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Geological Disposal of Energy-Related Waste

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Abstract

The production of waste materials during energy recovery processes is an unavoidable consequence of the need for energy; consequently, safe and efficient disposal or reuse alternatives for these waste materials is essential for sustainable development. For waste streams that must be geologically disposed, the largest volumes of energy related waste include Coal Combustion Products (CCPs) such as fly ash, coal mining wastes, and processed water and drill cuttings from oil and gas exploration, with relatively small amounts of silica resulting from pipe scaling in geothermal energy production. The fate of the vast majority of these energy-related wastes is geologic disposal, which ranges from placement in landfills (lined or unlined) or surface impoundments, to deep injection within geologic units. Applications for productive reuse of energy-related wastes are cost effective alternatives to disposal, and are gaining popularity as sustainability of processing becomes more critical. This review paper examines geologic disposal and reuse of energy-related waste streams within the U.S., and provides insight into fuel-to-waste production ratios, preferred disposal or productive reuse alternatives, and associated geotechnical/environmental considerations.

Keywords: *energy consumption, fossil fuel, coal combustion products, geologic disposal, landfilling, productive reuse*

1. Introduction

In 2009, total primary energy consumption in the U.S. reached approximately 9.2×10^7 MJ, which represented approximately 20% of global primary energy consumption (BP, 2010). Based on 2009 estimates, petroleum, natural gas, and coal supply more than 75% of U.S. primary energy, followed by nuclear, and renewable energy sources, respectively (EIA, 2010b). Considering energy consumption by demand sector for 2009, electric power uses the largest share of the total primary energy supply, followed by the transportation, industrial, and residential and commercial sectors, shown in Fig. 1 (EIA, 2010b).

While fossil fuels remain the least expensive and most abundant fuel sources available to date, the ramifications of their consumption range from the release of greenhouse gases to production of large volumes of energy-related waste products, and result in substantial environmental impacts which cannot be ignored (EIA, 2009; WEC, 2007). Geologic disposal of energy-related waste streams requires significant investments in control and management of the large quantities of waste materials generated[1]. The largest components of energy-related wastes include: Coal Combustion Products (CCPs) like fly ash, coal mining wastes, processed water and drill cuttings from oil and gas exploration, and silica from pipe scaling in geothermal energy production processes. The production of waste along with energy is an unavoidable consequence of the need for energy, and developing safe and efficient disposal or reuse alternatives for these waste materials is essential for sustainable development.

Examination of waste materials generated through the production of energy reveals three predominant waste streams that must be disposed within geologic formations: Coal Combustion Products (CCPs), coal mining waste, and petroleum and natural gas exploration and production wastes, along with smaller waste streams associated with renewable energy sources. These waste streams will be examined in more detail in the following.

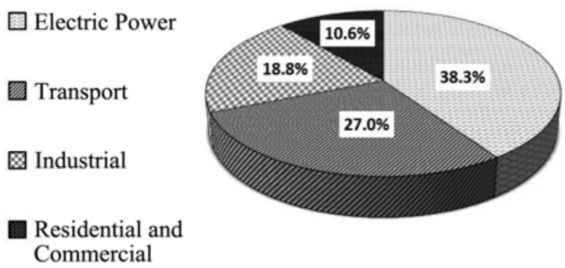

Fig. 1. 2009 Primary Demand Sectors for Total Energy Consumption (EIA, 2010)

[1]Nuclear power radioactive waste disposal is not dealt with herein.

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2. Geologic Disposal

Geologic disposal of energy-related waste can take a variety of forms, ranging from surficial disposal to deep injection within geologic units. Controlled surficial disposal, or landfilling, relies on disposal within an engineered barrier, which consists of low hydraulic conductivity soil liners, geosynthetic liners, and leachate collection systems. Geologic disposal of waste most commonly relies on advective containment of contaminants within a designated disposal region. For wastes disposed surficially, modern engineered barriers are constructed from a combination of earthen and polymeric liners, which are designed to slow the rate of contaminant release to the environment, while maintaining reasonable construction and operation costs. Because modern engineered barriers are designed to slow the rate of liquid leaving the waste, they perform well in terms of advective containment, but they are less effective at controlling the rate of diffusive transport through the liner. While design of waste containment systems is a relatively mature field, several critical components must be carefully controlled to ensure the long term performance of an engineered liner, including control of fluid leakage through careful construction and operation practices, protection of the liner from damage due to penetration of waste or heavy equipment, and long term monitoring of contaminant release from the liner. Excellent reviews of the issues involved in waste containment yield further insight into the most critical aspects of engineered barriers (Bonaparte *et al*., 2002; NRC, 2007; Rowe, 2005; Rumer and Mitchell, 1995).

Typically, lined landfills accept waste in dry form, requiring solidification before liquid waste can be disposed. Most commonly, modern landfills are excavated below ground surface and filled in lifts to a predetermined height above the ground surface. However, it is important to note that historically, uncontrolled waste dumps were frequently placed in naturally occurring, low lying surface depressions, and typically were not lined.

As an alternative to disposal in an engineered landfill system, surface impoundments are often used for land disposal of energy-related wastes. A surface impoundment is frequently placed in a low-lying surface depression, and may be constructed with or without a liner for containment. Additionally, height for waste disposal is often added through the use of dikes constructed on the side of the surface impoundment. Surface impoundments are used to dispose of liquid or high water content wastes, and allow for gravity separation of the solid/liquid waste components. Water is allowed to evaporate from the impoundment; consequently, the impoundment may have standing water, or a dry surface, depending on the disposal history.

When a landfill or surface impoundment has reached disposal capacity, final closure can be performed by placing a cover to contain the waste. Conceptually, covers are similar to engineered liners and can consist of geomembrane and compacted soil liners, integrated with gas vents and liquid drainage layers. The uppermost layer in a barrier's cover is constructed to provide erosion resistance and a stable growth medium for vegetation, in order to further reduce susceptibility to erosion. The primary function of a cover is to reduce infiltration and keep rainfall isolated from the underlying waste in order to reduce the quantity of leachate that is generated within the waste; consequently, covers are most effective when combined with an engineered bottom liner, but are also effective at reducing the generation of leachate in unlined systems.

In addition to surficial disposal, deep injection of wastes also exists as an alternative form of disposal that is frequently utilized by the petroleum industry. Deep injection wells are placed in porous permeable receiving formations and are used to dispose of high water content solids (slurry) and liquid waste. Of primary concern in the injection of liquid waste is the associated pressure buildup in the surrounding formation; consequently, the formation must be of sufficient permeability to prevent pressure buildup that can lead to hydraulic fracture within the formation. Deep injection wells are typically double cased, and placed below a confining unit in order to prevent vertical migration of contaminant and possible contamination of drinking water aquifers. A review of the geological criteria important for the location of deep injection wells intended for solids disposal is available in (Nadeem and Dusseault, 2007).

Most importantly, because geologic disposal of energy related wastes relies on engineered systems, there are inherent risks associated with the practice. In addition to contaminant release and transport, engineered surface disposal facilities must resist traditional failure mechanisms such as long-term settlement and deformation, slope stability, and seismic deformation, while deep injection disposal must not induce hydraulic fracture in the formation. More recent drives to develop renewable energy sources have also created additional waste streams that are not well understood in terms of geotechnical properties, such as combustion products resulting from the burning of biomass as an energy source.

3. Coal Combustion Products

Historically, coal has been mined throughout the world, with a significant increase in the rate of mining occurring first during the industrial revolution, and again in the 20^{th} century. Today, coal remains the world's most abundant and accessible fossil fuel, and its consumption rate is the fastest growing worldwide (NRC, 2006; WEC, 2010). In the U.S. alone, during 2008 1.06 billion tons (metric) of coal were recovered (EIA, 2010a), leaving an estimated 237 billion tons of recoverable reserves as of January 1, 2009 (EIA, 2009). Over 90% of U.S. coal is used domestically for electricity production, which, as shown in Fig. 2 accounts for approximately 20% of the total U.S. energy consumption (EIA, 2010b). In 2009, just over 122 million tons of coal combustion products (CCPs) were produced in the U.S. (ACAA, 2010), amounting to approximately 116 kg of CCPs generated for every 1000 kg of coal mined and burned. Assuming a U.S. population of 307 million (U.S. Census Bureau 2009, accessed 07/12/2010), this production rate results in just over 1kg of CCP per person,

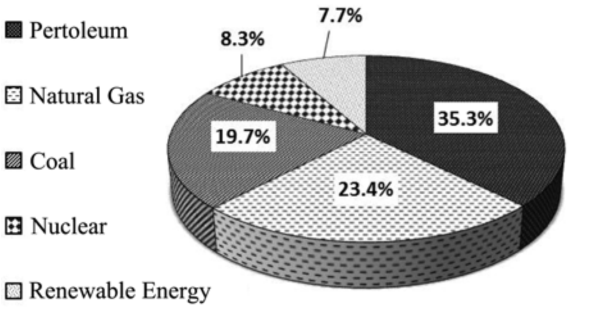

Fig. 2. 2009 U.S. Fuel Consumption by Fuel Source (EIA, 2010)

Table 1. 2009 U.S. CCP Production and Reuse Data

CCP Type	Produced		Reused	
	Mass ($\times 10^6$ tons)	Fraction of Total CCP Produced	Mass ($\times 10^6$ tons)	Fraction of Total CCP Produced
Fly ash	57.2	46.8%	22.4	18.3%
Bottom ash	15.1	12.3%	6.4	5.2%
Boiler slag	2.0	1.6%	1.7	1.4%
FGD gypsum	16.3	13.4%	8.1	6.6%
FGD material wet scrubbers	10.6	8.7%	0.8	0.7%
FGD material dry scrubbers	9.6	7.9%	0.3	0.3%
FGD other	0.1	0.1%	0.1	0.1%
FBC ash	11.4	9.3%	10.7	8.7%
U.S. Total	122.3	-	50.5	41.3%

Source: (ACAA, 2010)

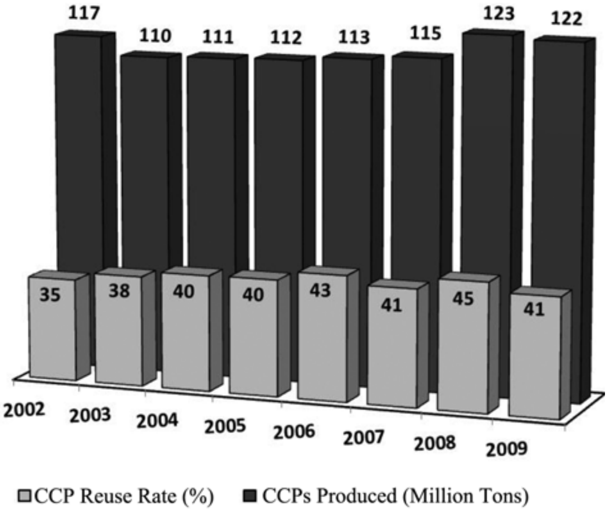

Fig. 3. 2002 to 2009 Total CCP Production and Reuse Rates (ACAA, 2011)

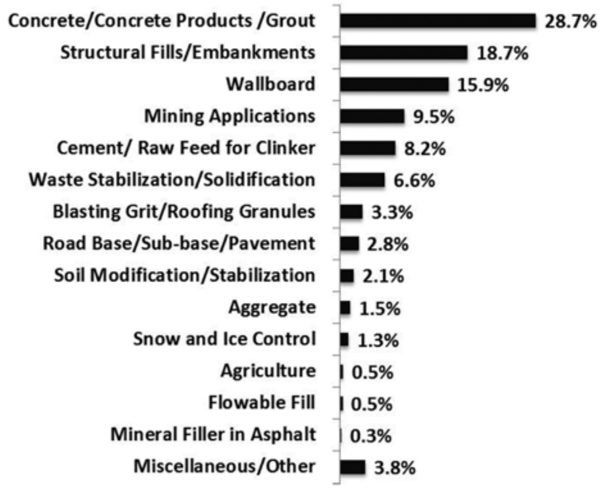

Fig. 4. 2002 to 2009 Average CCP Productive Reuse Sectors (ACAA, 2011)

per day. CCP production and reuse data for 2009 are summarized in Table 1.

CCPs consist predominantly of the noncombustible, or partially combusted fractions of coal, and these residues are typically categorized as fly ash, bottom ash, and boiler slag. Fly ash particles make up the largest CCP category (Table 1), and are the lowest density particles produced during coal combustion. Fly ash represents the portion of the waste products that are transported out of the firing process by the boiler exhaust or flue gases. Bottom ash particles are higher density particles that accumulate at the bottom of the boiler, while boiler slag consists of the molten products of coal firing, which are allowed to solidify after firing. CCPs also include residues from various air pollution control processes, including Flue Gas Desulphurization (FGD), and fluidized bed combustion (FBC) ash.

As of 2009, just over 41% of total CCPs generated were productively reused (Table 1) in the U.S., which has been relatively consistent over the last decade (Fig. 3). The average CCP reuse rates for 15 different reuse categories between 2002 and 2009 in the U.S. (ACAA, 2011), demonstrate that the most common application for fly ash reuse was as raw material for cement production and as a pozzolanic component in various concrete products (Ahmaruzzaman, 2010; Ganesan *et al*., 2007; Gao *et al*., 1997; Hall and Livingston, 2002; Hill *et al*., 1997; Kulaots *et al*., 2003; Pedersen *et al*., 2008; Sporel *et al*., 2009; Wang and Baxter, 2007) (Fig. 4). Other reuse applications for CCPs include construction materials such as gypsum wall board and light weight aggregate, structural fill and cover materials, roadway and pavement base materials, infiltration barriers, and underground void filling (Adriano *et al*., 1980; Ahmaruzzaman, 2010; Basu *et al*., 2009; Kim *et al*., 2005; Mishra and Karanam, 2006; Mulder, 1996; Pandey and Singh, 2010). CCPs with low concentrations of heavy metals can also be used in agricultural soil improvement, where the high concentrations of important soil nutrients (K, Na, Zn, Ca, Mg, and Fe) present in CCPs like fly ash, have been shown to improve crop yields (Basu *et al*., 2009). In such agricultural applications, fly ash could also replace lime application, thus reducing net CO_2 emissions to the atmosphere (Basu *et al*., 2009).

Using the 2009 rate of CCP production combined with the reuse rate of 41% leaves approximately 72 million tons of CCPs which must be land disposed in surface impoundments, commercial landfills, or in mine-filling. CCPs like fly ash are typically disposed in surface impoundments in the saturated state, where the ash slurry is pumped into the impoundment from the plant. The solids and liquid are allowed to gravity separate, with solids remaining in the impoundment as either a temporary or permanent disposal method. In contrast, landfilling of fly ash is typically done in the dry condition, with controlled filling in a series of landfill cells. When disposed in a modern landfill, the CCPs are typically placed on engineered liners, with provisions for drainage collection and capping once disposal capacity is reached. However, it is important to note that not all CCPs are disposed of in landfills with engineered liners; CCPs may be placed in surface impoundments with no bottom barrier. In such cases, the environmental consequences from leaching of heavy metals and other soluble contaminants from the CCPs must be considered. These contaminants can be associated with or sorbed to particles surfaces, in which case they are easily dissolved and leached out soon after disposal, or they are incorporated within the glassy fraction, where dissolution occurs at a much slower rate and over extended periods of time (Choi *et al*., 2002; Ugurlu, 2004). Some heavy metals, such as arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb) commonly found in fly ash, are harmful even at low concentrations, thus careful groundwater monitoring around landfill sites (both lined and unlined) is imperative (Choi *et al*., 2002). Apart from issues concerning contaminant leaching, extremely careful management of the placement of CCP deposits in commercial surface impoundments is paramount in preventing catastrophic containment breaches like the December 2008 Tennessee Valley Authority (TVA) ash spill in Kingston, Tennessee, which released over 4.1 million cubic meters of ash into the Emory River and its tributaries (Ruhl *et al*., 2009). The failure mechanism, although complex, was progressive in nature and due primarily to four concurrent factors: fill geometry and setbacks, increased fill rates, soft foundation soils and high ash water content (AECOM, 2009).

More recently, mine-filling is a method of CCP geologic disposal that has gained attention (CCSD, 2006; Mishra and Karanam, 2006; NRC, 2006). In this form of disposal, CCPs are returned to either surface or underground mines that are no longer in production. The placement of the residues can be used as a reclamation technology, in order to return the mined land to its approximate pre-mining state, or as infill for the mine in order to reduce future subsidence (Ahmaruzzaman, 2010; NRC, 2006). The placement of CCPs in mines is typically achieved by slurry pressure injection, which hardens upon drying with minimal shrinkage (Ahmaruzzaman, 2010). From an environmental perspective, mine disposal of CCPs can potentially ameliorate acid mine drainage in two ways: first through the acid neutralizing capacity of the highly alkaline ash when in contact with acidic groundwater, and secondly by preventing contact between water and the acid generating strata, which are typically pyritic (Ahmaruzzaman, 2010).

Compared to the volume of CCPs used in cement and concrete, mine filling, and disposed of in commercial landfills, a relatively small volume of CCPs (mainly fly ash and bottom ash) are used in geotechnical applications like highway embankment construction. The geotechnical properties of CCP/soil mixtures have been shown to be suitable for use as backfill materials (Baykal *et al*., 2004; Kim *et al*., 2005; Yoon *et al*., 2009). From a geotechnical perspective, fly ash particles possess morphological characteristics that distinguish them from typical soils. They are composed primarily of spherical (non-crystalline) particles that solidify from molten coal components in exhaust gases, along with irregularly shaped, porous, unburned carbon granules (Kutchko and Kim, 2006). SEM micrographs from a fly ash sample from an Alabama power plant are shown in Fig. 5. Fly ash particle sizes range from clay size grains to fine sand, and as mentioned above, bottom ash particles are coarser than fly ash, in the range of medium to coarse sand. Due to the presence of

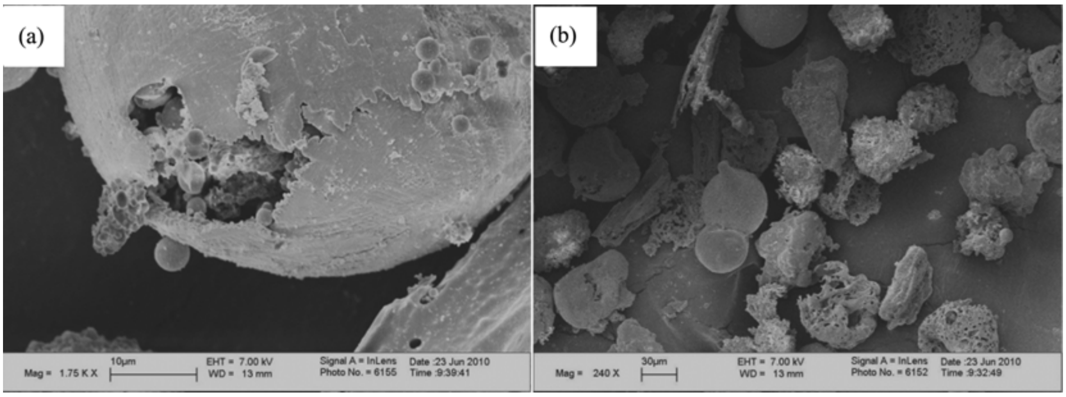

Fig. 5. SEM Micrographs of Fly Ash: (a) Cracked, Hollow, Spherical Fly Ash Particle Containing Smaller Spherical Fly Ash Particles, and (b) Irregularly Shaped, Porous Unburned Coal Particles from the Same Ash Sample

hollow cenospheres and brittle unburned carbon particles, fly and bottom ashes may exhibit higher compressibility than typical soils - particularly under high confining pressures due to particle crushing. Even so, Kim *et al*. (2005) reported compacted ash mixtures with comparable or higher strength than sands at similar compaction levels. The geotechnical properties of CCPs have been extensively studied and documented, the reader is directed to the following key works for more detailed information on this subject: (Baykal *et al*., 2004; Kim and Prezzi, 2008; Kim *et al*., 2005; Yoon *et al*., 2009).

4. Coal Mining Waste

The extraction of coal from the ground results in significant generation of waste materials, in addition to those that remain after the combustion of coal. Coal is typically recovered from both surface mines (strip mining or open pit mining) or underground mines, which are used to recover coal from deep seams. The primary waste stream associated with most mining operations consists of slurried fines (referred to as tailings) from beneficiation processes along with coal dust and pulverized formation rock fragments (US EPA, 1994). Each mining method results in varying proportions of waste generated, with surface mining typically producing more waste than underground mining (Table 2).

Waste materials from coal mines are typically disposed on site, in the form of gravel piles, and tailings dams/impoundments. Due to the acid generating strata (often pyritic) in the formation rock from which much of the solid waste materials originate, these wastes may require environmental control and remediation for potential Acid Mine Drainage (AMD) (Yeheyis *et al*., 2009).

Table 2. Coal Mining Waste Production

Waste Produced	Strip or Open Pit Mining (kg/1000 kg produced)	Underground Mining (kg/1000 kg produced)
Liquid Waste	0.24-1.2	1.0-1.6
Solid Waste	10	3-5
Dust	0.1-0.6	0.006-0.01

Sources: (Multilateral Investment Group, 2007)[1] and (Edgar, 1983)

[1]http://www.miga.org/documents/CoalMiningandProduction.pdf, accessed 7/27/2010

Typically, such environmental control measures involve the incorporation of neutralizing agents like lime stone or caustic soda with the acid generating tailings (Shang *et al*., 2006). More recently, coal fly ash has been used as a more cost effective acid neutralizing agent (Shang *et al*., 2006; Yeheyis *et al*., 2009), and as with the abovementioned mine-filling applications, its pozzolanic properties provide the added benefit of reducing permeability and increasing the strength/stability of debris piles and tailings dams. The dust and methane produced in coal mining is of concern from an air quality perspective, and in underground mining practices in particular, due to associated explosion risks (Bian *et al*., 2009; The World Bank Group, 1998).

5. Petroleum/Natural Gas Exploration and Production

Energy generated from petroleum and natural gas accounts for over 60% of the total energy consumption in the U.S. (Fig. 2). The most recent American Petroleum Institute (API) production report shows oil, natural gas and natural gas liquids production for 1995 of 6.6 billion barrels, which is a 6% decline from 1985 (summarized in Table 3 (API, 2000)). Exploration and production (EP) of such quantities of petroleum and natural gas results in the generation of a substantial volume of waste fluids and solids. These EP wastes are generally grouped in three major categories: produced water, drilling waste and associated wastes (API, 2000). Produced water is water which is typically saline originating from within the oil reservoir and is brought to the surface accompanied by the recovered oil and gas (API, 2000; E&P Forum, 1993; Veil, 2001). Drilling wastes include: drill cuttings (heterogeneous ground up fragments of formation rock produced by the grinding action of the drill bit), as well as drilling muds/fluids used for lubrication, cooling and well bore stabilization (API, 2000). Drilling fluids are water-based, oil-based, or synthetic and contain high density "weighting" materials such as barite and hematite, as well as bentonite or attapulgite clay for viscosity, and dispersants like tannins (Abbe *et al*., 2009; API, 2000; E&P Forum, 1993; Leonard and Stegemann, 2010; Veil, 2001, 2003). Typically offshore drilling is done with water based muds while onshore wells are drilled using oil-based muds (Veil, 2001). Associated wastes comprise a variety of small volume waste streams associated with oil and gas EP activities. These waste

Table 3. U.S. Crude Oil and Gas Production vs EP Waste Production for 1985 and 1995[1]

Crude Oil and Gas Production					Waste Production ($\times10^6$ barrels)			
Fuel Type	1985	1995	% Change	Units	Waste Type	1985	1995	% Change
Crude Oil	3,275	2394	-27	$\times10^6$ barrels	Produced water	20,900	17,911	-14
Natural Gas	4.87	5.52	+13	$\times10^{11}$ m^3	Drilling wastes	361	149	-59
Natural Gas Liquids	753	791	+5	$\times10^6$ barrels	Associated wastes	11.8	20.6	+75
Total	7,093	6,661	-6	$\times10^6$ boe	Total	21,273	18,080	-14

boe = barrels of oil equivalent; Source: (API, 2000)

[1]Most recent API data, accessed 07/11/2010, at: http://www.api.org/aboutoilgas/sectors/explore/waste-management.cfm

streams include: completion fluids, workover and stimulation fluids, tank bottoms and oily sludges, as well as dehydration and sweetening wastes (API, 2000).

Notably, over the past few decades, the volume of waste generated by the oil and gas industry has decreased substantially. In the decade between 1985 and 1995, total EP waste production decreased from 21.3 to 18.1 billion barrels (Table 3), with drilling waste production decreasing by nearly 60%. This decline in waste production is primarily due to advances in EP technology and drilling techniques (API, 2000). The marked 75% increase in associated waste production occurred because well completion fluids were included as associated wastes in 1995 and not in 1985. The 18 billion barrels of EP waste produced in 1995 equates to approximately 2.7 barrels of waste generated per barrel equivalent of net crude oil and natural gas production.

Produced water and associated wastes make up over 99% of the total EP waste. Over 90% of these wastes are either reused in Enhanced Oil Recovery (EOR) techniques, or disposed of in dedicated injection wells. Produced water and other water based wastes which are not injected, are disposed of in percolation pits or onsite evaporation (API, 2000). Evaporation, burial and injection account for over 80% of drilling waste disposal, and in 1995, only 2% of drilling wastes were disposed of in commercial EP landfills (API, 2000). Drilling wastes can be recycled and reused for drilling, treated and discharged or road spread. Disposal methods for drilling wastes include injection, evaporation on or off site, on site burial, land spreading (on or offsite), and commercial landfill disposal. Treated drill cuttings have been productively reused as landfill cover material (Veil, 2001), and more recently, processed drill cuttings have shown promise as potential non-toxic substrate able to support plant growth in wetland restoration efforts (Willis *et al*., 2005).

Storage or disposal of EP wastes in salt caverns represents a cost effective alternative that has gained popularity in the petroleum industry (Tomasko *et al*., 1997; Veil, 2001). Salt caverns are deep underground chambers formed in natural salt deposits, either by natural geologic processes or by human design through solution mining. In addition to the lower costs, this disposal alternative is advantageous for a few reasons. First, large volumes of materials can be contained in a single chamber. Salt caverns are used to store the U.S. strategic petroleum reserves, and each contain approximately 10 million barrels of crude oil (Tomasko *et al*., 1997). Additionally, from an environmental perspective, salt caverns are formed deep within the earth (on the order of 600 m) and are surrounded by relatively low permeability salt bearing strata that are much less likely to affect drinking water supplies than are more traditional waste disposal methods. Nonetheless, as with all other waste disposal methods, there are risks associated with contaminant release, which, in this case can occur through sidewall cracks, permeable interlayers, roof collapse, and other scenarios. To date, studies have shown these risks to be acceptably low (Tomasko *et al*., 1997).

6. Renewable Energy

Renewable energy sources include geothermal, hydroelectric, wind, and solar energy, as well as biofuels such as ethanol. Of these renewable sources, geothermal energy produces by far the largest waste that requires geological disposal. Geothermal energy, which involves extracting thermal energy from the subsurface, involves drilling deep within the earth and accessing high temperature fluids (with temperatures which can be in excess of 200^{o}C), contained within certain strata, pumping these fluids to the surface and extracting the heat (US EPA, 2009). Geothermal energy accounts for a small fraction of the total U.S. energy production, yet over 54, 0000 metric tons of waste materials are produced annually from this renewable energy source, which is not a trivial amount (US EPA, 2009). The majority of geothermal wastes are brines and produced water, the vast majority of which are re-injected to the subsurface, as is done in the petroleum industry (US EPA, 2009). Silica scaling that forms within production piping is typically disposed of in landfills; however, studies have shown this silica scale has pozzolanic properties with applications in cement and concrete products (Escalante *et al*., 1999; Gomez-Zamorano *et al*., 2004).

To date, the waste streams from hydroelectric, wind and solar energy production are relatively small, and it is believed that there is no tracking system in place for these wastes, which would likely account for only a small fraction of the total energy-related waste volume. Byproducts from biofuel production, such as distiller grains (leftover materials after ethanol production from corn) are actually commercially viable materials in the farming industry and are in high demand as feed for cattle and other livestock. Practically all of these materials are reused and are thus considered co-products rather than waste streams (Taheripour *et al*., 2010).

7. Conclusions

The development of safe and efficient disposal or reuse alternatives for the vast quantities of energy-related wastes generated annually throughout the world, is essential for sustainable development. Currently, the fate of the vast majority of these wastes is geologic disposal, ranging from surficial disposal to deep injection within geologic units. Surface disposed wastes include Coal Combustion Products (CCPs) like fly ash, bottom ash and boiler slag, crushed rock and tailings from beneficiation processes in coal mining, drill cuttings and produced sand from petroleum and natural gas exploration and production (EP wastes), and silica scaling from production piping in geothermal energy production. Controlled surface disposal, or landfilling, relies on disposal within an engineered barrier, which consists of low permeability soil and geosynthetic liners and leachate collection systems. When these surficial disposal facilities reach disposal capacity, final closure can be performed by placing an engineered cover to contain the waste.

More recently, surface disposed wastes have been alternatively disposed in underground cavities such as abandoned mines (CCPs), or salt caverns (EP). These disposal techniques are advantageous for a few reasons. They are cost effective, as engineered liners are not required, and the voids are large and can contain large volumes of waste. In mine-filling, the alkaline and pozzolanic properties of CCPs help to neutralize the acid generating capacity of formation rock and prevent contact with ground water, respectively, thus, ameliorating acid mine drainage. Salt caverns, on the other hand, are extremely deep and encased within low permeability salt-bearing strata and are thus, much less likely to affect drinking water supplies than the more traditional surface disposal methods.

In addition to surficial disposal, deep injection is an alternative disposal technique commonly utilized by the petroleum industry. Produced water, brines, and spent drilling muds from geothermal and petroleum EP, are the primary candidates for deep injection disposal. Injection wells are placed in porous, permeable receiving formations like sandstones. The primary challenge in the injection of liquid wastes is the associated pressure buildup that can lead to hydraulic fracture. Receiving formations should thus be of sufficient permeability to avoid such an eventuality.

From a sustainability standpoint, productive reuse of energy-related wastes has become an attractive alternative to disposal. Fly ash and silica scaling from geothermal energy production have been used in the production of cement and concrete products, due to their pozzolanic properties; while treated drill cuttings from oil and gas EP have been used in landfill covers as well as in wetland restoration. Other reuse applications for CCPs include construction materials such as gypsum wall board and light weight aggregate, structural fill and cover materials, roadway and pavement base materials, infiltration barriers, and in agricultural soil improvement. While the unique morphology of fly ash and bottom ash particles may result in unpredictable compaction behavior due to particle crushing and high sensitivity to water content changes during compaction, their pozzolanic properties, which are activated by excess water, provide favorable strength properties over time. Ultimately, the products that cannot be reused will be disposed in geologic barrier systems designed to reduce contaminant transport and protect surrounding ecosystems.

In terms of waste containment, the most pressing research needs include development of more effective monitoring tools to detect contaminant movement through and adjacent to engineered barriers, improved modeling capabilities (both deterministic and probabilistic) to predict long-term barrier performance, and assessment methodologies to determine the performance of engineered barriers (NRC, 2007). The research needs for disposal of energy related wastes are inherently coupled with the regulatory restrictions on carbon and other contaminant emissions to the environment. For example, as coal emission standards become more strict, the waste stream becomes more complex because additional contaminants, such as heavy metals, are retained in the CCPs at higher rates. In some cases, retaining more contaminants at the power plant also reduces the ability for productive reuse of the waste stream, as seen in the processing of CCPs. Characterization of the geotechnical properties of waste streams that result from renewable energy sources, such as biomass and geothermal, are of critical importance to engineer proper disposal, and also to develop effective reuse options. Due to the extremely large volumes of waste produced in the generation of energy, the most pressing research need is the development of productive reuse applications of the materials, which would reduce the need for geologic disposal.

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