UNIVERSITY OF VAASA

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MANAGING WASTEWOIMA® AIR POLLUTION CONTROL RESIDUES (APCR)

Master's Thesis in
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ABBREVIATIONS

APCr	Air Pollution Control residue
APC	Air Pollution Control
CO_2	Carbon Dioxide
EfW	Energy from Waste
EU	European Union
FA	Fly Ash
FGD	Flue Gas Desulphurization
FGT	Flue Gas Treatment
FGTr	Flue Gas Treatment residue
HCl	Hydrochloric acid
HW	Hazardous Waste
MSW	Municipal Solid Waste
MSW	Municipal Solid Waste
NH_3	Ammonia
NO_x	Nitrogen Oxides
PCDD	Polychlorinated dibenzodioxins
PO_x	Partial Oxidation
PVC	Polyvinyl chloride
REE	Rare Earth Elements
Ref	Reference
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SO_2	Sulphur dioxide
S/S	Stabilization/Solidification
SS	Sewage Sludge
TWT	Thermal Waste Treatment
um	Micrometre
VOCs	Volatile organic compounds
WtE	Waste to Energy

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ABSTRACT:

This thesis focuses on the management of air pollution control residue (APCr) that are produced by waste to energy (WtE) or energy from waste (EfW) incineration plant. The WtE or EfW plant uses a combustion chamber to incinerate wide range of waste materials to reduce the volume and the environmental impact of the waste. The incineration process generates bottom ash and flue gases. The flue gases generated by the plant are managed with flue gas treatment (FGT) and air pollution control (APC) systems to produce APCr.

WOIMA Finland Oy is the case company that requested for this research work. WOIMA aim to provide an innovative circular economy solution for global waste management, which includes the APCr WOIMA waste incineration plant will produce.

The research focused on two questions: What alternatives are available for managing the APCr onsite? And What solutions can be used to improve the management of the APCr offsite? The thesis work was theoretical based. The research used exploratory approach to examine literatures and conduct interviews. The thesis developed into a qualitative research with facts analysis and discussion. To solve the problem statement, the thesis observed all factors that influences APCr composition such as the waste used as fuel, waste management systems, flue gas treatment (FGT) and air pollution control (APC) systems.

The thesis research observed types of waste, classes of waste and waste management facilities since it has direct influence on the APCr produced by a waste incinerator plant. Westenergy plant was the facility visited for field studies with questionnaires for understanding the processes involved in a waste to energy incineration plant. Several topics were discussed during the interview, which included the type of waste used in their plant, flue gas treatment (FGT) systems, air pollution control systems, APCr removing process from the plant, APCr transportation and APCr treatment information.

The research examined the theories available for managing APCr which where Backfilling, treatment and landfilling, decontamination /detoxification, product manufacturing, practical applications and recovery of materials. Some criteria based on EU Directive 2018/851 and WOIMA Finland Oy requirement for managing WOIMA APCr was used for selecting the best APCr management theories. The thesis identified product manufacturing as the best and recovery of materials as the second best APCr management theory available for manage APCr according to the selected criteria.

Carbon8 Aggregate and Tetronics International knowhow were the technologies selected for further study because Carbon8 and Tetronics applications correlate to the protection of the environment alone with product manufacturing and recovery of materials. The objective of the thesis was to identify the best solutions for managing the APCr both on and off the plant site. To decide on the finest solutions for managing the APCr, some selected criteria was adopted. Carbon8 Aggregate technology was recognized as the top APCr managing solution with the most benefit both on and off the plant site. However, Tetronics International technology was acknowledged as the finest solution for reducing the harmful characteristics of all APCr.

KEYWORDS: Waste, flue gas treatment (FGT) and air pollution control residue (APCr) management.

1. INTRODUCTION

The global generation of municipal solid waste recorded in 2016 was over two (2) billion tonnes. Waste management is an important environmental topic because the generation of waste is a part of every active process. The generation of waste cannot be eliminated but it can be managed by reducing the waste output of a product, reusing, recycle, recovering material and treating waste as described by Directive 2008/98/EC. The process of managing waste by combustion treatment plant produces several by-products. One of such by-products is the air pollution control residue (APCr), which can be described as a fine powder, which is formed from the continues cleaning of the gases that exits the plant. An energy from waste (EfW) or Waste to Energy (WtE) plant is a waste management facility that converts the waste materials into heat, stream or other energy matter through processes like combustion, pulverization, plasma techno, gasification, pyrolysis, fermentation, and others. The management of APCr is currently one of the most difficult issues facing the EfW or WtE incineration industry. The legislations and enforcement of emission pollution control standard laws have helped the development of technology that reduce the air pollution emission levels of combustion facilities but the disposal of the APCr is becoming a more greater concern due to its chemical composition and it harmful effect to the environment. (WOIMA Blog 2018; FCC Environment 2018; Anu Antoney 2017)

The purpose of this thesis is to examine the theories for managing APCr from a WtE combustion plant. After examining the theories, the research focused on detecting some of the best management system for the APCrs. The purpose of this thesis was accomplished by investigating the processes involved in the EfW or WtE combustion facility and analyzing some of the available APCr management systems. This thesis observed the characteristics of waste that is fed into the EfW or WtE combustion plant, EfW or WtE combustion system, air pollution control (APC) systems and APCr management technologies. The thesis research only focused on Finland EfW or WtE combustion plant, factors that affect APCr chemistry, theories available for managing APCr and some existing APCr management technologies that can be used to recycle the APCr of WOIMA WtE plant on and off the plant site.

1.1. Background of the study

WOIMA Finland Oy is the case company for this thesis research. WOIMA Finland Oy is a Finnish company with team of experience Finnish project managers and engineers, who have worked over 20 years with prominent companies such as Wärtsilä, ABB, Valmet, Andritz and Cargotec. During those years, the team has attained experience in more than 1,000 projects with solving power and utility challenges in over 100 countries. (WOIMA Brochure 2018: 3)

Their experience has covered several fields such as civil, mechanical, electrical, automation, health, safety, security, environment and quality disciplines. The team has managed over 300 waste to energy, bioenergy and conventional energy projects in more than 30 countries to generate an annual energy over 25TWh. (WOIMA Brochure 2018: 4)

WOIMA corporation vision is to design and deliver innovative circular economy solution that will challenge the current waste management and power generation practices. WOIMA hope to increase the economic, environmental and social wellbeing of developed and developing countries by delivering the best waste to energy solutions and services. WOIMA mission is to mitigate waste-induced problems and offer sustainable growth to the energy sector, waste management companies, investors and the local population.

WOIMA is currently focusing on waste-based power generation by utilizing municipal solid waste (MSW), wastewater sludge, industrial, agricultural, commercial, institutional and engineered waste.

WOIMA aims to provide uninterrupted power to local communities and businesses by supporting investors, waste management company and/or independent power producers in the project development phase such as the feasibility studies, environmental impact assessment, social impact assessment, project profitability and the technical solutions. (WOIMA Brochure 2018: 5-6)

1.2. Research questions and confines

WOIMA Finland Oy aims to provide an innovative circular economy solution for global waste management which includes, the APCr that their waste incinerator will produce. To make their facility the unsurpassed circular economic solution available for managing waste, WOIMA expects this thesis research to find the finest solution for managing their APCr both on and off the plant site.

The research objectives are to identify the best solution for managing the APCr on and off the waste to energy plant. To realise these objectives, the research explored all the necessary components that affect the APCr. The investigation started from the type of waste been incinerated, the process that affect the APCr chemistry of a WtE facility and finally the available technology that can be used to manage or recycle the APCr. Two (2) research questions were designed to help find solution for the research objectives.

1. What alternatives are available for managing the APCr onsite?

2. What solutions can be used to improve the management of the APCr offsite?

Scientific articles, inquiries and interviews were used to help solve both questions. WOIMA Finland Oy expects the solution applied on the plant site to be portable and easily relocated like WOIMA facility. WOIMA expects the result for manage the APCr to satisfy the circular economic goals of reusing the by-products and should be easy to implement. The secondary materials used by the solution should be easy to obtain. The solution should be safe to human health and the environment.

The research for the thesis was focused on the factors that affect the APCr from waste to energy combustion plant. Only Finland waste to energy incineration facilities were observed for the study. Technical solution and recommendation by the study did not go throw further testing.

1.3. Thesis structure

To find solutions for the research objectives, the thesis used six chapters which include introduction, literature review, methodology, investigations, findings, discussion and conclusion.

The first chapter is the introduction section which contains the highlight on why this research was needed and some background information on the case company. It also contains the thesis structure, the research questions and limitations.

The second chapter is the literature review section where the thesis examines waste and waste management. This chapter also observes EU waste management hierarchy, Finland waste management scheme and WtE technologies.

The third chapter is the methodology section which describes the research design and methods. The research design explains the processes and methods used by the thesis. The research methods include the data collection methods, kinds of data collected and data analysis methods.

The fourth chapter is the investigations section which explores the main factors that influences the APCr composition such as the waste used as fuel, the flue gas treatment process and Air pollution control system that traps the harmful substance in the flue gas.

The fifth chapter is the findings section which examines existing APCr management theories and select available technologies on how the APCr can be managed. It also examines some pros and cons on the selected technologies for managing WOIMA APCr.

The sixth or final chapter is the discussion and conclusion section. This chapter discusses some solution to solve the management of APCr both on and off the WOIMA Plant site.

2. LITERATURE REVIEW

The annual global waste generation estimated for 2050 is 3,40 billion tonnes, which is about 70% from the recorded 2.01 billion tonnes in 2016. It consist of an estimation growth from 392 million to 490 million tonnes in Europe and Central Asia, 289 million to 396 million tonnes in North America, 129 million to 255 million tonnes in Middle East and North Africa, 468 million to 714 million tonnes in East Asia and the Pacific, 334 million to 661 million tonnes in South Asia, 174 million to 516 million tonnes in Sub-Saharan Africa, and 231 million to 369 million tonnes in Latin America and the Caribbean. The chemical reaction from global waste industry landfill, account for 10% of the greenhouse gases emitted. About 90% of low-income countries municipal waste end up in open dumps. Only 37% of global solid waste goes to managed landfills, with 33% to unsanitary open dumps, about 11% goes to incinerators and about 13% is recycled. (WOIMA Finland Oy 2018: World Bank 2018)

According to an official Journal of the European Union 'Waste Framework Directive 2008/98/EC' Article 3, defines waste as "any substance or object which the holder discards or intends or is required to discard" There are several clusters of waste and different ways they can be categorized. For the purpose of this investigation study let sorting waste into 2 categories mainly, types of waste and classes of waste.

2.1. Types of waste

The type of waste categorized in this area is a cluster which is directed towards the nature and chemical structure of the waste. There are different types of waste groupings, they can be hazardous or non-hazardous waste, recyclable or non-recyclable rubbish, organic or inorganic waste and solid, liquid or gaseous waste. (Rubbish Removal Blog 2016)

Hazardous waste is any waste which exhibits one or more of the hazardous properties listed in Annex III of the directive 2008/98/EC as shown in APPENDIX 1 of this thesis document. Non-hazardous waste therefore is any type of waste that does not have any of the properties listed in Annex III of the directive 2008/98/EC, such as toxic, flammable, corrosive or reactive.

Recyclable rubbish is all type of waste that can be reused or converted into usable products whiles non-recyclable rubbish are all kinds of waste that cannot be reused or converted into usable products. (Rubbish Removal Blog 2016)

Organic or biodegradable waste is any rubbish substance of biological origin, such as animals or plants, which can be broken down by micro-organisms. Inorganic or non-biodegradable waste is any rubbish substance of mineral origin, which cannot be broken down by micro-organisms. (Shuktiz Sinha 2015; WasteNet 2018).

Solid waste is any form of solid rubbish commonly located in homes, commercial and industrial facilities. Solid waste is characterized into plastic, paper or wood, metal and ceramic or glass. Liquid waste is any type of liquid or sludge remnant that is rubbish and can be harmful to humans or the environment. They are commonly liquid residues from homes, restaurants, cars, washing machines, agricultural and industrial operations. Gaseous waste is any waste product which is in a form of smoke, vapour or gas. Some gaseous waste includes methane (CH_4), carbon dioxide (CO_2), chlorofluorocarbon (CFC), carbon monoxide (CO), oxides of nitrogen (NOx), oxides of sulphur (SOx) and others. (Rubbish Removal Blog 2016; NITSCHKE Liquid Waste Blog 2015; Aman Raj 2015)

2.2. Classes of waste

The description of waste by classes is directed towards the place, area, process or medium where they were generated. These classes of waste are medical waste, agricultural waste, process or industrial waste and municipal solid waste (MSW). (Anu Antoney 2017)

Medical waste also known as biohazardous, biomedical, clinical or healthcare waste are all waste materials that’s potentially infectious which are generated by healthcare facilities such as hospitals, laboratories, medical research and veterinary facilities. Office paper, kitchen waste and sweeping waste generated from healthcare facilities are technically medical waste even though they are not hazardous. (MedPro disposal 2018).

Agricultural waste is any waste substance produced as a result of various agricultural operations. Agriculture waste includes all farm related waste such as slaughter house, poultry house, harvest waste, manure, fertilizer run-off from fields and pesticides that enter water, air or soils. (R. Nagendran 2011: 341-345).

Process or industrial waste is any waste substance produced by a factory, industry, mills or mining activity. These process or industrial substance rendered useless during the manufacturing process includes industrial by-products, radioactive waste, chemical solvents, sludge, ash, paper products, metals and pigments. (Maczulak, Anne Elizabeth 2010: 120).

Municipal solid waste (MSW) is any waste generated in homes, public service and private services. MSW includes packaging materials, glassware, tin cans, kitchen waste and others. The total MSW recorded in 2010 was 2,596,000tonnes. The MSW is mostly separated into bio, paper, plastic, metal, glass, battery and mixed waste. (Sari Piippo 2013:5)

Table 1. Estimated MSW of Finland in 2010 (Adopted from Sari Piippo 2013:5)

Waste sector	Households and public services (tonnes/a)	Private services (tonnes/a)
Mixed waste	1 199 000	376 000
Paper and cardboard	258 000	132 000
Bio-waste	156 000	121 000
Waste wood	3 000	29 000
Plastic	24 000	25 000
Others and unclassified	215 000	59 000
Total	1 854 000	742 000
All in total	2 596 000	

Table 1 shows the composition of Finland MSW in 2010. More than half of the total MSW collected in that year was mixed waste. The separated waste collected have more than one third (1/3) coming from paper and cardboard.

2.3. Waste management

The waste framework directive 2008/98/EC describe the priority of waste management from top to bottom. Waste prevention or avoiding and reducing is on top of the priority and most preferred, followed by re-use, then recycling, followed by recovery, treating and finally disposal. Figure 1 illustrate the waste management hierarchy.

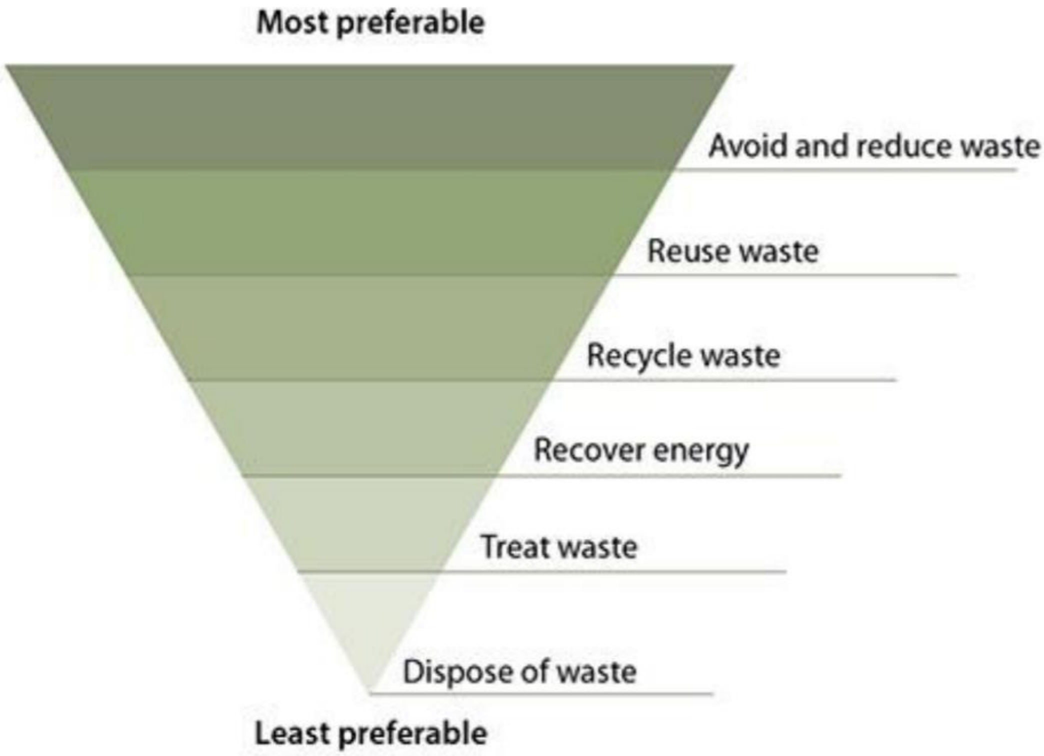


Figure 1. Waste management hierarchy (Adopted from Enoch Afrane Gyasi 2018)

The Directive 2008/98/EC Article 3 defines prevention as "measures taken before a substance, material or product has become waste"

a) Reducing the quantity of waste by making it re-usable or increasing the life span of the products.
b) Reducing the impacts, the product's waste will have on the environment and human health.
c) Reducing the harmful substance in the materials or product before it is finalized.

The Directive 2008/98/EC Article 3 defines preparing for re-use as “checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing”.

The Directive 2008/98/EC Article 3 defines recycling as “any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations”.

The Directive 2008/98/EC Article 3 defines recovery as “any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy”. The list of recovery operations is found in Annex II and shown in APPENDIX 2 of this document.

The Directive 2008/98/EC Article 3 defines disposal as “any operation which is not recovery, even where the operation has as a secondary consequence the reclamation of substances or energy”. The list of disposal operations from Annex I are shown in APPENDIX 2 of this document.

Article 3 of the Directive 2008/98/EC defines waste management as “the collection, transport, recovery and disposal of waste, including the supervision of such operations and the after-care of disposal sites, and including actions taken as a dealer or broker”. Figure 2 demonstrate the waste management system in Finland. After separation of the MSW from it source, it is collected and transported to a regional collection point or to landfilling. From the regional collection point the waste is either transported to a waste handling facility or sent to landfilling. The waste transported to utilization and handling of waste facilities, is sorted for landfilling, energy and raw material production. The waste utilized for energy sends it by-product to landfilling or for raw materials usage.

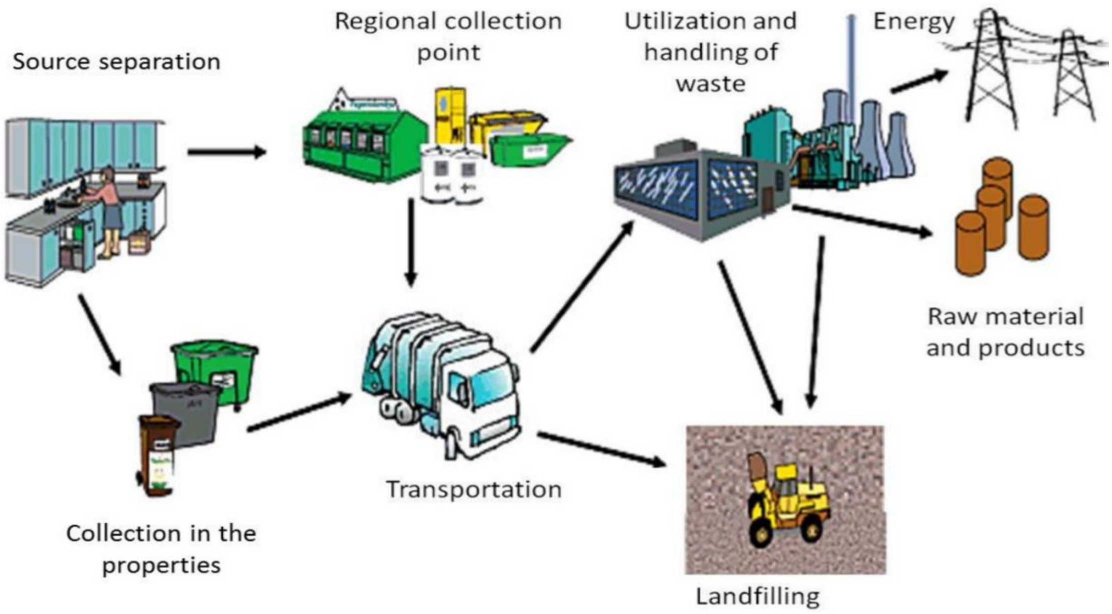
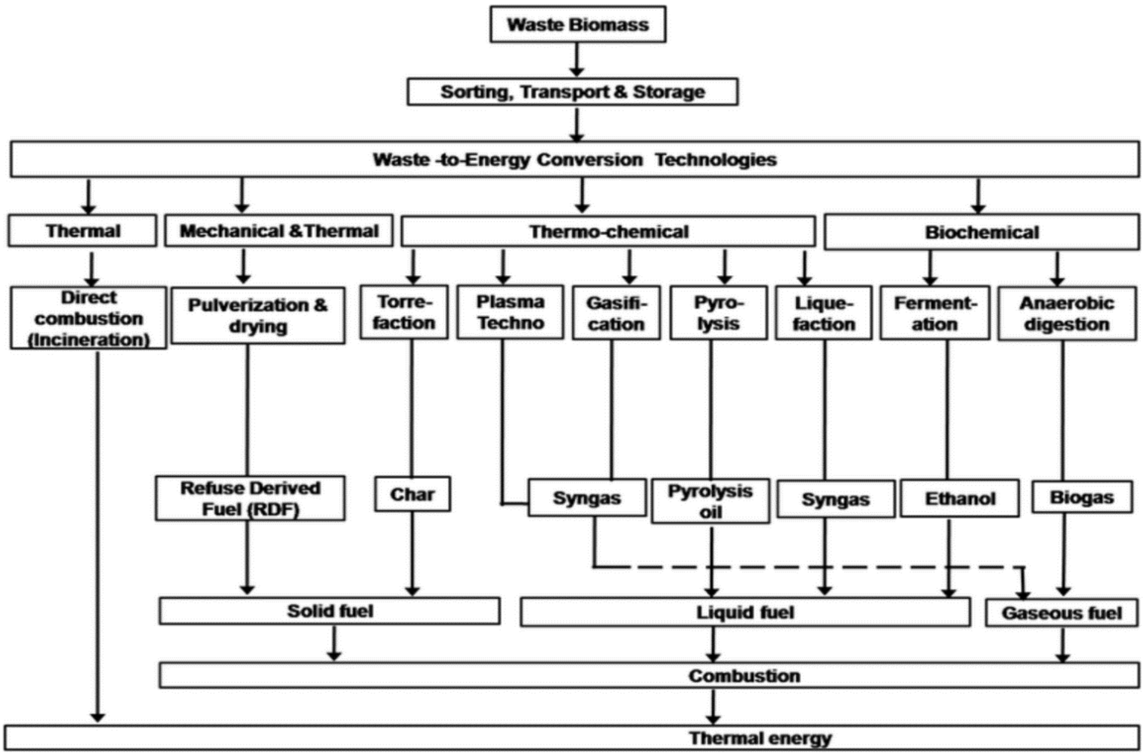


Figure 2. Waste management scheme in Finland (Adopted from Sari Piippo 2013)

The waste sorted for energy is sent to a WtE or EfW facility. The WtE or EfW plant converts the waste into energy by using processes such as thermal, mechanical, thermo chemical and bio-chemical. In the thermal system, the waste is directly combusted to thermal energy. In the mechanical and thermal method, the waste is pulverized and dry before it is refused into solid fuel which is combusted into thermal energy. The thermo-chemical method uses 5 different procedures which include torre-faction, pyrolysis, liquefaction, plasma techno and gasification. The torre-faction technique chars the waste into solid fuel, which is combusted into thermal energy. The pyrolysis technique transforms the waste into pyrolysis oil or liquid fuel, which is combusted into thermal energy. The liquefaction technique transforms the waste into syngas, in a form of liquid fuel, which is combusted into thermal energy. The plasma techno and gasification technique transform the waste into syngas, in a form of gaseous fuel, which is combusted into thermal energy. The biochemical method transforms the waste into 2 fuel forms through the process of fermentation and anaerobic digestion. The fermentation technique transforms the waste into ethanol, in a liquid fuel form, which is combusted into thermal energy. The anaerobic digestion transforms the waste into biogas, in a gaseous fuel form, which is combusted into thermal energy. Table 2 shows the WtE technologies diagram. (Anu Antoney 2017)

Table 2. Waste to energy technologies diagram (Adopted from R. Gumisiriza 2017)



This thesis is focused on the APCr formed from a thermal waste treatment by directly incinerate the waste. The objective of the thermal waste treatment can be seen in table 3.

Table 3. Purpose of WtE or EfW incinerator (GC/FN/JG/EIPPCB/WI 2017)

Objective	Duty
Destruction of organic substances	Furnace
Evaporation of water	
Evaporation of volatile heavy metals and inorganic salts	
Production of potentially exploitable slag	
Volume reduction of residues	
Recovery of useable energy	Energy recovery system
Removal and concentration of volatile heavy metals and inorganic matter into solid residue from the flue gas	Flue gas cleaning
Minimizing emissions to all media	

The intention of the direct incineration by WtE facility is to reduce the waste volume, destroy hazardous substances in the waste or released during the incineration process and to recover energy from the waste. (GC/FN/JG/EIPPCB/WI 2017: 3,5)

Westenergy Oy Ab is a WTE company which operate and maintain a modern waste incineration plant located at Mustasaari near Vaasa city in Finland. Westenergy plant has been in operation since 2012 and it uses non-recyclable waste as the plant fuel. The company is owned by five Finnish municipal waste management companies known as Millespakka Oy, Lakeuden Etappi Oy, Vestia Oy, Botniarosk Oy Ab and Stormossen Oy Ab. Westenergy operate in 50 municipalities, which covers over 400,000 inhabitants. The plant converts waste into steam which is used to produce electricity and one third of the Vaasa district heating by Vaasan Sähkö Oy co-operation partner of Westenergy. Figure 3 shows the processes the waste undergoes in Westenergy plant. (Mokomaki 2019)

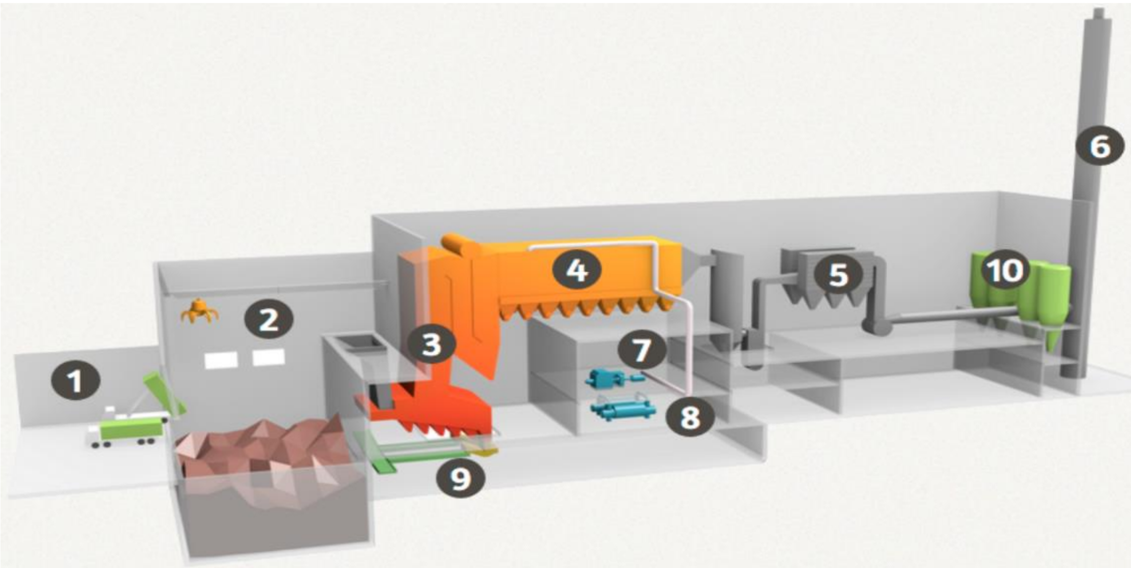


Figure 3. Westenergy plant process (Mokomaki 2019)

1. Tipping hall: Waste is transported and unloaded to the bunker through the tipping hall by waste trucks. The tipping hall have enough space for five regular waste trucks or one side-tipper truck. The doors of the tipping halls are kept closed to prevent odour from spreading and they open automatically when waste truck approaches. Primary air for combustion in the grate is taken from the tipping hall. (Mokomaki 2019)

2. Waste bunker: The Waste bunker is 14 meters deep, which can accommodate approximately 3,400 – 4,800tonnes of waste. The bunker can store a maximum amount of three weeks supply of waste. The bunker has a crusher, which is used to crush large objects like furniture and other large items. There is an automatic grab in the bunker which mix the waste to maintain homogeneity. (Mokomaki 2019)

3. Grate: The grate is $80m^2$ in dimension with a feed chute section, waste drying section, pyrolysis, gasification and incineration sections. The waste is moved from section to section by a ram feeder which is hydraulically operated. Hitachi Zosen Inova AG is the company that supplied the grate, bottom slag outlet systems and auxiliary equipment. (Mokomaki 2019)

4. Boiler: The boiler is the area where heat exchange take place between the flue gases and the boiler water. The boiler walls contain piping enclosed Inconel coating. In the first stage the water is preheated, and in the next stage the water is heated to steam and in the horizontal pass it is super-heated to 400degrees which is then directed to the turbine. (Mokomaki 2019)

5. Flue gas treatment: The flue gas treatment section consists of a cooling tower, a LAB-loop reactor where chemicals are added to adhere the impurities of the flue gases and 1500 fabric filter bags which filters the active carbon-lime dust and adhered impurities. The fabric filter is made of Teflon textile with a diameter of 13cm and 6m in length. LAB is a French company that supplies the flue gas treatment system. (Mokomaki 2019)

6. Stack: The stack is 75 meters high, and it is here the purified flue gases exit the plant. The flue gases exiting the plant is monitored and analysed continuously to ensure no harmful substance is released into the atmosphere. (Mokomaki 2019)

7. Turbine and generator: The turbine receive approximately 70tonnes of steam with 40bar pressure per hour. The speed of the turbine rotation is about 9,000rpm, which is received by the generator via gear box. The kinetic energy of the generator is 1,500rpm, which generate a maximum output of 15MW by 10,5kV and 50Hz. MAN Turbo and Diesel SE is a German company that supplied the turbine and generator for the plant. (Mokomaki 2019)

8. District heating: The district heating consists of two condensers which is situated under the turbine hall. The district heating condensers has a nominal output of 40MW which transfers the thermal energy from hot steam to district heating water. The temperature of the district heating water depends on the time of the year and the weather, where it is heated from 40-80degrees or from 65-115degrees. After the steam has been utilized, it is condensed and feed back to the water tank and to the boiler to repeats the heating process again. (Mokomaki 2019)

9. Bottom slag: The bottom slag is located underneath the grate. Hot bottom slag drops to this area from the grate and is cooled with water. The bottom slag is automatically transferred onto a conveyor. The conveyor allocates the slag into containers which is changed automatically in a large container hall. The plant produces about 4,000kg of bottom slag every hour. (Mokomaki 2019)

10. Silos: The plant has four silos which is located at the end of the building. Two of the silos are 80m^3 in volume and temporarily store the APCr from the plant. One of the APCr silo stores the ash removed from the heat exchange surface of the boiler and the other APCr silo stores the flue gas treatment residue. The other two silos are larger than the APCr silos and they store the lime and active carbon. (Mokomaki 2019)

In 2017, 188,208tonnes of MSW was converted to 92.31GWh of electricity and 320.91GWh of district heating. The plant operated for 8312hr with 89.1% efficiency. About 1,603tonnes of waste was separated for recycling. The bottom slag was 29,579tonnes and 4,130tonnes of APCr. (Mokomaki 2019)

The **wasteWOIMA®** power plant is a modular medium scale power plant designed to have a lifespan of 30 year. The power plant module can utilize approximately 30,000 to 200,000 tonnes of waste annually, which can cover waste collected from 100,000 to 500,000 inhabitance. The electricity generated by the plant is enough for a city of 20,000 people. The energy the plant produce is in a form of 400ºC/40 bar of stream which can also be used by industrial processes. The plant has a low flue gas emission with a low water and self-power consumption. The plant uses non-toxic waste such as MSW, solid recovered fuel (SRF), refuse derived fuel (RDF), industrial, commercial, institutional, construction, demolition, agricultural, different biomasses and landfill gas co-incineration. (WOIMA Presentation 2018)

Figure 4. WasteWOIMA® plant units (WOIMA Presentation 2018)

The plant modular structure is scalable for mobility and flexibility in terms of power configuration. The design of the plant units is based on 20ft / 40ft container to help with easy transportation of component, secure enclosures, provide protective housing on site, easy to replace parts or perform maintenance, easy installation and relocation of unit. Figure 4 shows an example of the WasteWOIMA® power plant installation units. (WOIMA Presentation 2018; WOIMA wasteWOIMA® 2018)

The wasteWOIMA® power plant module is based on powerlines or WOIMAlines. The plant comprises of one to four WOIMAlines. Each WOIMAline can use waste from approximately 200,000 inhabitants to produce 15MW at approximately 2.500kWe to 2.700kWe net with 10MW thermal energy or 17t/h of stream. Figure 5 demonstrates a common wasteWOIMA® power plant system, which is established on a concrete slab of approximately 1,500 to 5,000m^2. It consists of WOIMAline, chemical feed, condensers, water and steam treatment, steam turbine, operation and control, automation and electrification, DeNOx control, staff facilities, diesel and diesel generator. (WOIMA Presentation 2018; wasteWOIMA® 2018)

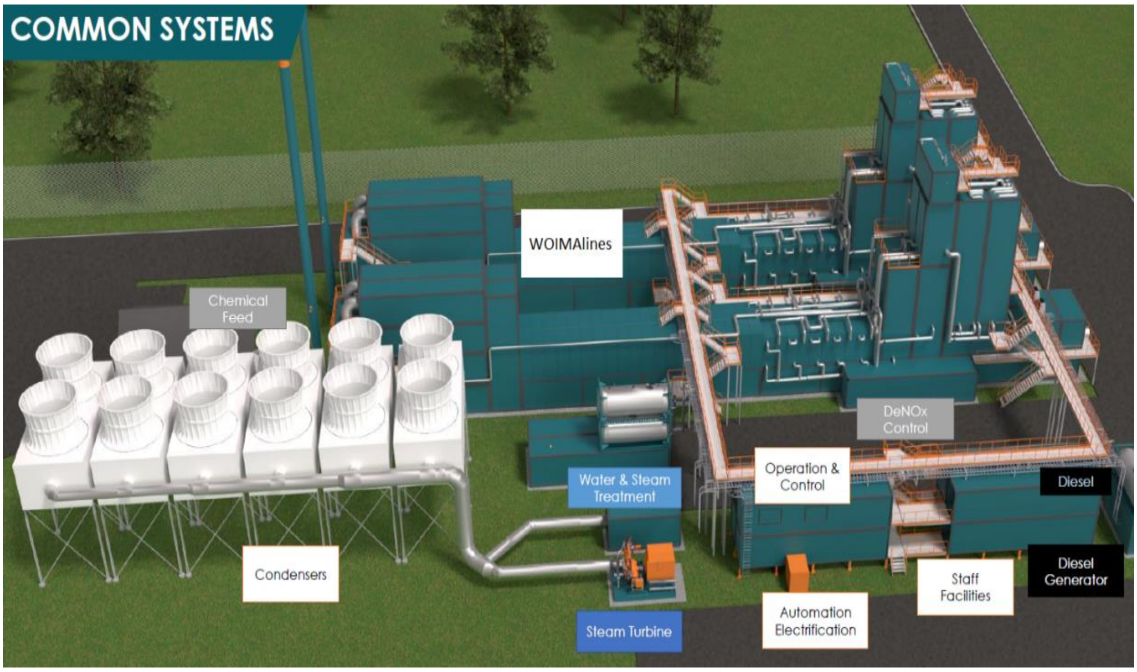


Figure 5. WasteWOIMA® power plant arrangement (WOIMA Presentation 2018)

The steam turbine receives saturated and superheated steam about 400^{o}C at 40 bars. The steam turbine consists of a generator. The pressure of the steam rotates the generator to produce electricity. Depending on the customer's requirements, WOIMA Finland Oy normally uses a standard back-pressure extraction turbine. The used steam goes to the condensers, where the condensing system turns the steam vapor back to water. The auxiliary diesel generator set is used during the start-up and shut-down of the plant for operating the conveyor belts and air blowers. It can also power local operation units to reduce dependence on outside power during maintenance period. In the WOIMAline the incineration process of the waste take place. The waste enters the plant through the fuel feed passageway. Figure 6 shows the WasteWOIMA® incineration process. (WOIMA webpage 2018)

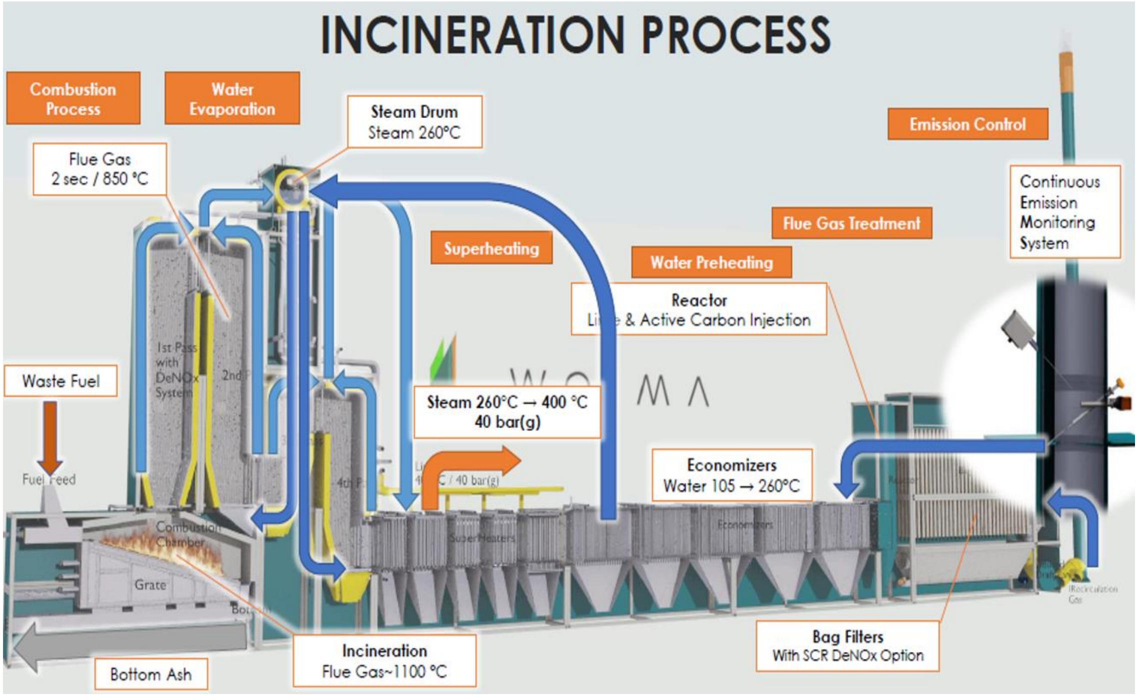


Figure 6. WasteWOIMA® incineration process (WOIMA Presentation 2018)

1. Grate: The waste used for fuelling the plant starts the combustion process at the grate. The waste fuel is chute onto a step grate furnace, where it is dried and incinerated with primary air fed through the grate. The incineration capacity varies from 5-7t/hr depending on the composition of the waste. The burnt waste or bottom ash is moved to the end of the gate automatically and falls off onto an ash hopper where excess water is removed. The bottom ash is sent for landfilling or utilization centres where it can be used for construction or cement production. The combusted waste form into gasifier fractions that goes to the second pass. (WOIMA webpage 2018)

2. Second furnace: The second furnace is located at the second pass. Here the gasifier fraction of the burning waste is also burn with assistance from a secondary and

tertiary air supply. The flue gas time in this chamber is 2sec at 850^{o}C to ensure a full burnout of the highly toxic element such as furans and dioxins. EU standard residence is guaranteed by the lengthy channel of the passage way. Ammonia is also added to help lower the NO_x emission. (WOIMA webpage 2018)

3. Heat radiator and cooling: The heat from the flue gases is absorbed by water and steam in pipes located in the membrane walls of the first, second, third and fourth pass. Mixed water and steam are circulated by gravity in the steam drum to return to the membrane walls. The radiation station cools down the flue gas temperature to protect the boiler from temperature corrosion. (WOIMA webpage 2018)

4. Heat recovery: The heat recovery system consists of the air preheater, economizer superheater and evaporator. These are series of piping arrays, design to collect the heat remaining in the flue gas through convection. The air preheater is responsible for heating the primary, secondary and tertiary air for the incineration. The economizer is responsible for preheating the water flowing into the steam drum from the water tank. The superheater and evaporator superheats saturated steam for the steam turbines. The fly ash that accumulate on the wall and pipe surface is removed by a soot cleaning process. (WOIMA webpage 2018)

5. Air pollution control (APC): The APC or the final flue gas treatment (FGT) occurs in the reactor, before the flue gases goes through the bag filters and exit the plant. The plant uses dry APC-system, where hydrated lime Ca $(OH)_2$ is added to react with the acidic contain and activated carbon traps dioxins/furans and heavy metal. The reacted acidic and heavy metals along with other small particles are trapped in fabric filters. The clean flue gases are then led by draft fan to exit the plant through the stack. The fly ash and bottom ash collected from the process is about 15% and the APCr is about 3%. The bottom and fly ash are safe enough to be used for construction purposes but the APCr have heavy metals and other toxic residues, so it should be placed in landfill or processed further. (WOIMA webpage)

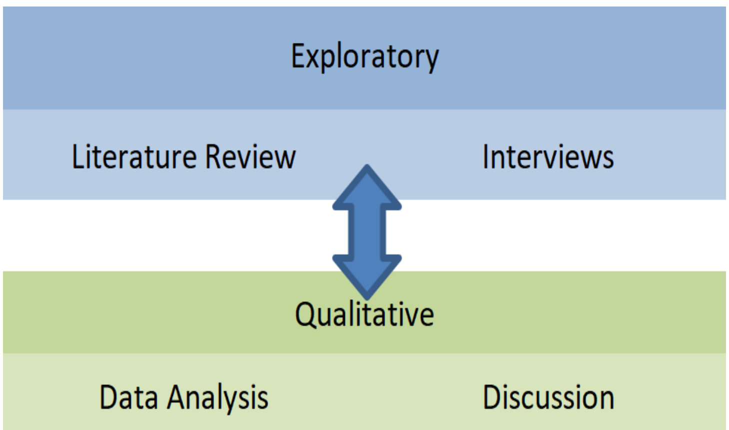
3. METHODOLOGY

This chapter describes the research, data collection, dataset and analysis methods used for the thesis. The data collection method and research process explained in this chapter was very important for realizing the research objective. The information gathered for this thesis used several data collection methods and research approach.

3.1. Research method

The study began as a desktop research with guidance from Tapani Korhonen and Jussi Kantola. The research then progressed into interviews before finally developing into data analysis, discussions and concluded with some recommendations. Table 4 shows the research approach employed by the thesis work. The main research approach selected for this thesis is exploratory and qualitative, because the thesis aims to examine all the factors that influences APCr from WtE plant before finding a solution for managing the APCr on and off wasteWOIMA® power plant site. Westenergy was the field study company for the thesis since WOIMA is waiting to implement their plant. Case study companies for solving the research question were Carbon8 Aggregate and Tetronics International.

Table 4. Research Approach



The main element of the research requires an investigation to identify the processes and challenges involved in the management of waste when using WtE combustion facility. The research required profound inquiries on the complications that faces the management of APCr both on and off the WtE plant site. A qualitative method was also selected to help collect reputable APCr management articles to help transcript interview questions and analyse data for the thesis. The qualitative method helped to find barriers and identifying solutions for managing the APCr.

3.2. Data collection methods

The information gathered came from many different sources and case studies. Several types of techniques were used for collecting primary and secondary data. The data collection methods were document reviews, interviews and questionnaires.

The document reviews involved the examination of online articles, reports, newsletters, broachers, blogs and available information accessible on the internet. This method was an inexpensive technique for information gathering but some data source was unreliable or incomplete. Qualitative research approach was used to select good source of data for providing precise information for specific topics.

Interviews were conducted in person with WOIMA and Westenergy separately during the company visits. One interview was made through online skype calls with both WOIMA and Carbon8 together. The interviews were engaged in a semi-formal and formal setup. The questions were focused on unrestricted details required for solving the thesis question and the responds recorded was agreed on by the companies as an accurate deduction.

The questionnaire organized for the companies help with understanding their processes. Four questionnaires were organized for four different companies. Westenergy and WOIMA questionnaires were submitted to the companies during the interview which was filled together with the companies. Carbon8 questionnaire was filled during the online skype call with the company representative. Tetronics questionnaire was forwards by email to the company to fill without any interview or call.

3.3. Dataset and analysis methods

This thesis is a theoretical research which means the information collected for the thesis was not directed towards numerical data, however there was several theories gathered and analysed. Other information was collected from interviews to assist with finding a solution for the research questions. The data type used for the thesis is mostly in a contextual format.

The information was analysed base on WOIMA requirement and limitation on what the solution for managing the APCr should conform to. Figure 7 below, shows how the contextual analysis was conducted. The analysis started with understanding WOIMA demands on the APCr managing solution. The solution required the research to undergo a study into WOIMA plant and accessible WtE facility which lead the researcher to Westenergy. The research began engaging EU laws and regulation on by-product recycling and disposal with WOIMA requirement. The research identified available theories for managing APCr.

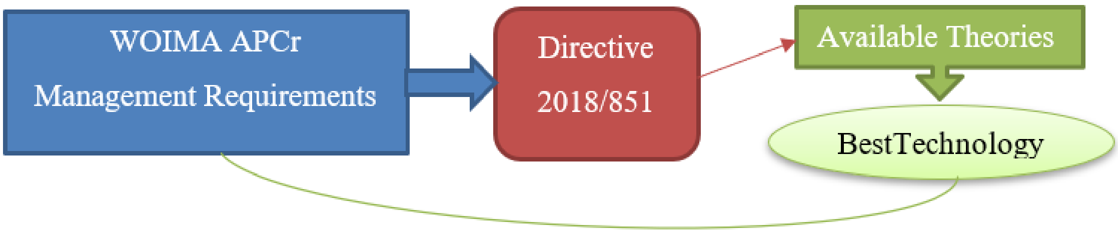


Figure 7. Contextual analysis

The concept selection from product design and development by Karl T. Ulrich and Steven D. Eppinger was used to select the best available theories for managing APCr. The research identified two popular existing technologies that corresponds to the first and second ranking of available theory for managing APCr.

Solutions for the research question was validated by comparing the pros and cons of the selected technology. Other recommendations where made based on the findings and data analysed.

4. INVESTIGATIONS

Jerry A. Nathanson define air to be polluted if it contains harmful substances with high concentration that cause undesirable effect to human health, property or atmospheric visibility. Human activities such as industrial operations and transportation contribute to air pollution. (Jerry A. Nathanson 2010)

The European Union Commission Implementing Decision 2018/1522 “Having regard to Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC”. The focus of the Directive 2016/2284 was to reduce and eliminate air pollution emission of industries by getting them to use cleaner fuels and processes. These industries were also allowed to trap and collect the atmospheric pollutants such as carbon monoxide, sulphur dioxide, nitrogen dioxide, lead, etc in their flue gas by applying air-cleaning techniques in the plant.

Air pollution control (APC) according to Jerry Nathanson is the systems used by industrial plant in eliminating or reducing the air pollution emissions into the atmosphere. The industrial air pollution control systems focus mainly on trapping specific criteria that contributes to urban fog and chronic public health problems. (Jerry A. Nathanson 2010)

The industrial air pollution control criteria are directed towards pollutants such as carbon monoxide, sulphur dioxide, nitrogen dioxide, ozone, lead and others. (Jerry A. Nathanson 2010)

There are several factors that affect the composition and chemical structure of the APCr produced by WtE or EfW combustion plant. The main factors that affect the APCr includes the type of waste used as fuel in the plant, the type of treatment the flue gas under goes and the type of air pollution control technique used to trap the harmful composition of the gas. (Jerry A. Nathanson 2010)

4.1. Waste composition on WtE incineration

There are many different materials that end-up as waste. The waste material generally consists of organic substances, minerals, metals and water. Some of these wastes are separated for WtE incineration plant. The APCr composition generated by these WtE incineration plant are directly linked to the waste materials that were used in the plant. The parameters of waste that affect the APCr is also an aspect that influences the design of a waste incinerator plant. Some of these parameters include waste chemical composition, waste physical composition and waste thermal characteristics. Waste that are separately collected can be managed by a specific method. The incineration processes deigned for waste containing similar materials can be optimised more effectively than for waste with greater variability. This optimisation is as a result of process stability and simplification, which can also reduce overall capital investment cost of the incineration plant by approximately 15 to 35%. The types of waste used in an incineration plant are MSW, pre-treated MSW, non-hazardous industrial waste, hazardous waste, sewage sludges and clinical waste. (GC/FN/JG/EIPPCB/WI 2017: 1, 9, 10)

Table 5. Impact of waste fraction removal (GC/FN/JG/EIPPCB/WI 2017)

Fraction removed	Main impacts on remaining waste
Glass and metals	Increase in calorific value
	Decrease in quantity of recoverable metals in slag
Paper, card and plastic	Decrease in calorific value
	Possible reduction in chlorine load if PVC is common
Organic wastes	Reduction in moisture load
	Increase in net calorific value
Bulky waste	Reduced need for removal/shredding of such waste
Hazardous waste	Reduction in hazardous metal loading
	Reduction in substances like CI, Br, Hg and others

Table 5 above, shows the impact the selected waste has on the incinerator and residue if it is pre-treated or removed. The constant variation in waste fed to the incinerator plant causes major and rapid changes to the ignition behaviour and the furnace temperature. The flue gas impurities recorded by Westenergy in 2017 consist of organic carbon, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), hydrochloric acid (HCl), ammonia (NH_3), hydrogen fluoride (HF), mercury (Hg), cadmium (Cd), thallium (TI), dioxins, furans and heavy metals such as antimony, arsenic, lead, chromium, cobalt, copper, manganese, nickel and vanadium. The composition of waste recorded in Germany consisted of a calorific value, water, ash, carbon, hydrogen, nitrogen, oxygen, sulphur, fluorine, chlorine, bromine, iodine, lead, cadmium, copper, zinc, mercury, thallium, manganese, vanadium, nickel, cobalt, arsenic, chrome, selenium, polychlorinated biphenyl (PCB) and Polychlorinated dibenzodioxins (PCDD/F). (GC/FN/JG/EIPPCB/WI 2017: 10; Bernd 2008: 10)

Table 6. Chloride composition in MSW (Adopted from Adam Penque 2007)

	% of component in MSW	Chlorine concentration in component, g/kg	Chlorine in MSW, g/kg
Paper	29.4	2	0.59
Plastics	10.4	25	2.60
Organics	34.7	3	1.04
Textiles	4.4	12.5	0.55
Wood	2.7	12.5	0.34
Miss. Combustible	5	12.5	0.63
Glass	4	0.6	0.02
Metals	4.7	0.6	0.03
Miss. Non-Combustible	4.7	0.6	0.03
Total	100		0.58 (5.82 %)

Table 6 above, shows the amount of chlorine content in MSW. Some chlorine residue used during the paper bleaching process remains even after it has been washed. Similarly, chlorine residues remain in textiles and wood after the bleach and dying process. Plastic, also known as PVC or polymer chloroethene (CH_2=CHCl) contains 56.7% chlorine relative to its weight. Organic material primarily the salt contains (NaCl) found in MSW also contains chlorine. Dioxins, polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are combustible materials that add a significant amount of chlorine in the MSW. (Adam Penque 2007: 6, 8)

4.2. Flue gas treatment (FGT) processes

David Hosansky defines flue gas treatment (FGT) as the procedure developed to reduce the pollutants emitted from the burning of fossil fuels at a power plant, industrial facility or other sources. Flue gas contain chemical elements such as nitrogen oxides, sulphur dioxide, mercury, carbon dioxide and others. FGT vary widely different facility because of the differences in processes and substances used for cleaning the gas. The chemical composition of the flue gas is treated by altering and trapping the toxic chemical element in the gas. The treatment of flue gas began in the 19th century due to the grew concern over the impact of sulphates on the environment. (David Hosansky 2014)

The treatment of flue gas usually involves the use of neutralizing reagent to react with the toxic substance in the flue gas to produce a solid compound. There are several FGT procedures, however a well-designed alkaline sorbent is more than 90% effective at neutralising and absorbing harmful matter from the flue gas. Some advantage is that the residue can be reused, the reagents are inexpensive and available. Hazardous waste incinerator uses post combustion chamber to completely oxidize some harmful gases like CO, chloride and other compounds. (May021994 2015; Jacquinot Bernard 2000: 13)

1. Rotary kilns are for incinerating hazardous waste ranging from 500^{o}C to 1,450^{o}C. Dioxins, furans and other toxic organic compounds can be destroyed by temperature of approximately 1,400^{o}C. This process reduces the waste volume by 60% or more and help the residue resistant to leaching. Melted slag can be reused as a resource. (GC/FN/JG/EIPPCB/WI 2017: 47; Charles H 2010: 1951)

2. The nitrogen oxides are neutralized with ammonia (NH_3) or urea (NH_2CONH_2) and oxygen as shown in the chemical reaction below. The aim is to produce nitrogen gas (N_2) instead of nitrogen oxides (NO_x). (David Hosansky 2014; WOIMA 2018: 10; Bernd 2008: 3)
   $4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$ (WOIMA 2018: 11)
   $2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$ (WOIMA 2018: 11)
   $NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$ (WOIMA 2018: 11)

$2NO + NH_2CONH_2 + {}_{1/2}O_2 \rightarrow 2N_2 + CO_2 + 2H_2O$ (Bernd 2008: 4)

The optimum temperature for neutralizing NO_x is 900 ^oC to 1,100^oC. Above this temperature ammonia is oxidised forming nitrogen oxides. Below this temperature the reaction rate is slowed down forming ammonia salts as shown in figure 8. Optimal temperature for SNCR is indicated with “A” and the optimal temperature for both SNCR and SCR is indicated with “B”. (Bernd 2008: 4)

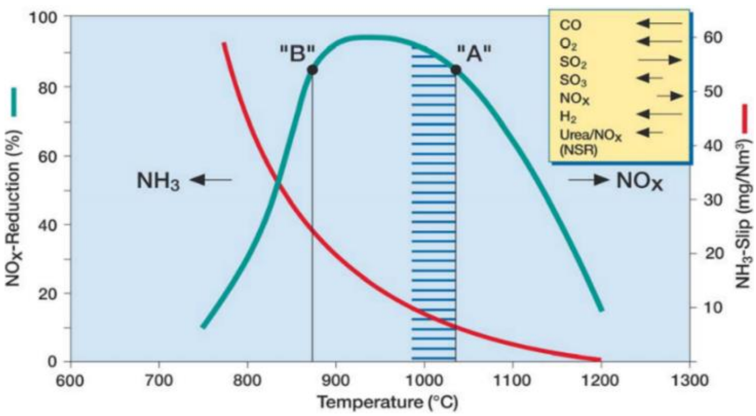


Figure 8. Temperature effect on flue gas and ammonia (Bernd 2008)

If ammonia or urea is injected into the flue gas within a water solution the droplets size is very important. As shown in figure 9, urea solution breaks down into NH_2 after the water evaporate whiles ammonia solution forms NH_3. (Bernd 2008: 6)

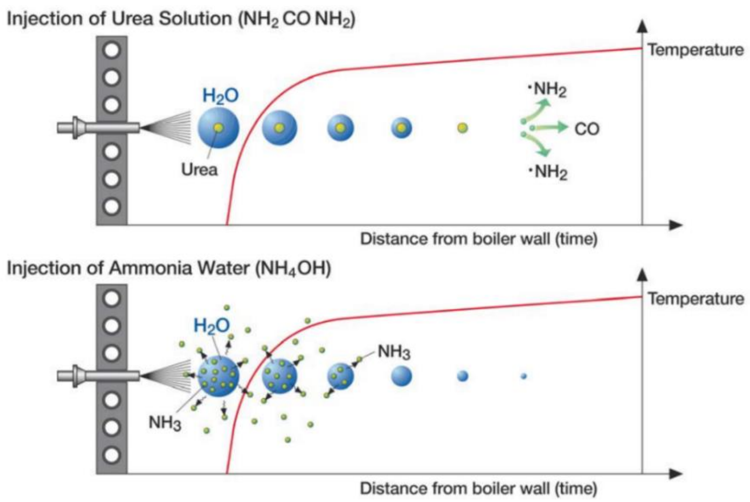


Figure 9. Injected reaction of urea and ammonia solution (Bernd 2008)

Small droplets will evaporate fast causing a reaction at a high temperature leading to more NO_x to be formed. Large droplets will evaporate slowly causing a reaction outside the temperature window leading to an ammonia slip and decrease in NO_x reduction. Urea solution may require different droplet to ammonia due to the chemical bonding of ammonia in urea molecule.

3. The sulphur dioxide content can be neutralized by ammonia and oxygen or water.
   $2SO_2 + O_2 \rightarrow 2SO_3$ (forms sulphur trioxide) (WOIMA 2018: 11)
   $2NH_3 + SO_3 + H_2O \rightarrow (NH_4)2SO_4$ (WOIMA 2018: 11)
   $NH_3 + SO_3 + H_2O \rightarrow NH_4HSO_4$ (WOIMA 2018)
   Seawater is also a technique for neutralizing sulphur. (David Hosansky 2014)

The process of adding ammonia or urea can be design as either a selective catalytic reduction (SCR) or as selective non-catalytic reduction (SNCR). In the SNCR the ammonia or urea is introduced to the flue gas in the combustion area as shown in figure 10. (Siemens 2013: 2; Bernd 2008)

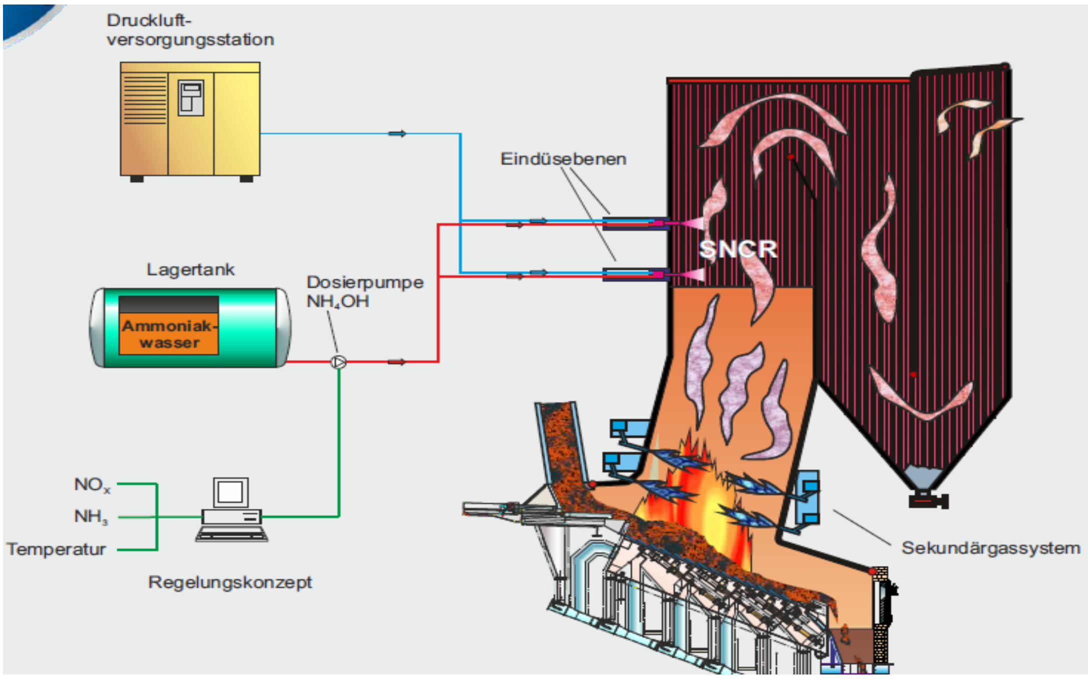


Figure 10. SNCR (Martin SNCR system)

In the SCR the ammonia or urea is introduced to the flue gas upstream as shown in figure 11. The SCR plant has a NOx clean gas efficiency of 20 mg/Nm³ to 80 mg/Nm³ and SNCR is about 150 mg/Nm³ to 180 mg/Nm³, however the SCR design cost five times as such as SNCR. SCR has a high possibility of (Siemens 2013: 2; Vlaanderen 2015)

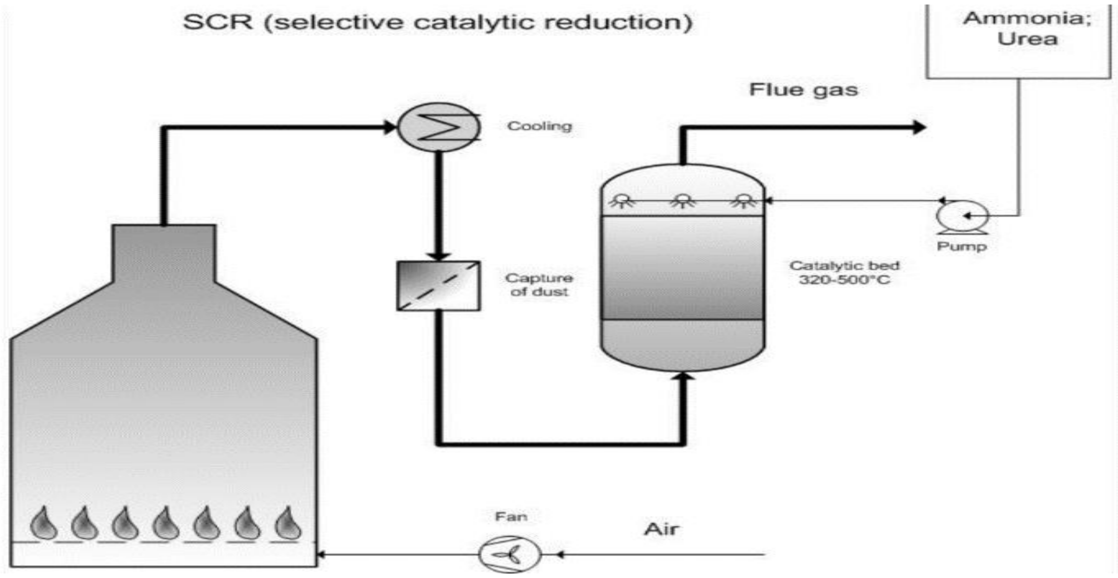


Figure 11. SCR (Vlaanderen 2015)

4. The sulphur dioxide is also neutralized with lime such as calcium hydroxide (CA(OH)$_2$), calcium oxide (CaO), calcium carbonate ($CaCO_3$), sodium bicarbonate ($NaHCO_3$) and sodium hydroxide (NaOH). The chemical formula are;
   $SO_2 + Ca(OH)_2 \rightarrow CaSO_3 + H_2O$ (WOIMA 2018: 11)
   $2CaSO_3 + O_2 \rightarrow 2CaSO_4$ (J. Vehlow 2007: 18)
   $SO_2 + Ca(OH)_2 + 1/2O_2 + H_2O \rightarrow CaSO_4 + 2H_2O$ (Bernard 2000: 54)
   $2SO_2 + 2Ca(OH)_2 + O_2 \rightarrow 2CaSO_4 + 2H_2O$ (J. Vehlow 2007: 18)
   $2SO_2 + 2CaO + O_2 \rightarrow 2CaSO_4$ (J. Vehlow 2007: 18)
   $2SO_2 + 2CaCO_3 + O_2 \rightarrow 2CaSO_4 + 2CO_2$ (J. Vehlow 2007: 18)
   $2SO_2 + 4NaHCO_3 + O_2 \rightarrow 2Na_2SO_4 + 4CO_2 + 2H_2O$ (J. Vehlow 2007: 18)
   $SO_2 + 2NaOH + 1/2O_2 \rightarrow Na_2SO_4 + H_2O$ (Bernard 2000: 55)
   $SO_3 + 2NaHCO_3 \rightarrow Na_2SO_4 + 2CO_2 + H_2O$ (Bernard 2000: 54)
   $SO_3 + 2NaOH \rightarrow Na_2SO_4 + H_2O$ (Bernard 2000: 55)
   $SO_3 + Ca(OH)_2 \rightarrow CaSO_4 + H_2O$ (forms Gypsum + Water) (WOIMA 2018: 11)

These procedures of using lime can be designed as a dry process, semi-dry process, wet process or semi-wet process.

The dry process uses solid or hydrated lime as neutralizing agent since lime has high surface area and porosity. Some examples are calcium hydroxide ($Ca(OH)_2$), calcium oxide (CaO), calcium carbonate ($CaCO_3$) and sodium bi-carbonate ($NaHCO_3$). The dry process can be seen in figure 12. (Bernard 2000: 15-16)

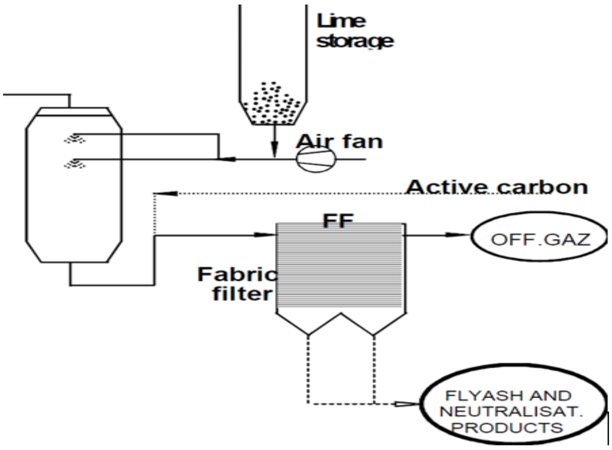


Figure 12. Dry process (Bernard 2000)

The semi dry process uses dry lime powder combined with water spray to trap and react with the flue gas, producing a dry residue. The semi-dry process can be seen in figure 13. (Bernard 2000: 16)

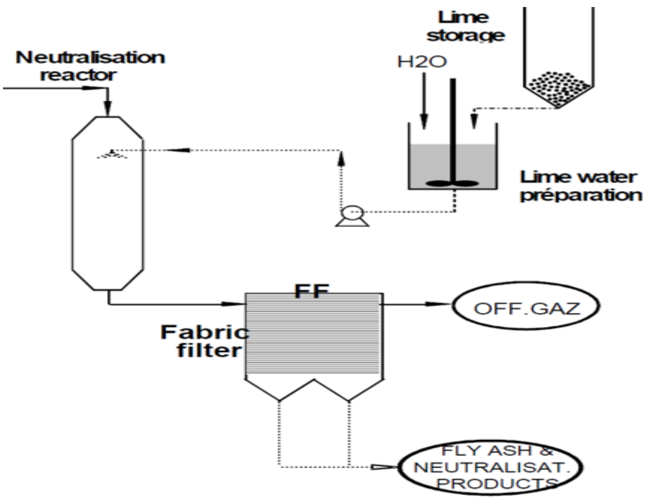


Figure 13. Semi-dry process (Bernard 2000)

The Wet process uses lime and NaOH solution as neutralization agents in gas / liquid reactor to trap flue gas which forms into liquid residue. The wet process is illustrated in figure 14. The disadvantages are its high capital, operation and maintenance cost. A water waste is produced with the wet system, which may result in visible trail. Should not be used on flue gas with SO_4 concentrations more than 2,000ppm. (Bernard 2000: 15-16; May021994 2015)

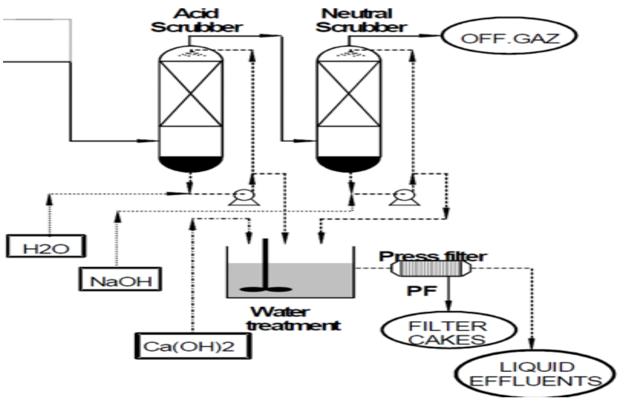


Figure 14. Wet process (Bernard 2000)

The semi-wet process seen in figure 15 uses salt spray and electrostatic precipitator in flue gas treatment. (Bernard 2000: 16)

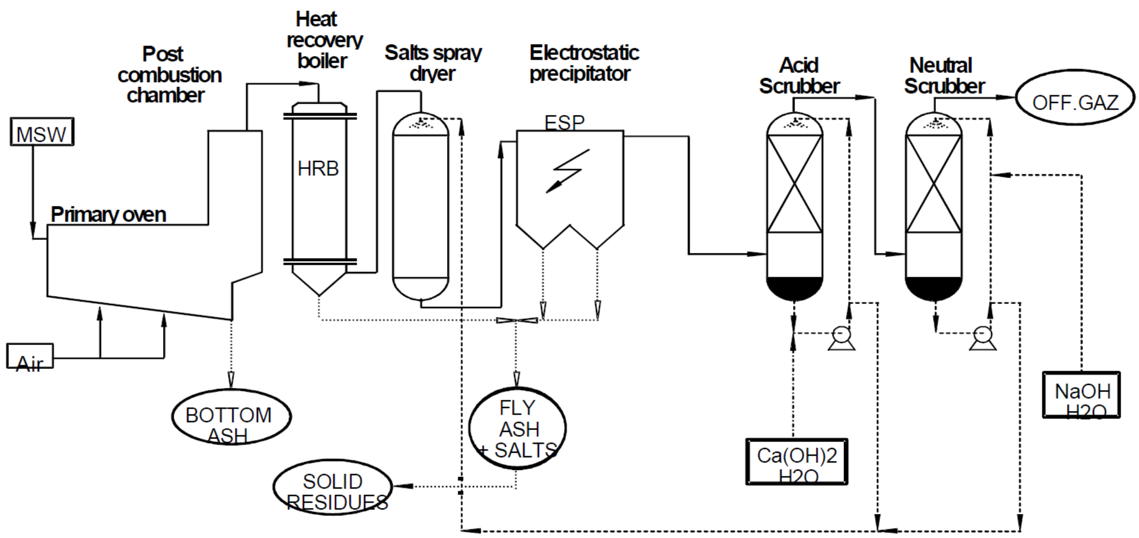


Figure 15. Semi-wet process (Bernard 2000)

The semi wet process uses lime and water solution as neutralization agents to react with flue gas which forms into solid residue. (Bernard 2000: 16)

5. Hydrogen fluoride, hydrochloric acid, carbon dioxide and calcium chloride can also be neutralised with lime as shown in the chemical formula below.
   $2HF + Ca(OH)_2 \rightarrow CaF_2 + 2H_2O$ (WOIMA 2018: 12)
   $CO_2+Ca(OH)_2 \rightarrow CaCO_3+H_2O$ (WOIMA 2018: 12)
   $2HCl + CaCO_3 \rightarrow CaCl_2 + H_2O + CO_2$ (J. Vehlow 2007: 18)
   $Ca(OH)_2 + CaCl_2 \leftrightarrow 2Ca\ (OH)Cl$ (WOIMA 2018: 12)
   $2HCl + Ca(OH)_2 \rightarrow CaCl_2 + 2H_2O$ (WOIMA 2018: 12)
   $HCl + Ca(OH)_2 \rightarrow CaOHCl + H_2O$ (Bernard 2000: 52)
   $HCl + CaOHCl \rightarrow CaCl_2 + H_2O$ (Bernard 2000: 52)
   $2HCl + CaCO \rightarrow CaCl_2 + H_2O$ (J. Vehlow 2007: 18)
   $HCl + NaHCO_3 \rightarrow NaCl + CO_2 + H_2O$ (Bernard 2000: 52)
   $2NaHCO_3 \rightarrow Na_2CO_3 + CO_2 + H_2O$ (Bernard 2000: 52)

6. Mercury and other substances can be removed by a combination of scrubbers and fabric filters with as much as 90% efficiency, however these systems are designed to remove other pollutants. Chloride, salts, alkali and heavy metals can be leached with liquid solution like water, acid scrubber etc. (David Hosansky 2014; Charles H 2010: 1949)

7. Stabilization/Solidification (S/S) process uses additive or binders to physically and chemically trap the hazardous content in the waste. Binders like cement are used to trap and reduce leaching. However, soluble salts and long-term leaching can result in environmental problems. Four stages have been developed for S/S to destroy toxic organic substances, reduce heavy metal reactivity and solidify without long term leaching. This stage is dissolution of chlorides, addition of phosphoric acid, calcination and solidification. (Charles H 2010: 1951)

8. A study done in Denmark used soda or carbon dioxide to bring the leachate quality close to the limited values of the leaching criteria. (Kim 2006: 39)

4.3. Air pollution control (APC) systems

Air pollution control (APC) technology is defined by Jerry Nathanson as the device used to reduce or eliminate air pollutants by trapping and collecting the air pollution elements in the dirty gas. There are two main techniques used by air pollution control technologies for trapping, gathering and neutralizing air pollutant elements in the plant. These two main techniques are particulates control and gases control. (Jerry A. Nathanson 2010)

The **particulates control** uses devices like cyclones, scrubbers, electrostatic precipitators and baghouse filters to trap and collect airborne particles in the flue gas. The procedure used in selecting a device for particulate control is influenced by the particle density, shape, size, pressure, temperature, viscosity, removal efficiency requirements, flow rate and allowable resistance to airflow. (Jerry A. Nathanson 2010)

1. Cyclone: These techniques are used to collect industrial dust emissions and as pre-cleaners for other collectors. Dirty air enters the chamber, at a tangential direction to the outer wall, forming a vortex as it spins in the chamber. The inertia causes large particulates to move against the chamber walls. The friction on the wall, causes the particle to slide down into a conical dust hopper at the bottom, whiles the clean air spins away. As shown in figure 16, the gas enters the device from a tangential direction to the walls and the clean air exit the chamber through the clean air outlet. (Jerry A. Nathanson 2010)

Figure 16. Vertical cyclone technique (Adopted from Jerry A. Nathanson 2010)

2. Scrubber: The simple scrubber system sprays liquid to the dirty air, to capture the particulates in the air. There are many scrubber systems due to the differences in configuration. The wet scrubber spray system is the most common and simple scrubber system. The spray-tower scrubber washes an upward flow of airstream by spraying water downward a series of nozzles as shown in figure 17. It can remove 90% of particulates larger than 8um. (Jerry A. Nathanson 2010)

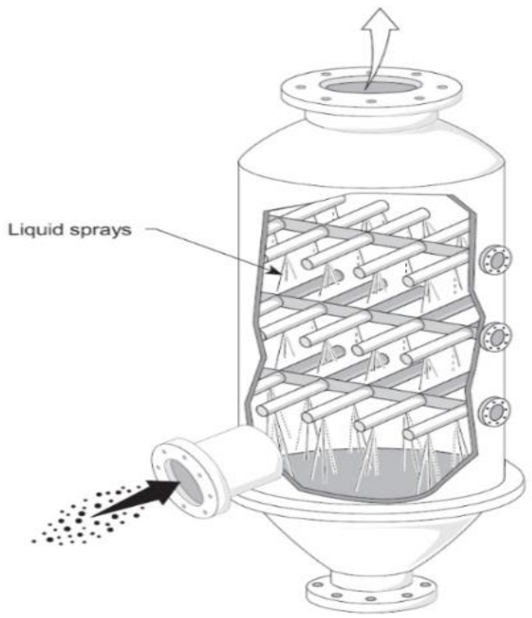


Figure 17. Spray-tower scrubber (BetacommandBot 2007)

Orifice scrubber and wet-impingement scrubbers use droplet mixture to collide with the air stream and solid surface. This method uses low water-recirculation rate and has 90% removal efficiency for particles larger than 2um. (Jerry A. Nathanson 2010)

Venturi scrubbers inject water into the throat of a venturi channel, the flow path of the particulate-laden air at a high speed. This scrubber technic has a 98% removal efficiency for particles larger than 0.5um. (Jerry A. Nathanson 2010)

There is a system that combines both the cyclone and scrubber technique which is known as cyclonic spray scrubber. As shown in Figure 18, the dirty airstream enters from the side of the cylinder. Liquid is spread from spray manifold located on the centre pole. The clean air exits upwards whiles the dirty water containing the particulates exits downwards. (GifTagger 2014)

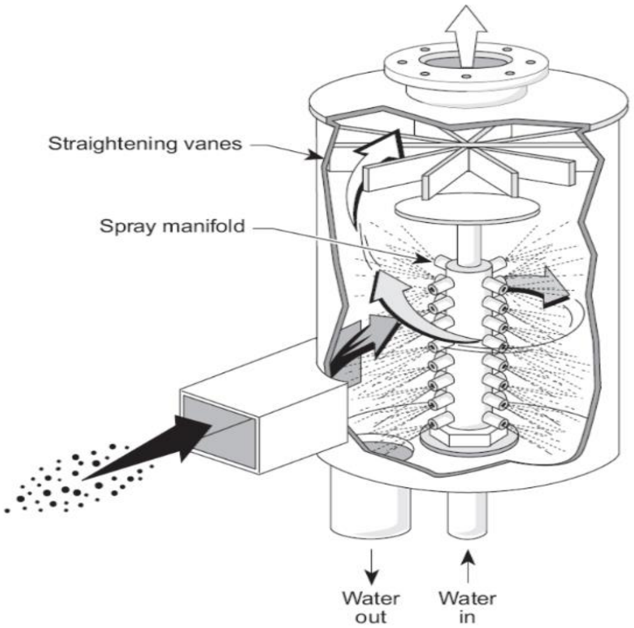


Figure 18. Cyclonic spray scrubber (GifTagger 2014)

3. Electrostatic precipitators: In this system, particles in the airstream are electrically charged as they enter the unit and are removed by electric field. The electrostatic precipitator system consists of baffles for airflow distribution, dust clean-out system, collection hoppers, discharge and collection electrodes. Electrostatic precipitators use direct current (DC) as high as 100,000volts in the discharge electrodes to charge the particles which is attracted to oppositely charged collection electrodes. A typical electrostatic precipitator unit consists of many large rectangular metal plates that are parallel to each other and suspended vertically inside a square structure as shown in figure 19. Rows of negative discharge electrode wires hang between the positively charged grounded collection plant. The trapped particles on the collection plates are removed periodically by shaken the plates or mechanically rapping the trapped particle from the plate. The mechanical rapping consists of impulse single blow or vibrating technique. The electrostatic precipitator is

99% effective for removing particulate as small as 1um. (Jerry A. Nathanson 2010)

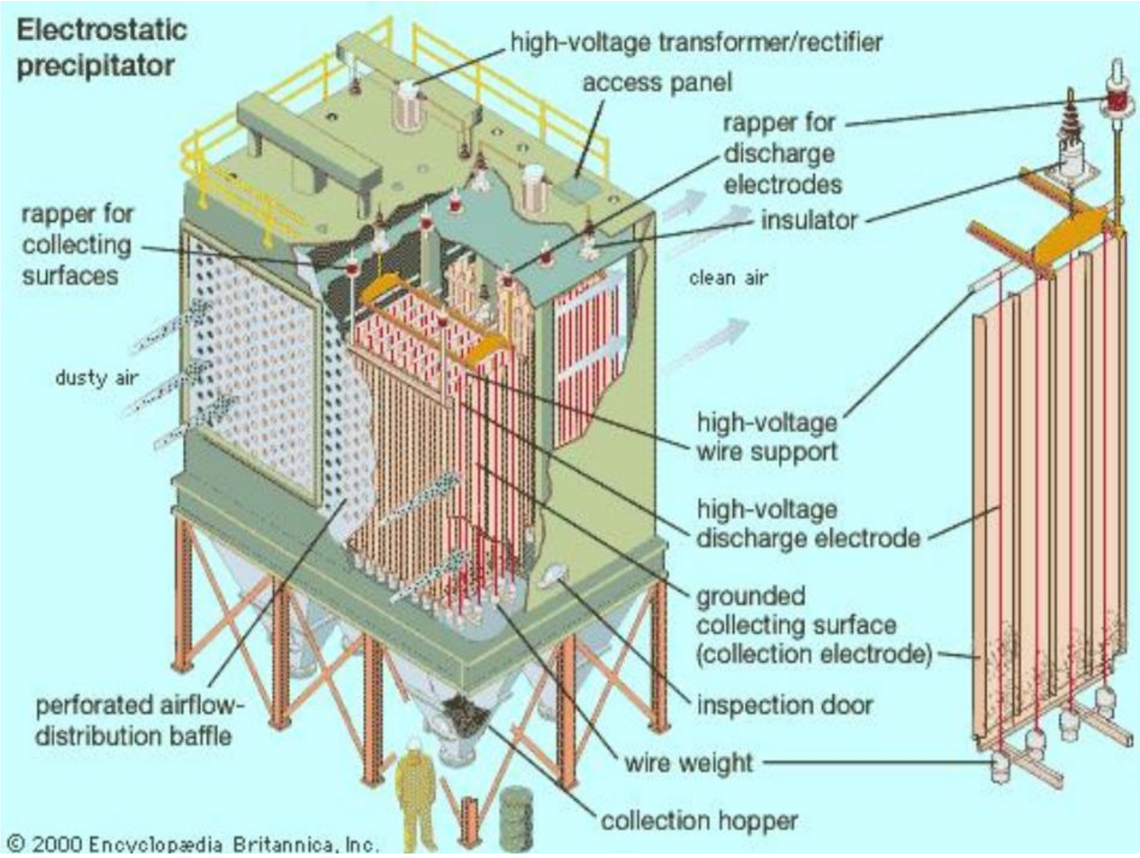


Figure 19. Electrostatic precipitator (Adopted from Jerry A. Nathanson 2010)

4. Baghouse filters: The baghouse system consists of upside-down suspended fabric-filter bags about 25cm in diameter enclosed in a box unit as shown in figure 20. The nature of the dust is very important when selecting the fabric filter. The dusty air aided by a fan is blown upward through the filter bag. The particulates within the dusty air are trapped inside the filter bag whiles the clean air exits through the clean air outlet. These system uses substantial amount of energy for the fan system due to the fabric filters high resistance to airflow. In addition, energy is used by the cooling coils for cooling the air to a temperature below 300^{o}C, before the air-stream passes through the unit, in order to prolong the useful life span of the filter fabric. For easy and efficient fabric filtering while the system remains in service, several compartments of filter bags are put in a single baghouse unit. The filter bags are cleaned by several different single or combination ways such as

mechanically shaking the filter bags, reversing the air flow temporarily or conveying a rapid burst of air down through the bag causing it to rapidly expansion. The cleaning process causes the particulates to fall into the collection hopper, which is collected and treated or disposed. The baghouse filter technique is 100% effective for removing particle as small as 1um and a significant fraction of particles as small as 0.01um. (Jerry A. Nathanson 2010)

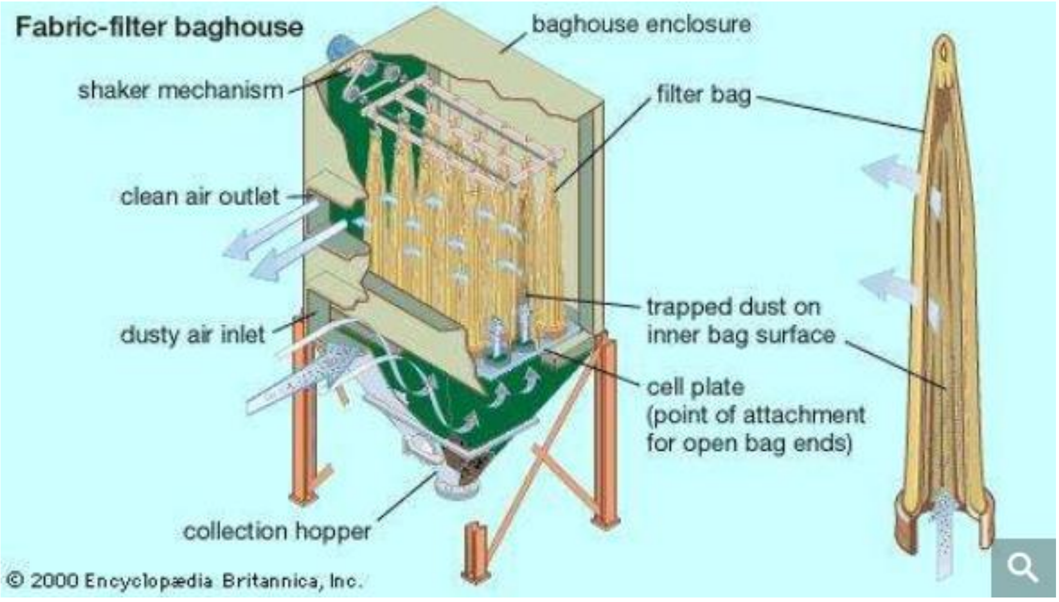


Figure 20. Baghouse filters (Adopted from Jerry A. Nathanson 2010)

The baghouse filter design is an old system used for trapping particulate, however the current system been used is the Jet-pulse bag filter or the pulse jet hose bag type filters. The jet bag filter type is used for large quantity airflow, with high temperature and materials difficult to handle. The pulse jet bag filter consists of a filtration element, a discharge valve to continuedly clean the bags and a hopper below the casing as shown in figure 21. There are several entry designs for the pulse jet hose bag type such as regular hopper entry, flush mounted insertable, flush mounted circular, casing entry, circular tangential entry, pre-separator extended hopper and pre-separator casing with baffle. There are mainly two types of jet pulse bag filter, they are the online pulse jet bag filter type and offline pulse jet bag filter type. (TECHFLOW 2019; Thermax Global 2018)

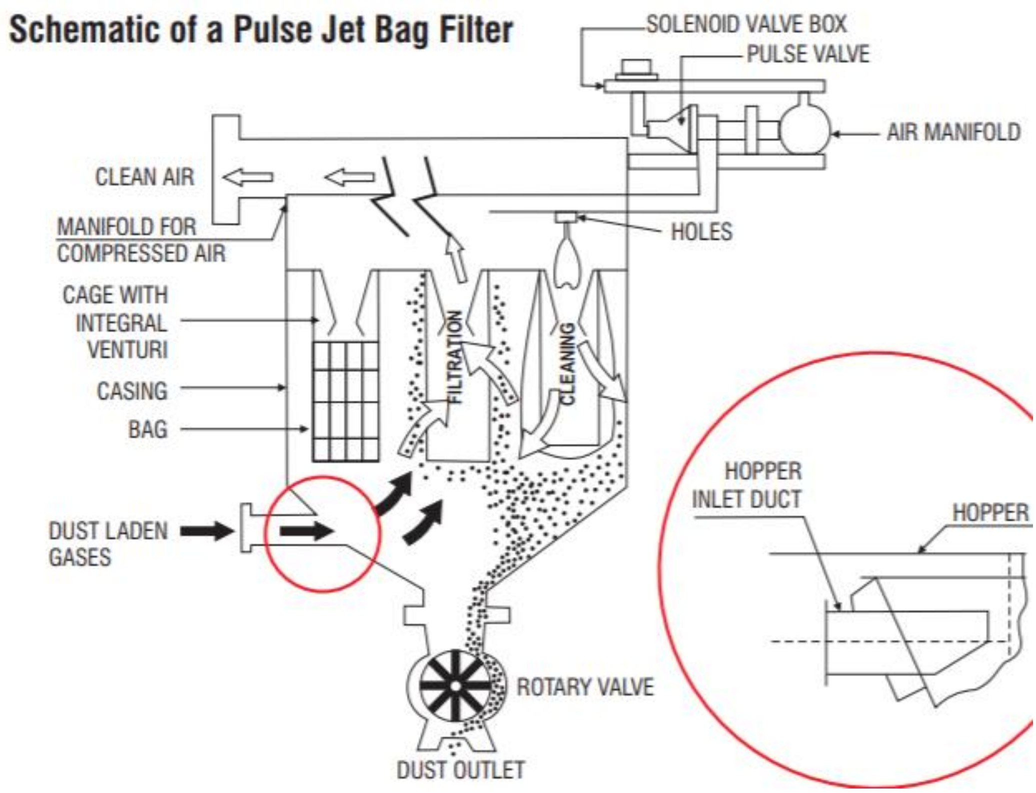


Figure 21. Pulse jet bag filter (Thermax Global)

The online pulse jet bag filters are controlled automatically by a sequence controller to clean the bags row by row when the dust loaded gas is filtered. Assembly of solenoid and pulse valves direct the airflow into the manifolds. (TECHFLOW 2019; Thermax Global 2018)

The offline pulse jet bag filter combines the advantages of a pulse jet bag filter and a reverse air baghouse. It has several isolated compartments with each one like an online pulse jet bag filter. Each isolated compartment is cleaned separately with compressed air. (TECHFLOW 2019; Thermax Global 2018)

The **gas control system** uses a single or combination of techniques such as absorption, adsorption, incineration and carbon sequestration to control criteria gaseous pollutants like volatile organic compounds (VOCs), toxic gases and greenhouse gases. (Jerry A. Nathanson 2010)

1. Absorption: In the absorption technique, gaseous pollutants are transferred from the airstream to liquid or unsolidified solvents by capture in chemical reactions. The absorption method uses scrubbers and flue gas desulphurization technique for it processes. (Jerry A. Nathanson 2010)

   There are several scrubbing systems and some of the applications have been explained in chapter 4.2.1 'particulate control system', however the absorption technique also uses wet scrubber system and packed scrubbers for absorbing gaseous pollutant in the airstream. The wet scrubber system use for gas absorption, works the same way as the wet scrubber system for particulate control. (Jerry A. Nathanson 2010)

   The packed scrubber method captures dirty gases when it meets the liquid absorber by using continues flowing liquid to wet a column surface instead of droplets suspended in the air. The differences in packed scrubber systems, mainly depend on the direction of the liquid absorber and the direction of the polluted gas. The most common application systems are the counter-current tower, co-current and cross-flow packed scrubber. (Jerry A. Nathanson 2010)

   In the counter-current tower design, the gas flows upward through a wet column whiles the liquid solvent moves uniformly downward throughout the unit's column. The counter-current tower method has 90-95% gas removal efficiency. (Jerry A. Nathanson 2010)

   In the co-current design, the gas flows vertically downward through the scrubber column, in the same direction as the liquid absorber. The co-current technique is not as efficient as the counter-current technique, but the co-current method prevents plugging of particulate due to the high flow rate of the liquid which makes the system very effective for absorbing gases with high levels particle and low air flowrate. (Jerry A. Nathanson 2010)

In the cross-flow design, the gas flows horizontally through scrubber pack whiles the liquid flows vertically downward. This method is effective for gases with high particulate level and low air flowrate. (Jerry A. Nathanson 2010)

The flue gas desulphurization (FGD) method is an absorption technique that targets the sulphur dioxide content in the flue gas. The FGD system can be categorised by regeneratable or non-regeneratable which depends whether the sulphur captured from the flue gas can be recovered or not. The FGD method is either wet or dry depending on the nature of chemical substance that is used in treating the polluted gas. The wet flue gas desulphurization (FGD) method uses liquid or fluid substance to absorb, react and dissolve the sulphur dioxide elements present in the flue gas. The absorption and reaction occur when the absorbent substance meets the gas by means of a wet scrubbing process as shown in figure 22.

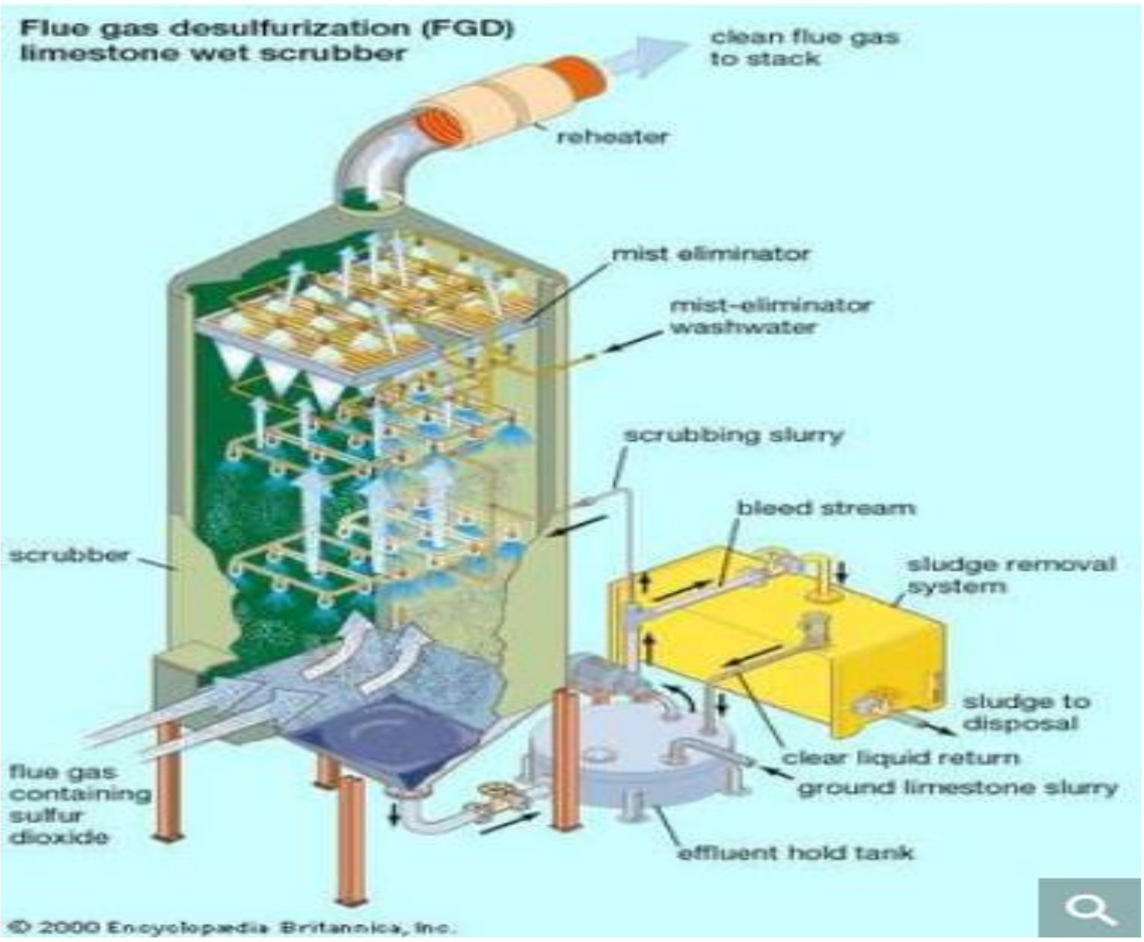


Figure 22. Flue gas desulfurization (Adopted from Jerry A. Nathanson 2010)

In the dry flue gas desulphurization (FGD) method, the process uses dry pulverized lime or limestone as the absorbent. The pulverized lime or limestone reacts with the sulphur elements in the flue gas to for solid particles which are trapped in baghouse filters for further treatment or disposal. The dry FGD system uses less energy, easier operations and it is cheaper than wet FGD system. The chemical reaction that occur in this system has been explained in chapter 4.1 'Flue gas treatment (FGT) process. (Jerry A. Nathanson 2010)

2. Adsorption: The adsorption system is a form of gas control technique that uses solid materials to attract and hold gas molecules on its surface. The adsorption method is used widely in various type of chemical-manufacturing and food-processing facilities to recover number of volatile solvents, adsorbing VOCs from airstream and odour control. The most commonly used adsorbent material is the activated carbon or activated charcoal or heated charcoal. The activated carbon is extremely pervious and has a high ratio of surface area to volume. They are made from wood, coconut shell, peat, coal, olive pits and other carbon materials through a high temperature steam. The carbon adsorption process can exceed 95% efficiency for removing pollutants in airstream if the design is properly crafted. (Jerry A. Nathanson 2010; Haycarb 2019)

   An adsorption process can either be configured as moving bed or stationary bed unity. In the moving bed unit, the polluted airstream moves horizontally across a slow vertically moving bed of activated carbon. In the stationary bed unit, the polluted gas enters the system from the top and moving vertically through the stationary bed of activated carbon. (Jerry A. Nathanson 2010)

3. Incineration: The incineration method is a gas control system where VOCs and other gaseous hydrocarbon pollutants are chemically combusted to form carbon dioxide and water. (Jerry A. Nathanson 2010)

A specific incineration process called an afterburner is used to incinerate VOCs and hydrocarbon gases. To completely incinerate the VOCs and hydrocarbons, the afterburning time must be prolonged with sufficiently high temperature and proper turbulence or fusion must also be provided. The afterburner is commonly constructed from steel shell lined with refractory foundations for example fire-brick. The refractive material will protect the shell, serving as heat-proofing. The incineration method can approach 100% efficiency for removing odours, toxic compounds and photochemical reactive substances if the process is given adequate time and high enough temperature. (Jerry A. Nathanson 2010)

A special incineration process called direct flame incineration can be used to burn the waste gases if the gases themselves are combustible fuse and does not require any addition air or fuel. (Jerry A. Nathanson 2010)

4. Carbon sequestration: The carbon sequestration is a gas control system that reduces the CO_2 pollutant in the atmosphere through the reduction of fossil fuels usage, by employing alternative energy, by using energy more efficiently and through the long-term storage of carbon dioxide in the forest or oceans. The method classified as natural or unnatural procedures. (Jerry A. Nathanson 2010)

   The natural carbon sequestration system relies on natural processes such as forests growth to collect and clean the carbon dioxide in the atmosphere. The pollution of the oceans and clearing of forest for agriculture and other purpose weakens the process of natural carbon sequestration. (Jerry A. Nathanson 2010)

   Geo-sequestration is unnatural method, that involves capturing carbon dioxide and storing them in underground geologic reservoir. (Jerry A. Nathanson 2010)

5. FINDINGS

There are several residues generated from the WtE or EfW plant which is as a result of the type of waste fed into the plant, the waste volume, the combustion processes, the FGT and the APC or trapping system. Some of the residues are boiler ashes, filter dust, sludge from waste water treatment, residues from the flue gas cleaning, bottom ash or slag. Some of the slag residue from very high temperature processes can be directly utilized without any treatment. Some residues contain substances such as calcium sulphate, hydrochloric acid, sodium carbonate, sodium chloride and other material which require further treatment. (GC/FN/JG/EIPPCB/WI 2017: 12)

During the interview with Westenergy, Petri Suomela the operating engineer and Juha Ripatti the information officer were the contact persons. The questionnaire used during the interview with Westenergy has been added to the APPENDIX 4 of the thesis document. They mentioned that the increase in PVC and gypsum does not affect the APCr due to their scrubber system, but it consumes more ammonia and water. The contact persons also stated the added chemical dose fluctuates depending on the fuel moisture and the furnace heat and air composition. Petri Suomela said the APCr is heated in storage silos to prevent from solidifying. The contact persons stated the APCr is removed from the plant approximately 2 tracks per week with each track collecting 40tonnes. The contact persons mentioned that the APCr is taken to a Fortum environmental construction facility treatment located in Pori. The contact persons said Westenergy has not looked into acquiring APCr post-processing system to treat their residue onsite because they do not produce high amount of APCr and they do not have license to treat APCr on the plant site.

Tapani Korhonen the chief technology officer at WOIMA Corporation was the contact person with WOIMA Finland. The questionnaire for WOIMA has been added to the APPENDIX 5 of the thesis document. During the interview he mentioned that their plant is estimated to produce 2 to 5% of APCr depending on the toxic components in the fuel. Tapani also said that most metals are inert, so they will not affect the APCr but the presence of heavy metals in the fuel will have some effect on APCr output. Tapani mentioned that small amount of sulphur (SO) in gypsum will protect the plant from corrosion but chlorine (Cl) in PVC forms into HCl during the incineration process which causes corrosion and increases chemical need. Tapani explained that when the balance between chlorine and sulphur is at the right levels the APCr output will not be affected, but imbalance of the chlorine and sulphur will cause an increase in the chemical needs and affect the output of APCr. He said the change in season may have an indirect influence on the fuel humidity which will affect the fuel temperature, ash, chlorophylls and other things but it is hard to define how it will affect the APCr. Tapani also said the removal of APCr will depend on the storage size, logistics and disposal method.

5.1. Flue gas treatment residue (FGTr) composition

Flue gas treatment residue (FGTr) is formed or generated from the continues cleaning of the flue gas within the plant. There are several types of FGTr which result from the types of flue gas treatment (FGT) or APC systems. The main types of FGTr are fly ash (FA) and air pollution control residue (APCr). The FA is the ash residue that are trapped and removed from the flue gas before the final flue gas treatment occur. The APCr is the residue that is collected after the final flue gas treatment, which is commonly a mixture of ash, carbon and lime. Figure 23 shows some example of fly ash and APCr. The FGTr properties, texture and colour depends on the kind of waste fuel used in the WtE plant, the kind of processes use for combustion and the system uses for trapping and collecting the flue gas. (FCC Environment 2018; Will Date 2017).

Figure 23. Flue gas treatment residue (FGTr) (modified from Dr Paula 2018)

Westenergy treated 188,208tonnes of MSW in 2017 with about 29,579tonnes of bottom slag and 4,130tonnes of APCr. The flue gas impurities were 74,466tonnes of CO_2 (carbon dioxide), 195,121kg of NO_x (nitrogen oxides), 22,143kg of SO_2 (Sulphur dioxide), 10,552kg of CO (carbon monoxide), 7,935kg of HCl (hydrochloric acid), 1,101kg of NH_3 (ammonia), 154kg of TOC (total organic carbon), 28kg of HF (hydrogen fluoride), 353g of Hg (mercury), 59g of Cd+TI (cadmium and thallium), 0.05mg of dioxins and furans, and 10,564g of heavy metals which includes antimony, arsenic, lead, chromium, cobalt, copper, manganese, nickel and vanadium. (Mokomaki 2019; WESTENERGY 2018)

Information about APCr is huge and different for every plant but there is some common element that can be identified when they are observed. Some of these elements are carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), hydrogen chloride, heavy metals and ammonia (NH_3) if the plant use ammonia or urea as a SCR or SNCR.

Carbon monoxide (CO) is a colourless and odourless gas which is produced during the burning of fuel in small engines, lanterns, fireplaces, furnaces, stoves, lanterns, grills and gas ranges. CO can build up in confined space or indoors and poison people and animals in the area if they breath it into their lungs. When CO is inhaled, it causes headache, dizziness, weakness, upset stomach, vomiting, chest pain, confusion and death if exposure continues for a long time. (National Center for Environmental Health 2018)

Carbon dioxide (CO_2) is a common by-product of any combustion process especially in WtE or EfW plants (Gumisiriza R et al., 2017). CO_2 is used in food processes, manufacturing some chemicals and other numerous uses. CO_2 is a colourless, odourless and incombustible gas however, containers with compressed CO_2 can explode if they are exposed to high temperatures. Low concentration of CO_2 is not harmful when it encounters the skin or when inhaled but in confined space, a continues supply of low concentration or higher concentration of CO_2 can displace oxygen in the atmosphere causing suffocation, nausea, convulsions, collapse, coma and even death. Liquefied CO_2 can chill or freeze the skin however it can damage the eye permanently causing blindness if it gets direct contact with the eyes. Protective equipment can be used when handling liquefied CO_2 however, a victim to exposure of CO_2 should be quickly removed from contaminated source. Lukewarm and a gentle flow water can be immediately and briefly flush on affected area however, the area should not be rub or heated directly. Cloth that stick to the skin should be carefully cut or detached from affected area before removing the unaffected garment. The affected area should be loosely covered with sterile dressing. (OSH 2019)

Nitrogen oxides (NO_x) are gases comprised of nitrogen and oxygen mixtures. They form into gases with molecular formula of nitrogen oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O) and nitrogen pentoxide (NO_5). Nitrogen dioxide (NO_2) is used for manufacturing nitric acid for producing fertilizers and explosives for both military and mining purposes. Nitrogen oxides (NO_x) have different physical and chemical properties. The nitric oxide (NO) is a sweet smelling and colourless gas with a melting point at -163.6°C and a boiling point at -151.8°C with 1.04 relative density. Nitric oxide (NO) only burns when heated with hydrogen. It forms into a strong acid called nitric acid when dissolved in water. While the nitrogen dioxide (NO_2) is reddish-brown gas with irritating odour and have a melting point at -9.3°C and boiling point at 21.15°C with 1.58 relative density. Nitrogen dioxide (NO_2) forms into a weak acid known as nitrous acid when dissolved in water. (National Pollutant Inventory 2019)

Sulphur dioxide (SO_2) is a highly toxic environmental air pollutant. It is a colourless, nonflammable gas with a pungent odour. It is used as food preservative, food container sanitizing agent, food stabilizer, flavour modifier, moisture control agent, texturize and as a fermentation equipment. It dissolves in water very easily and forms into liquid when under pressure. Sulphur dioxide (SO_2) in the atmosphere are produced during the burning of coal and oil at power plant or copper smelting facilities and volcanic eruptions. It can cause irritation when it encounters the eye or when inhaled. It can cause permanent injury or death after exposure to a low concentration or a small quantity. (Open chemistry database 2019)

Hydrochloric acid is a major component of gastric acid that can be found in gastric juice and human digestive fluids. It is secreted by parietal cells as a large energetic burden during a complex process in the lumen of the stomach. Industrial hydrochloric acid is a strong corrosive substance that is formed when hydrogen chloride (HCl) gas is dissolved in water. Hydrochloric acid is used in the photographic industry and during the production of chlorides, dyes in electroplating, fertilizers, textile, and rubber. Hydrogen chloride (HCl) consist of a hydrogen atom (H) and a chlorine atom (Cl) connected with a single covalent bond. Hydrogen chloride (HCl) gas is a highly corrosive, colourless and toxic gas which forms into a white fume on contact with humidity or body tissue causes redness, pain, severe burns to the skin or eyes leading to permeant eye damage. When hydrogen chloride (HCl) is inhaled, it can cause coughing, inflammation of the nose, throat and upper respiratory tract which can lead to choking. It can also cause circulatory system failure, lung problem and death. Appropriate safety precautions should be taken when handling hydrochloric acid. (Open chemistry database 2019)

Heavy metals are any metallic elements that are toxic at a low concentration with a high relative density such as antimony, cadmium, chromium, copper, lead, mercury, nickel, selenium, zinc, manganese, vanadium, arsenic, thallium and many more. Heavy metals are toxic because they tend to accumulate in biological organism faster than been metabolized or excreted. Antimony is used in flame retardant, batteries, pigments, glass and ceramics. High concentration of antimony can cause nausea, vomiting and diarrhoea even if exposed for short periods of time. Cadmium has similar properties to zinc since it is an inevitable by-product of zinc. Cadmium can be found in phosphate fertilizers, detergents and refined petroleum as an impurity. Cadmium is used in nickel/cadmium batteries, pigments, stabilizers for PVC, alloy and electronics, coating for marine and aerospace applications. High concentrate or long-term exposure can lead to lung disease, bone defects, high blood pressure and myocardium in animals. Humans are estimated to having a daily intake of cadmium about 0.15µg in air, 1µg from water and around 2-4µg when 20 packets of cigarettes are inhaled. Chromium is used in cement, alloys, paper, rubber, pigments for paint and many materials. Aquatic life often accumulates chromium. Long-term exposure can cause damage to circulatory, nerve tissue, kidney and liver. Exposure to high concentrations of copper can cause irritation in the stomach, intestine, damage to the kidney, liver and anaemia. Copper end up in drinking water normally through copper pipes. Depending on the level and duration of exposure to lead it can result in a wide range of biological effects such as problems in the synthesis of haemoglobin, reproductive system, kidneys, gastrointestinal tract, joints and acute or chronic damage to the nervous system. Lead intake often come from food, lead piping and plumbosolvent water, paint flakes in old houses, soil, dust and air emissions source. Mercury is found in the earth crust, volcanoes and natural bodies of water evaporations. There is an indirect discharge of mercury into the atmosphere during mining. Mercury is used in batteries, lamps, thermometers, amalgam in dentistry, pharmaceutical and industrial processes. Mercury poisoning can lead to tremors, gingivitis, minor psychological changes, abortion and inborn malformation. The body use small amount of nickel to produce red blood cells, but it is mildly toxic in large amounts which can cause decrease in body weight, heart and liver damage, and skin irritation. Small amount of selenium is needed by humans and animals, but large amounts can accumulate in living tissues cause fatigue, irritation, hair and fingernail loss, damage to kidney, liver, circulatory and nervous system. (Lenntech 2019)

Ammonia (NH_3) or urea (NH_2CONH_2) is a common neutralization agent used in some WtE or EfW plants (David Hosansky 2014). Safety precautions are required for storing ammonia but not urea because it starts forming into ammonia and carbon dioxide gas at 130^{o}C with a maximum reaching 380^{o}C (Bernd 2008). Some ammonia can be found naturally in humans and the environment. Ammonia serves as a precursor for amino acid and nucleotide synthesis in many biological processes. Ammonia is produced in soil from bacterial processes as part of the environment nitrogen cycle. Ammonia is colourless with a highly irritating, suffocating and strong odour. Ammonia is hygroscopic or readily absorbs moisture in its pure form. Ammonia is corrosive and has alkaline properties, but it is not highly flammable. However, containers with compressed ammonia can explode if they are exposed to high temperatures. Agriculture production uses about 80% of ammonia produced by industries. Ammonia is also used for the manufacturing of pesticides, explosive, plastics, textiles, dyes, other chemicals and for purification of water supplies when used as a refrigerant gas. About 5% to 10% of ammonia gas is used in water as household ammonia cleaning solution. Ammonia concentrations of 25% or higher is used by industries. Exposure to lower concentrations of ammonia can cause skin or eyes irritation but if inhaled it can cause coughing or nose and throat irritation. If high concentration of ammonia gets into the eyes, skin, oral cavity or respiratory tract it causes immediate burns because it forms ammonium hydroxide causing those tissues to die by disrupting the cell membrane lipids leading to inflammatory response which cause more damage. Ammonia exposure can be treated with humidified oxygen, bronchodilator, water or milk. (Department of Health 2005)

5.2. APCr management theories

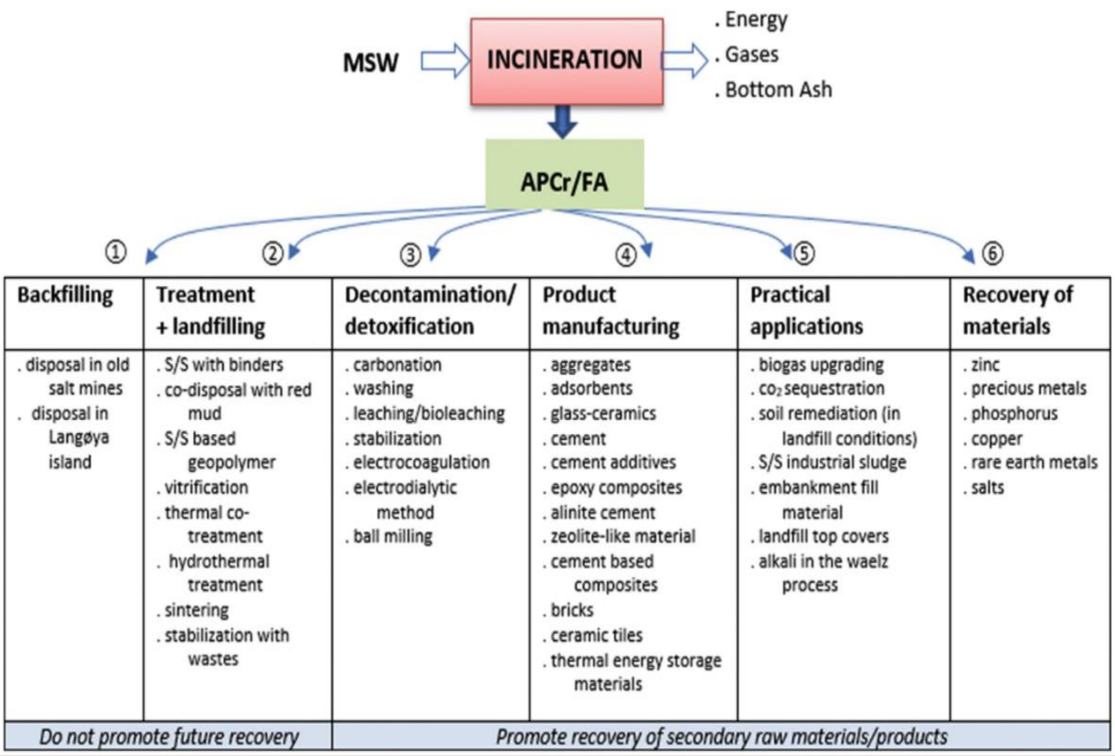
Directive 2018/851 appeal for the improvement of waste management to help prevent hazardous by-product whiles increasing the re-use and recycling of waste. The restrictions on leaching criteria is different in every country. Table 7 shows the leaching criteria for utilizing or disposing of bottom ash in Italy.

Table 7. Leaching criteria for utilization or Landfilling in Italy (Kim2006)

	Utilization (cement, concrete, landscaping, embankments)		Landfilling	
Substance	Government Decree n° 22 of February 5th of 1997 / Ministerial Decree of February 5th of 1998		Ministerial Decree n° 201 of 3rd August 2005 CEN 12457-4, L/S=10	
	mg/l.	mg/kg *(L/S = 5)*	mg/l.	mg/kg *(L/S = 10)*
Cl	200	1000	1500	15 000
F	1.5	7.5	15	150
SO4	250	1250	2000	20 000
Na	-	-	-	-
NO_3	50	250	-	-
Cyanid (CN)	0.05	0.25	0.5	5
As	0.05	0.25	0.2	2
Ba	1	5	10	100
Pb	0.05	0.25	1	10
Cd	0.005	0.025	0.02	0.2
Cr, total	0.05	0.25	1	10
Cu	0.05	0.25	5	50
Hg	0.001	0.005	0.005	0.05
Mo	-	-	1	10
Ni	0.01	0.05	1	10
Zn	3	15	5	50
Sb	-	-	0.07	0.7
Se	0.01	0.05	-	-
Sr	-	-	0.05	0.5
Be	0.01	0.05	-	-
Co	0.25	1.25	-	-
V	0.25	1.25	-	-
Asbesto	30	150	-	-
COD	30	150	-	-
pH	5.5<>12.0	5.5<>12.0	-	-
Aromatic organic solvents*	-	-	0.4	4
Nitrogenic organic solvents	-	-	0.2	2
Chlorid organic solvents	-	-	2	20
Total pesticides not phosphorates	-	-	0,05	0.5
DOC**	-	-	80	800
TDS***		-	6000	60 000

There are several theories that have been developed for managing APCr. They can be categorised into backfilling, treatment and landfilling, decontamination / detoxification, product manufacturing, practical applications and recovery of materials. All these applications and what it includes can be seen in Table 8. (M.J. Quina 2018)

Table 8. APCr management (M.J. Quina 2018)



Backfilling	Treatment + landfilling	Decontamination/ detoxification	Product manufacturing	Practical applications	Recovery of materials
. disposal in old salt mines . disposal in Langøya island	. S/S with binders . co-disposal with red mud . S/S based geopolymer . vitrification . thermal co-treatment . hydrothermal treatment . sintering . stabilization with wastes	. carbonation . washing . leaching/bioleaching . stabilization . electrocoagulation . electrodialytic method . ball milling	. aggregates . adsorbents . glass-ceramics . cement . cement additives . epoxy composites . alinite cement . zeolite-like material . cement based composites . bricks . ceramic tiles . thermal energy storage materials	. biogas upgrading . CO_2 sequestration . soil remediation (in landfill conditions) . S/S industrial sludge . embankment fill material . landfill top covers . alkali in the waelz process	. zinc . precious metals . phosphorus . copper . rare earth metals . salts
Do not promote future recovery		*Promote recovery of secondary raw materials/products*			

A. Backfilling is a disposal method of MSW residue where the APCr is often packed in big leaching resistance material bags and stored in old salt mines and underground cavities. (M.J. Quina 2018: 528)

B. Treatment and landfilling are a disposal method of MSW residue where the APCr is treated by a process of stabilization/solidification (S/S), thermal cotreatment or hydrothermal treatment before landfilling. Disposal operations (ANNEX I) of waste directive 2008/98/EC can be seen in the APPENDIX 3 of the thesis work. This method reduces leaching, but the thermal process require lot of energy and it does not support recovery of secondary raw materials since the final material is disposed to landfilling. (M.J. Quina 2018: 528)

C. Decontamination /detoxification is an APCr treatment method that applies washing, carbonation, leaching/bioleaching, stabilization, electrocoagulation, electro dialytic method and ball milling to remove or destroy the harmfulness of the residue. This method support recovery of secondary raw materials. (M.J. Quina 2018: 529)

D. Product manufacturing is an APCr material recovery technic that uses the residue to manufacture product while minimizing the impact on human health and environment. Due to the APCr physical and chemical properties, the residue can be used to manufacture product such as construction aggregate, bricks, adsorbents, glass-ceramics, ceramic tiles, cement, cement additives, epoxy composites and thermal energy storage materials. (M.J. Quina 2018: 529)

E. Practical applications are the method that directly uses the APCr to accomplish a specific objective such as biogas upgrading, CO_2 sequestration, S/S industrial sludge, embankment fill material, alkali, landfill top covers and soil remediation in landfill conditions. (M.J. Quina 2018: 529)

F. Recovery of materials refers to the salvaging of specific elements, precious metals, rare earth metals or minerals from the APCr. The residues from MSW incineration contain a substantial amount of salt and metals which are potentially toxic and valuable. (M.J. Quina 2018: 529)

To select the best theories for further discussions, the research employs the concept selection procedure provided in the product design and development by Karl T. Ulrich and Steven D. Eppinger. Making the finding understandable to read, let compare the available theories to some selected criteria to prepare a matrix for the selection. The selected criteria were based on Directive 2018/851 and WOIMA limitations for the thesis. For the concept selection process, we have selected criteria such as future recovery, useful by-product, safe for the environment, safe for human health, CO_2 capturing, easy to implement, cheap to implement, portable technology, available secondary materials and cheap supporting materials. Let represent Backfilling with A, treatment and landfilling with B, decontamination /detoxification with C, product manufacturing with D, practical applications E and recovery of materials with F. The theories were rated with a scale of +1 as an advantage, 0 as neutral and -1 as disadvantage. The total score of +1 were put in the pluses, 0 in the neutral and -1 in the minuses row. The +1, 0 and -1 were added put in the total score row. The result off all the theories were added and put in the rank row. Either or not the theory should be considered for further development were commented in the continues row as shown in table 9.

Table 9. Concept screening (Karl T. Ulrich 2012)

	Available theories						
Selection criteria	A	B	C	D	E	F	Ref
Future recovery	-1	-1	+1	+1	+1	+1	0
Reusing APCr	-1	-1	0	+1	0	+1	0
Safe for the environment	-1	0	0	+1	0	0	0
Safe for human health	-1	0	0	0	0	0	0
CO_2 capturing	0	0	+1	+1	+1	0	0
Easy to implement	+1	0	0	0	0	0	0
Cheap to implement	+1	0	0	0	0	0	0
Portable technology	0	0	0	0	0	+1	0
Available secondary materials	0	+1	+1	+1	+1	+1	0
Cheap supporting materials	0	+1	0	+1	+1	+1	0
Pluses	2	2	3	6	4	5	
Neutral	4	6	7	4	6	5	
Minuses	4	2	0	0	0	0	
Total score	-2	0	+3	+6	+4	+5	
Rank	6	5	4	1	3	2	
Continue	No	No	Yes	Yes	Yes	Yes	

Product manufacturing or D from the table 6 recorded the highest in ranking with recovery of materials or F coming in second place from the selected criteria used in the matrix. The matrix is an estimated scale and may not be 100% accurate since the supporting theories are not clearly defined with the selected criteria used. Let observe some available product manufacturing application and recovery of material methods.

Product manufacturing uses the APCr as a material to make a product while minimizing the impact on human health and environment. Some of these products are lightweight aggregate, glass-ceramics, cement and many others. (M.J. Quina 2018: 529)

1. Lightweight aggregate (LWA) is an APCr management technique that falls under using the residue as raw material. The APCr is turned into a synthetic LWA as shown in figure 24 which is used on an industrial scale for ceramics manufacture. (M.J. Quina 2018: 529)

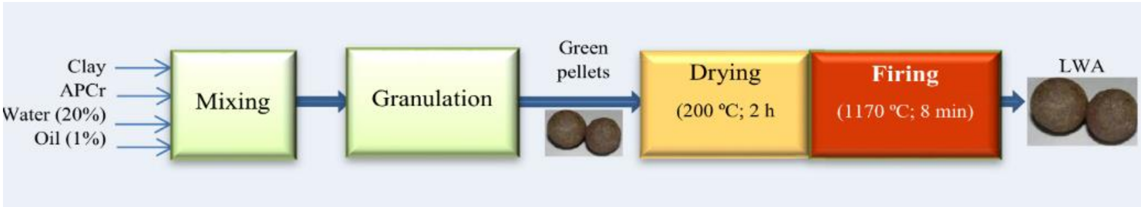


Figure 24. Lightweight aggregate process (M.J. Quina 2018)

2. Glass-ceramics is an APCr management method that uses amorphous silica source for toxic metals stabilization ash shown in figure 25. The technique originally employed the use of colloidal silica but developed into using a more sustainable silica source like silica fume and rice husk ash (M.J. Quina 2018: 529)

Figure 25. Ceramics from APCr (M.J. Quina 2018)

3. Cement are made from a mixture consisting of limestone, clay, sand and iron oxides which are heated to about 1450°C and then grinded together with an added calcium sulphate like gypsum or anhydrite as shown in figure 26. The presence of Ca-, Si-, Al-, and Fe- in APCr show the potential for cement manufacturing. Several researchers suggest that replacing untreated APCr with some of the cement manufacturing compounds can achieve a higher mortar strength. (M.J. Quina 2018: 531)

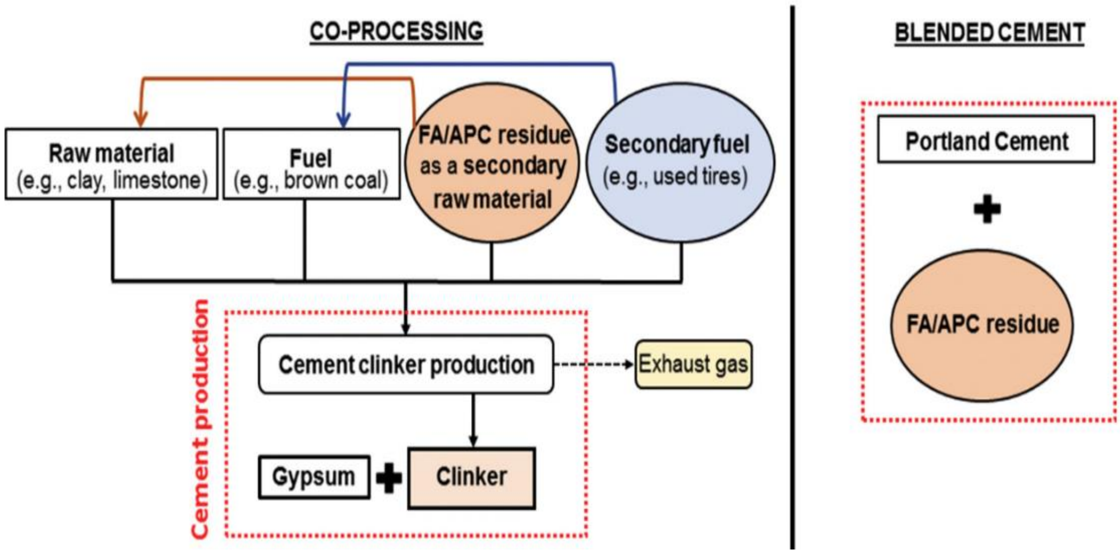


Figure 26. APCr in cement industry (M.J. Quina 2018)

Recovery of materials use technical procedure to retrieve specific elements, precious metals, rare earth metals or minerals from MSW incineration residues since it contains a substantial amount of salt and metals. (M.J. Quina 2018: 529)

1. Recovery of Zn, Cu, Cd, Pd and organic substances that have been accumulated in APCr can be effectively separated by using acidic fly ash leaching technique and any remaining organic substance can be returned to the combustion process for complete incineration as shown in figure 27. The technic uses several scrubbers, solvent and metal extraction methods to separate the material in the APCr. (M.J. Quina 2018: 532)

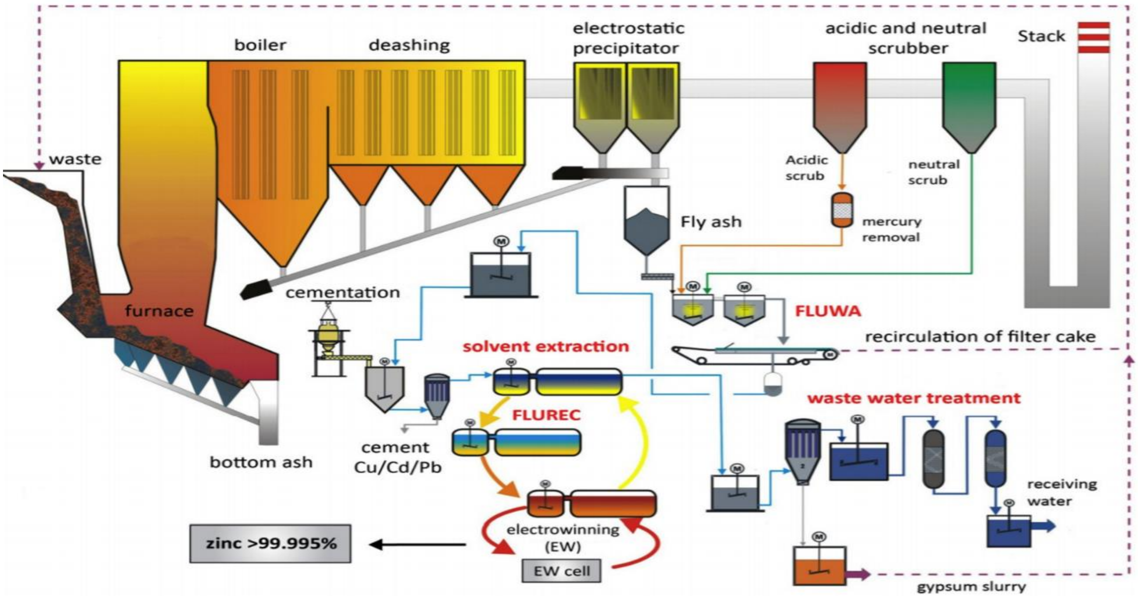


Figure 27. Recovery of Zn, Cu, Cd, Pd (Adopted from M.J. Quina 2018)

2. Recovery of rare earth elements (REE) and rare metals can be removed by employing hydrometallurgical technique such as bioleaching as shown in figure 28. The method is still been developed as a potential process for pre-treating certain metals in waste streams. (M.J. Quina 2018: 533)

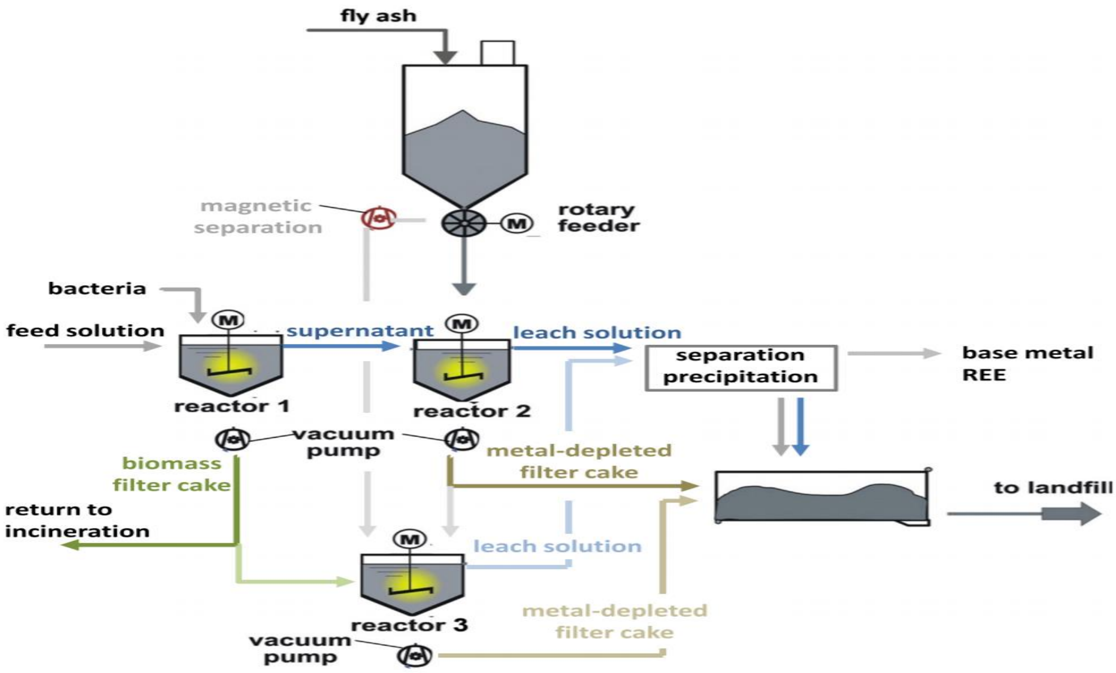


Figure 28. Recovery of rare earth element (Adopted from M.J. Quina 2018)

5.3. Selected technologies

Several technologies are used to manage the APCr from WtE or EfW plant. Carbon8 Aggregate technology has been selected for further study by this thesis because it uses the APCr for product manufacturing whiles combining it with CO_2 sequestration from practical applications process. Tetronics International technology has been selected as an alternative technology for APCr management by this thesis because it combines the treatment or decontamination /detoxification process with recovery of materials.

1. Carbon8 Aggregate limited

Carbon8 Aggregate use an accelerated carbonation technology (ACT) to permanently capture CO_2 through the recycling and treatment of APCr to manufacture construction aggregate. Carbon8 Aggregate Ltd was founded in 2010 to commercialize the accelerated carbonation process where water and CO_2 is used in treating APCr from thermal waste, after which binders and fillers are mixed to manufacture aggregate for construction. (Carbon8 aggregate; Carbon8 webpage 2019) As shown in figure 29, the APCr is mixed with water and CO_2 after which sand and cement are added in stage 2 mixing. The mixture is then pelletized and stored in a CO_2 atmosphere to form construction aggregate. The chemical reaction that goes on with the acceleration carbonation process is as follows:
$Ca(OH)_2 + H_2O + CO_2 \rightarrow CaCO_3 + 2H_2O$ (James Ng 2017)

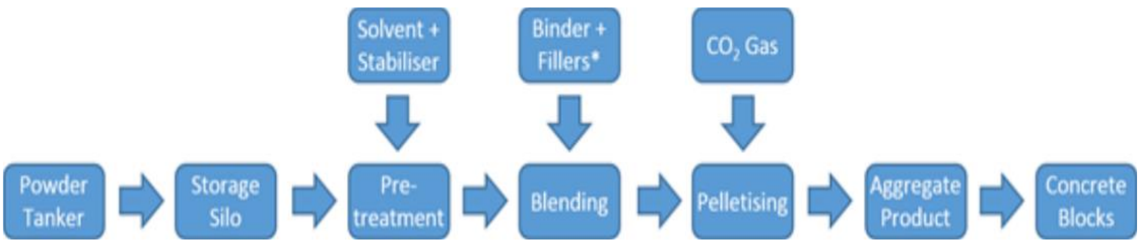


Figure 29. Carbon8 aggregate process (Dr Paula Carey 2018)

Carbon8 Aggregate limited has been certified by ISOQAR. The physical and mechanical performance of the lightweight aggregate is in compliance with ISO 14001, ISO 9001, OHSAS 18001, BS EN 13055-1:2002 and BS EN 771-3:2003. (BSI 2015)

Table 10. Carbon8 Aggregate leaching specifications (BSI 2015)

	Sb	As	Ba	Cd	Cr	Cu	Pb	Mo	Ni	Se	Zn
Max	0.06	0.5	50	0.04	1.5	0.15	0.5	1.0	0.4	0.1	3.5
Aver	bdl	0.05	17	bdl	0.5	bdl	0.1	0.2	0.03	0.06	0.26

The characteristics of Carbon8 Aggregate leaching can be seen in Table 10, where Max shows the specification agreement with the environmental agency and Aver shows the average leaching level of Carbon8 Aggregate.

Carbon8 Aggregate use the APCr to make construction aggregate, which is used for producing blocks, lightweight aggregate for ready mix concrete applications, precast concrete applications and no-fines screeding systems.

Table 11. Carbons Aggregate block mix properties (BSI 2015)

Material Properties				
Particle size		0 - 15	mm	
Dry loose bulk density	Minimum	950	kg/m^3	EN 1097
	Maximum	1100	kg/m^3	EN 1097
Particle density	Oven dried	1.94	kg/m^3	EN 1097
Crushing Resistance	Typical value	6.6	N/mm^2	EN 13055
	Minimum value	5.2	N/mm^2	EN 13055
Moisture content as delivered	Typical value	8	%	
Water absorption		18.8	%	EN 1097
Water soluble chloride		4.2	%	EN 1744
Water soluble sulfate		0.1	%	EN 1744
Total sulfate (as SO_3)		1.78	%	EN 1744
Resistance to Attrition (Los Angeles)		39	%	EN 1097
Magnesium sulphate soundness		30.1	%	EN 1097
Drying shrinkage		0.021	%	EN 1367

The characteristics of the aggregate of the block mix by Carbon8 Aggregate can be seen in Table 11. The block mix is used for concrete masonry blocks in applications relevant to the product standard and specification. (BSI 2015)

Table 12. Aggregate properties for ready-mix concrete (BSI 2015)

Material Properties				
Particle size		4 - 16	mm	
Dry loose bulk density	Minimum	950	kg/m^3	EN 1097
	Maximum	1100	kg/m^3	EN 1097
Particle density	Oven dried	1.94	kg/m^3	EN 1097
Crushing Resistance	Typical value	6.6	N/mm^2	EN 13055
	Minimum value	5.2	N/mm^2	EN 13055
Moisture content as delivered	Typical value	8	%	
Water absorption		18.8	%	EN 1097
Water soluble chloride		4.2	%	EN 1744
Water soluble sulphate		0.1	%	EN 1744
Magnesium sulphate soundness		30.1	%	EN 1097
Drying shrinkage		0.021	%	EN 1367

The characteristics of the aggregate for ready-mix concrete by Carbon8 Aggregate can be seen in Table 12. The aggregate for ready-mix concrete is used in trench fill foundation, pipe haunching, kerb haunching, oversites, fibre reinforced unit and mass concrete blocks where there is no steel reinforcement embedded in the cast concrete. (BSI 2015)

Table 13. Aggregate properties for precast concrete (BSI 2015)

Material Properties				
Particle size		4 - 16	mm	
Dry loose bulk density	Minimum	950	kg/m^3	EN 1097
	Maximum	1100	kg/m^3	EN 1097
Particle density	Oven dried	1.94	kg/m^3	EN 1097
Crushing Resistance	Typical value	6.6	N/mm^2	EN 13055
Moisture content as delivered	Typical value	8	%	
Water absorption		18.8	%	EN 1097
Water soluble chloride		4.2	%	EN 1744
Water soluble sulphate		0.1	%	EN 1744
Resistance to attrition (Los Angeles)		48	%	EN 1097
Magnesium sulphate soundness		30.1	%	EN 1097
Drying shrinkage		0.021	%	EN 1367

The characteristics of the aggregate for precast concrete by Carbon8 Aggregate can be seen in Table 13. The aggregate for ready-mix concrete is used in concrete lego blocks, fibre reinforced units, ornamental precast, street furniture, gullies, troughs, flags and kerbs where there is no steel reinforcement embedded in the cast concrete. (BSI 2015)

Table 14. Aggregate properties for no-fines screeding systems (BSI 2015)

No fines base		
Dry density	1436	kg/m3
Weight per sq m at 100mm thick	143.6	kg
System: 100mm base and 15 mm topping		
Dry density	1510	kg/m3
Weight per sq m	173.7	kg
Kg of CO2 per sq m	11	kg

The characteristics of the aggregate for no-fines screeding by Carbon8 Aggregate can be seen in Table 14. The aggregate for no-fines screeding system is used where in-situ crushing resistance is required. (BSI 2015)

James Ng the national business development manager of Carbon8 Aggregate was the contact person with Carbon8 Aggregate. All CONFIDENTIAL INFORMATION was erased from these discussions. James Ng said that the quantity of ammonia in the APCr can make their plant unit sticky, when that happens, they ask their APCr providers to reduce the ammonia content in their process. He said the aggregate their plant produce does not face any environmental issue, but they ask their partiers to reduce the X-chloride in the APCr. He mentioned that the aggregate they produce put in a close storage which is collected by our partners for construction purposes. He said that they are developing a portable plant to manage APCr. He said the costs of APCr will be dependent on the country of disposal, for example the average cost of disposal in the UK for Landfill with Landfill tax rates plus a gate fee is approximately £110 per tonne. The recycling of the APCr in the UK works because the landfill tax rates is set by the government at £89.00 per tonne.

Table 15. Advantages and disadvantage of Carbon8 Aggregate.

Advantages	Disadvantage
Captures CO_2	Prefer low ammonia APCr
Produces construction aggregate	Prefer low hydrochloride APCr
Uses cheap secondary materials	Portable technology is not completed
Uses easily assessable secondary materials	Process requires electricity
Low process time	Require storage space

Table 15 shows some advantages and disadvantages of the technology that was identified during the research. Some extra benefit is that Carbon8 Aggregate get some revenue for every APCr and for every construction aggregate they produce. The technology produces strong and consistent quality of construction aggregate.

Table 16. Parameters of Carbon8 Aggregate production

Parameters	Information
APCr capacity	CONFIDENTIAL INFORMATION
Carbon footprint	
Process duration	
Binder	
Fillers	
Water	
Aggregate produced	

Table 16 shows some selected parameters of Carbon8 Aggregate production, which was compiled from the interview questions and internet articles by Carbon8 Aggregate. All confidential information was erased from the table.

2. Tetronics International technology

Tetronics technology uses the plasma treatment to remove hazardous composition in the APCr but recovers precious metals, minerals and other raw material. The plasma technique uses intense temperature and ultra-violet light to destroy toxic substances in 30,000 tonnes to 50,000 tonnes of the APCr per year. As shown in figure 31, the APCr is mixed with silica. The plasma treatment is accomplished in a sealed furnace where a single or multiple plasma electrodes / torches creates plasma arc which destroys the hazardous element of the APCr. The bottom residue is distributed for construction purposes whiles the gases progress for further treatment. The gases first go to a combustion chamber to reduce any hazardous substances. The gas is cooled and filtered for secondary APCr. The gas then goes off to an acid absorption column where HCl is collected for industrial usage. The clean gas is analysed and discharged to the atmosphere. The exiting gas is continuously monitored with continuous emissions monitoring system (CEMS) before leaving the facility. Tetronics technology procedure is designed to effectively destroy the harmfulness of APCr before separate and recover the precious metals, minerals and other materials. (Tetronics International 2019)

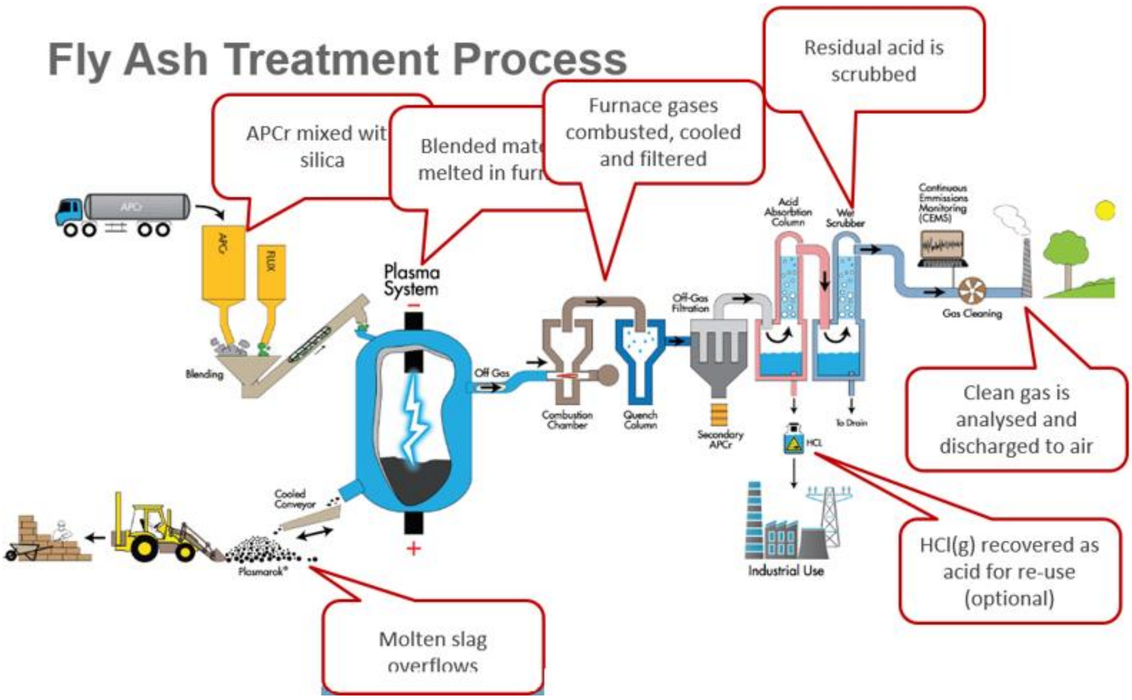


Figure 30. APCr treatment process (Tetronics International 2019)

Table 17. Leaching properties of Tetronics slag (Tetronics International 2019)

Leachate Analysis	APCr-1 Slag: Calculated cumulative amount leached @ 10:1	APCr-2 Slag: Calculated cumulative amount leached @ 10:1
	mg/kg (dry weight)	mg/kg (dry weight)
Arsenic	0.02	0.02
Barium	1.2	0.3
Cadmium	<0.001	<0.001
Chromium	0.02	0.03
Copper	0.02	0.06
Mercury	<0.001	<0.001
Molybdenum	0.02	<0.01
Nickel	0.02	0.02
Lead	0.15	<0.01
Antimony	0.09	<0.01
Selenium	<0.01	<0.01
Zinc	0.05	0.04
Chloride	110	50
Fluoride	3	3
Sulphate as SO4	70	110
Total Dissolved Solids	1,220	1,130
Phenol Index	<0.5	<0.5
Dissolved Organic Carbon	23	27
Total Organic Carbon (% M/M)	0.47	0.5
Loss on Ignition (%)	0.1	0.1
Acid Neutralisation Capacity (mol/kg) @ pH 7	2.88	2.86

Table 17 shows the leaching characteristics of the melted slag and the secondary APCr produced by Tetronics International technology.

Dr Tim Johnson technical director from Tetronics International was the contact person with Tetronics International. There were no interviews with Tetronics International, but Dr Tim Johnson accepted and answered the questioners with his colleagues. The questionnaire for Tetronics International has been added to the APPENDIX 7 of these thesis document. Dr Tim Johnson wrote that their plant process is a continuous one, with a continuous overflow of slag from the furnace to a slag casting/cooling system, e.g. a granulation tank or water-cooled slag conveyor. The typical residence time for waste material in the molten slag bath varies but is typically 1 to 2 hours. He wrote that the main use of water is for the off-gas system for quenching the thermal oxidizer exit gas and for the acid neutralization unit. Since both these items consume water differently depending on the APCr composition, it is difficult to give a single accurate answer. He mentioned that it is of course possible to use a venturi-style scrubbing/quenching/filtration system, which would lead to quite low water losses to steam. He also stated that the water usage will depend on whether on the HCl residua after the filter is wet-scrubbed (more water use) or recovered as hydrochloric acid (less water use). He mentioned that water is also used for cooling the slag from the furnace, but often these are closed loop water cooling systems. He mentioned that if a decision is taken to cool the slag using an open water system, then losses to steam would also need to be considered. He stated that Tetronics International normally discuss with the client at the feasibility study stage, as there are several options, each with its own implications. He wrote that more volatile species (e.g. Na and K-based compounds, Pb, Zn, etc.) mean more secondary APCr. He also wrote that it will depend on the balance between dry and wet scrubbing – more dry scrubbing means more secondary APCr but less scrubber liquor and lower water consumption. Dr Tim Johnson wrote that the secondary APCr is sometimes landfilled, but if the level of valuable heavy metals is high enough then it can be taken as an input for metal recovery (e.g. Zn), which reduces the cost and the amount of waste arising from the process. He mentioned that the decision to collect HCl (or not) is made jointly by Tetronics and the client, based on how much HCl is likely to be created and whether there is a local market for the recovered acid. He stated that where there is any doubt at the project concept stage, Tetronics International usually find the economic model needs to be based on simply neutralising any residual HCl, although recovery of acid will tend to improve the economics and reduce the waste arising from the process. He mentioned that the approximate electrical energy consumption required is typically around 900 to 1000 kWh per tonne of input APCr. He also stated that Tetronics International do not receive APCr for treatment because they do not own or operate the plants, but the treatment fee for APCr tends to be closely related to the cost of alternative disposal of the APCr, which normally means hazardous landfill. Dr Tim Johnson wrote that the melted slag is qualified by the UK Environment Agency as a product approved for sale as recovered (secondary) aggregate, which usually means a value of around €5 to €10 per tonne. In practice, this usually means being able to assume the slag is not a secondary waste and that someone will take it off site at zero cost.

Tetronics International technology has some advantages and restrictions. Table 18 shows some of the advantages and disadvantages of the technology that was identified through the presentation and questioner answers from Tetronics International.

Table 18. Advantages and disadvantage of Tetronics International.

Advantages	Disadvantage
Produces construction pellet	High energy demand
Produce HCl for industrial use	Require highly skilled maintenance team
Accept high ammonia and chloride APCr	Needs perfect regular maintenance
Portable technology available	Produces secondary APCr
Does not require storage space	Produce unwanted by-product

Table 19 shows the parameters of the Tetronics International technology which was compiled from the questionnaire that was forwarded to the company. All confidential information was erased from the table.

Table 19. Parameters of Tetronics International

Parameters	Information
APCr capacity	CONFIDENTIAL INFORMATION
Process duration	
Feeding time (nominal)	
Silica	
APCr feeding rate	
Plasma power	
Furnace diameter	
Slag generation	
Secondary APCr	

6. DISCUSSIONS AND CONCLUSION

All the APC technique are linked to the APCr management technology, but each method is unique due to their specific objective. An APC technique can be designed to help solve a specific problem, but it may not be able to solve another task. All solutions for managing the APCr may have some barrier or challenges which will need to be managed.

Making the findings understandable for review, the research compared both APCr management technologies by examining the operation cost. The setup cost including the land, construction, training, transportation and technology cost was not considered since the technology providers could not provide data on setup unless some specifications are given to them by a client to make a practicability analysis. Employees, insurance, taxes, maintenance and unexpected process costs were not included in the operation cost analysis.

Tapani Korhonen assisted by Prince Safo provided the Finland market prizes of electricity, binders, fillers and water. Table 20 show Carbon8 Aggregate technology estimate on a plant that manages 130,000tonnes of APCr per year. The table is an estimated scale for Carbon8 Aggregate operations. All CONFIDENTIAL INFORMATION was erased.

Table 20. Operation cost and revenue of Carbon8 Aggregate

<table>
<tr><th>Parameters</th><th>Measurements</th><th>Market prize €</th><th>Sum €</th></tr>
<tr><td>APCr</td><td rowspan="7">CONFIDENTIAL INFORMATION</td><td>126.5/t</td><td rowspan="8">CONFIDENTIAL INFORMATION</td></tr>
<tr><td>Electricity</td><td>0.10/kWh</td></tr>
<tr><td>CO_2</td><td>1.84/kg</td></tr>
<tr><td>Binders</td><td>0.25/kg</td></tr>
<tr><td>Fillers</td><td>9/t</td></tr>
<tr><td>Water</td><td>2.75/m^3</td></tr>
<tr><td>Aggregate</td><td>11/t</td></tr>
<tr><td></td><td></td><td>Total</td></tr>
</table>

Table 21 shows the Tetronics international plant estimation for manage 30,000tonnes of APCr per year. The operation time used was 6,424hr as because that was the feeding time given by Tetronics International. The table is an estimated scale of Tetronics International plant operation cost and revenue. Dr Tim Johnson the contact person from Tetronics International said the silica can sometimes be substituted by bottom ash, which tends to be much higher in silica then APCr. The amount of HCl expected to be recovered was not clearly defined so a red ink was used to express the condition. All CONFIDENTIAL INFORMATION was erased from the tables.

Table 21. Operation cost and revenue of Tetronics International

Parameters	Measurements	Market prize €	Sum €
APCr	CONFIDENTIAL INFORMATION	126.5/t	CONFIDENTIAL INFORMATION
Electricity		0.10/kWh	
Secondary APCr		126.5/t	
Construction slag		8/t	
HCl		-	
		Total	

The table 22 has been designed to help in selecting the best technology for managing the WOIMA APCr onsite. The selected criteria used in the table was based on Directive 2018/851 and WOIMA limitations for the thesis. The selected criteria were portability, reusing APCr, unwanted by-product, carbon capturing, available secondary materials, highly skilled maintenance team, cheap to implement, cheap to operate, accept all kinds of APCr, high energy requirement and met leaching standard.

The selected criteria were rated with a scale of +1 as an advantage, 0 as neutral and -1 as disadvantage. The total score of +1 were put in the pluses, 0 in the neutral and -1 in the minuses row. The +1, 0 and -1 were added put in the total score row. The result of all the criteria were added and put in the rank row. The technology that rank highest should be accepted as the APCr management technology that WOIMA should consider employ on the plant site.

Table 22. APCr management technology for Onsite.

	Selected Technology	
Selection Criteria	Carbon8 Aggregate	Tetronics International
Portability	0	+1
Reuses APCr	+1	+1
Unwanted by-product	+1	-1
Carbon capturing	+1	0
Available secondary materials	+1	+1
Low skilled maintenance team	+1	-1
Cheap to implement	0	0
Cheap to operate	0	0
Accept all kinds of APCr	-1	+1
Low energy requirement	0	-1
Met leaching standard	+1	+1
Pluses	6	5
Neutral	4	3
Minuses	1	3
Total	+5	+2
Rank	1	2
Accepted	Yes	Yes

The **research question 1.** for managing the APCr onsite can be solved by employing Carbon8 Aggregate technology on the plant site since it ranked the highest based on the criteria used for the selection. However, Carbon8 Aggregate technology prefer APCr with low ammonia and hydrochloride concentration. Therefore, Tetronics International technology can be used to reduce the ammonia and HCl substance in the APCr if the concentration found in the APCr is high before using Carbon8 Aggregate technology to transform the residues into construction aggregate.

The table 23 has been designed to help in selecting the best technology for managing the WOIMA APCr offsite. The selected criteria were based on Directive 2018/851 and WOIMA barriers given for managing their APCr offsite. The selected criteria were reusing APCr, unwanted by-product, carbon capturing, low transport cost of APCr, own facility that manage APCr low cost at accepting APCr, accept all kinds of APCr and met leaching standard. They were rated with a scale of +1 as an advantage, 0 as neutral and -1 as disadvantage. The total score of +1 were put in the pluses, 0 in the neutral and -1 in the minuses row. The +1, 0 and -1 were added put in the total score row. The result off all the criteria were added and put in the total row and ranked.

Table 23. APCr management technology for Offsite.

	Selected Technology	
Selection Criteria	Carbon8 Aggregate	Tetronics International
Reuses APCr	+1	+1
Unwanted by-product	+1	-1
Carbon capturing	+1	0
Low transport cost of APCr	0	0
Own facility that manage APCr	+1	0
Low cost at accepting APCr	0	0
Accept all kinds of APCr	-1	+1
Met leaching standard	+1	+1
Pluses	5	3
Neutral	2	4
Minuses	1	1
Total	+4	+2
Rank	1	2
Continue	Yes	Yes

Research question 2. improve the management of the APCr offsite can be solved with Carbon8 Aggregate technology since it will fit very well into the circular economy objective of reusing the APCr. The CO_2 capturing of Carbon8 Aggregate technology is an added environmental advantage for WOIMA to select Carbon8 Aggregate for managing the APCr off site. But if the toxic substance in the APCr cannot be reduce due to the high toxic materials in the waste, then WOIMA should considered both technology since Tetronics International technology can reduce the toxic materials in the APCr and Carbon8 Aggregate technology can reuse the residues.

Westenergy recorded 74,466tonnes of CO_2 impurities in their plant flue gas. The presents of CO_2 in the incineration process, make it attractive to combine or modify the APC system with CO_2 sequestration, stabilization and solidification procedures. However, the ammonia, chloride and other leaching content in the APCr need to be reduced. The chlorine and sulphur contain should be carefully balanced to reduce the plant corrosion and neutralization agent required by the FGT process. If the flue gas contains high amount of HCl, REE and precious metals, separators and electrostatic precipitators can be used to recover the HCl, REE and precious metal in the flue gas before it is absorbed with a mixture of activated carbon and sand after which it can be solidifying with cement. The solidified residue can be baked or scorched with heat and coated with leaching resistant protective paint. The final product can be used for construction, embankment fill construction, landfill top covers, natural or geo sequestration.

However, the waste incineration process can be modified for cement production since there is the presence of some materials in the APCr which are useful in the cement manufacturing process. If the impurities in the flue gas is too high, the untreated flue gas from the waste incineration can be cleaned with activated carbon before channelling the flue gas into the cement manufacturing process. By using the flue gas from the waste incineration to make cement, the amount of residue produced from the waste incineration process will reduce whiles reducing the raw materials needed for making cement.

LIST OF REFERENCES

Adam Penque (2007). Examination of Chlorides in Municipal Solid Waste to Energy Combustion Residue: Origins, Fate and Potential for Treatment. Columbia University.

Aman Raj (2015). What are the differences between solid waste, liquid waste and gaseous waste? Quora. Available 8.1.2019: https://www.quora.com/What-are-the-differences-between-solid-waste-liquid-waste-and-gaseous-waste

Anu Antoney (2017). What are some of the latest waste to energy technologies available? Prescouter. Available 6.1.2019: https://www.prescouter.com/2017/10/waste-to-energy-technologies-available/

BetacommandBot (2007). Cntrcrtspraytow. Available 26.1.2019: https://commons.wikimedia.org/wiki/File:Cntrcrtspraytow.jpg

Bernard Jacquinot, Hjelmar Ole and Vehlow Jurgen (2000). The influence of PVC on the quantity and hazardousness of flue gas residue from incineration. Bertin.

Bernd Von Der Heide (2008). Best Available Technology for NOx Reduction in Waste to Energy Plants. Milan

BSI (2015). Proposal for inclusion of a new source material in to the inventory list with classification codes for source materials. Carbon8 aggregate Ltd. Available 12.3.2019: http://www.ukqaa.org.uk/wp-content/uploads/2015/07/Carbon8-submission-for-EN-13055-v2.pdf

Carbon8 aggregate. Carbon8 aggregate Ltd FAQs. UK

Carbon8 webpage (2019). Our Process. Carbon8 aggregate Ltd FAQs. Available 30.1.2019: https://c8a.co.uk/our-process/

Charles H. K. Lam, Alvin W. M. Ip, John Patrick Barford and Gordon McKay (2010). Use of Incineration MSW Ash: A Review. ISSN 2071-1050

COMMISSION IMPLEMENTING DECISION (EU) 2018/1522 of 11 October 2018 laying down a common format for national air pollution control programmes under Directive (EU) 2016/2284 of the European Parliament and of the Council on the reduction of national emissions of certain atmospheric pollutants. Available 26.1.2019: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018D1522&from=EN

David Hosansky (2014). Flue gas treatment. Available 26.1.2019: https://www.britannica.com/technology/flue-gas-treatment

Department of Health (2005). The facts about ammonia. New York State. Available 07.3.2019: https://www.health.ny.gov/environmental/emergency/chemical_terrorism/ammonia_tech.htm

Dr Paula Carey (2018). Developing an innovative and profitable process that combines waste CO2 and thermal residues, to create a carbon negative aggregate for construction and lock CO2 in for good within our built environment. Carbon8 Systems. UK. Available 12.3.2019: nas-sites.org/dels/files/2018/02/1-5-CAREY-Carbon8-Systems-NAS.pdf

Enoch Afrane Gyasi (2018). Waste-to-energy, a solution to Ghana’s waste menace: A market entry for Finnish SMEs. University of Vaasa.

FCC Environment (2018). Whisby Landfill. FCC Recycling (UK) Ltd. Available 18.10.2018: https://www.fccenvironment.co.uk/apcr.html

GC/FN/JG/EIPPCB/WI (2017). Best Available Techniques (BAT) Reference Document on Waste Incineration. Circular Economy and Industrial Leadership Unit European IPPC Bureau. Joint Research Centre Science Hub

GifTagger (2014). Cyclonicspray. Available 27.1.2019: https://commons.wikimedia.org/wiki/File:Cyclonicspray.png

Haycarb (2019). Activated Carbon Basics. Available 3.2.2019: https://www.haycarb.com/activated-carbon

James Ng (2017). Company Presentation. Carbon8 aggregate Ltd

Jerry A. Nathanson (2010). Air pollution control. Available 25.1.2019: https://www.britannica.com/technology/air-pollution-control

J. Vehlow, B. Bergfeldt, C. Wilén, J. Ranta, H. Schwaiger, H.J.M. Visser, S. Gu, E. Gyftopoulou, J. Brammer (2007). Management of Solid Residues in Waste-to-Energy and Biomass Systems. Bioenergy NoE

Karl T. Ulrich and Steven D. Eppinger (2012). Product Design and Development. 5th Edition. Irwin McGraw-Hill.

Kim Crillesen, Jørgen Skaarup, Kirsten Bojsen, Henrik Ørnebjerg, Jörn Franck, Frans Lamers, Francis Angotti, Robert Morin and Martin Brunner (2006). Management of Bottom Ash from WTE Plants. An overview of management options and treatment methods. ISWA-WG Thermal Treatment Subgroup Bottom Ash from WTE-Plants

Lenntech (2019). Heavy Metals. Available 9.3.2019: https://www.lenntech.com/processes/heavy/heavy-metals/heavy-metals.htm

May021994 (2015). Flue gas desulphurization detailed process. Education. Available 10.2.2019: https://www.slideshare.net/may021994/flue-gas-desulphurization-detailed-process

Maczulak, Anne Elizabeth (2010). Pollution: Treating Environmental Toxins. New York. Infobase Publishing.

MCC (2018). Aggregate price per ton Portland oregon. Shanghai SBM Company. Available 23.3.2019: https://www.schoenmakerij-jandrenth.nl/2017_Jun_04-6782.html

MedPro disposal (2018). What is medical waste? Medical waste definition, types, examples and more. Available 8.1.2019: https://www.medprodisposal.com/what-is-medical-waste-medical-waste-definition-types-examples-and-more

M.J. Quina, E. Bontempi, A. Bogush, S. Schlumberger, . Weibel, R. Braga, V. Funari, J. Hyks, E. Rasmussen, J. Lederer (2018). Technologies for the management of MSW incineration ashes from gas cleaning: New perspectives on recovery of secondary raw materials and circular economy. Editor Frederic Coulon.

Mokomaki (2019). Westenergy converts your combustible waste into energy that powers your home and heats your house. ServicIT. WESTENERGY. Available 12.1.2019: https://www.westenergy.fi/?l=en

Mokomaki (2019). Process. ServicIT. WESTENERGY. Available 13.1.2019: https://www.westenergy.fi/?l=en&p=22&text=Process

National Center for Environmental Health (2018). Carbon Monoxide Poisoning. Centers for Disease Control and Prevention. Available 8.3.2019: https://www.cdc.gov/co/faqs.htm

National Pollutant Inventory (2019). Oxides of Nitrogen. Australian Government-Department of the Environment and Energy. Available 8.3.2019: www.npi.gov.au/resource/oxides-nitrogen-0

NITSCHKE Liquid Waste Blog (2015). What is Liquid Waste Disposal. Available 7.1.2019: https://www.nitschkeliquidwaste.com/what-is-liquid-waste-disposal/

Open chemistry database (2019). Hydrochloric Acid. National Center for Biotechnology Information. U.S. National Library of Medicine. Available 8.3.2019: https://pubchem.ncbi.nlm.nih.gov/compound/hydrochloric_acid

Open chemistry database (2019). Sulfur Dioxide. National Center for Biotechnology Information. U.S. National Library of Medicine. Available 8.3.2019: https://pubchem.ncbi.nlm.nih.gov/compound/sulfur_dioxide#section=Top

OSH (2019). Carbon Dioxide. Canadian Centre for Occupational Health & Safety. Available 8.3.2019: https://www.ccohs.ca/oshanswers/chemicals/chem_profiles/carbon_dioxide.html

P.Gunning, C.D.Hills and P.J.Carey (2013). Commercial application of accelerated carbonation: Looking back at the first year. Carbon8 Systems Ltd. Carbon8 Aggregates Ltd. University of Greenwich. UK.

R. Nagendran (2011). Waste. A Handbook for Management. Academic press. Elsevier.

R. Gumisiriza, Joseph Funa Hawumba, Mackay Okure and Oliver Hensel (2017). Biomass waste-to-energy valorisation technologies: a review case for banana processing in Uganda. Available 11.1.2019: https://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-016-0689-5

Rubbish Removal Blog (2016). There are 5 types of waste, do you know them all. 4 Waste Removals. Available 7.1.2019: https://4waste.com.au/rubbish-removal/5-types-waste-know/

Sari Piippo (2013). Municipal Solid Waste Management in Finland. University of Oulu. Greensettle Publications. Available 10.1.2019: http://nortech.oulu.fi/GREENSETTLE_files/Municipal%20solid%20waste%20management%20in%20Finland.pdf

Shuktiz Sinha (2015). What does organic and inorganic waste mean. Quora. Available 7.1.2019: https://www.wastenet.net.au/organic-waste.aspx

Siemens (2013). Process Analytics Minimizing Ammonia Consumption in DeNOx Plants In situ laser gas analyzer LDS 6 monitors NH3 slip in real-time

Techflow (2019). Pulse Jet Bag Filter - Pulse Jet Hose Bag Type Filter. Available 10.2.2019: https://techflow.net/pulse_jet_hose_bag_type_filter_or_pulse_jet_bag_filter.html

Tetronics International (2019). Waste disposal and treatment – how it works. Tetronics (International) Limited. Available 31.1.2019: https://tetronics.com/our-technology/how-it-works/

The European Parliament and of the Council of the European Union of 19 November 2008 on waste and repealing certain Directives. Available 6.1.2019: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN

The European Parliament and of the Council of the European Union of 30 May 2018 – amending Directives 2008/98/EC on waste. Available 30.1.2019:

https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0851&rid=5

Thermax Global (2018). Pulse Jet Bag Filters. Available 10.2.2019: https://www.thermaxglobal.com/thermax-air-pollution-control-systems/bag-filters/pulse-jet-bag-filters/

Thermax Global. Pulse Jet Bag Filters. Enviro Division. Custom engineered fabric filter system. Thermax Global Brochure

Vlaanderen (2015). Selective catalytic reduction. Available 25.2.2019: https://emis.vito.be/en/techniekfiche/selective-catalytic-reduction

WasteNet (2018). Organic Waste. Available 8.1.2019: https://www.wastenet.net.au/organic-waste.aspx

WESTENERGY (2018). 2017 Annual report. WESTENERGY. Available 13.1.2019: http://2017.westenergy.fi/en/production/

Will Date (2017). Defra scraps APC residue rule-change. Available 30.1.2019: https://www.letsrecycle.com/news/latest-news/defra-scraps-apc-residue-rule-change/

WOIMA Presentation (2018). WASTE-TO-ENERGY POWER PLANT. WOIMA Finland Oy

WOIMA wasteWOIMA® (2018). WOIMA Corporation Brochure – WASTE-WOIMA®.

WOIMA webpage (2018). WASTEWOIMA® – THE MODULAR WASTE-TO-ENERGY POWER PLANT. WOIMA Finland Oy. Available 24.1.2019: https://www.woimacorporation.com/technical-solution/

WOIMA (2018). Flue gas treatment system description. WOIMA flue gas treatment process. WOIMA Corporation Oy Brochure.

WOIMA Brochure (2018). WOIMA Corporation Brochure – Waste to energy solutions. WOIMA Finland Oy. Available 6.10.2018: https://www.woimacorporation.com/wp-content/uploads/2018/09/WOIMA-company-brochure-2018_10.pdf

WOIMA Blog (2018). Waste in Numbers 1/2. WOIMA Blog 12/2018. WOIMA Finland Oy. Available 3.1.2019: https://www.woimacorporation.com/woima-blog-12-2018-waste-in-numbers-1-2/

World Bank (2018). Solid Waste Management. waste and repealing certain Directives. Available 6.1.2019: http://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management

APPENDIX 1. Properties of waste which render it hazardous (ANNEX III)

- H 1 ‘Explosive’: substances and preparations which may explode under the effect of flame or which are more sensitive to shocks or friction than dinitrobenzene.
- H 2 ‘Oxidizing’: substances and preparations which exhibit highly exothermic reactions when in contact with other substances, particularly flammable substances.
- H 3-A ‘Highly flammable’ — liquid substances and preparations having a flash point below 21 °C (including extremely flammable liquids), or — substances and preparations which may become hot and finally catch fire in contact with air at ambient temperature without any application of energy, or — solid substances and preparations which may readily catch fire after brief contact with a source of ignition and which continue to burn or to be consumed after removal of the source of ignition, or — gaseous substances and preparations which are flammable in air at normal pressure, or — substances and preparations which, in contact with water or damp air, evolve highly flammable gases in dangerous quantities.
- H 3-B ‘Flammable’: liquid substances and preparations having a flash point equal to or greater than 21 °C and less than or equal to 55 °C.
- H 4 ‘Irritant’: non-corrosive substances and preparations which, through immediate, prolonged or repeated contact with the skin or mucous membrane, can cause inflammation.
- H 5 ‘Harmful’: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may involve limited health risks. H 6 ‘Toxic’: substances and preparations (including very toxic substances and preparations) which, if they are inhaled or ingested or if they penetrate the skin, may involve serious, acute or chronic health risks and even death.
- H 7 ‘Carcinogenic’: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce cancer or increase its incidence.
- H 8 ‘Corrosive’: substances and preparations which may destroy living tissue on contact.

- H 9 ‘Infectious’: substances and preparations containing viable micro-organisms or their toxins which are known or reliably believed to cause disease in man or other living organisms.
- H 10 ‘Toxic for reproduction’: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce non-hereditary congenital malformations or increase their incidence.
- H 11 ‘Mutagenic’: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce hereditary genetic defects or increase their incidence.
- H 12 Waste which releases toxic or very toxic gases in contact with water, air or an acid.
- H 13 ‘Sensitizing’: substances and preparations which, if they are inhaled or if they penetrate the skin, are capable of eliciting a reaction of hypersensitization such that on further exposure to the substance or preparation, characteristic adverse effects are produced.
- H 14 ‘Ecotoxic’: waste which presents or may present immediate or delayed risks for one or more sectors of the environment.
- H 15 Waste capable by any means, after disposal, of yielding another substance, e.g. a leachate, which possesses any of the characteristics listed above.

APPENDIX 2. Recovery operations (ANNEX II)

- R 1 Use principally as a fuel or other means to generate energy.
- R 2 Solvent reclamation/regeneration.
- R 3 Recycling/reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes).
- R 4 Recycling/reclamation of metals and metal compounds.
- R 5 Recycling/reclamation of other inorganic materials.
- R 6 Regeneration of acids or bases.
- R 7 Recovery of components used for pollution abatement.
- R 8 Recovery of components from catalysts.
- R 9 Oil re-refining or other reuses of oil.
- R 10 Land treatment resulting in benefit to agriculture or ecological improvement.
- R 11 Use of waste obtained from any of the operations numbered R 1 to R 10.
- R 12 Exchange of waste for submission to any of the operations numbered R 1 to R 11.
- R 13 Storage of waste pending any of the operations numbered R 1 to R 12 (excluding temporary storage, pending collection, on the site where the waste is produced).

APPENDIX 3. Disposal operations (ANNEX I)

- D 1 Deposit into or on to land (e.g. landfill, etc.).
- D 2 Land treatment (e.g. biodegradation of liquid or sludgy discards in soils, etc.).
- D 3 Deep injection (e.g. injection of pumpable discards into wells, salt domes or naturally occurring repositories, etc.).
- D 4 Surface impoundment (e.g. placement of liquid or sludgy discards into pits, ponds or lagoons, etc.).
- D 5 Specially engineered landfill (e.g. placement into lined discrete cells which are capped and isolated from one another and the environment, etc.).
- D 6 Release into a water body except seas/oceans D 7 Release to seas/oceans including sea-bed insertion.
- D 8 Biological treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations numbered D 1 to D 12.
- D 9 Physico-chemical treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations numbered D 1 to D 12 (e.g. evaporation, drying, calcination, etc.).
- D 10 Incineration on land.
- D 11 Incineration at sea.
- D 12 Permanent storage (e.g. emplacement of containers in a mine, etc.).
- D 13 Blending or mixing prior to submission to any of the operations numbered D 1 to D 12.
- D 14 Repackaging prior to submission to any of the operations numbered D 1 to D 13.
- D 15 Storage pending any of the operations numbered D 1 to D 14 (excluding temporary storage, pending collection, on the site where the waste is produced).

APPENDIX 4. Questionnaire for Westenergy

1. Does the waste stored for incineration release any pollutants? If yes how do you prevent it from going into the atmosphere? Yes, Closed bunker with Sealed connections to the incinerator.

2. How is it prevented that the fly ashes do not leak from the process? With a leak free closed system under high pressure.

3. What system is used to treat the flue gas? Ammonia and water to reduce NOx. And Dry sorbent injection uses cooling tower where there's only water injection, after that is the reactor where the reagents (slaked lime and activated carbon) and recirculated residues are added. LAB company provides the system.

4. Does increase in PVC and gypsum affect the APCr? It does not affect it so much due to the scrubber system, but it consumes more Ammonia and water.

5. Does the added chemical dosing quantity fluctuate during the day/year/seasons? If yes, how? Yes, it fluctuates but it depends on the moisture of the waste, the air and the heat in the furnace.

6. What system does the plant use in collecting the APCr? Fabric filter bags.

7. Does the APC system consume water and if yes, how much? Yes, depends on the mass flow and temperature of the flue gases. The cooling tower and the reactor combined consume slightly under $1m_3$/h.

8. Do the differences in the season affect the APCr chemical composition? No, only the waste composition affects the APCr but not so much.

9. What is the process used in removing the APCr? Conveyor belt, to a closed pressured cylinder, to tracks and to treatment site.

10. How often is the APCr removed from the plant? 2 tracks per week with each track collecting 40tonnes. The stored APCr is heated so it does not solidify.

11. What safety measures is taken when handling the APCr? Several high pressured open and closed systems. Track personals wear protective cloths.

12. How/where is the APCr stored and how large is the storage? The APCr is sent to Fortum environmental construction facility treatment located in Pori.

13. Does the chemical composition of the APCr change during storage? If yes when and how? It does not change. But contact Fortum for more details.

14. How is it prevented that the APCr do not leak from the storage? It solidifies.

15. Is the APCr ever relocated from storage? If yes, to where and when? No, it stays at landfill.

16. What caused the leakage in the waste feeding hoppers mentioned in the annual report? Warn out from constant metal friction.

17. What was it leaking? Water from cooling system.

18. What is the new flue gas scrubber Westenergy plans to use in the future? Is an improved flue gas scrubber condenser.

19. Have Westenergy looked in to APCr post-processing systems to treat the residue onsite? No, because of the low amount of waste incinerated and do not have license.

20. The sick leave rate according to the report was 2.98%. can you elaborate on what this was? Common flu or cold and if their children is sick.

APPENDIX 5. Questionnaire for WOIMA Oy

1. Is there any chemical added to the incineration process? If yes what? Yes, Urea or ammonia is used to reduce the NOx of the flue gas in the furnace.

2. How much quantity of APCr will the plant produce? The plant will produce 2…5% of APCr. Depending on the toxic components in the fuel.

3. What system does the plant use in it APC system? It is a dry APC-system. WOIMA power plant is equipped with hydrated Lime ($Ca(OH)_2$) and Activated Carbon dozing systems in the reactor and a fabric filter bag collect the APCr.

4. Does the APC system consume water and if yes, how much? Our standard plant does not require water for Flue gas treatment.

5. Does increase in metallic waste affect the APCr? Most metals are inert, so they do not affect the APCr. However heavy metals such as Zn, Hg and Pb etc. have some effect on APCr output.

6. Does increase in PVC and gypsum affect the APCr? Chlorine in PVC is one of the most problematic compounds. It forms HCl in incineration process (causes corrosion and increased chemical need). In smaller amounts, SO-gypsum will protect the plant from the corrosion and when the balance of Chlorine and SO is OK, the APCr output will not be affected. However, imbalance of the components will increase the chemical need and output of APCr.

7. Will the differences in the season affect the APCr chemical composition? Indirectly due to changes in the fuel (humidity, fuel temperature, components such as ash, chlorophyll etc.) but how it will affect the APCr is hard to define.

8. How often will the APCr be removed from the plant? Depends on storage size, logistics and disposal method.

9. What is the process used in removing the APCr from the plant? Standard big bag filling system which is properly sealed and regularly inspected for leakage.

10. What safety measures should be taken when handling the APCr from the system? All personal working in appropriate area, must wear protection equipment.

APPENDIX 6. Questionnaire for Carbon8 Aggregate Ltd

1. How long does the process take? All confidential information was erased.

2. How much quantity of water does the system use? Confidential information.

3. How much quantity of binder does the system use? Confidential information.

4. How much quantity of fillers does the system use? Confidential information.

5. How much quantity of CO_2 does the system use? Confidential information.

6. How much quantity of APCr to aggregate does the plant? Confidential information.

7. Does the quantity of ammonia affect the process? If yes how? Yes, it makes the plant units sticky. If that happen, we ask our APCr providers to reduce the ammonia content in their process.

8. Does the aggregate your plant produce face any environmental issues? No, however we asked our partiers to reduce the X-chloride in the APCr.

9. How is the aggregate stored? They are kept in a close storage which is collected by our partners for construction purposes.

10. Does the company plan to develop a smaller size plant? Yes, we are on the process of developing a portable plant.

11. How much are you payed to receive a tonne of APCr? The costs of APCr will be dependent on the country of disposal, for example the average cost of disposal in the UK for Landfill with Landfill tax rates plus a gate fee is approximately £110 per tonne. The recycling of the APCr in the UK works because the landfill tax rates is set by the government at £89.00 per tonne.

12. What is the selling price of your aggregate? Confidential information.

APPENDIX 7. Questionnaire for Tetronics International

1. How long does the whole process take? Here I assume you mean 'how long does the plasma treatment of a batch of APCr take?' On this basis, the process is a continuous one, with a continuous overflow of slag from the furnace to a slag casting/cooling system, e.g. a granulation tank or water-cooled slag conveyor. The typical residence time for waste material in the molten slag bath varies but is typically 1 to 2 hours.

2. Does the increase in ammonia quantity affect the process? If yes how? Interesting question and one we have not been asked before, to my knowledge. Certainly, this will increase the off-gas volumes produced by the plasma furnace (since it will all report to the off-gas system) but exactly what effect it will have is probably highly dependent on the other species in the waste. All plasma plants (not just for APCr) are supplied with off-gas abatement systems in compliance with EU regulations, including thermal oxidizers and other essential items. The interaction of all these items with the off-gas will need to be taken into account. Sorry I can't more help on that point.

3. How much quantity of water does the whole system use? The main use of water is for the off-gas system for quenching the thermal oxidizer exit gas and for the acid neutralization unit. Since both these items consume water differently depending on the APCr composition, it is difficult to give a single accurate answer. It is of course possible to use a venturi-style scrubbing/quenching/filtration system, which would lead to quite low water losses to steam. It also depends on whether residual HCl after the filter is wet-scrubbed (more water use) or recovered as hydrochloric acid (less water use). Water is also used for cooling the slag from the furnace, but often these are closed loop water cooling systems. If a decision is taken to cool the slag using an open water system, then losses to steam would also need to be taken into account. This is something we normally discuss with the client at the feasibility study stage, as there are several options, each with its own implications.

4. What is the flux you mix with the APCr before the plasma chamber? Lime-based APCr is high in lime but low in silica. Therefore, we usually add silica. The presentation attached gives some basic details of an example system.

5. What substance do you use in the quench column? Usually water, although air can also be used if regulations allow and the client expresses a preference.

6. How much ratio of primary APCr to secondary APCr does the plant produce? Depends on the APCr composition, especially the level of volatiles in the APCr. More volatile species (e.g. Na and K-based compounds, Pb, Zn, etc.) mean more secondary APCr. It also depends on the balance between dry and wet scrubbing – more dry scrubbing means more secondary APCr but less scrubber liquor and lower water consumption.

7. How is the secondary APCr managed? It is sometimes landfilled, but if the level of valuable heavy metals is high enough then it can be taken as an input for metal recovery (e.g. Zn), which reduces the cost and the amount of waste arising from the process.
8. What substance do you use in the acid absorption column? Typically, we assume sodium hydroxide. The off-gas system often sits outside our scope of equipment supply.

9. What is the clean gas composition? Mostly O_2, N_2, CO_2 and H_2O, in accordance with EU regulations.

10. What is the land size needed for the plant? Depends on the process requirements.

11. What is the energy consumption of the plant? The approximate electrical energy consumption required is typically around 900 to 1000 kWh per tonne of input APCr.

12. Since the off-gas system often sits outside your scope of equipment supply does that mean the HCl collection is also not included? If no how much estimated HCl will be collected every year. And how much money does your partners receive or give for the HCl to be used by other industries. A decision to collect HCl (or not) is made jointly by Tetronics and the client, based on how much HCl is likely to be created and whether there is a local market for the recovered acid. Where there is any doubt at the project concept stage, we usually find the economic model needs to be based on simply neutralising any residual HCl, although recovery of acid will tend to improve the economics and reduce the waste arising from the process.

13. How much money does your partners receive or give money for the molten slag to be used for construction? It is qualified by the UK Environment Agency as a product approved for sale as recovered (secondary) aggregate, which usually means a value of around €5 to €10 per tonne. In practice, this usually means being able to assume the slag is not a secondary waste and that someone will take it off site at zero cost.

14. What is the cost of the plant with and without HCl collection? Impossible to say without more project details.

15. Does your company own some of your plants? if yes how much will they charge for receiving and treating 1kg of APCr. If no how much does your partners charge for receiving and treating 1kg of APCr. We don't operate plants ourselves, but the treatment fee for APCr (or indeed any waste material) tends to be closely related to the cost of alternative disposal of the APCr, which normally means hazardous landfill.

16. How much does some of your partners pay each year for their Silica. The amount of silica needed depends on the APCr composition and can sometimes be

substituted by bottom ash (which tends to be much higher in silica then APCr), but only dry silica construction is required, so quite cheap.

17. The Plant uses 1.4t SiO_2 per hour at a Feeding time of 6,424h/yr. So, does it mean the plant uses 8,993.6t every year? Yes, correct. Note the annual 'feeding time' is a conservative figure for design and specification purposes. Operating hours are higher than this because of pauses in feeding for tapping operations, attaching of new electrode sections, minor maintenance, etc. and other activities when the feeding has to be paused.

18. The standard price of a plant that treat 30,000 tons of APCr a year? We would say CAPEX will be approximately £10m to £12m for the whole plant. As a general guide, the typical OPEX of the process (excluding capita payback) will be roughly £130 to £150 per tonne of APCr.

19. Does it need regular maintenance each year or only when it breaks down? All melting furnaces require relining regularly because of the erosion of the refractory by the liquid metal and slag. This will mean probably 1 shut down per year of 2 to 3 weeks. Unscheduled maintenance when the plant breaks down is on top of this, although of course everyone (plant suppliers, plant operators etc.) work hard to avoid this happening.

20. What is the cost of maintenance staff? This is included in the OPEX figure stated above (see Point 19).

21. Does the plant need special trained staff for regular operation? If Yes what is the cost of training? The CAPEX figure includes training costs by Tetronics.

22. How many employees is needed for every day operations of the plant? A typical plasma plant tends to have a total of 20 to 30 employees to cover shifts of operators, managerial and technical support staff. Depending on what other plant or operations are being carried out on the same site, typically at least one third of these could can be drawn from other on-site operations and possibly more. For day-by-day operation, we usually estimate around 15.