Supplementary Information

for

Material Flow Analysis and Occupational Exposure Assessment in Additive Manufacturing End-of-Life Material Management

John D. Chea[1], Gerardo J. Ruiz-Mercado[2,3*], Raymond L. Smith[2], David Meyer[2], Michael Gonzalez[2], and William M. Barrett[2]

[1] Oak Ridge Institute for Science and Education, hosted by Office of Research & Development, US Environmental Protection Agency, Cincinnati, OH 45268, USA
[2] Office of Research & Development, US Environmental Protection Agency, Cincinnati, OH, 45268, USA
[3] Chemical Engineering Graduate Program, Universidad del Atlántico, Puerto Colombia 080007, Colombia

Corresponding Author: Gerardo J. Ruiz-Mercado
Email: Ruiz-Mercado.Gerardo@epa.gov

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

Substance	Material Type	State (Solid/Liquid)	Additive Manufacturing Categories
Acrylic Styrene Acrylate	Polymer	Solid	MEX
Acrylonitrile Butadiene Styrene	Polymer	Solid	BJT/MEX
Alumide	Composite	Solid	PBF
Alumina Silica Ceramic Powder	Ceramic	Solid	PBF
Aluminum	Metal	Solid	DED/MEX/PBF
Brass	Metal	Solid	MEX
Bronze	Metal	Solid	MEX
Carbon Fiber Filled Materials	Polymer	Solid	MEX
Ceramic Resin	Photopolymer Resin	Liquid	VPP
Clear Resin	Photopolymer Resin	Liquid	VPP
Cobalt Chrome Alloy	Metal	Solid	DED/PBF
Composite (Carbon Fiber, Kevlar, Fiberglass)	Composite	Solid	MEX
Conductive Filament (Carbon black, carbon nanotube, graphene, metal additives)	Polymer	Solid	MEX
Copper	Metal	Solid	DED/MEX
Draft Resin	Photopolymer Resin	Liquid	VPP/MJT
ESD Resin	Photopolymer Resin	Liquid	VPP/MJT
Flexible And Elastic Resins	Photopolymer Resin	Liquid	VPP/MJT
Glass	Glass	Solid	BJT/DED/MEX /PBF
Gold	Metal	Solid	MEX
High Density Polyethylene	Polymer	Solid	MEX
High Impact Polystyrene	Polymer	Solid	MEX
High Temp Resin	Photopolymer Resin	Liquid	VPP
Inconel	Metal	Solid	PBF
Jewelry Resins	Photopolymer Resin	Liquid	VPP
Maraging Steel	Metal	Solid	PBF
Medical And Dental Resins	Photopolymer Resin	Liquid	VPP
Metal Filled Filaments (Iron, Copper, Stainless Steel, Brass)	Polymer/Metal	Solid	PBF
Nickel	Metal	Solid	DED/MEX/PBF
Nylon	Polymer	Solid	MEX
Nylon 11	Polymer	Solid	PBF
Nylon 12	Polymer	Solid	PBF
Nylon Composites (Glass, Aluminum, Carbon Fiber)	Composite	Solid	PBF
Papers	Paper	Solid	SHL
Plant-Based Resin	Photopolymer Resin	Liquid	VPP

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

Substance	Material Type	State (Solid/Liquid)	Additive Manufacturing Categories
Platinum	Metal	Solid	MEX
Polycarbonate	Polymer	Solid	MEX/BJT
Polyethylene Terephthalate Glycol	Polymer	Solid	MEX
Polyetheretherketone	Polymer	Solid	MEX/PBF
Polylactic Acid	Polymer	Solid	MEX
Polyphenylsulfone	Polymer	Solid	MEX
Polypropylene	Polymer	Solid	MEX
Polyurethane Resin	Photopolymer Resin	Liquid	VPP
Polyvinyl Alcohol	Polymer	Solid	MEX
Porcelain	Ceramic	Solid	PBF
Rigid Resins	Photopolymer Resin	Liquid	VPP
Silicon-Carbide	Ceramic	Solid	PBF
Stainless Steel	Metal	Solid	DED/MEX/PBF
Standard Resin	Photopolymer Resin	Liquid	VPP
Sterling Silver	Metal	Solid	MEX
Thermoplastic Polyurethane	Polymer	Solid	MEX/PBF
Titanium	Metal	Solid	DED/MEX/PBF
Tool Steel	Metal	Solid	MEX/PBF
Tough And Durable Resins	Photopolymer Resin	Liquid	VPP
Wax	Lipid	Solid	MEX/MJT
Wood-Based Filament	Wood	Solid	MEX

Note: BJT = Binder Jetting, DED = Directed Energy Deposition, MEX = Material Extrusion, MJT = Material Jetting, PBF = Powder Bed Fusion, SHL = Sheet Lamination, VPP = Vat Photopolymerization

Disclaimer: The tabulated materials do not necessarily represent 100% of all the usable materials within additive manufacturing.

Table S2. Parameters used 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:

a) 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.
b) Products produced from additive manufacturing are non-hazardous and do not contribute toward releases once fully cured.
c) 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)
d) 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.

e) 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.
f) Solvent washes post-processing for liquid-based AM processes are done twice to ensure sufficient uncured resin removal.
g) 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
h) Packaging EoL materials are excluded from the analysis.
i) AM products and scraps are recycled, incinerated, and landfilled; liquid resins and solvents are not recycled in the final processing.
j) Incineration of plastic EoL material results in ash content equal to 1% of the original volume
k) 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
l) All UV Curable Resins are fully cured post-UV Treatment
m) 10% of materials sent to landfill ends up in the environment/ocean either through mismanagement or littering.
n) 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

Note: The spreadsheet used for material flow analysis calculation is available at: https://github.com/cheajohn/Generic_Exposure_Assessment_EoL_AdditiveManufacturing/tree/main

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/m^3)	Maximum Daily Dermal Mass Exposure (mg/day)
Hydrogen sulfide	3.5×10^{-1}	1	5	0.49	1.1×10^{-6}
Ammonia	5.8×10^{0}	25	35	6.6	1.5×10^{-5}
Dimethyl disulfide	7.7×10^{-2}	0.5	-	0.30	6.7×10^{-7}
Acetic acid	1.1×10^{0}	10	15	2.8	6.2×10^{-6}
Benzene	5.6×10^{-2}	0.5	2.5	0.18	4.0×10^{-7}
Formaldehyde	1.1×10^{-2}	0.1	0.3	0.010	3.0×10^{-8}
Ethylbenzene	1.5×10^{0}	20	-	6.3	1.4×10^{-5}
Hexamethylcyclotrisiloxane	2.2×10^{-2}	0.3	-	0.20	4.5×10^{-7}
Decamethylcyclopentasiloxane	6.4×10^{-1}	10	-	9.6	2.2×10^{-5}
Acrolein	6.3×10^{-3}		0.1	0.010	3.3×10^{-8}
Octamethylcyclotetrasiloxane	5.8×10^{-1}	10	15	7.0	1.6×10^{-5}
α-Pinene	7.9×10^{-1}	20	-	4.4	9.9×10^{-6}
Toluene	6.9×10^{-1}	20	-	2.6	5.8×10^{-6}
1,2,4-Trimethylbenzene	1.8×10^{-1}	25	-	0.90	2.0×10^{-6}
Styrene	6.6×10^{-2}	10	-	0.28	6.3×10^{-7}
Dimethylamine	3.3×10^{-2}	5	-	0.060	1.4×10^{-7}
Aniline	9.8×10^{-3}	2	-	0.040	8.4×10^{-8}
Carbon disulfide	3.2×10^{-3}	1	-	0.010	2.2×10^{-8}
Methanethiol	1.3×10^{-3}	0.5	-	0.00	5.5×10^{-9}
Propionic acid	2.2×10^{-2}	10	-	0.070	1.5×10^{-7}

Table S5. Landfill gas chemicals of concern 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/m^3)	Maximum Daily Inhalation Exposure (mg/day)
Hydrogen sulfide	5.1×10^3	1	5	7.2×10^3	7.2×10^4
Chloroethene	3.4×10^1	1	-	8.7×10^1	8.7×10^2
Methanethiol	7.1×10^0	0.5	-	1.4×10^1	1.4×10^2
Toluene	2.5×10^2	20	-	9.5×10^2	9.5×10^3
Benzene	3.7×10^0	0.5	2.5	1.2×10^1	1.2×10^2
Carbon disulfide	5.4×10^0	1	-	1.7×10^1	1.7×10^2
2,4-Dimethylheptane	6.3×10^{-1}	200	-	3.3×10^0	3.3×10^1
Trichloroethene	2.8×10^1	10	25	1.5×10^2	1.5×10^3
Styrene	2.3×10^1	10	20	9.7×10^1	9.7×10^2
Dimethyl sulfide	2.3×10^1	10	-	5.7×10^1	5.7×10^2
Trimethylbenzene	3.8×10^1	25	-	1.9×10^2	1.9×10^3
Tetrachloroethene	3.7×10^1	25	100	2.5×10^2	2.5×10^3
1,1-Dichloroethane	1.1×10^2	100	-	4.4×10^2	4.4×10^3
o-Xylene	9.8×10^1	100	150	4.3×10^2	4.3×10^3
P-Xylene	9.2×10^1	100	150	4.0×10^2	4.0×10^3
α-Pinene	1.6×10^1	20	-	8.9×10^1	8.9×10^2
Ethylbenzene	1.4×10^1	20	-	5.9×10^1	5.9×10^2
Tetrachloromethane	3.3×10^0	5	10	2.1×10^1	2.1×10^2
Dimethyl disulfide	2.8×10^{-1}	0.5	-	1.1×10^0	1.1×10^1
Dichloromethane	2.5×10^1	50	-	8.5×10^1	8.5×10^2

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