A Critical Assessment of Pathways and Limitations to Recycling Fuel Combustion Residues in Florida

October 2014

Timothy G. Townsend

Justin Roessler

Wesley Oehmig

Nawaf Blaisi

Department of Environmental Engineering Sciences

Engineering School for Sustainable Infrastructure and the Environment

University of Florida

Hinkley Center for Solid and Hazardous Waste Management

University of Florida

P. O. Box 116016

Gainesville, FL 32611

www.hinkleycenter.org

Report # 97742

Acknowledgements

This document resulted from a research project funded by the Hinkley Center for Solid and Hazardous Waste Management. The information presented within was developed with input for a working group of professionals that met on five occasions discussing issues pertaining to the recycling of fuel combustion residues in Florida.

Contents

List of Tables

List of Figures

Introduction

Management of the byproducts and residuals generated from the combustion of fuels represents one of the more challenging and complex solid waste management issues facing Florida's regulators, policymakers and government officials. In 2010, approximately 25% of the electricity generated in Florida was produced through the combustion of coal or similar solid fossil fuels, occurring at 15 different facilities (Cordiano, 2011). Additionally, 13 waste-to-energy (WTE) facilities combusted 3.9 million tons of municipal solid waste (MSW) (FDEP, 2010) and 3 facilities converted woody biomass to renewable energy (NRDC, 2013). Solid wastes are produced at all of these facilities, both as a result of unburned and noncombustible residuals as well as air pollution control (APC) byproducts.

All solid wastes, including fuel combustion residuals (FCR), must be managed in a manner protective of human health and the environment. A number of state laws and regulations provide requirements for managing solid wastes in a safe and protective fashion, and these rules are often directly adopted from federal regulations. For example, regulations developed and administered by the US - Environmental Protection Agency (EPA) outline very specific management requirements for those wastes meeting the definition of hazardous waste and provide design and performance standards for landfills and WTE facilities managing MSW. Currently absent at the federal level, however, are regulations specifically designed to address the management FCR (regulations for the management of residues from coal combustion are currently proposed by the EPA).

In absence of specific federal rules or guidance, individual states have developed their own regulations to address FCR management. WTE combustion residuals are typically managed along with other MSW in engineered landfills. In some states, requirements for management of coal combustion residuals (CCR) are well defined, while in other states, decisions regarding CCR management are either defined on a facility-specific basis or they are not defined at all. Proposed federal legislation and regulations include several possible approaches for CCR management.

One of the larger challenges of FCR management is providing an appropriate regulatory structure that promotes recycling and beneficial use of these materials while ensuring that these materials are managed in a fashion that is protective of human health and the environment. A major emphasis by both government and industry today is sustainability, and a major component of this is appropriate use of material resources. A shift from the concept of waste management to that of materials management has been embraced by many. The beneficial use of FCR offers benefits through greenhouse gas reduction, energy conservation, reduction in environmental impacts associated with mining and processing virgin materials, and the avoidance of the consumption of landfill space where FCRs are disposed.

Recycling and beneficial use of many FCR has a long history. Coal combustion fly ash, for example, is a highly desired replacement for Portland cement in the manufacture of concrete products. In many countries, processed WTE bottom ash is used as a replacement for construction aggregate in applications such as road base. Recycling of ash from the combustion of woody biomass has long been practiced through land application to forest and agricultural lands. The desire to use waste resources in a sustainable fashion through recycling and beneficial use must be balanced with the need to protect human health and the environment. The combustion process and associated air pollution control systems result in materials with constituent concentrations that may be elevated compared to the original fuel. Some FCRs do contain chemical constituents that could pose a risk to human health and the environment if they are improperly managed.

A number of factors have motivated the development of this white paper. The State of Florida has established a 75% recycling goal, opening reconsideration of potential reuse opportunities for all waste materials. The body of knowledge regarding FCR characteristics and management continues to grow, including research and practice on FCR reuse under a variety of scenarios. More refined tools are now available to provide a better means of assessing potential risk. Furthermore, proposed EPA rulemaking regarding the management of CCRs provides motivation for state policy to clearly address the beneficial use of these materials. This ongoing EPA rulemaking was the genesis for the Florida Legislature's enactment of Section 403.7047, Florida Statutes, which addresses CCR beneficial use in Florida.

The goals of this white paper are to provide a concise assessment of the current state of FCR management in Florida, summarize relevant background information on the topic, and identify both the opportunities and limitations for FCR beneficial use in the state. While there are distinct differences among the different types of FCR described herein (CCR, WTE ash, wood ash), and specifics on each are provided throughout, the general approach to assessing the opportunities and limitations are deliberately outlined for FCR as a whole, as the general scientific and policy considerations with respect to evaluating beneficial use applies equally to all of these materials.

FCR Fundamentals

Coal Combustion Residuals

At a typical coal-fired steam electric generation facility, coal is pulverized and ground to a fine powder on site, it is then introduced into the combustion chamber of a boiler as fuel where it is burned at a high temperature. Water in jacketed walls surrounding the boiler is converted into superheated steam which spins a turbine that is connected to a generator resulting in the production of electricity. Several air pollution control methods are employed. These include optimized boiler operation, selective catalytic (or non-catalytic) reduction of NOx through ammonia injection into the boiler, particulate matter removal through an electrostatic precipitator or a baghouse, and lime scrubbing for SOx removal. More recently, "clean coal technology" has been developed to first pyrolize coal to form synthetic coal gas, or "syngas", which is scrubbed to remove SOx before being used to fire combustion turbines.

The solid residual falling to the bottom of the boiler is referred to as bottom ash while particulate matter retained in the electrostatic precipitator or baghouse is called fly ash. Though not produced on all newer coal fired boilers, boiler slag is a vitreous residue generated when molten bottom ash is quenched with water along the sides of the boiler. The byproduct of the coal gasification stage of the clean coal technology described above is also a slag material, similar to that produced by the traditional coal combustion process. Flue gas desulfurization (FGD) residue is generated by the scrubbing of SO_2 in lime slurry, converting $Ca(OH)_2$ into $CaSO_4 \bullet 2(H_2O)$, or gypsum.

In June 2010, the US-EPA proposed rules for management of coal combustion residuals which are still under consideration. Two options have been proposed by EPA for regulating CCRs: 1) CCRs would be regulated as "special waste" subject to regulation under subtitle C of the Resource Conservation and Recovery Act (RCRA) (e.g., in surface impoundments or landfills); and 2) CCRs can be disposed in accordance with requirements generally consistent (with some exceptions) to requirements for municipal solid waste landfills under subtitle D of RCRA.

MSW WTE Ash

Combustion of MSW for energy recovery, or waste to energy (WTE), typically involves the combustion of raw MSW, although some plants pre-process the waste into refuse derived fuel (RDF). RDF is produced by shredding, dewatering and recovering from the waste ferrous and non-ferrous metals prior to pelletizing. The added input of energy upfront results in a higher-BTU/lb fuel.

In a typical mass burn facility, raw MSW is deposited from collection trucks onto a large open floor to aid in inspecting the waste before it is placed in large hoppers above the boilers. The MSW cascades down revolving grates in the combustion boiler. Similar to coal fired generation, steam in jacketed walls is used for energy conversion.

Air pollution control technologies differ slightly when compared with coal-fired units. In many WTE plants, powdered activated carbon is injected into the gas stream to adsorb volatilized organics and metals such as dioxins and mercury. The particulate matter control systems generate a fly ash containing the particulate produced during waste combustion, activated carbon, and the residual generated from lime scrubbing. The solid MSW residual falling through the grates in the boiler (bottom ash) is quenched and conveyed to be combined with the fly ash in process. The mixed material is then subjected to magnetic and eddy current separation to removed ferrous and non-ferrous metals, respectively.

Other forms of waste conversion include gasification units, which may be operated at a wide range of temperatures. High temperature gasifiers rely on an arc furnace or plasma torch to generate large amounts of heat while keeping oxygen levels low enough to convert the organic waste into syngas (a high BTU/lb gas composed of H_2 and CO). Lower temperature gasifiers may rely on natural gas burners to aid the waste in conversion. The slag produced from high temperature gasification is a vitreous oxide with a lower content of certain heavy metals due to their volatilization in the furnace.

Ash from Biomass Combustion

An interest in renewable energy generation has led to a growing biomass combustion industry. In 2008, Florida produced nearly 2600 megawatt hours of electricity from wood, wood waste, and other biomass over half of the total renewable energy generated that year (EIA, 2008). Because the contaminants within biomass residues are similar to those in MSW WTE residues, some of the same techniques can be used for pollution control. It is important to note, however, biomass residues are often variable in quality, depending highly upon the feedstock. A 2007 study found that the Cd and Cr concentrations of straw and wood fly ash were lower than in MSW WTE ash analyzed (Lima et al., 2008). On the other hand, in a 2002 study, researchers found that wood ash from a feedstock composed of only 5% CCA treated wood leached high enough concentrations of As to be considered a hazardous waste (Solo-Gabriele et al., 2002). The high variability in residue quality from biomass combustion must be accounted for when developing strategies for reuse.

FCR in Florida

FCRs generated in Florida include residuals produced from coal-fired power plants, WTE facilities, and biomass combustion facilities. Several types of FCR are presently beneficially used in Florida. CCRs include coal fly ash, bottom ash, boiler slag, gasifier slag and (FGD) material. Coal fly ash is used as both a pozzolan in concrete and with bottom ash as an ingredient in Portland cement production. FGD material is used for gypsum drywall manufacturing and in agriculture as a soil amendment. Both coal bottom ash and slag are used as concrete block aggregate. Slag is also used in blasting grit and roofing shingles. In the State of Florida, 25% of the electricity was generated from coal combustion in 2010, and over 3 million tons of residuals were produced, with a reuse rate over 60% (Cordiano, 2010). Table 1 lists the 16 coal fired power plants in Florida capable of producing over 250MW. Ridge Generating Station produces ash from the co-firing of waste wood and tires, and sugarcane facilities commonly burn bagasse as a process fuel in their boilers. Ash generated from biomass combustion is regularly applied as a soil amendment.

Table 1. Florida Coal Power Plants

Facility Company	County
Crist Plant Gulf Power Company	**Escambia County**
Lansing Smith Plant No. 1&2 Gulf Power Company	**Bay County**
Scholz Plant Gulf Power Company	**Jackson County**
Deerhaven No. 2 Gainesville Regional Utilities	**Alachua County**
Cedar Bay Cogen Project * Cedar Bay Generating Company, L.P./Smurfit-Stone Container Corp.	**Duval County**
St. Johns River Power Park JEA	**Duval County**
Northside Generating Station JEA	**Duval County**
Seminole Generating Station No. 1&2 Seminole Electric Cooperative, Inc.	**Putnam County**
TECO Big Bend No. 1,2,3 Tampa Electric Co.	**Hillsborough Co.**
TECO Big Bend No. 4 Tampa Electric Co.	**Hillsborough Co.**
TECO Polk Power Station Tampa Electric Co.	**Polk County**
Crystal River No. 1&2 Progress Energy Florida	**Citrus County**
Crystal River No. 4&5 Progress Energy Florida	**Citrus County**
McIntosh No. 3 Lakeland Electric	**Polk County**
Stanton Energy Plant No. 1&2 OUC	**Orange County**
Indiantown Cogeneration* Project Indiantown Cogen., L.P.	**Martin County**

Combustion of MSW in waste to energy facilities accounted for 14.4% of the total MSW managed in Florida in 2010 (FDEP, 2010). Table 2 lists the 13 Florida WTE facilities; currently a 3000 ton per day facility is under construction in Palm Beach County. The comingled ash stream produced from WTE facilities in Florida is primarily landfilled or used in other landfill applications such as daily cover.

Table 2. Florida Waste to Energy Facilities

Florida Waste To Energy Facilities	County
Bay County Resource Management Center	**Bay**
North Broward County Resource Recovery	**Broward**
South Broward County Resource Recovery	**Broward**
Dade County Resource Recovery	**Dade**
Hillsborough Co. SW Energy Recovery Facility	**Hillsborough**
McKay Bay Refuse to Energy Project	**Hillsborough**
Lake County Resource Recovery Facility	**Lake**
Lee Co. Solid Waste Resource Recovery	**Lee**
Southernmost Waste-To-Energy Facility	**Monroe**
North County Regional Resource Recovery	**Palm Beach County**
Pasco Co. Solid Waste Resource Recovery	**Pasco**
Pinellas Co. Resource Recovery Facility	**Pinellas**
Ridge Generating Station, LLP (Waste Wood and Tires)	**Polk**

FCR Recycling and Beneficial Use

The term *beneficial use* has been widely adopted in the solid waste management community to describe the recycling or reuse of byproducts or residues such as FCR. While the term is not specifically defined in federal solid or hazardous waste rules, examples of definitions from other states include "the use of a material as an effective substitute for a commercial product or commodity" and "the legitimate use of a solid waste in the manufacture of a product or as a product, for construction, soil amendment or other purposes, where the solid waste replaces a natural or other resource material by its utilization." While federal laws and rules do not address the general beneficial use of wastes, programs have targeted specific wastes such as biosolids (40 CFR 503). Likewise the Florida statutes do not address general beneficial use, although specific rules have been developed for certain wastes (Section 403.7047, Florida Statues). However, other states do have comprehensive beneficial use programs.

Beneficial Use of FCR

A range of different beneficial use applications for FCR have either been practiced or proposed. Types of beneficial uses range from those where the FCR is utilized directly as a replacement for a raw ingredient in an industrial manufacturing process (e.g., use in cement manufacture) to those where the FCR is used as a substitute for a soil or aggregate in construction applications (e.g., material used as structural fill or road sub-base). Table 3 lists some of the more common beneficial use practices for FCR.

Table 3. Examples of Beneficial Use Options for FCR

Possible Combustion Residual Application	**Description**
Agricultural Soil Amendment	FCR added to agricultural land to add micronutrients, adjust pH, etc. Common examples include wood ash as a liming agent and FGD material as a source for calcium and sulfur.
Structural Fill	Using FCR as a replacement for fill dirt or similar media. Applications have included fill material in mine reclamation, roadway embankment construction, building foundation, and golf course grading.
Road Base	FCR is used to provide a substitute for soil or construction stone under a paved surface such as a road or parking lot. Several countries commonly utilize WTE bottom ash as a road base material.
Concrete Admixture	FCR takes the place of construction stone or sand as aggregate in the manufacture of concrete or asphalt. Coal slag and bottom ash, as well as WTE bottom ash, have been utilized in concrete mixtures. A percentage of traditional cement is replaced with the FCR. This has been a very common use of coal fly ash.
Abrasive Blasting Media	Boiler or gasifier slags are commonly used for grit blasting operations.
Industrial Ingredient	Residual is used in the manufacture of products such as cement or gypsum drywall. In cement manufacture, sources of calcium, iron, and aluminum are needed, and FCRs can provide these. Drywall is manufactured from gypsum, and coal combustion FGD material is often directly used for this purpose.

Regulatory Beneficial Use Determinations

While the EPA does not currently have specific regulations pertaining to the beneficial use of FCR, many states have developed their own beneficial use programs or protocols (Innovative Waste Consulting Services, LLC, 2012). In most regulatory programs, some FCR beneficial use options (a specific FCR for a specific use) are provided a *standing* beneficial use determination (BUD), while other FCR beneficial uses are *conditional* and require pre-use regulatory agency review and approval (often referred to as a case-by-case or site-specific BUD). In Florida, standing beneficial uses of CCRs are specifically addressed in Section 403.7047, Florida Statutes. That law generally identifies CCR beneficial uses that are exempt from solid and hazardous waste regulation under certain conditions. Those include:

- In building products and as substitutes for raw materials, necessary ingredients, or additives in products (such as wallboard, plastics, paints, insulation, roofing shingles, etc.)
- Structural fill and aggregate placed under industrial or commercial buildings, paved roads, parking lots, and paved walkways, provided:
    - FFCPs are not placed within
        - 3 feet of groundwater
        - 15 feet of wetlands or natural water bodies
        - 100 feet of a potable well
    - FFCPs are not used in a manner that may cause a significant threat to public health or contamination in excess of department standards and criteria.
    - FDEP is notified in writing where the FFCPs have been placed and how they were used.
- Synthetic gypsum for agricultural use in accordance with Florida Department of Agriculture and Consumer Services rules;
- Other uses that meet existing statutory reuse criteria or which are approved by FDEP prior to use as having an equivalent or reduced potential for environmental impact when used in equivalent quantities compared to the substituted raw materials or products.

Tables 14 and 15 in the supplemental information section at the end of this document provide examples of standing and conditional BUDs for FCR in other states.

During the BUD process, a number of factors will typically be assessed by the regulatory agency. This assessment includes examination of i) whether the use is a legitimate beneficial use (as opposed to simply disposal) ii) the amount of material to be used and iii) the process through which the use will take place. The potential impact to human health and the environment must also be considered. For those uses where FCR or similar waste materials are placed in the environment, two primary pathways of risk are assessed: direct human exposure and leaching to groundwater (ecological risk is considered in some, but not most programs).

Assessment of direct human exposure evaluates the risk posed by direct contact with the material in question. Toxicologists and risk assessors consider the amount of waste material an individual will be exposed to, the concentration of constituents of concern (COC), the mechanism of exposure (e.g., dermal, ingestion, inhalation), and the toxicity of the COC. While site-specific risk assessments are sometimes conducted when evaluating beneficial use of a waste material, a more common approach is to compare COC concentrations (typically in units of mg/kg) to generic risk-based thresholds that represent a level deemed acceptable by the regulatory agency.

In Florida, the Soil Cleanup Target Levels (SCTLs), a risk based regulatory threshold, were developed for use in contaminated site remediation. Because Florida does not have a general beneficial use program, the SCTLs are often used as a direct human exposure criteria when proposing beneficial use to FDEP. The Florida SCTLs were derived based on the risk of carcinogenic or non-carcinogenic effect due to exposure to certain elements in two different scenarios- residential and industrial/commercial settings. The difference between the two settings is the level of exposure assumed in calculating the SCTL. The calculation of SCTLs includes exposure in children, and takes into account parameters such as a dose-response slope from toxicological studies and soil ingestion rates. In the case of carcinogens, an acceptable cancer risk of 1 in 1,000,000 is used. Table 4 displays the SCTLs for select elements; these values are referred to in comparisons throughout this document.

Table 4. Florida Risk-Based Soil Cleanup Target Levels

Element	Residential SCTL (mg/kg)	Industrial/Commercial SCTL (mg/kg)
Aluminum	80,000	n/a
Arsenic	2.1	12
Barium	120	130,000
Cadmium	82	1,700
Chromium (total)	210	470
Cobalt	1,700	42,000
Copper	150	89,000
Iron	53,000	n/a
Lead	400	1,400
Manganese	3,500	43,000
Mercury	3	17
Selenium	440	11,000
Silver	410	8,200
Vanadium	67	10,000

Given that groundwater has the potential to become contaminated from a beneficially used waste even when that waste will not come into to direct human contact, leaching to groundwater is assessed as a separate pathway. This is typically conducted by creating a “leachate” from the waste and comparing leachate concentrations (typical units of mg/L) to a risk-based threshold for water quality. In Florida, as in the case with SCTLs, the Groundwater Cleanup Target Levels (GCTLs) (developed for use in contaminated site remediation) are often used when proposing beneficial use to FDEP. A number of leaching procedures have been developed, though the most commonly employed procedure for state BUDs has been the synthetic precipitation leaching procedure (SPLP). Table 5 presents a variety of leaching procedures that are available, including a new suite of procedures, recently promulgated by the EPA, that were developed partly with the goal of aiding in beneficial use determinations.

Table 5. Leaching Tests of Potential Use for Beneficial Use Determinations

Leaching Test	Description
TCLP **EPA SW 846-1311**	"Toxicity Characteristic Leaching Procedure" Leaching test used to define a hazardous waste through comparison with the toxicity characteristic (TC) standards. Leaching solution is a function of the alkalinity of the waste and is composed of buffered or unbuffered acetic acid. Sample is added "as is" at a 20:1 Liquid to solid ratio.
SPLP **EPA SW 846-1312**	"Synthetic Precipitation Leaching Procedure" Currently used as a tool to help assess a wastes potential for beneficial use. 100 grams of "as is" sample added at a 20:1 liquid to solid ratio. Leaching solution composed of dilute nitric and sulfuric acids at a pH of 4.2.
"pH Stat" **EPA SW 846-1313**	Batch leaching test that measures pH dependent leaching over a pH range from 2-13. Uses dilute additions of acid and base to achieve desired pH at a 10:1 liquid to solid ratio.
EPA SW 846-1314	Up-flow column leaching test to demonstrate leaching as a function of liquid to solid ratio. Water is pumped through a lightly packed column of size reduced sample material. Leachate samples are collected at cumulative liquid to solid ratios over a period of two weeks.
EPA SW 846-1315	Tank leaching test measuring mass release over time. Samples are submerged in monolithic or compacted granular form and leaching solution is renewed at set intervals over a 63 day period.
EPA SW 846-1316	Batch leaching test that evaluates leaching as a function of liquid to solid ratios (.5 to 10 mL of reagent water/gram of dry sample). A constant amount of reagent water is introduced to 5 increasing sample volumes.

Much like the SCTLs, Florida developed GCTLs to define risk-based thresholds for contamination in groundwater. Since the state of Florida relies on groundwater as a significant source of drinking water, federal drinking water maximum contaminant levels have been adopted for many constituents (including As, Cd, Hg, Pb and Se). When applying this type of standard in beneficial use determinations, it is important to understand the relationship between tested leaching concentrations, the pore water concentration in a reused material, and the point at which groundwater concentrations are measured for compliance. Figure 1 illustrates possible points of compliance for beneficially used FCR. Table 6 displays the GCTLs for select elements pertinent to this document.

Table 6. Florida Groundwater Cleanup Target Levels for Selected Inorganic Constituents

Element	GCTL (mg/L)
Aluminum (Al	0.2
Arsenic (As)	0.01
Barium (Ba)	2
Cadmium (Cd)	0.005
Chromium (total)	0.1
Cobalt (Co)	140
Copper (Cu)	1
Iron (Fe)	0.3
Lead (Pb)	0.015
Manganese (Mn)	50
Mercury (Hg)	0.002
Selenium (Se)	0.05
Silver (Ag)	0.1
Vanadium (V)	49

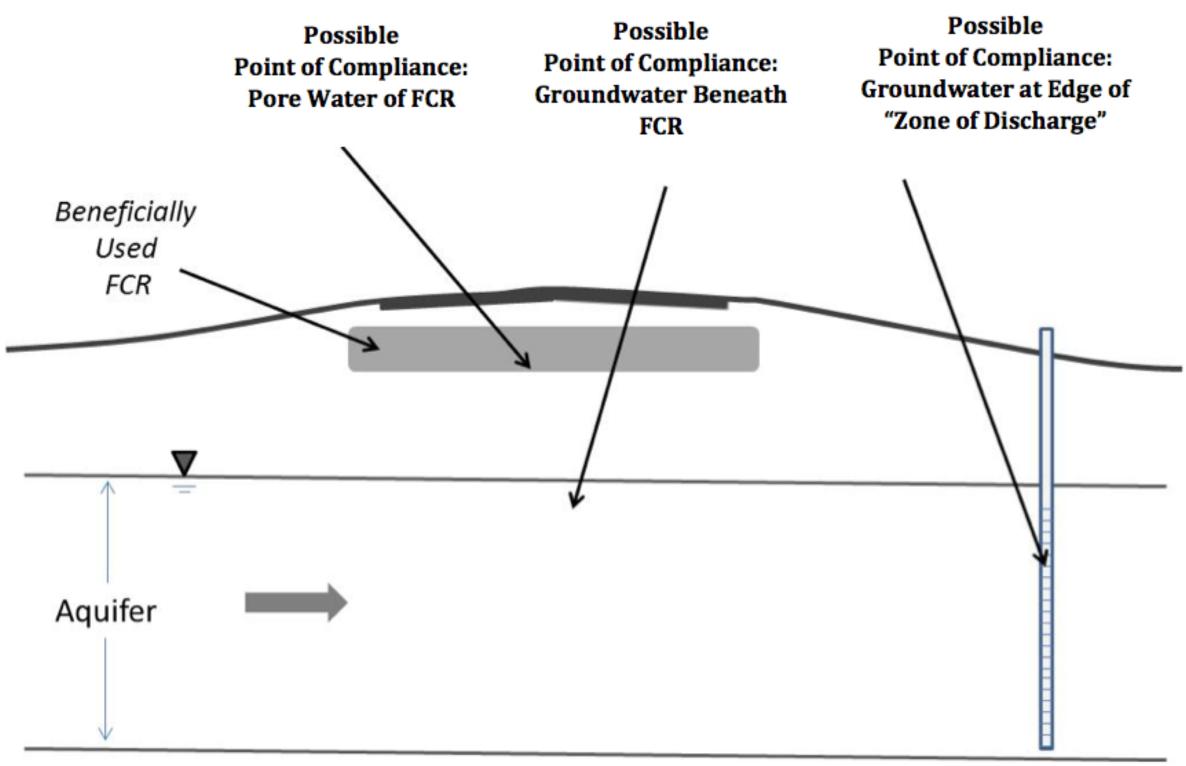

Figure 1. Illustration of Potential Locations for Point of Compliance for Leaching Assessment

Beneficial Use of Coal Combustion Residues

Utilization of coal combustion residuals (CCR) in beneficial use applications is a common practice in Florida, the United States, and throughout the world. The most prominent example of this is coal fly ash used as a substitute for Portland cement in the manufacture of concrete. Benefits of using coal fly ash as an admixture in Portland cement concrete include enhanced workability, a reduction in bleeding, and higher ultimate strength (USDOT, 2011). The use of coal fly ash for this purpose is now widely incorporated into federal and state department of transportation specifications and encouraged as part of environmentally sustainable construction practices.

Fly ash, bottom ash, and slag from coal combustion are often used as raw ingredients in the manufacture of cement (Yuno et al., 2010), serving as mineral replacement in cement kilns. These CCRs help to fulfill the role of an argillaceous ingredient, providing alumina and silica to the cement production (Bye, 1999). Additional uses of CCRs include use as soil substitutes or soil additive (Fungaro et al, 2004), manufacturing glass-ceramics (Zhang et al., 2007) and synthesis of chemical compounds (Hui and Chao, 2006; Murayama et al., 2003). As previously discussed, Section 403.7047, Florida Statutes, Laws of Florida, identifies a number of standing beneficial uses of CCRs, some of which are subject to certain prescribed conditions. Examples of CCR beneficial uses that must meet certain conditions include pavement aggregate and structural fill.

Pathways for the reuse of CCRs are typically driven by the material properties they exhibit. Table 7 in the Supporting Information section displays total concentration data, compiled by the US-EPA, for US coal fly and bottom ashes. From the perspective of direct human exposure in a reuse scenario, a comparison with Florida's SCTLs shows As and Ba could be of potential concern in coal fly and bottom ashes. Arsenic present in the coal fly ashes surveyed at an average concentration of 49.6 mg/kg, and in the coal bottom ashes at a concentration of 23.73 mg/kg, are elevated above the industrial SCTL of 12 mg/kg. In both cases (1,377 mg/kg in fly ash and 1,236 mg/kg in bottom ash), Ba is higher than the residential SCTL of 120 mg/kg.

SPLP leaching data for CCRs, compiled by the US-EPA, is presented in Table 8. Mean arsenic concentrations in the fly 0.227 mg/L and 0.037 mg/L bottom ash leachates tested are elevated above the FL-GCTLs (the Florida GCTL for As is the federal drinking water standard of 0.010 mg/L). Lead is shown to leach at nearly 5 times the GCTL of 0.015 mg/L in both ashes. Also of note are the mean leachable concentrations of Al (2.67 mg/L in fly ash and 1.43 mg/L in bottom ash); though not a hazardous constituent, and often in high concentrations in soils, Al does have a GCTL based on a secondary drinking water standard of 0.2 mg/L. It is important to note that coal ash total and leachable concentrations may vary based on a number of factors, and a range of values are presented for CCRs in Tables 7 and 8. Table 9 displays SPLP data for several CCRs generated and managed at Florida facilities. The Florida-specific CCR data are consistent with the US-EPA data in that As, Pb, and Al may leach in excess of groundwater standards or criteria.

Beneficial Use of Waste to Energy Ash

Although not currently practiced in the United States, waste to energy (WTE) ash reuse has become common in certain parts of the world due to advances in technology, understanding, and a push towards minimizing land disposal and increasing recycling. Arguably the most highly developed and effective policy on WTE ash reuse can be found in the European Union (EU). The EU Waste Incineration Directive (WID) of 2000, which was incorporated into the 2010 Directive on Industrial Emissions, contains rules for the operation of municipal solid waste incineration plants. Although not explicitly stated, the language of the directive implies WTE plants must generate bottom and fly ash as separate waste streams (European Parliament, 2010). This results in bottom ash that can be combed effectively for ferrous and non-ferrous metals and reused under EU state level policy. Germany, the Netherlands, and Denmark all exhibit well-established national and state level regulatory programs for the reuse of bottom ash; this is reflected in bottom ash reuse rates that approached 100% in the year 2008 for those nations. The vast majority of this bottom ash is used in road construction applications (CEWEP, 2010).

In Japan, roughly 79% of municipal waste is combusted with energy recovery (Japanese Ministry of Internal Affairs and Communications, 2013). Fly ash is considered a "general waste requiring special controls", and it must be treated prior to disposal by melting, solidification, chemical stabilization, or extraction of contaminants. Some have reported that melting, or vitrification of both bottom and fly ash are, or have been, commonly practiced (Sakai, 2000); however, official statistics are difficult to ascertain. The authors also indicate that the slag produced from ash melting is used in road construction applications.

Taiwan's Environmental Protection Administration (TEPA) has specific rules regarding the reuse of WTE ash, focusing primarily on bottom ash, as the majority of fly ash is washed and then land disposed. For reuse, bottom ash must undergo pretreatment in the form of size reduction followed by stabilization through chemical or thermal methods (Taiwan Environmental Protection Agency, 2011; Yang and Liao, 2012). The Taiwanese government reports that from 2003 to 2008, 1.72 million tonnes of bottom ash was reused; this equates to a rate of 53.2% (Environmental Protection Bureau, 2013).

In the US, a single commingled ash waste stream is generated by combining fly and bottom ashes in process. This is followed by ferrous and non-ferrous metal recovery, and final disposal is often in an onsite monofill. Aside from use as daily cover, reuse of this mixed ash stream is not typically practiced in the US. Several case studies and demonstration projects have been conducted. Included among these are a series of promising demonstration projects conducted at Stony Brook University in New York in the 1990's (Breslin and Roethel, 1995; Roethel and Breslin, 1995a; Roethel and Breslin, 1995b).

In the State of Florida, beneficial use of WTE ash was regulated under F.A.C, Chapter 62-702; however, this rule has recently been repealed as a result of state rule reduction initiatives. WTE ash beneficial use may be authorized under Section 403.7045(5), Florida Statutes if an applicant "demonstrates that no significant threat to public health will result and that applicable department standards and criteria will not be violated" due to said reuse. FDEP policy on beneficial use determinations is provided in a BUD guidance document (FDEP, 2001).

The state of Florida has seen several attempts at the beneficial use of WTE ash, including PERMABASE-PLUS in the early 1990's. PERMABASE-PLUS was a soil cement road base material containing up to 25% of processed combined WTE ash from a Hillsborough County WTE facility (Permabase, 1995). Another BUD attempt, in 2001, was Recyclable 100, which consisted of the construction and operation of an ash processing facility. Combined ash would have been received from the Lake County Resource Recovery Facility, undergone metals recovery, and ultimately used in the production of asphalt. FDEP determined that there was too great a concern of groundwater contamination based on the SPLP leaching of Al, Pb, chlorides, and TDS (Koogler and Associates, 2001). In 2002, the Solid Waste Authority of Palm Beach County attempted to demonstrate that combined ash produced at their WTE facility could be used as initial and intermediate landfill cover as well as fill material under landfill cells. According to external laboratory data, the total concentrations of As, Ba, Cu, Hg, Pb and the SPLP leaching concentrations of Al, Pb, TDS, and chlorides were all of concern when compared to SCTLs and GCTLs, respectively. Most notably, Pb leached at nearly 2 mg/L (GCTL = 0.015 mg/L) in the SPLP test (CDM, 2002).

Currently a research, development, and demonstration project on the beneficial use of WTE bottom ash is ongoing at the Pasco County Resource Recovery Facility. This project focuses on the use of WTE bottom ash in road construction applications, specifically use as an aggregate replacement in Portland cement concrete and hot mix asphalt and as a road base course. This project couples laboratory testing with the construction of pilot scale test strips to evaluate elemental release.

Concerns over the trace elemental content of WTE ashes are often at the forefront of beneficial use discussions. It is important to note that differences in MSW feedstock, combustion processes, APC technologies, and metals recovery systems can all influence total and leachable concentrations of elements in WTE ash a great deal. Although the data presented are used as a basis for discussion it cannot be assumed to be representative of ash generated in Florida at present. Due to in part to the fact that WTE bottom and fly ashes are combined in the United States, characterization data on the individual residuals in the United States and Florida are limited.

Table 10, in the Supporting Information section, shows WTE ash data collected from a variety of published sources. The mean total concentration of As among the fly ashes surveyed is 56 mg/kg, this is elevated in respect to the Florida residential and industrial/commercial SCTLs (2.1 and 12 mg/kg, respectively). The same can be said for Pb, with a mean value of 4,900 mg/kg it is present in concentrations above both Florida SCTLs. Cadmium and Hg are also at concentrations higher than their respective residential SCTLs. These volatile elements are enriched in fly ash due to their vaporization in the boiler and subsequent condensation in the flue gas. Table 12 presents total concentration data compiled by the International Ash Working Group (IAWG) in 1997; these data further identify constituents of potential concern with respect to WTE fly ash. Arsenic is in the range of 37-320 mg/kg, Cd 50-450 mg/kg, Hg 0.7-30 mg/kg, and Pb 5,300-26,000 mg/kg (all units in dry basis).

Total trace elemental concentrations for WTE bottom ash are shown in Table 10; As, Ba, and Pb have average concentrations of 15.8, 951, and 1,920 mg/kg, respectively. All are elevated above residential SCTLs, with As and Pb exceeding the industrial/commercial SCTLs. The IAWG data from Table 12 again shows As, Ba and Pb to be in concentration ranges exceeding Florida SCTLs.

Overall, the distribution of trace elements in the two ashes implies a higher risk of elemental release associated with fly ash. As mentioned above, a combined ash stream is generated in the US. Originally compiled by FDEP, total concentration data for Florida mixed WTE ashes are displayed in Table 11. In comparison to Florida SCTLs, As, Cd, Hg, and Pb are again constituents of concern; As and Pb exceed the industrial/commercial SCTLs while Hg exceeds the residential SCTL. These data reflect the idea that comingling fly and bottom ashes results in mixed ash that is often still enriched in certain potentially hazardous elements.

Another noteworthy aspect of the WTE ash data presented in Tables 10-12 are the elevated concentrations of major elements such as Al and Fe. Al is often present at concentrations on the order of 1-10% by mass, as shown in Table 12. This is not normally a concern when assessing direct exposure risk, but does become important when the assessing risk of groundwater contamination. Later sections will address the issue of leaching concentrations of constituents that have federal secondary drinking water standards (i.e., Al and Fe).

Several methods for improving the quality of WTE ash have been investigated and practiced. These can be generally divided into those that remove contaminants of concern from the residual and those that stabilize or immobilize the contaminants. Perhaps the most notable example of stabilization of WTE ash is the maturation, or weathering, of bottom ash that is commonly practiced in Europe. Additional removal or separation methods include water extraction, acid leaching, thermal vaporization, and electro chemical processes (Ferreira et al., 2008; Quina et al., 2008; Jiang et al., 2009; Fedje et al., 2010).

Beneficial Use of Wood Ash

As indicated in Table 2, one Florida WTE facility relies heavily on woody debris as a source of fuel. In addition, several industries combust woody materials as part of their operations, including pulp and paper mills and sugar mills. Wood ash has a history of being land applied as a soil amendment. Wood and paper mill ash is used as a liming agent to neutralize acid deposition in soils and increase pH (Muse and Mitchell, 1995; Williams et al., 1996). Previous research has shown these ashes also provide nutritional benefits to the soil (Muse and Mitchell, 1995; Krejsl and Scanlon 1996; Erich and Ohno 1992).

Ash from the combustion of waste wood, however, presents some challenges for recycling as concentrations of heavy metals may be elevated (Demeyer et. al, 2010). Trace metal chemical characterization data is provided in Table 13 of the Supporting Information. Data for the Florida co-fired wood and tire WTE facility ash as well as wood ash data from literature is listed. These data show elevated levels of As, with mean concentrations of 37.2 and 23.2 mg/kg in ashes surveyed. These both exceed the Florida industrial/commercial SCTLs.

Pathways for Moving Forward

Issues and Opportunities

Using the information gathered on FCR characterization and beneficial use, coupled with discussions and feedback from the working group, the research team formulated the following set of potential next steps. These steps are centered on observations that became evident during the process, and are grouped into two major categories: (a) programmatic actions and (b) policy development. Programmatic actions refer to those steps that could be undertaken by State government to foster additional beneficial use in Florida. Policy development refers to necessary policy decisions that would be considered critical to the implementation of targeted programmatic actions.

Programmatic Actions

Step: Establish Beneficial Use Regulatory Program

Observation. Many states have specific programs that address the beneficial use of waste materials such as FCRs. While Florida does provide statutory language on the beneficial use of CCRs, as well as guidance for the beneficial use of certain waste materials, it does not have beneficial use rules/guidance for other FCRs such as WTE ash and biomass ash.

Action: The Florida Legislature passes legislation and/or the appropriate state regulatory agency develops a regulatory program under state legislation that outlines requirements for beneficial use of waste materials either on a waste-specific basis or for beneficial use in general.

Considerations:

- Many states have formalized beneficial use programs that address the recycling and reuse of materials such as FCR. These regulatory programs often provide both standing BUDs for specific materials and reuse options, and procedures for applying for and granting case-by-case BUDs.
- In some states, regulations pertaining to FCR beneficial use are contained in waste-specific rules, not as part of a comprehensive beneficial use rule program.
- As mentioned previously, the Florida Legislature has identified by statute (403.7047, Florida Statutes) acceptable beneficial uses for CCRs with some of those uses being subject to certain conditions.
- In some states and countries, incentives are provided for the beneficial use of FCRs.
- Florida does have precedent for making beneficial use determinations, and guidance has been provided for waste materials such as recovered screened material, water treatment sludge, street sweepings, and WTE ash.
- Providing a framework that clearly outlines beneficial use by removing some of the current regulatory or statutory uncertainty associated with recycling of waste materials such as FCRs.
- Some states have general permits for reuse of waste materials, which require application for coverage under the permit, however if accepted a waste can be reused. This may be a middle ground between standing and case-by-case beneficial use determinations.

- Several states have standing BUDs that require fulfillment of certain conditions. These conditions can cover material or chemical properties, as well as environmental impact and usage requirements.
- Although implementation of standing use BUDs may encompass a large percentage of FCRs, a framework is needed for other avenues of reuse. Several states have utilized both standing and conditional beneficial use regulations.

Step: Define Allowable Standing Beneficial Uses

Observation: Several different categories of FCR have been beneficially used as a substitute for raw materials used as (i) ingredients in the manufacture of commercial products, (ii) agricultural and soil amendments, and (iii) rock and soil used for construction purposes. As part of regulatory programs governing beneficial use of waste materials, some states provide standing beneficial use determinations that allow unrestricted use of qualified FCR for specific markets.

Action: Define FCRs and associated beneficial uses that can be given standing beneficial use determination as part of legislation and/or regulatory program.

Considerations:

- Examples of common standing BUDs and the states that have enacted them are provided in Table 14 of the Supporting Information section.
- As mentioned previously, the Florida Legislature has identified by statute certain acceptable standing beneficial uses for CCRs.
- Some states provide standing BUDs as part of a beneficial use rule; others allow use through waste-specific rules or exemption from the definition of solid waste such as Texas and New Mexico.

Policy Development

Step: Determine Policy for Institutional Control

Observation: The concentrations of some constituents of concern in FCRs are likely to exceed some regulatory thresholds using standard assessment procedures. Through engineering controls, the risks posed by the constituents have the potential to be reduced. The possibility exists, however, that at some time in the future these materials will be removed from their original beneficial application and placed in an environment where these engineering controls are not in place.

Action: Develop policy on necessary level of institutional control required for beneficial use of waste materials in Florida.

Considerations

- Historical data on FCR's suggest that several chemicals often exceed direct exposure regulatory thresholds (e.g., SCTLs) and groundwater thresholds (e.g., comparing leach test results to GCTLs). Examples illustrated in this white paper include arsenic and aluminum.
- Engineering controls for direct exposure include placement under buildings, roads, and clean soil, or placement in areas where limited contact will occur. Encapsulated uses such as an aggregate in concrete are typically considered not to present a direct exposure risk.
- Examples of institutional control include placing deed restrictions or otherwise permanently noting property records. These requirements often are not feasible for beneficial use where the materials are used in many places or sold as a consumer product.
- Beneficial use projects done in conjunction with governmental agencies (e.g WTE or coal bottom ash used as road base) may provide easier application of institutional control.
- Some states have utilized exemptions from solid wastes as an avenue for recycling, however this could limit institutional control. Reused secondary materials, which have exited the realm of solid waste, effectively become part of the natural environment.
- Under 403.7047, Florida Statutes, CCRs used in specific scenarios are exempt from regulation as a solid waste and therefore not subject to institutional control practices.

Step: Identify Constituents of Concern and Establish Risk Thresholds

Observation: Regulatory programs for beneficial use require comparison of measured results for a suite of constituents to risk-based regulatory thresholds.

Action: Identify all current and potential uses of FCR materials and determine the appropriate suite of constituents that should be assessed for potential risk. Set the appropriate risk threshold for comparison purposes.

Considerations:

- Florida currently maintains a set of risk-based concentrations that can be used in the process of assessing direct exposure risk (residential and commercial/industrial SCTL) and groundwater contamination risk (GCTL) in the context of contaminated site cleanup. This list is extensive.
- These risk-based concentrations have been used as a tool to assess a waste's potential impact to human health and the environment in a beneficial use application; however, they were not developed as criteria for beneficial use. Consideration should be given to whether risk based thresholds for reuse may differ.
- In the case of carcinogens, the Florida SCTLs and GCTLs are based on a cancer risk level of 1 in 1,000,000.
- Some state beneficial use programs utilize a 1 in 1,000,000 cancer risk and others use alternative cancer risk levels.
- In the development of risk thresholds associated with the EPA biosolids rules (40 CFR 503), criteria for carcinogens were based on a 1 in 100,000 cancer risk.
- Anticipated exposure for beneficial use applications could differ from those criteria used in current risk based thresholds.

- Under 403.7047, Florida Statutes, CCRs used in specific scenarios are exempt from regulation as a solid waste.
- Some constituents in the Florida GCTLs are derived from secondary drinking water standards. These concentrations are not based on human health impact. The concentration of aluminum in FCR leaching tests, for example, often exceeds the current GCTL.

Step: Establish Policy for Background Materials

Observation: For some beneficial use applications, some COCs may also be elevated in raw materials and background soil concentrations.

Action: Establish a protocol for comparing the concentration (total and leachable) of constituents of concern to those materials they are replacing in a product or to background soil concentrations.

Considerations:

- Construction materials and soil often contain concentrations of elements such as manganese, iron and aluminum above Florida SCTLs.
- When the EPA was developing rules for land application of cement kiln dust (CKD), a regulatory threshold for arsenic was set at a higher level than warranted by risk thresholds. EPA set the limit at the high end of what was encountered in raw lime, the material being replaced by the CKD.
- In FDEP's guidance document for beneficial use of street sweepings, SPLP values for natural soils were used to justify allowance of greater leaching concentrations of iron and aluminum (natural soil constituents).
- This comparative analysis is specifically authorized for CCRs in Section 403.7047(1)(a) 5., Florida Statutes.

Step: Establish Policy for Diffuse Application

Observation: For some unencapsulated beneficial use applications, waste materials are mixed in with existing soil and thus potential pollutant concentrations are diluted.

Action: Establish a policy for consideration of diffuse applications.

Considerations:

- Many states set loading rate limits (i.e., kg of Fe per acre per year).
- The EPA 503 biosolids rules set loading rate limits.

Step: Establish Procedures for Predicting Groundwater Impact

Observation: The leaching concentrations of some constituents of concern in FCRs are likely to exceed regulatory thresholds using standard assessment procedures. Because of processes such as dilution and natural attenuation, along with engineering controls, the concentrations of constituents that occur in the environment should be less than those predicted through standard leaching assessments. New leaching tools and fate and transport modeling allow a better prediction of actual risk.

Action: As part of a statewide beneficial use rule or as part of material-specific rules or policies, the following need to be defined: (a) the point of compliance in the groundwater where risk thresholds should be met, and (b) accepted procedures for use of alternative leach procedures and risk assessment tools for demonstrating acceptable beneficial use.

Considerations:

- Historic data suggest that leaching test results for several constituents in FCRs often exceed groundwater thresholds (e.g., GCTLs). If this comparison is used as the sole basis for decision-making, leaching results will likely impede beneficial use.
- Alternative leaching tests now exist that allow leaching concentrations to be assessed over a wider range of leaching conditions (pH and liquid to solid ratio) and physical conditions (compacted media, monolith). The appropriateness of these alternative test methods to predict real world environmental conditions are currently being widely evaluated; further research in this area could help to answer some of these questions.
- Fate and transport models allow examination of dilution, attenuation, leaching risk and contaminant mobility.
- Policy and guidance regarding the appropriate selection of leaching tests and their application to the beneficial use determination process is lacking.
- Field demonstrations of beneficial use where upfront detailed laboratory characterization of the material (e.g., leaching tests) are compared to performance results from actual field application are lacking.

Step: Where Appropriate Establish Point of Compliance for Groundwater Assessment

Observation: Assessment of the risk posed to groundwater from beneficial use depends on defining a point where compliance must be reached. This is not well defined.

Action: Define the point of compliance in the groundwater where risk thresholds should be met when conducing a beneficial use assessment.

Considerations:

- The Florida statutes define a zone of discharge as a volume underlying or surrounding the site and extending to the base of a specifically designated aquifer or aquifers, within which an opportunity for the treatment, mixture, attenuation or dispersion of wastes in receiving ground water is afforded. These are often applied to landfills or other permitted facilities.
- Leaching tests generally reflect pore water concentrations within a reused material. However, attenuation within the vadose zone and dilution within surficial groundwater result in lower than pore water concentrations at points of compliance.
- Internationally, countries such as the Netherlands have instituted groundwater monitoring, for certain beneficial use applications where appropriate.

- Such an assessment would not apply to specified CCR beneficial uses in Section 403.7047, Florida Statutes (e.g., pavement aggregate and structural fill), where identified conditions are being met.
- The applicability of this assessment to “standing” and “conditional” beneficial uses of FCR and uses in cases where a specific FCR and corresponding use conditions are already established by another regulatory agency (e.g., U.S. Department of Agriculture, Florida Department of Agriculture and Consumer Services) would need to be defined.

Supporting Information

Tabulated Data on Coal Combustion Residue Chemical Quality

Table 7. Coal Ash Concentrations (Total) Reported in EPA's Coal Combustion Residuals Constituent Database

Trace Element	Coal Fly Ash Total Concentration (mg/kg)	Coal Bottom Ash Total Concentration (mg/kg)
	Min-Max (Average)	
As	0.0289-773 (49.6)	0.04-206 (23.7)
Al	20-280,000 (87,540)	9-231,000 (87,000)
Ba	0.05-7,140 (1,370)	0.025-5550 (1,230)
Cd	0.000165-30 (2.00)	0.0002-14 (1.38)
Cr	0.051-534 (58.8)	0.015-382 (32.8)
Cu	0.058-2,400 (83.3)	0.25-6,130 (57.4)
Fe	0.013-153,000 (22.2)	6.2-875,000 (28,300)
Pb	0.013-1,453 (62.5)	0.0087-762 (20.4)
Hg	0.00005-384 (1.96)	0.00005-208 (1.42)
Se	0.00005-166 (8.87)	0.0002-52 (2.64)
Ag	0.00005-38.5 (1.98)	0.005-338 (8.73)
Zn	0.034-33,000 (352)	0.5-600 (49.4)

Sources Bottom Ash: EPRI, 1983; EPRI, 1995; US-EPA, 1999; PPL Generation, 2001; IDNR, 1999; Dairyland Power Cooperative. 1991; Hower et al., 1993; Kin et al., 2001; PADEP, 1999a; PADEP, 1999b; Loop, 2000; Hower, 2001.
Fly Ash: EPRI, 1995; EPRI, 2001; Butler, 1995; IDNR, 1999; PPL Generation, 2001; Dairyland Power Cooperative, 1991; Kim et al., 2001.

Table 8. Coal Ash Concentrations (SPLP Leachable) Reported in EPA's Coal Combustion Residuals Constituent Database

Trace Element	Coal Fly Ash Leachable Concentration SPLP (µg/L)	Coal Bottom Ash Leachable Concentration SPLP (µg/L)
	Min-Max (Average)	
As	1-4,060 (227)	0.5-625 (37)
Al	20-16,800 (2670)	20-4,620 (1430)
Ba	22-690 (169)	15-314 (97)
Cd	0.5-25 (9.6)	0.5-50 (12)
Cr	5-320 (86)	2.5-125 (28)
Cu	2.5-348 (27)	2.5-100 (15)
Fe	0.25-850 (62)	2.5-600 (144)
Pb	1-375 (78)	1-500 (72)
Hg	0.1-250 (7.5)	0.1-250 (10)
Se	1-500 (115)	0.5-500 (29)
Ag	1.5-25 (8.1)	2.5-25 (9.5)
Zn	2.5-437 (47.5)	2.5-125 (21)

Sources: Loop,2000; PADEP, 1999a; PADEP 1999b; PPL Generation 2001; Reliant Energy, 2001; Longley, 1997

Table 9. Mean Coal Ash and Slag SPLP Concentrations from Preliminary FDEP Assessment

	TECO Big Bend Fly Ash Pond SPLP Ave. (mg/L)	TECO Big Bend Fly Ash Silos SPLP Ave. (mg/L)	JEA St. Johns River Pwr. Park Fly Ash SPLP Ave. (mg/L)	Gulf Power Smith Co-managed Ash Data SPLP Ave. (mg/L)	TECO Big Bend Bottom Ash Pond SPLP Ave. (mg/L)	TECO Big Bend Slag Sluice Pond SPLP Ave. (mg/L)	TECO Polk Power Slag SPLP Ave. (mg/L)
Al	1.8	4.35	NR	2.89	<0.2	<0.2	0.1
Sb	0.009	0.012	NR	NR	<0.006	<0.005	0.003
As	0.012	0.041	0.098	0.238	0.011	<0.01	0.005
Ba	<0.2	0.39	0.077	0.173	<0.2	0.271	0.14
Cd	<.005	<.005	NR	NR	<0.005	<0.005	0.003
Cr	<0.02	0.1005	<0.01	0.0118	<0.02	<0.02	0.01
Co	NR	NR	NR	NR	NR	NR	0.042
Cu	NR	<0.05	NR	NR	<0.2	<0.05	0.025
Fe	NR	<0.05	NR	NR	<0..05	<0.05	0.025
Pb	0.455	<0.015	<0.005	NR	<0.015	<0.015	0.008
Mn	0.126	<0.01	NR	NR	<0.01	0.041	0.109
Hg	<0.0005	<0.0005	NR	NR	<0.0002	<0.0005	0.0001
Se	0.018	0.077	0.052	NR	<0.01	<0.01	0.005
Ag	0.012	<0.02	<0.02	NR	<0.1	<0.02	0.01
Na	8.5	31.25	NR	36.3	13	5.96	7.66
V	0.063	0.7	NR	NR	0.02	0.01	0.01
Zn	0.24	0.103	NR	0.017	<0.1	0.412	0.412

Tabulated Data on WTE Ash Chemical Quality

Table 10. Range of Total Concentrations of Selected Elements in WTE Fly, Bottom and Mixed Ash

Element	Fly Ash Total Concentration (mg/kg)	Bottom Ash Total Concentration (mg/kg)	Mixed Ash Total Concentration (mg/kg)
	Min-Max (Average)		
As	4-307 (56)	2.2-39.79 (15.8)	2.9-92.58 (25)
Ba	NR	835-1,126 (951)	48-1,000 (420)
Cd	20-475 (200)	1.0-48.87 (13.6)	3.93-152 (37.9)
Cr	48-2,026 (207)	24-1,564 (337)	12-665 (77)
Cu	230-3513 (1,030)	500-10700 (3,400)	193-11347 (1,790)
Hg	0.94-35 (11.28)	0.004-2.6 (0.44)	0.1-25.1 (5)
Mn	100-1410 (760)	280-1520 (828)	110-3130 (675)
Pb	340-14400 (4,900)	647-3930 (1,920)	259-13200 (2,100)
Se	2-15.6 (7)	NR	All values were reported below detection limits
Zn	1400-49100 (16,000)	600-12400 (3,700)	545-15800 (43,600)

Values reported BDL were averaged using ½ the detection limit

Sources Fly Ash: Zheng et al, 2011; Mangialardi, 2003; Shi and Kan, 2009; Shim et al., 2005; Gao et al., 2008; US-EPA, 1987

Bottom Ash: Li et al., 2004; Banks et al., 2003; Forteza et al., 2004; Chang and Wey, 2006; US-EPA 1987

Mixed Ash: US-EPA, 1987; US-EPA, 1990

Table 11. WTE Ash Total Concentration Data from FDEP Data Base (2006-2010)

Element	Total Concentration Min-Max (Mean)
Sb	0.002-1,730 (175)
As	0.8-336 (37.4)
Be	0.001-39.8 (.738)
Cd	0.194-216 (54.6)
Cr	11.8-962 (67.7)
Cu	118-180,000 (3,630)
Pb	40-24,100 (1,570)
Hg	0.02-30.85 (2.67)
Ni	5.66-1,400 (91)
Se	0.003-46.8 (2.23)
Ag	0.05-189 (12.0)
Tl	0.002-30.9 (1.57)
Zn	0.091-84,000 (5,300)

Table 12. WTE Ash Characterization Data from International Ash Working Group (1997)

	Bottom Ash* (mg/kg)	Fly Ash (mg/kg)	Dry/Semi-Dry APC System Residues (mg/kg)	Wet APC System Residue w/o Fly Ash (mg/kg)
	Min-Max (Average)			
Ag	0.29–37	2.3–100	0.9–60	–
Al	22,000–73,000	49,000–90,000	12,000–83,000	21,000–39,000
As	0.12–189	37–320	18–530	41–210
B	38–510	–	–	–
Ba	400–3,000	330–3,100	51–14,000	55–1,600
Be	–	–	0.5–0.5	–
C	10,000–60,000	–	–	–
Ca	37,000–123,000	74,000–130,000	110,000–350,000	87,000–200,000
Cd	0.3–71	50–450	140–300	150–1,400
Cl	800–4,130	29,000–210,000	62,000–380,000	17,000–51,000
Co	6–350	13–87	4–300	0.5–20
Cr	23–3,170	140–1,100	73–570	80–560
Cu	190–8,240	600–3,200	16–1,700	440–2,400
Fe	4,120–15,000	12,000–44,000	2,600–71,000	20,000–97,000
Hg	0.02–7.8	0.7–30	0.1–51	2.2–2,300
K	750–16,000	22,000–62,000	5,900–40,000	810–8,600
Mg	400–26,000	11,000–19,000	5,100–14,000	19,000–170,000
Mn	83–2,400	900–1,900	200–900	5,000–12,000
Mo	2.5–280	15–150	9.3–29	1.8–44
N	110–900	–	–	1,600
Na	2,870–4,200	15,000–57,000	7,600–29,000	720–3,400
Ni	7–4,280	60–260	19–710	20–310
O	400,000–500,000	–	–	–
P	1,400–6,400	4,800–9,600	1,700–4,600	–
Pb	98–13,700	5,300–26,000	2,500–10,000	3,300–22,000
S	1,000–5,000	11,000–45,000	1,400–25,000	2,700–6,000
Sb	10–432	260–1,100	300–1,100	80–200
Se	0.05–10	0.4–31	0.7–29	–
Si	91,000–308,000	95,000–210,000	36,000–120,000	78,000
Sn	2–380	550–2,200	620–1,400	340–450
Sr	85–1,000	40–640	400–500	5–300
Ti	2,600–9,500	6,800–14,000	700–5,700	1,400–4,300
V	20–120	29–150	8–62	25–86
Zn	610–7,800	9,000–70,000	7,000–20,000	8,100–53,000

Tabulated Data on Woody Biomass Ash Chemical Quality

Table 13. Range of Total Element Concentrations in Wood Ash

Element	Florida Wood and Tire Ash Total Concentration Mean (mg/kg)	Historical Wood Ash Data Total Concentration Min-Max (Mean)
Al	3,940	NR
As	37.2	3- 63.6 (23.2)
Ba	39.3	NR
Ca	223,000	NR
Cd	2.71	0.2-20.8 (5.2)
Co	129	0.5-20 (8.7)
Cr	46.3	3.4-130 (39.0)
Cu	162	3.4-210 (75)
Fe	34,700	NR
K	6,670	NR
Mg	5,420	NR
Mn	307	30-9130 (4,370)
Na	1,800	
Ni	16.7	6.5-97.3 (25.6)
Pb	63.1	22.7-220 (65.6)
V	5.49	NR
Zn	18,200	63-2,200 (443)

Sources: Campbell, 1990; Naylor and Schmidt, 1983; Naylor and Schmidt, 1986; Pepin and Coleman, 1984; Greene, 1988; Etiegni et al., 1991; Lerner and Utzinger, 1986; Sell et al., 1990; Steponkus, 1992; Schulz, 1992; Ginn, 1984; Diebel et al. 1992; Muse, 1993; Maltby, 1989; Tolaymat et al., 2008

Graphical Data on Coal Combustion Residual Chemical Quality

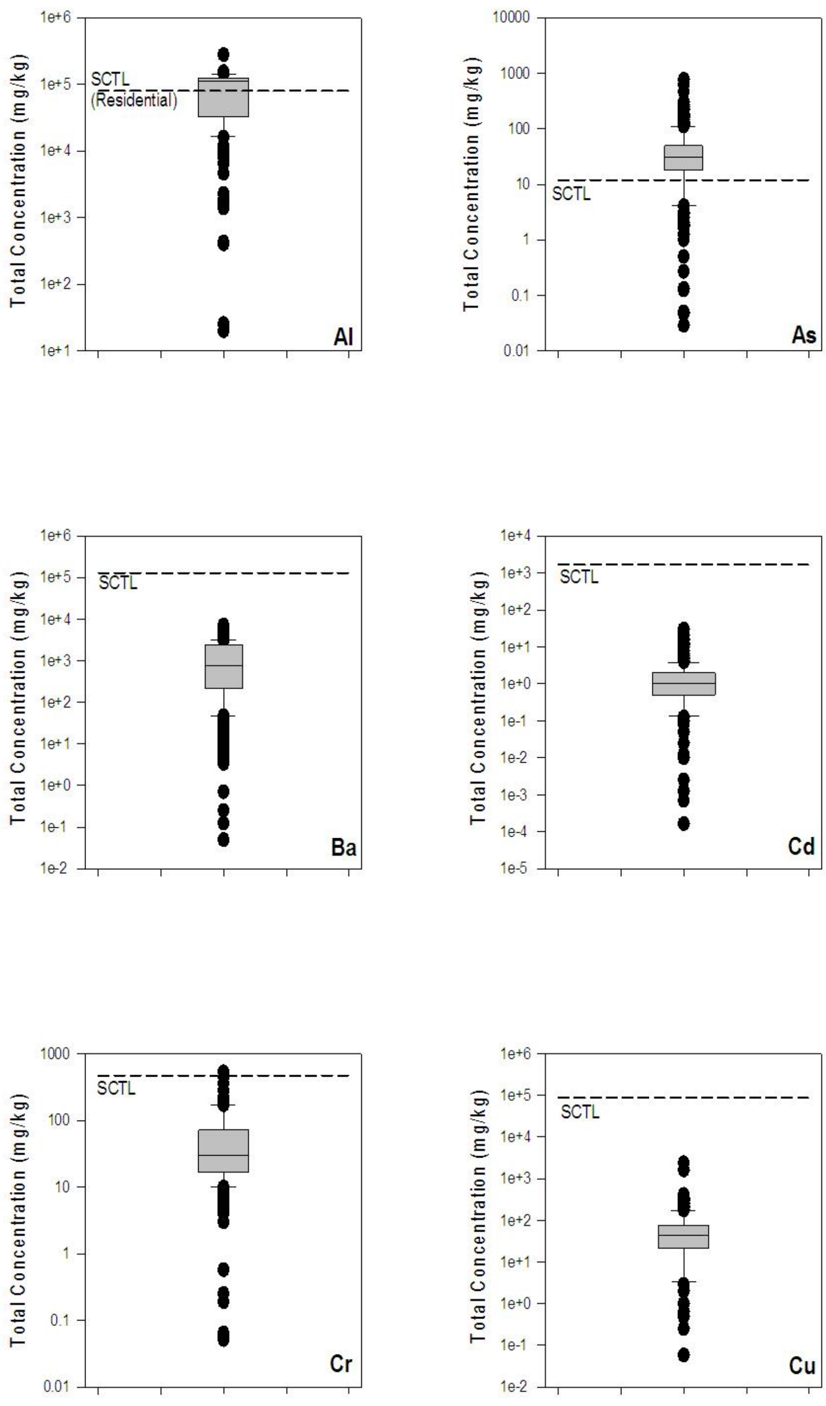

Figure 2. Range of Total Concentrations for Selected Elements in Coal Fly Ash

Florida SCTLs are Included for Reference and are Commercial/Industrial SCTL's unless specified

(Data from EPA Database)

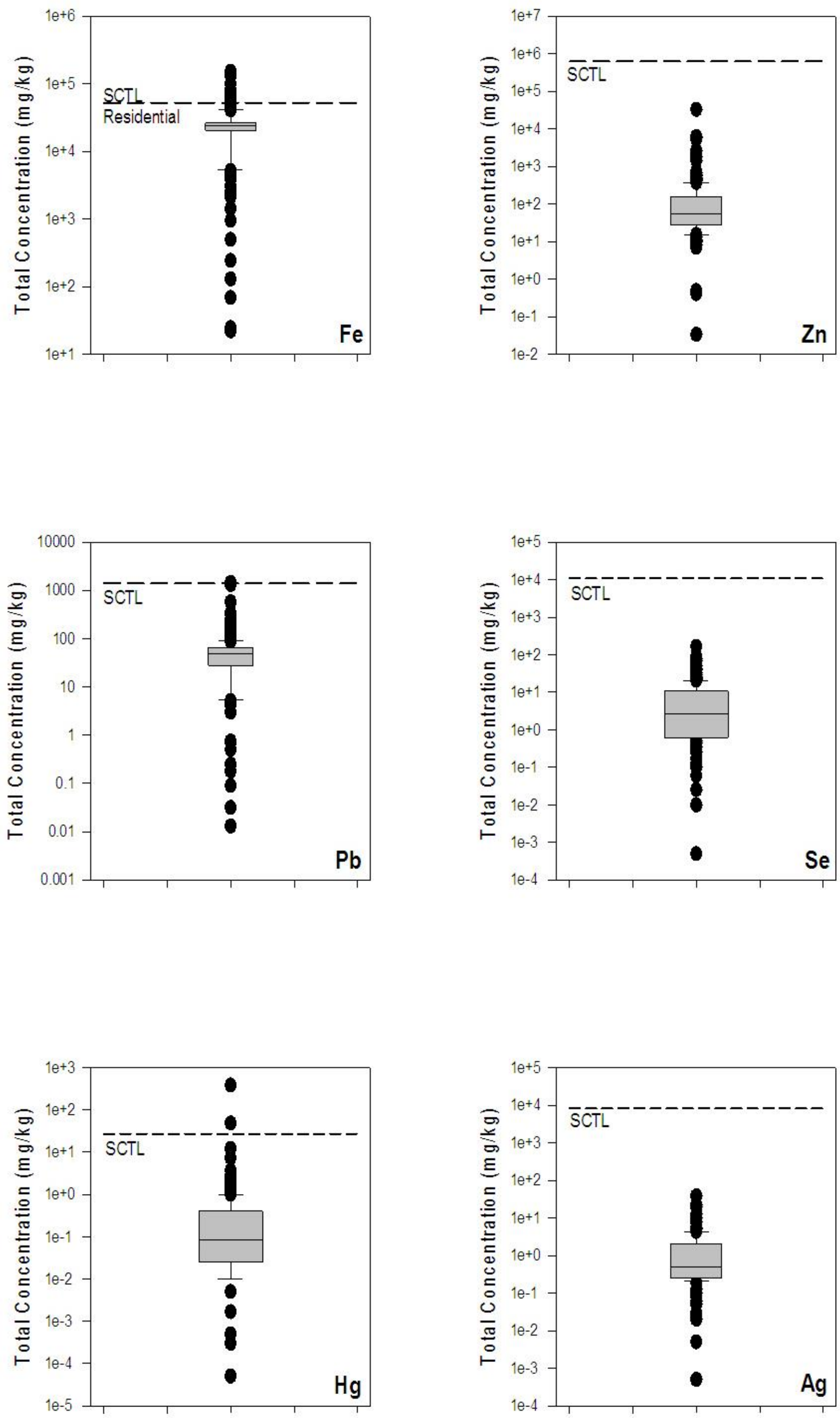

Figure 3. Range of Total Concentrations for Selected Elements in Coal Fly Ash

Florida SCTLs are Included for Reference and are Commercial/Industrial SCTL's unless specified

(Data from EPA Database)

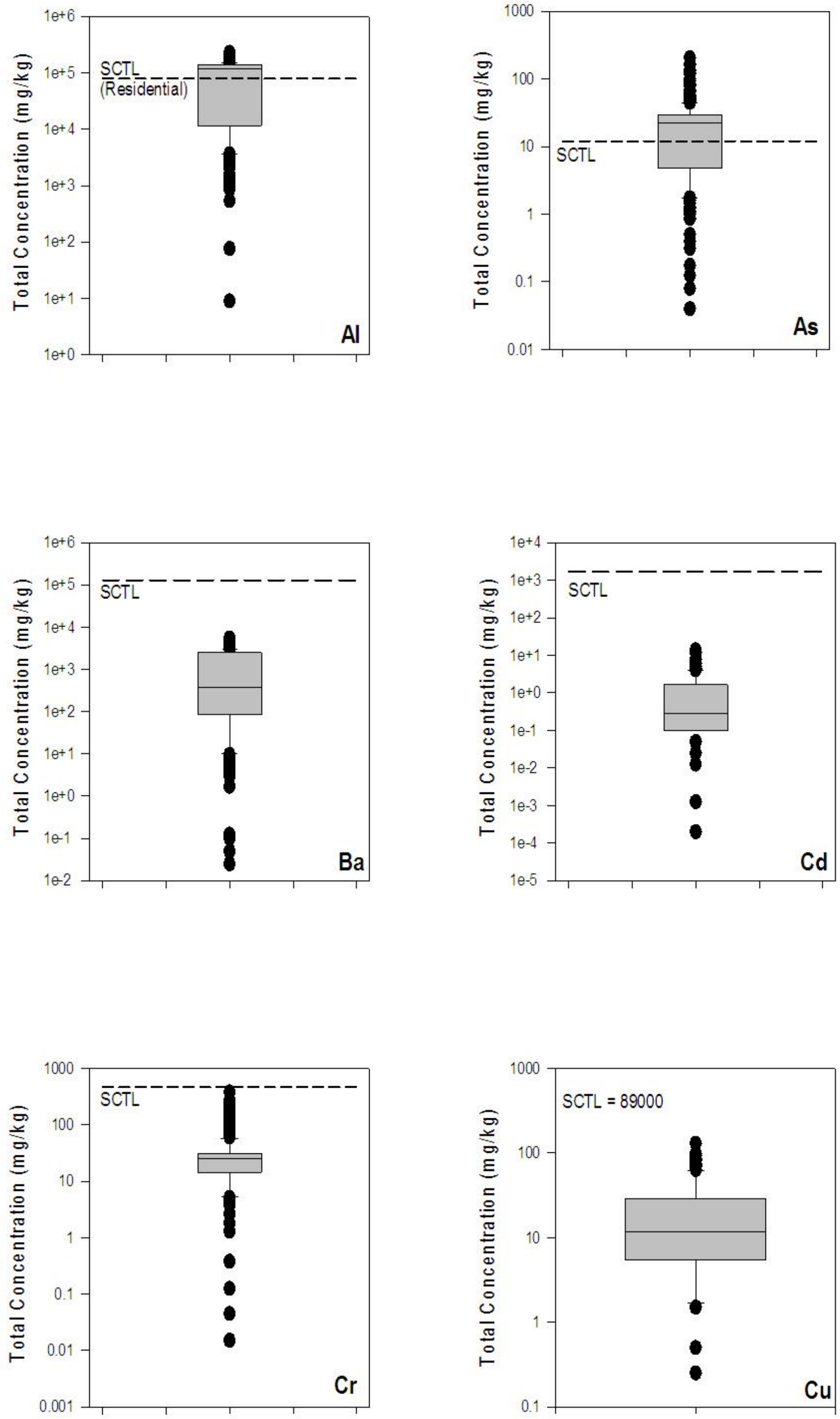

Figure 4. Range of Total Concentrations for Selected Elements in Coal Bottom Ash

Florida SCTLs are Included for Reference and are Commercial/Industrial SCTL's unless specified

(Data from EPA Database)

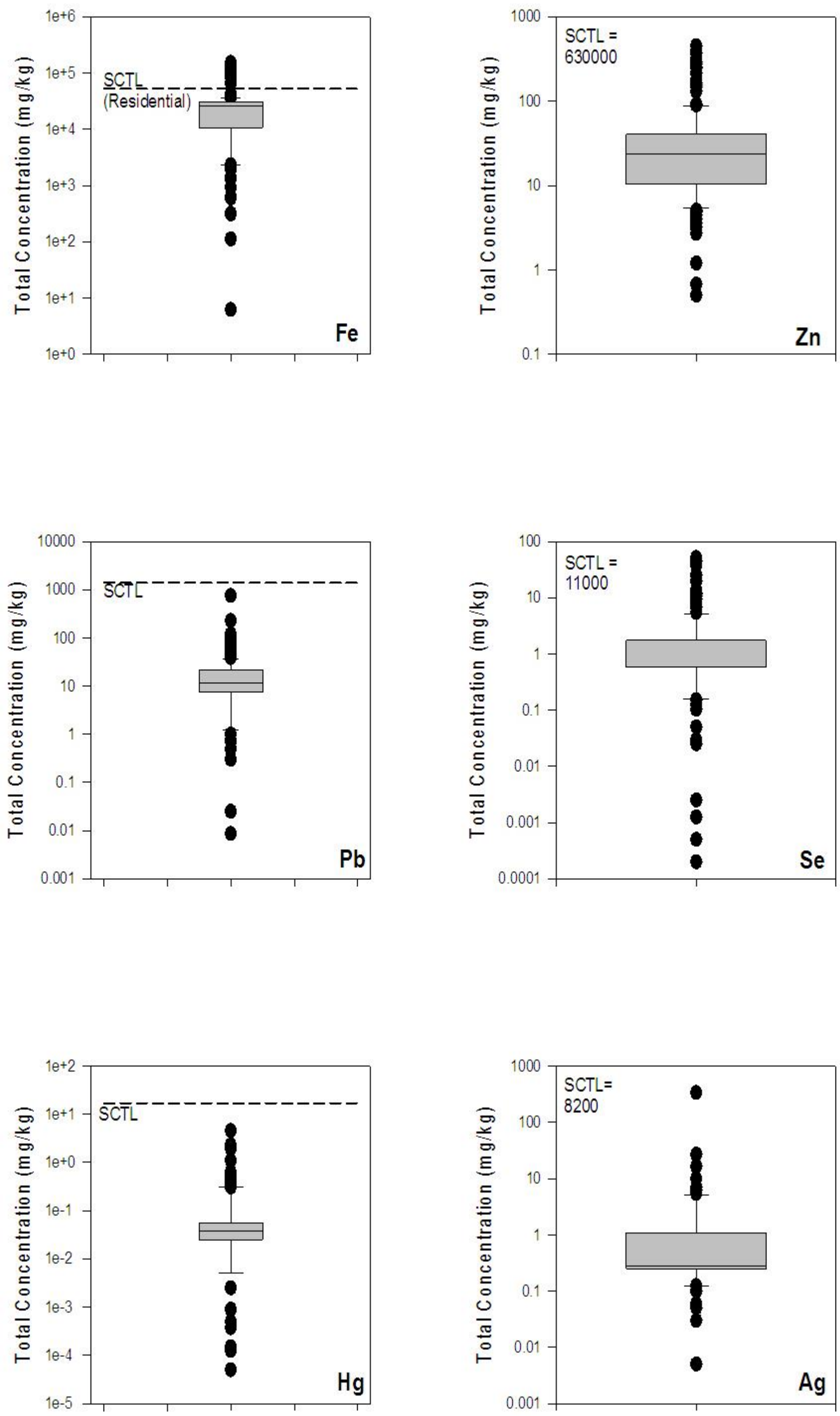

Figure 5. Range of Total Concentrations for Selected Elements in Coal Bottom Ash

Florida SCTLs are Included for Reference and are Commercial/Industrial SCTL's unless specified

(Data from EPA Database)

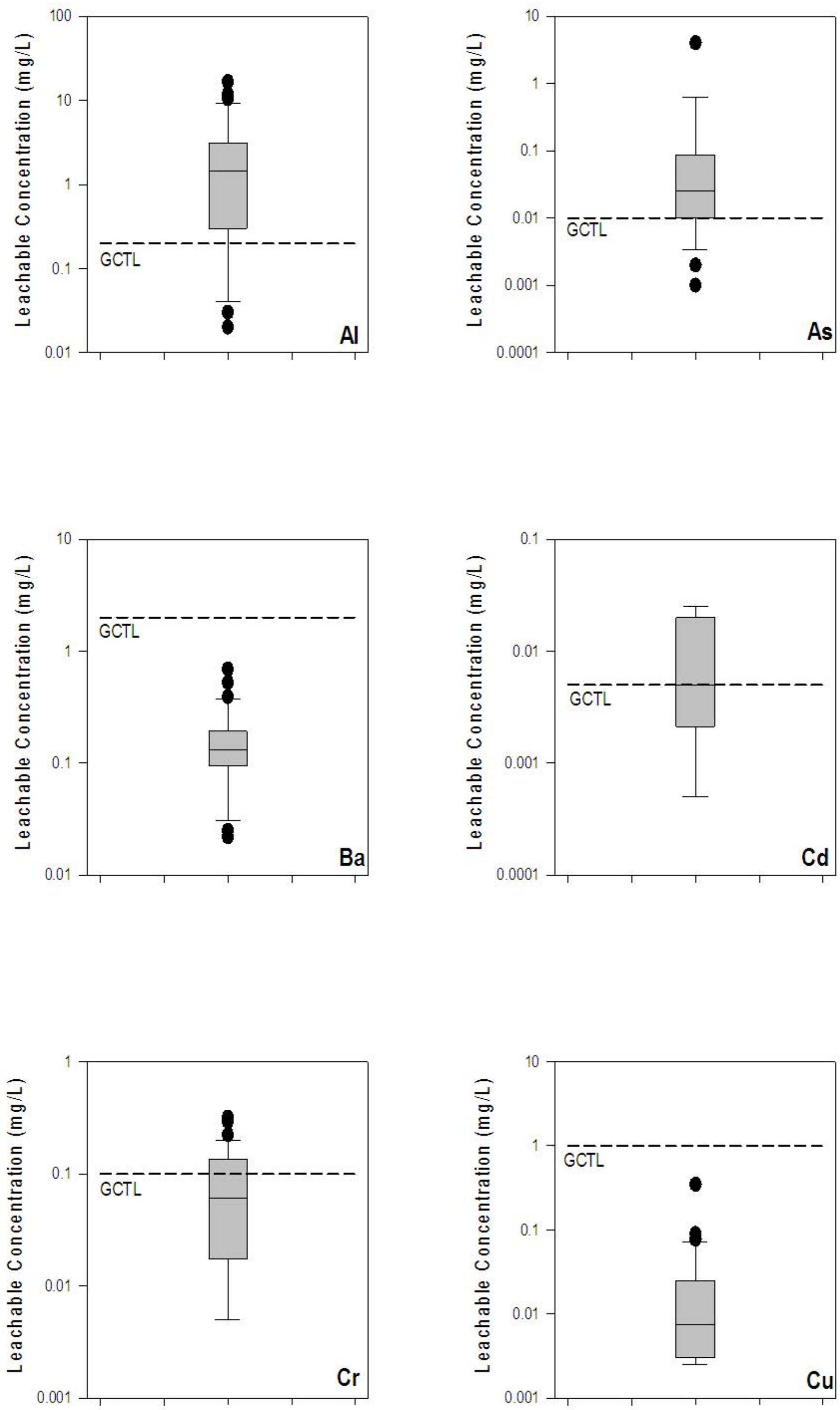

Figure 6. Range of SPLP Leachable Concentrations for Selected Elements in Coal Fly Ash

Florida GCTLs Included for Reference

(Data from EPA Database)

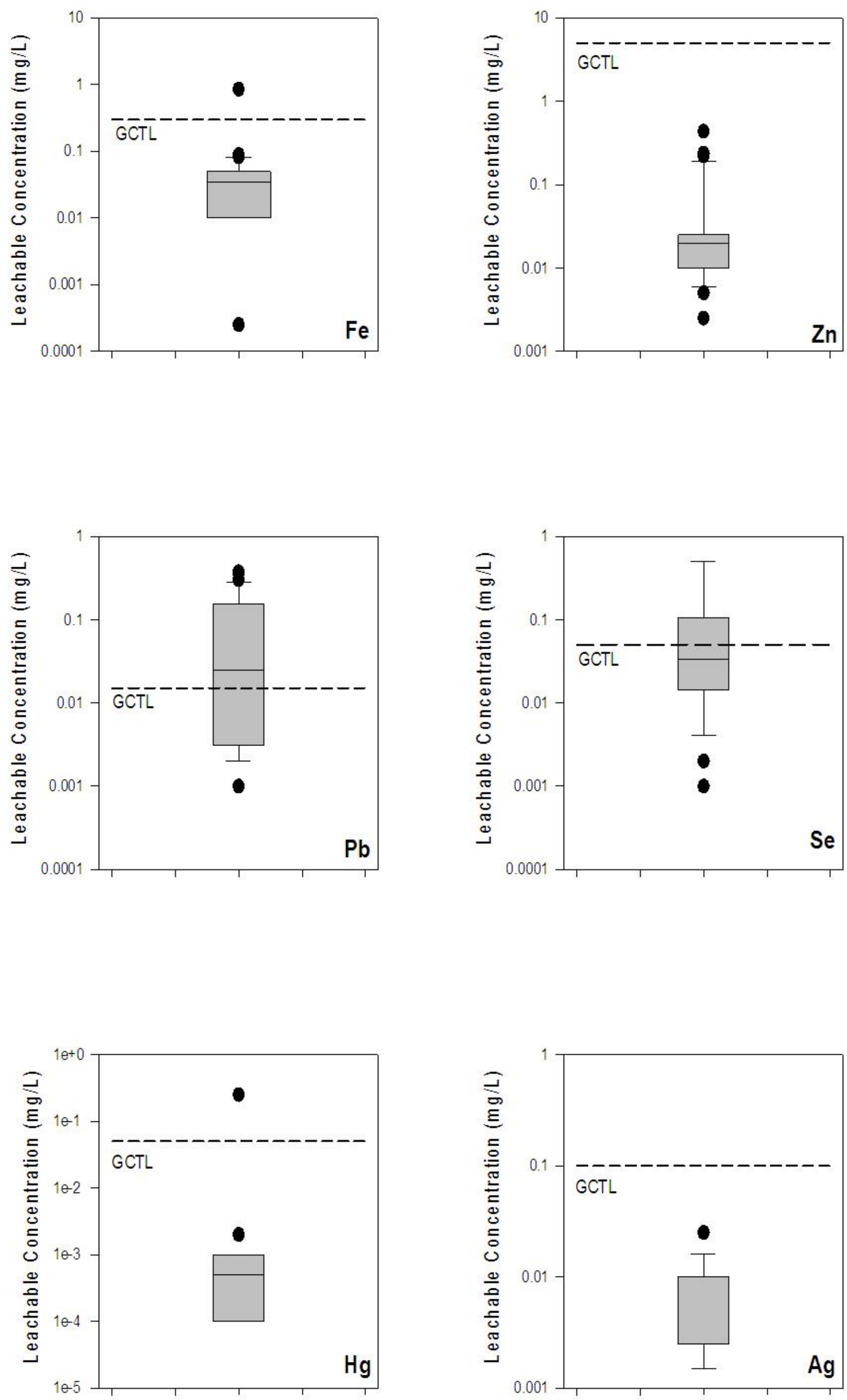

Figure 7. Range of SPLP Leachable Concentrations for Selected Elements in Coal Fly Ash
Florida GCTLs Included for Reference
(Data from EPA Database)

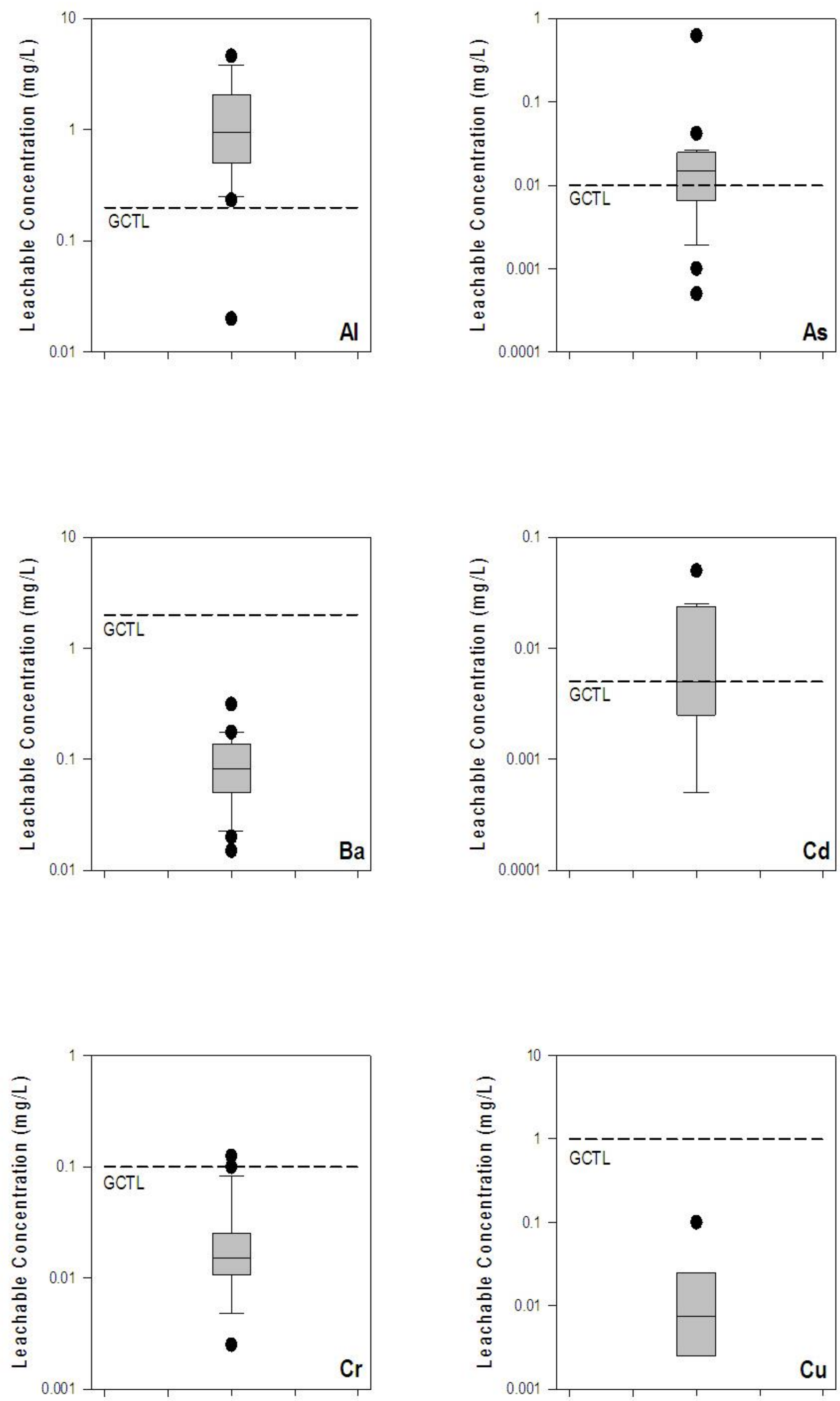

Figure 8. Range of SPLP Leachable Concentrations for Selected Elements in Coal Bottom Ash

Florida GCTLs Included for Reference

(Data from EPA Database)

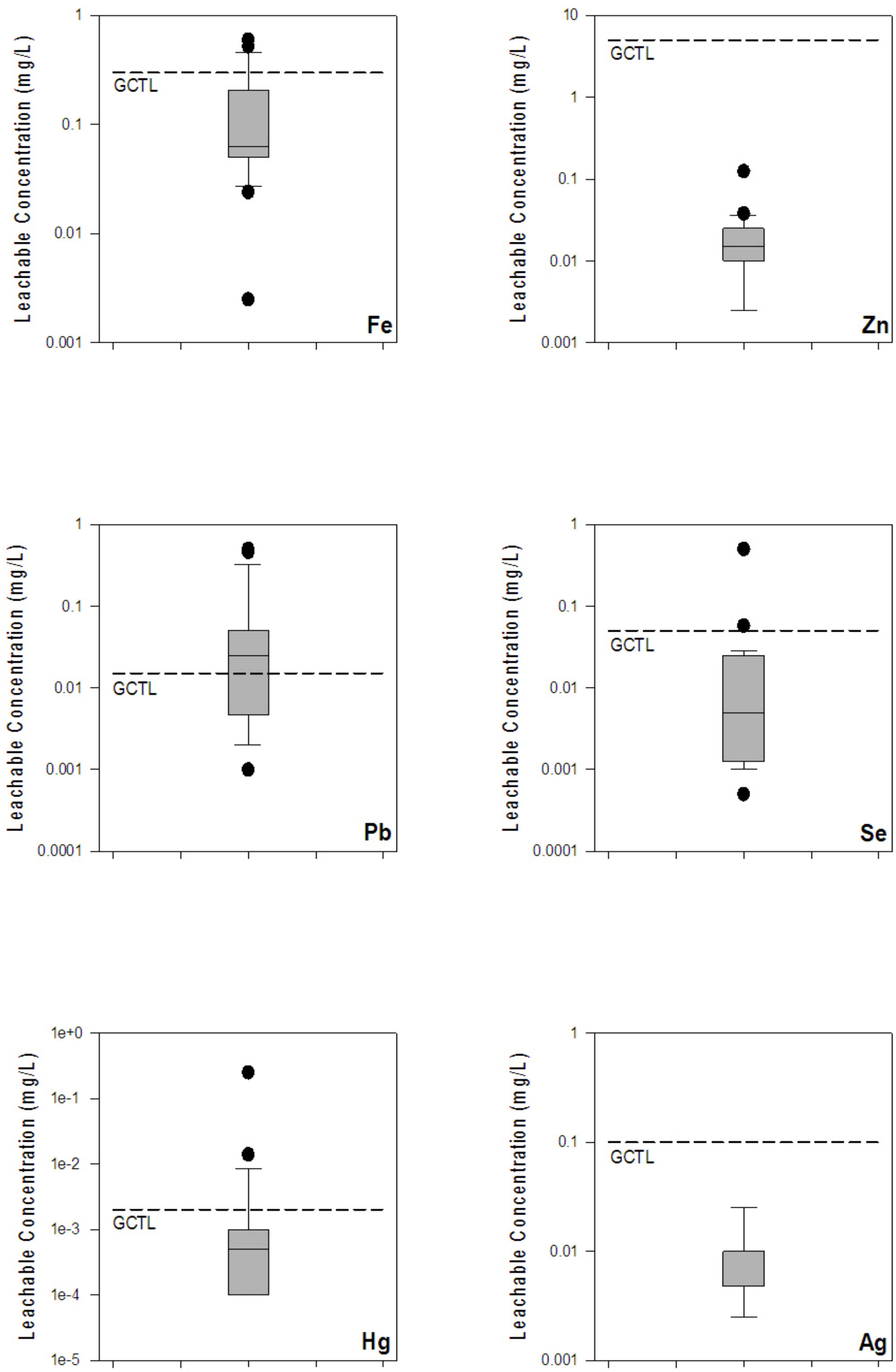

Figure 9. Range of SPLP Leachable Concentrations for Selected Elements in Coal Bottom Ash
Florida GCTLs Included for Reference
(Data from EPA Database)

Graphical Data on WTE Ash Chemical Quality

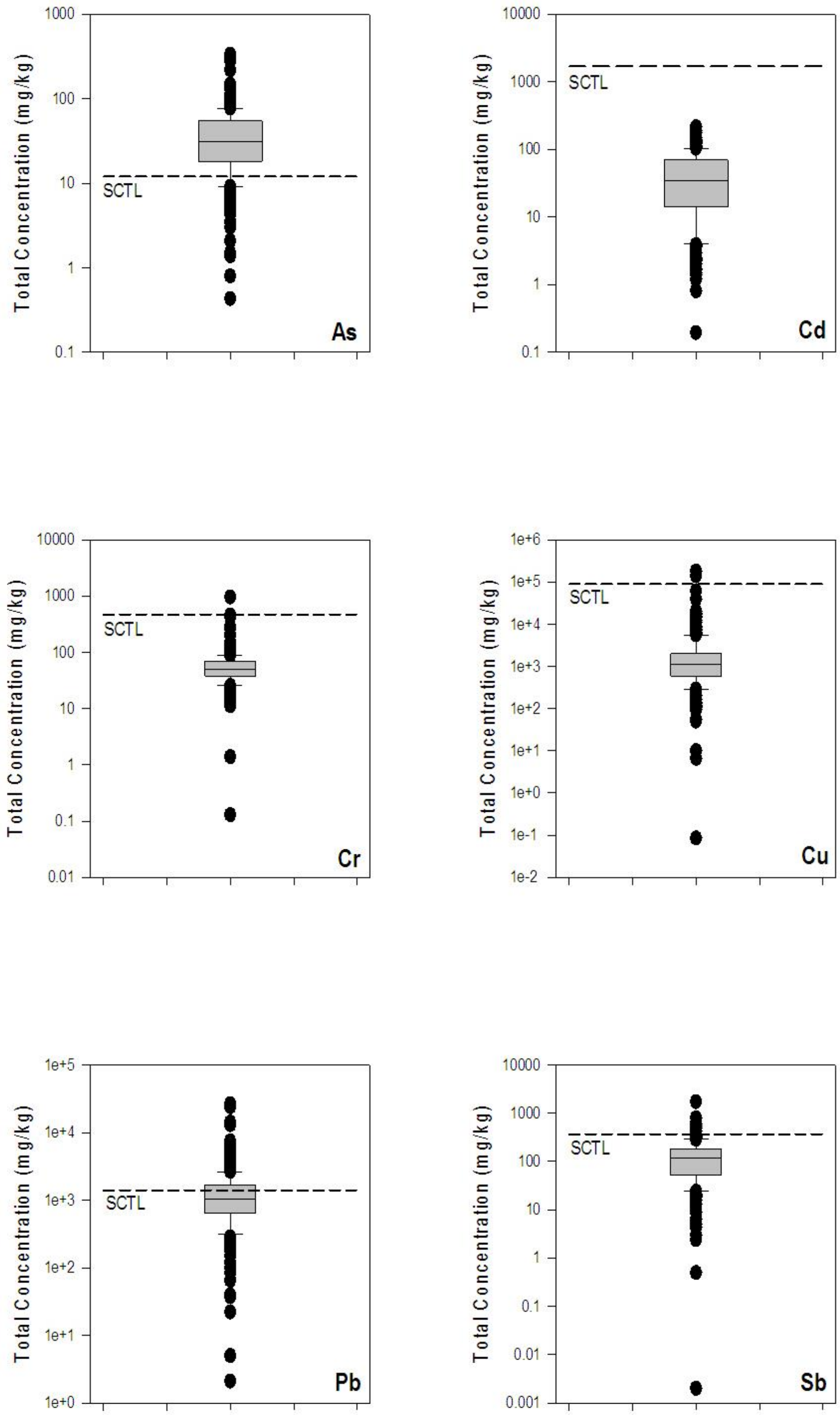

Figure 10. Range of Total Concentrations for Selected Elements in Mixed WTE Ash

Florida SCTLs are Included for Reference and are Commercial/Industrial SCTL's unless specified

(Data from FDEP Database 2003-2010)

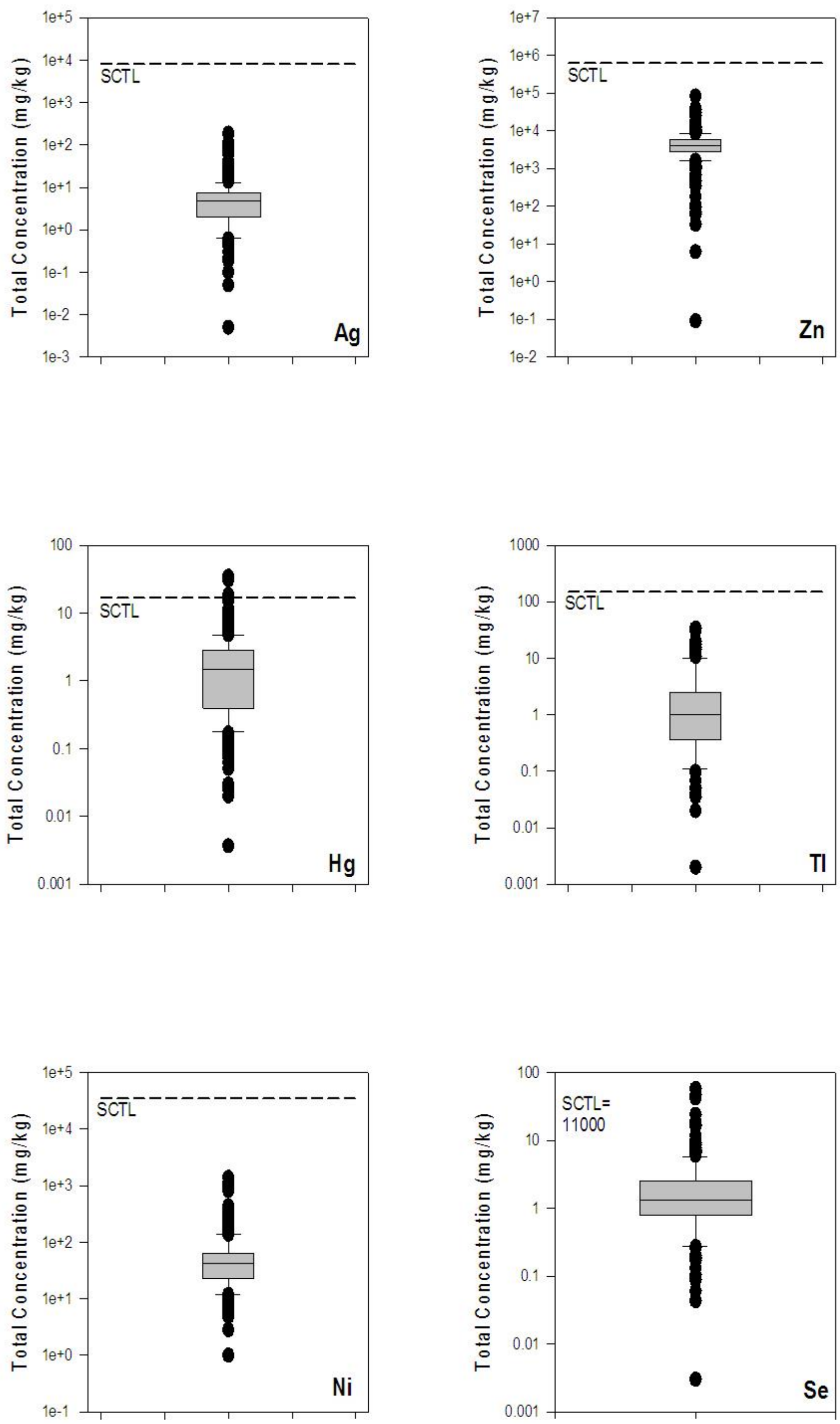

Figure 11. Range of Total Concentrations for Selected Elements in Mixed WTE Ash

Florida SCTLs are Included for Reference and are Commercial/Industrial SCTL's unless specified

(Data from FDEP Database 2003-2010)

Summary of State Regulations for Beneficial Use of FCR

Table 14. State Standing Beneficial Use Determinations for Specific FCR

Beneficial Use Application	State
Coal Fly Ash as a Pozzolan in Concrete Production	IL, IN, IA, ME, MD, MN, MS, NE, NJ, NM, NY, NC, OH, PA, TX, VA, WV, FL
Coal Bottom Ash in Structural Concrete	IL, IN, IA, ME, MD, MA, MI, NE, NJ, NM, NY, NC, OH, PA, TX, VA, WV, FL
Coal Bottom Ash as Road Base	IN, IA, MA, NE, NM, NC, TX, VA, WV, FL
Coal Bottom Ash or Boiler Slag as an Anti Skid Material	IL, IN, MA, MI, NE, NY, NC, PA, TX, VA, WV
Waste to Energy Bottom Ash as Road Base	None Listed
Wood Ash as a Soil Amendment	IA, ME, NY, VA
Flue Gas Desulfurization Residuals as an Ingredient in Wallboard	IL, IN, NE, NM, NY, NC, OH, TX , FL
Coal Combustion Products Used for Mine Reclamation	IA, MA, NE, NM, TX, VA, WV

Summary of State Regulations for Beneficial Use of FCR

Table 15. Conditional Beneficial Use Determinations for Specific FCR

Beneficial Use Application	State
Coal Fly Ash as a Pozzolan in Concrete Production	KY, MT, WI
Coal Bottom Ash in Structural Concrete	KY, MT, WI
Coal Bottom Ash as Road Base	IL, KY, MT, MO
Coal Bottom Ash or Boiler Slag as an Anti Skid	MO, MT
Waste to Energy Bottom Ash as Road Base	WI
Wood Ash as a Soil Amendment	MA, NH, PA, VT, WI
Coal Bottom Ash as Pipe Bedding	IL, MT, PA
Coal Combustion Products Used for Mine Reclamation	IL, IN, MT, PA

Literature Cited

Butler, R.D., Pflughoeft-Hassett, D.F., Docketer, B.A. & Foster, H.J. 1995. Stabilization of Underground Mine Voids by Filling with Coal Conversion Residuals.

Bye, G. C. 1999. *Portland Cement: Composition, Production And Properties*. Thomas Telford.

C. J. Banks and H.-M. Lo, "Assessing the effects of municipal solid waste incinerator bottom ash on the decomposition of biodegradable waste using a completely mixed anaerobic reactor," Waste Management & Research, vol. 21, no. 3, pp. 225 -234, Jun. 2003.

Campbell, A.G 1990. Recycling and disposing of wood ash. Tappi J. 73:141-146

Characterization of Municipal Waste Combustion Ash, Ash Extracts, and Leachates. Coalition on Resource Recovery and The Environment. US- EPA 530-SW-90-029-A

Characterization of MWC ashes and Leachates from MSW Landfills, Monofills, and Co-Disposal sites, US-EPA 530-sw-87-028E93

Cordiano, Victor. 2011. "Review of Coal Combustion Residual Storage and Disposal Processes of the Florida Electric Industry". Florida Public Service Commission.

Dairyland Power Cooperative. 1991. Letter to Wisconsin Department of Natural Resources. May 22, 1991.

Diebel, J., G.M. McGinnis, J. Pughani, S. Shetron, and M. Jurgensen. 1992. The environmental fate of wood ash applied to soils. P. 359-368. In Proc. Waste Wood Processing and Combustion for Enegry, 5th Annual National Biofuels Conf. and Exhibition, Boston, Ma. 19-22 Oct. 1992.

Demeyer, J.C Voundi Nkana, M.G Verloo, (2001) Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview, Bioresource Technology, Volume 77, Issue 3, Pages 287-295.

Dubey (2007). "Leaching of milled asphalt pavement amended with waste to energy ash." International Journal of Environment and Waste Management 1(2/3).

EIA (2008). Florida Renewable Energy Profile, US Energy Information Administration.

Eighmy, Crannell, Butler, Cartledge, Emery, Oblas, Krzanowski, Eusden, Shaw and Francis (1997). "Heavy metal stabilization in municipal solid waste combustion dry scrubber residue using soluble phosphate." Environmental Science & Technology 31(11): 3330-3338.

EPRI. 1983. Pilot Study of Time Variability of Elemental Ash Concentrations in Power Plant Ash. Report No. EA-2959

EPRI. 1995. Land Application of Coal Combustion By-Products: Use in Agriculture and Land Reclamation, Final Report. Report No. TR-103298.
EPRI. 2001. Environmental Evaluation for Use of Ash in Soil Stabilization Applications. Report No.
Erich, M.S. and Ohno T. (1992) Phosphorus availability to corn from wood ash amended soils. Water Air Soil Pollut., 64, pp. 475–485

Etiegni, L., A.G. Campbell, and R.L. Mahler. 1991. Evaluation of wood ash disposal on agricultural land: I. Potential as a soil additive and liming agent. Commun. Soil SCi. Plant Anal. 22:243-256.
F.A.C. (1990). Solid Waste Combuster Ash Management.

F.-Y. Chang and M.-Y. Wey, “Comparison of the characteristics of bottom and fly ashes generated from various incineration processes,” Journal of Hazardous Materials, vol. 138, no. 3, pp. 594-603, Dec. 2006.

FDEP (2008). Solid Waste Management in Florida 2008 Annual Report, State of Florida.

Fedje, Ekberg, Skarnemark and Steenari (2010). "Removal of hazardous metals from MSW fly ash-An evaluation of ash leaching methods." Journal of Hazardous Materials 173(1-3): 310-317.

Ferreira, Jensen, Ottosen and Ribeiro (2008). "Preliminary treatment of MSW fly ash as a way of improving electrodialytic remediation." Journal of Environmental Science and Health Part a-Toxic/Hazardous Substances & Environmental Engineering 43(8): 837-843.

Forteza, R., Far, M., SeguI, C., Cerdá,V. (2004) “Characterization of bottom ash in municipal solid waste incinerators for its use in road base,” Waste Management, vol. 24, no. 9, pp. 899-909, 2004.

Fungaro, D. A., Flues, M. S. M. and Celebroni, A. P. (2004). "Stabilization of zinc-contamined soil using zeolites synthesized from coal ashes." Quim Nova 27(4): 582-585.

Ginn, W. 1984. Bioash and paper mill sludge as agricultural soil conditioners. P. 242-249. In Proc of the 193 NCASI Northeast Regional Meeting. NCASI Spec. Re. 84-01. NCASI, Research Triangle Park, NC.

Greene,W.T. 1988 Wood ash disposal and recycling sourcebook. Northeast Regional Biomass Program, Coalition of Northeast Governors, Washington, DC.

H.-S. Shi and L.-L. Kan, “Leaching behavior of heavy metals from municipal solid wastes incineration (MSWI) fly ash used in concrete,” Journal of Hazardous Materials, vol. 164, no. 2-3, pp. 750-754, May 2009.

Hower, J.C., Robertson, J.D., Graham, U.M., Thomas, G.A., Wong, A.S. & Schram, W.H. 1993. Characterization of Kentucky Coal-Combustion By-Products: Compositional Variations Based on Sulfur Content of Feed Coal.

Hower. J.C., Robertson, J.D. & Roberts, J.M. 2001. Coal Combustion By Products from the Co-Combustion of Coal, Tire-Derived Fuel, and Petroleum Coke at a Western Kentucky Cyclong-Fired Unit. In EPRI. 2001. Proceedings from the 14th International Symposium

Hui, K. S. and Chao, C. Y. H. (2006). "Synthesis of MCM-41 from coal fly ash by a green approach: Influence of synthesis pH." J Hazard Mater 137(2): 1135-1148.

Indiana Department of Natural Resources (IDNR). 1999. Response to March, 1999, EPA Report to Congress, Wastes from the Combustion of Fossil Fuels, Volume 2 of 3.
Indiana Department of Natural Resources (IDNR). 1999. Response to March, 1999, EPA Report to Congress, Wastes from the Combustion of Fossil Fuels, Volume 2 of 3.

Innovative Waste Consulting Services, LLC. 2012. "Beneficial Use of Waste Materials: State of the Practice 2012". As yet unpublished. USEPA.

International Ash Working Group (IAWG), A.J. Chandler, T.T. Eighmy, J. Hartlen, O. Hjelmar, D.S. Kosson, S.E. Sawell, H.A. van der Sloot, and J. Vehlow. Municipal Solid Waste Incinerator Residues. Elsevier Publishers, Amsterdam (1997) ISBN 0-444-82563-0, pp. 974.

Jiang, Xi, Li, Zhang and Wei (2009). "Effect of water-extraction on characteristics of melting and solidification of fly ash from municipal solid waste incinerator." Journal of Hazardous Materials 161(2-3): 871-877.

Kim, A.G. & Kazonich, G. 2001. Release of Trace Elements from CCB: Maximum Extractable Fraction. In EPRI. 2001. Proceedings from the 14th International Symposium on Management and Use of Coal Combustion Products (CCPs).

Kim, A.G. & Kazonich, G. 2001. Release of Trace Elements from CCB: Maximum Extractable Fraction. In EPRI. 2001. Proceedings from the 14th International Symposium on Management and Use of Coal Combustion Products (CCPs).

Krejsl, J.A. and Scanlon T.M. (1996) Evaluation of beneficial use of wood-fired boiler-ash on oat and bean growth J. Environ. Qual., 25, pp. 950–954

L. Zheng, C. Wang, W. Wang, Y. Shi, and X. Gao, "Immobilization of MSWI fly ash through geopolymerization: Effects of water-wash," Waste Management, vol. 31, no. 2, pp. 311-317, Feb. 2011.

Lerner, B.R., and J.D. Utzinger. 1986. Wood ash as soil liming material. Hortscience 21:76-78

Lima, Ottosen, Pedersen and Ribeiro (2008). "Characterization of fly ash from bio and municipal waste." Biomass & Bioenergy 32(3): 277-282.

Longley, R.D. Jr. 1997. Examination of Fly Ash Grouts to be Used in Acid Mine Drainage Remediation.

Loop, C.M. 2000. The Impact of Ash Placement in a Surface Mine Pool on the Chemistry of the Silverbrook Basin.

M. Li, J. Xiang, S. Hu, L.-S. Sun, S. Su, P.-S. Li, and X.-X. Sun, "Characterization of solid residues from municipal solid waste incinerator," Fuel, vol. 83, no. 10, pp. 1397-1405, Jul. 2004.

Maltby, V. 1989. Experience with laboratory studies of the use of pulp and paper mill solid wastes in landfill cover systems. NCASI Tech. Bull. 599. NCASI, Research Triangle Park, NC.

Murayama, N., Tanabe, M., Yamamoto, H. and Shibata, J. (2003). "Reaction, mechanism and application of various zeolite syntheses from coal fly ash." Mater Trans 44(12): 2475-2480.

Muse, J.K. 1993. Inventory and evaluation ofpaper mill by-products for land applications. M.S thesis. Dep. Of Agronomy and Soils, Auburn Univ,, Auburn, AL.

Muse, J.K. and Mitchell, C.C (1995). Paper mill boiler-ash and lime by-products as soil liming materials. Agron. J., 87 pp. 432–438

Naylor, L.M and E.J. Schmidt. 1983. Assessment of chlorinated dibenzo-p-dioxin formation and potential emission to the environment from wood combustion. Chemosphere 12:617-627.

Naylor, L.M and E.J. Schmidt. 1986. Agricultural use of wood ash a fertilizer and liming material. Tappi J. 69(10):114-119.

Pennsylvania Department of Environmental Protection (PADEP). 1999a. Volume 2: Coal Ash Used as Minefill-Placement Not in Contact with Groundwater.

Pennsylvania Department of Environmental Protection (PADEP). 1999b. Volume 3: Coal Ash Used as Minefill-Placement in Contact with Groundwater.

Pepin, R.G., and P. Coleman. 1984. Paper mill sludge and ash as a soil conditioner.

Piantone, Bodenan, Derie and Depelsenaire (2003). "Monitoring the stabilization of municipal solid waste incineration fly ash by phosphation: mineralogical, and balance approach." Waste Management 23(3): 225-243.

PPL Generation, LLC. 1994-2001. Coal Ash Quality Results.

Quina, Bordado and Quinta-Ferreira (2008). "Treatment and use of air pollution control residues from MSW incineration: An overview." Waste Management 28(11): 2097-2121.

Reliant Energy. 2001. Coal Ash Analyses for Conemaugh, Keystone, Portland, Titus, Seward, and Shawville Facilities & Groundwater Assessments for Disposal Sites at Keystone, Conemaugh, Portland, and Shawville.

S.-Y. Kim, N. Tanaka, and T. Matsuto, “Solubility and adsorption characteristics of Pb in leachate from MSW incinerator bottom ash,” Waste Management & Research, vol. 20, no. 4, pp. 373 -381, 2002.

Sakai and Hiraoka (2000). "Municipal solid waste incinerator residue recycling by thermal processes." Waste Management 20(2-3): 249-258.

Schulz, S. 1992. Combustion of “clean” and “contaminated” in fluidized bed boilers p 5-10. In Proc. Waste Wood Processing and Combustion for Energy, 5th Annual National Biofuels Conf. and Exhibition, Boston, Ma 19-22 Oct. 1992.

Sell, N.J., T.H. McIntosh, T. Jayne, T. Rehfeldt, and M. Dishi. 1990. Burning screw-press-dewatered bulk sludge and briquetted sludge in a hog fuel boiler. Tappi J. 75:181-188.

Sheih (1999). Wood Ash in Florida: Production and Characteristics-Phase I, Hinkley Center for Solid and hazardous Waste Management.
Sheih (1999). Wood Ash in Florida: Production and Characteristics-Phase II, Hinkley Center for Solid and Hazardous Waste Management.

Shieh (1993). Environmental Acceptability of Precast Concrete Products Made of Treated Municipal Waste Incinerator Bottom Ash, Hinkley Center for Solid and Hazardous Waste Management.

"Solid Waste Management in Florida 2010 Annual Report | Recycling | Solid & Hazardous Waste | Waste Mgmt | Florida DEP." 2013. Accessed March 4. http://www.dep.state.fl.us/waste/categories/recycling/SWreportdata/10_data.htm.

Solo-Gabriele, Townsend, Messick and Calitu (2002). "Characteristics of chromated copper arsenate-treated wood ash." Journal of Hazardous Materials 89(2-3): 213-232.

Steponkus, P.C. 1992. Recycling wood ash in established loblolly pine plantations in eastern North Carolina. p. 33-39. In Proc. TAPPI Environmental Conf., Book1, Richmond, VA. 12-15 Apr. 1992. TAPPI Press, Atlanta, GA.

T. Mangialardi, "Disposal of MSWI fly ash through a combined washing-immobilisation process," Journal of Hazardous Materials, vol. 98, no. 1-3, pp. 225-240, Mar. 2003.

Technical Background Document for the Report to Congress on Remaining Wastes From Fossil Fuel Combustion, Waste Characterization. March 15, 1999.

Tolaymat, Dubey and Townsend (2008). "Assessing risk posed by land application of ash from the combustion of wood and tires." Journal of Residuals Science & Technology 5(2): 61-75.

Townsend, Dubey and Tolaymat (2006). "Interpretation of synthetic precipitation leaching procedure (SPLP) results for assessing risk to groundwater from land-applied granular waste." Environmental Engineering Science 23(1): 239-251.

USDOT. 2011. "Fly Ash." *Fly Ash*. April 7. http://www.fhwa.dot.gov/infrastructure/materialsgrp/flyash.htm.

Williams, T.M., Hollis, C.A., Smith B.R. (1996) Forest soil and water chemistry following bark boiler bottom ash application. J. Environ. Qual., 25, pp. 955–961

"Wind Powering America: U.S. Wind Resource Map." 2013. Accessed February 6. http://www.windpoweringamerica.gov/wind_maps_none.asp.

X. Gao, W. Wang, T. Ye, F. Wang, and Y. Lan, "Utilization of washed MSWI fly ash as partial cement substitute with the addition of dithiocarbamic chelate," Journal of Environmental Management, vol. 88, no. 2, pp. 293-299, Jul. 2008.

Y.-S. Shim, S.-W. Rhee, and W.-K. Lee, "Comparison of leaching characteristics of heavy metals from bottom and fly ashes in Korea and Japan," Waste Management, vol. 25, no. 5, pp. 473-480, 2005.

Yuno, K., Ishii, M., Hashimoto, C. and Mizuguchi, H. (2010). "Construction Placement and Hardened Properties of Shotcrete with Highly Functional Fly Ash." Int J Mod Phys B 24(15-16): 2472-2477.

Zhang, J., Dong, W., Li, J., Qiao, L., Zheng, J. W. and Sheng, J. W. (2007). "Utilization of coal fly ash in the glass-ceramic production." J Hazard Mater 149(2): 523-526.