Esperance Minerals Ltd.

BATCH ROTARTY GASIFIER ASSESSMENT REPORT

Final

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1 EXECUTIVE SUMMARY

This Batch Rotary Gasifier Assessment Report presents an assessment of the batch rotary gasifier (**BRG**) technology, the batch rotary gasifier plant (**BRG Plant**) and the associated business model.

The BRG Plant is a novel technology for thermal treatment of E-waste developed by Wayne Breeze and Mark Riddiford, the principals of Greenenz Group Limited (**Greenenz Group**). Greenenz Group is a company registered and operating in New Zealand.

Revenue from the process can be derived from precious metals recovery and energy generation and in certain commercial environments additional revenue may also be derived from tipping fees and charges for secure destruction.

The fundamental unit operations incorporated in the BRG Plant design are:

- E-Waste receipt – whole electronic devices. Shredding may be required (excluding items with batteries).
- Pyrolysis
- Combustion
- Heat Recovery
- Gas Emissions Treatment
- Precious Metals Recovery

These unit operations are not new. Rather they are established industrial processes that are well understood. The novelty of the BRG technology is the way these unit operations are combined and the scale of the operation.

Most industrial waste treatment processes rely on large scale and high volume through put to be viable, which involves building a small number of high capital value plants and usually require high transport costs.

The BRG Plant is a small-scale batch operation that can be fabricated at relatively low cost and located close to the waste source or could be mobile. The design is very flexible so that a number of batch gasification chambers could be installed in parallel feeding a single secondary combustion chamber and energy generation BRG Plant, through to refining/smelting.

The design of the BRG Plant has been sufficiently developed and tested at pilot plant scale to demonstrate that it is robust and fit for purpose. A valuable solid concentrate can be produced which contains precious metals which can be extracted by traditional smelting processes.

The most likely revenue stream will be from gold and silver extraction from the solid residue that is left after E-waste pyrolysis. The gold in the residue is at a concentration of 250 – 350 mg/kg (= grams/ton = ppm) or 8.8 - 12.3 oz/ton. This converts to approximately 60 mg/kg (2.1 oz/ton) in the original E-waste which compares favourably with the ore grade from operating gold mines which on average is 1.1 mg/kg[1] or 0.039 oz/ton.

[1] *source http://www.visualcapitalist.com/global-gold-mines-deposits-ranking-2012/*

The flammable gas (syngas) produced from gasification can be burned to generate heat which has the potential to be converted to useful energy in the form of either electricity or a heating fluid (steam, hot water, hot oil etc.) depending on end user requirements. There are a wide range of potential uses for the energy generated from the BRG Pant. One of particular interest is the ability to convert the energy to electricity using it to charge batteries for local use rather than export it to the mains grid.

Further, selected e-waste will also attract significant “tipping” or data destruction fees.

Air emissions testing has been carried out which shows that, with the addition of an emissions treatment system, the BRG Plant can be made to comply with the most stringent worldwide air quality standards.

Notwithstanding the comments above, the BRG Plant design still needs further refinement and testing in the areas of: - rotatory drum geometry, rotary union (joint between rotary drum and fixed piping), gas emissions treatment, instrumentation (temperature and pressure), process safety and pressure relief. These are minor design refinements and not significant design changes. This development work is currently being undertaken by Lodge-Cottrell (www.lodgecottrell.com) in the UK a emissions equipment supply company.

Lodge Cottrell are currently amending the BRG Plant design, having already installed the Pilot Plant on a selected site in the UK for further trials before progressing to a working commercial operation.

The site in the UK is already permitted to allow the BRG to operate commercially.

Conclusion

The main conclusion of this report is that the BRG process is a viable method for treating E-waste with potential revenue streams from precious metals recovery, energy generation, tipping fees and data destruction fees.

2 INTRODUCTION

This report presents an independent assessment of an innovative technology for thermal treatment of electronic waste (E-waste) to produce a valuable solid residue (concentrate) containing precious metals. The process also generates heat which can be utilised as an energy source. Precious metals can be recovered from the concentrate by traditional extraction methods, either smelting or hydrometallurgy.

2.1 History of Pyrolysis

The complex and diverse material content in the electronic equipment makes it ideal for recycling. At the same time, the presence of hazardous contents such as flame retardants and heavy metals makes it difficult to process using traditional recycling methods. An enormous amount of E-waste is either landfilled or incinerated, which results in leaching of chemicals and emission of toxic gases respectively.

Historically pyrolysis has been used since ancient times for converting wood to charcoal, which has a higher heat value, and was more useful as a fuel for high temperature processes e.g. metal working. More recently pyrolysis has been used for waste treatment. Worldwide there is a growing awareness of climate change and increased pressure to divert waste away from landfills. This has led to an increase in the development of industrial thermal waste treatment processes with a wide variety of capacities and different process conditions.

Pyrolysis is a well-established technology for thermal treatment of waste containing carbon-based materials.

2.2 BRG Process

The BRG process involves SIX (6) unit operations and is shown in Figure 2-1 Process Flow Diagram below:

1. E-waste receipt and shredding if required
2. Pyrolysis (primary chamber and heating chamber)
3. Combustion (secondary chamber)
4. Heat Recovery
5. Emissions Treatment
6. Precious Metals Recovery

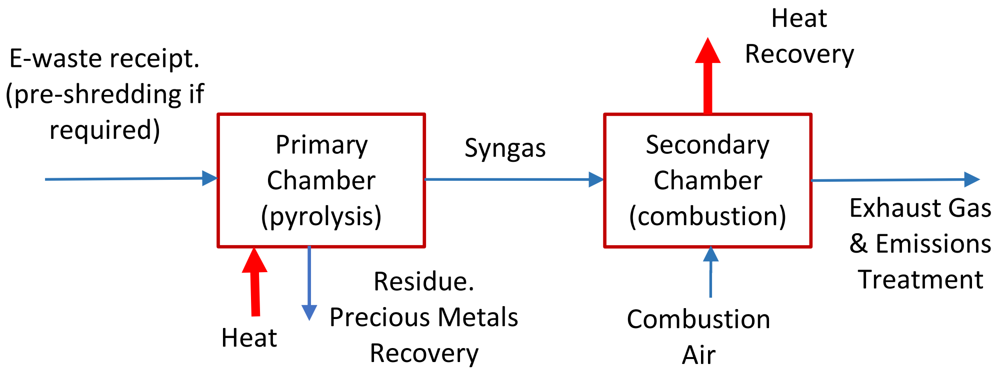

Figure 2-1 Process Flow Diagram

The fundamental process is Pyrolysis[2] which occurs in the Primary Chamber and converts the volatile organic components (plastics) of the E-waste, at high temperature (approx. 500C), in an inert atmosphere (zero oxygen) into a flammable gas (syngas) and leaves behind a solid residue.

The process is closely related to Gasification[3] which occurs at higher temperature (>700C) in a controlled, low oxygen atmosphere. Gasification is sometimes called “partial combustion” with the main combustion product being carbon monoxide rather than carbon dioxide. In this report the terms Pyrolysis and Gasification are used interchangeably.

2.3 BRG Features

There are several features of the BRG Plant that make it unique compared with other E-waste treatment processes: -

- Small Batch Process
  The small size and batch processing make the BRG ideal for processing a selected specific waste stream. It is ideal for secure destruction of electronic equipment where it will be economic to treat a relatively small quantity of electronic equipment, perhaps from a single customer.
  This small size also makes the process very flexible in that an installation is scalable by installing a number of BRG Plants in parallel to match demand.
- Batteries destruction
  The BRG Plant is able to treat (destroy) a variety of electronics batteries including lithium-ion type by pyrolysis without having to remove them from the devices. Testing has shown that batteries break down and the casings fail suddenly at a certain point in the cycle. This releases the batteries contents with nickel, cadmium and Lithium to be blended and recovered along with the other materials.

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[2] Pyrolysis – “ … thermal decomposition of materials at elevated temperatures in an inert atmosphere …” https://en.wikipedia.org/wiki/Pyrolysis
3 Gasification – “ . converts organic … materials into carbon monoxide, hydrogen and carbon dioxide …at high temperatures (>700 °C) … with a controlled amount of oxygen …” https://en.wikipedia.org/wiki/Gasification

2.4 E-Waste Receipt

The rate of pyrolysis increases with increased surface area of the material being processed. Other E-waste processing plants achieve increased surface area by shredding the waste. This is an option for the BRG Plant but trials so far have shown that whole devices like mobile phones and laptops can be loaded into the primary chamber and successfully processed.

The BRG design lends itself to receiving whole electronic waste devices and processing them with a minimum or in most cases no manual sorting. The rotary drum design allows grinding balls to be added to assist with pulverising the devices and providing extra surface area which will increase the rate of pyrolysis and syngas generation.

2.5 Pyrolysis (Primary Chamber)

This step involves creating an inert atmosphere (zero oxygen) inside the primary chamber and heating the waste to approx. 500C to produce syngas – a flammable mixture of hydrocarbons and hydrogen.

The current design introduces argon from cylinders via a pressure regulator to maintain a small positive pressure which creates the inert atmosphere and prevents the ingress of air from outside the chamber.

Pyrolysis occurs in the primary chamber which has TWO main components: -

- Primary Heating Chamber
- Primary Rotary Drum - fitted inside the Heating Chamber

The Heating Chamber is a refractory lined “box” fitted with an LPG fired burner which provides indirect heating to the E-Waste. The burner flame and hot combustion gases heat the rotary drum which in turn heats the E-waste.

Syngas is generated within the Rotary Drum by thermal decomposition of the organic compounds in the E-waste. Currently combustion gases and syngas become mixed before flowing to the secondary combustion chamber.

2.6 Precious Metal Recovery

The solid residue (concentrate) left after pyrolysis contains non-volatile carbon compounds (char), metals and inorganic solids. The concentrate has been analysed by Kemetco (kemetco.com) and has been shown to contain precious metals at levels that have been shown to be at concentrations that are commercially viable for recovery. Precious metals include gold, silver, copper, palladium and numerous other high value rare earths as detailed in fire assay reports.

The analysis results for the key precious metals are shown in Table 2-1 below.–.

Table 2-1 Precious Metals Analysis Results

Element	Sample 1 (computers) mg/kg	Sample 2 (Printed Circuit Boards) mg/kg	Sample 3 (mobile phones) mg/kg
Gold (Au)	248	371	264
Silver (Ag)	1142	1,181	1,403
Platinum (Pt)	0.59	0.43	1.19
Palladium (Pd)	19.3	36.2	18.1
Rhodium (Rh)	0.08	0.03	0.03
Ruthenium (Ru)	1.85	2.42	0.51
Iridium (Ir)	<0.02	<0.02	<0.02

Test Method: Fire Assay

As a rough comparison the highest reported grade of ore in a producing gold mine 2012 is 33 mg/kg (or grams per ton) and the average grade is 1.1 mg/kg

source http://www.visualcapitalist.com/global-gold-mines-deposits-ranking-2012/

2.7 Combustion (Secondary Chamber)

The combustion (secondary) chamber is standard technology used in most gas fired heating equipment such as boilers. Syngas flows from the primary chamber into the combustion chamber by a pressure differential. It is mixed with air (combustion air) and ignited by an LPG fired burner. The LPG burner protects against a build-up of uncombusted syngas which could explode in an uncontrolled way. It also maintains the desired combustion chamber temperature of 1000 degrees centigrade in the event that the fuel value (calorific value or heating value) of the syngas decreases. The target is to achieve complete combustion i.e. complete conversion of hydrocarbon and hydrogen to carbon dioxide and water, so excess combustion air is added.

2.8 Heat Recovery

The heat generated in the secondary chamber is available to be converted into useful energy by traditional technology. Below is a list of potential energy conversions that could be utilised: -

- Heat → Steam
- Heat → Hot Water
- Heat → Hot Oil
- Heat → Steam → Electricity

The BRG Plant energy conversion to electricity has a number of innovative options e.g. battery charging, that are being explored by Greenenz Group but are not discussed further in this report.

2.9 Emissions Treatment

The final air emissions from the secondary chamber will require treatment to remove hazardous components and meet the strictest regulatory limits.

This air emissions treatment technology is well established and readily available. It is discussed in more detail in Section 3.6

3 TECHNOLOGY ASSESSMENT

3.1 Technology Development

The BRG technology has been developed over several years by Wayne Breeze and Mark Riddiford, principals of Greenenz Group Limited (www.greenenz.com), a company incorporated and operating in New Zealand. A US patent application was lodged for the BRG technology in August 2017.

The BRG Plant design has progressed through two small scale BRG Plants to the point of building a 500kg capacity pilot BRG Plant (**Pilot Plant**). The contracted fabrication for the development work was carried out by contracted service provider TruFlow Systems in Utah, USA which is where the trials were conducted.

Figure 3-1 below shows the Pilot Plant installed for testing at TruFlow.

The Pilot Plant has been purchased by Lodge Cottrell and relocated to its headquarters in Birmingham, United Kingdom. Ongoing testing and commercial trials are being conducted by Lodge Cottrell on-site in the United Kingdom as part of an on-going upgrade of Greenenz's BRG technology.

3.2 Design Description

Key aspects of the BRG Plant design are described below.

3.2.1 Materials of Construction

- Structural members — Mild steel
- Primary Rotary Drum — Stainless Steel
- Primary Heating Chamber — Mild Steel, refractory lined
- Gas Ducting — Mild steel with external insulation
- Secondary (Combustion) Chamber — Mild Steel, refractory lined
- Vent Stack — Mild Steel

Figure 3-1 BRG Pilot Plant

3.2.2 Primary Rotary Drum

The primary rotary chamber is a high temperature stainless steel rotating drum. The chamber is mounted on rollers and connected to a variable speed drive. The internal surface of the drum is fitted with curved blades (similar to a concrete mixer) for mixing and conveying solids. See Figure 3-2 below.

Figure 3-2 Inside Primary Rotary Drum

The drum is designed to serve as a dual-purpose unit – for size reduction by means of grinding balls and gasification by heating. Grinding balls are added with the E-waste solids to pulverise which increases the surface area and speeds up the pyrolysis process.

3.2.3 Inert Atmosphere

An inert atmosphere is maintained inside the rotary drum by supplying Argon via a rotary union at the drive end and a series of pipes mounted on the outside of the drum, see Figure 3-3 below. The argon is supplied from a gas cylinder via a regulator to maintain a small positive pressure within the drum. A small amount of argon will flow with the syngas on to the secondary combustion chamber.

Figure 3-3 Rotary Drum – Inert gas pipes.

3.2.4 Heating Chamber

This is a refractory lined steel chamber fitted with a natural gas burner and combustion air fan. Hot combustions gasses indirectly (through the drum wall) provide the heat to the Rotary Drum for pyrolysis. Exhaust gases from the Primary Heating Chamber are mixed with the syngas generated from the Rotary Drum and then flow to the Secondary Chamber.

At the top of the Primary Chamber is a rotary union to allow a gas tight seal between the Rotary Drum and the fixed duct work.

Heating of the E-waste is achieved by indirect heating through the wall of the rotating drum.

3.2.5 Secondary (Combustion) Chamber

The secondary chamber is a “standard” chamber design for syngas processing. This chamber is fabricated with refractory lined mild steel. It is directly connected to the Primary Chamber via ducting. The secondary chamber has its own burner and combustion air fan to maintain the required temperature of at least ≥ 1,050C to comply with for air emissions standards.

3.2.6 Vent Stack

The Vent (exhaust) Stack is a crucial part of the process to control the Secondary Chamber pressure and discharge of exhaust gases. The Vent Stack is fitted with an induced draft fan which develops a vacuum on the discharge end of the Secondary Chamber to control secondary chamber pressure. Sampling ports are installed on the Vent Stack for air quality measurements.

3.3 Plant Trials

The BRG design has developed through THREE stages using several feedstocks (phones, laptops, computer towers and shredded PCBs): -

1. Mark I — small scale (approx. 10 kg of E-waste) static gasification chamber.
   No Mk I trials are discussed here
2. Mark II — small scale (approx. 20 kg of E-waste) rotary drum (pods) gasification chambers. Initial trials had four pods installed inside a single primary heating chamber. Subsequent trials used just a single rotary drum.
3. Pilot Plant — A large capacity (approx. 500kg of E-waste)

A selection of trial data is presented below along with the applicable BRG Plant configuration and trial process variables : -

- **Mk II - Trial # 1**

Feed stock		Printed Circuit Boards (PCBs)
Number of gasification chambers (pods)		4
Batch quantity (per pod)	Pod # 1	16kg PCBs, zero grinding balls
	Pod # 2	16kg PCBs, 9 kg grinding balls
	Pod # 3	9 kg PCBs, 9 kg grinding balls
	Pod # 4	16 kg PCBs, 9 kg grinding balls
Primary Chamber (Gasification)Temp.		650 C
Secondary Chamber (Combustion) Temp.		1,000 C

- **Mk II - Trial # 3**

Feed stock	Printed Circuit Boards (PCBs)
Number of gasification chambers (pods)	4
Batch quantity (per pod)	18kgs PCBs, 18kgs grinding balls
Primary Chamber (Gasification) Temp.	650 C

Secondary Chamber (Combustion) Temp.	1,000 C

- **Mk II - Trial # 4**

Feed stock	Printed Circuit Boards (PCBs)
Number of gasification chambers (pods)	1
Batch quantity (per pod)	18kgs PCBs, 18kgs grinding balls
Primary Chamber (Gasification)Temp.	650 C
Secondary Chamber (Combustion) Temp.	1,000 C.

- **Mk II - Trials #7, #8, #9, #10**
  This series of tests was arranged to allow air emissions testing to be carried out. The test variables are described in Section 3.5 below

- **Pilot Plant – Trial #3**

Feed stock	Shredded desk top computer towers.
Number of gasification chambers (pods)	1
Batch quantity	500kg e-waste
Primary Chamber (Gasification)Temp.	540 C
Secondary Chamber (Combustion) Temp.	1,000 C

3.4 Precious Metals Testing

The concentrate (solid) residue left after pyrolysis contains a range of precious metals. This is based on analysis work carried out by Kemetco Research Inc. (www.kemetco.com) and Greenenz Group at levels that establish the recovery of gold, silver, copper, tin, palladium and magnesium is viable.

It should be noted that the best metals extraction process is still being trialled by Kemetco (www.kemetco.com) and will be decided by consideration of extraction efficiency and the commercial economics of the process.

3.5 Air Emissions Testing

Air testing shows that emissions from the BRG Plant do not meet US Ambient Air Quality Guidelines without the addition of an Air Emissions Treatment system. Air testing and a proposed air emissions treatment system are detailed below.

As part of the trials conducted at TruFlow, air emissions testing was carried out by American Environmental Testing Inc. (www.americanenviroinc.com)

Four trial runs were arranged. The trial variables are summarised in

Table 3-1 below.

Table 3-1 – Air Emissions Tests – Trials Summary

Trial Number	**1**	**2**	**3**	**4**
Feedstock	PCBs	Desktop computers	Laptops incl. batteries	Laptops - no batteries
Batch quantity	18 kg E-waste 18 kg grinding balls	13.2kg E-waste 18 kg grinding balls	15.9 kg E-waste 18 kg grinding balls	13 kg E-waste 13.6 kg grinding balls
Gasification Temp (primary chamber)	650 C	650 C	650 C	650 C
Combustion Temp. (secondary chamber)	1,000 C	1,000 C	1,020 – 1,083 C	1,060 C

The results of the trials have been summarised and presented in Table 3-2 below. Note that Table 3-2 also includes a check against the maximum contaminant levels specified in the Lodge-Cottrell proposal for the Air Emissions Treatment system - see Section 3.6 below

Table 3-3 below presents the BRG air emissions data compared with the limits set by US National Ambient Air Quality limits.

The subject of air quality emissions analysis is complex and outside of the scope of this report. The raw data needs to be treated with caution and must be interpreted taking into account the sampling and analysis method. Also, air quality limits are applied at a point where members of the public are exposed, generally the site boundary. Testing is always done at a discharge point. Air dispersion modelling is required to predict the contaminants concentration at a site boundary based on the values at the discharge point. No dispersion modelling has been done here within the scope of this report and all comparisons with air quality limits is based on data at the discharge point.

That said it should be noted that the air emissions values for sulphur dioxide and nitrogen oxides exceed the air quality limits but can be brought in to compliance with an emissions treatment system (See sections 3.6 and 3.7 below). All other results are less than the applicable air quality emissions limits and therefore compliant.

Table 3-2 Summary of Air Emission Testing Results[4]

BRG Plant Emmissions

Ref: "IN-HOUSE TESTING FOR THE DETERMINATION OF PATICULATE (PM), HYDROCHLORIC ACID, GASES AND METAL CONCENTRATIONS IN THE GASIFIER LOVATED AT TRU-FLOW PLANT IN MAGNA, UTAH"

Date: 22 May 2017

Author: Mr V. Brent Benson (Technical Director), American Environmental Testing Inc.

	units	PM Total Particulates	HCL	SO_2	NO_x	CO	Lead	Cd	Hg	VOC
Input Data										
Emission Rate	lbs/DSCF	7.99 E-06	1.46 E-06				6.75 E-10	2.50 E-10	4.46 E-11	
	ppm (=mg/m^3)			1.103	62.27	2.34				3.72
Reference Data										
Density Dry Std Air	kg/m^3	1.225	1.225				1.225	1.225	1.225	
Conversion	lbs/kg	2.205	2.205				2.205	2.205	2.205	
Conversion	ft^3/m^3	35.31	35.31				35.31	35.31	35.31	
Calculated Values										
Emission Rate	kg/m^3	1.03 E-07	1.87 E-08				8.67 E-12	3.21 E-12	5.73 E-13	
	µg/m^3	102.66	18.70				0.0087	0.0032	0.0006	
	ppm (=mg/m^3)	0.08	0.02	1.103	62.27	2.34	7.08E-06	2.62E-06	4.67E-07	3.72
Lodge Cottrell Max. Values specification for emmissions treatment plant										
	µg/m^3						20.6	4.2	1.8	
	ppm (=mg/m^3)	189	29	5	154	5.3				14.6
	COMPLIES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Table 3-3 Air Emissions data vs US National Air Quality Standards[5]

BRG Emmissions v US Air Quality Standards by: G. Farrelly 3-May-2018

State		Particulates: Total Suspended Particulates				Particulates: PM_{10}		Particulates: $PM_{2.5}$		Sulfur Compounds: SO_2				Sulfur Compounds: H_2S	Sulfur Compounds: Tot. red. S	CO		NO_2		Ozone O_3		Lead Pb	
		24hr ave.	7d ave.	30d ave.	Ann. geo. mean	Ann. arith. ave.	24hr max. (1)	Ann. arith. ave.	24hr ave.	24hr max. (1)	3hr max. (1)	1hr max. (1)	Ann. arith. ave.	1hr ave.	1/2 hr ave.	8hr ave. (1)	1hr max. (1)	1hr ave.	Ann. arith. ave.	8hr ave.	1hr ave.	30d ave.	Rolling 3mth ave.
Abbr		µg/m^3	µg/m^3	µg/m^3	µg/m^3	µg/m^3	µg/m^3	µg/m^3	µg/m^3	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	µg/m^3	µg/m^3
BRG Plant Emmissions		102										1.10					2.34	62.3				0.009	
NATIONAL AMBIENT	Primary (2)						150	12	35			0.075				9	35	0.10	0.053	0.07			0.15
AIR QUALITY	Seconday (2)						150	15	35		0.50								0.053	0.07			0.15

3.6 Air Emissions Treatment Proposal

The final air emissions from the secondary chamber will require treatment to remove hazardous components and meet regulatory limits.

Greenenz Group has obtained from Lodge-Cottrell a proposal for an emissions treatment system that can be installed on the back end of the BRG. The proposal for a 2 t/d E-waste BRG Plant and is based on the results of the American Environmental Testing report. The omissions treatment system prepared by Lodge Cottrell will bring the sulphur dioxide and nitrogen oxide omissions referred to in section 3.5 above within the air quality limits set by US National Ambient Air Quality limits.

[4] PM = Particulate Matter, VOC -= Volatile Organic Compounds,

[5] PM10 = PM less than 10 µm, PM2.5 = PM less than 2.5 µm

The proposed Air Emissions Treatment system has the following features: -

- Venturi reactor
- Catalytic ceramic filter
- Sodium bicarbonate injection system from big bag with water mixing
- Powdered Activated Carbon (PAC) injection system from big bag
- Ammonia water injection system
- Equipment to be supplied ex. Korea.

The system comprises a cooling stage venturi reactor, where the cooling water and sodium bicarbonate solution and 25% ammonia water are injected directly into the gas stream. This stage will provide residence time for both the sodium bicarbonate and ammonia while also cooling the gases from 800°C down to 350°C.

The most stringent global emission standards identified for waste incineration processes are:

- **United States emissions standards:**
    - USA 40 CFR (Protection of Environment) Parts 60 & 62; and
    - Maximum Acheivable Control Technology (MACT) standards; and
- **European emissions standards:** Industrial Emissions Directive (IED) and EU 2006WID.

The BRG Plant will be designed to comply with the most stringent requirements of both the United States and European emissions standards and as such should be deemed suitable for World Bank financing.

3.7 Design Development – Lodge Cottrell July 2018

Lodge Cottrell has acquired the Pilot Plant that was situated at the Tru-Flow site, and moved it to Lodge Cottrell's site in the United Kingdom for the next development stage.

At the time of writing Greenenz Group has engaged Lodge Cottrell (www.lodgecottrell.co.uk) to develop and improve the BRG Plant design as part of the on-going development of the BRG technology.

Main changes suggested are as follows: -

1. Separate off take for the syngas line going to the thermal oxidiser. This is to stop mixing of the combustion and syngas as this may lead to auto combustion of the syngas in the ducting.
2. Separate off take for the combustion gases going to the thermal oxidiser. Reason for design is stated as above.
3. A secondary stationary seal in place to reduce the amount of air entering the syngas line (this is separate to the rotating seal). An increase in oxygen content can cause the syngas to auto combust in the duct work.
4. Baffle plates inside the secondary chamber to reduce mixing of combustion gas and syngas and to help with controlling the process.

5. A bypass duct taken off the combustion gas ducting, this gas flow will enter the primary chamber when the oxygen content is low. Benefits include reduced cost for inert gas, as well as heat recovery into the primary chamber.
6. The air fan supplying air to the secondary chamber for combustion has an off take to the inert gas line. This is to be used to cool the primary chamber to reduce cooling down time.
7. Coaxial ducting of the syngas duct and combustion gas duct is shown on the updated P&ID. The heat from the combustion gas will keep the syngas hot to reduce the chance of tars from condensing out. The use of the coaxial duct will be determined once the location of the unit is confirmed and the distance to JBR cut in point is established

These are all improvements that make the BRG Plant more viable.

4 MASS AND ENERGY BALANCE

A key tool for determining the amount of useful energy that can be produced from the BRG Plant, and potential revenue from it, is an analysis of the mass and energy inputs and outputs, referred to as the Mass and Energy Balance.

In general terms E-Waste consists of the following material fractions: -

a) Plastics – casings, buttons, cable insulation, printed circuit boards. Under pyrolysis/gasification, plastics yield volatile materials and solid (char) residue.

b) Precious Metals – Gold, Silver, Copper

c) Base Metals – Iron, Aluminium

d) Inert Non-metallic Materials – glass, silica,

4.1 Mass and Energy Variability

The Mass and Energy Balance for this process is complex and difficult to model due to the variability of E-waste composition. The E-waste composition variability arises for two reasons: -

1. E-Waste Source Variability
   To be viable the BRG Plant needs to be able to process E-waste from a variety of sources. This immediately introduces composition variability. For example, laptop computers are one E-waste stream that could be processed by the BRG. Laptops from different manufacturers will naturally have a different composition in terms of precious metals and plastic and flame retardants used.
2. Contamination from other waste
   When items of electronic equipment have reached the end of their useful life and are being disposed of, they are often stockpiled, sometimes for a long time, and inevitably other rubbish or waste items get added to the pile. This contamination by other waste types adds variability to the E-waste stream to be processed. Either the additional waste types must be handled by the BRG Plant or additional sorting must be done at the front end to remove it.

4.2 Mass and Energy Balance Assumptions:

The Mass and Energy Balance for the BRG Plant has been based on a set of assumptions.

These assumptions will need to be verified by further E-waste analysis and BRG Plant trials and the Mass and Energy Balance adjusted accordingly.

Assumption 1: Typical E-Waste Plastics Composition[6]

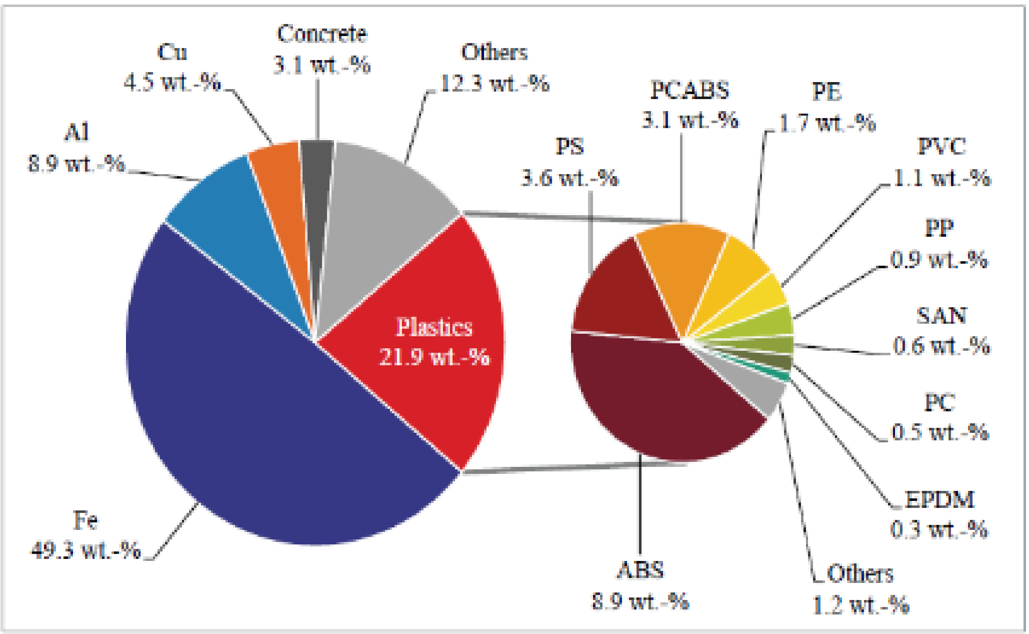

Fig. 1. Average composition of collected WEEE in the European Union for 2012 (without categories 5, 8, 9, 10; composition stands for 98.6 wt.-% of all WEEE collected) (Eurostat, 2015; Haig et al., 2012; Reuter et al., 2013)

Note: graphic is only used for plastics composition; other materials are not applicable to BRG.

Assumption 2: Pyrolysis Products (Wt. %)

Solids (Recyclable Metals & Concentrate)	50%
Liquids (Tar/Oil)	0% *
Gas (syngas)	50%

* most literature indicates that there is a significant liquid/tar fraction produced during pyrolysis. The BRG Plant trials found negligible liquid residue and the zero value has been used in this analysis for simplicity.

Assumption 3: Syngas Composition

Syngas from pyrolysis/gasification of plastics is a complex mixture of hydrocarbons, hydrogen, carbon monoxide and carbon dioxide.

To date no sampling or analysis on the BRG syngas has been possible so an assumed composition has been used. Stack testing and analysis has been carried out for the final emissions from the secondary chamber.

[6] Plastics Types: PS = polystyrene, PCABS = Blend of PC and ABS, PE =-polyethylene, PVC = polyvinylchloride, PP = polypropylene, SAN = styrene-acrylonitrile, PC = polycarbonate, EPDM = ethylene propylene diene monomer rubber, ABS = acrylonitrile butadiene styrene

Assumption 4: Heating Values (Lower Heating Value)[7]

Syngas	11.9 MJ/kg
	18.2 MJ/m3

4.3 BRG Mass & Energy Balance Results

Below is a summary of the Mass and Energy Balance results

Batch size	1,000 kg
Number of Primary Chambers	2
Batch time	4 hours
Total number of batches per day	10
Number of operating days per year	330
Total amount of E-Waste per year	3,300 t/y
Syngas generation	5,000 kg/day
Thermal Heat Output	59,500 MJ/day 690 kW
Electrical Power Output	210 kW (assuming 30% conversion)
Est. no. households powered	225 (assuming 8,000 kWh/yr. per household) from a single BRG Plant with the above

configuration.

[7] Lower Heating Value = nett heating value after any water has been evaporated (ref. https://en.wikipedia.org/wiki/Heat_of_combustion)

5 CONCLUSIONS

1. The main conclusion of this report is that the design of the BRG Plant has been sufficiently developed and tested at a pilot plant commercial scale to demonstrate that it is robust and fit for purpose.
2. The Pilot Plant trials demonstrate that a wide range of electronic devices – both whole and shredded can be processed through the BRG Plant
3. A valuable solid concentrate can be produced which contains precious metals which are able to be extracted by traditional smelting or hydrometallurgical processes. The most efficient extraction method is still being investigated.
4. The syngas produced can be burned to generate heat which can then be converted to useful energy in the form of either electricity or a heating fluid (steam, hot water, hot oil etc.) depending on end user requirements. In particular, one potential use for the electricity generated is to charge storage batteries rather exporting it to the mains grid. This would lend itself to local use contingent upon the BRG Plant siting close to potential users.
5. Air emissions testing shows that, with the addition of an air emissions treatment system on the back end of the BRG Plant, discharges from the BRG Plant can be made to comply with the most stringent international air quality standards.
6. Further design improvements are possible to make the BRG Plant more efficient.

6 HAZCOM PROFILE

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Director/Owner	Graham Farrelly

Graham Farrelly BSc, BE (Chemical & Materials)

I am a highly experienced Process Engineer with 25+ years in chemical safety, hazardous substances compliance and engineering projects. I have extensive experience in process plant design, technology assessment, plant commissioning and operation. Assessments and designs and prepared against national and international engineering standards I provide direction and advice on "best industry practice" relating to storage, handling and processing of hazardous substances. I have expertise in the current NZ Hazardous Substances Regulations and Major Hazard Facilities Regulations. I provide Safety and Risk Engineering utilising techniques such as HAZOP, FMEA, HAZAN and Hazardous Area Classification. I combine expert technical skills with a hands-on approach and excellent people skills to achieve successful projects.

Employment History

- Hazcom Ltd. – Director/Senior Process Engineer Mar. 2018 - present
- Fitzroy Engineering – Senior Process Engineer 2013 – Feb. 2018
- Waste Management Ltd. (ex. TPI Group (NZ) Ltd.) – Compliance Manager 2010 - 2013
- URS NZ Ltd. (now Aecom) - Associate, Senior Process Engineer, 2008 - 2010
- Omnia-Primaxa Ltd. (agri-chem & fertiliser manuf.) - NZ Ops Manager, 2006 - 2008
- URS NZ Ltd. (now Aecom) - Process Engineer, 1993-2006
- Watercare Services Ltd. Auckland, NZ – Process Engineer, 1993
- John Brown Engineers and Constr. Ltd, London, UK - Lead Process Engineer, 1991-1992
- Badger Catalytic Ltd, New Malden, UK - Process Engineer, 1990-1991
- New Zealand Steel Ltd - Production Engineer/Metallurgist, 1986-1990