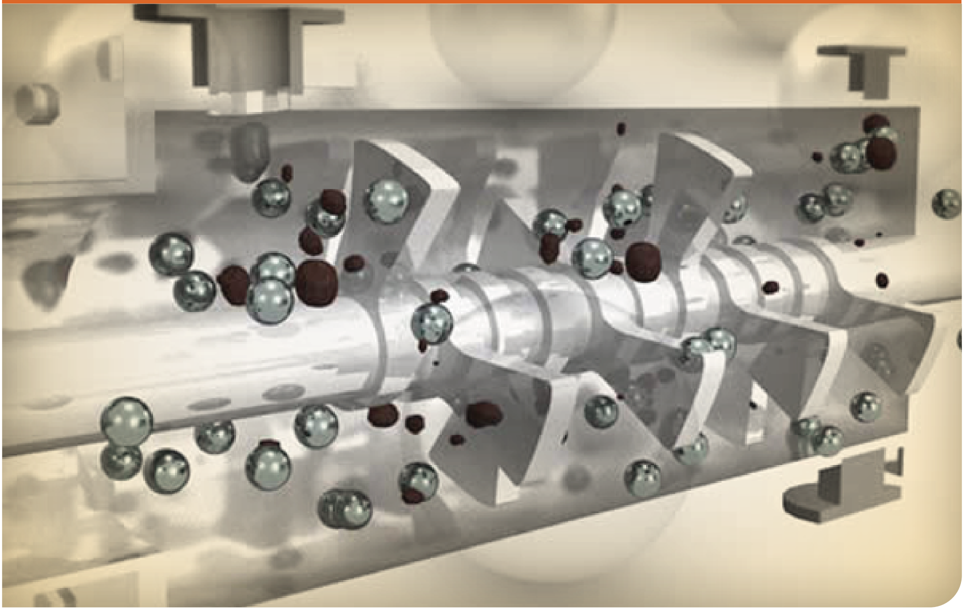
NON-COMBUSTION TECHNOLOGY FOR POPs WASTE DESTRUCTION

REPLACING INCINERATION WITH CLEAN TECHNOLOGY

April 2021



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NON-COMBUSTION TECHNOLOGY FOR POPs WASTE DESTRUCTION

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IPEN is a network of over 600 non-governmental organizations working in more than 120 countries to reduce and eliminate the harm to human health and the environment from toxic chemicals.

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Front cover photo: (top) **ecoSPEARS**, (bottom) **Mechano-Chemical Destruction (MCD) technology, EDL Europe.**

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EXECUTIVE SUMMARY

Non-combustion technologies for the destruction of persistent organic pollutant (POP) waste have been developed and commercialised since the 1990's. They provide a non-polluting and effective alternative to incineration of POPs waste, an old technology which continues to release and emit unintentional POPs (UPOPs). Incineration has become a trap with a never-ending cycle of attempted POPs waste destruction followed by more unintentional POPs creation in the form of dioxins and furans from the combustion process. Non-combustion processes can destroy the same waste and allow us to break free of the POPs cycle once and for all.

This report highlights those technologies that form the Non-combustion sector, their development, their ability to destroy POPs waste and their potential to be used in developing countries where small-scale, mobile and innovative solutions to POPs waste are needed.

To explain the importance of Non-combustion technologies in a global society that is striving to achieve sustainability goals, it is necessary to explain some of the international regulatory framework around POP waste – some of the most hazardous waste ever generated. The Stockholm Convention on Persistent Organic Pollutants and The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, contain elements and guidance that define and regulate POPs waste, its destruction and technical requirements for treatment. Their guidance operates within a shared policy framework commonly known as 'synergies' between the Conventions and are explained in section 1.

Section 2 of the report describes the most significant problems associated with incineration of wastes and the perpetual cycle of POPs waste incineration and subsequent generation of UPOPs such as dioxins, furans and dioxin-like PCBs in emissions and solid residues of the process. Understanding the problems of POPs waste incineration highlights the benefits of implementing Non-combustion technology.

Section 3 of the report provides details of the Non-combustion technologies that are most commonly used for the destruction of POPs waste including any relevant applications to clean-up of contaminated sites. Destruction of POPs that are contaminating different environmental matrices such as soil and sediment (as well as industrial rubble and machinery) can be very complex and requires differing techniques to destroying POPs waste such as obsolete pesticides. Section 4 describes the use of *treatment* *trains* where two or more technologies or techniques are combined in series to facilitate the destruction of the POPs content of the waste.

In the final section conclusions and recommendations are provided to highlight the need for the international policy making community and national governments to cooperate in the funding and selection of Non-combustion technology to destroy their POPs waste stockpiles and remediate POPs contaminated sites. Every few years new POPs are added to the Stockholm Convention annexes requiring restrictions or bans and must ultimately be destroyed. Many of these chemicals are present in common consumer goods and will become the massive stockpiles of POPs waste of the future. The world has had decades to destroy old POPs waste such as PCB and has only managed to deal with a small percentage of it. Without widespread adoption of Non-combustion technologies for POPs waste destruction, stockpiles of new POPs waste will join the old stockpiles and continue to grow and poison the planet. This report outlines an alternative range of technologies that can meet that challenge without causing further POPs pollution.

INTRODUCTION

With global recognition that resources are finite and dwindling, the first tentative steps towards the development of circular economies have begun. A key component of a circular economy is the integration of resources into the economy that were previously considered to be 'waste' to displace the use of virgin materials and the ecological impacts of their extraction. Waste and the way it is managed has now become an urgent policy issue for governments, the community and the corporate sector. There is now a recognition that how society deals with waste has serious implications for climate change, the health of our environment, the quality of our water supply and the health of current and future generations.

Traditional methods of dealing with waste have been dominated by burying or burning materials. However, throughout the twentieth century it became clear that both these methods of disposing of waste led to uncontrolled pollution of soil, groundwater and the atmosphere and new approaches were needed to reduce pollution. This situation was complicated with the understanding that carbon dioxide emissions and certain other gases produced by human activity were leading to global warming and climate change.

Even as methods of burning waste because more sophisticated through combustion of waste in incinerators with emission filters, the greenhouse gases they emitted could not be controlled. Some advances in controlling atmospheric pollutants from waste incineration were developed during the twentieth century and these were designed to cut down on heavy metal, particulate and acid gas emissions. However, incineration was always plagued by the problem of persistent organic pollutant (POP) emissions and releases. The realisation in the 1980's that incinerators were a key source of highly toxic emissions of POPs such as dioxins and furans (Polychlorinated dibenzodioxins and Polychlorinated dibenzofurans or PCDD/DF) , which build up in the food chain and the human body, led to increased efforts to reduce these emissions.

Despite spending hundreds of millions of dollars to prevent POPs emissions the incinerator industry has never been able to solve the problem. The addition of expensive flue gas cleaning equipment and other air pollution control (APC) equipment to incinerators, did significantly reduce airborne POPs emissions but only during stable operating conditions. Waste incinerators frequently experience upset conditions, filter failures and large temperature fluctuations during start up and shut down leading to high levels of POPs emissions. These are referred to as 'OTNOC' (Other Than Normal Operating Conditions) and can account for high dioxin emissions which are generally not measured or regulated (Arkenbout 2018). Even if these problems could be solved there is still the issue of the contaminated ash. By increasing the efficiency of the APC equipment, the incinerator operators only succeeded in transferring the POPs to ash. This has resulted in the generation of millions of tonnes of POPs contaminated ash worldwide which is entering the environment and contaminating the food chain (Petrlik and Bell 2017).

A great deal of the waste we create can be recycled, reused, re-purposed or composted and contribute to a circular economy. There is no need to bury or burn it. This applies to most organic and household waste and a large amount of industrial and commercial waste. However, there are some wastes that are extremely hazardous which must be destroyed and cannot enter the recycling chain. One group of such wastes are Persistent Organic Pollutant (POPs) wastes which include certain pesticides, industrial chemicals and products which have POPs added to them. These are the most toxic compounds ever created and many are banned or restricted under the Stockholm Convention[1]. They are not only toxic but extremely persistent in the environment, bioaccumulate and travel long distances across international borders.

This report examines how to destroy POPs waste without incineration using non-combustion techniques and technologies. Ironically, attempting to destroy POPs waste by incineration results in the creation of unintentionally formed POPs (UPOPs) during the combustion process.

Polychlorinatedbenzodioxins (PCDDs) and polychlorinateddibenzofurans (PCDFs) more commonly known as dioxins and furans, are the most toxic of a large range of POPs compounds that are either emitted to atmosphere or entrained in the incinerator residue (ash) when POPs are incinerated. In the same way as there is now a broad acceptance that renewable energy has to replace fossil fuels, so too has the time arrived for society to accept that incineration is a dead- end technology which promotes the redistribution of UPOPs through emissions and ash and must be replaced by the widespread uptake of non-combustion technologies for POPs destruction.

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[1] http://chm.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx

Across the globe communities are fighting to prevent the establishment of waste incinerators which pollute the environment, sink vast amounts of capital and lock out better, cleaner practices for waste management for decades. This report explains why incineration should be phased out and details the non-combustion technologies and techniques to destroy POPs waste and other hazardous waste without continuing the pollution cycle caused by incineration.

1. POPs WASTE DESTRUCTION

1.1 WHY POPs MUST BE DESTROYED?

POPs are mostly man-made chemicals (some dioxins are generated by volcanoes) that have certain characteristics which require them to be destroyed or irreversibly transformed to prevent negative impacts on human health and the environment.

Persistent Organic Pollutants (POPs) are organic (carbon-based) chemical substances. The characteristics that define POPs are that they "*possess toxic properties, resist degradation, bioaccumulate and are transported, through air, water and migratory species, across international boundaries and deposited far from their place of release, where they accumulate in terrestrial and aquatic ecosystems*".[2]

In essence, POPs are toxic and persistent, are difficult to destroy and can be deleterious to the health of humans, wildlife and ecosystems. They can be particularly problematic because they are lipophilic or attracted to fatty tissues in organisms accumulating over time. They also biomagnify through food chain systems resulting in high concentrations among higher trophic level species such as humans, killer whales[3], whales, eagles[4] and dolphins[5]. As a result of this high level of persistence and toxicity the Stockholm Convention requires that POPs listed under Annex A of the convention be subject to 'elimination'. Specifically, Article 6 1. (d) (ii) of the convention requires parties[6] to:

> *"Take appropriate measures so that such wastes, including products and articles upon becoming wastes, are… Disposed of in such*

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[2] UNEP (2009) Chapeau, Official Text of the Stockholm Convention on Persistent Organic Pollutants, page 4.

[3] Ross, P.S., Ellis, G.M., Ikonomou, M.G., Barret-Lennard, L.G., and Addison, R.F. (2000) High PCB Concentrations in Free-Ranging Pacific Killer Whales, Orcinus orca: Effects of Age, Sex and Dietary Preference. Marine Pollution Bulletin Vol. 40, No. 6, pp. 504-515, 2000

[4] Jaspers, V.L., Sonne, C., Soler-Rodriguez, F., Boertmann, D., Dietz, R., Eens, M., Rasmussen, L.M. and Covaci A. (2013) Persistent organic pollutants and methoxylated polybrominated diphenyl ethers in different tissues of white-tailed eagles (Haliaeetus albicilla) from West Greenland. Environ Pollut. 2013 Apr;175:137-46. doi: 10.1016/j.envpol.2012.12.023. Epub 2013 Jan 31.

[5] Jepson, P.D., Deaville, R., Barber, J.L., Aguilar, A., Borrell, A, Murphy,S., Barry, J., Brownlow, A., Barnett, J., Berrow,S., Cunningham, A.A., Davison, N.J., ten Doeschate, M., Esteban, R., Ferreira, M., Foote, A.D., Genov, T., Giménez, J., Loveridge, J., Llavona, A., Martin,V., Maxwell, D.L., Papachlimitzou, A., Penrose, R., Perkins, M.W., Smith, B., de Stephanis, R., Tregenza, N., Verborgh, P., Fernandez, A. & Law, R.J. (2016) PCB pollution continues to impact populations of orcas and other dolphins in European waters. *Scientific Reports Vol 6, Article number: 18573*

[6] The U.S. and Italy are not parties to the Stockholm Convention despite being major producers of some POPs (such as PCB) historically.

TABLE 1. CURRENT LISTING OF POPs BY ANNEXES IN THE STOCKHOLM CONVENTION.

ANNEX A (ELIMINATION)

Parties must take measures to **eliminate** the production and use of the chemicals listed under Annex A. Specific exemptions for use or production are listed in the Annex and apply only to Parties that register for them.

- ● Aldrin
- ● Chlordane
- ● Chlordecone
- ▲ Decabromodiphenyl ether (commerical mixture, c-decaBDE)
- ● Dieldrin
- ● Endrin
- ● Heptachlor
- ▲ Hexabromobephenyl
- ▲ Hexabromocyclododecane (HBCDD)
- ▲ Hexabromo diphenyl ether and Heptabromodiphenyl ether
- ● ▲ Hexachlorobenzene (HCB)
- ▲ Hexachlorobutadiene
- ● Alpha hexachlorocyclohexane
- ● Beta hexachlorocyclohexane
- ● Lindane
- ● Mirex
- ● ▲ Pentachlorobenzene
- ● Pentachlorophenol and its salts and esters
- ▲ Polychlorinated biphenyls (PCB)
- ▲ Polychlorinated naphthalenes
- ▲ Short-chain chlorinated paraffins (SCCPs)
- ● Technical endosulfan and its related isomers
- ▲ Tetrabromodiphenyl ether and pentabromodiphenyl ether
- ● Toxaphene

● **Pesticides**
▲ **Industrial Chemical**
■ **Unintentional Production**

ANNEX B (RESTRICTION)

Parties must take measures to **restrict** the production and use of the chemicals listed under Annex B in light of any applicable acceptable purposes and/or specific exemptions listed in the Annex.

- ● DDT
- ● Perfluorooctane sulfonic acid (PFOS), its salts and perfluorooctane sulfonyl fluoride

ANNEX C (UNINTENTIONAL PRODUCTION)

Parties must take measures to reduce the **unintentional releases** of chemicals listed under Annex C with the goal of continuing minimization and, where feasible, ultimate elimination.

- ■ Hexaclorobenzene (HCB)
- ■ Hexachlorobutadiene (HCBD)
- ■ Pentachlorobenzene
- ■ Polychlorinated biphenyls (PCB)
- ■ Polychlorinated dibenzo-p-dioxins (PCDD)
- ■ Polychlorinated dibenzofurans (PCDF)
- ■ Polychlorinated naphthalenes

> *a way that the persistent organic pollutant content is destroyed or irreversibly transformed so that they do not exhibit the characteristics of persistent organic pollutants...”*

Those POPs listed under Annex B of the Convention are subject to ‘restriction’ with strict regulatory controls on their production and use. Annex C of the convention lists unintentionally formed POPs or UPOPs. These are POPs that are created unintentionally through chemical production processes as impurities and contaminants or are emitted to air and released to land and waterways through combustion processes such as waste incineration, cement manufacture and metallurgy. The most commonly known of the UPOPs are dioxins and furans (PCDD/DF) which are strongly associated with waste incineration.

There are no safe levels of dioxins and currently the body burden of dioxin and dioxin-like chemicals that have been found in the general U.S population are at or near levels associated with adverse health effects[7]. Most other industrialised countries have similar levels of dioxin in their populations.

The fact that humans are at the health tipping point in terms of the amount of dioxin they have accumulated makes it important to eliminate existing sources of dioxins and dioxin like compounds and prevent the creation of new sources of this highly toxic compound. Dioxin is the most toxic of POPs causing cancer[8] and impacts on the human reproductive and endocrine systems[9] but many other POPs such as PCBs and those listed in the table below have similar toxicity characteristics.

While the Stockholm Convention processes define, assess and list POPs for global regulatory action, it is not the sole multilateral instrument that covers this issue. The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal entered into force in 1992 preceding the Stockholm Convention by 12 years. The Basel Convention was negotiated in response to the rise in dumping of hazardous waste by developed countries into developing countries during the 1980s and stricter regulatory controls and increased management costs were implemented in industrially developed jurisdictions.

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[7] Mandal PK, Tomkins A, Mandal A and Duffy J. Environmental Dioxin Pollution and its Influence on the African Americans. *SM J Bioprocess Biotech. 2017; 1(1): 1002.*

[8] Kogevinas, M. (2001) Human health effects of dioxins: cancer, reproductive and endocrine system effects. *Hum Reprod Update.* 2001 May-Jun;7(3):331-9

[9] Birnbaum, L.S., Staskal, D.F. and Dilibertoa, J.J. (2003) Health effects of polybrominated dibenzo-p-dioxins (PBDDs) and dibenzofurans (PBDFs). *Environment International. Volume 29, Issue 6, September 2003, Pages 855-860*

The Basel Convention defines a wide range of hazardous wastes and includes protocols for their movement across national boundaries including notification and prior informed consent rules. The key areas that the Basel Convention addresses issues related to POPs management and destruction are defining what is and what is not POPs waste by determining threshold levels. The Convention has also developed guidance documents for the management of individual POPs waste. Historically, the guidance was focused on the 12 initial POPs that were included in the annexes of the first agreed text of the convention. Since then, as new POPs have been added to the convention Annexes, new guidance has and continues to be developed for each of the new POPs or related 'families of POPs. For example, in 2017, *Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with HCBD* were released. In this case the guidelines address management issues for Hexachlorobutadiene, a single POP. In other cases, related families of POPs are addressed under a single guideline such as the *Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with PCBs, PCTs, PCNs or PBBs, including HBB.*

Within each guidance document, issues such as the technical description of the chemical, its various forms (including waste), historical uses and production are discussed alongside environmentally sound management (ESM) options for the stockpiles or product and wastes. This is a key intersection with the Stockholm Convention as expert groups in both conventions seek to harmonise definitions and define ESM techniques. One of the most important documents in terms of this report is the *General technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants*[10] otherwise known simply as the Basel General technical guidelines. This document is very important when assessing techniques to destroy POPs as Chapter IV G is dedicated to environmentally sound disposal of POPs. Table 4 of chapter IV G provides a matrix of some known technologies that destroy POPs and notes which POPs they are capable of destroying (in some cases this may be all POPs)[11]. However, this table still excludes a number of proven non-combustion technologies for POPs waste destruction which are detailed in subsequent sections of this report.

One of the most controversial aspects of the Basel and Stockholm Convention interaction or 'synergies' is that the Basel Convention General tech-

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[10] Available with other Basel Convention POPs Guidance documents at http://www.basel.int/Implementation/Publications/LatestTechnicalGuidelines/tabid/5875/Default.aspx

[11] The guidance (and Table 4) are currently subject to review and a number of modifications have been made in draft form that may be adopted at the next Conference of the Parties of the Basel Convention and so it is subject to change.

nical guidelines on POPs waste lists incineration (both hazardous waste incineration and 'Advanced' solid waste incineration) as an 'environmentally sound destruction' technologies for POPs waste. This directly contradicts the listing of waste incineration as one of the primary known sources of dioxin as a UPOP. This effectively creates guidance that says on the one hand it is acceptable to burn POPs waste in incinerators when those same incinerators will go on to produce UPOP emissions from their stacks and ash contaminated with POPs. This situation has arisen because of the narrow technical definition of POPs destruction by which technologies are assessed. Two key metrics by which destruction of POPs are measured partly allow the inclusion of incineration in the guidance despite their production of UPOPs. The measurements are destruction efficiency (DE) and destruction and removal efficiency (DRE) and are discussed further below. However, both of these measurement focus on the POPs destroyed by a process but ignores UPOPs that are created. Incinerators and other combustion technologies generate UPOPs while Non-combustion technologies do not generate any significant amount of UPOPs. When assessing both types of technologies for POPs waste destruction, the General technical guidelines focus on the DE and DRE rather than prioritising technologies that do not generate UPOPs in the first instance. A second important aspect of the Basel Convention Technical guidance on POPs waste is that for each POP a threshold limit is define to which wastes are considered to be 'POPs waste' based on their POP concentration and are therefore subject to obligatory management requirements (such as environmentally sound destruction) under the Stockholm Convention. This a key area of overlap between the Basel and Stockholm Conventions and such relationships between the conventions are known as '*synergies*'. The threshold at which a waste contaminated with POPs is defined as POPs waste (and not just general waste or hazardous waste) is called the Low POPs Content Level (LPCL) and varies between the different POP types.

For example, waste contaminated with Polychlorinatedbiphenyls (PCB) above 50 mg/kg (50 parts per million) is POPs waste and must be destroyed. If the level in the waste is 49 mg/kg or less then it is not considered POPs waste (yet may still be hazardous) and must be managed under other waste management systems used at national or state level in any given jurisdiction. For PCDD/DF the current LPCL is 15 parts per billion or 15 ppb. So, waste with a dioxin concentration below 15 ppb is not considered 'POPs waste'. Debate on whether these LPCL levels are appropriate and should be reduced are ongoing and the guidelines are periodically reviewed as new science on POPs impacts emerge. More detail on LPCL is provided below.

From *Table 4*: Overview of technologies for the destruction and irreversible transformation of POPs in wastes.

Technology	POPs									
	HBB	**HBCD**	**HCBD**	**PCB**	**PCDDs/ PCDFs**	**PCN**	**PCP**	**Pesticides POPs**	**PFOS**	**POP-BDEs**
Alkali metal reduction	ND	ND	ND	Yes	ND	ND	ND	Yes, for certain pesticides: chlordane, HCH	ND	ND*
Advanced solid waste incineration (ASWI)	ND	Yes	ND	ND	ND	ND	Yes	ND	ND	
Base catalyzed decomposition (BCD)	ND	ND	ND	Yes	Yes	ND	Yes	Yes, for certain pesticides: chlordane, HCH, DDT, HCB	ND	ND
Catalytic hydrodechlorination (CHD)	ND	NA	ND	Yes	Yes	ND	ND	ND	NA	NA**
Cement kiln co-incineration	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes, for all pesticides	Yes	Yes
Gas phase chemical reduction (GPCR)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes, for all pesticides	Yes	Yes
Hazardous waste incineration	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes, for all pesticides	Yes	Yes
Plasma arc	ND	ND	ND	Yes	ND	ND	ND	Yes, for most pesticides, including chlordane, chlordecone, DDT, endosulfan, heptaclor	ND	ND
Plasma melting decomposition method (PMD)	ND	ND	ND	Yes	ND	ND	ND	ND	ND	ND
Supercritical water oxidation (SCWO)	ND	ND	ND	Yes	Yes, for PCDDs	ND	ND	Yes, for certain pesticides: chlordane and DDT	ND	ND
Thermal and metaallurgical production of metals	ND	ND	ND	ND	Yes	ND	ND	ND	ND	Yes

** Not determined; ** Not applicable to this waste type*
Source: Adapted from the Basel Convention General technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants 2020

Once POPs waste has been identified (on the basis that it exceeds the LPCL) it must then be destroyed or irreversibly transformed so that it does not exhibit POPs characteristics. The Stockholm Convention does not address the issue of how to do this directly, so the Basel Convention General technical guidelines fulfil this role by listing some POPs destruction technologies and providing details of the processes. However, the list provided by the General technical guidelines is not exhaustive and other methods are available.

1.2 BEST AVAILABLE TECHNIQUE AND BEST ENVIRONMENTAL PRACTICE (BAT BEP)

There is one additional layer of complexity in terms of the interaction of the conventions on POPs destruction and this is the issue of guidance for Best Available Technique and Best Environmental Practice (BAT BEP). This guidance is created in recognition that some technologies such as incineration emit UPOPs and measures have to be taken to minimise them. The Stockholm Convention has its own expert advisory groups including the BAT BEP and Dioxin Toolkit Expert Group. This group develops guidance on the best methods and techniques to operate processes that are known to emit unintentionally formed POPs (UPOPs) such as dioxin, so as to reduce those emissions and releases. The guidance are collectively known as Best Available Technique and Best Environmental Practice (BAT BEP). The Dioxin Toolkit[12] is an associated useful guidance tool to estimate the emissions of PCDD/DF from a variety of known sources.

Annex C of the Stockholm Convention lists known UPOPs as well as the industrial sources known to be key sources of UPOPs and these include:

(a) Waste incinerators, including co-incinerators of municipal, hazardous or medical waste or of sewage sludge;

(b) Cement kilns firing hazardous waste;

(c) Production of pulp using elemental chlorine or chemicals generating elemental chlorine for bleaching;

(d) The following thermal processes in the metallurgical industry:

(i) Secondary copper production;

(ii) Sinter plants in the iron and steel industry;

(iii) Secondary aluminium production;

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[12] A very useful tutorial on using the Dioxin Toolkit by BAT BEP Expert Group member Pat Costner can be accessed here https://www.youtube.com/watch?v=hFMQwmKvIxQ

(iv) Secondary zinc production.

For the most part, the BAT BEP guidance documents that have been developed by the Stockholm Convention relate to these industries and production processes using certain restricted POPs. As new POPs are added to the Stockholm Convention, new BAT BEP guidance documents are developed to address any new sectors that are responsible for the emissions.

1.3 WHAT IS DESTRUCTION EFFICIENCY (DE) AND LOW POP CONTENT LEVELS?

If a technology provider claims that they have a technique or technology that is capable of destroying or irreversibly transforming POPs waste so that it no longer exhibits POPs characteristics then they must be able to measure and demonstrate this capability. The measurement of this capability must also be transferrable to other technologies and techniques to allow for comparison of performance on a common scale. The primary form of measurement used is Destruction Efficiency (DE). The official definition of DE is '*the percentage of originating POPs destroyed or irreversibly transformed by a particular method or technology*'.[13]

An acceptable level of DE is usually represented by the so called 'five nines' or 99.999% meaning that 99.999% of the POPs in a treated unit of waste has been destroyed. A level of 6 nines or better is considered a very high destruction level. Most non-combustion technologies have high DE but the efficiency can vary and be slightly lower when dealing with complex environmental matrices such as contaminated soil which is impacted by multiple contaminants that may interfere with the destruction technique.

The measure of DE *does not* account for UPOPs generated in any given technology in the process of destroying the target POPs in waste. So, if PCB is fed into an incinerator operating to BAT BEP requirements, with sufficient temperature and steady, optimal operating conditions, it may be able to destroy those PCBs to 99.999% DE. However, the dioxins and dioxin-like PCBs (dl-PCBs) and any other UPOPs released via emissions and in residual fly ash and bottom ash, are not included in the DE calculation. Therefore, the measure of DE only applies to the waste input destruction levels and does not in any way measure the UPOPs emitted and released in the process.

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[13] UNEP (2019) Draft updated general technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants.

This means that DE levels attributed to incinerator treatment of POPs waste do not reflect the 'generation' of additional POPs created and released to the environment in the process of incineration. The same issue applies to POPs waste treated in cement kilns, metallurgy plants and other forms of combustion technology. Nonetheless it remains the single most important measurement available to determine if a technology can destroy POPs.

An associated measurement is Destruction and Removal Efficiency (DRE) which is often used in association with incineration of POPs waste (along with other combustion technologies). This measurement only considers emissions to air and is the percentage of original POPs irreversibly transformed and removed from *gaseous emissions*. It does not consider any UPOPs generated in the process of destroying POPs waste and it does not provide a measurement of how much of the original POPs in waste is transferred to 'residuals' of the combustion process. A significant fraction of the original POPs in the waste treated may be trapped in the flue gas scrubbing medium (e.g. activated carbon), flue gas equipment (e.g. baghouse fabric), effluent (e.g. from wet spray scrubbers), the fly ash or bottom ash or even process pipework.

For this reason DRE is not an accurate measurement of POPs destruction, only removal from gaseous emissions leaving uncertainty about the future of the POPs treated and UPOPs generated which have been transferred to the solid or liquid waste from the destruction process. In turn these wastes may be released to the environment and eventually distribute their POPs content into the food chain (Petrlik and Bell 2017).

Finally, where significant uncertainty exists about the destruction efficiency of POPs in combustion technology or where it cannot be verified accurately, then use of *'absolute levels'* are permitted to be applied by the under the Basel Convention General technical guidelines[14]. The absolute levels referred to in the guidance are for atmospheric emissions, liquid waste and solid residue from a combustion facility treating POPs.

The guidance for air emissions relates only to dioxin and furans and is 0.1 ng TEQ/Nm^3 PCDD/DF with the assumption that all other UPOPs will have been sufficiently filtered by the pollution control devices to reduce emissions to an acceptable risk level. The 0.1 ng TEQ/Nm^3 PCDD/DF threshold does not include dioxin like PCBs (dl-PCBs) or brominated dioxins which are currently unregulated in emissions but exhibit similar toxicity.

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[14] Ibid p15

For all other POPs and UPOPs it is essentially up to national legislation standards and guidelines, which can vary dramatically or be non-existent.

For liquid wastes any party can revert to its own national legislation standards and guidelines which allows for the same weaknesses as above.

For solid residues of the combustion process (ash for incineration, cement kiln dust for cement works and slag residues for metallurgy plants) the remaining levels of POPs must be below the “Low POPs Content’ threshold and these levels vary between POPs.

What are Low POP Content levels?

The Low POPs Content levels is a threshold level for POPs concentration in waste above which a waste becomes ‘POPs waste’ and must be treated to destroy the POPs content as required under article 6 of the Stockholm Convention. If the waste is tested and the POP content is below the relevant Low POP Content level then it is not considered to be POPs waste and does not have to be treated by specialised equipment to destroy the POPs in the waste.

As examples: if an incinerator is burning PCB waste and the residual ash left over has a dioxin concentration that exceeds the Low POP content for dioxin and furans (currently 15 ppb) then the ash would be regarded as ‘POPs waste’ and would need to be treated to destroy the dioxin or reduce it below a concentration of 15 ppb. The current Low POP Content threshold for PCB is 50 mg/kg. If an incinerator was burning PCB waste and the incinerator ash at the end of the process had a PCB concentration above 50 mg/kg if would be deemed POPs waste and must be treated to destroy the PCB or reduce the PCB concentration below 50 mg/kg.

The objective of assigning a concentration threshold to classify certain wastes as ‘POPs waste’ is to ensure that human health and the environment are protected from these substances by requiring them to be sent to specialised treatment to destroy their POPs content – in line with the obligations of the Stockholm Convention. However, the determination of Low POP Content levels is not always science based and is decided by negotiation through the Basel Convention processes with advice from expert groups. This is open to political decisions influenced by industry lobbying. Certain industries may avoid the expense of having to send their waste for destruction treatment if the Low POP Content levels are set above the average POP content of the waste they produce. The higher the concentration number established for a Low POP Content value for any given POP, the weaker the control of that waste becomes. This allows waste materials with unsafe POPs levels to enter the environment and even be traded between countries for use in construction, landscaping and road building.

Most experts agree that a level of around 50 mg/kg is appropriate for most POPs as a Low POPs Content level that protects human health and the environment (with the exception of dioxin which is much more toxic and currently has a limit of 15 ppb with a proposed limit of 1 ppb). However, recent LPCLs proposals for POPs such as short chained chlorinated paraffins (SCCP) have been as high as 10 000 mg/kg, Hexabromocyclododecane (HBCD) at 1000 mg/kg and mixed PBDE at 1000 mg/kg as a sum. Studies into appropriate levels by expert consultants indicate that much lower levels are necessary to protect human health and the environment. Some industry sectors argue that stricter (lower) Low POPs Content levels will impact on the business.

1.4 WHAT ARE NON-COMBUSTION TECHNOLOGIES FOR POPs WASTE DESTRUCTION?

In a sense, non-combustion technologies are defined more clearly by what they are not. That is to say non-combustion technologies for POPs waste destruction is very broad definition that covers many technologies and techniques *that simply do not involve combustion of waste*. A secondary element of the definition is that they do not generate unintentionally produced POPs or UPOPs such as dioxins and furans. The main 'combustion' technologies which have been used to treat POPs waste are incinerators (including pyrolysis and gasification units) and to a lesser extent cement kilns (co-processing) and metallurgical plants and smelters. They share the characteristics of relatively high temperature operation (>800°C) with direct or indirect combustion of fuels and waste and a propensity to release UPOPs such as dioxins and furans in emissions, solid residues such as ash and to a lesser degree liquids, such as scrubber water. Incineration is the most common combustion technology used for treating POPs waste and is described in greater detail below.

Non-combustion technologies are sometimes also referred to as 'alternative' technologies meaning they are an alternative to combustion technology. They are often based on physio-chemical principles that dehalogenate POP waste and break down POPs chemical into much less harmful compounds or even non-toxic and useful substances such as hydrogen. They may use combinations of heat, pressure, chemical oxidation and catalysts to achieve the objectives of article 6 of the Stockholm Convention which is to destroy or irreversibly transform POPs waste so that it no longer exhibits POPs characteristics. Non-combustion technologies may also take the form of 'treatment trains' where one technology or technique is used to extract and concentrate POPs waste before a second technology or technique is used to destroy the smaller volume of concentrated POPs waste. Other forms of pre-treatment may also be used to prepare waste for destruction of its POPs content in a second stage.

Individual non-combustion technologies and techniques will be discussed in subsequent chapters including treatment trains and some applications for remediation of contaminated sites. Treatment of stockpiles of relative homogenous POPs waste often requires different logistical arrangements to the treatment of POPs waste and contaminated soils at contaminated sites. Contaminated sites may have more complex issues related to removal of the POPs contamination from environmental matrices such as groundwater, sediment or soil that require additional pre-treatment and concentration methods.

Before moving on to the detailed description of non-combustion technologies it is important to discuss why combustion technologies, and incineration in particular, undermine the objectives of the Stockholm Convention which is to eliminate POPs, by trapping us in a cycle of burning POPs while generating UPOPs.

2. WHAT IS COMBUSTION TECHNOLOGY AND WHY SHOULD IT BE AVOIDED?

Combustion technology for POPs waste treatment is generally understood to be incineration, cement kiln co-processing, and certain forms of metallurgical processes and smelters that operate at high temperatures thought to be capable of destroying POPs waste. The most common problem with their use to treat POPs waste is that they are a source of UPOPs creation and release, either through emissions or through solid waste residues such as fly ash and bottom ash (incinerators), Cement Kiln Dust (CKD) and particulate emissions. In some cases, poor operation of the combustion facility can also result in direct releases of the POPs waste supposedly being treated through the stack. When this occurs contamination of the local environment around the facility can result in significant contamination and clean-up costs. The next section provides a description of common combustion technologies used to treat POPs and the potential for them to be sources of UPOPs and other pollution.

2.1 WASTE INCINERATION

Waste incineration has been used in the UK since 1874 when the first 'destructors' were built by Manlove, Alliott & Co. Ltd. In Nottingham and in the US since the 1885[15] to dispose of waste in a manner that is described as 'controlled'. This is to distinguish the practice of waste incineration from the practice of 'open burning' or uncontrolled burning of waste which is still practiced in many parts of the world and especially developing countries. The primary purpose of waste incineration in the late nineteenth century and the early part of the twentieth century was to prevent the spread of disease from open dumping of waste in city streets where space to bury waste was restricted. In addition to burning waste for sanitary reasons the incinerators were able to reduce the total volume of waste by around 90% and the weight of the waste burned by about 70%. The remaining 30% fraction of waste after incineration being the solid residue or ash.

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[15] https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/basic.html

In the early twentieth century waste incineration facilities were, in some locations adapted to provide heating energy to adjacent industries. This was a beneficial by-product that was developed along with transfer infrastructure over decades to provide town heating in some countries such as Denmark and Sweden. Harnessing the energy that would otherwise be released to atmosphere through the stack was found to be a cost saving at a time where municipal heating was provided by oil, coal or timber.

In the past few decades, the waste incinerator industry has attempted to shed the stigma associated with the pollution it creates by rebranding itself from a waste disposal industry to an 'energy provider' industry. With the global recognition of anthropogenically driven climate change, the industry went a step further claiming that it creates, 'green' renewable energy. A part of this strategy has been to allow the incineration industry to access renewable energy subsidies, tax credits and associated benefits.

The reality is that the energy produced by incinerators is neither green nor renewable. Most of the calorific value derived from waste is from the plastics in the waste stream which are of petrochemical origin. Burning plastics is essentially a two-step process for burning fossil fuels. Instead of using burning liquid oil to generate energy, waste incinerators rely on oil in the solid form of plastics in the waste stream to provide the fuel. The issues described above apply to the sector of the industry more commonly known as municipal solid waste (MSW) incineration through to the end of the twentieth century and continuing into the 21st century. While MSW incineration is the most common form of waste incineration, medical waste incineration and hazardous waste incineration also account for a substantial part of the incineration industry sector.

This report will focus mainly on the hazardous waste incineration industry due to its direct role in the treatment of POPs waste, however there is considerable overlap between the industries for reasons described below and all sectors suffer from the same fundamental pollution problems to varying degrees.

2.2 MUNICIPAL SOLID WASTE INCINERATORS

MSW incinerators burn household waste collected by municipalities as well as some commercial and industrial waste. Municipal waste includes plastics, paper, discarded products of all kinds, textiles and organic wastes. These incinerators often have large-scale throughput of hundreds of thousands of tonnes per annum and some generate heat for energy production. They typically claim to operate at around 850°C and are used to reduce the overall volume of solid waste for disposal by 90% and reduce the weight by 70%. For every tonne of waste burned around 300 kg of contaminated ash is generated[16]. Of this total around 3-5% is fly ash, a highly toxic form of ash that is collected in the APC equipment of incinerators to prevent it from being emitted to atmosphere. The other 25% is bottom ash which is less toxic but contains significant quantities of heavy metals and POPs. Typical air emissions for MSW incinerators include but are not limited to:

- dioxins and furans (polychlorinated dibenzo-p-dioxins and dibenzofurans)
- brominated dioxins and furans (polybrominated dibenzo-p-dioxins and dibenzofurans)
- dioxin-like PCBs (dl-PCB)
- polychlorinated biphenyls (PCB)
- polyaromatic hydrocarbons (PAH)
- Perfluorooctanoic acid (PFOA)
- Perfluorooctanesulfonic acid (PFOS)
- Hydrochloric acid (HCl)
- Sulphur oxides (SO_x)
- Oxides of nitrogen (NO_x)
- Carbon dioxide (CO_2)
- Nitrous oxide (N_2O)
- Ammonia (NH_3)
- Particulate PM 2.5 and PM 10
- Nanoparticles[17]
- Heavy metals

2.2.1 The 'rebranding' of waste Incinerators

For the last two decades the waste incineration industry has spent a great deal of time and energy looking for ways to shake off negative public perception caused by incinerator pollution and expand into new markets

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[16] Kalogirou, E. (2012), The development of WtE as an integral part of the sustainable waste management worldwide, Recuwatt -Recycling and Energy conference-, Mataró (Spain), 4th October 2012.

[17] A nanoparticle is a sub-classification of ultrafine particle with lengths in two or three dimensions greater than 0.001 micrometer (1 nanometer) and smaller than about 0.1 micrometer (100 nanometers)

around the globe. Europe has an oversupply of incineration capacity in many jurisdictions such as Germany[18] and traditional incinerator markets in the US and Japan are stagnant with very few new proposals to build plants. In the US only one new incinerator has been built in the last 23 years[19].

This has forced the incinerator industry into a public-relations 'make-over' where the word 'incinerator' is rarely mentioned and has been replaced by terms such as gasification, pyrolysis, plasma arc and waste to energy (WtE). These technologies are all waste incinerator technologies according to the European Union[20] and the US Environmental Protection Authority[21]. The configuration of each technology varies but in their waste disposal format they are all designed around single stage or dual stage burning of waste. They all produce a similar profile of pollutants (although the concentrations may vary) and generate contaminated solid waste which can contaminate the food chain[22].

Incinerator proponents have also attempted to make a distinction between 'old' incinerators and 'new' technologies. This is part of promoting the argument that environmentalists and communities are objecting to the 'old polluting technology' which has now been replaced by 'new clean' technology. However, all of the 'new' technologies are basic incineration variants that have been subject to incremental changes over time. Despite claims by proponents that modern incinerators have 'solved' their emission issues (especially in relation to dioxins) the reality is that they continue to emit dioxins and furans, sometimes at very high levels.

While tighter air quality standards have forced waste incinerators to increase pollution controls (especially for dioxins) they continue to be responsible for discharges of a large range of atmospheric pollutants and dioxin release incidents. Waste incineration remains one of the highest sources of dioxin to atmosphere and this is acknowledged by its inclusion as a dioxin source on Annex C (Unintentional POPs) Part II of the Stockholm Convention on Persistent Organic Pollutants. The improvements to air emission controls have also led to a much higher level of contamination of incinerator residues such as ash, much of which must still be sent

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[18] NABU - Naturschutzbund Deutschland e.V.- (2009), Waste incineration in Germany is growing unchecked - recycling is endangered, waste import becomes more attractive. Results from the study carried out by Prognos AG: "The Waste Market in Germany and Perspectives by 2020", 2009.

[19] US Energy Information Administration (2016) Monthly Electric Generator Report. https://www.eia.gov/todayinenergy/detail.php?id=25732

[20] European Union (EU) Directive 2000/76/EC on the incineration of waste (the WI Directive)

[21] U.S. Environmental Protection Agency, Title 40: Protection of Environment, Hazardous Waste Management System: General, subpart B-definitions, 260.10, current as of February 5, 2008.

[22] Petrlik, J., and Bell, L. (2017) Toxic Ash Poisons Our Food Chain. International POPs Elimination Network (IPEN), Arnika Association (Czech Republic) and National Toxics Network (Australia). http://www.ipen.org/news/toxic-ash-poisons-our-food-chain

Figure 1. Zero Waste Hierarchy. Source: SCP/RAC 2020

to landfill. By increasing the capacity of incinerator scrubbers and filters to capture toxic pollutants that would otherwise be released to atmosphere, much of the POP contaminants are transferred from the gaseous or particulate phase to the solid phase such as ash and other residues.

2.2.2 The 'waste to energy' label

Many countries now have regulations and policies linking their waste management systems to a 'waste hierarchy' which prioritises actions based on the most ecologically sustainable practices (such as waste avoidance) through to the least preferable such as waste disposal (e.g. landfills and incinerators).

Incinerator proponents attempting to improve the perception of waste incineration caused by a poor track record on pollution and relegation to the bottom of the waste hierarchy, have used the issue of climate change to try and improve their prospects. Few incinerator proponents now promote the technology as waste disposal but have emphasized the issue of energy generation from burning waste. In its various forms this new advertising concept for incinerators is expressed as 'energy from waste (EfW)', 'waste to energy (WtE)', 'energy recovery' or 'resource recovery.

This perceptual reorientation away from traditional waste disposal is an attempt to create a market for waste incineration as part of the 'mix of renewable energy' options to combat climate change. It has the added benefit to incinerator proponents of allowing them to seek funding, subsidies, tax credits and other financial support that has been earmarked for renewable energy. This 'green' rebranding of energy from incineration also supported a push to create a new level on the waste hierarchy above 'disposal' called 'recovery' thereby creating the impression that waste to energy incineration was 'superior' to disposal technology such as landfill. Consequently, the debate over waste management has been dominated in many jurisdictions by a false dichotomy that compares the merits of landfill versus incineration to the exclusion of other options[23]. In this stage-managed debate incineration can be declared a 'superior' option because energy can be generated from burning the waste.

2.2.3 Is energy from waste incineration renewable?

Energy created from waste incineration is neither renewable, sustainable or 'green'. Waste incinerators contribute directly to climate change due to their high level of GHG emissions per unit of electricity generated even when compared to electricity from coal and oil-fired power stations. Waste incineration and landfill represent the worst outcomes in terms of climate change and how, as a society, we deal with our resources. If we are to divert waste away from landfill and incineration into alternate forms of resource recovery (recycling, reuse, composting and anaerobic digestion) the climate change benefits increase significantly. While incinerators emit more CO_2 pollution than coal or oil power plants[24] promoters of waste incinerators continue to claim that the energy they generate is 'climate friendly'.

Despite their poor performance, incinerator proponents maintain that they are generating renewable energy and are more climate friendly than landfill. However, the real issue for measuring the impact on climate change is how well incinerators compare to other energy generation sources - not other waste management practices. When this comparison is examined, GHG emissions from waste incinerators generating electricity is demonstrated to be the highest of all technologies.

Mixed municipal waste is a dirty, highly heterogeneous fuel with low calorific value when compared to standard fossil fuels used to generate electricity. In other studies, UK researchers have demonstrated that incin-

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[23] ENDS Report (2020) Incineration vs landfill: Why the debate over carbon intensity is far from over. October 2020 https://www.endsreport.com/article/1696759/incineration-vs-landfill-why-debate-carbon-intensity-far?bulletin=ends-report-products-chemicals-waste-resources-bulletin&utm_medium=EMAIL&utm_campaign=eNews%20Bulletin&utm_source=20201015&utm_content=ENDS%20Products%20Chemicals%20Waste%20and%20Resources%20(39)::&email_hash=

[24] U.S. EPA, eGRID 2000

eration of waste emits up to twice the amount of CO_2 of coal-fired power plants per kilowatt-hour of electricity.[25]

When compared to real renewable energy sources such as wind and solar the contrast becomes even more stark. The table below includes relative GHG emission factors for waste incineration compared to both fossil fuel sources and renewable energy based on regulatory authority estimates from the US. Waste incineration clearly has the highest emissions of CO_2 of all sources. However, incinerator proponents argue that despite the high levels of CO_2 per MWh emitted their technology is still climate friendly because a significant fraction of the waste they burn is from organic materials such as paper, food scraps, wood waste and so on. Because these organic materials can be regrown the incinerator industry claims that the 'biogenic' fraction of their fuels (as opposed to the petrochemical based materials they burn such as plastics) results in the production of renewal energy.

TABLE 2. AIR POLLUTANTS BY ELECTRICITY GENERATION SOURCE (US).

	CO_2 (lbs/MWh)	SO_x (lbs/MWh)	NO_x (lbs/MWh)
MSW Incinerators	2988	0.8	5.4
Coal	2249	13	6
Oil	1672	12	4
Natural Gas	1135	0.1	1.7
Wind	0	0	0
Geothermal	0	0	0
Solar	0	0	0

Source: U.S. EPA, eGRID 2000. U.S. EPA, Comilation of air Pollutant Emission Factors (AP-42)

Incinerator proponents often point to the IPCC ruling excluding biogenic CO_2 emissions from 'waste' in its protocol for calculating national inventories. However, because the IPCC national inventory calculation guidelines are intended to address every sector in a nation's emissions the biogenic emissions are accounted for in other sectors. When addressing a countries energy sources the IPCC specifically states that the biogenic fraction must be taken into account when comparing energy sources;

> *"The CO_2 emissions from combustion of biomass materials (e.g., paper, food, and wood waste) contained in the waste are biogenic*

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[25] Hogg, D., (2006) "A Changing Climate for Energy from Waste?" *Eunomia Research and Consulting*. May 2006. p 21.

> *emissions and should not be included in national total emission estimates. However, if incineration of waste is used for energy purposes, both fossil and biogenic CO_2 emissions should be estimated.... Moreover, if combustion, or any other factor, is causing long term decline in the total carbon embodied in living biomass (e.g., forests), this net release should be evident in the calculation of CO_2 emissions described in the Agriculture, Forestry and Other Land Use (AFOLU) Volume of the 2006 Guidelines.*[26]*"*

Searchinger *et al.* (2009) revealed that the failure of carbon inventory rules to account for CO_2 emitted from smokestacks when bioenergy is being used was a serious flaw in the carbon accounting rules of the IPCC as is the failure to account for changes in emissions from land use when biomass for energy is harvested or grown. Searchinger noted;

> *"This accounting erroneously treats all bioenergy as carbon neutral, regardless of the source of the biomass, which may cause large differences in net emissions. For example, the clearing of long-established forests to burn wood or to grow energy crops is counted as a 100% reduction in energy emissions, despite its causing large releases of carbon."*

There is also the issue of the time it takes to replace the forests that are converted to paper, timber, woodchip, sawdust and timber products which end up in incinerators. An incinerator instantly destroys large amounts of this resource and converts it into CO_2 releases to atmosphere and contaminated ash. The time taken for replacement trees to mature and become carbon sinks can be decades to hundreds of years. Large scale incineration of biomass therefore depletes biomass reserves and releases carbon at a rate well beyond that which nature can renew the biomass and absorb carbon thereby contributing to climate change at an ever accelerating rate.

At best, a very small proportion of the biogenic material destroyed for energy in incinerators might be considered to contribute to renewable energy, however other studies have demonstrated that much better sustainability and climate change outcomes can be achieved by directing those organic materials to composting and other organic materials processing. The findings of a major analysis by the European Union into this issue concluded; "Source-segregation of various waste components from MSW [municipal solid waste], followed by recycling or composting or anaero-

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[26] Institute for Global Environmental Strategies (IGES) (2006) IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/
Incineration and Open Burning of Waste, Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme, p. 5.5, 2006.

bic digestion of putrescibles offers the lowest net flux of greenhouse gases under assumed baseline conditions.[27]"

The vast majority of energy generated through MSW waste incineration cannot be considered renewable especially with the reliance of MSW incinerators on the high calorific value plastics which are essentially a solid form of petrochemical fossil fuel. It certainly cannot be considered a clean energy source when compared to renewable energy or even to other forms of fossil fuel generation. Energy from waste incineration cannot in any way be considered ecologically sustainable when the destruction of resources and embedded energy are considered alongside the productive alternatives for organic materials in composting and anaerobic digestion[28].

Finally, it is important to note that there are technologies that convert waste to energy as a primary or secondary option that are not waste incineration and which do have an important role in sustainable resource management outcomes and renewable energy production.

The most common is the technology known as Anaerobic Digestion (AD) which 'ferments' mixed organic matter including agricultural waste, paper, sewage, food scraps and so on to produce a methane gas for fuel in a closed system. The methane gas is trapped and can be used as a cooking gas, a fuel gas to power steam energy turbines or converted to liquid as a vehicle fuel. The key difference between the development of 'biogas' from AD and the use of heat energy from incinerators is that incinerators destroy the resource (organic matter) to extract the calorific value generating heat, toxic emissions and creating toxic ash. The use of AD results in a relatively clean burning gas while *retaining the resource* or organic matter which post-processing is known as 'digestate'. This material can then be added to compost or used as a soil conditioning adding to the carbon retention and fertility of soils.

A second form of energy that can be generated from waste is a POPs destruction technology known as Gas Phase Chemical Reduction. The generation of methane from the hydrogen-based POPs destruction technology can also be used for energy generation without toxic air emissions and solid residues. This technology is described in detail in following chapters.

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[27] Smith, Brown, *et al.*, "Waste Management Options and Climate Change: Final report to the European Commission, DG Environment: Executive Summary," July 2001.

[28] Bell, L., and Bremmer, J., (2013) Burning Waste for Energy – It Doesn't Stack Up. National Toxics Network Australia http://www.ntn.org.au/wp/wp-content/uploads/2013/11/NTN-waste-to-energy-incineration-report-2013.1.pdf

2.3 MEDICAL WASTE INCINERATORS

The primary purpose of medical waste incinerators is disinfection of biological pathogens in medical and clinical waste by combustion of waste at temperatures between 850-1000°C. This includes contaminated medical clothing, bandages, dressings, blood bags, plastics and even body parts among other materials. The high PVC content in medical waste plastics can lead to elevated formation of chlorinated POPs such as polychlorobenzodioxins (PCDDs) and polychlorodibenzofurans (PCDFs) more commonly known as dioxins and furans in air emissions and solid residues (ash). It is rare for medical waste incinerators to be designed to generate energy as a by-product.

2.4 HAZARDOUS WASTE INCINERATORS

Hazardous waste incinerators are used to burn solid and liquid hazardous waste with the intention of destroying it. The waste types can be diverse and include hydrocarbon wastes (oils, solvents, tars, refining by-products), pesticides and herbicides, wastes bearing heavy metals, POPs waste, plastics and chemical waste and so on. This type of incinerator operates at higher temperatures of 1000°C – 1200°C and is required to have very expensive and complex APC systems to try and prevent the emissions of POPs and other toxic materials. Hazardous waste incinerators do not typically generate energy for external consumption.

This chapter of the report has discussed some of the key sustainability and pollution issues associated more broadly with waste incineration. The impacts include destruction of valuable resources, atmospheric emissions of POPs, heavy metals and other toxic compounds along with the generation of millions of tonnes of toxic ash which are all key reasons to replace incineration with the widespread use of non-combustion technologies for POPs waste destruction.

The next chapter describes in detail the established and emerging technologies that are specifically being used for the destruction of POPs waste, the most toxic of all hazardous waste which are scheduled for destruction under the Stockholm Convention.

3. NON-COMBUSTION TECHNOLOGIES FOR POPs STOCKPILES AND CONTAMINATED SITES

Non-combustion technologies are generally discussed in terms of their ability to destroy discrete stockpiles of POPs waste such as PCB oils, pesticides and contaminated industrial wastes. However, they can also be adapted, using a range of techniques, to allow the remediation of contaminated sites. Technologies that have been developed to allow application to contaminated site remediation are also highlighted in the section below.

3.1 BALL MILLING (MECHANO-CHEMICAL DESTRUCTION)

Three vendors have developed pilot and commercial versions of this technology. Environmental Decontamination Limited[29] (EDL) is a New Zealand based company operating in Asia and Europe using the mechano chemical destruction (MCD) process. Tribochem, Germany operate a similar technology on the same principles (Birke and Brodowski 2002) named the Dehalogenation by Mechanochemical Reaction (DMCR) process[30]. 'Radical Planet Technology' Japan (USEPA 2005, Shimme *et al.* 2008) has been used for commercial PCB destruction. Currently, only EDL is engaged in commercial contaminated site remediation activity.

The basic principles of ball milling involve the high energy agitation of steel balls within an enclosed steel vessel filled with contaminated media such as POPs waste or POPs contaminated soil, and the addition of a reagent. The ball-to-ball and ball-to-surface collision points are the major regions of fracture and chemical reaction initiation. The reactions induced at the fracture point include radical formation and electron transfer resulting in the destruction of chemical bonds.

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[29] https://edl-europe.com/technology/

[30] http://www.tribochem.de/

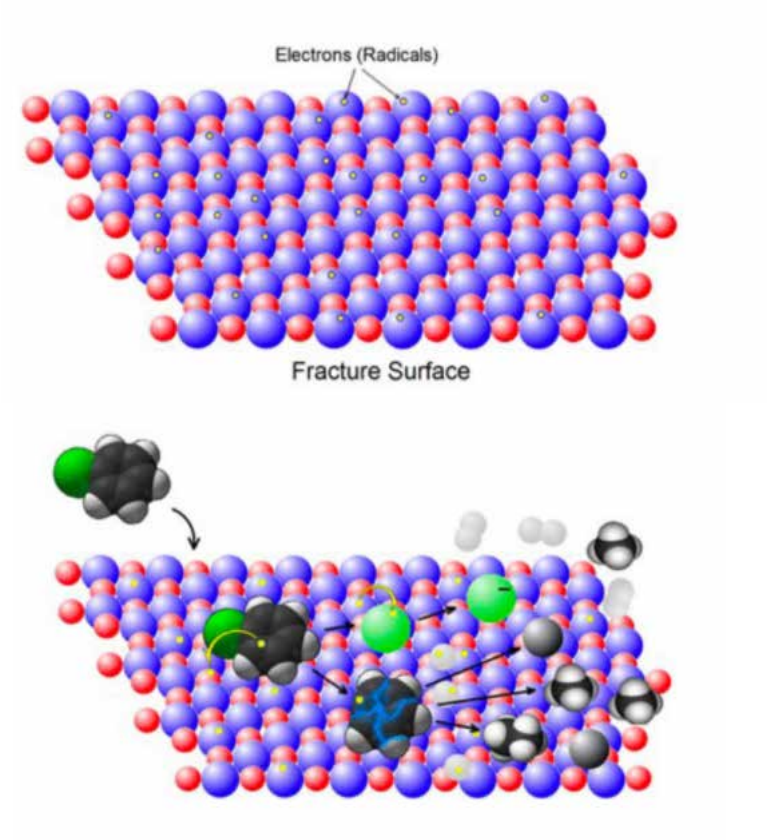

Figure 2. Destruction of chemical bonds from high impacts ball milling.
Source: EDL Europe

According to EDL:

> *"Research to date indicates that the mechanochemical destruction of organic contaminants is complex with two or more parallel reaction mechanisms. However, the dominant destruction pathway is ionisation which leads to complete dehalogenation and fragmentation of POPs. Fractured surfaces of the contaminated soil matrix are created by mechanochemical processing leading to highly reactive surfaces. These reactive sites can ionise contaminant molecules that land on them forming contaminant radicals which fragment into smaller 'daughter' ions and ultimately neutral species."* Fine tuning of parameters such as the length and frequency of agitation and type and concentration of reagent are

Figure 3. The compact and modular EDL ball mills are readily transportable to remote stockpiles. Source: EDL Europe

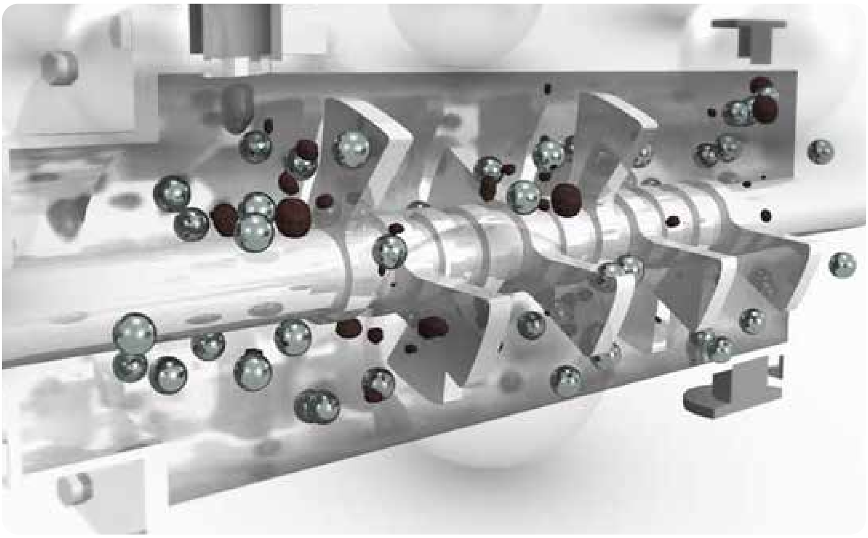

Figure 4. An internal graphic visualisation of the EDL MCD ball mill using 'rotors' to increase agitation. Source: EDL Europe

necessary to achieve full mineralisation of chlorinated POPs or dehalogenation of brominated and fluorinated POPs. Milling is conducted in a solid phase at modest temperatures and pressures without solvents. Co-reagents can include alkali earth oxides and metals, quartz or a combination thereof. The end product of treatment is carbon, carbon dioxide, water and inorganic halides (Cagnetta *et al.* 2016a). The major operating cost is the energy use of the system as the plant does not required hazardous solvent or other chemical inputs or any form of flue gas scrubbing. The process does not generate UPOPs under normal POPs waste treatment conditions but has been shown to reform dioxin when treating secondary copper smelting fly ash (Cagnetta *et al.* 2016b).

Reagents fall into 4 main categories:

1. Reducing agents, which are principally zero valent metals and metal hydrides
2. Lewis bases such as metal oxides, especially alkali and alkali earth oxides e.g., CaO
3. Neutral species such as quartz (SiO_2) and alumina (Al_2O_3)
4. Oxidizing agents such as manganese dioxide (Cagnetta *et al.* 2016b)

The advantage of ball milling systems using these reagents for POPs destruction is that they are generally not hazardous, are relatively inexpensive and widely available making them attractive for site remediation in developing countries and countries in economic transition. An additional attraction is the transportability of the small-scale ball milling machines such as the EDL models which can be operated in-situ at contaminated sites and scaled up to increase throughput.

Pre-treatment of contaminated matrices may involve pre-crushing to optimum 10mm input, moisture reduction to less than 2% and magnetic removal of metal debris from highly disturbed sites.

The EDL process was initially used for a large scale contaminated site remediation in New Zealand in 2004 at Mapua where 8,650 m^3 of soil heavily contaminated with Lindane, DDT, Dieldrin, and Aldrin allowing the site to be used for residential and residential purposes within regulatory soil guidelines values. The process has also been used to treat contaminated soil in the US, Japan and the Netherlands to treat dioxin and PCB contaminated sites.

Since 2012 the company has been engaged in a project to remediate the Bien Hoa site in Vietnam. The site was a former US air force base during

TABLE 3. THROUGHPUT, FEED RATES AND ENERGY CONSUMPTION OF MECHANOCHEMICAL TECHNOLOGIES.

Essential characteristics of existing pilot/full-scale mechanochemical technologies.

Company	Technology	Milling device type	Through-put	Maximum feed	Energy re-quirement
Environmental Decontamination Ltd., New Zealand ww.edl-asia.com	Mechano-Chemical Destruction, MCD™	Stirred ball mill	Continuous	15 t/h	75 kWh/t
Radical Planet Research institute Co. Ltd., Japan www.radicalplanet.co.jp	Radical planet technology	Planetary ball mill	Batch	200 kg	540 kW
Tribochem.de, Germany www.tribochem.de	Dehalogenation by Mechano-Chemical Reaction (DMCR)	Vibrational mill	Batch/ Continuous	1 t/h	160 kW*

** Retrieved from Siebtechnick GmbH web site, www.siebtechnik-gmbh.de*

the Vietnam war which stored large quantities or dioxin contaminated defoliant (Agent Orange) leading to soil and groundwater contamination. The UNEP-GEF funded pilot resulted in the successful treatment of 150 tonnes of soil with high dioxin concentrations.

TABLE 4. REDUCTION OF POPS LEVELS IN DIOXIN CONTAMINATED SOILS AT BIEN HOA VIETNAM BY EDL MCD PROCESS.

Contaminant	Untreated Concentration (ng/kg TEQ)	Treated Concentration (ng/kg TEQ)	Percent Reduction
PCDD/F	28,500	338	98.80%
Dioxin-like PCBs	15.9	0.41	**97.40%**

Source: EDL Europe

Pilot trials at the site saw dioxin levels in soils reduced by close to 99% although optimising destruction parameters (adjusting reagent ratios) was impacted by lab turn-around times[31] However the dioxin destruction trial prompted support from UN Assessors:

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[31] EDL (2018) Technology Factsheet: Mechano-Chemical Destruction (MCDTM)

Figure 5. EDL ball mills treating high strength dioxin waste in Bien Hoa, Vietnam.

> *"In summary EDL's MCD technology is considered technically qualified for remediation applications on the large majority of PCDD/F contaminated soil likely to be encountered for even the most restrictive land use and as such should be considered in any commercial opportunities that arise including for pending remediation work at Bien Hoa without further demonstration of this type, and likewise would be candidate for POPs contaminated sites being addressed by the GEF globally."*
>
> – GEF/UNDP Independent Technology Evaluation (2015)

3.2 GAS PHASE CHEMICAL REDUCTION (GPCR)

The GPCR process[32] involves the thermochemical reduction of organic compounds. At temperatures greater than 850 °C and at low pressures, hydrogen reacts with chlorinated organic compounds to yield primarily methane, hydrogen, hydrogen chloride (if the waste is chlorinated), and minor amounts of low molecular weight hydrocarbons (benzene and ethylene). The hydrochloric acid is neutralized through the addition of caustic soda during the initial cooling of the process gas or can be taken off in acid form for reuse. The GPCR technology can be broken down into three basic unit operations: a front-end system (where the contaminants are transformed into a suitable form for destruction in the reactor), a reactor (which reduces the contaminants, at this stage in gas phase, using hydrogen and steam), and a gas scrubbing and compression system.

Destruction efficiencies of 99.9999 % have been reported for DDT, HCB, PCBs, PCDDs and PCDFs (Kümmling *et al.* 2001; Kümmling *et al.* 2002; CMPS&F 1997; Rahuman *et al.* 2000). DEs of more than 99.999 % have been reported for PCBs, 99.999 % for PCDD contained in waste oils containing PCBs (UNEP, 2000), as well as DE above 99.9999 % for HCB and chlorobenzenes (Kümmling *et al.*, 2002, Arnold, 2003).

TABLE 5. PERFORMANCE OF GPCR IN FULL SCALE PLANTS.

Site	Location	Period	POP	Quantity of Soil Treated	Scale	Destruction Efficiency
Kwinana Commercial Operations	Australia	1995 to 2000	PCBs DDT	2,000 tonnes	Full	>99.9999%, >99.9999%
Kwinana Hex Waste Trials	Australia	April 1999	HCB	8 tonnes	Full	>99.9999%
General Motors of Canada Limited	Canada	1996 to 1997	PCB Dioxins	1,000 tonnes	Full	>99.9999%, >99.9995%

Source: D. Hallett

GPCR is an ex situ technology used for the treatment of high strength POP wastes and operates in two stages. In the first stage, contaminated soil is heated in a thermal reduction batch processor (TRBP) in the absence of oxygen to temperatures around 600°C. At high temperature the organic compounds desorb from the solid matrix and enter the gas phase. The treated soil is allowed to cool prior to its appropriate disposal on or

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[32] The process can also be called hydrogenation (European Commission, 2017).

TABLE 6. GPCR DESTRUCTION TESTS ON HALOGENATED COMPOUNDS.

Project	Contaminant	Destruction and Removal Efficiency (%)	Target Criteria (%)
US EPA - Bay City (oily water - 3 tests)	PCBs	99.9999	99.9999
US EPA - Bay City (oily water - 3 tests)	PCBs	99.9999	99.9999
General Motors of Canada Limited (PCB Oil - 3 tests)	PCBs	99.9999996	99.9999
	PCBs	99.9999985	
	PCBs	99.9999808	
PCB Oil (Kwinana Regulatory Testing)	PCBs	99.999998	99.9999
DDT in Toluene (Kwinana Regulatory Testing)	DDT	99.999984	99.9999
PCB Oil (Japanese Regulatory Testing)	PCBs	99.99998098	99.9999
	PCBs	99.99999977	99.9999
HCB Treatment Trials (HCB crystals - 3 tests)	HCB	99.999999	99.9999
	HCB	99.999999	99.9999
	HCB	99.9999	99.9999
Refrigerant Treatment (CFC R-12 - 1 test)	Dichlorodifluoromethane	> 99.999	99.99

Source: D. Hallett

off site. The thermal reduction batch processor can also be used for bulk solids other than soil, including drums, electrical equipment, drummed waste, wood pallets, concrete, rubble and miscellaneous solids. This allows for comprehensive decontamination of sites where demolished structures, dismantled processing equipment and used personal protective equipment may also require decontamination.

In the second stage, the desorbed gaseous-phase contaminants pass to a GPCR™ reactor, where they react with introduced hydrogen gas at temperatures ranging from 850 to 900°C. This reaction converts organic contaminants into primarily methane, water and hydrogen. Acid gases such as hydrogen chloride may also be produced when chlorinated organic contaminants are present. The gases produced in the second stage are scrubbed by caustic scrubber towers to cool the gases, neutralize acids, and remove fine particulates.

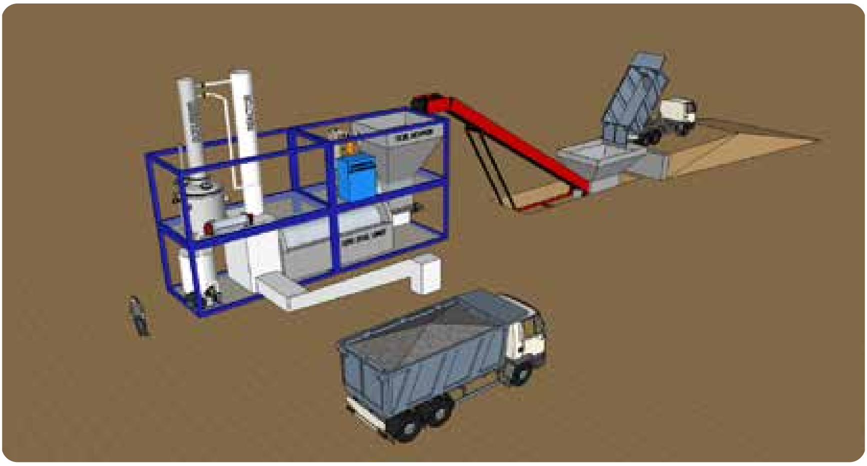

Figure 6. GPCR configured for contaminated soil treatment. Source: D. Hallett

Figure 7. Thermal reduction batch processor (TRBP) of GPCR system. Source: D. Hallett

The off-gas exiting the scrubber is rich in methane and is collected and stored for reuse as fuel. Methane is also used to generate hydrogen in a catalyzed high-temperature reaction. Spent scrubber water is treated by granular activated carbon filters prior to discharge via standard wastewater systems (USEPA 2010). To assure the complete dechlorination of

Figure 8. GPCR operating in 24 hour, 7 day cycle for high strength PCB oil/ waste. Kwinana Australia 1999. Source: D. Hallett

POPs an on-line mass spectrometer is provided which can divert all gases into the recirculation mode. Following the scrubbing step the resulting mixture of gases, which is rich of methane, propane and hydrogen can be recirculated entirely or partially, and a fraction of the gas can be used as fuel in the system boiler (UNIDO 2007).

GPCR has operated at pilot and commercial scale in a range of locations and has treated a wide range of halogenated wastes to a high DE and DRE including fluorinated compounds.

While the GPCR process uses hydrogen under pressure to break down persistent organic pollutants it also generates hydrogen and methane as part of the process. According to the vendor and designer of the technology, Hallett Environmental and Technology Group Inc., the third-generation version of the technology is designed to export surplus hydrogen generated during the process for use as a fuel[33]. Methane can also be generated for this purpose. The first generation of the technology was used in Kwinana, Australia to destroy around 2000 tonnes of PCB waste in the late 1990's (IHPA 2002). A pilot plant using the GPCR technology is currently being developed in Ontario Canada to treat BFR contaminated auto

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[33] Pers comm D. Hallett, September 2019

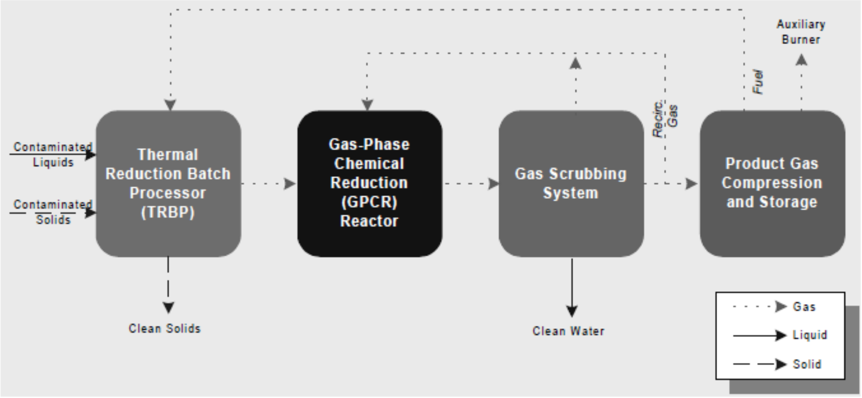

Figure 9. GPCR operating schematic. Source: D. Hallett

shredder residue, POPs impacted plastics and other wastes. Operating under a new patent this version of the technology is known as *Hydrogen Reduction*. Cost of establishment of a 50 ton per day throughput plant for automotive shredder residue (ASR) is currently in the order of USD 18 million and a full commercial scale POPs destruction unit would cost approximately USD 50 million.[34]

3.3 SUPERCRITICAL WATER OXIDATION (SCWO) AND INDUSTRIAL SUPERCRITICAL WATER OXIDATION (ISCWO)

Both *supercritical* and *subcritical* water oxidation systems have been developed by a number of companies over the last 30 years and some have substantial commercial experience in destroying POPs such as PCB. The technologies share similar principles of destruction of organics using an oxidant agent such as hydrogen peroxide, oxygen or nitrite. The term *supercritical* refers to the state of water just prior to its phase change from liquid to gas under heat and pressure (e.g. 374°C and 218 atmospheres). Subcritical water refers to the state of water just below its critical level (e.g. 370°C and 262 atmospheres). In this state organic materials can be rapidly oxidised and decomposed. For destruction of PCB typical reaction conditions are temperature 400 - 500° C, pressure 25MPa, with a reaction time of 1 - 5 mins.

Supercritical systems generally injected the waste along with water and oxygen into a column; mixed, heated and compressed to the point of supercriticality. The system is totally enclosed. The properties of the water in this phase have elevated molecular kinematic energy that is highly reac-

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[34] Ibid.

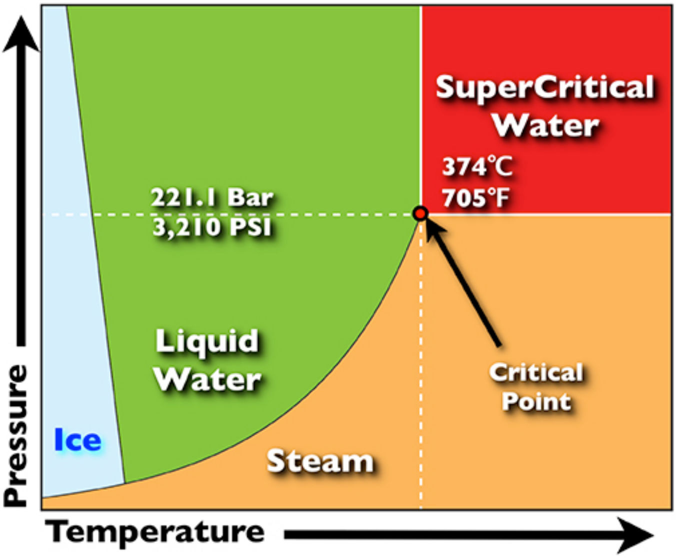

Figure 10. Parameters for Supercritical water.

tive and, combined with oxygen, can oxidize and destroy organic waste. The outputs of the reaction are nitrogen, water and carbon dioxide. The destruction of chlorinated POPs results in an output of elevated hydrochloric acid. The highly acidic environment this generates requires the structural equipment of the process vessels to be corrosion-resistant, such as titanium alloys in combination with anti-corrosive additives such as sodium carbonate.

The process is not suited to bulk solids but can treat aqueous wastes, oils, solvents, slurries, and solids with a diameter less than 200 µm. SCWO treatment of solid wastes after they have been ground into a fine slurry has been demonstrated using feed materials containing up to 25 percent suspended solids (USEPA 2010) Earlier versions of the technology were prone to corrosion and salt plugging but his has been resolved with the use of corrosion-resistant materials (UNIDO 2007).

In the context of POPs contaminated sites, SCWO has usually been operated in an ex-situ mode with POPs having been removed from contaminated soils by desorption or similar methods or, in the case of high strength powdered matrices ground and reduced to a slurry, before being fed to the reactor.

As of 2013 there were 3 fully operational plants, 5 constructed and 9 planned for construction. In the interim, many of these plants will have become operational. The longest established plant is operated in Japan by Japan Environmental Safety Corporation (JESCO) for PCB destruction, with a capacity of 2000 kg of PCB per day (Marrone *et al.* 2013). One plant in Japan treating high strength PCB (100%) using subcritical water oxidation, had emissions of PCDD/DF and dl-PCBs to air of 0.00009 ng TEQ/m^3 and to water of 0.0006–0.004 ng TEQ/L. (Hosomi 2006).

While costs can vary significantly due to the capacity and type of SCWO developed, a study by Aki *et al.* (1998) found that destruction of hazardous waste from the petrochemical industry could be achieved at significantly lower costs by implementing SCWO rather than by using incineration. Installation costs were 15% less expensive and running costs for SCWO were only around 10% of the costs of incineration of hazardous liquids. SCWO is now used extensively by the US military for destruction of hazardous wastes and chemical weapons, including mobile ship-based units.

Marrone, in summarising a comprehensive review of the global state of SCWO, notes that "*SCWO technology commercialization remains an area of great interest and activity.*" The main advantages of SCWO are very low emissions, low costs, high DE and low associated resources (catalysts) for operation in remote locations. Studies have been conducted on plastic waste SCWO by researchers (Goto 2016, Liu *et al.* 2016) and industrial operators.

General Atomics have developed a relatively high throughput feed model designed for general industrial hazardous wastes as well as non-hazardous waste. Their technology is referred to as Industrial Supercritical Water Oxidation or iSCWO. A GEF funded project to treat large stockpiles of DDT waste at a contaminated site in Tajikistan and the Kyrgyz Republic is currently being implemented using the technology (GEF 2017).

The General Atomics iSCWO operates with the following process. Air is pumped into the reactor vessel and pressurised to 3200 psi and then heated to 650° C. Water is pumped in and as the liquid flows into the reactor vessel pre-ignition is activated. Water is heated and pressurised above thermodynamic critical point of 650° C and 235 bar. When the stable critical point is reached, organic waste mixed with quench water (and if required sodium hydroxide) is added). The supercritical conditions render organic materials, oxidation reactants and oxidation products miscible in water and they are destroyed. Remaining liquid is then discharged through a pressure let down to atmospheric conditions.

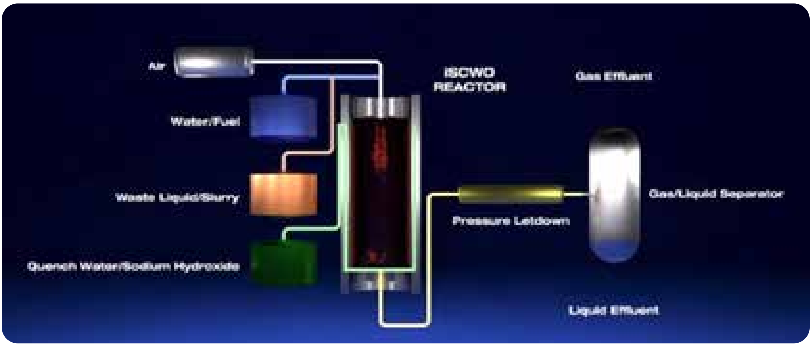

Figure 11. Schematic of iSCWO. Source: General Atomics

The liquid and gas waste products from the process consist of carbon dioxide, water and depending on the waste feed, salts and/or metallic oxides. Steam is vented to atmosphere. The are no particulates released or pollution abatement filters required. Clean water is produced requiring no pre-treatment to dispose to sewer (elevated salinity and metal oxides limit the use of the effluent water).

3.4 BASE CATALYZED DECOMPOSITION (BCD)

BCD is an ex-situ technology and has been used for destruction of PCBs and treatment of soil contaminated at high concentrations with PCBs. BCD was developed jointly between the US Navy and the US Environmental Protection Authority (US EPA) to decontaminate liquids, soils, sludge and sediments contaminated with chlorinated organic compounds, especially PCB, dioxins, and furans. The BCD process has received approval by EPA's Office of Toxic Substances under the TSCA10 for PCB treatment (UNIDO 2007). The technology patent was then passed on to developers and held by BCD Group USA and licensed to operate in the US, Australia, New Zealand, Mexico, Japan, Spain, and the Czech Republic.

At higher soil concentration levels, a pre-treatment step such as indirect thermal desorption may be necessary to reduce bulk material to treatable volumes. Contaminated soil and alkali (e.g. sodium bicarbonate) are mixed and heated to a range of 315°C - 500°C to allow the evaporation of the halogenated compounds. The volatilised contaminants are sent to a second stage condenser. The resulting concentrate is then subject to the BCD process. The BCD process consists of mixing the POPs concentrate waste in a reactor vessel with a reagent mixture consisting of hydrogen-donor oil, alkali metal hydroxide, and a proprietary catalyst. After heating the mix to 326°C, for between 3-6 hours highly reactive atomic hydrogen is created and under exothermic conditions the hydrogen splits from the donor oil and hydrogenates the bonded chlorine of the POPs (assuming chlorinated POPs). In combination with a proprietary reagent, the reaction results in water vapor and sodium chloride. Following assessment of the reaction, the oil and sludge are dumped from the reactor and the oil can be recycled into the next batch process. The sludge can be neutralized for landfilling or used for treating acidic waste-water (UNIDO 2007).

Modular, transportable and fixed BCD plants have been built. Throughput capacity for the desorption stage differs according to application and ranges between 100 kg/hr and 20 tons/hr (STAP GEF 2004). BCD reactors are limited by solid contents in the reactor waste and usually treat 1-3 tons per batch and 2-4 batches per day. High destruction efficiencies (4-6 nines or 99.9999%) have been demonstrated for DDT, PCB, PCP, HCB, HCH, and dioxins (PCDD/F). Emissions are very low, as for most batch reactors and indirect desorption units. The total mass of emitted off-gas is orders of magnitude smaller than incinerators or similar directly fired desorption units (STAP GEF 2004).

Measurement of levels of PCDD/PCDF in air emissions for a BCD ranged between 0.013 and 0.031 ng TEQ/Nm^3; for PCBs between 0.005 and 0.0014 ng TEQ/Nm^3. For one plant, the residual amounts of PCDD/PCDF in the output oil were less than 0.016 ng TEQ/g (Holoubek 2006)

This technology has been demonstrated to treat both high strength POPs and large throughputs of contaminated soil, including heavily contaminated dioxin-impacted soil in Spolana, Czech Republic (UNEP Expert Group BAT BEP 2006). The relatively low costs of additives (sodium hydroxide is the major input cost) make this a suitable technology for application in most developing countries. Prior to thermal desorption of POPs from contaminated media, other pre-treatment steps may be required such as reduction of moisture levels and adjustment of pH, crushing of larger rubble and soil materials to a small diameter. Wet sludges must also be dewatered prior to treatment. Volatile solvents should be removed from contaminated media by distillation prior to treatment (e.g. pesticides with solvent carriers) (CMPS&F – Environment Australia 1997).

3.5 CATALYTIC HYDROGENATION (CHD)

Catalytic hydrogenation has been used by technology vendors in Australia, the US and Japan almost exclusively for the treatment and destruction of PCBs although the technology can be used to treat other chlorinated POPs.

Figure 12. Hydrodec plant Canton Ohio, USA.

The Hydrodec system using catalytic hydrogenation was a technology developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia for the refurbishment of transformer oil and simultaneous destruction of PCB, and was originally known as catalytic hydrogenation. The company "Hydrodec" was established in 2004 and commenced operations in Australia. The Australian plant currently processes 6.5 million litres of oil a year and the US plant 45 million litres per year. A similar process in Japan can treat 2 tons per day of pure PCB with DE of 99.9996~99.9999%. (Vijgen 2008).

According to the Australian technology developers (Duffy and Fookes 1997), the Hydrodec process is based on the mild hydrogenation of spent oil in a packed bed catalytic reactor (hydrogen gas and palladium on carbon (Pd/C) catalyst dispersed in the paraffin oil), operating at moderate temperatures and pressures. Under process conditions hydrogen reacts with heteroatoms in the oil itself, and also with any organochlorines present. Noble metal catalysts are effective but are known to be easily poisoned by contaminants such as sulphur in the oil. Hydrodec developers overcame this issue by using a proprietary additive that scavenges the hydrogen chloride and ensures that the hydrochloric acid produced does not lead to degradation of the catalyst, and which reduces hydrocarbon cracking reactions on the surface of the catalyst. After a program of catalyst and process optimization, it was possible to keep the hydrocarbon structure of transformer oil essentially unchanged, while achieving better than 99.999% destruction of PCB (Duffy and Fookes 1997).

TABLE 7. DESTRUCTION EFFICIENCY OF CHD PROCESS.

Compound	Feed Concentration (mg/kg)	Product Concentration (mg/kg)	Destruction Efficiency (%)
PCB	40000	< 0.027	> 99.99993
DDT	40000	< 0.004	> 99.99999
PCP	30000	< 0.003	> 99.99999
HCB	1340	< 0.005	> 99.9996
1,2,3,4-TCDD	46	< 0.000004	> 99.99999

While the commercial application for the process is PCB destruction and PCB-free transformer oil rejuvenation, it has been trialled on a range of POPs (see table above) with high DE results and is considered applicable to most POPs in liquid form. In the context of contaminated sites the POPs would need to be removed from the contaminated matrices via pre-treatment before dehalogenation in the CHD unit.

Japan has also been operating catalytic hydrogenation plants since the early 2000's. In a two tonne per day Japanese plant operated by JECSO (Osaka) and developed by Kanden Engineering, very low levels of PCDD/Fs and dl-PCBs of around 0.00001-0.0001 ng TEQ/g in biphenyls after the reaction by distillation and also very low levels of PCDD/Fs and dl-PCBs in air emissions in the order of 0.0001 ng TEQ/Nm^3 were measured (Hosomi 2006).

3.6 CATALYTIC DECHLORINATION USING COPPER CATALYSIS (CDC)

CDC is a process based on selective dehalogenation as its primary operation while suppressing coupling reactions. The process uses a reaction via an arylcopper intermediate which drives electron transfer. CDC operates at 250-300o C with a reaction time of 3-6 hours in an oxygen deficient atmosphere with a concentration of copper to waste of approx. 0.1 wt.%. (Vijgen 2014). Destruction efficiency of 99.999966 percent has been reported for treatment of waste contaminated with DDT, HCB, PeCB, PCDD/PCDFs, PCBs and PCP (Ocelka 2017).

It has demonstrated ability to treat different types of wastes including contaminated soil and construction materials, fly ash, liquid and solid wastes containing POPs and filtration sands (Ocelka 2010). For sands and soils contaminated with POPs, a pre-treatment process such as thermal desorption can be useful for concentrating the POPs waste to reduce volume in the reactor. This process can manage concentrated POPs waste and has been proven to destroy the majority of chlorinated aromatic and/or cyclic compounds (Vijgen 2014).

The HCl which is released as a part of the hydrodechlorination of organochlorine compounds is captured in wet scrubber. Possible semi-volatile effluents from the reaction are captured in carbon filter, recycled back in CDC reactor; POPs residuals from wet scrubbers are captured on organophilic clays or carbon column, with further destruction of solid phase in CDC reactor (Vijgen 2014).

CDC technology has been used at one commercial operation in Jaworzno, Poland and partly also applied to decontamination of POPs pesticides contaminated soils from Klatovy, Czech Republic (Ocelka 2011; Ocelka 2017)

3.7 ALKALI METAL REDUCTION (SODIUM REDUCTION)

Alkali metal reduction involves the treatment of wastes where dispersed alkali metal reacts with chlorine atoms contained in the chlorinated compounds of halogenated waste to produce salts and non-halogenated waste. Typically, the process operates at atmospheric pressure and temperatures between 60°C and 180°C (Ariizumi, Otsuka *et al.* 1997). Treatment can take place either in situ (e.g. PCB-contaminated transformers) or ex situ in a reaction vessel. There are several variations of this process (Piersol 1989). Although potassium and potassium-sodium alloy have been used, metallic sodium is the most commonly used reducing agent. The process must avoid the formation of a polymer (which occurs in one or two of the technologies identified) or must take the formation of such this solid into account and introduce a separation step to yield the pure reusable oil.

In the context of contaminated sites this technology can be used to treat stockpiles of electrical transformers containing PCB oils and also to treat PCBs directly, once extracted from solid matrices in a pre-treatment step.

Treatment of whole capacitors and transformers could be carried out following size reduction through shearing. Pre-treatment should include dewatering by phase separation, evaporation, or another method *to avoid explosive reactions* with metallic sodium. Equipment should be washed with organic solvents. Similarly, the POPs which are solid or in the

Figure 13. In-situ PCB destruction using SR France.

Figure 14. Waste from an SR unit.

adsorbed state would need to be dissolved to the required concentration or extracted from matrices (Piersol 1989, UNEP 2004). The process is available in transportable and fixed configurations (UNEP 2000). Mobile facilities are capable of treating 15,000 litres per day of PCBs transformer oil (UNEP 2000).

Destruction efficiency (DE) values of greater than 99.999% and destruction removal efficiency (DRE) values of 99.9999% have been reported for chlordane, HCH, and PCBs (Ministry of the Environment of Japan 2004). Apart from the European Union, the sodium reduction process has also been demonstrated to meet regulatory criteria in Australia, Canada, Japan, South Africa and the United States of America for PCB transformer oil treatment, i.e. less than 2mg/kg in solid and liquid residues (UNEP 2004).

The highest concentration of Alkali Metal Reduction facilities are based in Japan. The plants operating in 2006 were treating oils contaminated with polychlorinated biphenyls (PCB). A number of plants treated PCB with concentrations in the range of 100 parts per million, while some plants were treating concentrations up to 10 per cent. In all plants, the exhaust gas was treated with activated carbon (UNEP – EG BAT/BEP 2006).

Japan has considerable experience in alkali reduction techniques for POPs destruction and achieves high destruction levels. In one plant, (Toyota/ JESCO alkali reduction) the measured emissions of PCDD/DF and dl-PCBs to air and water were low when destroying PCBs. Levels were achieved of <0.002 ng TEQ/Nm^3 in exhaust gas and 0.00005–0.0001 ng TEQ/L in water wastes. The residual solid material from the process was in the range of 1.7–54 ng/g for PCB and 0.0018 ng TEQ/g for PCDD/DF and dl-PCBs (Hosomi 2006).

3.8 SOLVATED ELECTRON TECHNOLOGY (SET)

Solvated Electron Technology (SET) is an ex-situ non-combustion technology used in the treatment of contaminated soils and reduces PCBs to metal salts and molecules that have been dehalogenated.

In general, solvated electrons are formed when certain alkaline earth metals (e.g., sodium, calcium, lithium, and potassium) are dissolved in ammonia and form metal ions and free electrons. These free electrons produce a strong reducing agent that removes halogens (primarily chlorine) from organic molecules and reduces other contaminants. By-products from treating PCB- contaminated waste include petroleum hydrocarbons, sodium chloride, and sodium amide (Tauw 2020).

The SET process can treat contaminated soils, waste oils, sludge and pesticides (Vijgen 2003).

For contaminated soils, after screening, PCB contaminated soil is dewatered and placed into a sealed treatment vessel and mixed with ammonia into a slurry. The slurry is mixed with calcium or sodium until the reaction is complete. The mixture is moved to an ammonia soil separation vessel and the liquid ammonia removed. Further mixing removes remaining ammonia as vapour. The liquid and vapour ammonia can be collected in an ammonia/water separator, the water is removed and the ammonia recycled to the storage tank for further use (Tauw 2020).

The solvated electron process has been used to destroy POPs and other contaminants in soil including PCBs, PAHs, chlorinated solvents, dioxins, furans, pesticides, hexachlorobenzene, BTXs, volatiles, and semi-volatiles (Vijgen 2003).

SET has been treating soils contaminated with PCBs, dioxins and other POPs since the late 1990's and results indicate high levels of destruction of target compounds.

Figure 15. SET™ treatment of dioxin contaminated waste oil.

Contaminant	Pre-Treatment (ppt)	Post-Treatment (ppt)
Dioxins	418500	2.3
Furans	14120	1.3

Source: Vijgen 2003. McCormick and Baxter site, Stockton, CA

Figure 16. SET™ destruction of PCB in oils.

Material	Pre-Treatment (ppm)	Post-Treatment (ppm)
Used motor oil	23339	< 1.0
Transformer oil	509000	20*
Mineral oil	5000	< 0.5
Hexane	100000	0.5

** Required additional sodium for better reduction*

Source: Vijgen (2003)

The SET process is a mobile technology that can be established at contaminated sites for treatment of POPs wastes. They are issues around health and safety as the chemicals used in the process can be hazardous and the solvated electron process is exothermic in the presence of water. That is why the material must be pre-dried before treatment. As noted in the figure above insufficient addition of reagents may only lead to partial decomposition of target contaminants.

3.9 ELECTROCHEMICAL OXIDATION

According to UNIDO electrochemical oxidation technologies can cover a range of techniques including: non-thermal oxidation technologies (without oxygen) and oxidation technologies with oxygen in the dense phase (non-flame). These processes include mediated electrochemical oxidation processes (MEO), and oxidation with oxygen in water or in melts (UNIDO 2007).

The principle of MEO processes are described by UNIDO (2007) as:

> *An electrochemical mediator is being brought to its higher oxidation state via electrochemical reaction, and is then being put in contact with an organic compound to be oxidized; the mediator, now in a lower oxidation state, is brought back to the electrochemical cell. Cerium ions, formed as a result of dissolution of metallic cerium in a strong acid, maintain a stable* Ce^{3+} *form. When oxidized to* Ce^{4+}*, cerium appears deep amber in colour and becomes a very strong oxidizing agent.* Ce^{4+} *then vigorously reacts with any kind of organic substance oxidizing it to* CO_2 *and water and being itself reduced to* Ce^{3+}*. After the cerium is reduced to* Ce^{3+} *by taking an electron from an organic compound, the cerium is brought to the electrochemical cell and reoxidized to* Ce^{4+} *which is then again introduced in the reaction with an organic compound thereby closing the cycle. This cycle only seems to be catalytic, as cerium participates and is not consumed in the reaction, every time being recovered for a new transformation. However, this process should not be confused with true catalysis since the recovery of the mediator takes place artificially and separately.*

The various electrochemical oxidation processes have advantages and disadvantages in treating POPs waste but when targeted toward suitable waste streams can be very effective. One of the most recent applications of this technology has been developed to destroy the extremely challenging PFAS POPs, PFOS and PFOA. The De-Fluoro technology by AECOM is described below along with earlier electrochemical oxidation processes.

Electrochemical oxidation processes have the main advantages of low dioxin generation potential, compact, modular and transportable design, mild operating conditions, ability to treat a wide variety of wastes including radioactive, pharmaceutical and biotechnology wastes. Its disadvantages are high levels of energy use and it is unsuitable for high strength POPs which are poorly soluble.

3.9.1 CerOx

CerOx is a variation of Mediated Electrochemical Oxidation (MEO) technology. It is based on the oxidation of organic compounds with the use of cerium^{4+} ions, which is defined as catalyst or mediator.

CerOx is a non-thermal destruction technology designed to destroy liquid organic hazardous waste materials. It is electrochemically driven aqueous phase process oxidising organic wastes at close to ambient pressure and temperature in a contained tank system. It can be scaled from a relatively small tank size to full plant size (Varela *et al.* 2001). CerOx uses cerium in its highest valence state (IV) to oxidise organic compounds. The resulting products are carbon dioxide, water and inorganic acid gases (USEPA 2010).

An electrochemical cell produces cerium (IV) from cerium (III). The process must use a liquid waste stream and soil or sediment must be mixed with water to produce a slurry for treatment. After the waste is mixed in the vessel with cerium (IV) and subject to sonication mixing the material is then moved to a reactor. The liquid phase reaction at 90-95°C destroys the organic compounds in the waste. The cerium (IV) is reduced to cerium (III) in the process and is recirculated to be recycled back to the electrochemical cell (USEPA 2010). Gases generated during this first phase including CO_2, chlorine gas and VOCs are then reacted in a gas phase chamber with cerium (IV) to destroy VOCs. A final scrubber removes acid gases before venting to atmosphere.

The process has been used at the University of Nevada, Reno to treat POPs pesticides. Trials conducted by CerOx corporation prior to installation at the university achieved destruction efficiency of 99.995% when treating high strength chlordane. Treatment tests on PCBs and dioxins dissolved in isopropyl alcohol. The input concentration of dioxins was 5 ppb. The results of three on output effluent test showed two non-detects (LOD was 0.397 ppt) and one level of 0.432 ppt (USEPA 2010). A sample of PCB in isopropyl alcohol at an input concentration of 2 ppm was reduced to an output level35 below the LOD of 0.4 ppb.

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35 CerOx™ Corporation. 2005. Process Technology Overview

Figure 17. CerOX Corp system University of Nevada. Source: CerOX Corporation

3.9.2 DE-FLUORO (AECOM)

The most recently developed electrochemical oxidation technology for treating POPs waste is DE-FLUORO by AECOM. This version of electrochemical oxidation had been developed specifically to destroy PFAS compounds and specifically the 'regulated' substances Perfluorooctanoic acid (PFOA) and Perfluorooctanesulfonic acid (PFOS) in water. Both PFOS and PFOA tend to occur together in contaminated groundwater systems as a result of their legacy use in aqueous fire fighting foams (AFFF) during fire events and more often through its use in fire fighting training at airports, military bases, oil and gas facilities, emergency service depots.

Contamination of groundwater with Per- and polyfluoroalkyl substances (PFAS) is now a major contamination issues across many countries. In the US around 700 PFAS-contaminated sites have been identified nationwide contaminating the groundwater drinking supplies of up to 110 million people (EWG 2018). Health effects of exposure to PFAS include:

- Increased chance of thyroid disease
- Decreased immune response
- Increased cholesterol levels
- Increased chance of cancer, especially kidney and testicular cancers[36]
- Developmental and immunotoxicity (Lee *et al.*, 2017; Nordén, Berger,& Engwall, 2016)

The C8 Science Panel was established to investigate probable links between the PFAS contamination of drinking water supplies in the Mid-Ohio Valley and illness among local residents. They concluded that health impacts included diagnosed high cholesterol, ulcerative colitis, thyroid disease, testicular cancer, kidney cancer, and pregnancy-induced hypertension[37].

The incredibly strong carbon-fluorine bond is the polar covalent bond between carbon and fluorine that is the basis of all organofluorine compounds including PFAS compounds. The strength of this bond makes PFAs substances very difficult to destroy and has led to many problems when attempting to remediate groundwater contaminated with PFAS. While there are more than 4000 organofluorine compounds (Sunderland *et al.* 2019) within the PFAS category, only PFOA and PFOS have currently been assessed as POPs.

One of the few techniques that can successfully break the carbon-fluorine bond is electrochemical oxidation. Studies have demonstrated that it can completely mineralize PFOA and PFOS at fast rates and relatively low energy consumption, under room temperature and atmospheric pressure.

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[36] PFAS Exposure and Your Health, 4/2019, https://www.michigan.gov/documents/pfasresponse/2019-4-23_PFAS_Exposure_and_Your_Health_-_APPROVED_WEB_653460_7.pdf

[37] http://www.c8sciencepanel.org/index.html

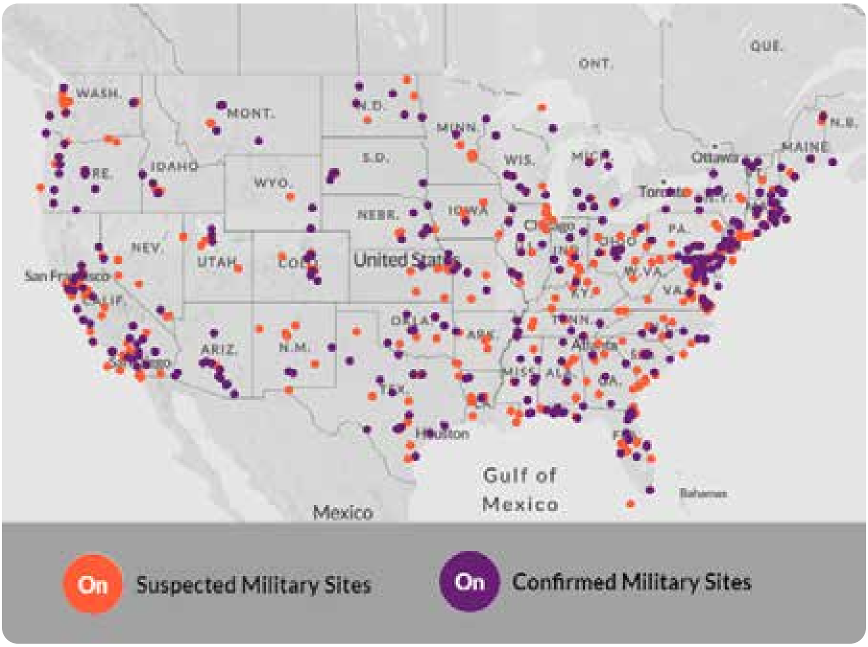

Figure 18. 704 US military sites with confirmed and suspected PFAS releases.
Source: EWG 2018

Studies have shown it can mineralise PFASs mixture compositions and co-contaminants under in situ conditions (Gomez-Ruiz *et al.*, 2017; Trautmann, Schell, Schmidt, Mangold, & Tiehm, 2015; Zhuo *et al.*, 2012)

DE-FLUORO technology is an electrochemical oxidation technology that has been optimised for the destruction (mineralisation) of PFOA and PFOS. Its development team at AECOM have conducted a range of trials using different electrode materials and optimisation of process variables to reach significant destruction efficiencies on concentrated PFAS compounds.

The DE-FLUORO process varies from other mediated electrochemical oxidation technologies by using *Magnéli phase* Ti_4O_7 electrodes. Magnéli phase titanium suboxide is a novel ceramic electrode material that has shown potential in degradation of a range of contaminants[38] (Liang *et al.* 2018). However, limitations of this titanium oxide in treating large volume

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[38] Liang S, Pierce D, Lin H, Chiang D, Huang Q. Electrochemical oxidation of PFOA and PFOS in concentrated waste streams. Remediation. 2018;28:127–134. https://doi.org/10.1002/rem.21554

low concentration flowing from mass transfer limitations mean that it is better suited to lower volume, high concentration contaminated media.

The use of ion exchange resins (IXR) and granulated activated carbon (GAC) to adsorb and concentrate PFAS from high volumes of contaminated groundwater, results in significant volumes of 'spent' materials which have adsorbed the maximum amount of PFAS contaminant before they lose efficiency or start to release contaminants due to insufficient adsorbent surface remaining. The adsorbents GAC and IXR can be regenerated after removal of the highly concentrated PFAS. While IXR can be regenerated on-site using can be regenerated on site using a mixture containing methanol and NaCl solution, GAC must be regenerated off-site under different conditions.

When IXR is subject to the regeneration process the remaining liquid residue is referred to as 'still bottoms' and is a mixture of high concentrations of PFAS, salts and residual organic content (Liang *et al.* 2018).

DE-FLUORO electrochemical oxidation was able to effectively destroy 'regulated' PFAS (PFOA and PFOS) in still bottoms from IXR filtration and in a range of contaminated wastewaters.

In some cases (3M AFFF concentrate) treatment of high strength wastes resulted in lower mass destruction but this was largely due to the limited time of reactions permitted by the trials and AECOM indicate that a longer residency in the process would have resulted in 100% destruction (AECOM 2019).

TABLE 8. MASS REDUCTION OF PFAS BY DE-FLUORO PROCESS.

Sample Description (Client Sector)	Initial total PFAS concentration (µg/L)	% Mass Reduction (total PFAS) DE-FLUORO™	Initial 'regulated' PFAS concentration (µg/L)	% Mass Reduction (regulated PFAS) DE-FLUORO™
Source area groundwater (New Zealand Government)	27	84%	13	98%
Industrial wastewater (Chemical Manufacturer)	354	100%	310	100%
Source area groundwater (Australian Government)	455	99%	445	98%
IX R – soft wash recipe (Remediation Contractor)	1570	63.6%	54.9	100%
Remediation derived wastewater (Aviation)	1590	90%	1088	98%
Spent C6 AFFF solution (Oil & Gas)	4620	83%	6	71%
Remediation derived wastewater (Remediation Contractor)	10700	99%	6572	100%
3M AFFF Concentrate/Product (Oil & Gas)	6380000	58%	5837000	62%

Source: AECOM 2019

4. TREATMENT TRAINS

Treatment trains combine pre-treatment technologies or techniques in sequence with destruction technologies to maximise the destruction of POPs waste from a contaminated site. The following examples combine aspects of pre-treatment techniques outlined in with destruction technologies described in the previous section.

4.1 CASE 1: SPEARS AND RIDS

This two-stage remediation system for sediments impacted by PCBs, dioxin and other chlorinated POPs was developed by NASA to clean up some of its former operational sites and has now been licenced for commercialisation to ecoSPEARS[39], a US based company. The process is designed to passively remediate contaminated sediments and other near shore aquatic environments. It has the advantage of minimal disturbance of the benthic form unlike the most commonly used method of dredging which physically damages the benthic habitat and often results in re-suspension of the POPs contaminants within the water column leading to increased bioavailability for biota. In cases where landforms may have cultural significance such as beaches of spiritual value to indigenous people the sediment can be remediated without excavation and damage to the landform.

Stage one

The Sorbent Polymer Extraction and Remediation System (SPEARS) consists of hollow polymer 'spears' or spikes which are pressed, in grids, into the sediment penetrating up to around 400mm. The spears are filled with a proprietary solvent. The hydrophobic nature of chlorinated POPs and their attraction to polymers combine to attract the POPs out of the sediment and onto the surface of the spears. Over time the POPs are absorbed through the outer polymer layer and into the liquid solvent inside the spear. Each spear has a zone of influence of 100mm in all directions. When arranged in suitably spaced grids the clusters of spears can be scaled up to cover large areas.

After several months the sediment can be analysed to determine if the remedial criteria has been met and sufficient POPs have been absorbed from the sediment. If necessary, the spears can be left in-situ longer.

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[39] https://ecospears.com/

Figure 19. Sorbent Polymer Extraction and Remediation System.
Source: ecoSPEARS

Stage two

When the remedial goal has been reached, the spears are removed and sent to the second part of the treatment train, the Reductive Integrated Dehalogenation System (RIDS), where the solvent is decanted and subject to dehalogenation.

The RIDS component of the system is an ex-situ facility using a proprietary form of alkali metal reduction to dehalogenate the POPs which have been absorbed from the sediment, through the spear and into the solvent.

4.2 CASE 2: INDIRECT THERMAL DESORPTION UNIT (ITDU) AND BASE CATALYSED DECOMPOSITION (BCD)

In this case an IDTU was paired with a BCD process to concentrate and then destroy POPs waste from the partial remediation of a former chemical manufacturing plant in Spolana, Czechia. The Spolana chemical complex located 25 km north of Prague on the Elbe River manufactured chlorine based chemicals and pesticides including pentachlorophenol and 2,4,5-T. Due to the technology used in production of the chlorinated pesticides there was heavy contamination of the product and site with dioxin and specifically the most toxic of the dioxin congeners 2,3,7,8-TCDD (Holoubek *et al.* 2007).

Figure 20. Indirect Thermal Desorption Unit (ITDU) Spolana Neratovice.
Source: Arnika Association

Stage 1

Over the years of manufacture the buildings, groundwater and soil at the site also became contaminated with dioxins, pesticides, and tons of contaminated process waste were also stored on-site in poor conditions. A decision was made by the government to use an indirect thermal desorption unit to treat bulk wastes including contaminated building rubble and soil. The waste material was placed in the unit and heated by indirect means releasing POPs contaminants and a fine mineral dust which was captured in the ITDU filters. The filter cake and cyclone dust from the scrubbing units of the ITDU contained most of the dioxin and pesticide contamination stripped from the soil and rubble.

Stage 2

The scrubber waste was then treated in the BCD unit to dehalogenate the contaminants. The BCD process involves treatment of wastes in the presence of a reagent mixture consisting of a hydrogen-donor oil, an alkali metal hydroxide and a proprietary catalyst. When the mixture is heated to above 300 °C, the reagent produces highly reactive atomic hydrogen. The atomic hydrogen reacts with the waste to remove constituents that confer toxicity to the compounds.

The resulting residue from the BCD process is a dioxin free sludge containing primarily water, salt, unused hydrogen-donor oil and carbon residue and can be disposed to landfill and a mineral oil which can be recycled back into the process for use with subsequent batches The combination of the ITDU and BCD technologies proved very effective at destroying dioxins, HCB and others POPs in the Spolana waste. High levels of destruction efficiency were reported and are summarised in the tables below.

For the BCD process, the residual amounts of PCDD/PCDF in the output oil were less than 0.016 ng TEQ/g and hexachlorobenzene (HCB) <0.2 µg/g. Levels of PCDD/PCDF in the process off-gas (combined off-gas from

TABLE 9. DIOXIN DESTRUCTION BCD PROCESS – PILOT SCALE DEMONSTRATION IN SPOLANA NERATOVICE.

Material	Inlet ng/kg I-TEQ	Outlet Oil Matrix ng/kg I-TEQ
Chemical waste	209,000	0 (Reported value)
Chemical waste	200,000	4,3
Chemical waste	11,000	0,23
Chemical waste	47,000	0
Chemical waste	35,000	0
Dust	1,620,000	0,52
Chemical waste	78,000	0
Concentrate Aqueous	96,000	0
Concentrate Organic	876,000	0

Source: Kubal, Fairweather et al. 2004

TABLE 10. HEXACHLOROBENZENE AND LINDANE DESTRUCTION IN THE BCD PROCESS

Material	Inlet ng/kg I-TEQ		Outlet ng/kg I-TEQ	
	HCB	Lindane	HCB	Lindane
Soil	2,643	1.34	< 1.0	< 1.0
Brick Concrete	49,000	11	< 1.0	< 1.0
Concrete	5,100	18	< 1.0	< 1.0
Plaster	270	< 1.0	< 1.0	< 1.0

Source: Kubal, Fairweather et al. 2004

TABLE 11. DECOMPOSITION OF HEXACHLOROBENZENE AND LINDANE BY BCD PROCESS DURING PILOT OPERATION IN SPOLANA NERATOVICE.

Material	Inlet mg/kg		Outlet Oil Matrix mg/kg	
	HCB	Lindane	HCB	Lindane
Chemical waste	29,000	1,500	< 1.0	< 1.0
Chemical waste	200,000	900	< 2.0	< 2.0
Chemical waste	550,000	1,000	< 2.0	< 2.0
Chemical waste	270,000	1,000	< 2.0	< 2.0
Chemical waste	160,000	1,000	< 2.0	< 2.0
Dust	7,600	7	< 2.0	< 2.0
Chemical waste	1,598	19,000	< 2.0	< 2.0
Concentrate Aqueous	630	< 2.0	< 2.0	< 2.0
Concentrate Organic	11,000	< 2.0	< 2.0	< 2.0

Source: Kubal, Fairweather et al. 2004

TABLE 12. PCDD/FS CONCENTRATIONS ON IN INPUTS AND OUTPUTS OF ITD AND BCD TECHNOLOGIES IN SPOLANA NERATOVICE.

Levels of PCDD/PCDF [TEQ ng/g]				
Matrix	Technology			
	ITD/BCD		BCD	
	inlet	outlet	inlet	outlet (oil)
Concrete	4780	0,066		
Soil	45	0,0030		
Concentrate aqueous from ITD			96170	0
Waste chemicals			209	0

Source: Kraitr, Richtr et al. 2006

soil treatment and BCD reactors) ranged between 0.013 and 0.031 ng TEQ/Nm^3; for PCBs between 0.005 and 0.0014 ng TEQ/Nm^3; for HCB between <6.7 and 187 ng/Nm^3; and for Σ of organochlorine pesticides, between 17 and 235 µg/Nm^3 (Holoubek 2006).

Extensive air monitoring during the remediation indicated that remediation activities caused a significant (up to 1.5 order of magnitude) increase of the POP contamination of the ambient air both, within the factory, and in neighbouring residential areas. However, the dioxin emissions from the fully operational BCD unit were 0.0017–0.0424 ng TEQ m^3 (Veverka, Čtvrtníčková *et al.* 2004) indicating that ambient elevated air concentrations were most likely due to excavation and site works combined with volatilisation of POPs from soil contamination. This points to the need to carefully assess the potential fugitive emissions from site works of a remediation.

5. CONCLUSION AND RECOMMENDATIONS

It is understandable that in the mid-20th century, with a lack of alternatives, incineration was used in an attempt to destroy POPs, many of which were novel chemicals at the time and the consequences of burning them was not clear. However, by the 1980s it was clear that burning chlorinated POPs waste led to significant dioxin and other UPOPs emissions. This revelation should have been an opportunity for government and industry to refocus on the emerging Non-combustion technology and support its rapid development. Instead, the incineration sector intensified its political lobbying, claimed a range of technical breakthroughs to minimise UPOPs emissions and used its waste management market dominance to promote relatively cheap disposal of POPs waste. Non-combustion technology continued to develop rapidly but faced significant market entry barriers from the entrenched incinerator industry. Eventually, the benefits of Non-combustion technology were recognised including effective POPs destruction, no UPOPs creation, no toxic ash outputs, mobility and community acceptance. Despite several decades of lost momentum, a variety of sophisticated Non-combustion technologies to destroy a broad range of POPs wastes and clean up contaminated sites, have been refined and commercialised. With new POPs continuously being added to the Stockholm Convention annexes, stockpiles of POPs waste are growing rapidly. This is an ideal opportunity for developed countries to implement broad scale Non-combustion technology and break the UPOPs cycle driven by incineration.

For developing countries and countries in economic transition it represents an opportunity to 'leap-frog' the incineration and UPOPs cycle and move straight to clean POPs destruction technology. International policy and funding bodies should take this opportunity to drive sustainable development goals through capacity building and Non-combustion technology transfer mechanisms to the countries that need it most and have the least resources to destroy POPs stockpiles.

This report demonstrates both that incineration has not solved its UPOPs emissions problems and at best has transferred these pollutants to vast volumes of residue ash which are eventually lost to the environment. At worst, incinerators create both polluted ash and continue to operate with hidden UPOPs emissions.

This report also confirms that Non-combustion technology has reached a point of maturity where its diverse approaches can manage virtually all forms of POPs waste. The field is continually evolving with new and innovative technology and technique combinations that can sustainably destroy or convert POPs waste.

IPEN recommends:

- Recognition by the International environmental policy community that Non-combustion technology represents the long-term sustainable solution to the world's POPs waste stockpiles and should be a priority sector for expansion.
- Global environmental financial bodies and developed countries should rapidly expand technology transfer and capacity building to establish non-combustion technologies in developing countries and countries in economic transition to destroy POPs stockpiles.
- Joint involvement of the Stockholm and Basel Conventions in the establishment of a global *Non-combustion Centre for Excellence* to showcase technology developments and engage with national authorities to build capacity to tackle POPs stockpiles.
- An end to investment, subsidies and other support, including renewable energy credits, for the POPs waste incineration industry.
- Recognition by the international environmental policy community that incineration is not an appropriate or sustainable technology for POPs destruction due to its UPOPs creation.
- Incineration should no longer be promoted through subsidiary bodies or guidance of the Stockholm, Basel or other conventions as an appropriate destruction technology for POPs waste.
- International financial institutions such as the World Bank and World Economic Forum should discontinue the promotion and financing of incineration and focus on implementation of Non-combustion technology.

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