Investigations of Process Parameters using Microwave Technology for the Treatment of Radioactive Waste

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Nuclear Waste Management

Radioactive wastes produced by

- Energy production by nuclear fission
- technological uses of radioactive sources
- medical and scientific usage of radionuclides

Large volumes of low and intermediate level wastes and small volumes of high level wastes

Different composition of wastes have resulted in a large variety of treatment methods.
Plasma Treatment

Plasma treatment could simplify treatment methods as all material can be treated by plasma: (IAEA TECDOC 1527)

- combustion
- melting/sintering

Existing plasma treatment plants (e.g. ZWILAG, Kozloduj) use higher power levels and utilise easily consumable plasma electrodes and/or

are specialised to treat one material only (e.g. RADON ion exchange resins)

Novel approach: utilisation of microwave induced plasma
Concept for Sustainable Waste Management

1. Avoid waste production
2. Process radioactive wastes at the place of origin as this avoids shipment to processing facilities for sorting and treatment.

Average volume of radioactive waste produced in a nuclear power plant is 250 m$^3$ per year equivalent to ~ 70 t. Composition is similar to household wastes.

If processing takes places with 50% of capacity utilization a continuous throughput is estimated to be ~20 kg/h (PhD Thesis F. Nachtrodt, 2013)

It is anticipated that a facility could be constructed with rather small footprint.
Construction of a Closed Plasma Oven System

Based on the thesis by Nachtrodt who tested microwave plasma torches driven by a high frequency (2.45 GHz) microwave generator (PlasMaster PCU-L 200.3) by HHFT (Aachen) with input power up to 200 W.

M. Eichhorn and A.P. Karumalikkal improved operational parameters to transfer more plasma power to the materials.

A.P. Karumalikkal constructed and built a closed oven system.
Free parameters

- Plasma microwave power
- Gas flow (gas type)
- Incident angle
- open/closed system
- fixed/rotating sample crucible
## Proof of Principle (in compressed air)

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass [g]</th>
<th>Treatment Time [s]</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>0.1403</td>
<td>less than 1s</td>
<td>no residue</td>
</tr>
<tr>
<td>Textiles</td>
<td>0.2369</td>
<td>less than 1s</td>
<td>no residue</td>
</tr>
<tr>
<td>Wood</td>
<td>0.3471</td>
<td>1.27</td>
<td>flame, no residue</td>
</tr>
<tr>
<td>Latex gloves</td>
<td>0.4533</td>
<td>30</td>
<td>soot, flame, no residue</td>
</tr>
<tr>
<td>PE</td>
<td>0.578</td>
<td>27</td>
<td>no residue</td>
</tr>
<tr>
<td>PVC</td>
<td>0.613</td>
<td>37</td>
<td>flame, soot, no residue</td>
</tr>
<tr>
<td>PE+PP</td>
<td>0.564</td>
<td>27</td>
<td>yellow residue</td>
</tr>
<tr>
<td>Activated charcoal</td>
<td>0.109</td>
<td>150</td>
<td>completely vanishes, melting was observable</td>
</tr>
<tr>
<td>Brazen chippings</td>
<td>0.136</td>
<td>50</td>
<td>melt together</td>
</tr>
<tr>
<td>Stone salt</td>
<td>0.3308</td>
<td>240</td>
<td>breaking of structure, melting</td>
</tr>
</tbody>
</table>
Improvement of experimental design

- when treating a mixture of typical LILW and glass particles, all substances melt together to form an amorphous substance,
- proving the possibility to vitrify material with this plasma torch.
- treatment time could be reduced to ~ 50% by optimization of the oven configuration treatment of 25 gr of LILW standard sample:

<table>
<thead>
<tr>
<th>setup</th>
<th>mass of before [g]</th>
<th>mass of after [g]</th>
<th>mass reduction [%]</th>
<th>Treatment time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>no.1</td>
<td>25</td>
<td>11</td>
<td>60</td>
<td>02:48</td>
</tr>
<tr>
<td>no.2</td>
<td>25</td>
<td>11</td>
<td>60</td>
<td>01:30</td>
</tr>
</tbody>
</table>

- For some other synthetic mixtures resembling types of radioactive wastes, volume reduction factors of 40-50 were found
Energy Efficiency

Most of the electrical energy (>99%) is transferred to the plasma zone.

\[
E_s \left[ \frac{J}{g} \right] = \left(C_p \cdot \frac{J}{gK} \right) \cdot \left( T_m [K] - RT[K] \right) + \Delta H_F \left[ \frac{J}{g} \right]
\]

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>( C_p [J/g , K] )</th>
<th>( DH_F [J/g] )</th>
<th>( T_m [K] )</th>
<th>( E_S [J/g] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>0.897</td>
<td>397</td>
<td>933.47</td>
<td>966.9</td>
</tr>
<tr>
<td>Iron</td>
<td>0.449</td>
<td>247</td>
<td>1811.00</td>
<td>926.3</td>
</tr>
<tr>
<td>E-Copper</td>
<td>0.385</td>
<td>209</td>
<td>1356.15</td>
<td>616.3</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.387</td>
<td>113</td>
<td>692.68</td>
<td>265.7</td>
</tr>
<tr>
<td>Antimony</td>
<td>0.210</td>
<td>161</td>
<td>903.78</td>
<td>288.2</td>
</tr>
<tr>
<td>Bismuth</td>
<td>0.123</td>
<td>51.9</td>
<td>544.45</td>
<td>82.2</td>
</tr>
</tbody>
</table>

\[
E_{s,P} \left[ \frac{J}{g} \right] = P[W] \times \left( \frac{t[s]}{m[g]} \right)
\]

\[
\eta = \left( E_s \left[ \frac{J}{g} \right] / E_{s,P} \left[ \frac{J}{g} \right] \right) \times 100
\]
Energy Efficiency : Optimum conditions

- plasma impinging at 40° to the turntable (10 rpm)
- argon plasma: power levels of 80-120 W and gas flow 0.35 – 0.50 l/min.
- compressed air, 140W, 2.1 l/min
- most material samples were melted and fused within less than 3 min.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>$E_s$ [J/g]</th>
<th>$\eta$ [%] open system</th>
<th>$\eta$ [%] this work</th>
<th>$\eta$ [%] plasma oven</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminium</td>
<td>966.9</td>
<td>21.1 ± 1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>iron</td>
<td>926.3</td>
<td>9.7 ± 0.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>e-Copper</td>
<td>616.3</td>
<td>25.8 ± 1.3</td>
<td>14.2 ± 1.9</td>
<td>30.2 ± 0.1</td>
</tr>
<tr>
<td>zinc</td>
<td>265.7</td>
<td>35.8 ± 0.9</td>
<td>87.7 ± 0.9</td>
<td>48.4 ± 0.5</td>
</tr>
<tr>
<td>antimony</td>
<td>288.2</td>
<td>40.8 ± 1.0</td>
<td>19.6 ± 3.0</td>
<td>43.0 ± 0.1</td>
</tr>
<tr>
<td>bismuth</td>
<td>82.2</td>
<td>20.1 ± 3.9</td>
<td>7.8 ± 2.9</td>
<td>14.4 ± 0.7</td>
</tr>
</tbody>
</table>
Energy Efficiency (3)

Energy efficiency depends on sample size and shape

i.e. zinc powder has much higher efficiency

large bismuth chippings show significantly smaller efficiency
NO$_x$ production

At reasonably high energies nitrogen from the air (~79.9 vol.%) reacts with the oxygen of the air (~21 vol%) according to

\[ \text{N}_2 + \text{O}_2 \iff 2 \text{NO} \quad \text{and} \]
\[ 2 \text{NO} + \text{O}_2 \iff 2 \text{NO}_2. \]

After rinsing the plasma oven for three hours with argon 5.0 (containing < 5 ppm N$_2$, < 2 ppm O$_2$, and <3 ppm H$_2$O)
NO$_x$ Production (2)

When using argon plasma and air as sheath gas:
Conclusion

It could be shown

• plasma treatment with microplasma is possible for all types of materials
• High energy efficiency can be achieved
• NO\textsubscript{x} formed needs to be removed from the exhaust gases
• Operation of a closed plasma oven system is possible

Next steps

• design study for a 20 kW prototype plasma plant with all components from waste collection to management of exhaust gases and solid residues
• apply for funds to build the prototype plant
Thank you for your attention!

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