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Sustainable Materials Management Options for Construction and Demolition Debris





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Land and Materials Management Division

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Sustainable Materials Management Options for Construction and Demolition Debris

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Notice/Disclaimer

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Foreword

The U.S. Environmental Protection Agency (US EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, US EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) within the Office of Research and Development (ORD) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

Cynthia Sonich-Mullin, Director
National Risk Management Research Laboratory

Introduction

Construction and demolition debris (CDD) is a significant component of the solid waste stream in the United States (US). Depending on estimate methodology, CDD represents between 230[1] and 530[2] million metric tons of waste generation annually in the US. Regulation of CDD typically occurs at the state level, leading to a wide range of standards and practices for CDD management across the country. The U.S. Environmental Protection Agency (EPA) recognizes the significant role of CDD management in moving towards more sustainable materials management (SMM). The research summarized in this document is primarily concerned with non-disaster related CDD, and emergency management practices may differ from scenarios described in this report. This document summarizes the following reports produced by EPA since 2012 to help practitioners, regulators, and other stakeholders manage CDD in a manner that is protective of human health and the environment:

- EPA (2012). Data Gap Analysis and Damage Case Studies: Risk Analyses from Construction and Demolition Debris Landfills and Recycling Facilities. EPA/600/R-13/303
- EPA (2014). Best Management Practices to Prevent and Control Hydrogen Sulfide and Reduced Sulfur Compound Emissions at Landfills that Dispose of Gypsum Drywall. EPA/600/R-14/039
- EPA (2014). Multimedia Environmental Assessment of Existing Materials Management Approaches for Communities. EPA/600/R-14/375
- EPA (2015). A Comparative Analysis of Life-Cycle Assessment Tools for End-of-Life Materials Management Systems. EPA/600/R-15/232
- EPA (2015). Methodology to Estimate the Quantity, Composition, and Management of Construction and Demolition Debris in the United States. EPA/600/R-15/111
- EPA (2017). The State of the Practice of Construction and Demolition Material Recovery. EPA/600/R-17/231

The six reports are briefly summarized below. Appendices A through F present expanded summaries of the reports.

Data Gap Analysis and Damage Case Studies: Risk Analyses from Construction and Demolition Debris Landfills and Recycling Facilities

This study was conducted to revisit results from a 1995 study by EPA on the impacts of CDD landfills on groundwater, surface water, and ecological resources. This study involved five steps, the first of which was a review of state-level CDD disposal and recycling requirements including construction, operation, and monitoring requirements of CDD disposal facilities. The second step compiled a list of active CDD disposal and recycling facilities. The third step identified damage cases based on information provided by state environmental agencies (SEAs). The fourth step included a review of scientific literature and state datasets to record the extent and types of damage recorded. The final step was a case study of three CDD management facilities, which have been reported to cause damages, from

[1] USEPA (2015a). Methodology to Estimate the Quantity, Composition, and Management of Construction and Demolition Debris in the United States. EPA/600/R-15/111.
[2] USEPA (2015b). Advancing Sustainable Materials Management: Facts and Figures 2013. EPA530-R-15-002.

diverse geographical locations for an in-depth review. Key issues of concern included risks associated with CDD landfill leachate releases and associated groundwater impacts, odor issues, and landfill fires.

While most states were found to regulate CDD disposal, many did not regulate CDD processing and recycling. Regulations on construction, operation, and monitoring of CDD disposal varied by state. For example, 26 states required groundwater monitoring for all CDD landfills, while 11 states required groundwater monitoring only on a conditional basis. The most frequent violations such as improper compaction, or insufficient cover soil use found at CDD facilities based on a review of the SEA data are discussed in the report. A total of 1,540 active CDD disposal facilities and 512 active CDD recycling facilities were identified for the year 2012.

Groundwater monitoring data for CDD landfills from multiple states were compared to assess the prevalence of groundwater impacts from these facilities. It was found that in some cases, CDD landfill leachate may have concentrations higher than leachate from that of municipal solid waste (MSW) landfills.

The three CDD facilities in Florida, California, and Ohio were examined in detail to assess the economic and environmental impact of CDD management facility damages. Issues included groundwater exceedances related to leachate, odor issues related to the presence of drywall, and odor and site damage issues related to landfill fires. Factors identified as contributing to these issues included the insufficient application of cover soil, a large working face, disposal of prohibited waste, the presence of steep side slopes, and insufficient liquids control. Remedial measures at these facilities ranged from $4 million to $6.5 million.

This study provides CDD regulators and site operators with valuable information to reduce damage to human health and the environment from CDD management facilities. For more information, see Appendix A.

Best Management Practices to Prevent and Control Hydrogen Sulfide and Reduced Sulfur Compound Emissions at Landfills that Dispose of Gypsum Drywall

Hydrogen sulfide (H_2S) and reduced sulfur compound emissions are a commonly documented issue at CDD and MSW landfills and are the principal cause of the odor issues discussed in the Damages Case Studies report discussed above. H_2S emissions represent a risk to human health and safety and have the potential to corrode equipment used in landfill gas collection, control, and beneficial use. EPA recognized a need to expand on previous work and provide additional information on H_2S formation, emission, and control at CDD and MSW landfills.

This study involved a review of basic factors contributing to H_2S formation in both CDD and MSW landfills, followed by a review of measures to prevent and control the formation and/or emission of H_2S. Strategies identified to minimize H_2S formation included diverting waste that can form H_2S, minimizing water entry into the landfill via operational strategies, and the use of bacterial inhibitors to inhibit sulfate-reducing bacteria. Strategies to control and treat H_2S emissions included leachate management to minimize off-gassing, cover soil amendment, low permeability capping systems, odor neutralizers, and landfill gas collection. Because of the danger of high concentrations of H_2S and other reduced sulfur compounds to site workers, the report detailed types of equipment and monitoring strategies for conducting site investigations to assess the presence of these compounds.

This best management practices (BMP) framework can help regulators and site operators reduce the risk to human health and the environment posed by H_2S emissions. EPA has developed a mobile application (H_2S Less) to estimate H_2S generation rates as a function of landfill characteristics (such as waste placement rate, years of operation, and drywall content). This application also includes information on reducing and controlling H_2S generation. For more information on this report, and the app, see the summary of this report in Appendix B.

Multimedia Environmental Assessment of Existing Materials Management Approaches for Communities

EPA's goal of this research was to provide state and local decision-makers with data and tools to enable them to integrate environmental, societal, and economic factors into decisions to help communities achieve sustainability. Life cycle assessments (LCAs) provide a tool to analyze the impacts of these decisions. LCAs use an underlying set of quantitative inputs and outputs associated with a materials management strategy known as a life cycle inventory (LCI) to assess the impact of a strategy. This study provides a series of US-specific LCIs that quantify the inputs and outputs of different CDD materials management pathways.

While LCAs often neglect to include the end-of-life (EOL) phase of a material's life cycle, this study provided necessary data to include this phase. The primary material management pathways for which LCIs were developed in this study included landfilling and, when applicable, recycling, combustion, and composting. Some of the major impacts quantified in this study for most materials included the impacts of electricity, fuel, and consumable materials used in recycling or landfilling. Some major impacts from landfilling included landfill construction and operation impacts from equipment use and material use, as well as emissions from leachate and landfill gas generation and management. Some of the LCIs produced in this study included material production to quantify the impact of recycled material replacing virgin material.

These LCIs provide a foundation for LCA work on the EOL phase of several CDD materials, which can be used by state and community level decision makers in SMM planning. For more information, see Appendix C.

A Comparative Analysis of Life-Cycle Assessment Tools for End-of-Life Materials Management Systems

Many of the decisions on strategies for the management of MSW and CDD are made at the local community level. EPA recognizes a need for tools that can be used by decision-makers to characterize the social, economic, and environmental impacts associated with solid wastes typically managed by communities. This report reviewed 29 LCA software tools and identified five that could provide insight into the EOL phase of materials management. These tools, which model the impacts of various materials management and disposal strategies, included three U.S.-specific tools, Waste Reduction Model (WARM), Municipal Solid Waste Decision Support Tool (MSW-DST), and Solid Waste Optimization Life-Cycle Framework (SWOLF); and two European tools, Waste and Resources Assessment Tool for the Environment (WRATE), and Environmental Assessment System for Environmental Technologies (EASETECH).

This study evaluates the features of these five tools by modeling a series of materials management scenarios that are of interest to local solid waste decision makers, including changes to collection and management strategies for bulk or specific components of the solid waste stream. The tools were compared based on features and flexibility to model these scenarios.

Comparing the results of these models was challenging due to the use of different impact methods, starting assumptions, and solid waste material category definitions. Community decision makers can see examples of the types of results they could obtain using each of the tools and potentially select a tool that best matches their scenarios and conditions of interest. No one tool could model all the scenarios, and two scenarios could not be modeled in any of the tools. Two of the tools were able to evaluate the economic impacts of the different scenarios.

Each of the tools offers a unique set of features that a community decision maker may find valuable in solid waste management planning. This report provides a guide to the features, and limitations of each tool, and their relevance to model scenarios of interest to local communities. For more information, see Appendix D.

Methodology to Estimate the Quantity, Composition, and Management of Construction and Demolition Debris in the United States

The ability to estimate the amount of CDD generated is essential to develop and implement SMM plans. EPA estimates CDD generation through a materials flow analysis (MFA) approach. This study provides and evaluates an alternative estimation methodology that incorporates measured CDD generation reported by several states—coupled with indicators for CDD generation for states that do not report CDD generation—and municipal solid waste CDD composition data reported at the state and regional scale to estimate nationwide CDD generation. In addition, this methodology uses trade organization data to estimate asphalt pavement from large infrastructure projects that are not captured by the CDD facilities reported data.

After testing multiple indicators, statewide building permits data were found to best correlate to CDD disposal of the states reporting annual disposal data the coefficient of correlation for individual year ranged from an r^2 of 0.82 to 0.93. In addition, data from the National Asphalt Pavement Association (NAPA) on recycled asphalt pavement (RAP) generation and recovery was incorporated to capture some CDD generation from infrastructure projects. No reliable methodology to estimate recycled concrete aggregate from large infrastructure projects, or for land clearing debris, was identified.

This study provides an example estimate of CDD generation based on the proposed methodology, which used data reported by eight states to estimate CDD generation in states that do not report CDD data. The methodology was used to estimate that a total of 154 million tons of CDD was managed at permitted/registered facilities in 2011. Twenty-eight percent of this estimate represents measured data, with the remaining 72 percent coming from data extrapolated from building permit data. Seventeen percent of the overall generation figure represents facility-measured disposal, and 11 percent of the overall generation represents facility-measured recycling amounts.

This methodology provides additional useful information to SMM planners at the national and regional levels on the generation, disposal, and recovery of CDD materials. For a more detailed summary of this report, see Appendix E.

The State of the Practice of Construction and Demolition Material Recovery

Many of the materials in the CDD stream can provide substantial environmental, economic, and social benefits when recovered. This study provides insights to communities on the state of the practice of CDD material recovery, including the process, opportunities, and recovery challenges. This report examines how different CDD materials are managed, key factors that influence CDD recovery, and key environmental and human-health considerations associated with CDD recovery.

The report discusses CDD recovery methods, which vary depending on the material and the recovery strategy. CDD recovery is typically a multi-step process, which begins with a material recovery facility that separates mixed CDD into individual material categories. Once separated, these materials may be sold "as is" to material brokers (i.e., scrap metal) or further processed (e.g., aggregate crushing and screening) to increase material value. CDD may be source-segregated at the job site, through demolition with selective material recovery or deconstruction, allowing for reuse with less effort expended on sorting or processing the material after removal from the site. The CDD recovery is primarily dictated by the availability of end-markets. Other factors including transportation costs, tipping fees for disposal and recovery facilities, labor requirements, and public and corporate policies such as disposal bans, disposal taxes, and green building certifications also influence CDD recovery. This report discusses material-specific factors such as reuse markets and regulations that impact the recovery rates for several CDD materials.

Care must be taken to properly manage materials that could pose a risk to human and environmental health. Though the use of many of these materials (such as asbestos, lead, or polychlorinated biphenyls) has been reduced, banned, or discontinued, these may appear in CDD materials generated from older buildings. Policy guidance on the proper management of these materials is available from several states such as Minnesota and Florida. Proper training, equipment and best practices are critical to ensuring appropriate recovery.

The recovery of CDD is an important part of SMM. This study provides important insights on CDD recovery, factors that influence recovery rate, and risks to human health and the environment. For more information, see a further summary of this report attached in Appendix F.

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Appendix A: Data Gap Analysis and Damage Case Studies: Risk Analyses from Construction and Demolition Debris Landfills and Recycling Facilities

Why was the Study Conducted?

Construction and demolition debris (CDD) represents a major component of the non-hazardous solid waste stream in the United States (U.S.). In 1995, the U.S. Environmental Protection Agency (EPA) conducted studies of CDD to understand the impacts of CDD landfills on groundwater, surface water, and ecological resources.

In 2012, US EPA published this study to review data that have emerged since 1995 including changes in CDD composition and CDD management, regulations for CDD facilities promulgated by the states, and scientific community's understanding of actual or potential risks, to develop a better understanding of the damages from CDD landfills and recycling facilities with respect to groundwater and surface water impacts as well as air emissions and fires.

CDD and MSW are generated in similar quantities. Unlike MSW, there are no federal regulation for CDD disposal. The information in this report could be helpful to state regulators and CDD facility owners, operators, and their consultants in identifying and/or implementing best management practices in CDD facilities.



Tolaymat, T. *Data Gap Analysis and Damage Case Studies: Risk Analyses from Construction and Demolition Debris Landfill and Recycling Facilities*. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-13/303, 2012.

How was the Study Conducted?

Step 1: Reviewed local CDD disposal- and recycling-related practices with the focus on the nature and extent of each region's requirements for construction (e.g., bottom liner installation), operation (e.g., cover soil application) and monitoring (e.g., groundwater quality analysis).

Step 2: Compiled a nationwide inventory of active CDD disposal and recycling facilities based on data provided by the state environmental agencies (SEAs); identified 1,540 active CDD disposal facilities and 512 CDD recycling facilities.

Step 3: Identify damage cases based on data/information provided by SEAs; identified 44 damage cases across 17 states, covering eight of ten US EPA regions.

Step 4: Reviewed scientific literature and statewide datasets to record the extent and types of damages observed.

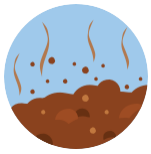
Step 5: Selected three CDD management facilities from different geographical locations for in-depth review based on site information availability, and primary damage type(s). For each of the three sites, compiled information on operations, environmental damage, applicable regulatory and/or remedial actions, and historical monitoring.

Impacts of CDD Disposal and Recycling

Studies conducted by US EPA in the mid-1990s related damage at CDD disposal to management at CDD disposal facilities that resulted in groundwater, surface water, and ecological impacts. In contrast, this study defines a *damage case* CDD site, which had one or more of the following concerns: groundwater impacts, leachate release, recurring odor and fire issues, or other issues that impact the human health and the environment. It should be noted that this discussion is limited to non-disaster related waste generation.



Leachate Releases and Groundwater Impacts: The absence or malfunction of a liner/leachate collection system may lead to the migration of leachate into the groundwater. Disposed CDD may contain and leach contaminants that may cause human health impacts, such as lead (from paint, flashing), mercury (from lighting, electrical switches), polychlorinated biphenyls (PCBs) (from light ballasts, paints) and arsenic from chromated copper arsenate-treated wood. Biogeochemical changes associated with landfill development may lead to mobilization of natively occurring contaminants (e.g., iron, and arsenic release from reductive dissolution) and impact groundwater quality.



Odor Issues: The disposal of gypsum drywall within the moist and oxygen-depleted environment of a landfill can lead to the formation of H_2S. H_2S causes odor issues and nuisance and potential health concerns to surrounding residents.





Fires: CDD landfills are more susceptible to a major landfill fire compared to other types of landfills. These fires can result from deposition of smoldering waste loads or by spontaneous combustion, causing hazards for onsite workers and emitting air pollutants. The bulky nature of CDD, infrequent cover soil application, and formation of steep slopes may all contribute to fires development. Moreover, applying water to remediate fires can impact the amount and quality of the leachate and promote the production of more H_2S. Fires may cause additional emission of pollutants with potential impacts to human health and the environment both through air emissions and leachate generation.



Key Findings

STATE REGULATIONS

State and local governments are the primary planning, regulating, and implementing entities for the management of nonhazardous solid waste, including CDD. While most states regulate CDD disposal activities, only some regulate CDD recycling and processing activities. A state may exempt specific CDD materials (e.g., clean concrete rubble, land clearing debris) from solid waste public policy directives to allow more flexible end-of-life management options and promote CDD recovery and recycling. Several states exclusively exempt source-segregated CDD materials from the solid waste regulations to promote their recovery and recycling.

CDD FACILITY OPERATIONS

Requirements for the design, siting, permitting, construction, and operation of CDD management facilities vary from no requirements to mandatory ones. Twenty-six states require groundwater monitoring for all CDD landfills, while 11 states require groundwater monitoring on a conditional basis (i.e., based on landfill size, location). An engineered liner with a leachate collection system is required in 17 states. The application of cover material, at least weekly, on the landfill's active face, is required by 26 states' regulations.

The most frequent violations cited at active CDD landfills included improper compaction; insufficient cover soil use; and permit non-compliance. Some damages are related to non-compliance with permits, while others are unrelated to compliance (i.e., they could have occurred even if facilities complied with permits).

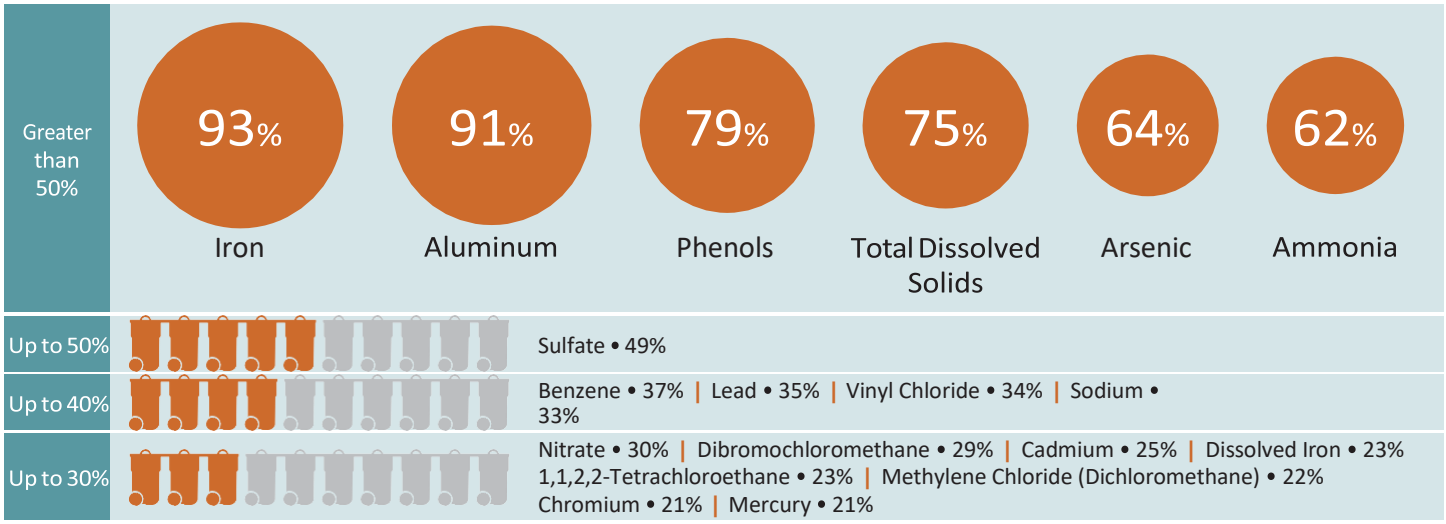
ECONOMIC IMPACTS

Remedial measures for the damages caused by CDD management facilities can be significant, ranging from $4 million to $6.5 million.

ENVIRONMENTAL IMPACTS

Data for more than 400 parameters from 91 sites in Florida were analyzed to assess the impacts to groundwater from CDD disposal facilities. Iron, aluminum, phenols, total dissolved solids, arsenic, and ammonia showed at least one exceedance above the respective Florida groundwater clean-up target level at a downgradient monitoring well at more than half of landfills analyzed. The quality of untreated leachate reported for CDD landfills in Ohio, Maryland, and Wisconsin were summarized. For Ohio landfills, the CDD landfill leachate quality was found to be comparable to that of MSW landfill leachate, and for some parameters the measured concentrations were higher than MSW landfills.

SITES EXCEEDING FLORIDA GROUNDWATER CLEAN-UP TARGET LEVEL



Case Studies—Damage Assessment

In-depth examination of three specific CDD disposal and recycling sites led US EPA to confirm findings from previous evaluations, while helping further understand the confluence of factors that can lead to damage. Moreover, the examination found that permit non-compliance was not the only contributor to the damage issues observed at each site; issues still occurred even if the facility operated in compliance with its permit.

SAUFLEY LANDFILLE (FLORIDA)



Ammonia, iron, and manganese exceeded groundwater clean-up target levels, as the landfill was not constructed with a bottom liner or leachate collection system, while built in a hydrogeologic setting that is not expected to slow leachate percolation to the groundwater.



Presence of drywall, percolation of moisture into the waste (especially due to water use in fire- fighting), and recurring non-compliance on cover soil application caused the formation of H_2S and thus odor issues.



The presence of steep slopes, substantial amounts of waste accepted, and failure to appropriately compact the waste contributed to the formation of fires at the site.

ARCHIE CRIPPEN EXCAVATION SITE (CALIFORNIA)



Damage incurred at the site included the hazard of a large, uncontrolled fire, along with emissions of particulate matter into the surrounding neighborhood. A lesson learned was the storage of stockpiled woody CDD should follow procedures consistent with the National Fire Protection Association code for outside storage of forest products (e.g., pile turnover times and size, temperature, water supply, and access roads)..

WARREN RECYCLING LANDFILL (OHIO)



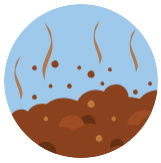
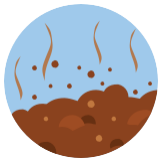
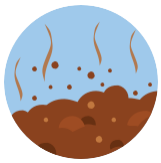
The facility had an unlined cell as well as cells with improperly functioning leachate collection systems, thus, both conditions contributed to the groundwater impacts, along with permit non-compliance..



Acceptance of gypsum drywall led to the formation of odor-causing H2S. H2S emissions were exacerbated by an improperly functioning leachate collection system (leading to leachate build-up) and the acceptance of pulverized CDD (increasing the reactive surface area of the gypsum).

Factors Contributing to CDD Facility Damage

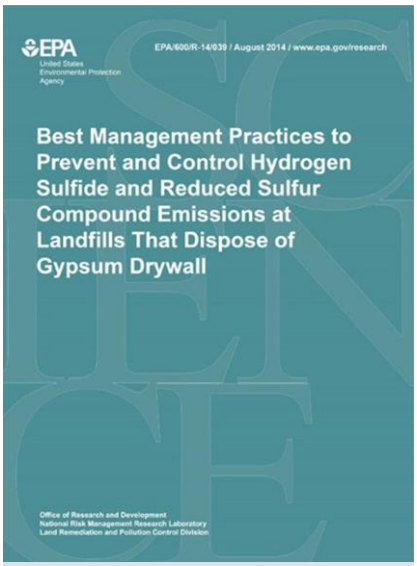
The observed damages that occurred were attributed to the following:

	RESULTING ISSUES		
Insufficient Application of Cover Soil **– lack of adequate** cover soil increases air intrusion into the landfill and thus increasing the likelihood of a subsurface fire. Subsurface fires can increase the generation of leachate and associated risk to groundwater. Cover soil helps to limit the release of odors.			
Large Working Face **–** a large working face increases the amount of rain and air that can enter the waste and potentially increase leachate and odor emission.			
Disposal of Prohibited Waste **–** disposal of prohibited waste (e.g., MSW, industrial waste) can negatively impact groundwater quality.			
Presence of Steep Side Slopes **–** steep side slopes can lead to poor waste compaction, increased air entry into the waste, and an increased potential for fires.			
Insufficient Liquids Control **–** ponded liquids and wet conditions encourage the growth of bacteria that produce H_2S. Standing pools of leachate increase the possibility of leachate discharges into nearby surface water bodies.			

Appendix B: Best Management Practices to Prevent and Control Hydrogen Sulfide and Reduced Sulfur Compound Emissions at Landfills that Dispose of Gypsum Drywall

Why was the Study Conducted?

Hydrogen sulfide (H_2S) gas emission has been a widely documented issue at both construction and demolition debris (CDD) and municipal solid waste (MSW) landfills, due to its odor potential, risk to human health and safety, and potential to corrode equipment used in landfill gas (LFG) collection, control, and beneficial use. The disposal of sulfur-containing materials such as gypsum drywall, wastewater treatment plant sludge, or other sulfur-containing industrial wastes has been attributed to H_2S emissions at landfills, and addressing related problems can be time- and cost-intensive for landfill owners and operators.



Best Management Practices to Prevent and Control Hydrogen Sulfide and Reduced Sulfur Compound Emissions at Landfills that Dispose of Gypsum Drywall. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/039, 2014.

H_2S is slightly denser than air and may accumulate in enclosed, poorly ventilated, and low-lying areas. It is a poisonous, flammable, and colorless gas. Once released, it can remain in the environment from 18 hours to 42 days, typically persisting longer in cold weather. In the atmosphere, H_2S transforms into sulfur dioxide (SO_2) and/ or sulfuric acid (H_2SO_4).

H_2S has a detectable rotten-egg-like odor at low concentrations (approximately 8 parts per billion, (ppb). At concentrations ranging between 2 to 20 ppm, it can cause a variety of negative health effects, including breathing problems (in people with asthma), eye irritation, tiredness, dizziness, irritability, poor memory, and loss of appetite. At higher H_2S concentrations (approximately 100 ppm with a 2 to 15-minute exposure), humans may lose the ability to detect an odor and may experience respiratory distress (>400 ppm) and even death due to respiratory failure (>500 ppm). Thus, odor is not always a reliable indicator of the presence of H_2S and may not provide adequate warning of hazardous concentrations.

A previous effort by the United States Environmental Protection Agency (US EPA)[3] focused on practices that help control H_2S emission from CDD landfills in Ohio that accepted pulverized gypsum debris. The US EPA Office of Research and Development, in coordination with US EPA Region 5, commissioned this study to expand on the scope of the previous work, with the goal of including the current body of knowledge available on the H_2S formation, emission, and control at both CDD and MSW landfills; H_2S measurements reported from laboratory and field case studies; and updated best management practices (BMPs).

[3] U.S. Environmental Protection Agency (2006b). Management practices to prevent and control hydrogen sulfide gas emissions at CDD debris landfills which *dispose of pulverized gypsum debris in Ohio.*

How was the Study Conducted?

Knowledge of the factors that contribute to the H_2S formation in a landfill is essential to identify strategies to effectively control its formation and emission. Therefore, first, a review of the basic factors contributing to H_2S formation and emissions at CDD and MSW landfill was conducted, followed by an extensive literature review to identify the H_2S measurements reported for MSW and CDD landfill at various measurement locations (e.g., LFG, landfill surface, and landfill vicinity). The human health and safety thresholds used by different organizations (e.g., Occupational Safety and Health Administration (OSHA), Agency for Toxic Substances and Disease Registry, US EPA) for H_2S were identified and used to assess the impact of the reported H_2S measurements. Information regarding production and emission of other reduced sulfur compounds was summarized.

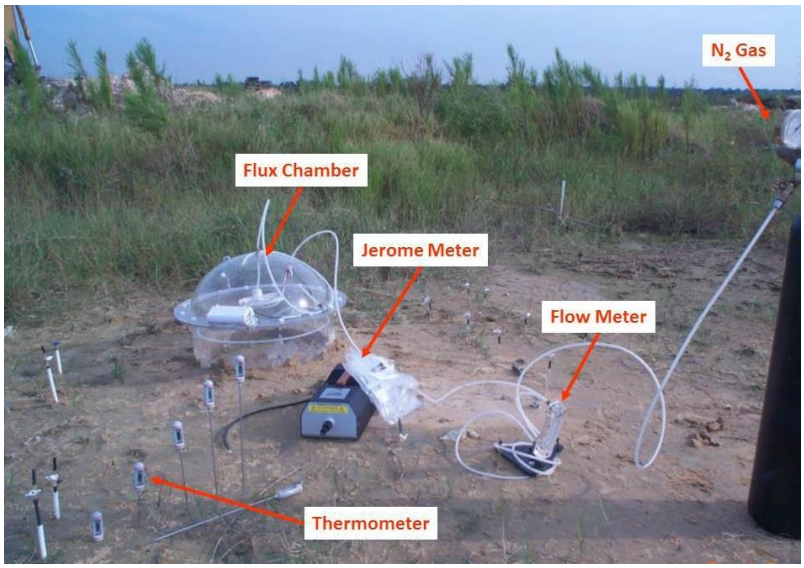
Second, a review of measures to prevent and control the formation and/or emission of H_2S from CDD and MSW landfill was conducted. Technologies to treat LFG to reduce H_2S concentrations were identified and summarized. Considerations and approaches for site investigation and monitoring techniques for H_2S were presented. Finally, a framework that landfill owners and operators can use to develop a BMP guide for their facility was developed based on the data and insights gained.

Key Findings

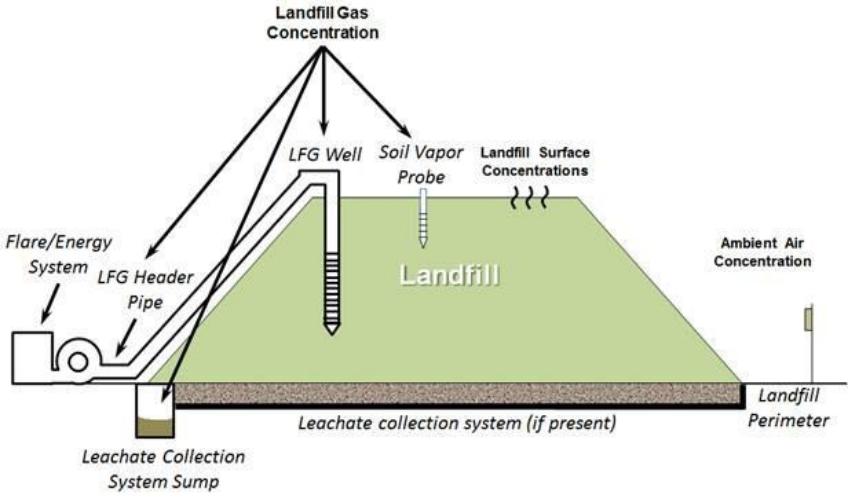
H_2S REGULATORY STANDARDS

Currently, there are no enforceable federal standards for offsite H_2S gas emissions from landfills, or H_2S monitoring requirements specific to landfills. Some US EPA regions and states have developed or adopted H_2S air quality standards. The health effects due to H_2S exposure have led to the development of H_2S workplace standards, which are typically expressed as a concentration and referenced to an exposure time limit. *Acute Exposure Guideline Levels* for H_2S have been developed, and are intended to describe the risk to humans that would result from a rare exposure to airborne chemicals.

FORMATION, EMISSION, AND MEASUREMENT OF H_2S AT MSW AND CDD LANDFILLS



H_2S in a landfill is primarily generated through the reduction of sulfate (SO_4^{-2}) in an oxygen-depleted environment of a landfill. Sulfate containing waste (e.g., gypsum drywall, recovered screened materials which is mostly unrecognizable material resulting from CDD processing), biodegradable organic matter, and moisture are the primary inputs to the reaction that coverts sulfate to H_2S. Organic matter present in CDD materials (e.g., drywall paper backing) is adequate to sustain the reaction in CDD landfill. The rate of H_2S generation is impacted by other factors such as pH, temperature, moisture, and the particle size of sulfate-containing materials.



Once formed, H_2S migrates through pore space and is captured by the active LFG collection and control system (if installed) or emitted into the atmosphere and dispersed offsite with the ambient air. Factors such as type and frequency of cover soil application, as well as ambient conditions, may inflate emission of H_2S from landfills. H_2S may react with other materials (e.g., concrete) or cover soil present in a landfill and may be *oxidized into a non-odorous* compound. *This can lead to lower levels of H_2S in surface emissions compared to measurements taken below the cover*. At unlined landfills, H_2S may migrate into the soil and impact groundwater. At a landfill, H_2S concentrations may be measured at distinct locations:

LFG (header pipe, well, or soil vapor probe): Concentrations measured at these locations would be expected to be the highest measured H_2S levels at a landfill, as there is limited dilution with atmospheric air.

Landfill Surface: Measurements at the landfill surface are typically conducted anywhere from just above the surface, to the normal breathing zone, depending on the goals of monitoring and the instrument used.

Ambient Air/Landfill Vicinity: Measurements in ambient air are typically conduced to measure the concentration of H_2S that may be present at the landfill's perimeter, property boundary, or even offsite. Although dilution with ambient air can significantly reduce H_2S concentrations with increasing distance from the landfill, the reported measurements suggest the potential for detecting H_2S at concentrations above nuisance odor, and human health thresholds exist both at and beyond the landfill property boundary.

In general, the reported H_2S measurements range widely (e.g., the reported MSW landfill gas H_2S concentration ranges over 7 orders of magnitude). The upper end of the reported landfill gas H_2S measurements at MSW landfills (~14,000 parts per million volume, (ppmv) are comparable to those reported for LFG at CDD landfills (~18,000 ppmv). High H_2S emissions impact the design and operation of projects where LFG is captured for beneficial use and may have implications for Title V permitted SO_x emission limits in some cases. H_2S measurements above 100 ppmv, which is OSHA's "immediately dangerous to life and health" threshold for H_2S, have been reported at CDD landfill surfaces.

Along with H_2S, landfills may emit other malodorous reduced sulfur compounds, such as methyl mercaptan, isopropyl mercaptan, isobutyl mercaptan, dimethyl sulfur, dimethyl disulfide, dimethyl trisulfide, carbonyl sulfide, carbon disulfide, and tert-butyl mercaptan. These reduced sulfur compounds are present at low concentrations in comparison to H_2S, and in most cases, just the measurement of H_2S can provide enough information regarding the presence and magnitude of other reduced sulfur compounds at a landfill.

STRATEGIES TO PREVENT AND/OR MINIMIZE H_2S FORMATION

Waste Diversion: H_2S generation can be controlled by diverting gypsum drywall from landfills and limiting sulfate content of the recovered screened materials accepted by landfill. Communities have used strategies such as banning drywall landfill disposal, charging an additional fee for accepting drywall, enhancing drywall recovery and recycling, or a combination of these to achieve drywall diversion.

Minimizing Water Entry: The amount of water entering the landfill can be minimized by reducing the working face of the landfill, grading the working face and surface to promote stormwater runoff, and using specific types of daily/intermediate cover.

Bacterial Inhibitors: In laboratory-scale studies, the use of bacterial inhibitors such as nitrate, chlorate, perchlorate, and molybdenum has been shown to reduce H_2S emission by inhibiting the growth of sulfate-reducing bacteria. Additional research is necessary to evaluate the applicability of these chemicals at the field scale, as well as their impacts on leachate and groundwater quality.

H_2S EMISSION CONTROL AND TREATMENT METHODS

Leachate Management. Leachate can be a significant source of H_2S off-gassing; therefore, preventing leachate accumulation on the landfill surface and in leachate control infrastructure such as sumps, cleanout pipes, and tanks can help reduced H_2S emission. Leachate can be treated with an oxidizing agent to convert H_2S and other odorous reduced sulfur compounds into sulfate or elemental sulfur.

Cover soil. Cover soils can be amended with materials such as fertilizer, coal ash, compost, concrete fines, Fuller's earth (clay-like material), lime, steel tire shreds, and metallic filter materials, to control H_2S emission. These materials potentially can react with and reduce the amount of H_2S released into the atmosphere.

Capping Systems. Low permeability landfill caps help control H_2S generation by minimizing moisture (e.g., rainfall, snowmelt) infiltration into the landfill and controlling H_2S emissions from the landfill.

Odor Neutralizers. Several chemicals such as bleach, sodium bicarbonate, and amines can be applied at or near the working face or at the site perimeter to neutralize the H_2S odor.

LFG Collection. H_2S emissions can be controlled with an active or passive LFG collection and control system. The collected LFG may need to be treated to lower H_2S content if it is to be beneficially used, as H_2S results in corrosion to equipment and the combustion process can result in SO_2 emissions. Several different treatment technologies such as liquid treatments (used with scrubbers), solid treatments (e.g., activated carbon, iron sponges, ash) and oxidizing agents, which may be used to reduce the H_2S content of LFG, are described in the report.

SITE INVESTIGATION AND MONITORING FOR H_2S



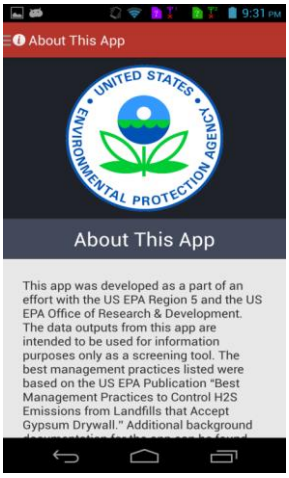


Site investigations may occur as part of routine operations or in response to an odor complaint. As H_2S has a low odor threshold, the detection of odors by site personnel may serve as an initial indication of H_2S emissions at a site.

However, higher concentrations are dangerous to personnel, and may not be detectable because of the olfactory paralysis that can occur. Thus, various instruments that detect H_2S over a range of concentrations and for a variety of purposes (e.g., assessing human exposure levels, measuring concentrations at distinct locations) may be used. The report presents considerations for site investigation and H_2S monitoring. The applications and limitations of several measurement techniques for various monitoring purposes (e.g., human exposure levels, measurement in confined spaces, landfill gas or ambient air) are described.

MOBILE APPLICATION

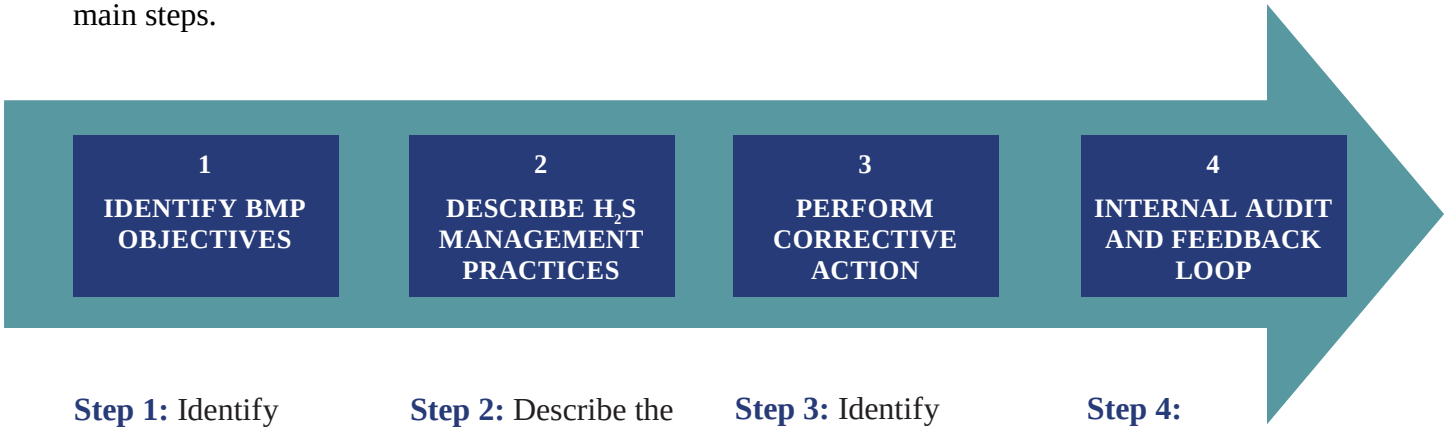
The US EPA developed a mobile application (*H_2S Less*) to estimate the H_2S generation rate as a function of the waste placement rate, years of operation of the landfill, the drywall content of waste placed in the landfill and the woody debris content of waste paced in the landfill. The application provides operating strategies for reducing and controlling H_2S generation and emissions based on the guidance provided in this report. The mobile app is available for free for both Apple and Android operating systems.



BMP Framework for H_2S Management

The development of a site-specific BMP guide allows landfill owners and operators to understand the specific issues and challenges associated with H_2S, provide the landfill operators with documentation that can be used to address the H_2S emissions, and provide direction to landfill staff to promptly observe, document, and manage the issues encountered with the H_2S emissions. The efficacy of the BMP guide should be periodically evaluated or audited to ensure the guide matches up with the needs of the site, as operating needs and conditions at landfills may change frequently.

The report proposes a framework for developing such a guide has been proposed, and consists of four main steps.



Step 1: Identify the objective of the BMP guide, such as reducing offsite odors or cleaning- up landfill gas for an energy project.

Step 2: Describe the mitigation and management practices to control H_2S generation and emission. Consider how to monitor and keep record of H_2S emissions. Identify responsible parties and communication lines. This step identifies thresholds that would trigger corrective action(s) if H_2S measurements above the thresholds are identified.

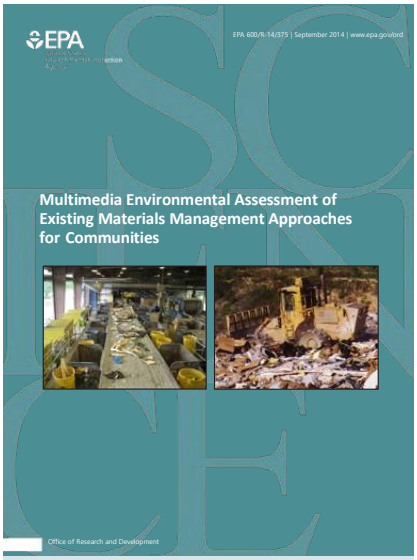
Step 3: Identify corrective actions and related implementation strategies for circumstances where H_2S at levels above thresholds are encountered.

Step 4: Perform periodic internal audits and provide provisions to update the BMP guide if needed, accommodating changes in the conditions and operations of the landfill.

Appendix C: Multimedia Environmental Assessment of Existing Materials Management Approaches for Communities

Why was the Study Conducted?

Waste and materials management decisions have been identified as one of the key factors in implementing sustainable practices. The United States (U.S.) Environmental Protection Agency's (EPA's) goal as part of this research is to empower state and local decision-makers with data and tools that enable them to integrate environmental, societal, and economic factors into their decisions, thus helping communities achieve sustainability.



Multimedia Environmental Assessment of Existing Materials Management Approaches for Communities. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/375, 2014.

Life cycle assessment (LCA) can be used as a tool for analyzing the impacts of a material over its entire life cycle. An important component of an LCA is the underlying **life cycle inventory (LCI)**, where quantitative inputs and outputs associated with the management of a material (e.g., energy, material properties, emissions) are compiled.

Construction and demolition debris (CDD) originates from the construction, renovation, repair, and demolition of structures such as residential and commercial buildings, roads, and bridges. While several tools exist to model end-of-life (EOL) management for municipal solid waste (MSW) management, CDD management has largely been excluded from existing LCA tools.

Due to the lack of data for this large stream of material, US EPA's Office of Research and Development identified CDD management pathways, and then developed LCI datasets for the most dominant CDD materials. The CDD materials studied included concrete, wood, asphalt pavement, land clearing debris, asphalt shingles, gypsum drywall, recovered screened material (i.e., mostly unrecognizable material resulting from CDD processing), and clay bricks, which collectively represent the bulk of CDD generated annually in the U.S. These LCI datasets are intended to complement the existing US EPA LCI database, which includes information for a variety of processes and services (e.g., natural resource extraction, manufacturing, energy production, and transportation).

How was the Study Conducted?

Typically, LCA studies focus on building materials either from extraction of feedstock to the point of sale (cradle-to-gate), or in their service phase (while in active use). However, the EOL phase-- which begins when the material is removed from service -- is often neglected. Thus, the main-focus of this study is specific for the EOL phase. In addition, if materials were recycled in a closed-loop process (e.g., reclaimed asphalt pavement used for asphalt pavement production), then the upstream processes (e.g., raw material extraction and processing) were considered. Upstream processes were considered in some open-loop recycling cases. For example, dimensional lumber recycled into particle board or concrete recycled as road-base aggregate would include consideration of upstream processes associated with primary wood or aggregate production.

U.S.-specific LCI datasets for EOL management for CDD, such as landfilling, processing (i.e., typically involving a separation step and/or size reduction), recycling, combustion, and composting were developed for the targeted CDD materials. Peer-reviewed literature and publicly available government and industry publications were reviewed to identify EOL management pathways. Both domestic and international LCA models, which included CDD material management and (if available) associated LCI data, were reviewed to find the primary source of the data for inclusion and/or validation of the study-developed datasets. If sufficient data on a process were not available or a given CDD management practice was not used, a related LCI was not compiled. This study identified data gaps pertaining to CDD LCI, thus identifying areas needing further research.

CDD-related LCI Inputs and Considerations

Transportation: Emissions associated with transportation are often normalized by expressing in terms of ton-miles (amount of material multiplied by the shipment distance) for a given transport type, providing a single measure of the overall demand for freight transportation services.

Electricity: Many CDD management processes require electricity for operation, where electricity consumption is correlated with the amount of material handled by the process.

Fuel Combustion in Equipment: CDD management processes require the use of heavy equipment for a variety of tasks (e.g., material loading/unloading, sorting, on-site transport).

Other Fuel Combustion Applications: Several processes—other than equipment operation--require the combustion of other fuels (e.g., gasoline, natural gas, residual fuel oil), such as natural gas fired at a hot mix asphalt plant.

Operations & Maintenance (O&M) Consumables: In addition to direct emissions, emissions associated with the production and use of O&M consumables (e.g. lubricating oils, filters, drilling fluids, belts) are considered.

Aggregates and Soil: Several CDD materials incorporate aggregates to increase load-bearing capacity (e.g., asphalt pavement). The practice of reusing these materials eliminates the need to produce an equivalent quantity of primary aggregates, and it is, therefore, necessary in understanding the fuel-related and non-fuel-related emissions from primary aggregate production.

Landfilling: The materials and energy inputs and emissions associated with landfill construction, waste placement and compaction, and closure/post-closure activities, along with the long-term liquids and gaseous emissions from the decomposition of deposited materials, need to be considered.

Landfill Leachate Emissions: Leachate emissions are caused by the release of elements in the waste materials themselves, resulting in waste-specific emissions. Due to the relative lack of data on emissions from individual waste components, models and/or databases often do not handle leachate emissions on a waste-specific basis but based on assumptions of leachate composition from mixed waste streams (e.g., MSW leachate). Where available, material-specific leaching data are used in this report.

Landfill Gas Emissions: As compared to MSW, CDD typically have smaller quantities of readily biodegradable wastes, so there is less gas production. However, CDD landfill sites experience the generation of hydrogen sulfide (H_2S), produced typically from decay of sulfur-containing wastes (e.g., gypsum drywall). Since gas production rates are expected to be low at CDD landfills, there is no federal requirement for active gas collection and control at these sites, and treatment systems based on combustion can be challenging due to the small amount of gas produced.

CDD Materials Evaluated



Asphalt Pavement: Asphalt pavement is constructed in multiple layers: top surface, intermediate, and base. The top two layers typically consist of approximately 95% aggregate and 5% asphalt. Aggregates used for asphalt pavement production may include gravel, sand, and crushed stone. Crushed stone may include various rock types such as limestone, dolomite, and granite. Asphalt pavements are routinely rehabilitated, resurfaced, and reconstructed due to surface wearing over time. Once removed, asphalt pavement, which is the second largest component of CDD in the US, may be recycled or disposed of. Recycling most commonly includes introduction into new asphalt or use as an aggregate in a fill application.



Asphalt Shingles: Asphalt shingles are more commonly used over other roofing alternatives (e.g., wood, tile, slate, and metal) due to their lower material and installation cost and superior durability. The sources of discarded shingles are post-manufacturing and post-consumer (i.e., from construction, renovation, and demolition activities). Discarded shingles are transported either to a landfill for disposal or to a processing facility and eventually primarily used for asphalt pavement production.



Gypsum Drywall: Gypsum drywall (referred to as gypsum board, wallboard, or plasterboard), typically manufactured and sold as sheets or panels, is widely used as an interior wall and ceiling fitting in residential, commercial, and institutional structures. Primary mined, by-product, and recycled gypsum are all input streams used for gypsum drywall manufacture. Drywall sheet-fitting generates scraps that are often free of tarnish or paint. Drywall that is recovered for recycling is typically taken to drywall processing facilities where contaminants are removed, and gypsum is separated from the paper backing. The processed drywall can be recycled in closed loop (e.g., new drywall manufacturing) or open loop (e.g., soil amendment) applications.



Wood: Wood is one of the third largest components of CDD in the U.S. CDD wood is typically landfilled in the US. It can be size-reduced to produce mulch or combusted for energy recovery. The reuse of recovered CDD wood in new construction or renovation or for manufacturing new wood products is limited in the U.S.



Land Clearing Debris (LCD): LCD is comprised of tree tops, branches, and stumps and can include materials such as soil, rocks, and shrubs resulting from vegetation removal for building/ infrastructure construction and land development. LCD can be combusted onsite or as a biomass fuel for power generation, composted, used for mulch production, or landfilled.

Recovered Screened Material (RSM): RSM, sometimes referred to as CDD fill, is a by-product of CDD material recovery (i.e., processing) operations. RSM includes soil, sand, and small aggregates from land clearing and demolition, as well as small particles of larger CDD materials that break off during material handling and sorting (e.g., gypsum drywall). RSM EOL management options may include landfill disposal or used as landfill alternative daily cover or application as a general fill. Of

interest is the drywall component of RSM, as the placement of drywall in anaerobic conditions of a landfill contributes to the production and release of H_2S gas.



Portland Cement Concrete (PCC): PCC is the largest component of CDD in the US and is a composite material formed from fine aggregates (i.e., sand), coarse aggregates (e.g., gravel, crushed stone), binder (Portland cement), water, and stabilizers, where aggregates make-up most of the mix. Once removed, reclaimed PCC may be recycled or disposed of in a landfill. The concrete is typically processed (e.g. crushing, sorting, metal removal) prior to use in a recycling application.



Clay Bricks: Clay bricks represent a small fraction of the total CDD material stream and are generated from the demolition of buildings, structures, and pavements. Disposal appears to be dominant EOL management of clay bricks. Clay brick can be reused or processed to use as aggregate.

Key Findings

This study provides an up-to-date compilation of U.S.-specific LCI datasets for the EOL management of the most prevalent CDD materials, giving state and community decision makers an additional tool for the selection of CDD management options that minimize impact to human health and the environment.

Material	*Manufacturing*	*Recycling*	*Landfill*	*Combustion*	*Composting*
Asphalt Pavement	✓	✓	✓	N/A	N/A
Asphalt Shingles	N/A	✓	✓	N/A	N/A
Gypsum Drywall	✓	✓	✓	N/A	N/A
Wood	N/A	✓	✓	✓	N/A
Land Clearing Debris	N/A	✓	✓	✓	✓
Portland Cement Concrete	N/A	✓	✓	N/A	N/A
Recovered Screened Materials	N/A	✓	✓	N/A	N/A
Clay Bricks	✓	✓	✓	N/A	N/A

N/A: *The material management process dataset was not developed since the management pathway does not occur, was considered atypical at the time of the study, or because the material is not recycled in a closed-loop process.*

Data Gaps and Areas for Further Research

Several major data gaps/future research opportunities were identified that would allow the development of more complete datasets. These data gaps include:

Amount of CDD Materials Handled through Different Management Pathways: Several state environmental agencies track the amount of CDD landfilled; however, only four states (Florida, Massachusetts, Nevada, and Washington) appear to be closely tracking the amount recycled for individual components of CDD.

CDD Processing Facility Operations Data: Such as electricity and diesel consumption, equipment uses, and future land redevelopment impacts.

CDD Travel Distance: Distances materials travel from the point of origin to various management locations.

Long-term Performance of Materials Produced from Recycled CDD: Although the use of recycled materials to replace primary resource extraction would reduce the overall impact on the environment, additional factors may reduce the anticipated benefits of recycling. For example, pavement made from recycled concrete aggregate and/or RAP may have a shorter service life compared to pavements manufactured entirely from primary materials. Additionally, these materials may not be as readily recycled again, and may result in disposal impacts after future use.

Liquid Emissions from CDD Landfills: Laboratory leaching data are needed for specific CDD components as a surrogate for estimating liquids emission due to lack of reliable field-scale estimates.

Gas Emissions from CDD Landfills: This study estimates gas emissions for methane, carbon dioxide, and (when applicable) H_2S. However, due to an absence of gas emission data for the specific CDD materials studied, surrogate data were used from similar materials in several instances.

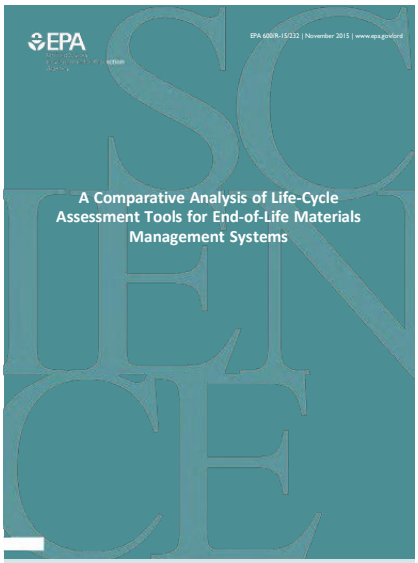
Environmental Burdens from CDD Management Operations:

- From land development, facility equipment manufacturing, and building material production for different CDD management facilities.
- From equipment and facility decommissioning (e.g., management of steel from heavy equipment at equipment EOL).
- From use of CDD management equipment operation and maintenance consumables (e.g., lubricants, filters, worn mechanical components).

Appendix D: A Comparative Analysis of Life-Cycle Assessment Tools for End-of-Life Materials Management Systems

Why was the Study Conducted?

Municipal solid waste (MSW) and construction and demolition debris (CDD) are the primary materials that communities (through their local governments) are responsible for managing. The approaches that communities use for collecting and managing the end-of-life phase of these materials have a significant impact on their economy, environment, and the health and well-being of their residents. The United States (U.S.) Environmental Protection Agency (EPA) recognizes a need for tools that can be used by decision-makers to characterize the social, economic, and environmental impacts associated with the solid wastes typically managed by communities. This report evaluates multiple tools that can be used to assess the sustainability of the EOL phase management of MSW and CDD.



A Comparative Analysis of Life-Cycle Assessment Tools for End-of-Life Materials Management Systems. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/232, 2015.

How was the Study Conducted?

A comprehensive literature review was performed to identify 29 software tools that can be used for conducting life cycle analysis (LCA) related to the EOL collection and management of MSW and CDD. The primary consideration for screening these tools was the solid waste manager's decision-making domain, which is limited to the EOL phase of materials management. Following this screening, five tools were selected for more detailed evaluation:

- **Waste Reduction Model (WARM) I** US EPA
  (under contract from US EPA)
- **Municipal Solid Waste Decision Support Tool (MSW-DST) I** RTI, Inc.
  (under contract from US EPA)
- **Solid Waste Optimization Life-Cycle Framework (SWOLF) I** North Carolina State University
- **Environmental Assessment System for Environmental Technologies (EASETECH) I** Technical University of Denmark
- **Waste and Resources Assessment Tool for the Environment (WRATE) I** Golder Associates (UL) Ltd and ERM on behalf of the Environment Agency of England and Wales

These tools are specifically developed for materials EOL management and offer flexibility to include U.S.-specific materials and processes. They were evaluated using criteria such as user interface, tool flexibility (e.g., ability to adjust materials composition and properties, and management pathways), tools scope (e.g., materials and management pathways for collection, transport, recovery), analysis/output (e.g., impact categories, sensitivity analysis) and other general attributes (e.g., training and tutorials available, documentation thoroughness, ease of use, frequency of updates).

A series of EOL management scenarios were then applied to the tools to evaluate and illustrate their potential uses and limitations for community decision-making. Scenarios were representative of the current practices used for MSW management (e.g., landfilling, organics collection and processing, material recovery, collection and transport, thermal treatment, and landfill mining), as well as issues that community decision-makers are facing across the U.S. in implementing these processes. A uniform material composition—representative of the U.S. MSW composition—was developed to compare the various scenarios with the same waste streams. However, due to variation in materials classification and nomenclature, management options, and user-specified parameters among the tools, the same input values could not be specified across all the tools. The results for the model runs were compared to each other and predetermined baseline conditions when applicable. Data gaps and key research needs were identified.

Key Findings

FEATURES OF TOOLS EVALUATED

Table 1 summarizes the salient features of all five LCA tools. All the reviewed LCA tools can evaluate the environmental impact of commonly practiced EOL phase materials management; however, their capabilities vary, and some management options and material streams could only be analyzed with specific tools. Tools have a varying degree of flexibility in simulating the scope of emission and impact categories.

Except for WARM, all tools provide a process-specific breakdown of emissions. The tools analyze a wide variety of impact categories; however, global warming (greenhouse gas (GHG) emission) is the only impact category that is common and can be used to compare the outputs among tools. Only MSW-DST and SWOLF analyze and provide cost data as an output. All five tools allow exporting data in tabular spreadsheet format. The consistent output format provides ease to the user in analyzing and comparing results between the modeled materials management scenarios.

Table 1: Comparison of salient features of EOL materials management LCA tools

Consideration	*WARM*	*MSW-DST*	*SWOLF*	*EASETECH*	*WRATE*
Procurement Cost	Free	Free	Free to non-commercial use. Cost for commercial use is not yet determined.	€5,000[3] (Approx. $5,700)	£1,400/yr. (Approx. $1,800/year)
Version and Year[4]	13 (2015)	1.0 (2002)	Pre-release (2015)	2.0.0 (2014)	3..0.1.5 (2014)
Country/Region of Materials and Management Strategies Modeled	U.S.	U.S.	U.S.	Europe	Europe
Construction, Operating, and Maintenance Cost Estimates	-	✓	✓	-	-
Material Categories					
MSW	✓	✓	✓	✓	✓
CDD	✓	-	-	-	-
Electronic Waste	✓	-	✓1	-	✓
Source Reduction	✓	-	-	-	-
Materials Collection					
Bin/cart options	-	✓	✓	-	✓
Drop-off	-	✓	✓	-	✓
CDD Collection	-	-	-	✓	✓
Source Separated Organics	-	-	✓	-	✓

Consideration	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Materials Transport					
Multiple Fuel Options	-	✓	✓	✓	✓
Multiple Vehicle Options	-	-	-	-	✓
Multiple Modes (e.g., Rail, Ship)	-	✓	✓	✓	✓
Multiple Road Options	-	-	✓	✓	✓
Transfer Station	-	✓	✓	-	✓
Material Recovery Facility (MRF)					
Single Stream	-	✓	✓	✓	✓
Dual Stream	-	-	✓	-	✓
Mixed EOL materials	-	✓	✓	-	✓
Landfill					
MSW Landfill	✓	✓	✓	✓	✓
Ash Landfill	-	✓	✓	✓	✓
Carbon Storage	✓	✓	✓	✓	-
Leachate	-	✓	✓	✓	✓
Landfill Gas (LFG)—Generation Rate Adjustable	✓	✓	✓	✓	✓
LFG—Flaring	✓	✓	✓	✓	✓
LFG-to-Electricity	✓	✓	✓	✓	✓
LFG—Direct Beneficial Use	-	-	-	✓	-
Emerging Technologies					
Gasification	-	-	✓[1]	-	✓
Pyrolysis	-	-	-	-	✓
Anaerobic Digester	-	-	✓	✓	✓
Incineration					
Mass Burn	✓	✓	✓	✓	✓
Refuse-Derived-Fuel	-	✓	✓	-	✓
Incineration without Energy Recovery	-	-	✓	✓	-
Composting					
Windrow Composting	✓	✓	✓	✓	✓
In-vessel Composting	-	✓	✓	✓	✓
Backyard Composting	-	-	-	-	✓
Tool Output					
Simultaneous Comparison of Multiple Scenarios	-	-	-	-	✓
Process-specific Emissions		✓	✓	✓	✓
Impact Categories[2]					
Global Warming	✓	✓	✓	✓	✓
Ozone Depletion	-	-	-	✓	-
Human Toxicity—General	-	-	-	-	✓
Human Toxicity—Carcinogenic	-	✓	-	✓	-
Human Toxicity—Non-Carcinogenic	-	✓	-	✓	-
Ionizing Radiation	-	-	-	✓	-
Smog Formation	-	✓	✓	✓	-
Eutrophication	-	✓	✓	-	✓
Freshwater Eutrophication	-	-	-	✓	-
Marine Eutrophication	-	-	-	✓	-
Ecotoxicity	-	✓	-	✓	-
Freshwater Aquatic Ecotoxicity	-	-	-	-	✓
Depletion of Abiotic Fossil	-	-	✓	✓	-

Consideration	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Fuel Resources					
Depletion of Abiotic Non-Fossil Fuel Resources	-	-	-	✓	-
Acidification	-	✓	✓	✓	✓
Terrestrial Eutrophication	-	✓	-	✓	-
Particulate Matter	-	✓	-	✓	-

1 *Planned but not included in version evaluated.*

2 *SWOLF has an editable impact assessment method section that could add or remove categories. Note EASETECH has multiple impact assessment methods available.*

3 *The EASETECH license is provided free to the registered user and the training cost (provided by DTU) for consultants, authorities, and developers to become registered users is € 5,000 (Approximately $5,700).*

4 The latest version available at the time of the study was evaluated. Newer version (e.g., Version 14 for WARM) with more capability may be available.

5 "✓" and "-" represent presence and absence, respectively, of the associated consideration/feature.

APPLICATION OF SCENARIOS TO TOOLS

Several relevant waste management scenarios were modeled. Table 2 provides a summary of scenarios and the simulation capabilities of the evaluated models for these scenarios. The following observations were made based on simulations performed using these tools:

- Most of the EOL materials management scenarios could be simulated using EASETECH and WRATE due to the high degree of flexibility offered by these tools; however, it is slightly challenging to use these models because of the variation in materials nomenclature.
- All tools included features to compare environmental impacts of the commonly practiced EOL materials (specifically MSW) and management options in the U.S., such as recycling, composting of biodegradable materials, incineration, and landfilling. However, some management options and material streams could only be analyzed with specific tools. For example, only WARM can analyze impacts associated with source reduction and the management of CDD materials while pyrolysis can only be analyzed using WRATE.
- Several materials management options are either not included in some tools or not referred to by the names used by the EOL materials management community in the U.S. The inconsistent use of nomenclature as compared to US industry standards may make the application of tools slightly difficult for less experienced users.
- The magnitude of the estimated GHG emissions impact varied among tools; however, in general, the tools provided consistent and expected qualitative interpretations of environmental benefits for the various materials management options simulated.
- Among all the landfill scenarios simulated, LFG and carbon storage had the greatest influence on the overall GHG impact and remanufacturing credit.
- Although the tools evaluated primarily focus on the EOL phase of materials management, data used and results of some of these tools (e.g., source reduction feature of WARM) can be used to assess the environmental impacts through all phases of the life cycle of materials.

Table 2: A list of the scenarios that could be evaluated using the given LCA tools[5]

Scenario Title and Section Number	*Options*	*WARM*	*MSW-DST*	*SWOLF*	*EASETECH*	*WRATE*
Baseline Scenario	Landfill with no LFG treatment	✓	✓	✓	✓	✓
Landfill Gas Treatment Options	Flaring	✓	✓	✓	✓	✓
	LFG-to-electricity	✓	✓	✓	✓	✓
	LFG-to-electricity with bioreactor	✓	✓	✓	✓	
Source-Separate Organics Processing	Collection and Composting	✓		✓	✓	✓
	Collection and anaerobic digestion with gas-to-electricity			✓[a]	✓	✓
Backyard Composting	Decreased organics collection due to home composting	✓	✓	✓	✓	✓
Materials Recovery	Single stream MRF	✓	✓	✓	✓	✓
	Dual stream MRF	✓		✓[a]	✓	✓
	Mixed waste MRF	✓	✓	✓	✓	✓
MRF Automation	Various levels of manual vs automated work			✓[a]		
Recycling Plastics vs Recycling Glass		✓	✓	✓	✓	✓
Pay-as-You-Throw		✓	✓	✓	✓	✓
CDD Recycling	Landfilling of CDD	✓				
	Recycling of CDD	✓				
E-waste Collection and Recycling	Landfilling of e-waste	✓		✓[a]		✓
	Recycling of e-waste	✓		✓[a]		✓
Collection Vehicle Fuels	Diesel	✓	✓	✓	✓	✓
	CNG			✓[a]		✓
	Biodiesel					✓
Collection Vehicle Types	Vehicles with different mechanisms for waste collection					
Transfer Station	Adding a centrally located transfer station	✓	✓	✓	✓	✓
Thermal Treatment Options	Mass burn WTE	✓	✓	✓	✓	✓
	Gasification			✓[a]		✓
	Pyrolysis					✓
Plastic Incineration vs Recycling	Plastic incineration	✓	✓	✓	✓	✓
	Plastic recycling	✓	✓	✓	✓	✓
RDF Recovery Before and After Landfilling	RDF production from fresh MSW		✓	✓		✓
	RDF production from landfill mining					

[5] The latest version available at the time of study was evaluated. Newer version (e.g., Version 14 for WARM) with more capability may be available. [a] *Not in the version evaluated but is expected to be included in future versions.*

✓ indicates that the listed scenario can be modeled using the tool.

Data Gaps and Potential Research Opportunities



- None of the selected tools evaluate the social impacts of EOL materials management options.
- Only MSW-DST and SWOLF assess the economic impacts of materials management, and these tools only produce an estimated annualized cost, which is limited to the cost of constructing, operating, and maintaining materials management facilities, while not accounting for overall economic impacts, such as job creation.
- The tools analyze environmental and economic impacts independent of each other, not accounting for interactions or trade-offs between these impacts.

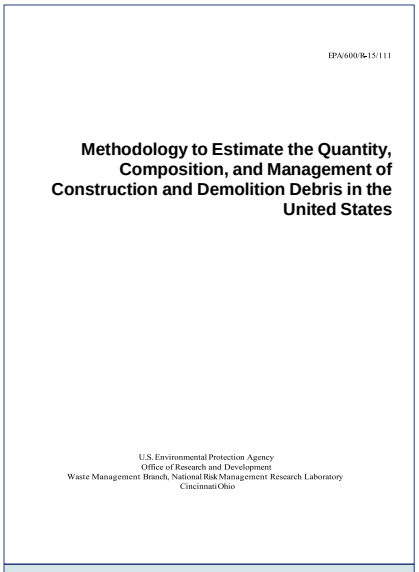
Recommendations for Enhancing Existing Tools or Developing New Tools

- Using materials nomenclature that is consistent with the US EPA Facts and Figures report, as well as categories and descriptions used by communities.
- Using tool architectures that allow easy updates of the background data (e.g., life cycle inventories) and the inclusion of new materials and technologies.
- Designing to assess the impact of source reduction.
- Designing for users with varied educational levels and skill sets.
- Designing to assess trade-offs amongst all three categories of impacts—environmental, social, and economic.

Appendix E: Methodology to Estimate the Quantity, Composition, and Management of Construction and Demolition Debris in the United States

Why was the Study Conducted?

Accurate estimates of regional and national solid waste generation and management are essential to develop and implement sustainable materials management plans. Estimates of generation can be used to assess large-scale life-cycle impacts, set waste management policy priorities, and monitor progress towards material reuse or recycling goals. The United States (US) Environmental Protection Agency (EPA) has estimated municipal solid waste (MSW) generation and management for several decades, principally by using a materials flow analysis (MFA) approach coupled with limited measured data.



Methodology to Estimate the Quantity, Composition, and Management of Construction and Demolition Debris in the United States. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/111, 2015.

In contrast with MSW, estimates of historical construction and demolition debris (CDD), which consists of materials produced from construction, demolition, or renovation projects, have been sporadic in the US. US EPA has started to regularly estimate the CDD generation amounts in its annual sustainable materials management reports. US EPA is employing an MFA approach developed using the Cochran and Townsend methodology[4] and reclaimed asphalt pavement (RAP) data reported by the National Asphalt Pavement Association (NAPA). Prior to the aforementioned effort, US EPA previously estimated the CDD generation amounts for 1996[5] and 2003[6] using a different methodology. US EPA encompassed only building-related CDD and extrapolated the project-level CDD generation (from a small number of building construction, renovation, and demolition projects using routinely tracked housing statistics) to a nationwide CDD generation amount (170 million short tons in 2003). These estimates did not include CDD generation from large infrastructure projects such as construction, maintenance and demolition of roads, bridges, and airports. In comparison, using the MFA approach, Cochran, and Townsend[7] estimated 680 to 860 million tons of total CDD generation from buildings, as well as infrastructure projects in the U.S. in 2002. Of that total amount, 121 to 242 million tons were estimated to be building related.

[4] Cochran, K. and Townsend, T. (2010). *Estimating Construction and Demolition Debris Generation Using a Materials Flow Analysis Approach*. Waste Management. 30(11):2247-2254.

[5] US EPA (1998). *Characterization of Building-Related Construction and Demolition Debris in the United States*. United States Environmental Protection US EPA. June 1998.

[6] US EPA (2009). *Estimating 2003 Building-Related Construction and Demolition Materials Amounts*. EPA 530-R-09-002. United States Environmental Protection US EPA. March 2009.

[7] Cochran, K. and Townsend, T. (2010). *Estimating Construction and Demolition Debris Generation Using a Materials Flow Analysis Approach*. Waste Management. 30(11):2247-2254.

Neither of the previous studies estimated CDD disposal and diversion amounts. However, such estimates are needed to assess the environmental impacts associated with current CDD management practices. Moreover, MFA estimates were not based on any directly measured CDD data and other estimates incorporated only limited-scale project-level data. Neither accounted for land clearing debris (LCD), which can constitute a significant fraction of the overall CDD.

Over the past few years, several states in the U.S. have started routinely tracking and publishing the amount of CDD disposed of and/or recycled by the regulated facilities in the state. Furthermore, efforts by numerous states and municipalities have led to extensive studies of CDD management at disposal and processing facilities. The availability and analysis of these large datasets present an opportunity to develop an estimate of CDD generation and management that incorporates actual CDD quantities measured at operating solid waste management facilities.

How was the Study Conducted?

Some states routinely aggregate facility-level data to estimate statewide CDD disposal and/or recycling amounts. The definition and domain of materials regulated as CDD varies among states. The following steps were undertaken to develop the estimation methodology:

Step 1 (CDD Estimates): Reported estimates of statewide CDD disposal and/or recycling were compiled from the websites of State Environmental Agencies and were reviewed for level of completeness with respect to the domain of facilities that are permitted to accept CDD, facility types that are required to track and report CDD amounts to states, and CDD flow across the state boundary.

Step 2 (CDD Definition): To give the proper context to state data, an extensive examination was performed of the current regulatory definition of CDD, the associated major CDD components and sources, and requirements for tracking and reporting CDD data for all 50 states.

Step 3 (Representative Indicators): As discussed below, only a limited number of states comprehensively track CDD disposal and diversion, indicators that were considered to extrapolate the available state-reported CDD landfilling and diversion amounts to a U.S.-wide CDD estimate included several relevant economic and construction statistics routinely reported at the state level—those by the U.S. Census Bureau, the U.S. Department of Housing and Urban Development, and the U.S. Bureau of Economic Analysis. State-level statistics were compiled for the 1997-2012 period, to account for any major fluctuation related to the U.S. housing market in the mid-2000s and the recession in the 2008-2010 period. Only the statistics that are tracked on at least an annual basis at the state level were analyzed for use as indicators.

Several state-level statistics were examined against state population: total wages and salaries; construction industry employees' compensation; waste management and remediation services sector employees' compensation, total gross domestic product (GDP), construction GDP, and number of building permits. Datasets other than building permits strongly correlated with the state population data. The state population and the building permit numbers were then separately analyzed against the CDD disposal and diversion amounts.

Building permits were found to mimic the trend in CDD disposal better than state population, and thus, the number of building permits was selected as the surrogate extrapolation factor to estimate the nationwide CDD disposal data from the reported statewide disposal data. The number of CDD

MRFs was used as the surrogate extrapolation factor to estimate nationwide CDD diversion amounts from the reported state diversion data.

Step 4 (CDD Composition Data): Data from state and regional-scale waste composition studies were used to estimate the composition of the landfilled and recycled CDD.

Step 5 (CDD Data for Infrastructure Projects and Land Clearing): Large volumes of source-segregated CDD debris, typically originating from land clearing activities and from infrastructure projects (e.g., roads and bridges construction, maintenance, and demolition), is managed by the recyclers that are generally exempt from state solid waste regulations and not required to report the data to the state. The state reported CDD data, therefore, do not include CDD debris from infrastructure and land clearing activities. Consequently, an extensive search of other data sources was conducted for CDD amounts generated from infrastructure projects (e.g., asphalt concrete, Portland Cement Concrete), and LCD. The examined data sources included the federal and state government agencies, and relevant trade organizations.

Following the data collection and analysis steps, ***a bottom-up approach*** (where data are based on measured amounts of CDD managed by processors and disposal facilities) was developed to estimate nationwide CDD disposal and recycling amounts. An approach was included to estimate CDD commingled with MSW (e.g., CDD from do-it-yourself projects discarded with MSW) to estimate the composition of disposed and diverted CDD streams, based on a review of CDD composition studies. Finally, a discussion of limitations was included in this study to capture some uncertainties associated with the methodology.

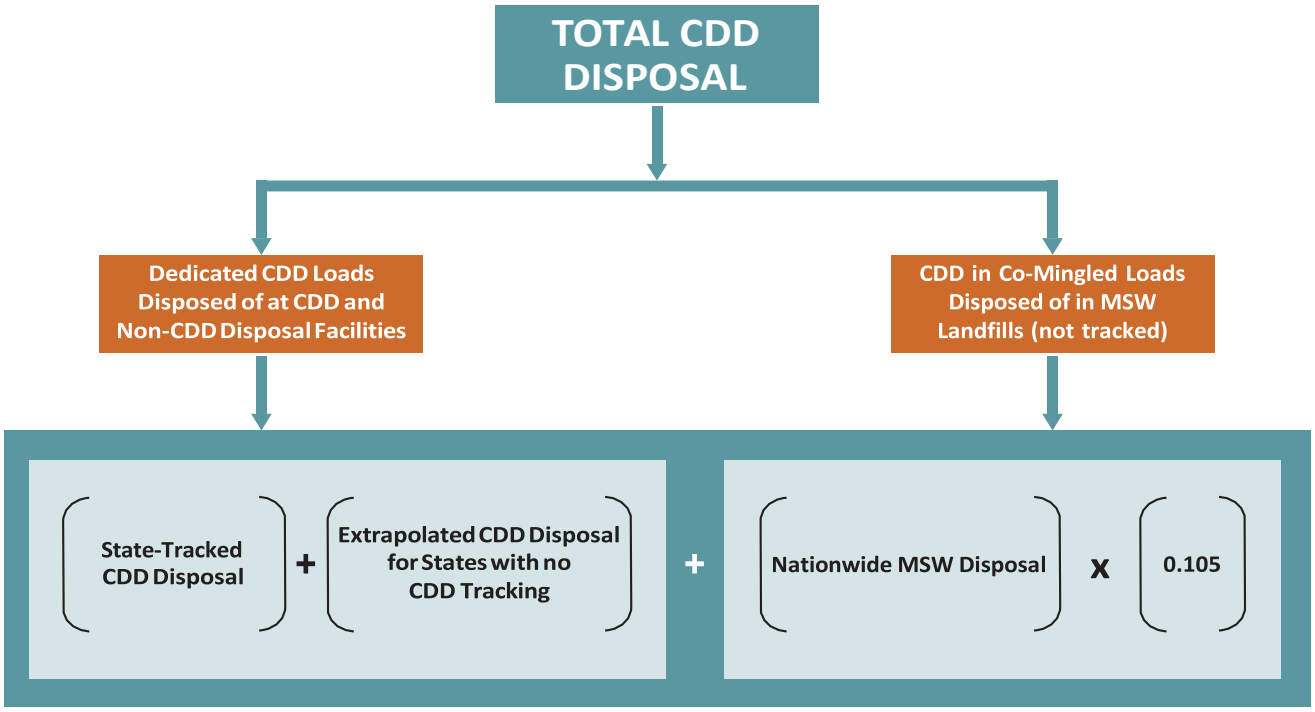
Methodology

CDD DISPOSAL

Unit CDD Disposal Rate: During the 2003-2011 timeframe, only 8 states routinely reported both disposal and recycling amounts, while 4 states reported only disposal data, and 3 states reported only recycling data. All disposal data reported by the states that comprehensively tracked CDD amounts from all disposal facilities that were permitted to accept CDD and import and export of CDD across the state were summed, and then the unit CDD disposal rate (CDD disposal amount per building permit) was calculated by dividing the sum of the CDD disposal amounts for all states by the total number of building permits issued in these states. The unit CDD disposal amount for states that do not routinely report/track the CDD disposal amounts was estimated by multiplying the calculated unit disposal rate by the total number of building permits issued in these states.

Commingled Waste: CDD commingled with MSW is typically tagged and tracked as MSW. To calculate it, the MSW disposal quantity for the year of interest and the typical CDD content of MSW loads were determined. Based on 12 regional-scale waste characterization studies documenting the percentage of CDD arriving in commingled loads at MSW landfills, the average weighted fraction of CDD was estimated to be 10.5 percent of the total landfilled MSW (on a wet-weight basis). The MSW disposal amounts reported by the State of Garbage in America[8] survey were used for total landfilled MSW.

[8] van Haaren, R., Themelis, N., Goldstein, N. (2010). State of Garbage in America. *Biocycle* 51(10) p. 16



CDD RECYCLING AND PROCESSING

As part of a different study, US EPA had developed a database of the number of CDD permitted or registered processing facilities for each state. Statewide diversion amounts coupled with the number of permitted or registered processing facilities in the states that reported diversion amounts were used to develop a unit diversion rate. This unit diversion rate was multiplied by the number of processing facilities in the states that do not track CDD diversion amounts to estimate the CDD diversion amount for these states.

RECLAIMED ASPHALT PAVEMENT, PORTLAND CEMENT CONCRETE AND LAND-CLEARING DEBRIS

Review of state solid waste regulations found that states representing 94 percent of the U.S. population (as of 2013) have an exemption in their state-level solid waste management rules for source-segregated "clean" debris or some analogous term, which enables these materials to be managed at facilities other than state-permitted solid waste management facilities. Asphalt pavement and clean concrete were frequently found to be enumerated materials that met the definition of source-segregated clean debris, and LCD was often given a similar exemption or was simply not defined as CDD. Because these three material streams are expectedly large in volume, data sources other than state regulatory agencies were reviewed for measured quantities.

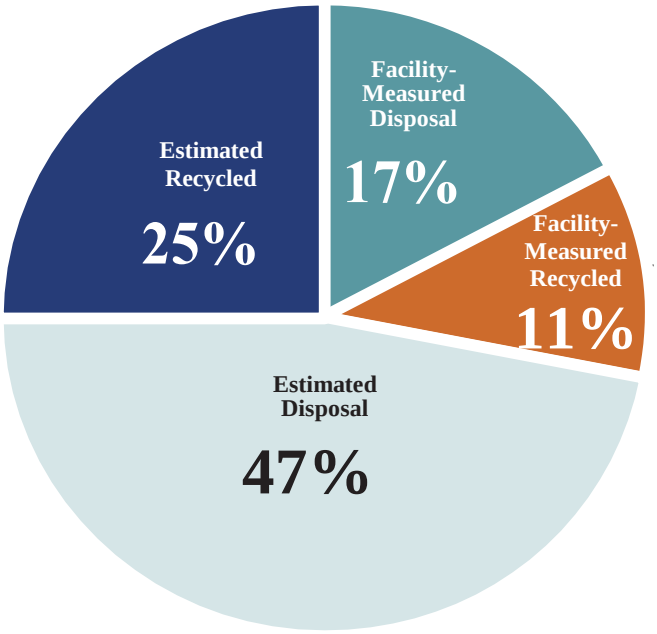
NAPA publishes an annual survey of asphalt mix producers in the U.S. and the survey report lists the quantity of reclaimed asphalt pavement recycled each year. Data from the NAPA survey were included in the methodology. An alternative method to estimate the quantity of RAP using statistics tracked by the Federal Highway Administration was included, and can be used in the event NAPA discontinues the survey in the future. **However, none of the available estimates appear to present a reliable estimate for Portland Cement Concrete and land clearing debris generated in the U.S. The developed methodology, therefore, does not include provisions to estimate these CDD streams**.

APPLICATION AND FINDINGS

The overall methodology was expressed as the sum of the three main CDD management components, providing a way to estimate the national CDD generation rate:



Based on this methodology, CDD managed by the permitted/registered facilities in the U.S. in 2011 was estimated to have been 154 million tons. Approximately 28 percent of that amount represents measured data. The proposed methodology includes a greater fraction of measured data than any of the previous CDD generation estimates, suggesting a lower potential for errors associated with extrapolation. This estimate does not include RAP recycled by asphalt mix plants and concrete and LCD processed by facilities exempted from state CDD management regulations.



METHODOLOGY NEEDS AND LIMITATIONS

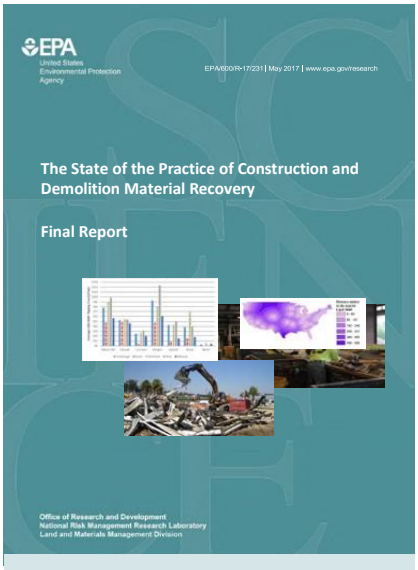
This methodology was developed to fill an existing gap in measurement-based waste generation estimation. Additional data can improve the quality of the estimate and provide a more complete picture of CDD generation and management. These data include:

1. State or trade organization data on PCC generation from infrastructure projects.
2. State or trade organization data on LCD generation.
3. Additional data on the specific weight of CDD for each state's waste stream.
4. Additional states CDD generation, diversion, and disposal data based on facility-level measurements

Appendix F: The State of the Practice of Construction and Demolition Material Recovery

Why was the Study Conducted?

Construction and demolition debris (CDD) is generated in the construction, renovation, and demolition of buildings, roads, bridges, and other structures. The components of CDD vary depending on the activity, type and structural materials used; however, CDD predominantly consists of concrete, wood, metal, asphalt pavement, asphalt shingles, drywall, masonry products, and land-clearing debris.



The State of the Practice of Construction and Demolition Material Recovery. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-17/231, 2017.

CDD represents a substantial portion of the total material discarded in the United States (U.S.), and communities may consider its end-of-life management a priority for their sustainable materials management initiatives. In the U.S., CDD is primarily managed through landfilling or recovery, where ***recovery may refer to one or a combination of reuse, recycling, and/or energy recovery***. Many materials in the CDD stream can be recovered, which provides potential for significant environmental, economic, and social benefits to communities.

The US Environmental Protection Agency (EPA) conducted this study on the current state of the practice of CDD material recovery – the processes, opportunities, and limitations associated with it - to help community decision-makers incorporate CDD recovery into their sustainable materials management programs. The study talks about the properties of the CDD stream, typical processing methods for CDD, the end markets for recovered CDD, and important incentives and disincentives to CDD recovery. It includes environmental and human health considerations associated with recovering CDD materials.

How was the Study Conducted?

Three overall guiding questions were used in the design of the study:

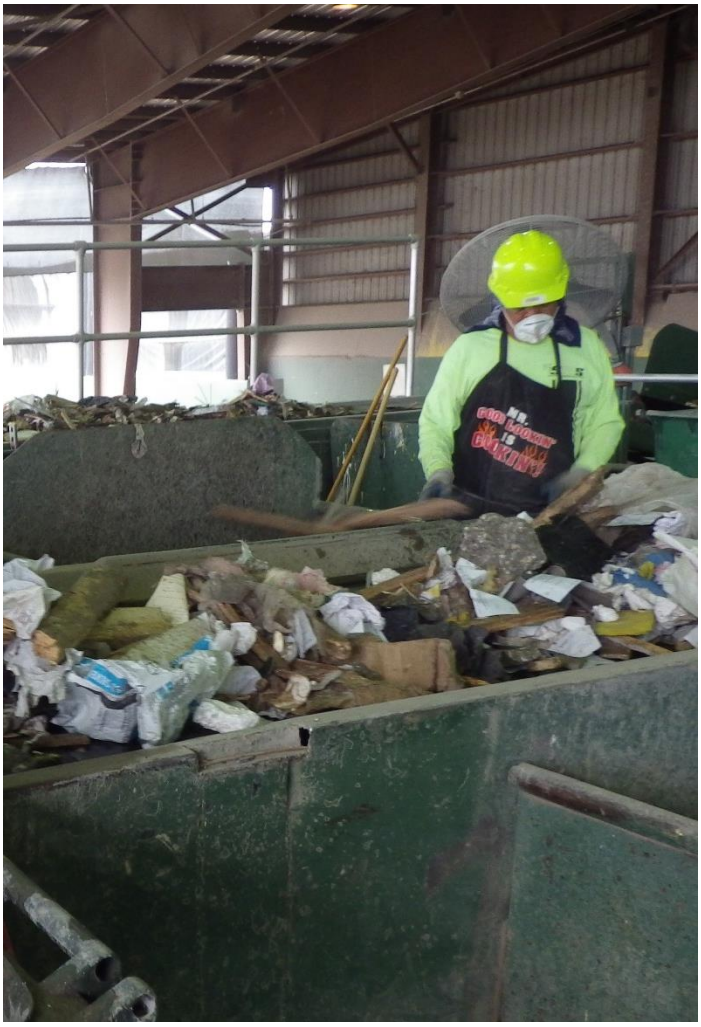
How are CDD materials managed? CDD recovery is a multi-step process. The study describes the properties of the CDD stream, the handling at the point of generation, the types of processing facilities used for CDD materials, and the end markets for those materials.

What are some key factors that influence CDD recovery? The study focuses on the major factors that drive the success of CDD recovery programs. These factors include the economics, public and corporate policies, and the availability of end markets (e.g., green building materials) for CDD materials.

What are the key environmental and human health considerations associated with CDD recovery? While numerous benefits are associated with the recovery of CDD, certain materials (particularly present in older structures) may pose a risk to human health and the environment, if not properly managed. This study highlights examples of CDD materials of known concern and discusses the steps the CDD industry employs to identify and properly manage them.

Key Findings

HOW ARE CDD MATERIALS MANAGED?



CDD recovery is a multi-step process that includes material segregation (e.g., separation of wood and aggregate from mixed debris), processing (e.g., size reduction, removal of nails), and end-use of the material in lieu of virgin material. Recovery involves a unique set of challenges due to the heterogeneous nature of the CDD stream and the occasional presence of harmful substances. Depending on the methodology, data sources and scope of data reviewed, studies in 2014 and 2015 placed CDD-material generation in the U.S. in the range of 230 million to 530 million tons per year, with 30% to 70% of the generated materials being recovered. A compilation of CDD characterization studies has shown that wood, roofing materials, and concrete are disposed of in the greatest amounts (in order by mass).

CDD materials are most commonly recovered in material recovery facilities (MRFs). CDD MRFs may accept individual CDD materials - segregated at the point of generation - or mixed CDD materials that will be separated at the MRF using a combination of equipment and manual labor. Materials segregated onsite can be transported directly to a related recovery end-market or material-specific processing facilities.

Deconstruction at the project site, prior to or without demolition, is the opposite of construction and installation, and it facilitates material separation. Deconstruction minimizes damage to CDD materials, increasing their potential for salvage and reuse. However, onsite CDD separation is challenging because of the need for multiple containers, additional labor, space (for staging and separating materials), and increased worker coordination.

The availability of end markets for recovered CDD is a primary consideration in CDD recovery. Although recovered materials have multiple end markets, these markets may not be available in each area. The market availability and comparative price of virgin materials play a significant role in determining recovery options. The table below lists material-specific markets and important considerations associated with the recovery of materials.

SUMMARY OF MARKETS AND UNIQUE RECOVERY CONSIDERATIONS BY MATERIAL

CDD Material	*Major Material-Specific Markets and Considerations Associated with Recovery*
Portland Cement Concrete	Commonly recycled as aggregate in transportation applications; sometimes recycled in place (after processing) as a fill material; must meet specifications in construction applications; the presence of rebar and large, oversized pieces impact market suitability.
Asphalt Pavement	Most commonly recycled into new asphalt pavement, sometimes recycled in place; recycling can help offset the excessive cost of raw material (asphalt).
Gypsum Drywall	Land application is historically the major application, but state and local restrictions may apply; quality (e.g., moisture content, presence of paint coatings/wallpaper) impacts suitability for recycling; the amount of paper in processed gypsum drywall is a consideration in remanufacture and few U.S. remanufacturing facilities are in place; competes with flue gas desulfurization of gypsum in the manufacture of new drywall.
Wood	Mulch, compost, and biomass fuel production are the most common recycling options for wood waste; Identification and removal of treated and painted wood; large trees and stumps cost more to process; tipping fee/processing cost, meeting boiler fuel specifications (e.g. moisture content, size, level of contaminants); leaching concerns with mulch and boiler fuel ash.
Asphalt Shingles	Used in paving applications, but not universally; can offset some of the pavement virgin asphalt cost; must be non-asbestos; must meet specifications in construction applications.
Fines and Residuals	Fines typically used as alternative daily cover for landfills and residuals may be used as a refuse-derived fuel; the amount of drywall in fines is a major consideration for use in landfill cover applications since drywall presence creates the potential for hydrogen sulfide release; contaminant level and moisture content of residuals are major considerations for marketability as a fuel.

WHAT ARE SOME KEY FACTORS THAT INFLUENCE CDD RECOVERY?

Economic Factors: Economic factors such as transportation costs and variability in tipping fees between recovery and disposal facilities are important considerations influencing end-of-life management decisions. Other economic factors, such as labor requirements and restrictions on materials storage during construction projects, may impact whether materials are recovered.

Public Policies: State, local government, and corporate policies such as disposal bans, disposal taxes, subsidized recycling, as well as material-specific and overall recycling goals can drive CDD recovery.

Corporate Policies: An additional driver for increased CDD recovery is green building certification. A certified green building performs better, improves well-being, reduces environmental impacts, and provides life-cycle cost benefits compared to a conventional building. Green building is a growing and important trend due in part to government incentives and tax breaks at local and national levels for builders, developers, and homeowners. The factors influencing the adoption of green building certifications include government regulations, changes in energy costs, awareness of the benefits of green technologies, costs of green building materials, product performance, changes in construction design, and resale value of green buildings.

In many cases, green building materials can be recycled using existing CDD recycling technologies. However, the physical and chemical characteristics of a recycled-content material may differ from the original material and limit its future recyclability. Those interested in recycling green building materials may encounter a lack of appropriate recycling facilities, or the material may not be available in sufficient quantities to allow the development of a market and ensure economic viability.

WHAT ARE KEY ENVIRONMENTAL AND HUMAN HEALTH CONSIDERATIONS ASSOCIATED WITH CDD RECOVERY?

Although CDD recovery can provide significant environmental benefits, care must be taken to properly manage materials and products that contain asbestos, lead, mercury, PCBs, batteries, certain wood preservatives, and refrigerants. Even though the use of many of these products has been reduced, banned, or discontinued, they can still be encountered in older buildings. Several states have developed policy and educational guidance for the removal of certain building components prior to commencing demolition or renovation work.



In addition, CDD material processors must use procedures to appropriately sort materials and identify those appropriate for recovery and recycling; proper equipment, health and safety training, and implementation of best practices are key to ensuring appropriate recovery.

Data Gaps and Potential Research Opportunities

Quantifying the Nationwide Reuse of CDD: Insufficient information exists on quantities and types of CDD materials that are recovered for reuse.

Quantifying Recovered CDD Material Markets: Apart from asphalt pavement, there is limited information about quantities of CDD materials in different end-uses.

Identification of Factors that Promote Community CDD Recovery: A large-scale analysis of factors (public policy, economic, and social) that promote CDD recovery does not exist.

Beneficial Use of CDD Fines (from mixed CDD MRF): One of the primary end-uses of CDD fines is as a landfill alternative daily cover, but large-scale studies documenting the success or challenges of such use at landfill sites are absent.

Beneficial Use of CDD Processing Residuals (from mixed CDD MRF): Use of these processing residuals as a refuse-derived fuel can reduce the quantity of CDD being landfilled. A study that reviews cases of beneficial use of CDD processing residuals could be helpful.

Market Analysis of CDD Diverted from Landfills Landfill owners may preserve air space by diverting certain CDD from landfills, and as a result, they may profit financially. A related nationwide, region-specific market analysis is needed.

EPA Disclaimer

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication.