**Generic Exposure Assessment of End-of-Life Material Management in Additive Manufacturing**

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**Supporting Information**

Table S1. Potential materials entering end-of-life material management contributed by additive manufacturing

|  |  |  |  |
| --- | --- | --- | --- |
| **Substance** | **Material Type** | **State (Solid/Liquid)** | **AM Techniques** |
| Acrylic Styrene Acrylonitrile | Polymer | Solid | FDM |
| Acrylonitrile Butadiene Styrene | Polymer | Solid | FDM |
| Alumide | Composite | Solid | SLS |
| Alumina Silica Ceramic Powder | Ceramic | Solid | PBSLP |
| Aluminum | Metal | Solid | FDM/SLM/DMLS |
| Brass | Metal | Solid | FDM |
| Bronze | Metal | Solid | FDM |
| Carbon Fiber Filled Materials | Polymer | Solid | FDM |
| Ceramic Resin | Photopolymer Resin | Liquid | SLA |
| Clear Resin | Photopolymer Resin | Liquid | SLA |
| Cobalt Chrome Alloy | Metal | Solid | DMLS |
| Composite (Carbon Fiber, Kevlar, Fiberglass) | Composite | Solid | FDM |
| Conductive Filament (Carbon black, graphene, metal additives) | Polymer | Solid | FDM |
| Copper | Metal | Solid | FDM |
| Draft Resin | Photopolymer Resin | Liquid | SLA |
| ESD Resin | Photopolymer Resin | Liquid | SLA |
| Flexible And Elastic Resins | Photopolymer Resin | Liquid | SLA |
| Glass | Glass | Solid | DED/FDM/MBJ/MJF/SLM |
| Gold | Metal | Solid | FDM |
| High Density Polyethylene | Polymer | Solid | FDM |
| High Impact Polystyrene | Polymer | Solid | FDM |
| High Temp Resin | Photopolymer Resin | Liquid | SLA |
| Inconel | Metal | Solid | DMLS |
| Jewelry Resins | Photopolymer Resin | Liquid | SLA |
| Maraging Steel | Metal | Solid | DMLS |
| Table S1. Potential materials entering end-of-life material management contributed by additive manufacturing (Continued) |
| **Substance** | **Material Type** | **State (Solid/Liquid)** | **AM Techniques** |
|  |  |  |  |
| Medical And Dental Resins | Photopolymer Resin | Liquid | SLA |
| Metal Filled Filaments (Iron, Copper, Stainless Steel, Brass) | Polymer/Metal | Solid | SLM |
| Nickel | Metal | Solid | FDM/SLM/DMLS |
| Nylon | Polymer | Solid | FDM |
| Nylon 11 | Polymer | Solid | SLS |
| Nylon 12 | Polymer | Solid | SLS |
| Nylon Composites (Glass, Aluminum, Carbon Fiber) | Composite | Solid | SLS |
| Papers | Paper | Solid | SDL |
| Plant-Based Resin | Photopolymer Resin | Liquid | SLA |
| Platinum | Metal | Solid | FDM |
| Polycarbonate | Polymer | Solid | FDM |
| Polyethylene Terephthalate Glycol | Polymer | Solid | FDM |
| Polyetheretherketone | Polymer | Solid | FDM/SLS |
| Polylactic Acid | Polymer | Solid | FDM |
| Polyphenylsulfone | Polymer | Solid | FDM |
| Polypropylene | Polymer | Solid | FDM |
| Polyurethane Resin | Photopolymer Resin | Liquid | SLA |
| Polyvinyl Alcohol | Polymer | Solid | FDM |
| Porcelain | Ceramic | Solid | PBSLP |
| Rigid Resins | Photopolymer Resin | Liquid | SLA |
| Silicon-Carbide | Ceramic | Solid | PBSLP |
| Stainless Steel | Metal | Solid | FDM/SLM/DMLS |
| Standard Resin | Photopolymer Resin | Liquid | SLA |
| Sterling Silver | Metal | Solid | FDM |
| Thermoplastic Polyurethane | Polymer | Solid | FDM/SLS |
| Titanium | Metal | Solid | FDM/SLM/DMLS/EBM |
| Tool Steel | Metal | Solid | FDM/SLM/DMLS |
| Tough And Durable Resins | Photopolymer Resin | Liquid | SLA |
| Wax | Lipid | Solid | FDM |
| Wood-Based Filament | Wood | Solid | FDM |

Note: DMLS = Direct Metal Laser Sintering, EBM = Electron-beam Melting, FDM = Fused Deposition Modeling, MBJ = Metal Binder Jetting, MJF = Multi-Jet Fusion, PBSLP = Powder Bed Selective Laser Processing, PJ = PolyJet, SDL = Selective Deposition Lamination, SLA = Stereolithography, SLM = Selective Laser Melting, SLS = Selective Laser Sintering

Table S2. Parameters and assumptions made for the material flow analysis in the end-of-life stage following additive manufacturing

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameters** | **Value** | **Unit** | **Reference** |
| Total 3D Printers | 870000 | units | [1] |
| Typical Material Consumption | 12 | kg/operator/yr | [2] |
| Waste Rate (1-40%) | 10 | % | [2] |
| Liquid Resin Process Use Rate  | 35 | % | [3] |
| Solid Resin Process Use Rate  | 65 | % | [3] |
| Failed Parts Waste Rate (Solid/Liquid) | 5 | % | [4] |
| Failed Parts Liquid Resin Contamination | 5 | % | [4] |
| Inorganic Filler in Liquid Resins (0 - 15%) | 5 | % | [5] |
| Wash Solvent Consumption Rate | 3 | kg/2 weeks/operator) | [6] |
| Wash Solvent Consumed Ratio to Materials Used | 6.5 | Unitless | Calculated |
| Resin and Filler waste in Liquid/Solid Resin Process | 5 | % | Assumption |
| UV Treatment VOC post-cure Releases (1 - 360 μg/day) | 360 | μg/day | [7] |
| Wastewater Treatment Plants Inorganic Removal Efficiency | 90 | % | [8] |
| Litter Rate of Materials Discarded to MSW | 2 | % | [9], [10] |
| MSW Recycled (Of total MSW) | 23.6 | % | [11] |
| MSW Incinerated (Of total MSW) | 11.8 | % | [11] |
| MSW Landfilled (Of total MSW) | 50 | % | [11] |
| MSW Recycled Normalized % | 27.6 | % | Calculated |
| MSW Incinerated Normalized % | 13.8 | % | Calculated |
| MSW Landfilled Normalized % | 58.5 | % | Calculated |
| MSW Recycling/Transportation Spill Rate | 0.01 | % | [12] |
| Ash Generated (15 - 25% wt of MSW) | 20 | % | [13] |
| Fly Ash Generated (10 - 20% wt of ash) | 15 | % | [13] |
| Pollution Control - Fly Ash Removed (95 - 99.5% efficiency) | 95 | % | [14], [15] |
| Bottom Ash Generated (80 - 90% wt of ash) | 85 | % | [13] |
| MSW Landfilling Mass Release | 10 | % | [12] |
| MSW Leachate Release (0.1 - 2%) | 2 | % | [16] |
| MSW Landfill Gas Release (8 - 11%) | 11 | % | [16] |

Note. All percentage values are on an annual basis.

**Assumptions:**

1. The mass flow looks strictly at the end-of-life stage, and we assume that there is no true accumulation; thus, Eventually, all products made get discarded.
2. Products produced from additive manufacturing are non-hazardous and do not contribute toward releases once fully cured.
3. Solid resin/Filaments are recycled by a special recycling center rather than through MSW, and a filament extruder handles these materials. Byrley et al. (2020) estimated that 1.7E9 - 3.5E11 particles are released/min of extrusion use (ABS and PLA)
4. While recycling filaments and failed parts through a filament extruder is possible, there is no established infrastructure to handle EoL recycling of these materials. Additionally, material management programs vary from region to region. It is possible to throw scraps into filament machines to recycle. However, solo AM users do not justify purchasing a filament extruder solely for this purpose. Therefore, recycling is assumed negligible.
5. Solvents used during the post-processing of liquid-based AM processes are recyclable (up to 99%), but it is often not recycled in-house due to the processing costs.
6. Solvent washes post-processing for liquid-based AM processes are done twice to ensure sufficient uncured resin removal.
7. Washing agent consumption may last up to 2 weeks per gallon (Frequency of replacement changes based on needs). This assumption leads to a “wash solvent consumed ratio to materials used” of 6.5 kg solvent/kg input
8. Packaging EoL materials are excluded from the analysis.
9. AM products and scraps are recycled, incinerated, and landfilled; liquid resins and solvents are not recycled in the final processing.
10. Incineration of plastic EoL material results in ash content equal to 1% of the original volume
11. Incinerator ash generated ranges between 15 - 25% wt. (20% avg) for MSW, with 15% of the total ash being fly ash and 85% being bottom ash
12. All UV Curable Resins are fully cured post-UV Treatment
13. 10% of materials sent to landfill ends up in the environment/ocean either through mismanagement or littering.
14. Hazardous EoL material treatment may have overlapped with MSW management. Stream 12 release is related to mass loss from transportation rather than hazardous EoL material treatment.

Table S3. Material flow analysis results tracing the material distribution post-additive manufacturing

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Stream | 1 | 2 | 3 | 4 | 5 | 6 |
|   | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr |
| UV Curable Resins (liquid) | 3,471,300 | 3,471,300 | 0 | 0 | 173,565 | 0 |
| Inorganic Fillers | 182,700 | 182,700 | 0 | 0 | 9,135 | 8,222 |
| Solvents | 0 | 0 | 21,435,278 | 0 | 21,435,278 | 0 |
| Solid Feedstocks  | 6,786,000 | 0 | 0 | 6,786,000 | 0 | 0 |
| Printed Products | 0 | 0 | 0 | 0 | 3,297,735 | 3,297,735 |
| Scraps/Failed Prototypes/Supports | 0 | 0 | 0 | 0 | 173,565 | 0 |
| Fly Ash | 0 | 0 | 0 | 0 | 0 | 0 |
| Bottom Ash | 0 | 0 | 0 | 0 | 0 | 0 |
| Leachate | 0 | 0 | 0 | 0 | 0 | 0 |
| Landfill Gas | 0 | 0 | 0 | 0 | 0 | 0 |
| Total (kg/yr) | 10,440,000 | 3,654,000 | 21,435,278 | 6,786,000 | 25,089,278 | 3,305,957 |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Stream | 7 | 8 | 9 | 10 | 11 | 12 |
|   | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr |
| UV Curable Resins (liquid) | 173,565 | 8,678 | 1.140 | 8,677 | 164,887 | 1,649 |
| Inorganic Fillers | 914 | 46 | 0.000 | 46 | 868 | 9 |
| Solvents | 21,435,278 | 0 | 0.000 | 0 | 21,435,278 | 214,353 |
| Solid Feedstocks  | 0 | 0 | 0.000 | 0 | 0 | 0 |
| Printed Products | 0 | 0 | 0.000 | 0 | 0 | 0 |
| Scraps/Failed Prototypes/Supports | 173,565 | 173,565 | 0.000 | 173,565 | 0 | 0 |
| Fly Ash | 0 | 0 | 0.000 | 0 | 0 | 0 |
| Bottom Ash | 0 | 0 | 0.000 | 0 | 0 | 0 |
| Leachate | 0 | 0 | 0 | 0 | 0 | 0 |
| Landfill Gas | 0 | 0 | 0 | 0 | 0 | 0 |
| Total (kg/yr) | 21,783,321 | 182,289 | 1.14 | 182,288 | 21,601,032 | 216,010 |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Stream | 13 | 14 | 15 | 16 | 17 | 18 |
|   | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr |
| UV Curable Resins (liquid) | 163,238 | 0 | 0 | 163,238 | 0 | 0 |
| Inorganic Fillers | 859 | 773 | 0 | 86 | 0 | 0 |
| Solvents | 21,220,925 | 0 | 0 | 21,220,925 | 0 | 0 |
| Solid Feedstocks  | 0 | 0 | 0 | 0 | 339,300 | 0 |
| Printed Products | 0 | 0 | 0 | 0 | 6,107,400 | 6,107,400 |
| Scraps/Failed Prototypes/Supports | 0 | 0 | 0 | 0 | 339,300 | 0 |
| Fly Ash | 0 | 0 | 0 | 0 | 0 | 0 |
| Bottom Ash | 0 | 0 | 0 | 0 | 0 | 0 |
| Leachate | 0 | 0 | 0 | 0 | 0 | 0 |
| Landfill Gas | 0 | 0 | 0 | 0 | 0 | 0 |
| Total (kg/yr) | 21,385,022 | 773 | 0 | 21,384,249 | 6,786,000 | 6,107,400 |

Table S3. Material flow analysis results tracing the material distribution post-additive manufacturing (Continued)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Stream | 19 | 20 | 21 | 22 | 23 | 24 |
|   | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr |
| UV Curable Resins (liquid) | 0 | 0 | 0 | 0 | 0 | 8,677 |
| Inorganic Fillers | 0 | 0 | 0 | 0 | 0 | 46 |
| Solvents | 0 | 0 | 0 | 0 | 0 | 0 |
| Solid Feedstocks  | 0 | 0 | 339,300 | 0 | 339,300 | 339,300 |
| Printed Products | 9,405,135 | 9,405,135 | 0 | 0 | 0 | 9,405,135 |
| Scraps/Failed Prototypes/Supports | 0 | 0 | 339,300 | 0 | 339,300 | 512,865 |
| Fly Ash | 0 | 0 | 0 | 0 | 0 | 0 |
| Bottom Ash | 0 | 0 | 0 | 0 | 0 | 0 |
| Leachate | 0 | 0 | 0 | 0 | 0 | 0 |
| Landfill Gas | 0 | 0 | 0 | 0 | 0 | 0 |
| Total (kg/yr) | 9,405,135 | 9,405,135 | 678,600 | 0 | 678,600 | 10,266,023 |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Stream | 25 | 26 | 27 | 28 | 29 | 30 |
|   | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr |
| UV Curable Resins (liquid) | 0 | 8,677 | 171,915 | 0 | 0 | 171,915 |
| Inorganic Fillers | 0 | 46 | 132 | 0 | 0 | 132 |
| Solvents | 0 | 0 | 21,220,925 | 0 | 0 | 21,220,925 |
| Solid Feedstocks  | 0 | 339,300 | 339,300 | 93,764 | 938 | 46,882 |
| Printed Products | 188,103 | 9,217,032 | 9,217,032 | 2,547,096 | 25,471 | 1,273,548 |
| Scraps/Failed Prototypes/Supports | 10,257 | 502,608 | 502,608 | 138,894 | 1,389 | 69,447 |
| Fly Ash | 0 | 0 | 0 | 0 | 0 | 0 |
| Bottom Ash | 0 | 0 | 0 | 0 | 0 | 0 |
| Leachate | 0 | 0 | 0 | 0 | 0 | 0 |
| Landfill Gas | 0 | 0 | 0 | 0 | 0 | 0 |
| Total (kg/yr) | 198,360 | 10,067,663 | 31,451,911 | 2,779,754 | 27,798 | 22,782,848 |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Stream | 31 | 32 | 33 | 34 | 35 |
|   | kg/yr | kg/yr | kg/yr | kg/yr | kg/yr |
| UV Curable Resins (liquid) | 1,719 | 0 | 0 | 0 | 0 |
| Inorganic Fillers | 1 | 130 | 0 | 773 | 90 |
| Solvents | 212,209 | 0 | 0 | 0 | 0 |
| Solid Feedstocks  | 469 | 0 | 198,653 | 198,653 | 19,865 |
| Printed Products | 12,735 | 0 | 5,396,389 | 5,396,389 | 539,639 |
| Scraps/Failed Prototypes/Supports | 694 | 0 | 294,267 | 294,267 | 29,427 |
| Fly Ash | 34,174 | 649,307 | 0 | 0 | 64,931 |
| Bottom Ash | 0 | 3,873,062 | 0 | 0 | 387,306 |
| Leachate | 0 | 0 | 0 | 0 | 208,252 |
| Landfill Gas | 0 | 0 | 0 | 0 | 1,145,384 |
| Total (kg/yr) | 262,003 | 4,522,500 | 5,889,309 | 5,890,082 | 2,394,894 |

Table S4. Chemicals of concern found in landfill leachate and the corresponding maximum dermal exposure, adapted from [17]

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Compound | Maximum Concentration (ppm) | TLV-TWA (ppm) | TLV-STEL (ppm) | Maximum Concentration in Leachate (mg/m3) | Maximum Daily Dermal Mass Exposure (mg/day) |
| Hydrogen sulfide | 3.5 x 10-1 | 1 | 5 | 0.49 | 1.1 x 10-6 |
| Ammonia | 5.8 x 100 | 25 | 35 | 6.6 | 1.5 x 10-5 |
| Dimethyl disulfide | 7.7 x 10-2 | 0.5 | - | 0.30 | 6.7 x 10-7 |
| Acetic acid | 1.1 x 100 | 10 | 15 | 2.8 | 6.2 x 10-6 |
| Benzene | 5.6 x 10-2 | 0.5 | 2.5 | 0.18 | 4.0 x 10-7 |
| Formaldehyde | 1.1 x 10-2 | 0.1 | 0.3 | 0.010 | 3.0 x 10-8 |
| Ethylbenzene | 1.5 x 100 | 20 | - | 6.3 | 1.4 x 10-5 |
| Hexamethylcyclotrisiloxane | 2.2 x 10-2 | 0.3 | - | 0.20 | 4.5 x 10-7 |
| Decamethylcyclopentasiloxane | 6.4 x 10-1 | 10 | - | 9.6 | 2.2 x 10-5 |
| Acrolein | 6.3 x 10-3 |  | 0.1 | 0.010 | 3.3 x 10-8 |
| Octamethylcyclotetrasiloxane | 5.8 x 10-1 | 10 | 15 | 7.0 | 1.6 x 10-5 |
| α-Pinene | 7.9 x 10-1 | 20 | - | 4.4 | 9.9 x 10-6 |
| Toluene | 6.9 x 10-1 | 20 | - | 2.6 | 5.8 x 10-6 |
| 1,2,4-Trimethylbenzene | 1.8 x 10-1 | 25 | - | 0.90 | 2.0 x 10-6 |
| Styrene | 6.6 x 10-2 | 10 | - | 0.28 | 6.3 x 10-7 |
| Dimethylamine | 3.3 x 10-2 | 5 | - | 0.060 | 1.4 x 10-7 |
| Aniline | 9.8 x 10-3 | 2 | - | 0.040 | 8.4 x 10-8 |
| Carbon disulfide | 3.2 x 10-3 | 1 | - | 0.010 | 2.2 x 10-8 |
| Methanethiol | 1.3 x 10-3 | 0.5 | - | 0.00 | 5.5 x 10-9 |
| Propionic acid | 2.2 x 10-2 | 10 | - | 0.070 | 1.5 x 10-7 |

Table S5. Landfill gas chemical of concerns maximum concentration and daily inhalation exposure estimation, adapted from [17]

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Compound | Maximum Concentration (ppm) | TLV-TWA (ppm) | TLV-STEL (ppm) | Maximum Concentration in Landfill gas (mg/m3) | Maximum Daily Inhalation Exposure (mg/day) |
| Hydrogen sulfide | 5.1 x 103 | 1 | 5 | 7.2 x 103 | 7.2 x 104 |
| Chloroethene | 3.4 x 101 | 1 | - | 8.7 x 101 | 8.7 x 102 |
| Methanethiol | 7.1 x 100 | 0.5 | - | 1.4 x 101 | 1.4 x 102 |
| Toluene | 2.5 x 102 | 20 | - | 9.5 x 102 | 9.5 x 103 |
| Benzene | 3.7 x 100 | 0.5 | 2.5 | 1.2 x 101 | 1.2 x 102 |
| Carbon disulfide | 5.4 x 100 | 1 | - | 1.7 x 101 | 1.7 x 102 |
| 2,4-Dimethylheptane | 6.3 x 10-1 | 200 | - | 3.3 x 100 | 3.3 x 101 |
| Trichloroethene | 2.8 x 101 | 10 | 25 | 1.5 x 102 | 1.5 x 103 |
| Styrene | 2.3 x 101 | 10 | 20 | 9.7 x 101 | 9.7 x 102 |
| Dimethyl sulfide | 2.3 x 101 | 10 | - | 5.7 x 101 | 5.7 x 102 |
| Trimethylbenzene | 3.8 x 101 | 25 | - | 1.9 x 102 | 1.9 x 103 |
| Tetrachloroethene | 3.7 x 101 | 25 | 100 | 2.5 x 102 | 2.5 x 103 |
| 1,1-Dichloroethane | 1.1 x 102 | 100 | - | 4.4 x 102 | 4.4 x 103 |
| o-Xylene | 9.8 x 101 | 100 | 150 | 4.3 x 102 | 4.3 x 103 |
| P-Xylene | 9.2 x 101 | 100 | 150 | 4.0 x 102 | 4.0 x 103 |
| α-Pinene | 1.6 x 101 | 20 | - | 8.9 x 101 | 8.9 x 102 |
| Ethylbenzene | 1.4 x 101 | 20 | - | 5.9 x 101 | 5.9 x 102 |
| Tetrachloromethane | 3.3 x 100 | 5 | 10 | 2.1 x 101 | 2.1 x 102 |
| Dimethyl disulfide | 2.8 x 10-1 | 0.5 | - | 1.1 x 100 | 1.1 x 101 |
| Dichloromethane | 2.5 x 101 | 50 | - | 8.5 x 101 | 8.5 x 102 |

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