Appendix G:

Coal Combustion Byproduct Assessment

Table of Contents

List of Tables

List of Figures

Background

Under the Navajo Mine's fuel supply contract with Arizona Public Service, the Navajo Mine accepted CCBs from the Four Corners Power Plant units 4 and 5 for disposal in final pits and ramps from 1971 to 2008. CCBs disposed of at Navajo Mine included: fly ash, scrubber sludge, and bottom ash. CCBs from the Four Corners Power Plant were placed in mined-out pits and ramps of the Navajo Mine to help achieve approximate original contours (AOC) (BHP Billiton 2010, Ch. 11).

Fly ash and bottom ash are generated by the combustion of coal at the Four Corners Power Plant. The fly ash is collected in emission control baghouses. Fabric bags in the baghouses act as a filter removing the fly ash from the flue gas stream of units 4 and 5. Ash too large to be carried by the flue gas to the baghouse falls to the bottom of the boiler during the combustion process and is removed as bottom ash. Scrubber sludge is the byproduct of removing SO_2 from the flue gas. The SO_2 reacts with lime to form calcium sulfite and calcium sulfate. The major chemical constituents of CCBs disposed of at the Navajo Mine include: Silicon Dioxide ($Si0_2$), Aluminum Oxide ($Al0_3$) and Calcium Sulfite ($CaS0_3$).

Coal fly ash is made up of 3 different types of materials: un-reactive and stable solids ($Si0_2$, $Al2O_3$, Fe_2O_3, etc.), semi-soluble solids (borates, sulfates, carbonates, etc.), and solids that react with water (CaO, MgO, Na_2O, etc.). The insoluble constituents of fly ash are composed of spherical, glassy mixtures of metal-oxides and sometimes other compounds. The chemistry of the coal determines whether the coal ash is basic or acidic, and this in turn affects leaching properties of the ash once it is in contact with water (Vories 2001). Coal ash typically exhibits a point of zero charge, PZC_{pH}, of around 4.6, and sorption/leaching properties within a given ash are greatly controlled by the pH of the mixture once it is slaked. With regards to alkaline or Class C coal ash, the main constituents of concern in terms of leaching are boron, arsenic, and possibly selenium (Manoharan 2007). Although arsenic is fairly susceptible to attenuation in the subsurface, boron can be quite chemically stable while being transported over large geographic areas.

Disposal History and Techniques

The Navajo Mine and the San Juan Mine formerly used CCBs from adjacent generating stations as a backfill material to achieve AOC. Approximately 4 million tons of ash was placed in mined out pits and ramps at the two mines annually. Disposal of CCBs in this manner at the Navajo Mine was seen as the best long-term solution for CCB disposal in the absence of other beneficial uses for the ash. Placement of ash was governed by a detailed ash disposal plan developed and approved for the Navajo Mine. It described performance standards for the use of ash as mine backfill.

The performance standards required physically characterizing the ash, covering the ash with spoil, not burying ash beneath large drainages, and performing reclamation on the affected areas. The precautionary measures were designed to prevent the ash from being exposed on the ground and to prevent plant roots and surface water from directly coming into contact with the buried ash. Due to the arid environment of Northwest New Mexico and the absence of any significant groundwater, ash placement was in dry pits and ramps.

The AOC surrounding all ash disposal areas was designed to have positive drainage away from the ash and avoid any puddling, sheet flow, or other collection of water above or adjacent to disposal areas. This design specification has kept most of the permanent program and interim ash disposal areas unsaturated, which can be verified from the monitoring well data. In addition to this, all post-mining drainages that intersected an ash disposal area were modified to flow across the ash disposal area at approximately right angles to the long axis of the disposal site to minimize potential infiltration of surface waters into the ash. This design specification limits the amount of contact time that running water has with the ash-reclaimed areas.

Navajo Mine monitors a suite of wells in a historic, Pre-Law CCB disposal area (Bitsui and Watson Pits) that has become water-saturated due to NAPI activity adjacent to the area. It is important to note that disposal of CCB in this area occurred not only prior to SMCRA but prior to NAPI activities. A map displaying the outline of the Bitsui ash disposal area and relevant wells is seen in Figure 1. The influence of NAPI activity in the area has raised groundwater tables and increased surface water movement contributing to the saturation level of the buried CCBs.

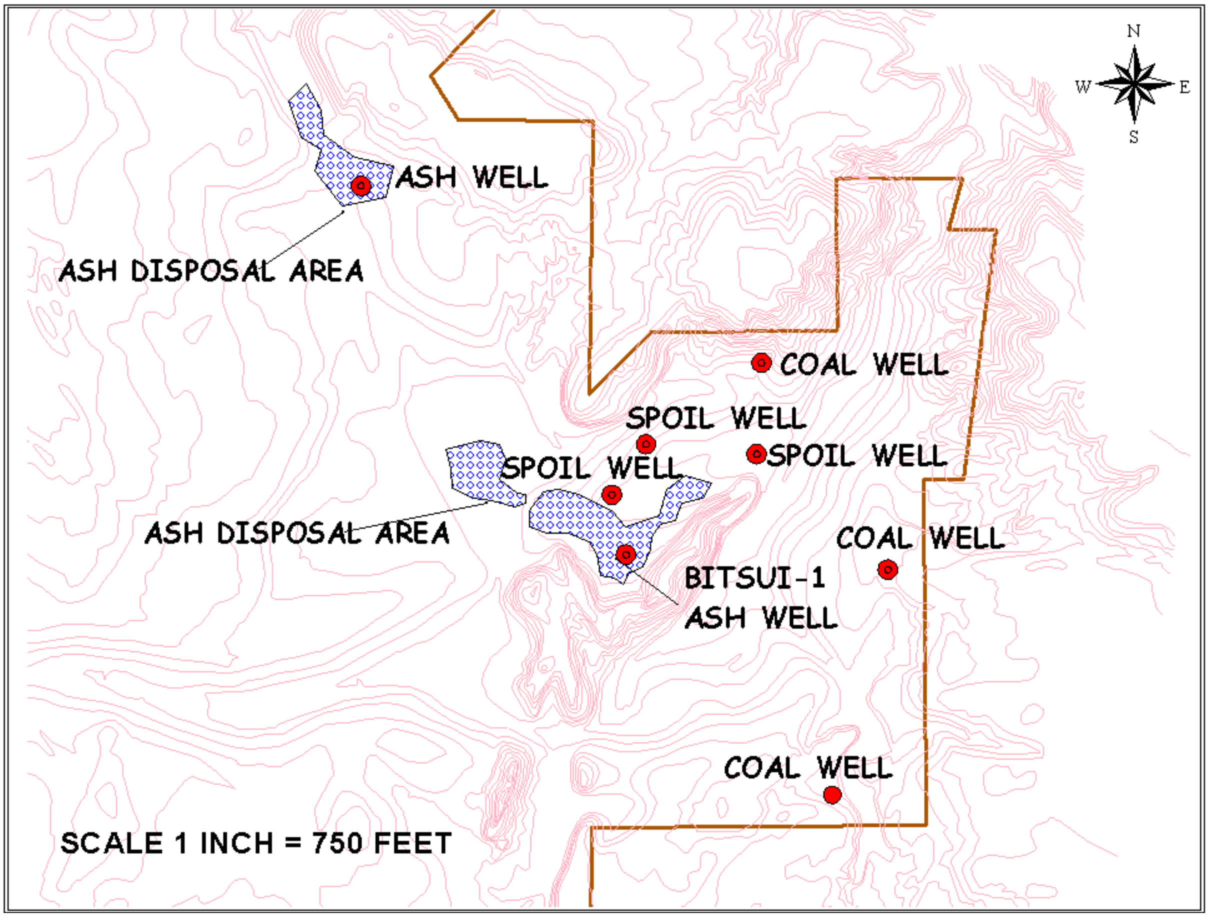

Figure 1: Bitsui Ash Disposal Area Delineation and Monitoring Wells

Ash was covered by a minimum of 10 feet of spoil material, plus any required topdressing and the required topsoil thickness. The spoil material has a low hydraulic conductivity of 10^{-6} cm/sec (four samples ranged from 1.66 x 10^{-6} to 5.4 x 10^{-6} cm/sec), which has helped to minimize vertical infiltration of surface water. During the process of reclamation, active ash disposal areas were regularly overlain with spoil material to cover the surface and minimize fugitive dust as the ash was backfilled into the pits (BHP Billiton 2010, Ch. 12).

The geological conditions surrounding the Navajo Mine pits where the ash was disposed create favorable condition for ash disposal in pits. After mining was completed in the ash disposal areas, the pit floor was directly on top of a low-conductivity (10^{-7}cm/sec, comparable to many commercial grade liners) shale/mudstone stratigraphic unit which is part of the lower shale members of the Fruitland Formation. This layer mitigates vertical transport of CCB leachate-laden water into the underlying PCS unit. The surrounding spoil disposed in the pits along with the CCBs is a mixture of sandstones, mudstones, coal processing waste, and shale.

Hydrologic Effects

Pre-mine water level data from the coal seams record that the seams were dry (unsaturated) in the majority of the lease, particularly Barber, Pinto, and Doby pits, except for a few localized areas in Area III (Lowe/Dixon pits). Hydraulic conductivity within the coal seams in the Navajo Mine, determined from aquifer tests reaches a maximum of 2.68 X 10^{-5} cm/sec in some places (BHP Billiton 2010, Ch. 6). It could potentially take quite a long time for ash disposal areas to become saturated in some places because of the slow groundwater velocities in the lease area and because of the small effective porosity of the coal seams through which transport occurs.

Intense irrigation of NAPI agricultural fields immediately to the east of the Bitsui pit have contributed to cause portions of backfilled and reclaimed pits in Bitsui to become saturated with water. Shallow groundwater has accumulated in aeolian sand units south and east of the Bitsui area and is perched on top of the low permeability shale and mudstone units of the Fruitland Formation. The saturation measured in the reclaimed area results in part from excess irrigation water migrating down gradient from the agricultural fields and toward the backfilled pit and also from the gradient created by Morgan Lake (0.01 ft/ft). Regional shallow groundwater gradients (Keller-Bliesner 1997) in the sand unit indicate that the groundwater contained in the aeolian sand will discharge to Bitsui Wash.

The Bitsui area was mined between 1964-1965 and was backfilled in the mid-1970s. Some of the backfill in this area consisted of ash from the Four Corners Generating Station. NAPI activity began in the late 1970s. The Navajo Mine has been monitoring groundwater levels and quality in the Bitsui area since 1995. A total of seven monitoring wells were placed in both spoil and ash disposal areas, and in the No. 8 coal seam within the immediate Bitsui area as seen in Figure X5. Additionally, water level and chemistry data was collected from the No. 8 coal seam well KF84-16 that is 1,400 feet to the east of the Bitsui area. Monitoring of static water level in the No. 8 seam coal in the Bitsui area began in 1985 in wells KF83-1 and KF84-16. Over an 11-year period from 1985 to 1996, water levels in the No. 8 coal seam rose 11 feet in well KF83-1 to the southeast and 6 feet in well KF84-16, further to the east. Water levels in both wells appear to have reached an equilibrium stage with relatively little change since 1996. Monitoring of these two particular wells has since ceased.

No. 8 coal seam wells Bitsui-2 and Bitsui-3 are located in the former highwall adjacent to the mined out area and have been monitored since 1995. Water levels from these two wells record a pattern of initial recharge followed by a period of steady state that is similar to wells KF-84-16 and KF83-1. The cumulative effect of the return flows from irrigation has produced perennial surface water flows in Bitsui Wash and a large perennial pond upslope of the mined out area. These perennial sources of water located at a higher elevation than the former Bitsui pit would have sufficient volume of flow, given enough time, to migrate down slope and saturate the Bitsui mined out area. The likely sequence is that soon after NAPI began irrigating, return flows began accumulating in the mined out areas until a steady state condition developed. Due to the low groundwater velocities in the area and the large distance (about two miles) from Morgan Lake, it probably has contributed significantly less to the affected saturation levels in the Bitsui pit.

Leachate Studies

The CCBs from the Four Corners power plant were analyzed along with coal spoil from the Navajo Mine to determine chemical constituents. Column leaching tests were performed on the CCBs to measure how much a number of key constituents were susceptible to leaching. Chromium, boron, molybdenum, potassium, magnesium, calcium, and sodium were determined to be key species for evaluation (Lamkin 1981). These elements were selected because they were found to approach or exceed the drinking water standards in the RCRA leachates or because they were seen as being representative of the behavior of the major species. The specific method used in this study was the Extraction Procedure (EP) method, which was congruent with RCRA requirements at the time the study was published. Furthermore, the attenuation capacity of the overburden was examined to ascertain the amounts of leachate that could be effectively removed by being filtered through it. The results from this study and a chemical analysis of the spoil and CCBs are presented in Table 1 and Table 2.

Table 1: Leachate Analysis of CCBs (Lamkin 1981)

Chemical of Concern	Total Solid Phase Concentration in CCBs (mg/kg)	Leachable Concentration from CCBs (mg/kg)	Attenuation Capacity of Overburden (mg/kg)
Potassium	6000	34	10
Magnesium	2500	1	0
Calcium	24000	1570	1260
Sodium	16000	270	0
Chromium	30	0.22	0.49
Molybdenum		2.6	0
Boron	220	52	0

In the mid 1980s, an additional study was conducted on the Navajo Mine to determine whether leaching of spoil material and CCBs could potentially have any effects on the environment. Mixtures of spoil and CCBs were leached in the batch leaching process with natural waters from the site. The batch leaching procedures accelerated the leaching process and determined in a shorter time period what the long term contact between native groundwater, CCBs, and spoil would produce in terms of water chemistry. The data collected from this study was evaluated to determine the net geochemical impact expected as a result of the CCB disposal at the mine site. Additionally, the attenuation properties of various solid materials was evaluated. This study was a follow up to the initial one that characterized the ash composition.

Concentrations in the surface water leachate for boron and selenium increased when leached through fly ash (BHP Billiton 2010, Appendix 11-K). However, the levels of boron declined slightly when leached through a mixture of ash and spoil, and the increased selenium concentrations were similar to the selenium concentrations in leachate produced by spoil alone. The iron concentration in both surface and groundwater decreased following leaching through spoil, CCBs, or a mixture of the two.

Overall, the conclusions from the study were that the leachate nearly always had higher TDS than the initial groundwater. One exception to this was in the case of leachate produced from a particular mixture of ash and spoil that had lower TDS and lower trace metal concentrations than natural groundwater from coal seams #4-6, though this instance isn't representative of prevalent conditions in the reclaimed areas. Many different attenuation processes such as high cation exchange capacity (CEC) of the spoil, formation of polymeric iron hydroxide complexes, and sorption to CCBs and spoil were suggested.

Table 2: Concentration of Chemical Constituents in CCBs and Spoil (Lamkin 1981)

Element	Concentration (mg/kg)	
	CCBs	**Spoil**
Aluminum	120000	7400
Arsenic	32	6
Barium	700	42
Beryllium	<0.1	
Boron	220	8
Cadmium	<1.6	0.9
Calcium	24000	17000
Chromium	30	3
Cobalt	21	7
Copper	61	6
Iron	23000	13000
Lead	55	32
Magnesium	2500	3100
Manganese	160	200
Mercury	0.033	0.2
Molybdenum	<0.40	<6
Nickel	<0.60	9
Potassium	6000	1400
Selenium	4	<2
Silicon	260000	
Silver	<0.40	<0.2
Sodium	1.60%	2700
Strontium	320	
Titanium	5100	
Uranium	<6.0	
Vanadium	97	
Zinc	150	63

Potential Offsite Migration

Based on the potentiometric surface for the No. 8 coal, the discharge locations for the re-saturated mine spoil within Area I are projected to be: the subcrop of the No. 8 coal and the Fruitland Formation beneath the alluvium of San Juan River Valley to the northeast of Area I and down-dip in the No. 8 coal Seam toward the drawdown influences of nearby coal bed methane wells (BHP Billiton 2011, Chapter 11).

The subcrop of the No. 8 coal seam beneath the alluvium in the San Juan River Valley occurs at elevations below the water levels in the coal seam to the south. The approximate location for the coal subcrop is depicted in Figure 2. The extent of the San Juan River alluvium along the Fruitland Formation subcrop is also mapped out in this figure. This subcrop location along the alluvium of the San Juan River is thought to be the primary discharge location for groundwater in the No. 8 coal seam and in the undifferentiated Fruitland Formation.

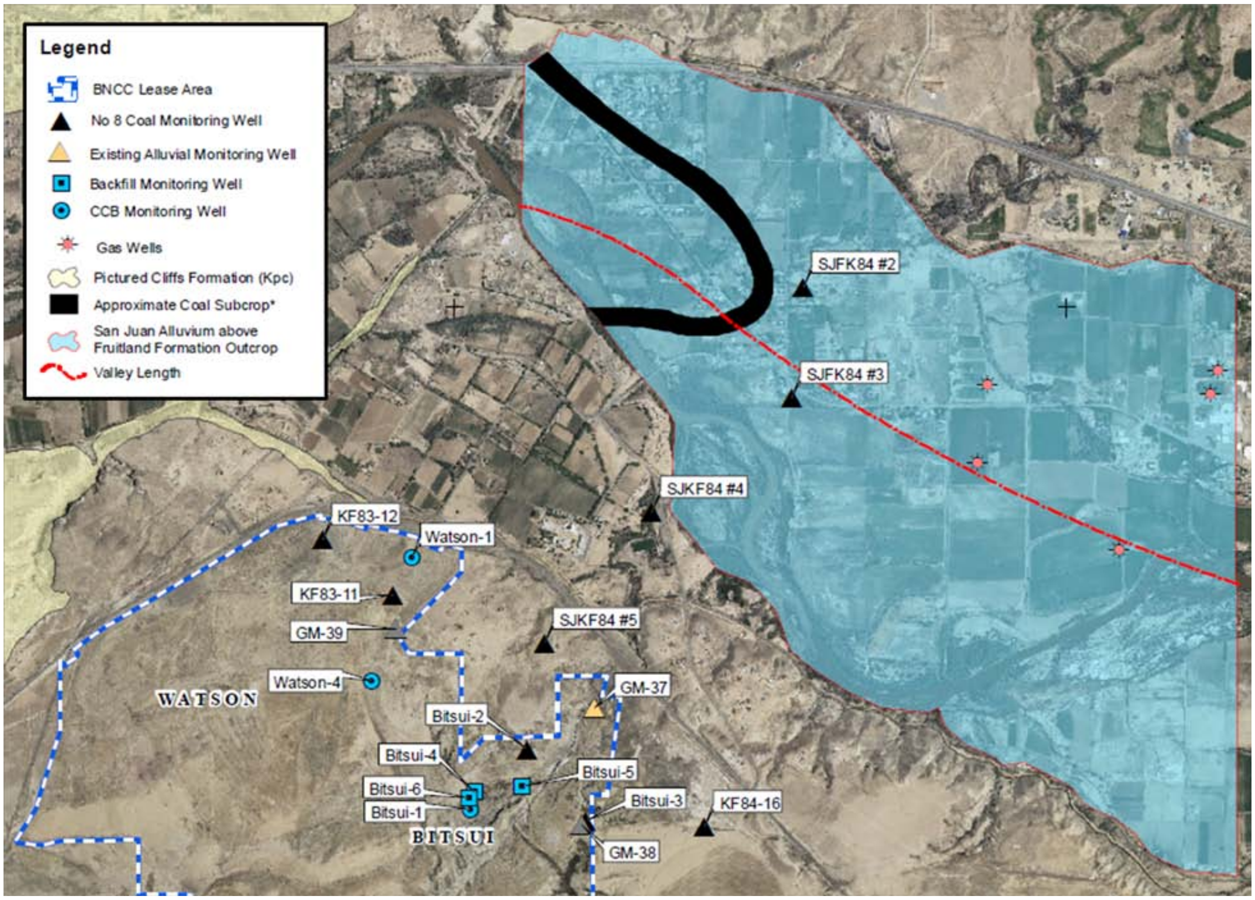

Figure 2: Fruitland coal subcrop and San Juan Alluvium

A hydraulic conductivity of 0.08 feet per day from this table is considered a reasonably conservative estimate for the No. 8 coal based on the test results for wells SJKF84 #3, SJKF84 #4 and SJKF84 #5 located in the coal down gradient of the Bitsui Pit. The porosity of coal seams is primarily associated with cleating and small scale fracturing of the coal. Porosity estimates ranging from 0.02 to 0.007 were obtained for the Fruitland Formation coals from tests conducted for the Western Cretaceous Coal Seam Project (Mavor 1992). An estimate of coal porosity of 0.01 was used for modeling. This estimate also appears to match the rate of transport from the Bitsui Pit to well Bitsui-2 and has been used in the model calibration and simulations.

An elevation difference of 63 feet is calculated for the water elevation of 5,164 feet measured in the Bitsui Pit and the water elevation of 5,101 feet estimated in the alluvium at the coal subcrop. The horizontal distance between the Bitsui Pit and the coal subcrop is approximately 7,300 feet resulting in an average hydraulic gradient between the Bitsui Pit and the groundwater at the coal subcrop of 0.0086 ft/ft.

Based on the porosity and hydraulic conductivity for the coal, the groundwater velocity is estimated to be 0.069 feet per day, and it would take 290 years for water from the mine pit to flow the 7,300 foot distance through the coal from the Bitsui Pit to the coal subcrop under the San Juan River alluvial aquifer. The groundwater velocity in the undifferentiated Fruitland Formation is expected to be at least 5 times lower based on an estimated effective porosity of 5% and because of the low hydraulic conductivity estimates based on the extent of shale and claystone within the unit and the observations from mining and exploration drilling.

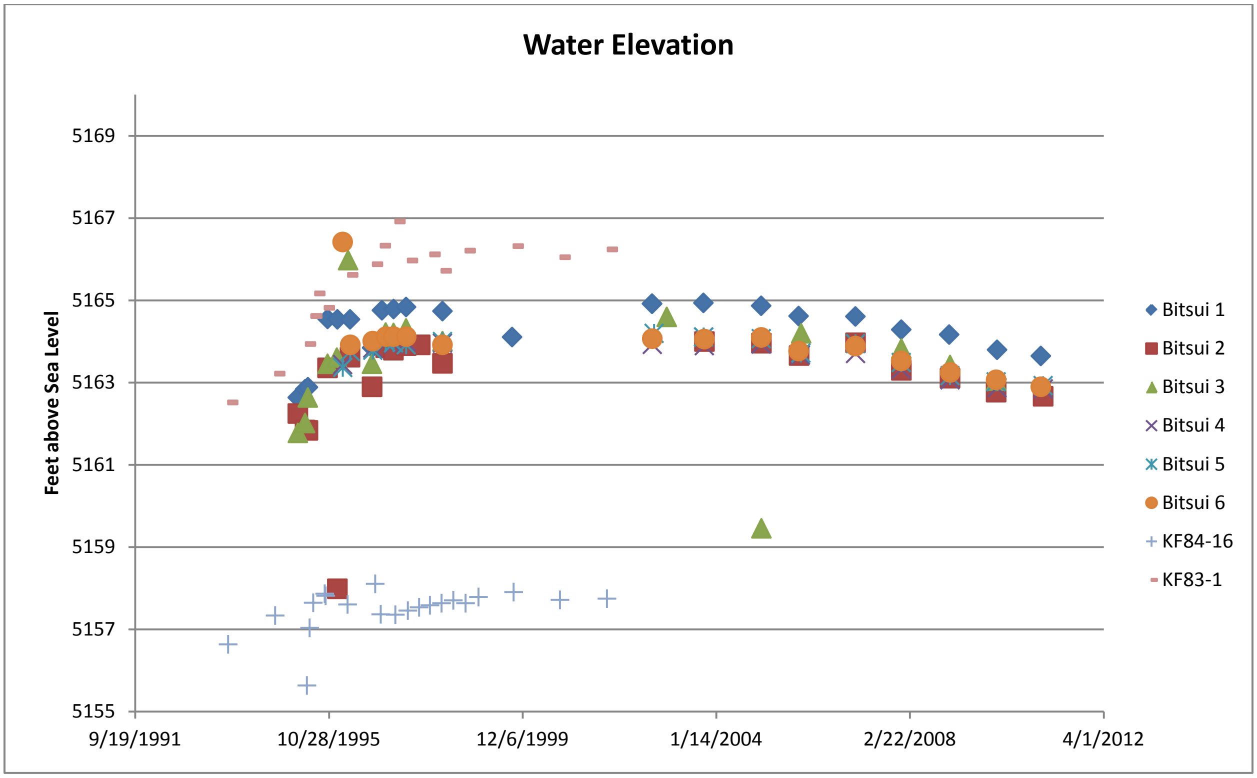

Figure 3: Water Table elevation of Select Wells in the Bitsui Pit Pre-Law Area

Groundwater Modeling

A simple advection-dispersion model was built to attempt to understand the characteristics of groundwater movement and leachate attenuation in the Bitsui pit section of Area 1. It is thought that the conditions in this area represent a worst-case scenario for the long-term impacts of CCB disposal at the Navajo Mine. Specifically, the model measures the transport of boron, modeled as a conservative geochemical tracer, from the upgradient Bitsui CCB disposal area to the downstream Bitsui 6 spoil well. The distance between the maximum extent of the CCB disposal and the downgradient well is a horizontal distance of about 33 feet, or 10 meters (BHP Billiton 2011, PHC). Approximate concentrations of boron and other parameters of interest within this CCB disposal area are inferred by data recorded at the Bitsui 6 ash-disposal well. The groundwater gradients in the Bitsui area trend towards the northwest where discharge ultimately occurs in outcrops of the Fruitland Formation next to the San Juan River. In an effort to reduce the uncertainty and the number of variables, boron was chosen in an attempt to derive as much information about the groundwater conditions as possible, since other chemical species may degrade and attenuate considerably over time and distance.

Advection-dispersion models assume that a center of mass is traveling through the subsurface at the same speed as the average groundwater velocity (Fetter 2001). As the plume moves through the subsurface over time, dispersional effects cause it to exhibit a Gaussian normal-distribution concentration gradient, similar to a bell shaped curve. Dispersion is a function of the tortuosity in the subsurface, but in this model it was calculated based on an empirical formula. If the initial time in which transport began is known, as well as the distance the plume traveled, the groundwater velocity (pore water velocity) and hence the dispersion coefficient can be calculated iteratively.

Certain assumptions went into making the model. One assumption that is typical of groundwater modeling is that the aquifer is homogeneous. In the case of the CCB/spoil disposal pits, this is a more than reasonable assumption. Since the area was reclaimed sometime around 1975 and because extensive NAPI activity in the area didn't occur until 1980, the transport is assumed to have started in 1985. This is assumed because it would have taken some time for the pit to become saturated, for the boron to start leaching out of the CCBs, and for the plume to start moving at any appreciable rate. The nature of the loading that created the plume is assumed to be impulse, or slug loading because it was found to fit the data more accurately than a continuous load. Model parameters are shown in Table 3.

Depending on what assumption is made for the distance the plume traveled from the source to the receiving well (Bistui 6), different groundwater velocities can be calculated from this model. The results of the model were evaluated using two distances from the assumed point source to the downgradient well. In one case 33 feet was used since it is the distance between the maximum extent of the CCB disposal and Bitsui 6 well and in the other case 172 feet was used because it is the distance between Bitsui-1 (CCB well in Bitsui pit ash disposal) and Bitsui-6 (closest downgradient spoil well in the Bitsui pit). Based on the assumption that the distance between the source and downgradient well is 33 feet, a groundwater velocity of 0.6 meters/year, or about 10^{-6} cm/second, was calculated after calibrating the model to fit the breakthrough curve in the downgradient well, as shown in Figure 4. If one assumes that the distance between the source and the downgradient well is 172 feet a groundwater velocity of 3.285 meters/year, or 10^{-5} cm/second, is calculated. Because of the slow velocities involved in the groundwater transport, it could take anywhere from 85 to 450 years for leachate to even reach the coal seams at the edge of the CCB and spoil disposal area of Bitsui Pit given the current conditions.

The results of the model show that transport through the areas reclaimed with fly ash is considerably slower than what can be expected in the coal seams. The model fit the data with a coefficient of determination (R squared) value of 0.96, making it an accurate reflection of the data. This being said, there is always uncertainty concerning groundwater modeling. An alternative possibility to explain the data is one in which a continuous load rather than an impulse load is released from the ash disposal area and then migrates down-gradient and becomes attenuated in the spoil. Although this is also a possibility, the evidence in the literature concerning boron attenuation concludes that it remains fairly stable as it moves through the subsurface (Heebink 2001) (Manoharan 2007). In addition to this, based on the ash characterization studies, the amount of boron present within the ash is limited and most likely would have been released immediately following water-saturation as an impulse load.

The model was calculated using the following equation (Fetter 2001):

$$C = \frac{Co}{2}\left[erfc\left(\frac{L - vxt}{2\sqrt{Dlt}}\right) + \exp\left(\frac{vxL}{Dl}\right) erfc\left(\frac{L + vxt}{2\sqrt{Dlt}}\right)\right]$$

Where;

C=concentration at a specific x coordinate and time

Co=the initial source concentration

Dl=*aLvx* =longitudinal dispersion coefficient $\left(\frac{Length^2}{Time}\right)$

L=flow path length

$aL = 0.83(\log L)^{2.414}$ = the apparent longitudinal dynamic dispersivity (length)

vx=average ground water velocity $\left(\frac{Length}{Time}\right)$

t=time since movement began

Table 3: Advection Dispersion Model Input and Output Parameters

Year	1990	1992	1994	1996	1998	2000	2002	2004	2006	2008	2010
C (g/m^3)	0.016	0.221	0.874	1.959	3.246	4.510	4.783	3.786	2.930	2.226	1.667
Co (g/m^3)	9	9	9	9	9	9	9	9	9	9	9
L (m)	10.06	10.06	10.06	10.06	10.06	10.06	10.06	10.06	10.06	10.06	10.06
vx (m/d)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Dl (m^2/d)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
t (d)	1825	2555	3285	4015	4745	5475	6205	6935	7665	8395	9125
aL (m)	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835

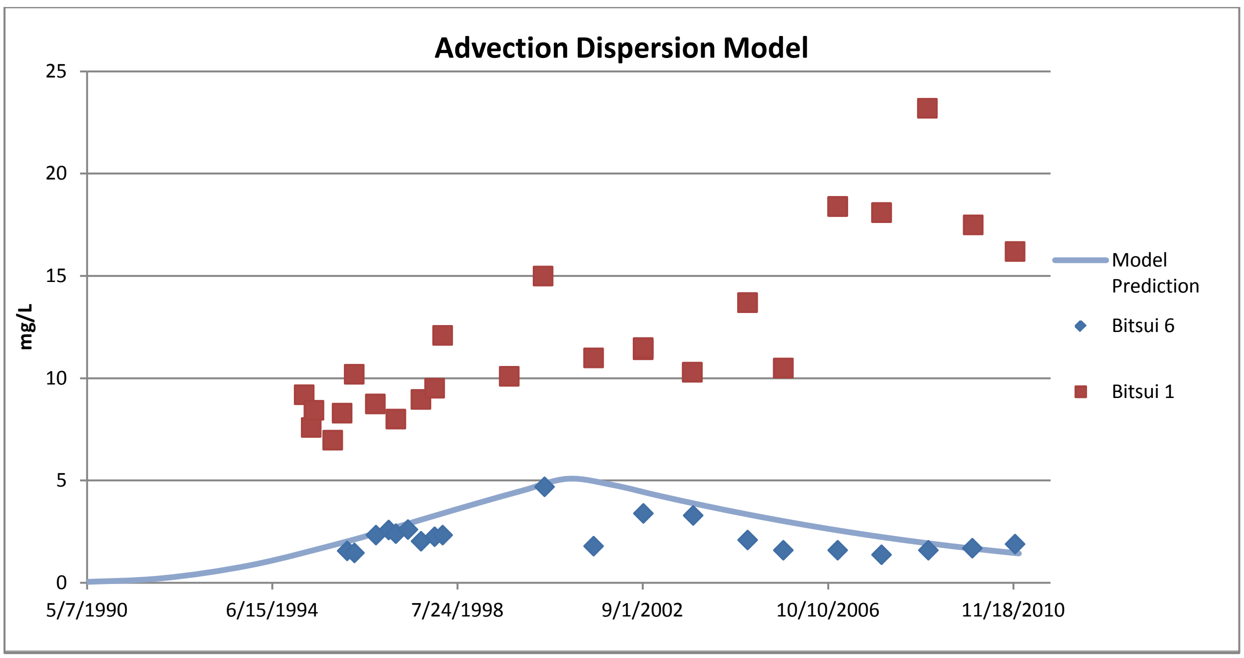

Figure 4: Advection-Dispersion Modeling of a Boron Breakthrough Curve

Conclusions

There were varying hydraulic gradients during the timeframe that was modeled. This is important to consider because hydraulic gradient is the driving force for determining groundwater velocity, particularly in unconfined conditions (Fetter 2001). The gradients varied from extremes of 0.02 ft/ft in 1996 to 0.005 ft/ft in 2008, as is seen in Figure 3. The gradients could have also been greater at the beginning of the transport sequence while the reclaimed area was becoming saturated from NAPI water; however, there is no data to back up this claim. Nevertheless, it is concluded that the groundwater velocity calculated from the model represents a steady state condition in the reclaimed area where there is minimal driving force for groundwater movement.

The reclamation of the CCB disposal areas at the mine has been sufficient in part because of the natural conditions prevalent in the area and also because precautions were taken when engineering the disposal and reclamation. Thus far negligible impacts have resulted from the CCB disposal. It is also unlikely that any significant future effects will ensue from the CCB disposal at the Navajo Mine because of the very slow groundwater movement and the likely attenuation of contaminants of concern as they migrate through the subsurface. Therefore, OSMRE concludes that potential impacts from CCB disposal at the Navajo Mine are negligible.

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