Modelling of Solid Recovered Fuel (SRF) Properties Based on Material Composition – Chloride Quality

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1. Introduction

Producing solid recovered fuels (SRF) is a well-established route for recovering energy resources from municipal solid waste (household and/or commercial) [17]. Chloride content critically impacts the quality of SRF [19]. It directly influences operation of thermal processes, having deleterious effects through the high temperature corrosion of the boilers [16] and through demands placed on the flue gas treatment (FGT) system, which could impact emissions control.

Whereas design and specification of process plant can mitigate the technical issues associated with the presence of chloride experienced during thermal treatment, processing such fuels is associated with increased capital, operating and maintenance costs. This, at best, restricts the uptake/use of SRF or increases the cost of its treatment towards achieving a reduced chloride content.

Understanding the sources of chloride in SRF along with the processing and technology factors which influence its concentration, and to what extent it can be influenced and controlled, is important for waste operators; particularly of mechanical biological treatment (MBT) plants. At the moment, SRF is mainly utilized in the cement industry and this market is well established [11]. Whilst the cement industry, despite the variations in thermal recovery technologies in place – feeding SRF into the pre-calciner, main burner or low-heat end of the kiln; presence of chloride by pass or not – represents perhaps a uniquely robust technical solution for using SRF, extending the market for SRF outlets requires producing SRF of a quality that is acceptable for a broader selection technology options, perhaps on a smaller scale, and which may have more stringent fuel specifications. For these reasons the effective control of SRF quality is critical for the development of the related waste industry in Europe.

Quality control requires the production of a clearly specified product, characterised by a known and acceptable range of properties across all key parameters, controlling both the average target values and the variability. Chloride is one of the key parameters impacting SRF quality, and its suitability for end-user market outlets. Yet, anecdotal evidence from producers of SRF producers indicates that it remains a problem for the waste industry. The challenge is characterised by a low level of understanding as to how SRF producers can implement an effective quality assurance (QA) system to manage chloride within acceptable boundaries which are understood, and communicated in a transparent manner to an end-user of the SRF, and what techniques are available to operators to influence and control fuel quality.

This paper illustrates the potential for adopting Monte Carlo simulations to develop an understanding of the key issues impacting chloride concentration in SRF. It uses different modelled scenarios to illustrate the extent of uncertainty surrounding chloride content in SRF and how this compares with modern recognised fuel standards.

2. Chloride and SRF quality

The Committee of European Standardisation (CEN) has developed specifications regarding terminology, quality assurance, classes, fuel specifications, sampling, physical and chemical tests for SRF. A key determinant of the class of SRF depends on its chloride content. The CEN specifications for SRF quality based chloride content are shown in the Table 1 [5].

Table 1: CEN/TS 15359 specified values for chloride content (Cl) in SRF classes

Classification Property	Statistical Measure	Unit	Class				
			1	2	3	4	5
Chloride (Cl)	Arithmetic mean	wt.% d	≤ 0.2	≤ 0.6	≤ 1.0	≤ 1.5	≤ 3

d: dry reporting basis

3. Chloride in waste materials

3.1. Chloride in consumer market products

Chloride can be found in waste in two broad forms: *organic* chloride as associated with the inclusion in organic compounds e.g. plastics; and *inorganic* chloride e.g. salts.

Approximately 1/3rd of industrially produced chlorine production goes to chemical formation of ethylene dichloride (EDC), which is the precursor of polyvinyl chloride (PVC) [4]. PVC is used in plastic manufacturing for products such as tubes, pipes, films, packaging material and many others. PVC is commonly recognised in the waste industry as being an acute, concentrated source of chloride that can be problematic for thermal treatment processes.

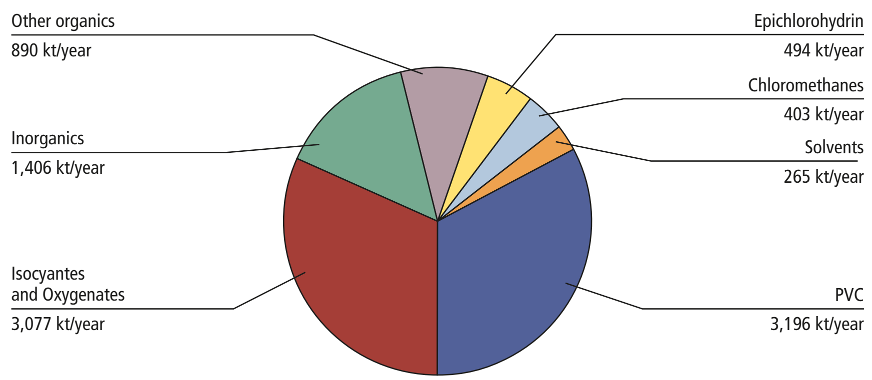

Figure 1: Major industry uses for industrially produced chloride in Europe

After Eurochlor: European Chlorine Industry Review 2012-13. Towards a new European Industrial Policy for more competitiveness. Eurochlor, 2013

However, a comparable quantity of the industrial chlorine produced each year is used in the production of isocynates and oxygenates [4]. Isocyantes are intermediates used to produce polyurethane polymers, which in turn are used in products such as chemicals, foam, insulation materials, surface coatings, furniture, under-carpet padding, packaging materials, shoes, and adhesives. At end of life, all of these may contain substantial quantities of chloride, and add to the total chloride load found in mixed waste containing such items. Whereas chloride in this chemical form may not be as concentrated as PVC, the breadth of the products which includes these compounds is significant and widespread.

Inorganic chloride can be found in such products as *table salt* (NaCl). In solid wastes it is identifiable in such materials as biological wastes, including kitchen waste and garden waste (*bio waste*). Whilst, the specific concentration of chloride as *inorganic* chloride in these wastes is lower for example, than that found in PVC, the overall composition of the waste may mean that inorganic chloride contributes a greater proportion of the overall chloride load – i.e. there may be more biological waste than PVC in a mixed waste stream.

Inorganic chloride and organic chloride exhibit distinctly different thermal behaviour, but both will largely volatilise the temperatures required for waste combustion and therefore they both are likely to be found mainly in the flue gas [9].

3.2. Chloride data for waste materials

Studies sought to quantify the concentration of chloride (*organic* and *inorganic*) in representative materials that comprise mixed (municipal: household or commercial) solid waste [1, 2, 3, 6, 7, 10, 12, 13, 14, 15, 18, 20, 21]. A summary of the data from a review of the literature on chloride is presented in Table 2.

The data illustrate a couple of key aspects regarding the current state of knowledge regarding chloride in solid waste. Firstly, some material categories exhibit large variation in potential chloride content. This is best exemplified by the data for *Plastic (hard)* where the range of chloride concentration spans 5 orders of magnitude from 16.8 percent to 0.001 percent.

Secondly, the lack of research data for the majority of material categories resulting in a corresponding high degree of uncertainty associated with our understanding and ability to predict chloride content in any SRF subsequently produced. There are 4 material types which stand out as contrary to this general observation regarding data paucity due to having significantly more data associated with them – these are: Biological waste; Paper & Card; Plastics (soft); and Plastics (hard); each of which has over 20 data.

In addition, there exists a further source of uncertainty – that of allocation rules. There is no international standard governing how specific materials (or products) are allocated to different material categories, i.e. what is *Plastic (hard)* vs. *(soft)*, when there are almost 5,000 different variations of polymers available in the market. This challenge is exacerbated by the presence of more complex, multi-material, products that may also feature plastic items, laminates or glues; which have been identified as potentially containing high concentration of chloride. Similar products from different manufacturers may feature different materials in their construction, which further contributes to the uncertainty associated with assessing and predicting chloride content when adopting (by necessity) generic material classes to characterise waste streams.

Material	Chloride wt.% d		Data No.
	Max.	Min.	Count
Ash	0.070	0.000	2
Batteries	1.580	0.000	2
Biological	1.492	0.119	27
Cartons	0.060	0.001	3
Composites	0.740	0.530	2
Fe Metals	0.760	0.000	3
Fines < 10 mm	0.740	0.020	3
Fluff	1.080	0.170	2
Glass	0.008	0.000	4
Non-Fe Metals	0.000	0.000	3
Other Combustibles	2.290	0.000	6
Paper & Card	0.630	0.002	22
Plastic (soft)	3.880	0.020	29
Plastic (hard)	16.80	0.001	30
Rubber	9.380	0.355	4
Shoes/leather	6.050	1.940	3
Stones/ceramics	2.190	0.000	3
Textiles/fabrics	1.690	0.011	9
Tissues	0.240	0.008	2
Wood	0.400	0.050	9
All Materials	**16.800**	**0.000**	**168**

d: dry reporting basis

Table 2:

Overview of chloride concentration data ranges by material type category

Sources:

Velis, C. A.; Longhurst, P. J.; Drew, G. H.; Smith, R.; Pollard, S. J. T.: Production and Quality Assurance of Solid Recovered Fuels Using Mechanical – Biological Treatment (MBT) of Waste: A Comprehensive Assessment. Critical Reviews in Environmental Science and Technology, 40: 12, 2010, pp. 979-1105

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4. Methods

4.1. Monte Carlo simulation

It is evident that we need to explicitly address the issue of uncertainty in assessing, monitoring and predicting chloride concentration in any methodology seeking to address SRF quality issues. Monte Carlo simulation [8], with its inherent ability to accommodate and quantify uncertainties in data, is therefore ideally suited as a tool to examine and address these issues.

Monte Carlo techniques allow for consideration of uncertainty by generating input values randomly from a range of possible values associated with a probability distribution based upon the available input data. This allows quantification of the confidence limits (upper and lower) associated with any conclusion derived from the model's results.

4.2. Chloride probability distributions

The data set out in Table 2 were used as the basis to create probability distributions that describe the likely chloride content of each waste material. The approach assumes that chloride concentrations for each material category followed a normal distribution. In order to fit the normal distribution to the data, the mean value was specified to the midpoint of the range and the spread of data was taken to be equivalent to 4 standard deviations. This is to say: 95 percent of all expected values were forecast to be within the range of chloride distributions identified within the literature, and that the values were normally distributed around the centre of the range.

4.3. SRF composition scenarios

The Monte Carlo simulation was repeated for 3 different scenarios, each with different assumptions regarding SRF material composition. The composition for each scenario was defined to reflect different types of SRF, as follows (Table 3):

- **Biogenic Rich** – comprised of a relatively high proportion of biogenic materials including paper & car, and biological waste.
- **Typical** – comprised of a composition representative of that which might be expect from an MBT treating municipal wastes.
- **Plastic Rich** – comprised of a composition with a higher plastic component, as might be associated with commercial wastes – for example material recycling (MRF) plant residues.

The specified material composition for each scenario are shown in Table 3.

Waste fraction	SRF scenarios		
	1	2	3
	Biogenic Rich wt.% ar	**Typical** wt.% ar	**Plastic Rich** wt.% ar
Ash	0.10	0.10	0.10
Batteries	0.01	0.01	0.01
Biological	8.70	2.70	2.70
Cartons	3.30	1.30	1.30
Composites	3.90	3.90	3.90
Fe Metal	0.20	0.20	0.20
Fines < 10 mm	0.90	0.90	0.90
Fluff	0.40	0.40	0.40
Glass	0.30	0.30	0.30
Non Fe Metal	1.70	1.70	1.70
Other Combustibles	0.80	0.80	0.80
Paper & Card	46.0	40.8	33.8
Plastic (soft)	9.80	14.8	18.8
Plastic (hard)	11.2	19.2	23.2
Rubber	0.40	0.40	0.40
Shoes/leather	1.50	1.70	1.70
Stones/ceramics	0.40	0.40	0.40
Textile/fabric	5.10	5.10	5.10
Tissues	1.40	1.40	1.40
Wood	3.90	3.90	2.90
Total	**100**	**100**	**100**

ar: as received reporting basis

Table 3:

SRF composition scenarios

5. Results

The Monte Carlo models for each scenario were each run with 32,000 iterations in order to provide a smooth result. The Monte Carlo models (frequency curves) for each scenario are displayed in Figure 2. Key numeric parameters of each scenario's results are displayed in Table 4:

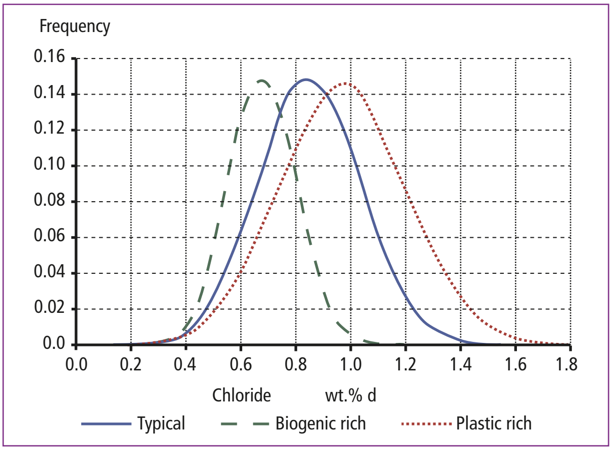

Figure 2:

Chloride concentrations predicted from normal distributions for each SRF scenario

Table 4: Statistical characteristics of chloride concentration for each SRF scenario

	SRF scenarios		
	1	2	3
	Biogenic Rich wt.% d	Typical wt.% d	Plastic Rich wt.% d
Arithmetic mean	0.657	0.817	0.931
Standard deviation (SD)	0.122	0.185	0.228
LCL (95 %)	0.418	0.455	0.484
UCL (95 %)	0.896	1.179	1.378
Q1	0.573	0.690	0.773
Q3	0.740	0.941	1.084

UCL (95 %) = upper confidence limit Q3 = 3rd quartile
LCL (95 %) = lower confidence limit Q1 = 1st quartile

6. Discussion

The results of the Monte Carlo simulations illustrates the impact of different scenarios (compositions) on the chloride concentration of SRF. Firstly, as might be intuitively expected looking at the data for chlorine concentrations in individual materials, increasing concentration of plastics increases the predicted chlorine content of SRF. The highest Mean value (Table 4) is associated with the *Plastic Rich* scenario, and the lowest Mean value with the *Biogenic Rich* scenario.

However, the Monte Carlo methodology provides further insights into the influence that SRF composition has on chloride concentrations: it also illustrates the impact of uncertainty, how uncertainty varies, and how uncertainty might be related to SRF composition (scenarios). The modelling illustrates that the spread of chloride values also changes between the different scenarios. This is visible when comparing the plots in Figure 2 – with the plot for the *Plastic Rich* scenario being wider than that for the *Biogenic Rich* scenario – and this is numerically quantified via the SD values (Table 4).

The SD ranges from 0.122 for *Biogenic Rich* SRF to 0.228 for *Plastic Rich* SRF. The larger values signify a greater spread of chloride values, and with it a greater to degree of uncertainty. Such increases in uncertainty in a key fuel characteristic, such as chloride, have a direct impact on the quality control achieved by a process producing SRF. To illustrate this, and the potential impact of the uncertainty values indicated by the Monte Carlo simulations, the results of the modelling can be compared to the bands defined within the CEN standard for chloride concentrations, an application of compliance statistics (Figure 3).

Figure 3 illustrates if, for example, an end user's requirements for an SRF includes a specification for chloride content of ≤ 1.0 percent, which would be consistent with that expected for a cement kiln [9], whilst all scenarios achieve this value on the expected arithmetic mean, only the Biogenic Rich scenario is capable of producing such an SRF with greater than a 95 percent confidence. That is to say, in a sizeable number of cases the average SRFs that could be produced under the *Typical* and *Plastic Rich* scenarios may not meet the required standard for chloride.

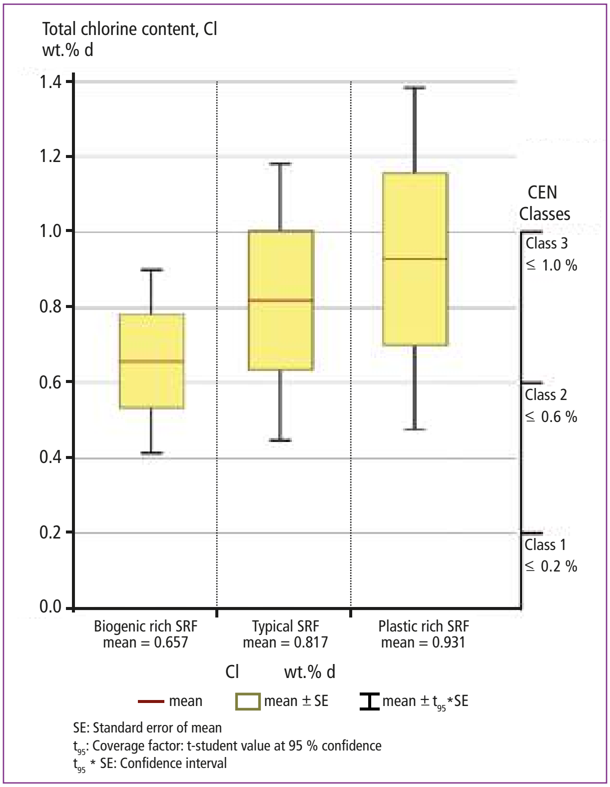

Figure 3:

Box-whisker plots of chloride distributions compared with CEN classes

As the composition to an SRF producing facility varies, a proportion of the SRF may not meet the standard for chloride, if the processing cannot alleviate for such input changes. Whether this *non-compliance* becomes important, in that it constitutes an unacceptable problem for SRF acceptance and recovery, would be down to end-user and could depend on various factors e.g. further processing technology, or regulatory compliance. However, the data for chloride concentration will also be impacted by issues inherent to the sampling regime itself e.g. sampling techniques, sampling rate/ frequency, and averaging period, sample lot, etc. and it is important that these are understood by both the SRF producer and its end-market SRF user and a common understanding is adopted, or issues could arise within Fuel Supply Agreements (FSAs) between the parties.

In all cases, in the planning/designing phase of a SRF producing facility or in the preparation of a FSA, Monte Carlo simulations may be able to assist with demonstrating that it may or may not be probable to produce an SRF *product* that consistently satisfies the quality requirements of an end-user of the fuel – e.g. thermal process plant. Employing such analytical tools can minimise the potentially detrimental impacts to the technical and financial viability of a facility producing SRF which would result if it cannot meet the standard required by its market outlets. This preliminary tool is currently further developed by the University of Leeds to a fuller suite with a view to assist a quantified quality assurance of SRF production and use.

7. Conclusions

The data and discussion presented in Section 4.2 demonstrates the uncertainty with respect to defining the chlorine content of individual waste categories – i.e. within Paper & Card, Plastics etc. – as illustrated by the broad range of chloride values observed within the literature and, frequently, the paucity of data for many individual material types.

Monte Carlo simulation is a tool ideally suited to assessing and forecasting SRF quality as it address and quantify uncertainty within the methodology and results. The application of Monte Carlo simulation, as illustrated by this paper, shows how the methodology can be used to assess the impact of different SRF scenarios will have on SRF quality – in this case through the manipulation of SRF composition, and comparing chloride concentration with industry standard specification for SRF quality classes.

Given the significant technical, commercial and resource implications that can be involved in seeking to manage and monitor SRF quality on an industry scale, it is believe that Monte Carlo simulation is an important tool which could be used to ensure that resources are appropriately directed when addressing quality aspects, and that the measurement and performance of MBT processes is understood in a transparent and easily communicated way.

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