

WP3 is a separate project within the overall EcoSort project and has been carried out by FORCE Technology with finance from EACI only. This final report therefore does not have any contribution from WP3.
FORCE Technology is the project coordinator of the EcoSort project and leader of WP1, WP4 and WP5. nomi i/s is the project leader of WP2.

The present final report primarily describes the work carried out in connection with WP2 but will also deals with WP4 and WP5. WP1 is focussed on management of the project and as such not of interest for the report describing the technical results and the dissemination.

It should be mentioned that FORCE Technology has built the basic sensor separately from the work packages. Only implantation and installation of the first full scale RDF-Sorter (incl. the basic sensor delivered by FORCE Technology) is part of the project.

### *1.2.1 The sensor*

At the beginning of the project the requirement specification of the sensor for use at nomi i/s was defined. The requirement specification, which was made by nomi and FORCE in cooperation, specified the following:

- Correct identification of 50 g PVC (app. 23 g Cl) in 95% of all incidents
- False indications may not occur with less than 1 minute between them
- Calculated position on conveyor better than +/- 10 cm in 80% of all incidents
- The waste stream must not exceed 6 tonnes per hour and should arrive as evenly distributed on the conveyor as possible at a speed of no more 1 m/s.

To reach the specification listed above the sensor has to use the PGNAA (Prompt Gamma Neutron Activation Analysis) method for investigating the content of chlorine in the waste. The basic of the PGNAA method will shortly be described in the following. The waste stream is sent through the tunnel of the sensor in which a neutron field is applied to the waste.

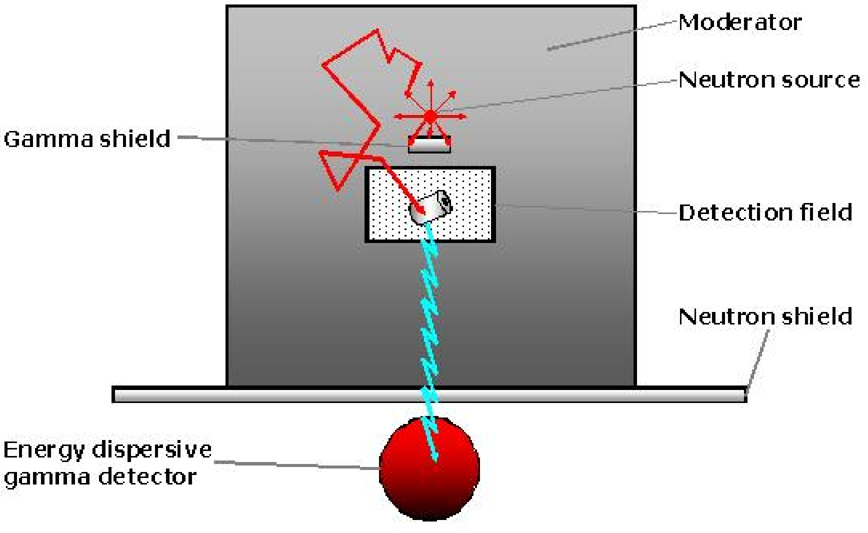



**Figure 1: Measurement zone between Source/detector systems**

The mode of operation of the sensor is as follows:

- The neutron source emits fast (high energy) neutrons
- The moderator slows down the neutrons, and they become reactive
- The neutrons react with the nucleus of elements in the object in the detection field
- The element emits a specific gamma-spectrum
- The gamma detector detects the gamma-spectrum
- The computer analyses the spectra and estimates the content of the element

The gamma shield protects the detector from gamma photons emitted from the neutron source. The neutron shield protects the detector from neutrons escaping the moderator.

As mentioned one of the major project goals was to implement the basic sensor as a part of the complete sorting facilities at nomi i/s. Therefore the hardware surrounding the sensor had to be designed specifically for the installation site. The main hardware design included:

- Conveyor for transporting the waste stream through the sensor tunnel (designed by nomi i/s)

- Ejector for removing waste containing chlorine from the waste stream (designed by nomi i/s)
- Frame for the sensor (designed by FORCE Technology)
- Shielding for gamma and neutron radiation from the sensor (designed by FORCE Technology)
- Hydraulic system for adjusting the height of the sensor tunnel (designed by FORCE Technology)
- Rail system for moving the sensor (designed in cooperation)
- Electronics cabinet for controlling the conveyors and ejector (designed by nomi i/s)
- Electronics cabinet for data collection and communication to ejector and GUI (Designed by FORCE Technology)

In the Figure below the hardware designs mentioned (except the electronics cabinets) are illustrated as the final product – the RDF-Sensor.

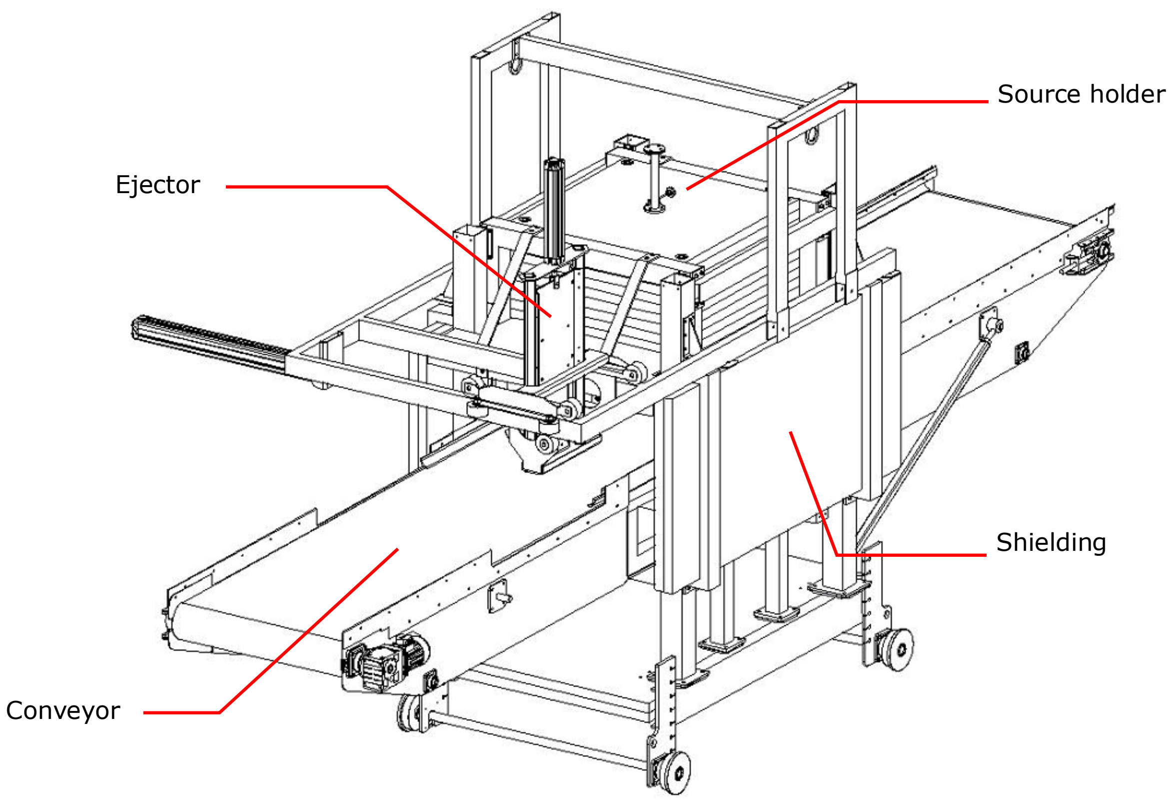



**Figure 2: Schematic overview of the RDF-Sorter**

When the waste is passing the sensor it will be subject to a neutron field and PGNAA reactions will take place. The results from the PGNAA reactions are measured as spectral data series using the four detectors. With a predefined interval the latest recorded part of the spectral data series is analysed using an advanced full spectrum analysis based on a principal component analysis. The spectral analysis isolates the signal coming from the PGNAA reaction with chlorine in the waste i.e. the 'fingerprint' of the chlorine.

Using a calibration based on reference situations with known amounts of chlorine present in the sensor the amount of chlorine can be calculated. The calculated amount is used to determine if the ejector should be activated or not.

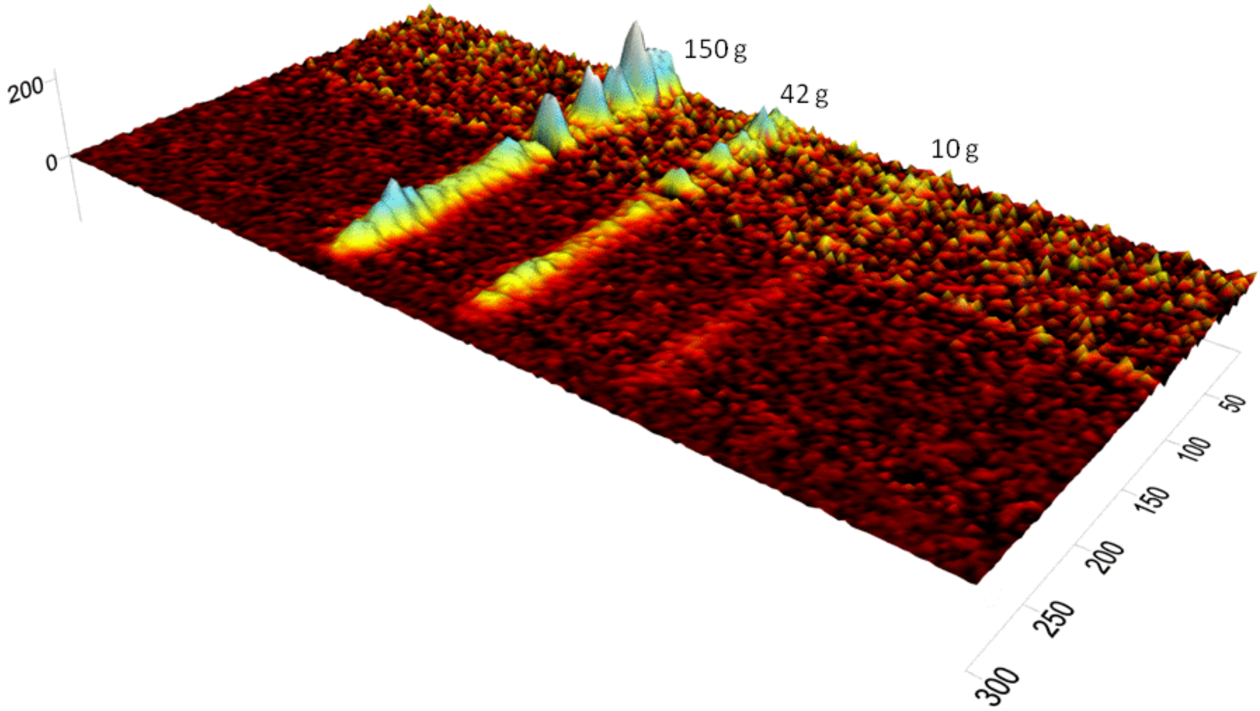



**Figure 3: Example of isolated chlorine spectral signals**

The RDF-Sorter installed at nomi i/s has been calibrated specific for this installation. The calibration therefore consist of both the pre-calibration using a reference signal with known amount of chlorine and measurements with PVC test pieces from the waste stream in different sizes and weights.

Finally the dose rate levels have been measured around the RDF-Sorter. Danish regulations stipulate dose rate limits of 500 µSv/h at a distance of 5 cm and 7.5 µSv/h at a distance of 1 m from the device. The measurements revealed that the dose rate levels were below the limits (see section 1.3.8). However, during measurements operators should refrain from placing any part of the body in the sensor tunnel and avoid staying in front of the tunnel opening for too long periods, which in any case is difficult.

### *1.2.2 System capacity and efficiency*

The capacity of the RDF-Sorter depends on the actual design of the RDF-Sorter. For the RDF-Sorter installed at nomi i/s a maximum capacity is estimated to be app. 40 tons of waste per hour using the maximum tunnel size, highest conveyor speed and sufficient source strength and assuming continuous and steady flow of waste through the sensor tunnel. However, the capacity is to a high degree also dependent on the type of waste. The waste stream at nomi i/s is not a continuous and steady flow but often arrives at the sensor in clumps and tends to be entangled. This is caused by the nature of the waste and the fact that the waste is pre-sorted and placed on the conveyor using manually operated devices such as excavator type machinery. The throughput of waste at nomi i/s is therefore typically 3-4 tons per hour i.e. only 10% of the maximum capacity.

The RDF-Sorter has been calibrated to remove waste pieces with minimum chlorine content of 23 g corresponding to a piece of hard PVC of app. 50 g. The reason for choosing this limit is based on tests performed with manually sorting of waste from a RDF waste stream (taken from the waste stream from nomi i/s). From the manual sampling of waste it has been shown that when removing the PVC pieces with a weight of more than 50 g the result will be a waste stream where at least 75% of all PVC has been removed.

**Figure 4: Example of waste stream at nomi i/s**

Due to the nature of the waste stream produced it is difficult to design a 100% efficient ejector. As mentioned the waste stream is somewhat inhomogeneous and tends to pass the sensor in clumps and often as several entangled pieces. Using air jets to blow the waste containing chlorine off the conveyor is not suitable in this situation. It was therefore decided to design the ejector as flat surface parallel to the conveyor belt that can transverse across the conveyor and push the waste of the conveyor and thereby remove it from the stream.

Due to the nature of the ejector design and the type of waste stream some waste not containing chlorine will always be removed together with the waste containing chlorine. At one of the long term tests where app. 3-4 tons of waste was measured per hour, a total of 100 kg waste was removed during a measurement period of a little more than 5 hours (i.e. app. 15-20 tons of waste was measured). The data showed that of the 100 kg waste removed app. 70 kg was PVC i.e. the fraction of waste removed containing no chlorine is around 30%. Assuming that the removed PVC consists of 30% hard PVC and 70% soft PVC, this corresponds to a total removal of 21 kg of chlorine and as the tests have shown that the sensor removes app. 75% of all chlorine in the waste streams produced at nomi it can be calculated that the resulting waste product contains no more than 0.1%.

Looking at the results from the test series it was shown that less than 5% of all registered incidents (an incident is a situation where the sensor identify pieces of waste with more the 23 g of chlorine) were false alarms and that the false alarms occurred more than 10 minutes apart. The requirement specification of the sensor is therefore fulfilled for the RDF-Sensor installed at nomi i/s.

The RDF-Sorter at nomi i/s has been calibrated and the sensor setup has been adjusted to meet the actual type of waste stream at nomi i/s. However, in general the RDF-Sensor can be scaled to many different sizes and capacities.

### *1.2.3 Dissemination*

Dissemination has been on going through the whole project period. FORCE Technology and nomi i/s has participated in conferences and FORCE Technology has delivered articles to different papers. Further a number of visits to potential customers or future partners for cooperation have been carried out.

Product sheets, conference papers, project reports, technical information about the project and information about the project partners are available on the website www.elementsort.eu.

#### 1.2.3.1 Contact to potential customers

Four main suppliers of turnkey products for solid waste treatment have been visited during the project.

Common for the four suppliers of turnkey products is that they focus on delivering complete sensor systems with own developed control software and sorting systems. However, typically they all buy basic sensors from a third party and afterwards develop the software and sorting systems to meet their clients' demands. The three turnkey suppliers are therefore considered as potential partners as FORCE Technology can supply the basic sensors incl. the PGNAA sensor used in the RDF-Sorter.

Another major output of one of the conferences FORCE Technology participated in is the contact to company producing waste from the automotive sector. The company produces waste from cars from which the e.g. the interior and the outer trimmings are shredded. This type of waste contains large amounts of plastic that is black or near black in colour and therefore not suitable for measuring with techniques such as NIR (Near Infra Red)but ideal for the PGNAA method. PGNAA has a major advantage over another potential technique, namely XRF (X-Ray Fluorescence), in that XRF is a surface measurement where as PGNAA measures in bulk. FORCE technology has measured on some hundreds kilo of samples from the producer and the results are very promising. Further talks are being scheduled.

#### 1.2.3.2 Conferences

FORCE has participated in the following conferences, symposiums and the like:

- Waste-To-resources 2011" in Hannover, Germany, May 24th to May 27th 2011.
- Sensor Based Sorting 2012, Aachen, Germany, March 17th to March 19th 2012.
- Participation in cluster workshop in Aachen, Germany on March 19th 2012.
- Industrial Technologies 2012, Århus, Denmark, June 19th to June 21st 2012.
- Participation in Eco-Innovators Day, b2match-making session and cluster session on Recycling in Brussels, Belgium on November 8th to November 9th 2012.

#### 1.2.3.3 Articles

During the project the following articles have been published:

- Government Gazette : 'EcoSort; finding the harmful substances using a novel sensor'
- BioPress: 'ECOSORT, reduktion af klorindhold i brændbart affald'
- Conference paper Sensor Based Sorting 2012: 'The NiCd sorter; a demonstration plant separating NiCd-batteries'

### *1.2.4 Conclusion*

As one of the main results of the EcoSort project the RDF-Sorter has been installed successfully and commissioned at nomi i/s.

All test carried out showed that the RDF-Sorter performed as specified in the requirement specification or better. That is the precision of the position calculation of the waste on the conveyor can be done with an accuracy better than +/-10 cm and the rate of false alarms is sufficient low. All of this was obtained with a waste stream passing the RDF-Sorter on the conveyor with a speed of up to 1 m/s and with a capacity of at least 3-4 tonnes per hour for the setup used at nomi i/s.

From the test runs and the long term testing it has been demonstrated that production of high quality RDF is indeed the result of using the RDF-Sorter. The final RDF product contains, after it has been measured and sorted by the RDF-Sorter, less than 0.1% chlorine. This makes it well suited for use as a substitute for coal as fuel in power plants which also will reduce the emission of greenhouse gasses when used as fuel for electricity generation.

As the RDF produced is of sufficient quality high and therefore can be used as a substitute for coal in power plants it is also profitable as the end product can be sold as fuel and the RDF producer do no have to pay for getting the waste incinerated or deposited in land fills.

However, at the beginning of the project DONG indicated that they were going to use Danish produced RDF as a substitute for coal in their power plants. Unfortunately DONG does not at present use Danish produced RDF which has a relatively large impact on the market where nomi i/s can sell their product (RDF). At the moment it is not known if DONG in the future will begin using Danish produced RDF.

Through dissemination during the whole project contact to a number main suppliers of turnkey products for solid waste treatment has been established and work is ongoing trying to either sell the basic sensor as an OEM part, to sell the complete sensor (without conveyors) or to join co-operation with the companies for selling complete sorting devices.

## 1.3 Project results

In the interim reports delivered as a part of the project, the development of the project was described by the following phases:

1. Definition of scope
2. Design
3. Manufacturing and construction
4. Testing and adjustments at FORCE
5. Installation at nomi
6. First tests at nomi
7. Adjustments as a result of the first tests
8. Further testing and integration with ejector mechanism
9. If needed, second round of adjustments
10. Handover of device to nomi

Each phase was considered a milestone for the project. However, the original project does not operate with milestones as such. Again it should be noted that each phase does not constitute an equal amount of work. As such the first three phases encompass by far and large the biggest amount of work.

At the time of delivery of the last interim report the project had reached phase 7 as the first preliminary tests had been carried out. Now the project has finished all 10 phases.

The following will try to describe the decisions made for implementation of the sensor and the results obtained from on-line measurements at nomi i/s.
Besides the sensor that FT has developed there was a need for designing shielding, arrangement of detectors, possibilities for adjustment of the tunnel opening, choice of source strength to the application etc.

First the theory will be briefly described in order to get an idea of how the basic principle of the detector works. This is done in the first sections of this chapter.

1.3.1 Theoretical basis for the method – PGNAA
1.3.2 PGNAA in principle
1.3.3 Properties of chlorine in the PGNAA context

Next the instrumentation and choice of material for building the RDF-Sorter (the basic sensor has been build by FORCE separately from the project) will be described taken the actual installation site at nomi i/s into consideration.

1.3.4 Neutron considerations
1.3.5 Detection of gamma-rays
1.3.6 Instrumentation
1.3.7 Instrumentation for system control
1.3.8 Radioactive source and dose rate levels

The calibration and implementation of the system is described next i.e. the data collection, the on-line calibration, the precision obtained and the long term testing.

1.3.9 Data recording, analysis and presentation
1.3.10 Calibration
1.3.11 Achieved precision
1.3.12 Long term test

Finally the benefits for the environment will be described using the measured results as examples.

1.3.13 Environmental benefits

### *1.3.1 Theoretical basis for the method – PGNAA*

PGNAA is an abbreviation of Prompt Gamma Neutron Activation Analysis, which is one of several so called neutron interrogation methods whereby the special properties that neutron radiation displays, when interacting with matter, is employed. The method relies on the identification of the emitted gamma radiation and in this context the neutron radiation is merely a means to achieve this end.

PGNAA is a method well known from other industries, notably the mining industry where the ore produced is in many cases partially characterised by large PGNAA-devices and from the cement industry where the feedstock entering the kilns is likewise characterised.

The basic process of PGNAA is neutron capture at so-called thermal neutron energies; that is neutron energies of about 0.025 eV, as opposed to the high energy neutron capture processes employed in for example carbon detection, which employs neutron capture at energies at around 14 MeV.

In the general case neutron capture reactions can be formulated as:

$$n + {}^{A}_{Z}X \rightarrow {}^{A+1}_{Z}X^{*} \rightarrow {}^{A+1}_{Z}X + \gamma$$

**Equation 1**

${}^{A}_{Z}X$ is the original nucleus X, containing Z protons and A=Z+N protons and neutron, being impacted by the neutron n; ${}^{A+1}_{Z}X^{*}$ designates the newly formed nucleus, an isotope of X, which is left in an excited state; ${}^{A+1}_{Z}X$ is the resulting nucleus, which may or may not be radioactive, and $\gamma$ is the sum of the gamma photons emitted as a result of the process, carrying with it the excess energy of the process [Ref 1].

As the kinetic energy of the impacting neutron is negligible in thermal reactions, the sum of energies of the gamma photons is equal to the binding energy of the neutron, which is typically in the range of 7 to 9 MeV, except for the lighter elements where it is typically in the range of a few MeV [Ref 2].

The process is an (n,$\gamma$) reaction and is also called radiative capture.

With regards to prompt gamma emission, the main parameter is the elemental capture cross section, $\sigma_\gamma$, (also referred to as the "gamma ray production cross section") of the material. Given a flux of $\phi$ thermal neutrons per second per cm$^2$, an elemental capture section of $\sigma_\gamma$, a material density of $\rho$ and an atomic weight of the material of A, the reaction rate of thermal neutron capture events per unit of volume in the material can be expressed as:

$$R = \phi\sigma_\gamma\frac{\rho N_A}{A}$$

**Equation 2**

given that the material is the only one present in the neutron field and the field is uniform.

As mentioned above the parameter determining whether or not a material is susceptible to capture thermal neutrons is the elemental capture cross section, or just cross section, $\sigma_\gamma$. The reasons for this are that the neutron flux, $\phi$, or rather the strength of the neutron source, is most often limited by other consideration such as dose limits and likewise the density of the material being measured is usually fixed or at least outside the control of the experimenter.

As the cross section for an isotope is the one of the most significant factors for using the PGNAA method it is only the isotopes with relatively high cross section that are of interest. The key properties of a selection of isotopes, for this application, at thermal neutron energies, can be seen from Table 1 and Table 2:

| Isotope | Abundance in natural element in % | $\sigma_\gamma$(0.025 eV)/b |
|---|---|---|
| $^{1}$H | 99.9885 | 0.3326 |
| $^{7}$Li | 92.41 | 0.045 |
| $^{12}$C | 98.93 | 0.00353 |
| $^{16}$O | 99.757 | 0.00019 |
| $^{35}$Cl | 75.78 | 43.5 |
| $^{56}$Fe | 91.754 | 2.59 |
| $^{58}$Ni | 68.08 | 4.5 |
| $^{64}$Zn | 48.63 | 1.1 |
| $^{nat}$Cd | 100 | 20600 |

**Table 1: The cross sections of the various isotopes incl. Cl and Cd. [Ref 3], [Ref 4], [Ref 5]**

As seen from Table 1 Cd is by far the isotope with the highest cross section, but Cl has also a reasonable high cross section and is therefore also well suited for PGNAA. In Table 2 below the most prominent prompt gamma lines are listed for the isotopes in Table 1.

| Isotope | $E_\gamma$/keV | $k_0$ | $N_\gamma$ |
|---|---|---|---|
| $^{35}$Cl | 517.0730 | 0.648 | 384 |
| | 788.4 | 0.46 | |
| | 1164.865 | 0.762 | |
| | 1951.1 | 0.54 | |
| | 1959.3 | 0.35 | |
| | 6110.8 | 0.56 | |
| | | | |
| $^{1}$H | 2223.2 | 1.00 | 1 |
| $^{7}$Li | 2032.3 | 0.0166 | 3 |
| $^{12}$C | 4945.3 | 0.000659 | 6 |
| $^{16}$O | 870.7 | 3.35E-5 | 4 |
| $^{56}$Fe | 7631.1 | 0.0354 | 193 |
| | 7645.5 | 0.0298 | |
| $^{58}$Ni | 465.0 | 0.0435 | 236 |
| | 8998.4 | 0.0769 | |
| $^{64}$Zn | 115.8 | 0.00774 | 78 |
| | 855.7 | 0.0031 | |
| | 7863.6 | 0.00653 | |
| $^{113}$Cd | 558.3 | 50.1 | 135 |
| | 651.2 | 9.65 | |
| | 805.9 | 3.61 | |
| | 1209.7 | 3.29 | |
| | 1364.3 | 3.32 | |
| | 5824.3 | 1.86 | |

**Table 2: The most prominent prompt gamma ray energies for 35Cl (the dominant isotope in chlorine as far as PGNAA is concerned) and select other elements. The factor k0 is a measure of the abundance of the gamma ray line relative to hydrogen, E□= 2223 keV. Also stated below is the total number of recorded gamma ray energies for each isotope, $N_\gamma$. [Ref 6].**

Based on the figures in Table 1 and 2 it can be concluded that Cl can be used as the isotope to look for when applying PGNAA to a waste stream.

Please note that Table 2 complies with the convention usually applied, where the nuclide *before neutron impact* is stated, rather than the nuclide from which the gamma rays are actually emitted. Thus $^{35}Cl$ is used instead of $^{36}Cl$, which in its excited form is the nuclide from which the prompt gamma rays are emitted.

### 1.3.2 PGNAA in principle

The waste stream produced at nomi i/s has been pre-sorted in order to remove the largest pieces of PVC before the stream is sent to the shredder. After shredding and some additional handling, the waste stream arrives at the RDF-Sensor.

The sensor is basically made of a tunnel through which a conveyor can transport the waste stream. In the sensor tunnel a neutron source is placed above the waste stream together with different shielding for both neutron and gamma rays. As the waste stream is sent through the tunnel of the sensor the neutron field is applied to the waste.

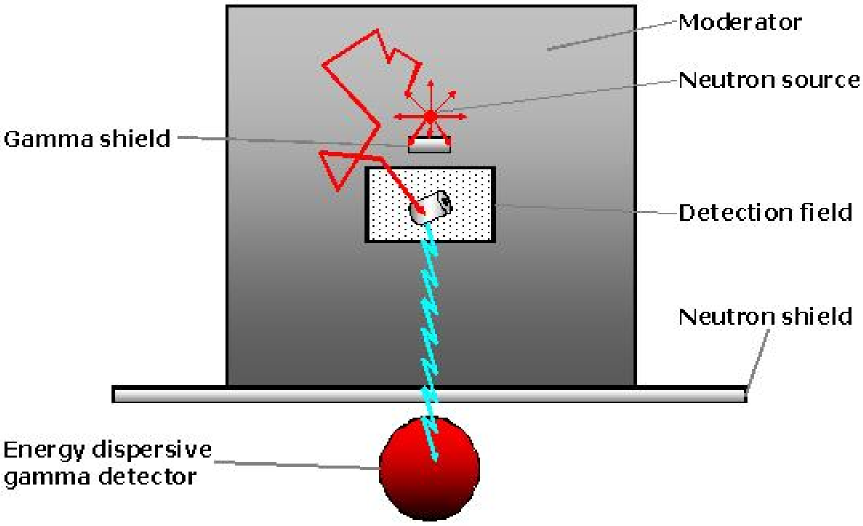



**Figure 5: Measurement zone between Source/detector systems**

The mode of operation of the sensor is as follows:

- The neutron source emits fast (high energy) neutrons. The source used in the system is a Cf-252 source which emits neutrons as result from spontaneous fission.
- The moderator slows down the neutrons, and they become reactive i.e. the energy is reduced from several MeV to as low as 0.025 eV.
- The neutrons react with the nucleus of elements in the object in the detection field. In this case the reaction is with chlorine and as chlorine has a relatively large cross section compared to the other nuclei in the waste stream this reaction will be very prominent.
- The element emits a specific gamma ray spectrum. As mentioned it is the gamma rays emitted from the PGNAA reaction with chlorine that are of interest.
- The gamma detector placed beneath the conveyor going through the tunnel detects the gamma-spectrum. The gamma ray spectrum covers typically an energy range from 0 to 3 MeV.
- The computer analyses the spectra using an advanced full spectrum analysis method based on principal component analysis. Based on this analysis the program estimates the content of the elements (chlorine).
- If chlorine has been indentified a signal is sent to the ejector in order for the system to remove the waste containing chlorine from the waste stream.

The gamma shield protects the detector from gamma photons emitted from the neutron source. The neutron shield protects the detector from neutrons.

### *1.3.3 Properties of chlorine in the PGNAA context*

While chlorine is not quite as ideal for PGNAA purposes as cadmium, it is by no means ill-suited (Cadmium is the element search for in the other part of the EcoSort project). It has a comparatively high cross section and a large and complex emitted gamma spectrum which is distinct; a key property with regards to the possibility of identifying a substance correctly using PGNAA.

In Table 3 below the capture cross section and the abundance of the two chlorine isotopes are shown. As the capture cross section for $^{37}$Cl is much lower than the capture cross section for $^{35}$Cl and the abundance is lower as well, it is the $^{35}$Cl isotope that is of main interest for the PGNAA method.

| **Isotope** | **Abundance in natural element in %** | **$\sigma_\gamma$(0.025 eV)/b** |
|---|---|---|
| $^{35}$Cl | 75.78 | 43.5 |
| $^{37}$Cl | 24.22 | 0.43 |

**Table 3: The cross sections the two isotopes of chlorine (Cl). Not only is 35Cl much more abundant than 37Cl, the radioactive capture cross section is two orders of magnitude larger [Ref 3] [Ref 4] [Ref 5].**

In Table 4 the most prominent prompt gamma ray energies are listed for the two chlorine isotopes. Also listed is the factor $k_0$, that is a measure of the abundance of the gamma ray line relative to hydrogen, $E_\gamma$= 2223 keV. Table 4 also state the total number of recorded gamma ray energies for each isotope, $N_\gamma$. [Ref 6].

| **Isotope** | **$E_\gamma$/keV** | **$k_0$** | **$N_\gamma$** |
|---|---|---|---|
| $^{35}$Cl | 517.1 | 0.65 | 384 |
| | 788.4 | 0.46 | |
| | 1164.9 | 0.76 | |
| | 1951.1 | 0.54 | |
| | 1959.3 | 0.35 | |
| | 6110.8 | 0.56 | |
| $^{37}$Cl | 1980.9 | 0.0038 | 71 |
| | 2166.9 | 0.0049 | |

**Table 4: The most prominent prompt gamma ray energies for the two naturally occurring isotopes of chlorine. The isotope 35Cl, which makes up 75% of all naturally occurring chlorine, dominates the spectrum for naturally occurring chlorine as can be seen above, with $^{37}$Cl playing only a very small role.**

Although the cross sections and the $k_0$-value for the various cadmium isotopes (Table 1 and Table 2) are much larger than the corresponding values for $^{35}$Cl (with $^{37}$Cl being of little consequence in terms of PGNAA) it is worth noting that $^{35}$Cl actually has more has more gamma lines ($N_\gamma$) than $^{113}$Cd, 384 versus 135, as can be seen by comparing Table 2 and Table 4. This provides for a unique spectrum and forms the basis for the identification of the element.

### *1.3.4 Neutron considerations*

The most basic requirement of PGNAA is the availability of neutrons. There are three methods available for their generation: a nuclear reactor, a neutron generator or a radioactive source. The nuclear reactor is for the purpose of device construction obviously impractical and will not be considered further here.
When choosing between neutron generators and radioactive sources, there are number of important points to consider.

#### 1.3.4.1 Choice of neutron source

While neutron generators offer many benefits and there are many designs available on the market, none have been deemed suited for the purpose of device construction. The most relevant pros and cons are listed below:

Pros:

- Can be turned off if needed
- Neutron output can (usually) be varied

Cons:

- Predominantly operates in pulsed mode
- Most designs emit very high energy neutrons
- Many designs have limited life spans
- Many designs employ $^{3}H$ (tritium)
- Price

The fact that a generator can be turned off is a trait so beneficial to device construction that a high price (including the price of frequent renewals of the investment due to limited life span as well as need for occasional refilling of $^{3}H$) could potentially be tolerated.
A similar list of pros and cons can be made for the radioactive sources:

Pros:

- Continuous and dependable output, decreasing in a predictable manner.
- Price (not applicable for all types and makes)

Cons:

- Cannot be switched off
- Output decreases over time
- Usually requires extra safety measures compared to generators

Many considerations regarding the choice of neutron generators over radioactive sources can be made, but for the purpose of the device in question the problem could be reduced to the choice of which radioactive sources to choose, as none of the generators available offered either a suitable mode of operation, a sufficient degree of dependability or a sensible price.
Although there a number of different radioactive sources available which offer neutron emission, the choice is in practice reduced to two different types: either $^{241}Am/Be$ or $^{252}Cf$. The key properties of these two sources are listed below in the table below:

| | **$^{241}$Am/Be** | **$^{252}$Cf** |
|---|---|---|
| Half life/years | 432.61 | 2.65 |
| Relevant decay type | $\alpha$ | Spontaneous fission |
| Probability of decay type/% | 100 | 3.09 |
| Neutron emission process | $(\alpha,n)$ in Be | Neutrons ejected as part of fission process |
| Neutron yield/(n/sec/MBq) | 60 | $1.15 \cdot 10^5$ |
| Mean neutron energy/MeV | ~4.5 | ~2 |

**Table 5: Comparison of 241Am/Be or 252Cf. [Ref 3] and [Ref 4].**

From the table above it is seen that $^{241}$Am/Be has a higher mean energy than that of $^{252}$Cf increasing the size of the moderator somewhat. Also the $^{241}$Am/Be sources have more associated gamma than $^{252}$Cf.
$^{252}$Cf is thus easier to moderate and has less associated gamma radiation. Its shorter half life necessitates more frequent source substitutions, increasing the price, but this is not prohibitive and so $^{252}$Cf becomes the source of choice for this application.

#### 1.3.4.2 Neutron energy and moderators

The energy of the neutrons employed is, as mentioned above, critical to the PGNAA method. The neutrons entering the material to be characterised must be at or around thermal energies; that is energies at about 0.0025 eV.

Although the neutron emission energies vary a great deal with the type of emitter, all available neutron emitters have some common features; namely that a significant fraction of the emitted neutrons have energies in the MeV range and that the bulk of the emitted neutrons have energies in the keV range and higher. This means that the majority of the available neutrons will have energies that are at least eight orders of magnitude higher than the energies needed, regardless of choice of neutron emitter.

There is only one available method for reducing the energy of a neutron and that is elastic scattering; collisions with other particles or nuclei in other words. In such a collision energy is lost according to laws of conservation of momentum and the greatest energy loss per collision will thus occur when the particle or nucleus the neutron is impacting has a mass as close to that of the neutron itself. Thus from the perspective of energy loss the best moderator material is hydrogen, provided of course that the density of hydrogen is sufficient. One drawback with employing hydrogen as a moderator is the fact that it has a non-negligible cross section and a prominent gamma line as seen in Table 1 and Table 2.

Another common choice of moderator is carbon which, as can be seen from Table 1 and Table 2, has a low cross section and a low probability of gamma ray emission. However, due to its greater mass it is less effective as a moderator, but most importantly pure carbon in the form of graphite, which is what is used when it is employed as a moderator, is expensive, requires great care in machining and is fragile compared to the forms of hydrogen usually employed.

Thus hydrogen becomes the moderator choice. A common way to increase the hydrogen density to acceptable levels while at the same time making it readily available is to use water. In device construction it does, however, pose some handling challenges, especially with regards to maintaining the integrity of moderator as a radiation shield. It is problematic that a radiation shield can drain away if a container is breached.

Offering a slightly lower hydrogen density but much greater ease in handling and machining, polyethylene, which in nuclear terms can be viewed simply as $CH_2$, is a good choice as moderator/shielding in device construction.

*1.3.5 Detection of gamma rays*

The signal on which the whole PGNAA method hinges is of course the promptly emitted gamma rays from the material being measured, in this case cadmium. Gamma detection and spectroscopy is a very large field with many interesting branches, but for the sake of simplicity and brevity we shall only address the actual detector choice.

Although there are many permutations on detector choice, and the reasoning for that choice, we have chosen the type which is most readily available, while providing both adequate stopping power and a degree of simplicity in operation: the scintillation detector, which is basically a material which emits light upon being irradiated.

In this case the choice fell on BGO, Bismuth Germanium Oxide, with a density of. 7.13 g/cm$^3$ compared to 3.67 g/cm$^3$ for a very common type of scintillator such as NaI(Tl) [Ref 7]. The only drawbacks in choosing BGO over NaI(Tl), apart from the higher price, are a somewhat lower light yield leading to a somewhat lower resolution. However, as the energy increases the advantages displayed by NaI(Tl) decrease and for the very high energy components, which are present in all elements being measured in this context and which are significant to the identification, BGO ends up being a better choice.

There are four detectors used at the RDF-Sorter the entire type BGO scintillation detector – size 5”× 2”. The detectors are mounted in a separate steel box fixated below the conveyor belt in the measuring tunnel.

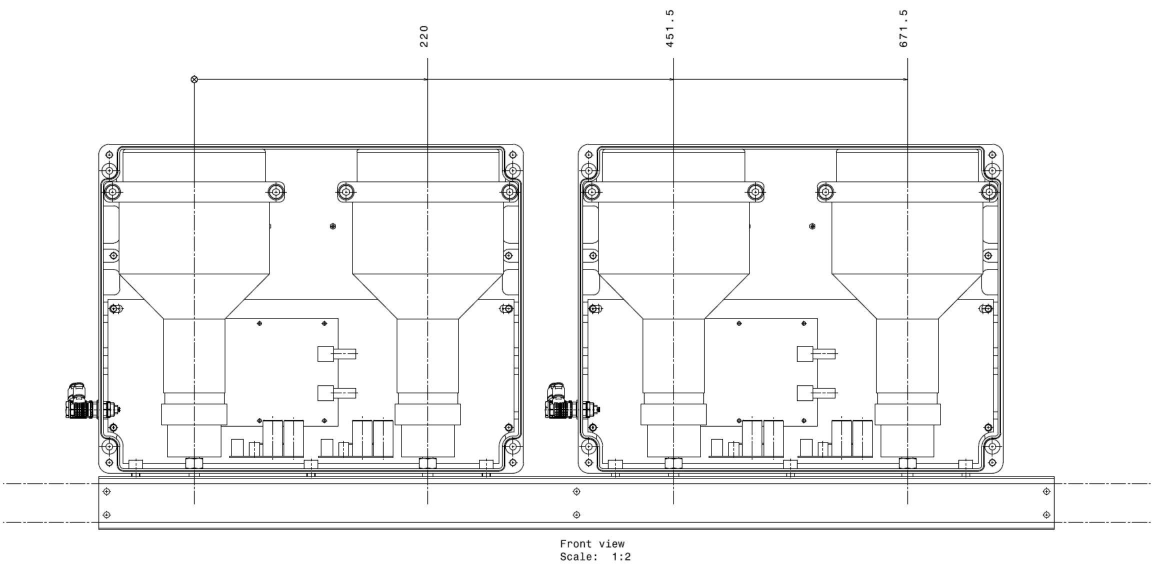



**Figure 6: Detector positions – two boxes with two detectors on a line**

### *1.3.6 Instrumentation*

The consideration outlined in sections 1.3.4 and 1.3.5 lead to a choice of instrumentation for the RDF-Sorter, which in the case can be summarised as:

| Design parameter | Selected solution |
|---|---|
| Detectors | 4 BGO-crystal, ø127 mm, 51 mm thick |
| Neutron source | $^{252}Cf$, 100 MBq, $11.5 \cdot 10^6$ n/sec (As of February 1st 2012) |
| Source shielding (gamma) | 50 mm lead (Pb) |
| Moderator | Polyethylene, minimum thickness 300 mm (Except directly below the conveyor) |
| Detector shielding (neutrons) | $LiCaO_3$-based shield on 3 sides |
| Conveyor material | Non-chlorinated rubber material, not otherwise specified |

**Table 6: Main design choices for the RDF-Sorter**

#### 1.3.6.1 Actual design

The RDF-Sorter's design consists of the following main elements:

- Sensor unit housing:
    - Neutron source
    - Lead shielding
    - LiCaO3 shielding
    - Detector unit
- Conveyor moving through the sensor unit
- Ejector, moving perpendicularly to the direction of the conveyor

The sensor unit and the conveyor have been designed by FORCE Technology while the ejector has been designed nomi i/s and a subcontractor.

The actual design can be seen in Figure 7. In Figure 7 the RDF-Sorter can be seen, including the nomi i/s designed ejector at the front of the drawing. The ejector is a rectangular sheet of steel moving perpendicularly to the direction of movement (towards the reader in this image) across the conveyor. Also seen in the drawing are the two cylinders, operated by pressurised air, which manage the movements of the ejector; one in the up-down direction and one across.

The result of the final refit, the wheels, can be seen in Figure 7. The whole of the RDF-Sorter, including the sections of conveyor seen in the figure, is mounted on these, which in turn run on a small rail. This means that the device can be moved to a position where the waste stream passes through it or it can be placed effectively offline.

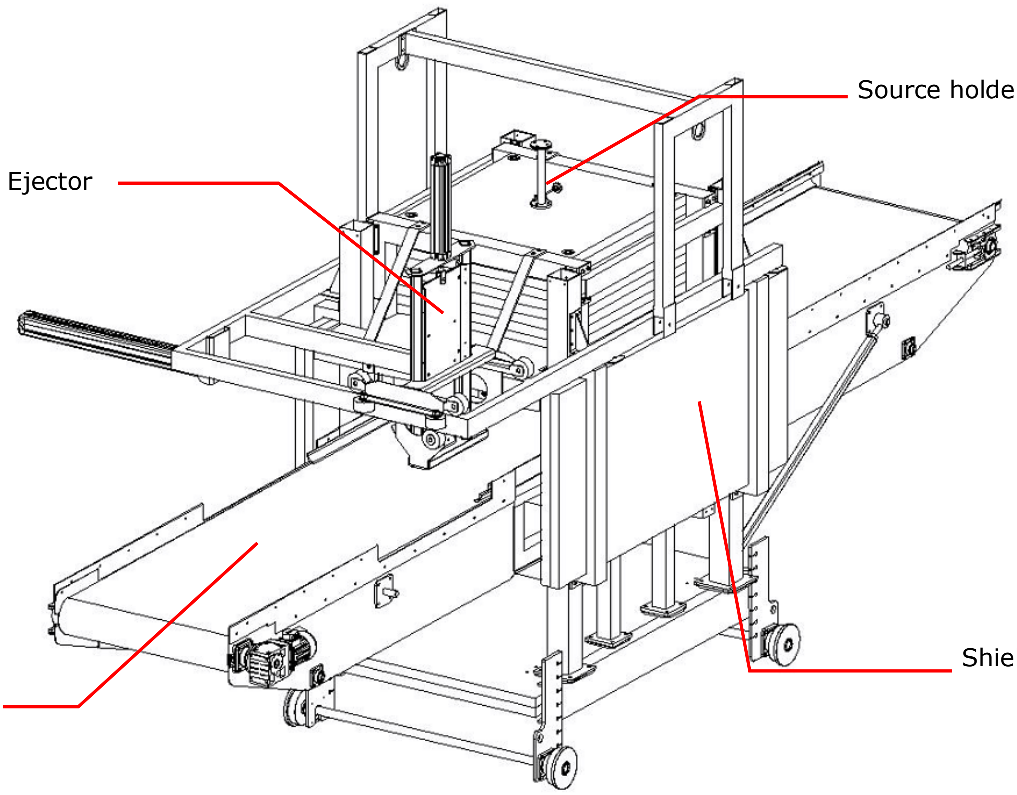



**Figure 7: The overall layout of the RDF-Sorter.**

#### 1.3.6.2 Conveyor system

The conveyor going through the sensor tunnel has a width of 1 meter. The speed of the conveyor can be varied from 0 to 1.5 m/s using the controls on the cabinet placed on the side of the sensor containing the electronics.

The vertical position of the conveyor in the tunnel can be adjusted by use of the hydraulic jack (the detectors placed just below the top side conveyor belt will be moved accordingly).

#### 1.3.6.3 Ejector

Due to the nature of the waste stream produced it is difficult to design a 100% efficient ejector. The waste stream is somewhat inhomogeneous and tends to pass the sensor in clumps on the conveyor and not as separate pieces but often as multiple pieces filtered together. Using air jets to blow the waste containing chlorine of the conveyor is not suitable in this situation. It was therefore decided to design the ejector as flat surface parallel to the conveyor belt that can transverse across the conveyor and push the waste of the conveyor and thereby remove it from the stream.

#### 1.3.6.4 Hydraulic jack

The hydraulic jack is operated using compressed air. The hydraulic jack is used to adjust the height of the tunnel opening i.e. the distance from the top of the conveyor belt to the ceiling of the sensor tunnel. Reducing the height causes the system to be more sensitive as the neutron field around the waste becomes more intense.

### *1.3.7 Instrumentation for system control*

The instrumentation for system control and data processing is housed in a RDF-Sortercabinet mounted on the wall close to the RDF-Sorter connected by cables to the RDF-Sorter. The cabinet and system functions are separated from the electronics cabinet placed on the side of RDF-Sorter frame delivered by skanroll A/S (see section 1.3.7.3).

#### 1.3.7.1 System overview

A schematic overview of the system is shown below.

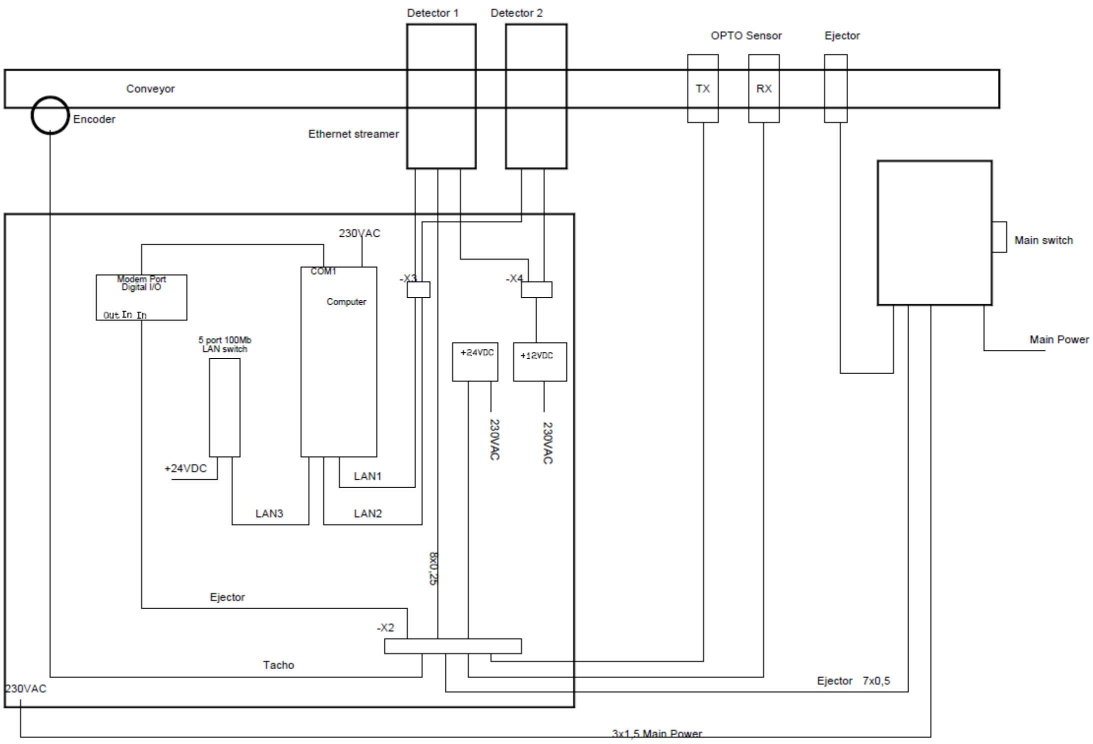



**Figure 8: Block diagram for the RDF-Sorter**

The PC in the system control cabinet is connected to the two detector packs using Ethernet streamer (i.e. four detectors in total, see section 1.3.5), receives data from two optical sensors for indication of waste is present on the conveyor and receives signal from the encoder (the distance the conveyor travelled). A switch with 5 ports connected to the PC makes communication to e.g. the GUI PC possible.

The layout of the cabinet is shown in the figure below.

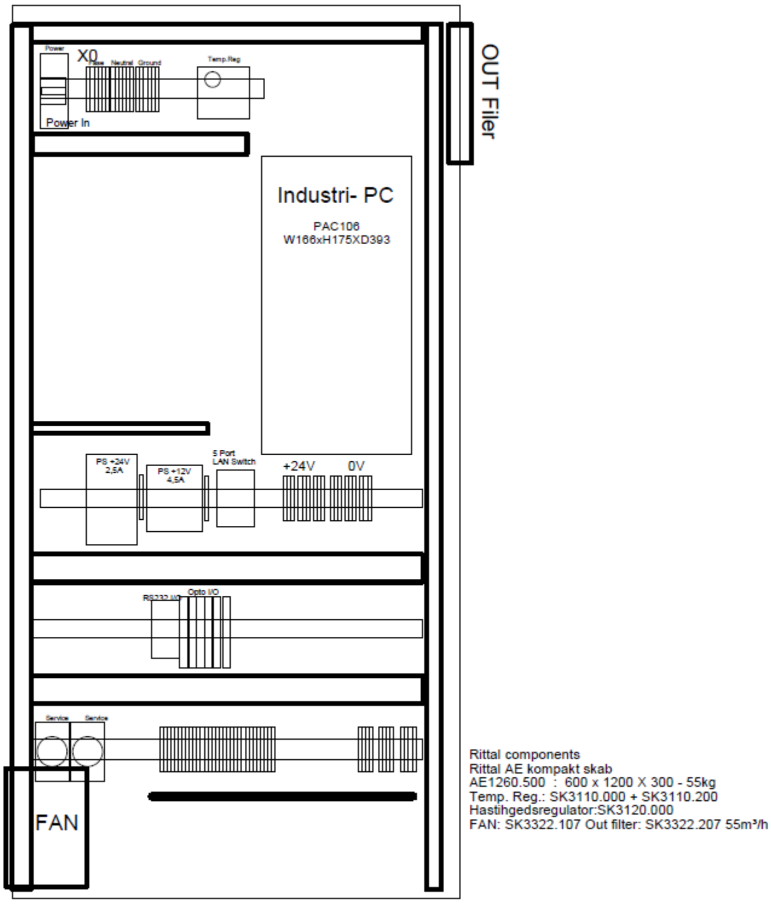



**Figure 9: System cabinet containing system PC**

The system PC is based on a LINUX operating system. The system PC controls the data collection and the analysis of the collected data. It is also the system PC that sends signals to the ejector when a piece of waste containing chlorine is detected. The communication with the GUI PC is controlled from the TCP/IP server running on the system PC.

### 1.3.7.2 System and GUI PC

System PC: iEi industrial

- Cabinet: PAC106GW-4
- Backplane: PE6S2
- Motherboard : SPCIE5100P
- RAM: 2G Byte (REG ECC)
- CPU: P9500 Core 2 duo; 2.53GHz
- 2 x Serial port
- 1 x Bi-direct parallel port
- 6 x USB 2.0
- VGA display port
- 2 x LAN 10/100/1000 Ethernet

Boot disk : 4GB SSD
Harddisk Disk : 120GB SSD
OS : LINUX

Plug-in cards : 1 x 1 port LAN 10/100/1G

The GUI PC is based on a Windows operating system. The GUI PC is in principle a standard office PC and deso not need any special features.

GUI PC: Lenovo M82 Tower

- CPU: Intel Core i3-2130 Processor; 3.4GHz
- RAM: 4G Byte (DDR3 1600 MHz)
- 1 x Serial port
- 4 x USB 2.0, 4 x USB 3.0
- Intel HD Graphics 2000
- VGA display port
- 1 GB Ethernet

Harddisk Disk : 500GB SATA, 7200 rpm
OS : Windows 7 Professional 64
Monitor : Samsung 22” S22A045BW

#### 1.3.7.3 System for controlling the ejector and conveyor

On the side of the RDF-Sorter an electronics cabinet is placed. The emergency stop can be activated / deactivated from the cabinet and 2 conveyors can be controlled. Also the PLC controlling the ejector is placed in this cabinet. The cabinet is built and delivered by skanroll A/S. For more detailed information about the electronics used please refer to skanroll A/S. Only a short description of the functions available from the front of the cabinet will be listed below.

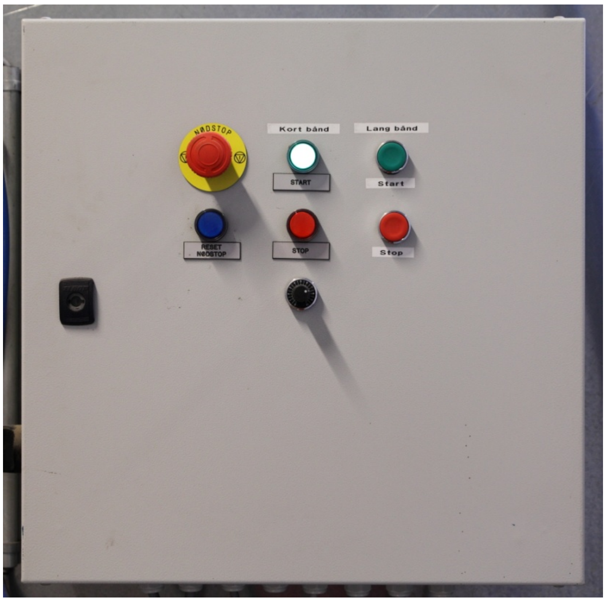



**Figure 10: Front of the electronics cabinet placed on the RDF-Sorter**

**Short Conveyor:** Start and stop of the short conveyor accessible from the front of the cabinet. The short conveyor is the one running through the tunnel of the sensor connecting to the long conveyor transporting waste away from the sensor after analysis. The speed of the short conveyor can be adjusted to match the speed of the other connecting conveyors.

**Long Conveyor:** The long conveyor used to transport the waste away from the sensor (from the short conveyor) after analysis can be started and stopped from the front of the cabinet. It is not possible from the cabinet to adjust the speed of the long conveyor.

**Emergency stop:** In case of emergency the conveyors can be stopped pressing the emergency stop button. If the emergency stop button has been used it must be released before the system can be restarted. It should be noted that the emergency stop does not stop the measurements as the sensor will continue (assuming measurement active when emergency stop activated).

**Ejector control:** The electronics cabinet placed on the side of the RDF-Sorter contains a PLC for controlling the ejector. Detailed information about the PLC software and function is specified by the supplier skanroll A/S.

**Mains supply:** The Power supply to RDF-Sorter is 1 x 240 V AC 50 Hz.
The electrical installations shall be powered via and grounded in accordance with all appropriate codes and ordinances.

### *1.3.8 Radioactive source and dose rate levels*

The radioactive source used is a Cf-252 source that emits neutrons as a result of spontaneous fission and some gamma radiation. The source is placed inside in the large cube of PE placed on the upper part of the sensor. The source can be moved from measuring position to safe position using the guide tubes that are inserted in the PE cube. It is important that the source always stay in either the measuring position or the safe position. The source should only be removed from the guide tubes in the PE cube when the source has to undergo service or be exchanged.

#### 1.3.8.1 Protective shielding

As the source emits both neutrons and gamma rays shielding for both types has to be present. The large amount of PE in which the source is placed act as the shielding for the neutrons only and allows the neutrons to travel to the tunnel of the sensor and react with the waste. The gamma rays emitted are of low energy and are shielded partly by the PE and partly by lead and iron.

In the tunnel of the sensor only neutrons are used for measuring, the tunnel has to be shielded from the gamma rays emitted by the source. The shielding of the gamma rays is made of a thick piece of lead placed below the source in measuring position (neutrons can travel through the lead).

The shielding used lowers the intensity of scattered radiation outside the tunnel to acceptable levels. The actual levels measured are listed in section (1.3.8.3).

#### 1.3.8.2 Safe position and measurement position

The source can be retracted to a safe position away from the measurement position in order to reduce the dose rate levels to the surroundings when the equipment is not in use. During periods without measurements the source should be locked in the safe position e.g. when the system has to be moved and during cleaning.

In the measurement position the source is at the closest position to the tunnel of the sensor. Therefore the dose rate levels are the highest in the tunnel when the source is in this position. When the source is in the measurement position operators should not place any part of the body in the tunnel and refrain from standing in front of the tunnel opening for longer periods of time.

The installation at nomi i/s will during normal measurements conditions naturally prevent the possible access to the tunnel openings i.e. the ejector is placed in front of one end and the connecting conveyor at the other end limit the access possibilities. In case of waste piling up in the sensor tunnel during measurement the waste pile can be cleared by use of a long wooden stick or similar i.e. avoiding placing any part of the body in the sensor tunnel.

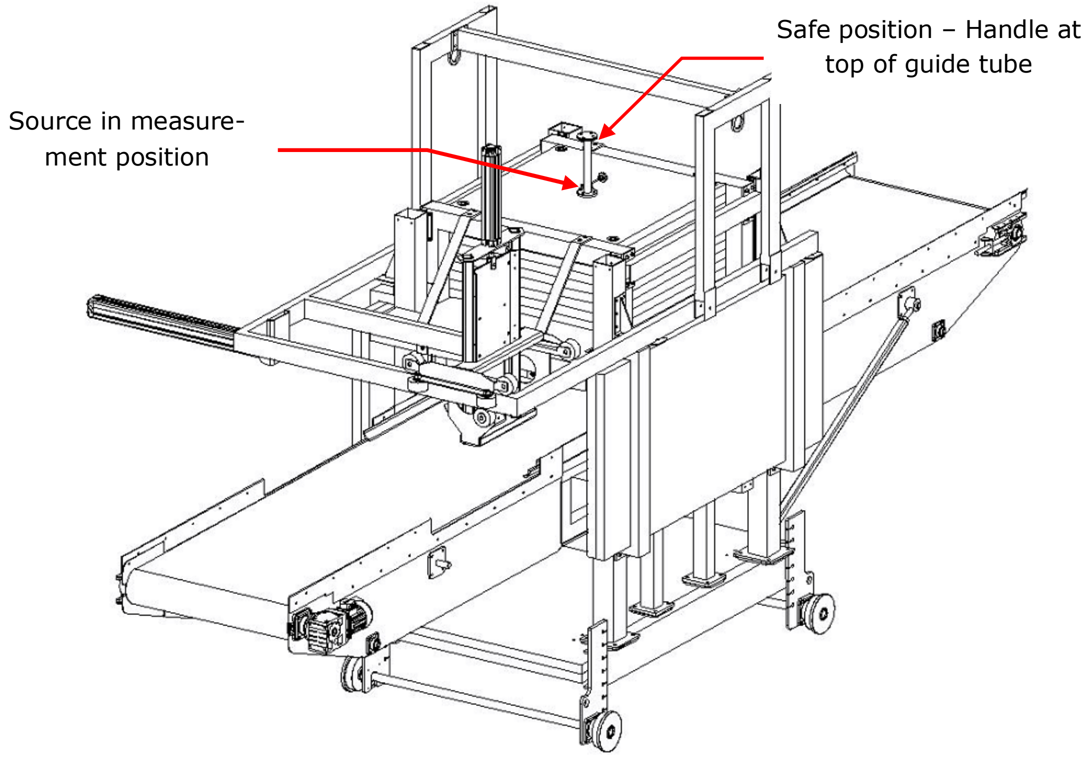



**Figure 11: Source in measurement position**

### 1.3.8.3 Dose rate levels

The first initial design of the shielding against ionizing radiation showed that in some places it was necessary to add extra shielding material. The dose rate measurements showed that half way between the floor end the PE side (the shielding) the dose rate was too high. The first dose rate measurements were performed without the conveyor in place. Afterwards additional shielding was placed under the detector and the conveyor, with these acting as shielding as well.

To check that the additional shielding (conveyor and PE) lowered the dose rate to levels that meet the requirements from the national regulations, a series of measurements were performed along the side of the system.

Dose rates have been measured at distances 1.0 m, 0.5 m and 5-10 cm from the surface of the sensor. For all distances measurements has been performed at ground level and at 0.5 meter height. Above 0.5 meter the large PE shielding and the system structure attenuates the radiation so no levels are above 1.0 μSv/h.

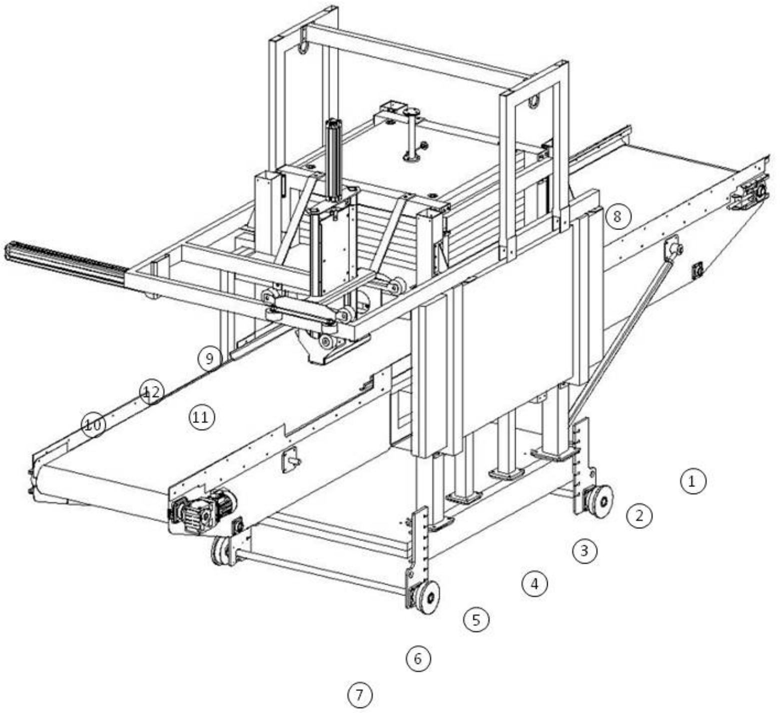



**Figure 12: Overview of the positions for dose rate measurements**

| n-dose rate - µSv/h | | | | | | |
|---|---|---|---|---|---|---|
| **Position** | **Dist.: App. 10 cm** | | **Dist.: 50 cm** | | **Dist.: 100 cm** | |
| | **H = 10 cm** | **H = 50 cm** | **H = 10 cm** | **H = 50 cm** | **H = 10 cm** | **H = 50 cm** |
| **1** | 2.2 | 2.5 | 1.2 | 1.7 | 0.7 | 1.0 |
| **2** | 2.2 | 2.9 | 1.3 | 1.8 | 0.7 | 1.0 |
| **3** | 5.6 | 6.9 | 2.9 | 1.8 | 1.1 | 1.0 |
| **4** | 5.7 | 4.0 | 2.9 | 1.9 | 1.2 | 1.0 |
| **5** | 2.6 | 3.5 | 2.8 | 1.9 | 1.1 | 1.0 |
| **6** | 2.1 | 2.0 | 1.2 | 1.4 | 1.1 | 1.0 |
| **7** | 1.6 | 1.8 | 1.0 | 1.3 | 1.1 | 1.0 |

**Table 7: Neutron dose rates measured at the side of the system as indicated in Figure 8**

| γ-dose rate - µSv/h | | | | | | |
|---|---|---|---|---|---|---|
| **Position** | **Dist.: App. 10 cm** | | **Dist.: 50 cm** | | **Dist.: 100 cm** | |
| | **H = 10 cm** | **H = 50 cm** | **H = 10 cm** | **H = 50 cm** | **H = 10 cm** | **H = 50 cm** |
| **1** | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 |
| **2** | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 |
| **3** | 1.3 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 |
| **4** | 1.3 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 |
| **5** | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 |
| **6** | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 |
| **7** | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 | < 1.0 |

**Table 8: Gamma dose rates measured at the side of the system as indicated in Figure 8**

| Dose rate - µSv/h | | |
|---|---|---|
| **Position** | **Position** | **Position** |
| **8** | **8** | **8** |
| **9** | **9** | **9** |
| **10** | **10** | **10** |
| **11** | **11** | **11** |
| **12** | **12** | **12** |

**Table 9: Neutron and gamma dose rates measured close to the tunnel opening as indicated in Figure 8**

On top of the system, at the source holder, the dose rate levels remains higher than the levels dictated by the legislation (up to 25 µSv/h total i.e. including both dose rate from gamma and neutrons). The top of the system is therefore considered as restricted area that will be marked with signs telling that the top of the system only should be accessed when the source has to be moved from measuring position to safe position. Further the access to the top of the system is restricted as it requires a ladder to gain access.

When the system is placed online at nomi i/s there is a natural fencing of the tunnel opening i.e. the access to the tunnel openings is naturally restricted.

As it is seen from the tables above both the neutron and gamma dose rates on the side of the system (position 1-7) is now below the limit of 500 µSv/h at a distance of 5 cm from the surface and 7.5 µSv/h at a distance of 1 meter from the surface of the equipment. At position 9 the neutron dose rate is higher than the other measuring points as it is closer to the tunnel opening. However, during measurements access to the position is naturally restricted as it is behind the ejector and therefore not possible to access without disabling the ejector.

### 1.3.9 Data recording, analysis and presentation

The RDF-Sorter uses 4 large BGO gamma-ray detectors to measures the gamma-ray spectra every 70 ms. A sample time of 70 ms is selected in order to cover app. half a detector width at a conveyor speed typical used for a waste stream at nomi i/s. The detector system used is capable of measuring spectra with a count rate up to 45.000 cps. The setup used at nomi i/s has a neutron source installed that approximately corresponds to using half the detector capacity i.e. the RDF-Sorter at nomi can be scaled to cope with a neutron source of approximately double size without causing any problems with the spectral measurements. This would, however, cause some radiation protection issues.

As the system is measuring a series of spectra is recorded for each of the 4 detectors. With a predefined interval the latest recorded part of the spectral data series is analysed using en advanced full spectrum analysis based on a principal component analysis. The spectral analysis isolates the signal coming from the PGNAA reaction with chlorine in the waste. The analysis is pre-calibrated using known amounts of chlorine placed in the system tunnel and based on a spectral data series containing both the signal from the chlorine and the background signal (i.e. signal without chlorine present in the sensor tunnel) a reference signal representing the chlorine signal can be calculated. Using this reference on the measured spectral data series, the chlorine signal can be isolated and the amount of chlorine can be calculated and used to determine if the ejector should be activated or not.

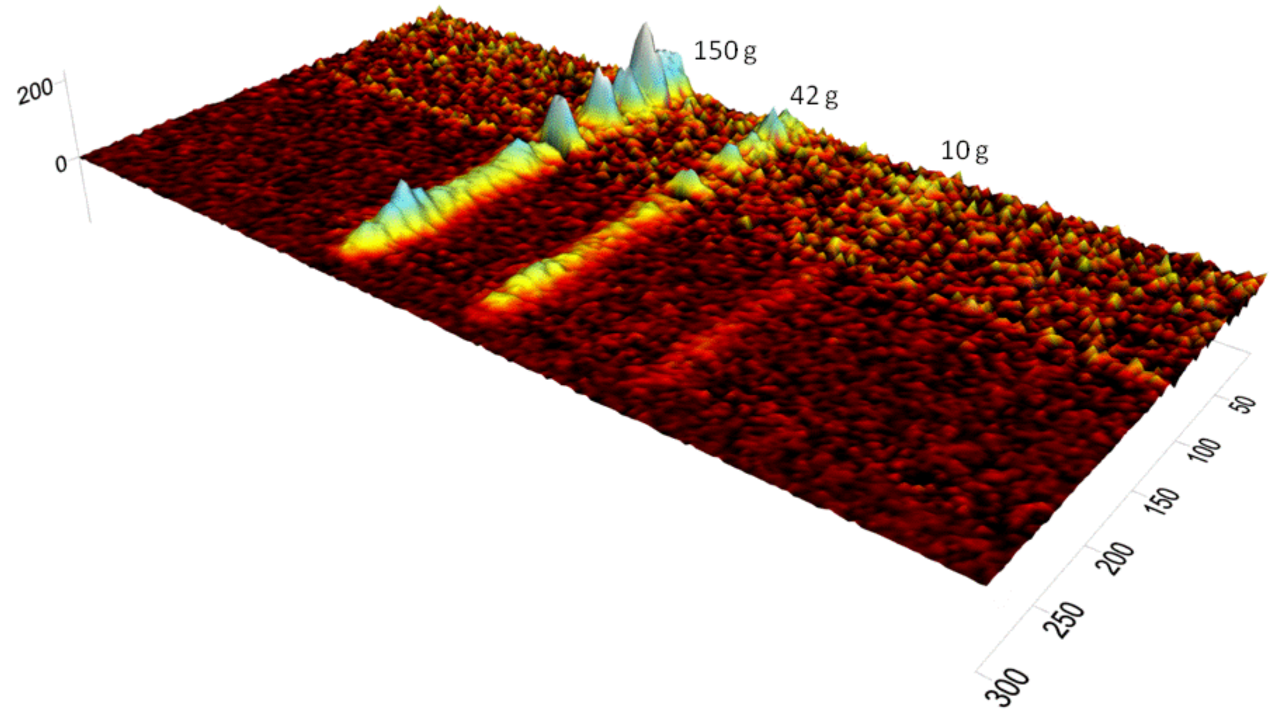



**Figure 13: Series of chlorine prompt gamma spectra, showing the passage of 3 PVC items of different size**

In order for the system to keep track of the chlorine signal in the spectral data series the background has to be continuously monitored. The background is described as the spectral signal measured when no chlorine is present in the sensor tunnel. However, the background may change over time due to changes in the surroundings. Also natural variations in the background signal have to be taken into account.

Besides keeping track of the background signal of the spectra also has to be performed on-line stabilization. FORCE Technology has developed an algorithm for keeping the spectra stabilized and the system is capable of keeping the spectra stabilized, even if large shifts of the energy calibration occurs. Larger shifts in the energy calibration may occur  when the near by magnetic sorter used by nomi i/s as a part of the total waste sorting system is turned on or off. The system can recognize such shifts and allows for fast adjustment of the energy calibration.

An incorrect background or an incorrect energy calibration can cause false alarms and it is therefore important that the system checks both continuously and reacts quickly to changes. The software used at the RDF-Sorter is capable of keeping the background and energy calibration correct within 0.5 %.

#### 1.3.9.1 Data presentation (GUI)

The RDF-Sorter is controlled by the system PC mounted in the electronics cabinet near the RDF-Sorter. The system PC has no direct Graphical User Interface (GUI). To present the data and keep track of the amount of chlorine removed, specially designed software incl. GUI has been developed.

The GUI PC receives data from the system PC via a TCP/IP connection established from the GUI PC. The system PC run and maintains a TCP/IP server. The system PC sends data as requested by the GUI PC using XML documents in a simple format corresponding to the command sent by the GUI PC e.g. a subscribe command for a certain buffer containing results from the latest chlorine analysis. An example of the result presented in the GUI is shown below.

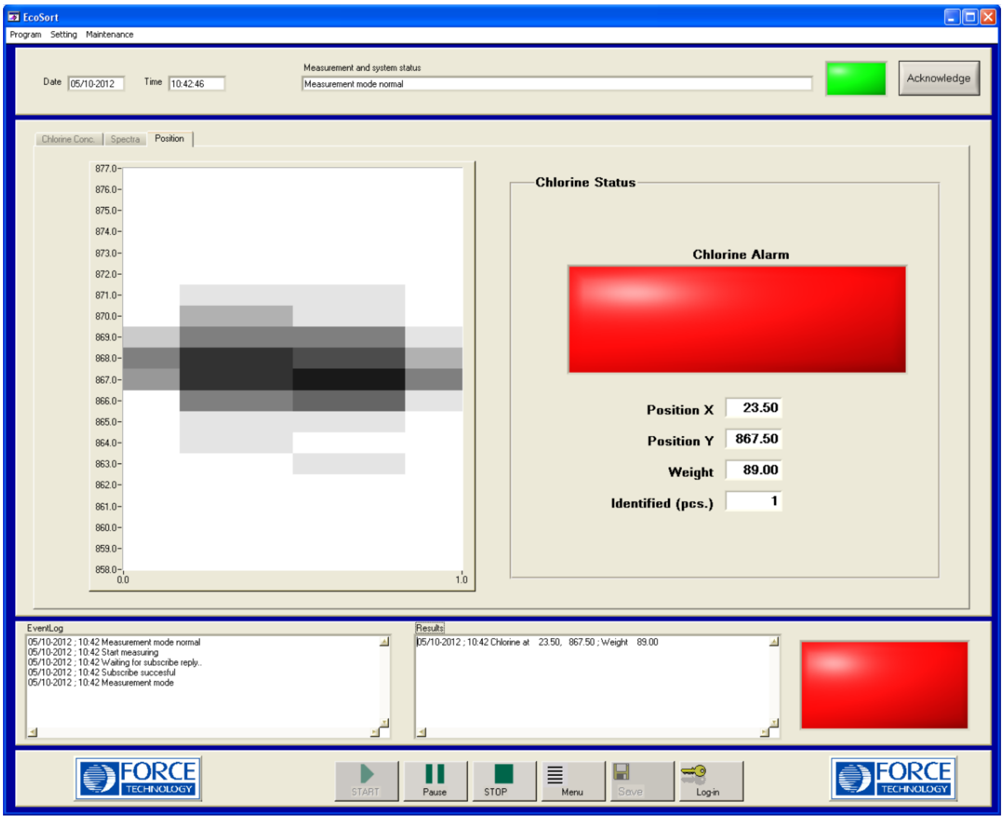



**Figure 14: The main user screen of the GUI software showing the first received XML document with results from a chlorine analysis**

The figure shows in the middle left part of the screen the 4 chlorine signals represented by four squares in each row (the left and right square are due to limitations in the graph viewing options only shown as half size). The cluster shown in the figure consists of a total of 23 incidents in 9 samples. The calculated position of the waste is shown in the middle right part of the screen together with the calculated weight and the running number of how many waste pieces has been identified containing chlorine. The two main LEDs on the screen turn red when a waste piece containing chlorine is identified. After a few seconds the LEDs will return to normal state i.e. turn back to green.

For every incident (every identified piece of waste containing chlorine) an XML document is sent from the system PC to the GUI PC for display on the main user screen. The system PC and the TCP/IP server cannot guarantee that the XML documents will be sent one at a time but sometimes the XML documents will be sent in several parts and one data package sent to the GUI PC may consist of the last part of the previous XML document and the start of the new XML document. The GUI software was tested for this situation as a test TCP/IP server was used to continuously send non-complete XML documents in order for the GUI software to keep track of the fractions of XML documents and create correct XML documents of the received XML fractions.

During these tests the system also showed no lag in memory or time and all XML documents sent from the server were received and displayed correctly by the GUI software.

The GUI software is designed to handle three levels of users with different permissions: operators, technicians and administrators.

**Operators**: The operators can start and stop the standard measurements and create the results logs that document the removal of chlorine during the measurement series.

**Technicians**: Technicians can further set the system up using different options available e.g. scale of the graph, TCP/IP settings etc.

**Administrators**: Administrators have complete control of the software. They have the options to subscribe on more than one type of results at a time and can setup the system to view the spectra from the detectors.

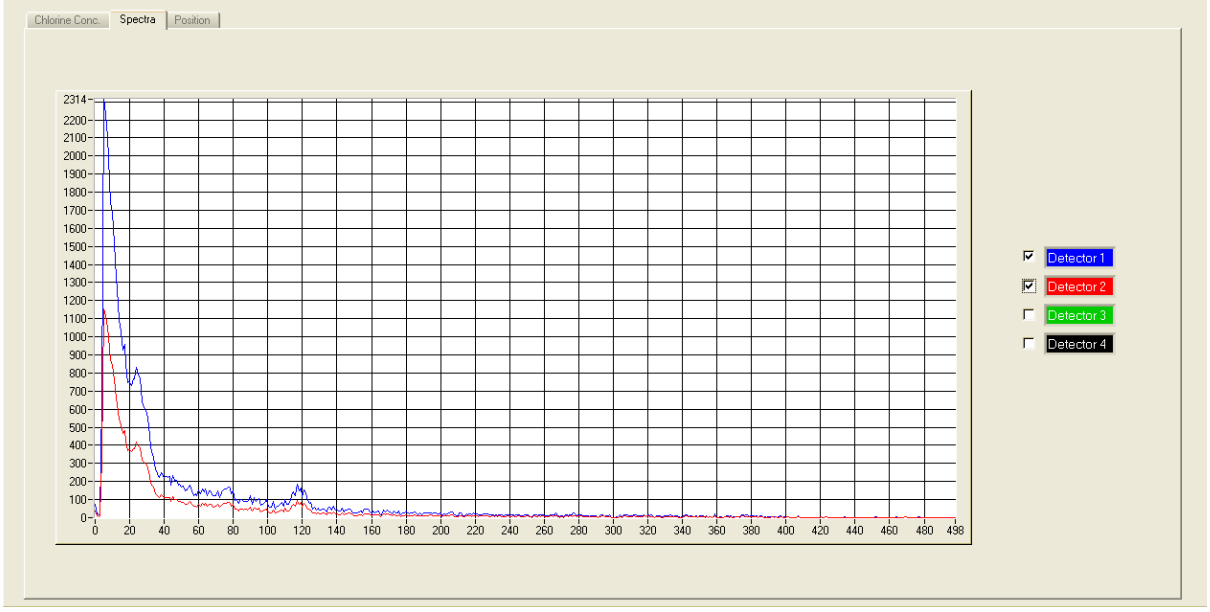



**Figure 15: Example of viewing spectra in the RDF-Sorter GUI software**

Administrators can also access the calculated output from the advanced full spectral data analysis together with a view of the complete last received XML document.

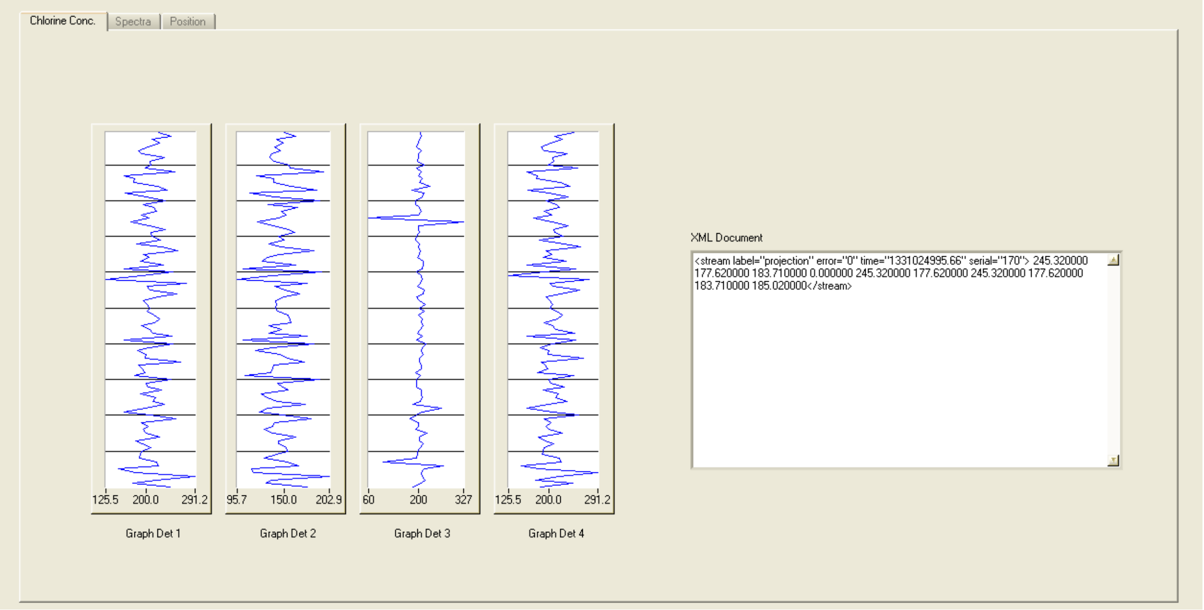



**Figure 16: Example of the RDF-Sorter GUI software showing the calculated concentration of chlorine using the advanced full spectrum analysis method and the viewing of the last received XML document.**

### *1.3.10 Calibration*

To test the system and to calibrate the weight calculation 8 PVC test items were selected in the range from 42 g to 1050 g. 5 of the items were made of hard PVC and 3 were made of soft PVC. Hard PVC is assumed to have a chlorine content of 45 % and soft PVC is assumed to have a chlorine content of 25%.

The test items were measured from 6-9 times in two different transversal positions of app. 25 cm from the edge of the conveyor belt and at 50 cm from the edge of the conveyor belt i.e. positioned at the centre of the conveyor. The test items vary in size from small 10 by 10 cm to larger lumps of PVC measuring up to 40-50 cm in width and 20 cm in length. The items were positioned on the conveyor aiming at placing the centre of the item at the two selected transversal positions.

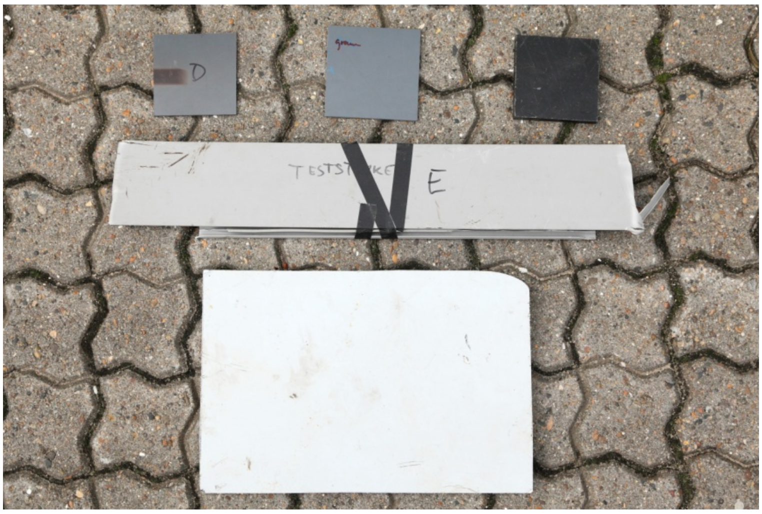



**Figure 17: Test item A to E (the written numbers on the items do not correspond to the numbering in the test). Top left (A), top middle (B), top right (C), centre (D) and bottom (E). All items made of hard PVC.**

**Figure 18: Test item F (left) and G (right). Both made of soft PVC.**

**Figure 19: Test item H made of soft PVC.**

As seen from Table 10 there is no significant difference in weight calculation caused by different transversal positions. This is due to the concept of the data analysis method. For every identified piece of waste containing chlorine (content above the lower level threshold) the signal from each of up to 4 detectors and every measurement in the series covering the piece of waste contribute to the weight calculation.

Assuming that hard PVC has a chlorine content of 45% and soft PVC has a chlorine content of 25% the content of the chlorine is calculated for each of the 8 test items. For both hard and soft PVC the non calibrated content of chlorine for each single measurement is calculated using the pre-calibration of the system. Comparing the assumed chlorine content to the average calculated chlorine content from each series of measurements it is seen that the deviation is in general no more than +/- 25%.

From the measurements series with the 8 test items it is therefore concluded that a calibration factor of 1.33 (chlorine content / signal strength) can be used to calculate the actual chlorine content in waste detected with chlorine present.

| # | Item | Weight (g) | Clfrac | g Cl | Measurements (arbitrary units) | | | | | | | | | mean | gCl/unit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | |
| A | 42 g hard gray PVC - dim. 100 x 100 x 3 mm | 42.0 | 0.45 | 18.9 | 8.05 | 11.5 | 9 | 16.8 | 11.2 | 8.3 | | | | 10.8 | **1.75** |
| B | 53 g hard gray PVC - dim. 110 x 110 x 3 mm | 53.0 | 0.45 | 23.9 | 7.8 | 19.9 | 22.5 | 28.8 | 28.1 | 30.8 | | | | 23.0 | **1.04** |
| C | 150 g hard black PVC - dim. 105 x 105 x 10 mm | 175.0 | 0.45 | 78.8 | 49.2 | 49.9 | 41.3 | 47.0 | 60.7 | 69.1 | | | | 52.9 | **1.49** |
| D | Cable duct of Hard PVC | 409.0 | 0.45 | 184.1 | 116.8 | 120.2 | 126.3 | 176.5 | 184.3 | 185.8 | 150.1 | 150.3 | 161.6 | 152.4 | **1.21** |
| E | Plate of hard PVC (foam) | 1040.0 | 0.45 | 468.0 | 271.1 | 267.8 | 270 | 269.3 | 362.9 | 371.7 | 360.6 | 345.9 | 352 | 319.0 | **1.47** |
| F | Old toy made of soft PVC | 549.7 | 0.25 | 137.4 | 89.7 | 97.7 | 92.6 | 131.6 | 112.8 | 118.7 | 124.7 | | | 109.7 | **1.25** |
| G | Tube of soft PVC | 509.0 | 0.25 | 127.3 | 94.2 | 86.2 | 93.1 | 127.4 | 112.8 | 125.6 | | | | 106.6 | **1.19** |
| H | Lump of soft PVC | 1050.0 | 0.25 | 262.5 | 178.6 | 147.9 | 186.5 | 242.9 | 236.9 | 237.8 | 217.9 | 200.4 | 219 | 207.5 | **1.26** |
| | **Calibration factor** | | | | | | | | | | | | | | **1.333** |

**Table 10: Weight calibration data.**

### *1.3.11 Achieved precision*

During the development of the sensor the position calculation was performed by an external PC (i.e. a GUI PC) using a simplified vision process. However, during installation of the sensor as a part of the first generation production unit the position calculation is now carried out on the system PC (LINUX platform). In the earlier version only those parts of the data series where the signal from the detectors reached a level above a lower level discriminator were included in the calculation and a linear correlation of the signal between the detectors was assumed.

The procedure for calculation of the position used on the first generation production unit now searches the data stream on-line. The data stream consist of a series of samples where each sample include the 4 chlorine signals calculated from the spectral information i.e. the data stream can be considered as an array of data with 4 columns and number of rows equal to the number of samples.

A search for groups of incidents (an incident is a calculated chlorine signal from one detector) that makes up clusters is carried out. Therefore all possible signals that may be a result of chlorine present in the waste stream are also analysed if the signals are comparable to the level of statistical noise. The decision on whether it is a real piece of waste containing chlorine is therefore based on the on the evaluation of the cluster of signals where incidents included in the cluster may have levels comparable to the noise level.

As all incidents in a cluster are part of the position (and weight) calculation of the chlorine in the waste the system becomes more sensitive than the first introduced calculation method (the simplified vision method).

At the setup used at nomi i/s a typical signal from waste containing chlorine will cover from a few samples up to app. 20 samples. The waste may not necessarily yields signal in all four detectors for each samples as the piece of waste ca be positioned close to the edge of the conveyor belt and thereby only yield signal to one maybe two detectors. The piece of waste can also be positioned angled from one side of the conveyor to the other side and therefore first are seen as signal in the two rightmost detectors with the signal moving to the two left most detectors as the number of samples increases. This will still be considered as one cluster of incident and be included in the calculations as one object.

The measured signal from the waste containing chlorine, the basis for the position calculation, is sent to the GUI PC to be viewed. An example of the presentation of the signal is shown in the figure below.

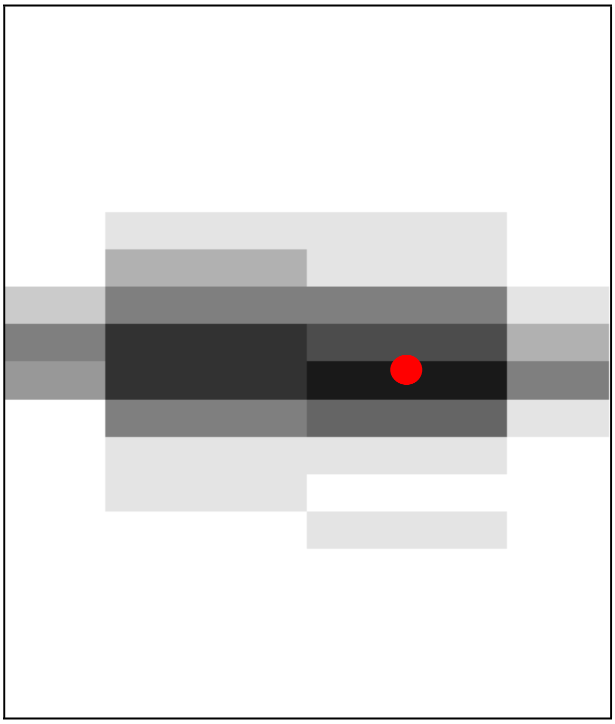


**Figure 20: Example of cluster (9 samples) of incidents – black corresponds to the highest level and light gray to the lowest signal (calculated chlorine). White corresponds to no chlo-rine signal. The red circle indicate the mass centre of the waste containing chlorine**

The figure shows the 4 chlorine signals represented by four squares in each row (the left and right square are due to limitations in the graph viewing options only shown as half size). The cluster shown in the figure consists of a total of 23 incidents in 9 samples and the calculated position of the waste is indicated by a red dot on the figure (the red dot is not a part of the GUI software but only shown on the figure for information).

To calculate the position of the waste containing chlorine the centre of gravity is calculated based on the signal strength of each incident in the cluster. The position can therefore deviate from geometrical centre position as the calculation is based on the signal strength.

#### 1.3.11.1 Control of position calculation and ejector precision

Due to the nature of the waste stream produced at nomi i/s it is difficult to design a 100% efficient ejector. The waste stream is somewhat inhomogeneous and tends to pass the sensor in clumps on the conveyor and not in separate pieces but often as multiple pieces entangled together. Using air jets to blow the waste containing chlorine of the conveyor is not suitable in this situation. It was therefore decided by nomi i/s to design the ejector as a flat surface parallel to the conveyor belt that can traverse the the conveyor at a minimum height and push the waste of the conveyor,thereby removing it from the stream.

The first tests of the ejector after installation showed that the speed of the ejector when the movement across the conveyor belt was too slow. This caused the dead time for the ejector to be too high i.e. the time where system cannot eject following waste containing chlorine because the ejector is occupied with removing the previous waste. Also the design of the ejector as a flat surface parallel to the conveyor belt proved not to be ideal.

The speed of the ejector has been approximately doubled, thereby reducing the dead time to approximately half the initial dead time. However, there is still a dead time of 2-3 seconds after activating the ejector where the system cannot eject new identified waste objects containing chlorine.

In order to optimize the ejector system and to compensate for the relatively large dead time of the ejector FORCE Technology has introduced an algorithm where the identified waste pieces containing chlorine will be prioritized by the system. If two pieces of waste with chlorine are detected close to each other, thereby making it impossible for the ejector system to remove both, then based on the calculated weight the biggest item will be removed by the ejector.

The design of the ejector has also been improved after the initial test. A small 90 degree angle piece of iron has been mounted on the ejector in order to improve the removal of the identified waste pieces. In that way the waste to be ejected is less likely to slide off the ejector and continue in the waste stream.


**Figure 21: RDF-Sorter installed at nomi i/s**

The system uses the position and the conveyor speed to time the start of the ejector movement in order to hit the identified piece of waste correctly. To test if the ejector is activated correctly a number of tests with a piece of PVC with known weight, repeatedly placed in a number of different positions on the conveyor were carried out. The test object was a piece of hard PVC with the dimensions 100×100×3 mm and a weight of 42 g i.e. less than the minimum demand of the system specification of 50 g PVC.

At the test 4 different positions on the conveyor were selected 0.80 m, 0.65 m 0.50 m 0.53 m. As the system is symmetrical in the transversal direction there is no need for repeating the test with the test piece placed in similar distances from the other edge of the conveyor.

#### 1.3.11.2 Series 1

Position 0.8 m is at the outer most part of the conveyor and thereby also on the side of the outermost placed detector. The system sensitivity is therefore somewhat lower in this position compared to the other positions placed closer to the centre of the conveyor.

From the test where the 42 g piece of PVC was measured 10 times at position 0.8 m it was observed that 1 measurement did not identify the test piece and in two incidents a false identification was observed. The false identifications were caused by statistical noise.

The average of the ten calculated transversal positions (Y-Pos) is within the required specification of +/- 10 cm from the correct position. Only one calculated position besides the position of the one missed identification is calculated to have a transversal position more than 10 cm from the correct position.

| Test item placed 0.80 m from edge of conveyor | | | | |
|---|---|---|---|---|
| | **Detected** | **Ejector** | **X-Pos (m)** | **Y-Pos (m)** |
| 1 | √ | √ | 6352.43 | 0.834 |
| 2 | √ | √ | 6358.428 | 0.727 |
| 3 | √ | √ | 6364.786 | 0.794 |
| 4 | √ | √ | 6370.859 | 0.795 |
| 5 | √ | √ | 6377.286 | 0.818 |
| 6 | √ | √ | 6383.334 | 0.735 |
| 7 | | | 6389.849 | 0.973 |
| 8 | √ | √ | 6396.086 | 0.743 |
| 9 | √ | √ | 6400.787 | 0.477 |
| 10 | √ | √ | 6407.525 | 0.888 |
| | 90% | 90% | | 0.7784 |

**Table 11: The results from the first test with the 42g PVC placed close to the edge of the conveyor.**

### 1.3.11.3 Series 2

Series 2 was a measurements series with the test PVC item measured 11 times placed approximately one third from the conveyors edge i.e. placed close to the centre of detector no. 2 placed below the conveyor. As seen from the table the test item was identified at all 11 measurements.

The calculated transversal position (Y-pos) is in average within the required +/- 10 cm from the correct position. Only one of the eleven calculated positions was more than 10 cm from the correct position. It should be noted that the test items was placed on the conveyor while this was running, thus introducing some uncertainty as to the manual positioning of the test items on the conveyor.

| Test item placed 0.65 m from edge of conveyor | | | | |
|---|---|---|---|---|
| | **Detected** | **Ejector** | **X-Pos (m)** | **Y-Pos (m)** |
| 1 | √ | √ | 6434.482 | 0.643 |
| 2 | √ | √ | 6440.419 | 0.577 |
| 3 | √ | √ | 6446.325 | 0.652 |
| 4 | √ | √ | 6452.29 | 0.706 |
| 5 | √ | √ | 6458.46 | 0.765 |
| 6 | √ | √ | 6464.596 | 0.688 |
| 7 | √ | √ | 6470.638 | 0.729 |
| 8 | √ | √ | 6476.549 | 0.492 |
| 9 | √ | √ | 6482.473 | 0.73 |
| 10 | √ | √ | 6488.621 | 0.702 |
| 11 | √ | √ | 6494.822 | 0.642 |
| | 100% | 100% | | 0.666 |

**Table 12: The results from the second test with the 42g PVC placed app 1/3 of the conveyor with from the edge.**

#### 1.3.11.4 Series 3

Third measurement series had the test item placed on the centre on the conveyor belt i.e. the centre of the test item passed between detector 2 and 3 causing approximately the same signal level in both detectors.

From the table it is observed that the test item was identified in all 9 measurements and no false or missing identification were seen.

Also the average calculated transversal position (Y-Pos) was within the required +/- 10 cm from the correct position. However, two calculated (no. 2 and 4) positions deviated more than the required +/- 10 cm and in both cases it was towards detector no. 3 i.e. towards the detector that in theory receives the second highest signal.

| Test item placed 0.50 m from edge of conveyor | | | | |
|---|---|---|---|---|
| | **Detected** | **Ejector** | **X-Pos (m)** | **Y-Pos (m)** |
| 1 | √ | √ | 6523.706 | 0.496 |
| 2 | √ | √ | 6528.941 | 0.377 |
| 3 | √ | √ | 6534.547 | 0.553 |
| 4 | √ | √ | 6540.305 | 0.372 |
| 5 | √ | √ | 6545.988 | 0.522 |
| 6 | √ | √ | 6551.848 | 0.523 |
| 7 | √ | √ | 6557.605 | 0.447 |
| 8 | √ | √ | 6563.349 | 0.566 |
| 9 | √ | √ | 6569.215 | 0.439 |
| | 100% | 100% | | 0.477 |

**Table 13: The results from the third test with the 42g PVC placed close at the centre of the conveyor.**

#### 1.3.11.5 Series 4

The fourth series of measurements consisted of 10 measurements with the test item placed on the conveyor in order for the centre of the test item to pass detector 2 on the side facing detector 3. This should create the strongest signal in detector two but with a relatively high signal in detector 3 as well.

From the table below it is observed that in all 10 measurements the test item was identified i.e. no false or missing identifications.

The calculated position was on average within the required +/- 10 cm from the correct transversal position (X-Pos). Only one of the ten measurements had a calculated position that deviated more than 10 cm.

| Test item placed 0.53 m from edge of conveyor | | | | |
|---|---|---|---|---|
| | **Detected** | **Ejector** | **X-Pos (m)** | **Y-Pos (m)** |
| 1 | √ | √ | 6623.913 | 0.616 |
| 2 | √ | √ | 6629.804 | 0.543 |
| 3 | √ | √ | 6635.755 | 0.62 |
| 4 | √ | √ | 6641.793 | 0.585 |
| 5 | √ | √ | 6647.678 | 0.514 |
| 6 | √ | √ | 6653.535 | 0.568 |
| 7 | √ | √ | 6659.278 | 0.556 |
| 8 | √ | √ | 6665.327 | 0.48 |
| 9 | √ | √ | 6671.158 | 0.565 |
| 10 | √ | √ | 6677.087 | 0.671 |
| | 100% | 100% | | 0.5718 |

**Table 14: The results from the fourth test with the 42g PVC placed close to the centre of the conveyor.**

### *1.3.12 Long term test*

The system has been tested online during RDF production at nomi i/s in week 38 and 39, 2012. During the weeks the system was also calibrated using pieces of waste with known contents of chlorine (see section 1.3.10). The long term test included in total more than 13 hours of production during 4 runs in 4 days.

The data series from the primary long term test is shown in appendix A where each graph shows app. 0.5 hours of data. The colour coding of the graph indicates incidents caused by pieces of waste with three different levels of chlorine content. Blue colour shows incidents with an original signal strength of more than 20 units (i.e. 27 g Cl in the piece of waste causing the incident), red colour shows the incident having an original signal strength between 10 and 20 units (i.e. between 13 g chlorine and 27 g chlorine in the piece of waste causing the incident) and finally green color show incidents with an original signal strength lower than 10 units i.e. lower than 13 g of chlorine in the waste piece causing the incident. A signal strength below 10 units is comparable to the noise observed in the system and is considered below the lower level threshold.

#### 1.3.12.1 Primary long term test

The primary long term test was carried out during Thursday 27th of September 2012 where more than 5 hours of RDF production was analysed using the sensor (from 10:18 to 15:30 – i.e. 5 hours 12 min). The data was recorded both on the system PC and the GUI PC. The system PC logs all incidents that give even a smallest signal whereas the GUI PC during the test was set to receive the incidents with signal strength above a lower level threshold of 12 units (corresponding to 16 g of Cl in the piece of waste).

From the collected data the sum of all incidents with chlorine content larger than 13 g, 20 g and 27 g was calculated. The following results was obtained

| | Number of incidents | Fraction of total no. of incident above 13 g Cl | Total weight – kg |
|---|---|---|---|
| **Above 13 g Cl/incident** | 415 | 1.0 | 23.18 |
| **Above 20 g Cl/incident** | 269 | 0.65 | 20.86 |
| **Above 27 g Cl/incident** | 229 | 0.55 | 19.99 |

**Table 15: Statistics from primary long term test**

The measurement series was performed with a lower level of chlorine amount per incident equal to 20 g Cl (original signal strength of 15 units) thus yielding a total weight of 20.86 kg of chlorine ejected from the waste stream. 20 g of chlorine also corresponds to a piece of hard PVC of app. 50 g which is the minimum required amount the sensor should be able to identify.

After the measurements were stopped the weight of the ejected waste was found to 100 kg total. In the ejected waste a red coloured soft plastic/tape was the most significant type of waste. Test with selected parts of this characteristic waste was performed in order to verify that it contained chlorine.

It is estimated that the content of hard PVC is app 30% and the content of soft PVC is app. 70% i.e. 6.3 kg chlorine is caused by hard PVC and 14.6 kg chlorine is caused by soft PVC (see picture below).

**Figure 22: Ejected waste from stream 27-09-2012 – app. 100 kg ejected**

As soft PVC contains app. 25% chlorine and hard PVC contains app. 45% chlorine it can be calculated that the ejected 20.86 kg of chlorine corresponds to

Removed amount of PVC: 6.3kg/0.45 + 14.6kg/0.25 = 72.4 kg PVC

The total amount of waste ejected during the measurements series was app. 100 kg of which 72 kg was PVC. During the measurement series the ejector removed waste not containing chlorine of app 30 kg.

Based on manual sorting of samples from the waste stream produced at nomi i/s it is our experience that when removing PVC pieces above 50 g a total of app. 75% of all PVC is removed from the waste stream. Given this the remaining amount of PVC and Cl in the waste stream after measurements by the RDF-Sorter will be:

Remaining PVC: 72.4 kg/0.75 – 72.4 kg = 24.1 kg PVC
Remaining Cl: 0.3 · 24.1 kg · 0.45 + 0.7 · 24.1 kg · 0.25 = 7.47 kg Cl

The total amount of PVC original in the waste stream before the stream entered the RDF-Sorter and the total amount of Cl original in the waste stream before the stream entered the RDF-Sorter can be estimated as (again assuming 70% soft PVC and 30% hard PVC):

Original amount of PVC: 72.4 kg + 24.1 kg = 96.5 kg PVC
Original amount of Cl: 0.3 · 96.5 · 0.45 + 0.7 · 96.5 · 0.25 = 29.92 kg Cl

The amount of RDF produced on the day of the measurements was estimated to be app. 3-4 tons per hour indicating that during the measurements period of app. 5 hours a total of 15-20 tons RDF was produced. Based on these numbers the chlorine and PVC content of the RDF before waste containing chlorine (PVC) was removed by the RDF-Sorter was app.

29.92 kg Cl / 20000 kg -> 29.92 kg Cl / 15000 kg = 0.15% Cl -> 0.20% Cl
96.5 kg PVC / 20000 kg -> 96.5 kg PVC / 15000 kg = 0.48% PVC -> 0.64% PVC

The remaining PVC and Cl fractions in the waste after sorting by the RDF-Sorter can be calculated to

7.47 kg Cl / 20000 kg -> 7.47 kg Cl / 15000 kg = 0.04% Cl -> 0.05% Cl
24.1 kg PVC / 20000 kg -> 24.1 kg PVC / 15000 kg = 0.12% PVC -> 0.16% PVC

The above calculated fraction is also the estimated fractions of PVC and Cl in the produced RDF after the waste has been sorted using the RDF-Sorter.

#### 1.3.12.1.1 Distribution over time

In order to get an idea about the distribution over time of the PVC content in the waste stream passing the RDF-Sorter the incidents observed and the calculated amount of chlorine have been identified for each 30 minutes interval of the measurement series. Incidents are defined as the situation where the sensor detects a possible occurrence of chlorine (PVC). For the specific setup at nomi i/s there is introduced a lower level of app. 13 g chlorine i.e. the lowest amount of chlorine that can be detected with accuracy as specified in the requirement specification when using the nomi setup of the system.

| **Incident distribution over time – time interval 30 min** | | | | | | |
|---|---|---|---|---|---|---|
| **Half hour no.** | **Incident with Cl indication above 13 g** | **Incident with Cl indication below 13 g** | **Total number of incidents** | **Fraction with Cl indication above 13 g** | **Fraction with Cl indication below 13 g** | **Cl weight incidents above 13 g** |
| 1 | 56 | 115 | 171 | 0.33 | 0.67 | 3.54 |
| 2 | 108 | 106 | 214 | 0.50 | 0.50 | 5.75 |
| 3 | 47 | 99 | 146 | 0.32 | 0.68 | 2.97 |
| 4 | 37 | 131 | 168 | 0.22 | 0.78 | 1.94 |
| 5* | 4 | 96 | 100 | 0.04 | 0.96 | 0.06 |
| 6 | 23 | 125 | 148 | 0.16 | 0.84 | 1.26 |
| 7 | 43 | 118 | 161 | 0.27 | 0.73 | 2.70 |
| 8 | 20 | 108 | 128 | 0.16 | 0.84 | 1.61 |
| 9 | 20 | 99 | 119 | 0.17 | 0.83 | 0.72 |
| 10 | 31 | 126 | 157 | 0.20 | 0.80 | 1.31 |
| **Average (without no 5)** | **43 (39)** | **114 (112)** | **157 (151)** | **0.26 (0.24)** | **0.74 (0.76)** | **2.42 (2.11)** |

**Table 16: Distribution over time for primary long term test**

The table above shows that the waste stream measured over time has a relatively constant fraction of the registered incidents with a chlorine signal that corresponds to more than 13 g of app. 25%. The rest of the incidents (the remaining app. 75%) were registered as having a signal corresponding to a possible chlorine weight of less than 13 g – the majority of the incidents with the low weight are assumed to be caused by noise alone.

Looking at the weight distribution of chlorine the amount of chlorine identified per half hour varies from 0.7 kg to 5.7 kg not taking interval no. 5 into account as this partially covers the lunch break. However, 6 out of 9 intervals yields between 1 and 3 kg chlorine and the average is 2.11 kg.

#### 1.3.12.1.2 Result log vs. raw data from system PC

In appendix B a comparison is made between the raw data registered in the log on the system PC and the result log created by the GUI PC. During the test the GUI PC received all incidents with signal strength equal to 12 or more corresponding to a chlorine weight of more than 16 g. The RDF-Sorter software installed on the GUI PC can locally also sort the incoming data based on a lower level threshold which can be set by the operator in service menu of the RDF-Sorter software.

As the log containing raw data include all incidents i.e. also the incidents with a signal strength less than 12 a sorting of the data has been carried out in order to select a subset of the raw data containing incidents with signal strength equal to or larger than 12. This subset is next compared to the data from the results log created by the GUI PC. In appendix B only part of the complete log is shown in order to illustrate the comparison between the two logs.

Looking at the data from appendix B it can be concluded that all incidents above the lower level threshold of 12 in signal strength has been correctly listed in the results log. In other words the communication between the system PC and the GUI PC works correctly and all data is received correctly by the GUI PC using XML as the basis for data transfer.

#### 1.3.12.2 Other long term test

Besides the primary long term test three other long term tests were carried out during RDF production at nomi i/s.

The first measurement series was performed the 21st of September and lasted 2 hours and 15 minutes (11:11 to 13:26).

The next measurement series was performed on the 26th of September and lasted 6 hours and 29 minutes (10:29 to 16:58).

The third measurement series was performed on the 28th of September and lasted 1 hours and 34 minutes (09:25 to 10:59).

In the requirement specification 50 g hard PVC is listed as the minimum amount that should be identified positively by the sensor i.e. a lower level threshold of app. 22.5g Cl per incident. In the following analysis of the three tests a lower level threshold of 20 g chlorine per incident was used. The lower level threshold was used for creating the result log on the GUI PC, however, at the system PC a log of all incidents is kept as a basis for the further analysis.

During the more than 13 hours the sensor has been running online for long term testing and during all the preliminary tests and trial runs no mechanical breakdown were observed.

Data from the long term tests showed the waste can be divided in two fractions one with the possibility of removal of a high amount of chlorine (app 4 kg per hour) and one with possibility of removal of somewhat lower amount of chlorine (app 2 kg per hour). The original and remaining amount of PVC and chlorine for each series in each fraction can be seen in the tables below.

| | ***Waste streams with an average of app. 4 kg chlorine removed per hour*** | | |
|---|---|---|---|
| | ***Series*** | ***Original amount (%)*** | ***Remaining amount (%)*** |
| ***PVC*** | *26-09-12* | *0.49 – 0.62* | *0.12 – 0.16* |
| | *27-09-12* | *0.48 – 0.64* | *0.12 – 0.16* |
| ***Cl*** | *26-09-12* | *0.15 – 0.19* | *0.04 – 0.05* |
| | *27-09-12* | *0.15 – 0.20* | *0.04 – 0.05* |

**Table 17: Calculated Cl and PVC content of waste stream with high amount of chlorine**

| | ***Waste streams with an average of app. 2 kg chlorine removed per hour*** | | |
|---|---|---|---|
| | ***Series*** | ***Original amount (%)*** | ***Remaining amount (%)*** |
| ***PVC*** | *21-09-12* | *0.16 – 0.24* | *0.04 – 0.06* |
| | *28-09-12* | *0.15 – 0.18* | *0.04 – 0.05* |
| ***Cl*** | *21-09-12* | *0.05 – 0.06* | *0.01 – 0.02* |
| | *28-09-12* | *0.05 – 0.06* | *0.012 – 0.014* |

**Table 18: Calculated Cl and PVC content of waste stream with low amount of chlorine**

Using the gained experience that the RDF-Sorter can remove up to 75% of the chlorine present in the waste stream a reduction factor of 4 will be the result for the measured data series. As the waste stream at nomi i/s has been manually cleaned for all the larger PVC pieces (from 1-5 kg and upwards) the fraction of PVC and chlorine in the waste stream that reaches the RDF-Sorter was for the tests performed all below 0.5% for PVC and thereby below 0.15% for chlorine alone.

From the measurement series it can be concluded that the RDF-Sorter is able to remove approximately 75% of the PVC and chlorine in the waste stream even after the waste stream has been pre-sorted i.e. the largest pieces of PVC has been manually removed. Using the RDF-Sorter on a shredded waste stream as the one at nomi i/s will result in a remaining PVC and chlorine content acceptable for further use of the RDF as fuel.

### *1.3.13 Environmental benefits*

The RDF-Sorter is designed to identify waste containing chlorine and remove it from the waste stream. In order for RDF to be approved for co-combustion the chlorine content has to be verified to very low content e.g. chlorine content of 0.1% or better.

If the chlorine content is sufficiently low then the RDF can substitute coal as fuel in the power plants.

Chlorine also is an unwanted substance for the incinerators as the chlorine can speed up the corrosion of the kiln and also deteriorate the quality of the produced cement, as it will cause chlorine mediated corrosion of any rebar.

#### 1.3.13.1 Removal of chlorine

The capacity of the RDF-Sorter is estimated to be app 40 tons of waste per hour dependent on the waste type, the source strength, the tunnel size and the speed of the conveyor transporting the waste through the RDF-Sorter. At nomi i/s the average production measured by the RDF-Sorter was app. 3-4 tons per hour. The system's design and capacity of the RDF-Sorter at nomi i/s ensures that system worked within specified limits at the production rate of 3-4 tons.

To calculate the potential removal of chlorine the following variables have to be considered.

| | | |
|---|---|---|
| The capacity of the system | $C_{RDF}$ | < 40 t/h |
| The original chlorine content in the waste | $m_{Cl}$ | < 0.5% |
| The original PVC content in the waste | $m_{PVC}$ | < 1.6% |
| The fraction removed by the RDF-Sorter | $r_{Device}$ | 0.75 |

Assuming PVC in the waste stream consists of 30% hard PVC (chlorine content 45%) and 70% soft PVC (chlorine content 25%) the correlation between $m_{Cl}$ and $m_{PVC}$ becomes

$$m_{Cl} = m_{PVC} \cdot (0.3 \cdot 0.45 + 0.7 \cdot 0.25) = m_{PVC} \cdot r_{Cl/PVC} = m_{PVC} \cdot 0.31$$

Where $r_{Cl/PVC}$ is the ratio between the chlorine content and the PVC content (again assuming a 30/70 correlation between hard and soft PVC).

In Denmark the typical chlorine content of waste is assumed to be 0.5%. Using the RDF-Sortersorter with settings similar to the settings used at nomi i/s, the potential for removal of chlorine will be:

$$C_{RDF} \cdot m_{Cl} \cdot r_{Device} = 4000 \text{ kg/h} \cdot 0.5\% \cdot 0.75 = 15 \text{ kg/h}$$

At nomi i/s the waste is manually pre-sorted and therefore the chlorine content of the waste stream measured by the RDF-Sorter is somewhat lower. The long term test of the RDF-Sorter indicated a typical chlorine content of the waste stream reaching the RDF-Sorter of app. 0.15%. A chlorine content of 0.15% of the waste passing the sensor will potentially remove chlorine of app.

$$C_{RDF} \cdot m_{Cl} \cdot r_{Device} = 4000 \text{ kg/h} \cdot 0.15\% \cdot 0.75 = 4.5 \text{ kg/h}$$

The total amount of removed chlorine per year per RDF-sorter depends on the throughput of waste per year, the original amount of chlorine in the waste and the fraction of chlorine removed by the RDF-Sorter ($r_{Device}$). The graph below shows the expected amount of chlorine removed from the waste stream for the two cases with original chlorine content of 0.5% and 0.15% respectively. A chlorine content of 0.15% corresponds to the pre-sorted waste stream at nomi i/s.

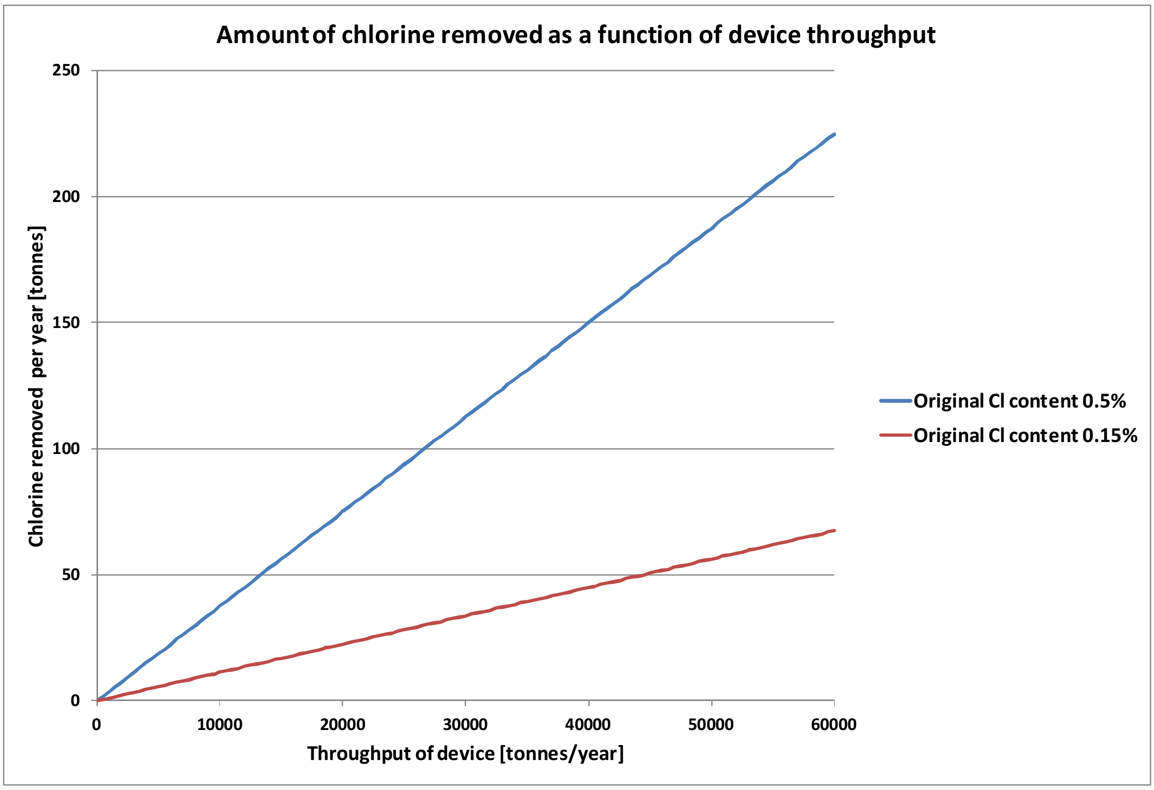



**Figure 23: Amount of chlorine removed as a function of waste stream throughput of the device**

The two graphs showing the chlorine removed per year is calculated assuming that the fraction of waste containing chlorine removed by the RDF-Sorter is the same in both cases. From this assumption follows that the number of waste pieces with chlorine content of 23 g or less in the waste stream with 0.5% chlorine is equal to the number of waste pieces with chlorine content of 23 g or less in the waste stream with 0.15% chlorine.

### 1.3.13.2 Carbon footprint and extra power generation

If the RDF produced has a chlorine content which is sufficiently low (e.g. lower than 0.1%) then the RDF can be used for co-combustion in power plants. The RDF used can substitute coal and thereby reduce the emission of greenhouse gasses (assuming that the RDF is produced from non fossil material).

As RDF can substitute coal as fuel in power plants it will also lower the emission of $CO_2$ assuming that the RDF is produced from non fossil material. Coal has a calorific value of 24.5 MJ/kg and RDF (produced at nomi i/s) has a calorific value of 20 MJ/kg. A production of RDF similar to the production at nomi i/s of 15.000 tonnes/y therefore corresponds to the following amount of coal:

$$15.000 \text{ tonnes} \cdot 20/24.5 = 12.244 \text{ tonnes coal}$$

Using 1 ton of coal as fuel the emission of $CO_2$ will be 44/12=3.67 tonnes CO2 (molecular mass of $CO_2$ is 44 and 12 for C). The substitution of 12.244 tonnes coal with 15.000 tonnes RDF as fuel in power plants will therefore reduce the $CO_2$ emission with

$$12.244 \text{ tonnes coal} \cdot 3.67 = 44.895 \text{ tonnes } CO_2$$

Using RDF in power plants instead of waste incineration plants will create an amount of extra power generated as the efficiency of the power plants is higher than the efficiency of the waste incineration plants. The power plants have an efficiency of app. 40% whereas the waste incineration plants have an efficiency of app. 17%.A production of 20.000 tonnes/y of RDF with a calorific value of 20 MJ/kg (5.56 MWh/tonnes) will if used as fuel in an incineration plant with an efficiency of 17% result in a power production of:

$$5.56 \text{ MWh/tonnes} \cdot 0.17 \cdot 20.000 \text{ tonnes/y} = 18.888 \text{ MWh/y}$$

If a similar RDF production is used as fuel in a power plant with an efficiency of 40% the power production will be:

$$5.56 \text{ MWh/tonnes} \cdot 0.40 \cdot 20.000 \text{ tonnes/y} = 44.444 \text{ MWh/y}$$

A production of 20.000 tonnes/y of RDF will therefore generate extra power of:

$$44.444 \text{ MWh/y} - 18.888 \text{ MWh/y} = 25.556 \text{ MWh/y}$$

### 1.4 Utilization of project results

The implementation and installation of the RDF-Sorter carried out during the EcoSort project has shown that using advanced sorting technologies it is possible to produce RDF with a documented low content of chlorine. The project showed that even that the goal was reached i.e. a full scale first generation sorting machine has been installed then there is a potential for further development of the sensor and connected hardware.

The technique used in the in the basic sensor (PGNAA and the advanced full spectrum analysis) can be further developed to handle identification of other types of material in different waste streams.

The pre-sorting of the waste and the ejection of identified waste with content of e.g. chlorine can be optimized. It can be investigated if the waste stream can be more homogenous and evenly distributed on the conveyor.

FORCE Technology will therefore continue to develop the sensor technology using the experience gained from the EcoSort project as a basis. Possibilities for further development of the sensor are e.g. identification of rare earth minerals, black (near black) PVC and copper in waste streams etc.

Nomi i/s will continue using the RDF-Sorter as an integrated part of the sorting facilities for production of RDF. Based on the experience that will be gained with future use of the RDF-Sorter it will be investigated if the pre-sorting and/or the ejector mechanism can be improved.

Efforts are ongoing to sell the device to companies such as nomi, which are in the business of sorting household waste for co-combustion. The main barriers here are:

- Situations in which there is no need or incentive, economic or technical, to reduce or document the chlorine content.
- Competing devices, not employing a radioactive source and as such more easily accepted.

We cannot address the first barrier directly, but given the signals we are picking up we believe that this will become less and less of a problem, as we see the trend being towards more control of the feedstock composition and the elimination of harmful substances from it.

The common denominator for these devices (usually employing NIR or XRF) is that they are all surface measurements, whereas PGNAA is a bulk measurement, putting the RDF-Sorter at an advantage.

Furthermore NIR, which has the advantage of not employing ionising radiation, cannot at present be used on surfaces that are black or near black.

This fact has opened another possible sales avenue for the RDF-Sorter; plastic waste from the automotive sector most, if not all, of which is black and has a fairly high content of PVC. This is at present the main avenue we are pursuing to ensure the economic viability of the product.

FORCE Technology and nomi i/s will continue to market the RDF-Sorter and FORCE Technology will look in to the possibilities' for selling the basic sensor as an OEM sale. The continued marketing of the RDF-Sorter or basic sensor will be based on attending the upcoming conferences where new contacts hopefully can be established. Already established contacts will be pursued and the marketing from the website will continue with updates.

## 1.5 Project conclusion and perspective

The first generation full scale production unit has been installed and commissioned successfully. The RDF-Sorter works well as an integrated part of the complete sorting facilities at nomi i/s and no problems have been observed during the initial tests and long term tests.

Co-operation between the nomi i/s and FORCE Technology has been a success. Nomi i/s was responsible for designing and producing the hardware for integrating the basic sensor in the main sorting facilities and FORCE Technology designed the frame and shielding for the sensor and the layout of the basic sensor together with the software for controlling the system adapted to the facilities at nomi i/s.

The RDF-Sorter has a theoretical capacity of up to 40 tonnes of waste per hour. However the waste stream at nomi i/s is somewhat lower and follows the requirement specification. The system uses at the present setup at nomi i/s a capacity of 3-4 tonnes per hour i.e. app. 10% of the maximum device.

As noted the device can expanded considerably in capacity as the only real limitations to this are economy and radiation safety.

The sorting accuracy has proven to be within the requirement specification i.e. the precision of the calculated position of the waste containing chlorine on the conveyor is within +/- 10 cm and the number of false alarms is well below the specifications.

The obtained precision and efficiency of the RDF-Sorter makes it possible to produce RDF with high quality making it suitable for substitute coal as fuel in power plants.

If the RDF produces is used as fuel in power plants it will substitute coal as fuel and thereby cause less emission of greenhouse gasses. An annual production of RDF similar to nomi i/s production, 15.000 tonnes per year, will cause a reduction in emissions of $CO_2$ of app. 45.000 tonnes. The annual production of 15.000 tonnes can be measured with just one RDF-Sorter with a setup like the sorter installed at nomi i/s

As the RDF produced is of high quality it will also be profitable for the end user as the high quality RDF can be sold as opposed to the lower quality (with higher chlorine content) that the producer has to pay for in order to burn it as in incineration plants.

However, the conclusion that there is a rather large potential for chlorine removal from RDF with the use of just one such device is hard to escape.

The RDF-Sorter can also be employed as a quality assurance device, documenting that the chlorine content of a given stream is indeed below the limit imposed. This is as measurement the value of which we have as yet been unable to quantify properly, but one that is potentially very valuable, especially when considering economics of scale.

Besides the technical part of the project also dissemination has been carried out during the whole project. A number of conferences have been attended, papers have been written, product sheets and information about the project and project partners available on the web site www.elementsort.eu. Dissemination or marketing of the RDF-Sorter and the basic sensor will continue after the project conclusion.

As mentioned both nomi i/s and FORCE Technology will continue to develop the RDF-Sorter and the basic sensor after the conclusion of the project. FORCE Technology has identified a market potential for identifying black PVC and copper in waste streams, but also identification of e.g. rare earth minerals is potentially a new market. Nomi i/s will continue using the RDF-Sorter and gain experience that will be used to improve e.g. the distribution of the waste stream on the conveyor and improvement of the ejector all with the aim of using the RDF-Sorter as efficiently as possible.

## 1.6 Updating Appendix P and submitting the final report

Appendix P has been updated with the financial numbers for the whole period for both project partners. Further appendix P has been signed by the registered accountant without any comments to the financial numbers.

Appendix P has been uploaded to the project website www.forskel.dk.

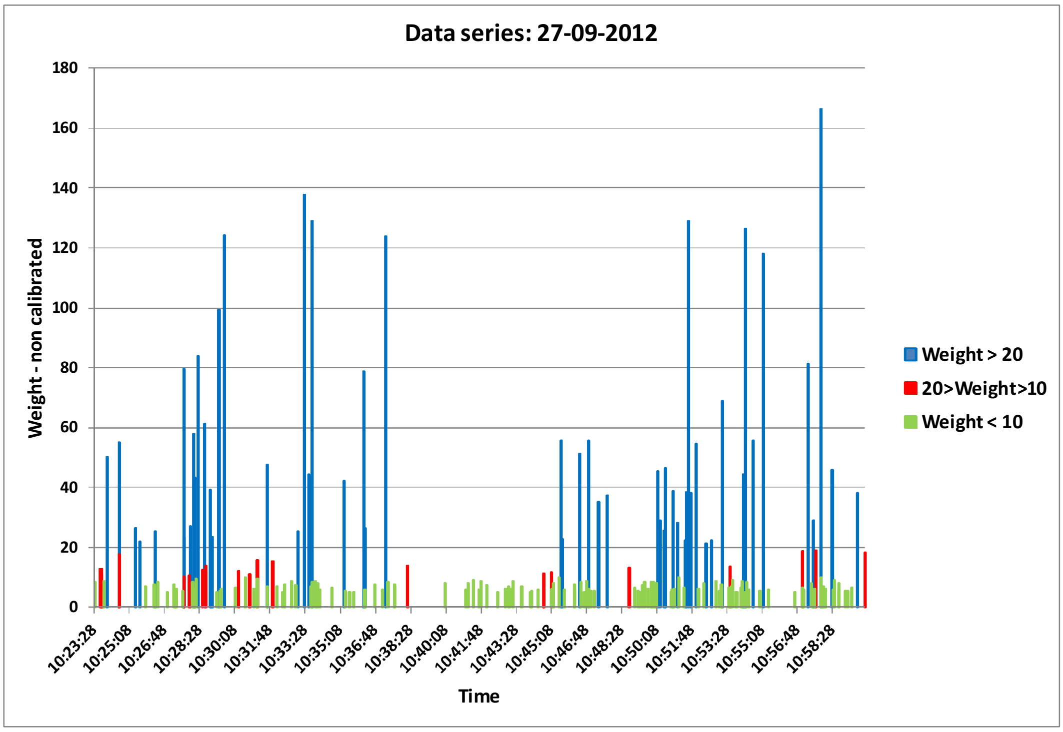
### 1.7 References

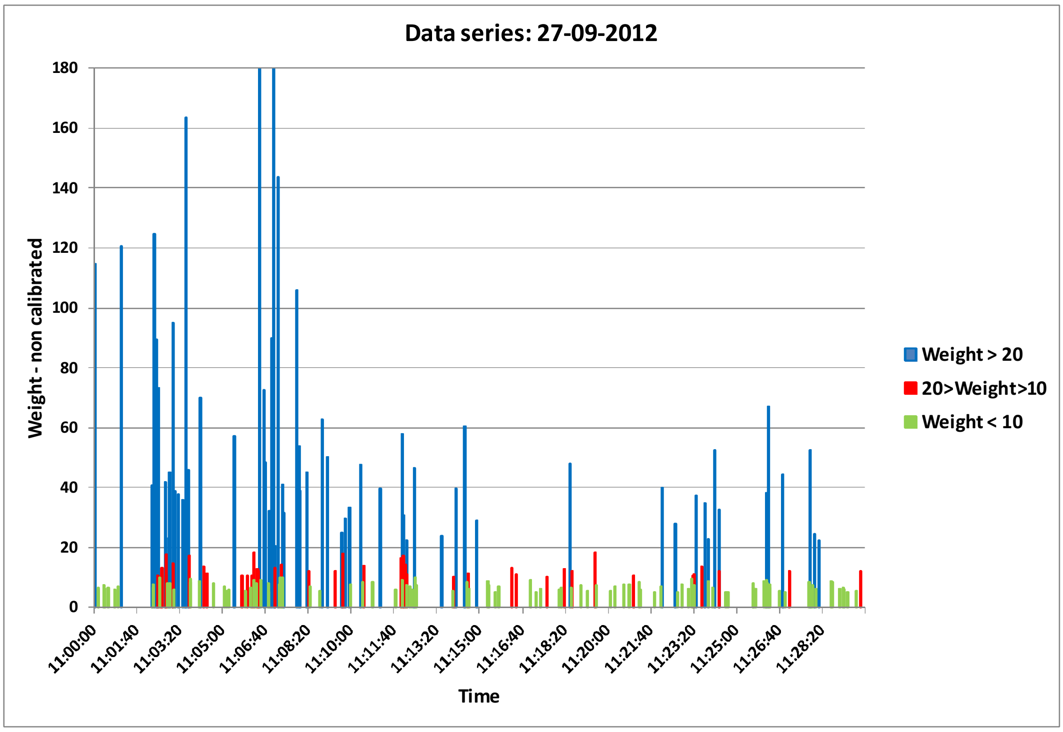

1. Kenneth S. Crane: "Introductory Nuclear Physics". John Wiley & Sons Inc, 1988. Chapters 11 and 12.
2. P.L.Ølgaard: "Kursus 4033. Forelæsningsnoter til industriel anvendelse af kernefysiske målemetoder. Neutroner I-V". Afdelingen for Elektrofysik, Danmarks Tekniske Højskole. Marts 1977.
3. JANIS 3.3 (Java-based Nuclear Information Software) drawing on ENDF/B VII.0 (Evaluated Nuclear Data File) and JEFF 3.1.1 (Joint Evaluated Fission and Fusion File) OECD Data Bank 2011
4. Edward M. Baum, Harold D. Know and Thomas R. Miller: “Chart of the Nuclides”, 16$^{th}$ Edition revised to 2002. Knolls Atomic Power Laboratory.
5. National Nuclear Data Center (Brookhaven National Laboratory) web based retrieval: http://www.nndc.bnl.gov/exfor/endf02.jsp
6. IAEA : “Database of prompt gamma rays from slow neutron capture for elemental analysis”, International Atomic Energy Agency, Vienna 2007, STI/PUB/1263
7. Glenn F. Knoll: “Radiation Detection and Measurement. Third Edition”. John Wiley & Sons, Inc. 2000.

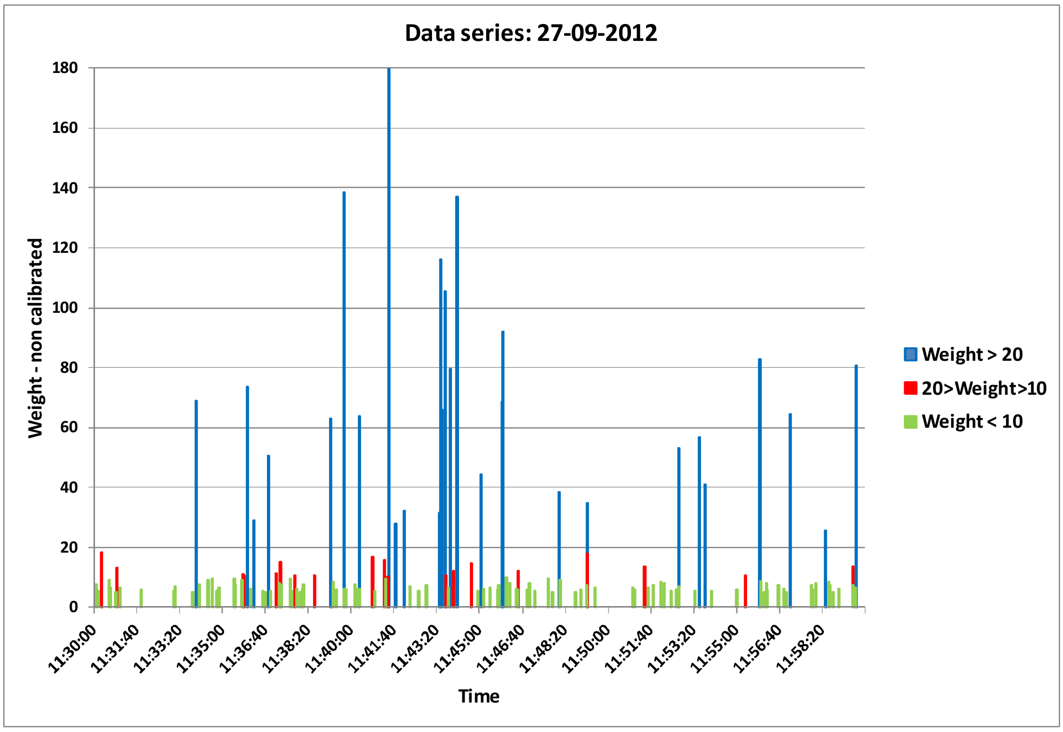
### 1.8 List of Figures

## 1.9 List of tables

## 1.10 Appendix A





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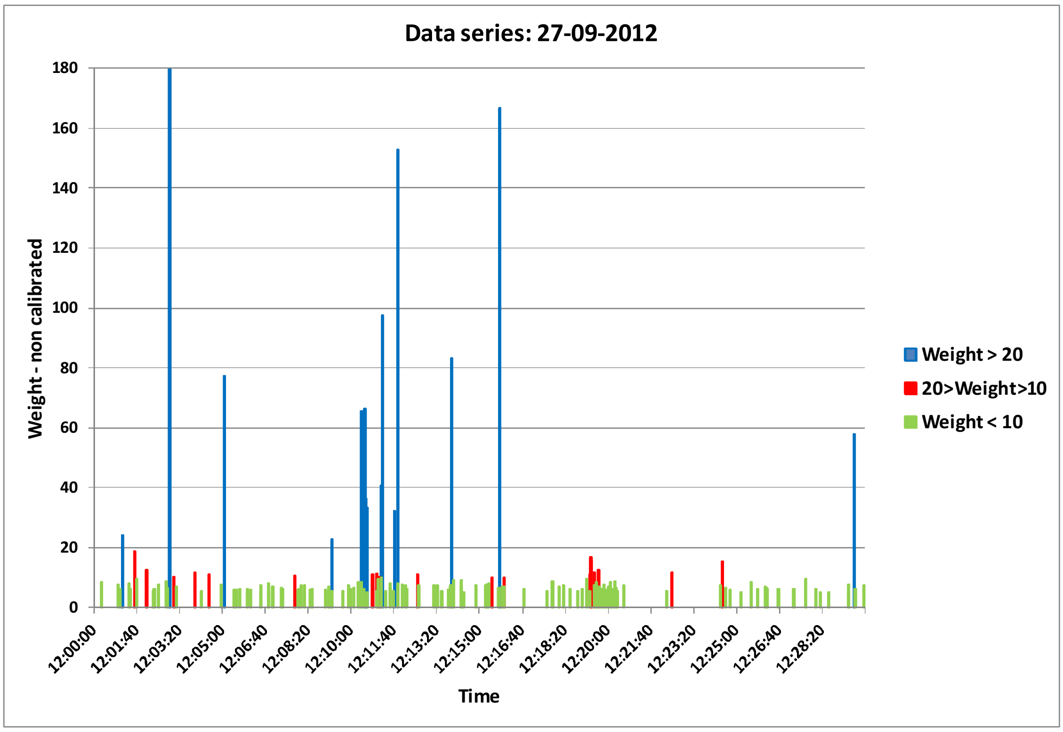

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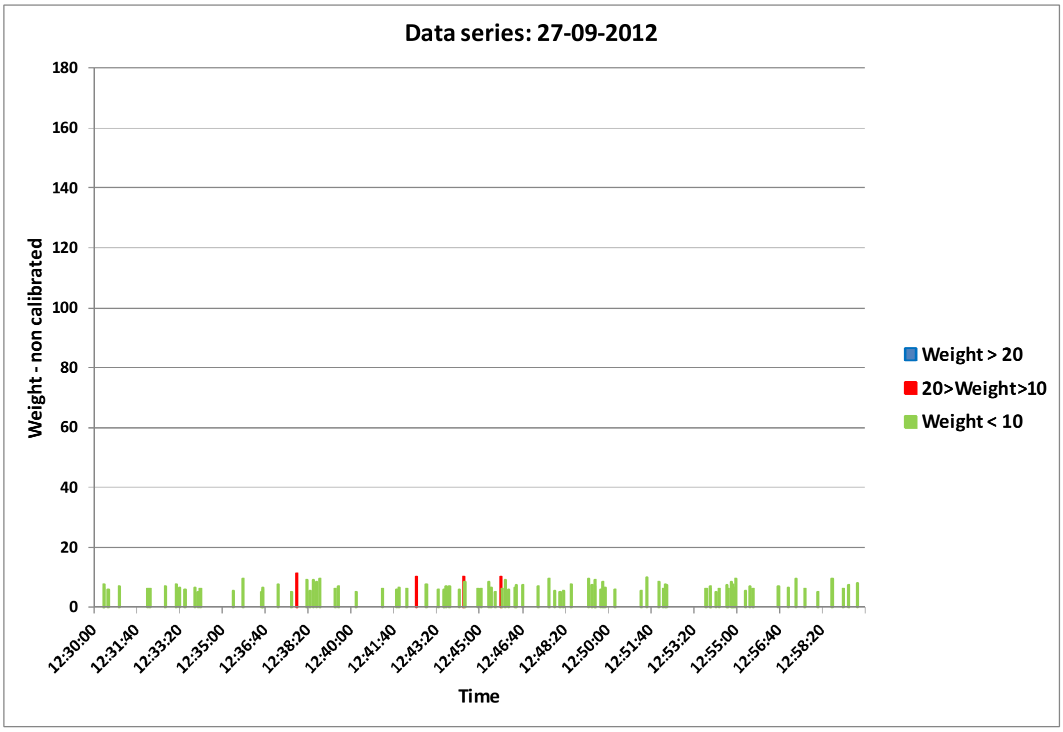
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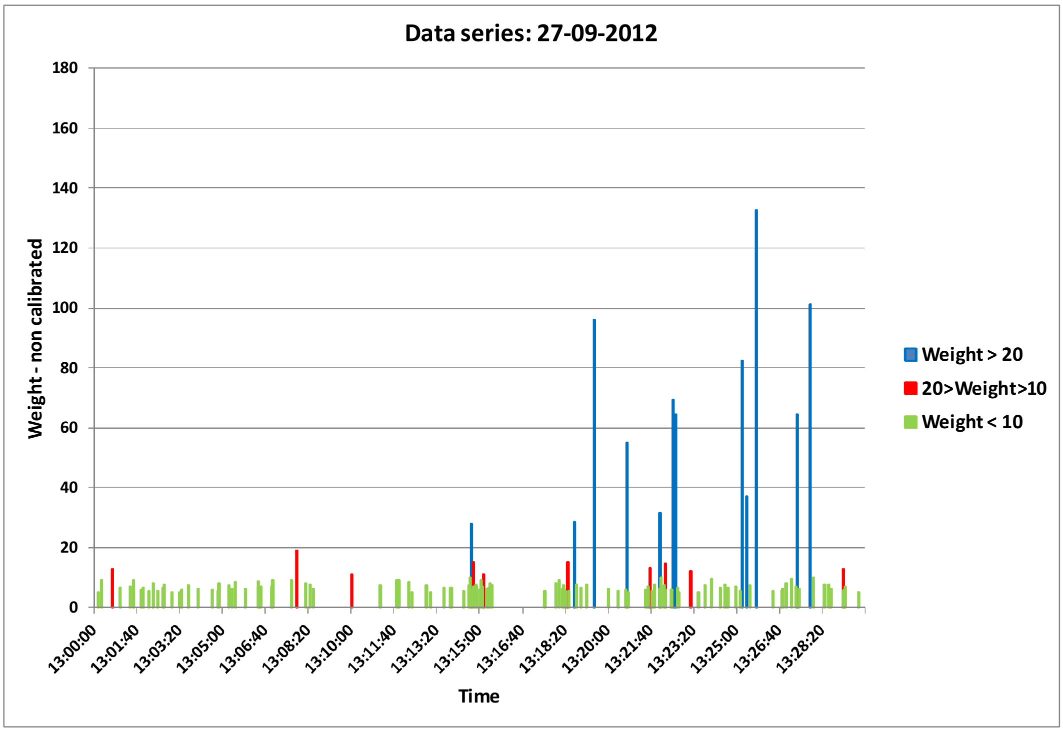
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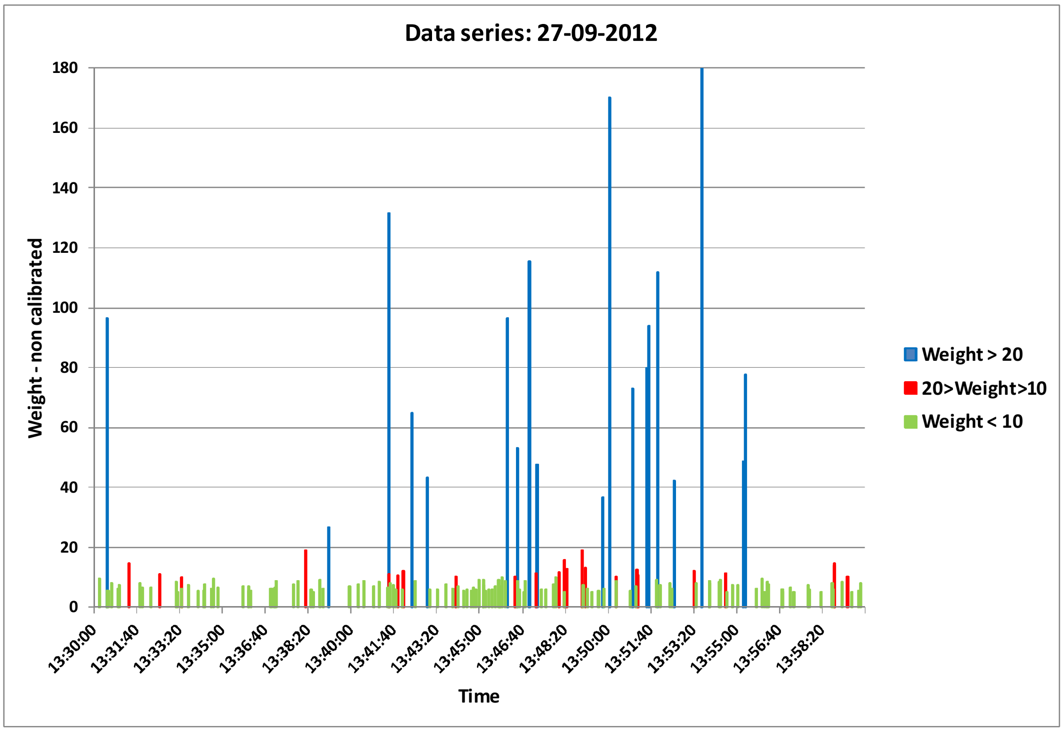
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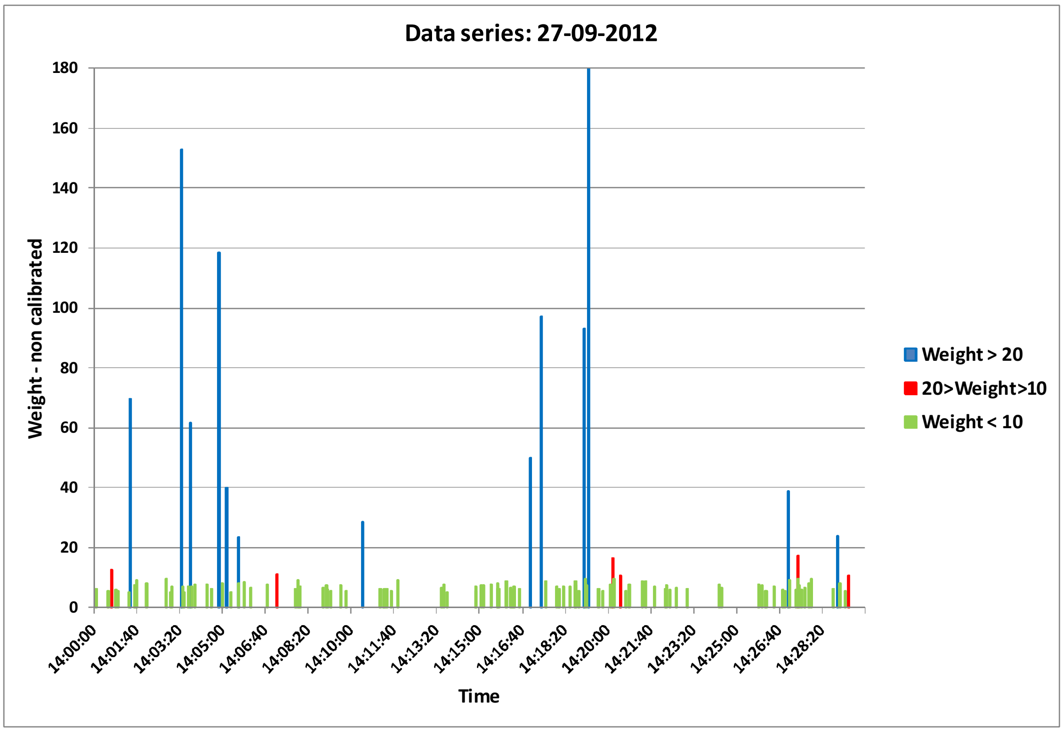
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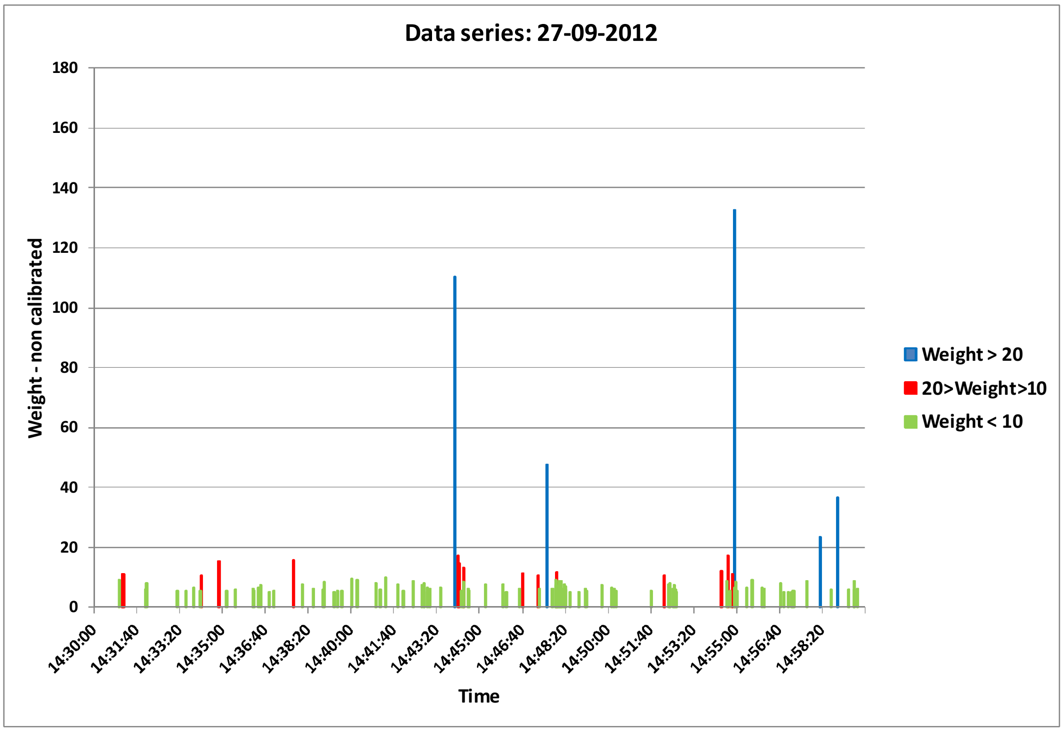
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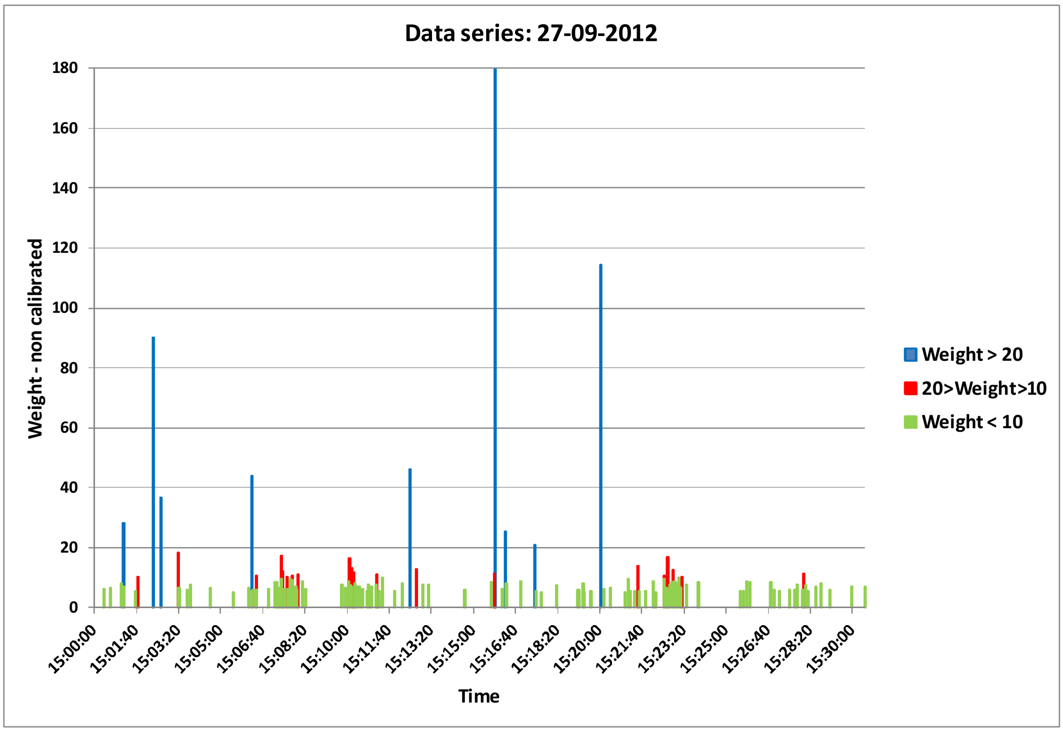
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## 1.11 Appendix B

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