PFAS Waste treatment

- Non-confidential information -

Summary:
This report describes how PFAS waste is typically managed as that Linde prefers thermal incineration and gasification routes. In business, Linde will apply ESG overarching rules, including but are not limited to

- Concentrate PFAS waste, not dilute
- Ensure tight waste packaging, to prevent losses during logistics
- Selection “on purpose” thermal waste treatment facilities, not mixed with municipal waste
- Qualify waste processing partners along criteria including special focus on PEM waste (both electrolysis and fuel cell applications)
    - Experience with PTFE/PFAS production and end-of life waste,
    - Practicing BAT temperature and residence time control (> 1s at > 1,200°C) with advanced instrumentation systems
    - State-of-the art waste stream processing with multi-stage scrubber and liquids recycle to hot decomposition chamber
    - Focus on final stack exhaust gas condensate and flying ash for PFAS analysis by agreed laboratories
- Ensure sustainable operation of waste processing partners be repetitive controls

Contents

1 PEM Electrolysis Value Chain

The PEM value chain is divided in several sub-steps, see figure 1:

- Precursor material production
- Membrane production
- Stack assembly
- PEM electrolysis plant erection
- PEM electrolysis plant operation
- End of Life material reuse or incineration

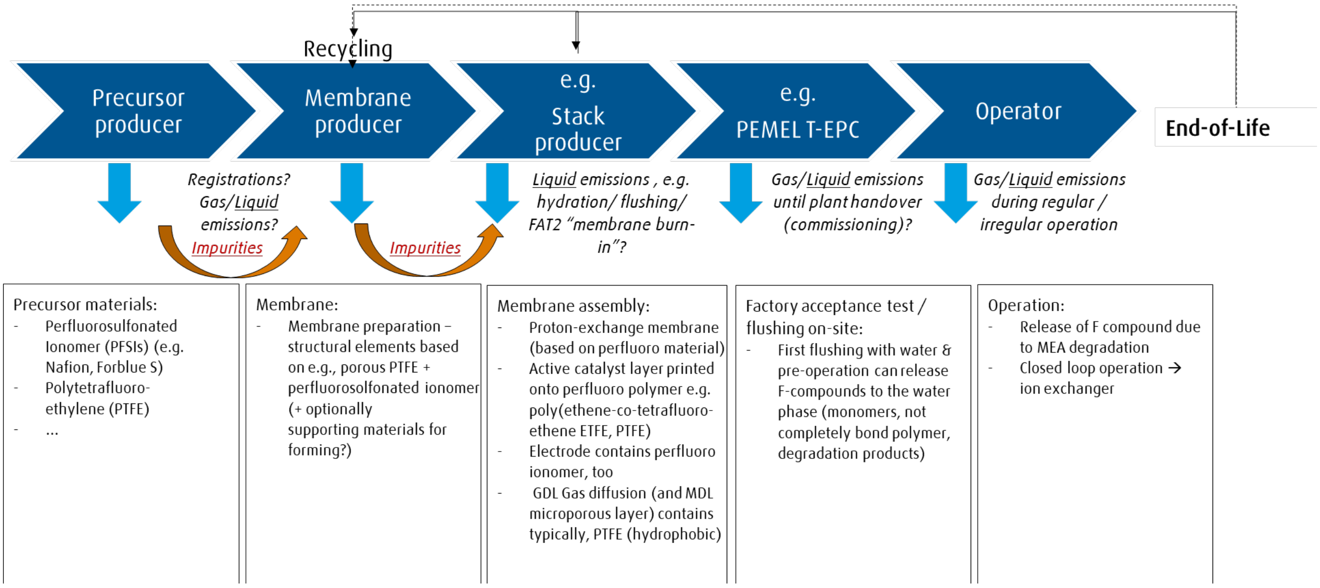

Figure 1: Simplified value chain for PFAS materials used in PEM Electrolyzer stacks

This report is focussing on the End-of-Life stage.

2 PFAS Waste Management

There are several options for managing PFAS waste, including:

Landfilling: This involves burying the waste in a specially designed landfill that is lined with impermeable barriers to prevent contamination of groundwater. However, PFAS can still leach into the environment over time, and there is also the risk of accidental releases during transportation and disposal upfront covering.

Incineration: This involves burning the waste at high temperatures to destroy the PFAS compounds. However, incineration can create other hazardous by-products, such as **dioxins and furans**, if kinetics of formation and the waste-gas cooling is not well-understood and managed.

Thermal treatment: This involves using high-temperature processes, such as pyrolysis or gasification, to break down the PFAS compounds. This can be an effective method for destroying PFAS, but it can also be expensive and energy intensive.

Chemical treatment: This involves using chemicals to break down or remove the PFAS compounds. This can include methods such as oxidation, reduction, or adsorption. Chemical treatment can be effective, but it can also be expensive and may create other hazardous by-products.

Recycling: This involves recovering and reusing materials from the PFAS waste, such as metals or other valuable components. However, this is not always possible with PFAS waste, and there is also the risk of contaminating the recycled materials. Anyhow, decomposition into monomers is the ultimate target and hence an area of R&D with expectation of commercial solutions by the end of this decade.

Summarizing the status quo,

- Few technologies exist to safely destroy PFAS in waste materials [3]
- **Thermal destruction is currently the preferred technology for PFAS waste** that requires complete destruction or breakdown of the PFAS compounds [4]
- There are a variety of thermal treatment facilities that manage PFAS waste, including hazardous waste incinerators, waste to energy plants, cement kilns, and wastewater treatment plant biosolid thermal treatment facilities [5].
- Special attention to be given to stack air emissions from thermal oxidizer and other air emission treatment equipment [5].

Aspect	Incineration	Pyrolysis	Gasification
Process	Burning waste at high temperatures to destroy PFAS compounds	Heating waste in the absence of oxygen to break down PFAS compounds	Heating waste in a low-oxygen environment to produce a gas that can be used for energy
By-products	Can create other hazardous by-products, such as dioxins and furans	Produces a solid residue and gas by-products, which can be further treated or disposed of	Produces a gas that can be used for energy, as well as a solid residue
Applicability	Suitable for a variety of PFAS waste types	Suitable for solid and liquid PFAS waste types	Suitable for solid and liquid PFAS waste types

Table 1: Alternative thermal waste processing technologies

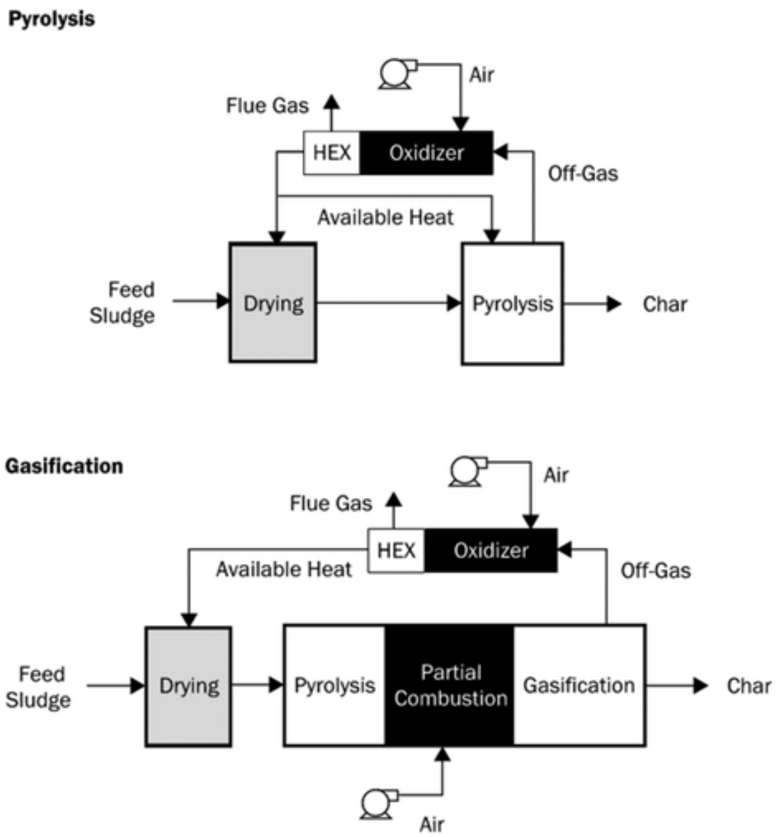

Figure 2: Block flow diagrams for pyrolysis and gasification technology

3 PFAS Waste Pre-Treatment

- If PFAS in waste stream is highly diluted, removal can be carried out by adsorption on activated carbon, ion exchange, nanofiltration, and reverse osmosis. It should be noted that, reverse osmosis is only capable of removing all PFAS to the greatest possible extent in long term operation. [1].
- If PFAS in waste is concentrated direct end of life process such as thermal decomposition is applicable.
- However, these methods should be carefully controlled and monitored to prevent the release of toxic by-products.
- In the context of PFSA membranes, membrane and electrodes coatings will be delaminated to recover the precious Platinum Group Metals more selectively

4 Thermal Decomposition of PFAS

- Thermal treatment for PFAS destruction: Incineration with excess oxygen, lean combustion or gasification, pyrolysis, high temperature liquefaction of liquid streams, and hydrogen reduction [5].
- Thermal stability of PFAS decreases in the following order: PFSAs ≥ PFUnDA > PFDA > PFNA > PFOA > PFBA > HFPO-DA [7], [8].
- PFAS compounds are difficult to break down due to fluorine’s electronegativity and the chemical stability of fluorinated compounds [6].

- The stability of perfluorinated radicals lead to higher concentrations and correspondingly increased propensity to recombine, creating larger molecules that are products of incomplete combustion (PIC). [6]
- PFAS needs a great deal of energy to break the atomic bond between carbon and fluorine. Only through high temperature treatment and long dwell times, as is possible in waste incineration plants, can PFAS molecules be completely broken down. [1]
- Thermal decomposition of PFAS may involve a series of processes such as melting, boiling, sublimation, radical chain-transfer reactions, oxidation, and pyrolysis [7].
- The word "destabilization" in the original letter refers to the overall change in stable solid-state PFAS compounds via these processes [8].
- Thermal degradation of PFOA results from free radical reactions initiated by bond breaking, which generates a range of products [8].

4.1 Incineration

Incineration is oxidation of the combustible materials contained in the waste with creation of flue gases [9]. The general steps following the pre-treatment involved in the incineration process are:

Loading and feeding: The waste is loaded into the incinerator and fed into the combustion chamber. The incinerator may be a rotary kiln, multiple hearth furnace, fluidized bed reactor, or other type of incinerator. Special attention is on a proper packaging of waste bundles, so that no lose parts – membranes are foil like – will fly around. **Linde/ITMs preferred waste treatment partner will practice clean-floor policies so that no PFAS solid waste is released unconsciously as litter.**

Combustion: The waste is burned in the presence of oxygen at high temperatures, typically between 800°C and 1,200°C. The PFAS compounds are broken down into simpler molecules, such as carbon dioxide, water, and hydrogen fluoride.

Emissions control: The gases and by-products produced during combustion must be treated to remove any remaining PFAS compounds and other pollutants. This may involve using scrubbers, filters, or other types of pollution control equipment.

Ash and residue management: The ash and other solid residues produced during incineration must be handled and disposed of properly. This may involve treating the residues to stabilize any remaining contaminants or sending them to a hazardous waste landfill.

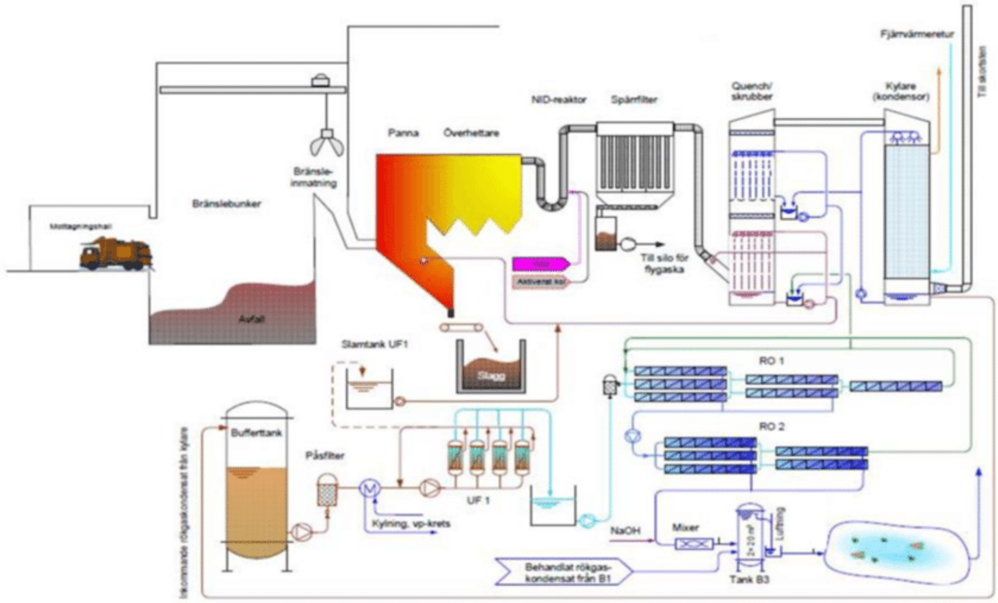

Figure 3: Shows various stages involved in thermal treatment of the PFAS in waste stream. 1. Waste storage and preparation for feeding Furnace for waste incineration 2. Gas treatment: temperature reduction (heat recovery) and 3. Pollutant removal

4.1.1 Key aspects of incineration – general aspects

- Incineration consists of three stages: drying and degassing, pyrolysis or thermal degradation and gasification and oxidation [9]
- Incomplete combustion due to low temperature or insufficient oxygen supply will result in the formation of CO or carbon-containing particles.[10]
- All gases will leave the furnace as flue gas, while the incombustible particles constitute the fly ash. The incombustible waste residuals that remain in the bottom at the furnace after combustion from the bottom ash. [10]
- Optimal operation: temperature, airflow, and combustible waste.
    - Temperature: high enough to ensure complete combustion, but not too high so that equipment is damaged or unwanted NOx are formed [10]
- Wastewater can be treated through incineration of the organic materials. This is a special technology for the treatment of industrial wastewater where the organic and sometime inorganic material is chemically oxidised with the help of atmospheric oxygen with the evaporation of the water, at high temperature. [9]

4.1.2 PFAS incineration - 3rd party view

- The Interstate Technology and Regulatory Council (ITRC) highlights that ex situ thermal treatment is a partially demonstrated technology for PFAS-contaminated soil [5].
- The USEPA recommends temperatures above 1,000°C to achieve 99.99% destruction of fluorinated organic compounds in 1 second residence time, which equals 10 times the half-life period [5].
- The effectiveness of incineration to destroy PFAS compounds and the tendency for formation of fluorinated or mixed halogenated organic by-products is not well understood [5]; there is still much to learn about PFAS thermal decomposition at the molecular level [2].
- Data (exhaust gas and liquid streams analyzed for PFAS) from Industrial waste processing plant in commercial scale is not available, only mixed with municipal waste
- To ultimately destroy PFAS compounds, typical hazardous waste incinerators operate around 1.000°C for 30 minutes in the first stage and 1.200°C for 2 or more seconds in the second stage [5].
- Limited information is available for the combustion rate of PFAS between 850 -1200 °C [10]
- Incomplete destruction of PFAS compounds can result in the formation of smaller PFAS products, or products of incomplete combustions (PICs) [6]
- For PTFE as mono fraction [12]:
  - No correlation between temperature corridor (800-1100°C)
  - No evidence of back reaction
- A Focus report shows repetitively high PFAS destruction rates > 99.999% for various chemicals within a BAT engineered incineration plant, above all ensuring high residence time ant high temperatures, a multi-stage scrubber system and a recycling of potentially PFAS contaminated scrubber liquids to the combustion chamber [13], see figure 4.

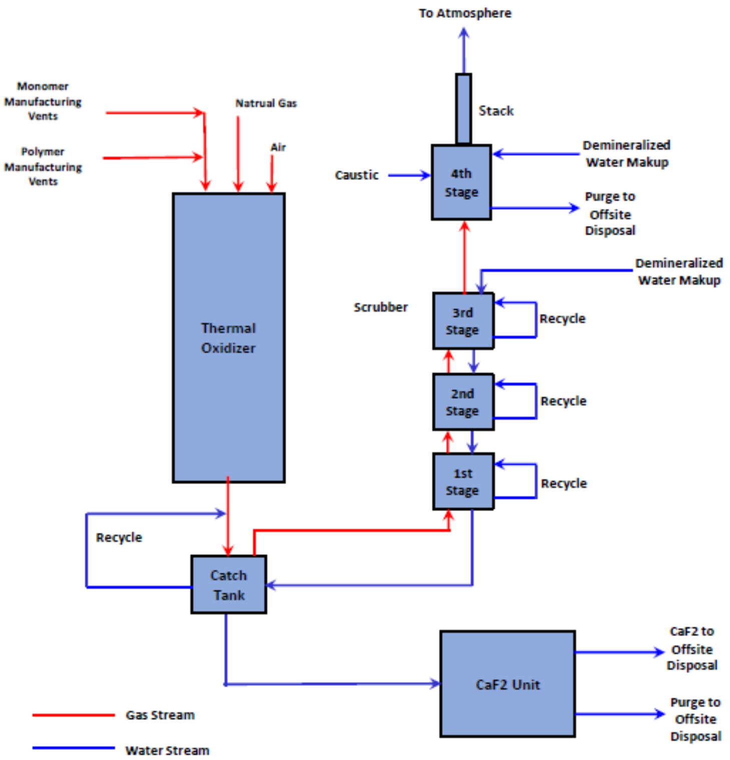

Figure 4: Chemours special waste incinerator – block flow diagram; special attention is on the multi-stage scrubber and internal recycling system for best complete PFAS oxidation

5 Status quo assessment by Linde

What to do

- Selection “on purpose” thermal waste treatment facilities, not mixed with municipal waste
- Keep waste well packaged until feeding
- If PFAS has been measured at boundary limits, then mainly in the exhaust gas condensate (adsorption/ solid product less critical) ➔ focus area to qualify waste treatment partner
- Qualify waste processing partners along criteria including special focus on PEM waste (both electrolysis and fuel cell applications)
    - Experience with PTFE/PFAS production and end-of life waste,
    - Practicing BAT temperature and residence time control (> 1s at > 1,200°C) with advanced instrumentation systems
    - Presence of water as Hydrogen donor
    - State-of-the art waste stream processing with multi-stage scrubber and liquids recycle to hot decomposition chamber
    - Focus on final stack exhaust gas condensate and flying ash for PFAS analysis by agreed laboratories
- While PFAS monomers and PTFE has been processes in studies, no expect results are available for PFSA ➔ focus area to jointly[1] watch and investigate with trusted waste treatment partner
- If practicing waste heat recovery, long residence time at lower temperatures seem to be uncritical; but a quenching step of hot exhaust gas down to 800°C is recommended, if checking temperatures windows being favourable for radical recombination as described by Krug et al. [14]

What not to do

- PFAS decomposition in temperature corridor 300 – 600 °C leading to various fragment and, hence, is to be avoided in any case; note: such corridor is sometimes occurring in municipal waste incineration facilities (locally in combustion chamber) so that a PFAS slipstream will occur ➔ temperature control and minimization of slip streams as key aspects to qualify / validate waste treatment partner, see above.
- Partnering with waste treatment companies w/o proper scrubber and recycling technology

[1] Linde’s supplier ITM Power has started to sample at their local waste recycling partner; results will be uploaded during the consultation process once available

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