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Progress Report

Radioactive Emissions from Coal Production and Utilization

July 1, 1978—September 30, 1979

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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RADIOACTIVE EMISSIONS FROM COAL PRODUCTION AND UTILIZATION

by

Paul Wagner, David R. Dreesen
Eugene M. Wewerka and N. Roy Greiner

ABSTRACT

Radioactivity from the uranium-238 and thorium-232 series was measured in a variety of coals and wastes from the coal-based power production cycle. Leachates prepared from these coals and wastes were also analyzed for radioactivity. For the most part, the radioactivity encountered in coals and coal-cleaning waste is about the same as that found in ordinary rocks and soils. The radioactivity in the ashes is generally about five times higher than in the coals. In some cases fly ash contains even higher levels of radioactivity, especially from the volatile radionuclides lead-210 and polonium-210. Lead-210 is the only radionuclide that appears to be readily leached from the solids.

I. INTRODUCTION

The potential health hazards posed by low level releases of radioactive substances in the various sections of coal production and use have been the subject of some controversy. Because of the uncertainty in this area, several studies have been directed at identifying resultant potential environmental problem areas. These, for the most part, have concerned the partitioning and discharge of radioactive substances and other trace elements [1-4] during coal combustion. Some radionuclide contents of gaseous and particulate stack emissions, boiler and precipitator ash, and vegetation and soils surrounding coal burning facilities have been determined, and the evidence from these studies indicates that most of the radionuclides in the U and Th decay chains accu-

mulate in either the bottom ash or precipitator ash during coal combustion, although the concentrations of each are often not equal, due to elemental partitioning. It appears that air-borne radionuclide emissions during coal combustion can be maintained within acceptable levels by using efficient modern particle precipitators in the stacks of coal-fired boilers.[1] Studies of coal waste compositions have also yielded evidence of a small increase in radionuclide concentrations as compared to the original, mined material.[5]

Less is known about the environmental behavior of the radionuclides concentrated in the various ashes and sludges produced by coal combustion. Our measurements and those of others[4] indicate that radioactive materials in the ash fractions can be enriched by factors as high as 15 over those in the original coals. This is partly due to the normal concentration of these substances in the inorganic fraction that remains after removal of the organic coal components by combustion. An additional factor is the volatility of some radionuclides, such as Pb, Rn, and Po. After disposal, either in ash ponds or shallow land burial, these ashes could weather and be leached to release undesirable quantities of mobilized radionuclides. At this time there are not sufficient data available to assess the exact nature and the magnitude of the seriousness of such an ensuing environmental circumstance; however, we are currently performing laboratory leaching experiments to determine quantitavely the nature and magnitude of any such releases. In addition to the possible occurrence of leachable radionuclides, Rn gas might be emitted from coal storage, ash or sludge disposal areas in harmful concentrations.

Insufficient attention has been given to radionuclide release from other parts of the coal utilization cycle. One area that could prove to be even more troublesome than the ash disposal sites are the dumps for the wastes produced by coal cleaning. These wastes, which are primarily composed of coal mineral matter, contain U, Th, and presumably their radioactive daughter products. Coal cleaning wastes produce highly acidic leachates that are adept at dissolving or degrading the refuse structure. The drainage from high sulfur coal refuse dumps is often highly contaminated with trace elements and dissolved mineral matter, including appreciable quantities of radionuclides.[5] This is particularly true of the runoff or drainage from the highly pyritic refuse produced in the Midwest and Eastern U. S..

Although numerous expressions of concern about the seriousness of radioactive releases from mining and burning of coal have been made, little sub-

stantive information has been generated to indicate that radionuclide releases from any part of the coal utilization cycle pose an unusual risk to human health or to natural ecosystems.[2] Indeed the results of our own experiments and those of the Mound Laboratory (ML) and the EPA Eastern Environmental Radiation Facility (EERF) are in accord with these general conclusions. Mobilization of radionuclides by leaching, however, does raise an issue that has potentially significant environmental implications and must be considered in more detail. At this point in time, existing evidence has begun to indicate that radionuclide releases associated with all aspects of coal usage pose a minimal threat to the environment; however, it is imperative that any conclusion of this nature be backed by sound and substantiated evidence such as that now being generated at LASL, ML and EERF.

II. TASK DESCRIPTION

Three basic tasks are being performed to achieve the ultimate goal of this research, which is the definiton of environmental control strategies to mitigate undesirable impacts on the environment as a result of the release of radionuclides from coal usage. Simply stated, these tasks are:

I. Determine the actual radionuclide content of the coals and waste materials and the partitioning of radionuclides in the various sectors of the production and utilization of coals. It is recognized that the differences in coals (i.e. high sulfur coals, low sulfur coals, lignites, etc.) may exert a significant influence.

II. Assessment of the magnitude of radionuclide releases resulting from coal production and use and from the weathering and leaching of coals, coal wastes and combustion residues. This will include release of gaseous ^{222}Rn from coal storage piles. Results from Task I will direct our attention to those materials where the radionuclides have been concentrated, and laboratory investiagtions will identify those radionuclides that can be mobilized by wind suspension or leached by aqueous systems.

III. Identification of appropriate controls to ensure that any radionuclide releases recognized in Task II are kept within environmentally acceptable limits.

A. Task I

The overall experimental program has been a coordinated effort by the Los Alamos Scientific Laboratory (LASL), the Environmental Protection Agency (EPA) Eastern Environmental Radiation Facility (EERF), and the Mound Laboratory (ML). Sample collection is being done by the TRW Corporation under contract with the EPA Office of Radiation Programs. These field samples are being distributed to the appropriate laboratories for analysis. "Round-Robins" among LASL, EPA, and ML have compared analytical procedures for radionuclides in coals, coal residues, and aqueous solutions. These techniques and other existing techniques are being used to determine the mineral compositions, trace elements (where appropriate), and radionuclide contents of the field samples. LASL is currently concentrating on the high-sulfur Eastern coals and their utilization, ML on Western coals and their utilization. LASL also plans to investigate control technologies designed to prevent releases of concentrated gaseous radionuclides.

As a final exercise in these researches, more representative field samples especially effluents, should be collected and analyzed to establish the correspondence between the laboratory data and the actual environmental circumstances.

B. Task II

The second task makes use of laboratory and field experiments to define the nature and magnitude of the radionuclide releases from coal mines, storage areas, refuse dumps and ash disposal sites. This is being done by means of laboratory leaching experiments involving various coal, coal waste and ash samples and by conducting radon release measurements.

Little attention has been given to radionuclide releases from coal mining and cleaning. While considerable work has been done on the acid character and trace element content of underground and surface mine drainages, there have been few studies of radionuclide leaching and releases from these sources. The extent of the undesirable environmental impact due to the mining activities should be evaluated for potentially hazardous radionuclide contamination, and a similiar study should be conducted on stored coals. Our data indicate that the radioactivity in the coal cleaning wastes may be twice that of the cleaned coals and that some of the radionuclides are released and mobilized in the drainages. These wastes are primarily composed of coal mineral matter, which contain U, Th, and their daughter products. A major factor in radionuclide

release from coal cleaning wastes is that the weathering of many refuse materials produces highly acidic leachates that are adept at dissolving or degrading the refuse structure. The drainage from high sulfur coal refuse dumps is often highly contaminated with trace elements and dissolved mineral matter, and could also contain worrisome quantities of radionuclides. This is particularly true of the runoff or drainage from the highly pyritic refuse produced in the Midwest and Eastern U. S.. Such dissolved radionuclides can be transported and could be accumulated by natural processes in the downstream ecosystems. For completeness this study will be expanded to include storage and wastes from western coals, particularly those with high lignite content.

The environmental behavior of the radionuclides concentrated in the various ashes and sludges produced by coal combustion is not well known. Our measurements indicate the radioactive materials in the combined fly and bottom ash fractions are enriched over those in the original coals. This is due to the normal concentration of these substances in the inorganic residues that are produced upon removal of the organic coal components by combustion. After disposal, either in ash ponds or by burial, these ashes could weather and be leached to release radioactive substances; our leaching experiments are addressing this issue. In addition to the leachable radionuclides the release of radon gas from coal piles and waste disposal areas should be addressed. In particular, areas where large quantities of raw coal or ash have been stored should be monitored to determine if ^{222}Rn releases constitute an environmental problem.

Experiments designed to quantify radionuclide releases in these areas just described are necessary to the assessment and evaluation of environmentally sensitive issues related to coal use.

C. Task III

The third part of the program, that of the environmental controls development, will follow the first tasks. As environmentally troublesome areas appear as a result of the distribution and release of radionuclides, appropriate environmental control technologies will be developed. Here, experience gained in LASL's program on coal wastes will be utilized where applicable. In general control technologies for coals and coal wastes fall into one or more of the following classes.

1. Treat to prevent contaminant release from the waste itself (e.g. calcining or preleaching).

2. Treat to prevent contaminant release from the storage pile or waste dump (e.g. co-disposal with lime in high sulfur wastes can prevent trace element releases).
3. Treat the effluent (e.g. pH control, ion exchange, etc.)

These strategies have proved to be effective for trace element contaminants. This gives us confidence that they will also apply in a situation where pollution by radionuclides exceeds acceptable levels. Activities in this area would proceed as soon as problems of radionuclide release(s) are identified.

III. RESULTS OF EXPERIMENTAL PROGRAM

Figures 1 and 2 show the decay chains for ^{238}U and ^{232}Th. These are the major radionuclide decay series that must be considered in an analysis of radioactive emissions associated with coal utilization. In this work ^{238}U, ^{226}Ra, ^{214}Bi, ^{210}Pb, ^{210}Po, ^{232}Th and ^{208}Tl are the key radioisotopes of merit for which we analyze.

Both solids and liquids are analyzed for the radioactive isotopes. The solid samples include coal, coal preparation wastes, ashes (bottom, precipitator, and fly), and scrubber sludge. Liquid samples are leachates from these solids. In general, results from the solid analyses tell us where a radionuclide is being concentrated, and analyses of the leachates tell us which of these radionuclides can be solubilized and transported by ground or surface waters.

One of the early problems encountered in this research was the reproducibility of the analyses of the radionuclides. To be able to compare interlaboratory results it was first necessary to certify that all laboratories could get the same answers on a group of "standard" samples. To accomplish this we compared analytical results on a set of round robin materials. These were samples of coal, bottom ash, and fly ash that were distributed to the Los Alamos Scientific Laboratory, the Mound Laboratory and the EPA Eastern Environmental Radiation Facility. At each laboratory they were analyzed for ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po, and ^{232}Th. The results of these measurements are tabulated in Appendix A, where it can be seen that the agreement of the analyses among all three laboratories is quite good.

Table I lists the samples that we have received. The power plants sampled are listed by number and represent major coal producing areas in the U.S..

Nuclide	Half-life	Energies (MeV) α	β
$^{238}_{92}U$	4.5×10^9 y	4.2	
$^{234}_{90}Th$	24 d		0.15
$^{234}_{91}Pa^m$	1.2 m		2.3
$^{234}_{92}U$	2.5×10^5 y	4.8	
$^{230}_{90}Th$	8.0×10^4 y	4.7	
$^{226}_{88}Ra$	1600 y	4.7	
$^{222}_{86}Rn$	3.8 d	5.5	
$^{218}_{84}Po$	3.0 m	6.0	
$^{214}_{82}Pb$	27 m		0.8
$^{214}_{83}Bi$	20 m		1-3
$^{214}_{84}Po$	164 μs	7.7	
$^{210}_{82}Pb$	21 y		0.02
$^{210}_{83}Bi$	5 d		1.2
$^{210}_{84}Po$	138 d	5.3	
$^{206}_{82}Pb$	Stable		
		8α (∿ 5 MeV)	6β (0.02 - 3 MeV)

Fig. 1.
Principal Activities of the ^{238}U (4n + 2) Series

Nuclide	Half-life	α	β
$^{232}_{90}Th$	1.41×10^{10} y	4.0	
$^{228}_{88}Ra$	6.7 y		0.06
$^{228}_{89}Ac$	6.13 h		1.5
$^{228}_{90}th$	1.91 y	5.4	
$^{224}_{88}Ra$	3.64 d	5.7	
$^{220}_{86}Rn$	55 S	6.3	
$^{216}_{84}Po$	0.15S	6.8	
$^{212}_{82}Pb$	10.64 h		0.4
$^{212}_{83}Bi$	60.6 m		
64% / 36%			
$^{212}_{84}Po$	304 ns	8.8	
$^{208}_{81}Tl$	3.10 m		1.5
$^{208}_{82}Pb$	Stable		
		6α (∿ 6 MeV)	4β (0.06 - 1.5 MeV)

Fig. 2.
Principal Activities of the ^{232}Th (4n) Series

TABLE I

STATUS OF POWER PLANT SAMPLES

Power Plant	Feed Coal	Bottom Ash	Fly Ash	Scrubber Output	Scrubber Input	Limestone Feed
M-1	A*	A*	-	A	A*	A*
M-2	A*	A*	A*	-	-	-
M-3	A*	A*	A*	-	-	-
M-4	A*	A*	A*	-	-	-
M-5	A*	A*	A*	A*	A*	-
M-6	A*	A*	A*	A*	A*	A*
A	-	A*	A*	A*	-	-
M-7	†	†	†	-	-	-
M-9	†	†	†	-	-	-
M-10	†	†	†	-	-	-
M-11	†	†	†	-	-	-

Symbols:
A Solid analysed
* Static leach test performed
† Sample received
- No sample

Of the seven plants analyzed to date two are from the Illinois Basin, two from the Appalachian Region, one from the Midwest, and one from the West.

At this time, we have performed leaching experiments using coal, fly ash, botton ash, and scrubber sludges (these results are described in the Discussion section of this report). The leachates are prepared by shaking 250 g of -20 mesh solid sample and 1250 ml of de-ionized water for 30 days. These are then filtered, and the pH, electrical conductivity, and total dissolved solids are measured. They are then analyzed for ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po and ^{232}Th.

IV. DISCUSSION

A. Coals and Coal Power Plant Residues.

Tables of the results of our analyses of radionuclide concentrations (i.e. activity) in coals and power plant residues are collected in Appendix B. The radioactivities are expressed as picocuries per gram (pCi/g) and, for reference, the following table lists some typical approximate ^{238}U activities for some of our samples and for four more familiar materials using these units.

TABLE II

SOME TYPICAL RADIOACTIVITIES

Material	Approximate ^{238}U activity (pCi/g)**
Carbonate Rocks*	0.7
Granite*	1
Soils*	0.6
Shale*	1
Coals	0.9 ± 0.5
Coal Wastes	1.7 ± 1.3
Fly Ash	5 ± 3
Bottom Ash	4 ± 2

* NCRP Report No. 45, pg. 59 (1975)
** Std. deviation given for our data, not available for NCRP data.

It is clear from the data contained in the tables in Appendix B that the ^{238}U radioactivity seen in raw coals approximates that found in naturally occurring soils and in sedimentary rocks. We have performed x-ray diffraction mineralogy measurements† on archive samples (obtained from EERF) of mid-western coal. This feed coal was from a single plant, but different samples had different ^{238}U activities. We found that the uranium appears to reside in the clay fraction of the coal ash. These measurements show a linear correlation between the illite content that we measured and the reported uranium activity (see Figure 3.). While this is not definitive, it is becoming increasingly clear, despite published remarks to the contrary,[2] that assessment of the radioactivity in coal must be viewed in light of the minerology of the contained ash.

The data in the tables indicate that the uranium and thorium in the coals are in secular equilibrium with their decay products. The scatter in our data precludes our concluding whether or not secular equilibrium has been obtained in the residues (ashes, sludges), at this time. This scatter is probably related to a combination of sampling and analytical uncertainties.

B. Radionuclides in Coals and Power Plant Wastes

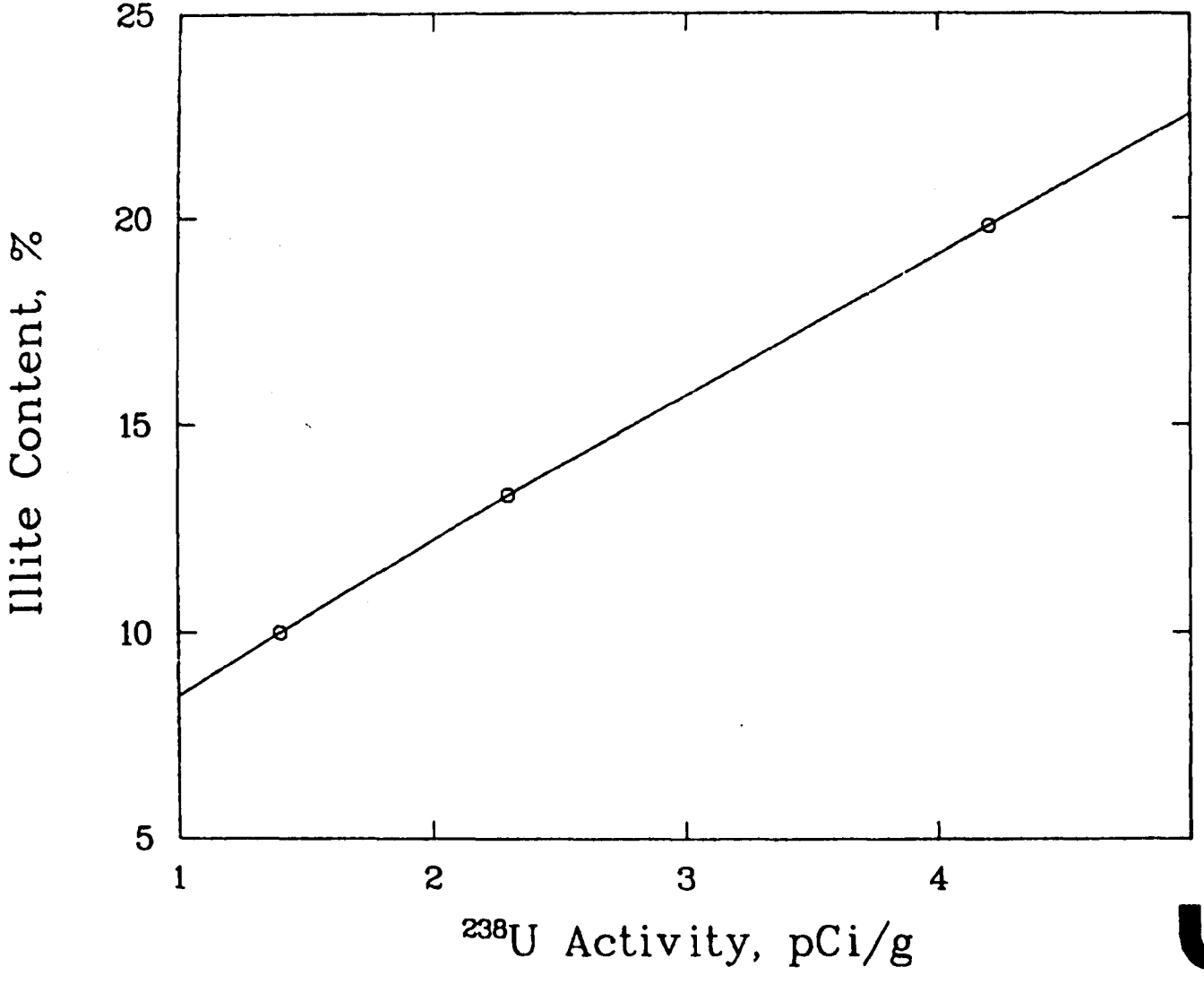
Comparison of the data in Tables B-1 through B-7 with the data in Table II shows that our coals generally have less ^{238}U activity than typical soils and rocks. Assuming secular equilibrium in both the coals and soil materials, the coals themselves appear to pose no particular hazard from the radionuclides measured here. On the average, bottom ash and fly ash show significant concentration (see below) of the radioactivity initially in the coal, which brings the absolute activity in the ashes somewhat above that in the average soil.

Tables B-8 and B-9 compare the concentration ratios of radionuclides to the concentration ratios of major mineral elements in the fly ash and bottom ashes. It should be recognized that secular equilibrium no longer necessarily exists for these samples, because of fractionation during combustion of the coal.

The concentration ratios for the major elements provide a baseline for comparisons of the radionuclide concentration ratios among the various plants and coals and also give a measure of the relative amounts of combustible and

† This work was done by J. M. Williams, J. P. Bertino, and P. L. Wanek

Figure 3. Variation of Illite Content with ^{238}U Activity



noncombustible (mineral) matter in the coal. In the bottom ash (Table B-9) ^{238}U, ^{226}Ra, ^{214}Bi, ^{232}Th (except for one case), and ^{208}Tl all appear to behave as the major elements, Al, Ti, and Fe. However, the bottom ash is depleted in ^{210}Pb by about a factor of three and in ^{210}Po by somewhat larger factors. The fly ash samples for Plants M-2 and M-4 show concentration ratios for all radionuclides that are considerably greater than the concentration ratios for the major elements. This is a curious result, because it involves elements that are not considered volatile. This result could be explained if the radionuclides were concentrated in minerals that form fine particles. All four plants for which there are data show a large concentration ratio for ^{210}Pb in the fly ash which complements the depletion of ^{210}Pb in the bottom ash. In the two plants that show large concentration ratios in the non-volatile radionuclides, there are even larger concentration ratios for ^{210}Po. But, in the two plants that show normal concentration ratios for the non-volatile radionuclides in fly ash there is no evidence of high concentration of ^{210}Po in the fly ash, even though the bottom ash from these plants was significantly depleted in ^{210}Po. This observation suggests there is an additional loss mechanism for ^{210}Po from these two plants.

Table B-10 summarizes the data on radionuclides in the coals and wastes from the several plants surveyed. This table gives a general idea of the situation, but it tends to obscure some of the important details discussed above.

C. Radionuclides in Coal and Waste Leachates

Presently we have analyses completed for the radionuclides ^{226}Ra, ^{210}Pb, and ^{210}Po in the leachates from coal, bottom ash, and fly ash. The analyses for ^{238}U and ^{232}Th have not been completed for these leached samples. These data are shown in Tables B-11, B-12, and B-13. Table B-14 shows some guidelines for effluents from the nuclear industry. These are presented for comparison purposes only.

Coal leachates appear to pose no serious hazard from the radionuclides for which we have analyses. However, two samples, M-3 and M-6, show small amounts of leachable ^{210}Pb. These happen to be fairly acidic leachates, but M-2, which also has a somewhat acidic leachate, shows effectively no ^{210}Pb. The worst fly ash leachate, M-2, has 4.7 pCi/ℓ, which is still small compared to the maximum permissible soluble concentration of ^{210}Pb in Table B-14.

The bottom ash and fly ash leachates appear to present no significant hazard from these radionuclides.

Radionuclide leachability studies were also done on some coal cleaning plant wastes in conjunction with the studies on coal and combustion wastes. These results are shown in Tables B-15 and B-16. Because coal cleaning removes mineral matter from the coal, one would expect the radionuclides to be somewhat concentrated in the waste. Data in Table B-15 show activities in these wastes that are generally higher than activities in raw coal (See Tables B-1) through B-7), although these wastes were derived from a different set of raw coals.

The highest activity in the coal preparation plant waste leachates comes from ^{210}Pb, as with the coal leachates. The highest ^{210}Pb activities are associated with acidic leachates, but one acidic leachate (plant G) shows very small ^{210}Pb activity. Evidently pH is not the sole factor governing ^{210}Pb leachability.

These data suggest that acidity is a factor in the leachability of ^{210}Pb. If so, the highest activities observed here (all from ^{210}Pb) may be substantially reduced by the pH control technology used to reduce other trace elements in leachates. This would reduce an already small risk from ^{210}Pb even further. The highest ^{210}Pb activity noted here, that in the coal gob leachate from plant C, comes from the gob that has the highest amount of ^{238}U and its daughters, which include ^{210}Pb.

V. SUMMARY AND CONCLUSIONS

The radionuclide activities in these bituminous and sub-bituminous coals and their solid wastes are not substantially larger than the activities seen in ordinary soils and rocks. The greatest potential hazard noted in these studies so far is from ^{210}Pb in coal gob leachate from a coal gob high in elements of the ^{238}U decay series. Although this leachate had only one-tenth of the maximum permissible soluble concentration of ^{210}Pb, it should be realized that the leaching was done under limited oxygen conditions. It is conceivable that natural conditions in a waste pile could result in increasing the leachable ^{210}Pb activity enough to cause concern in some cases. Use of higher ^{238}U content coals or concentration in soils or plants could also lead to hazardous levels of ^{210}Pb in the environment.

Our data suggest that there may be a lack of material balance on ^{210}Po in some plants, which raises the possibility of release of this radionuclide in the stack gas or on fine ash particles that escape from the scrubbers.

The mobilization of ^{222}Rn gas from these coals and other solid wastes remains to be addressed, as does the hazard from radionuclides in lignites. Some lignites are known to contain very large quantities of ^{238}U and presumably its daughters. These materials and their combustion products should be investigated to establish the magnitude of the environmental concerns, if any, that might result from the combustion of such lignites.

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APPENDIX A

RESULTS FROM THE ROUND ROBIN ANALYSES BY LASL, ML, AND EERF

TABLE A-1

ACTIVITY OF ^{238}U IN THE ROUND ROBIN SAMPLES

	Activity (pCi/g)		
SAMPLE	**LASL**	**MOUND**	**EERF**
Round Robin M-4 Coal (137-ORP-CF)	0.81	0.80	0.98
M-4 Coal	0.78		
Round Robin M-4 Bottom Ash (137-ORP-19)	3.6	3.6	3.9
M-4 Bottom Ash	3.2		
Round Robin M-2 Fly Ash (EERF-80083)	5.6	5.8	6.4
M-2 Fly Ash	5.9 5.5		

TABLE A-2

ACTIVITY OF ^{226}Ra IN THE ROUND ROBIN SAMPLES

	Activity (pCi/g)			
	LASL			
Sample	^{222}Rn Emanation	Gamma Spectroscopy	MOUND	EERF
M-4 Coal (137-ORP-CF)	0.74	0.90 1.4	0.81	0.85
M-4 Bottom Ash (137-ORP-19)	4.1	4.7 5.9	3.8	4.1
M-2 Fly Ash (EERF-80083)	4.2	5.8 5.7	4.3	3.1

TABLE A-3

ACTIVITY OF ^{210}Pb IN THE ROUND ROBIN SAMPLES

	Activity (pCi/g)		
Sample	LASL	MOUND	EERF
M-4 Coal (137-ORP-CF)	0.84	0.82	0.18
M-4 Bottom Ash (137-ORP-19)	0.9	0.36	0.25
M-2 Fly Ash (EERF-80083)	12	9.5	7.9

TABLE A-4

ACTIVITY OF ^{210}Po IN THE ROUND ROBIN SAMPLES

	Activity (pCi/g)		
Sample	LASL	MOUND	EERF
M-4 Coal (137-ORP-CF)	0.97	0.74	0.71
M-4 Bottom Ash (137-ORP-19)	0.37	0.17	0.20
M-2 Fly Ash (EERF-80083)	7.2	8.1	6.8

TABLE A-5

ACTIVITY OF ^{232}Th IN THE ROUND ROBIN SAMPLES

	Activity (pCi/g)			
	LASL			
Sample	Neutron Activation	Gamma* Spectroscopy	MOUND	EERF
Round Robin	0.55**	0.55	0.53	0.39
M-4 Coal (137-ORP-CF)	0.52			
M-4 Coal	0.51			
Round Robin	2.92**	3.55	2.96	3.05
M-4 Bottom Ash (137-ORP-19)	2.53			
M-4 Bottom Ash	1.97			
Round Robin	1.85**	1.96	1.87	2.04
M-2 Fly Ash (EERF-80083)	1.97			
M-2 Fly Ash	2.11		1.98	

* Activity of ^{228}Th determined from ^{208}Tl gamma

** Special neutron activation-long irradiation, long count

APPENDIX B

TABLES OF RADIOACTIVITIES FOR COALS, COAL CLEANING WASTES, POWER PLANT RESIDUES, AND THEIR LEACHATES.

TABLE B-1

^{238}U CONTENT (pCi/g) OF COALS AND POWER PLANT RESIDUES

Power Plant	Coal(C)	Bottom Ash(BA)	Fly Ash(FA)	Scrubber Output(SO)	Scrubber Input	Scrubber Reactants	BA/C	FA/C	SO/C	FA/BA
M-1	1.9	7.3	*	3.2	0.8	1.2	3.8	-	1.7	-
M-2	0.5	2.9	5.7	*	*	*	5.8	11.4	-	2.0
M-3	0.7	2.1	4.2	*	*	*	3.0	6.0	-	2.0
M-4	0.8	3.4	10.3	*	*	*	4.3	12.9	-	3.0
M-5	1.0	6.6	5.8	2.8	**	2.7	6.6	5.8	-	0.9
M-6	0.5	2.5	2.2	1.1	0.2	0.2	5.0	4.4	2.2	0.9
A	**	5.3	4.3	2.2	**	**	-	-	-	0.8
Mean	0.9	4.3	5.4	2.3	* -	-	4.8†	6.0†	2.6†	1.3†
Std. Dev.	0.5	2.1	2.7	0.9						
Range	0.5-1.9	2.1-7.3	2.2-10.3	1.1-3.2	0.2-0.8	0.2-2.7	3.0-6.6	4.4-12.9	1.7-2.2	0.8-3.0

* This waste material not produced at this power plant
** No Sample collected
† Ratio of the means
ND No data

TABLE B-2

^{226}Ra CONTENT (pCi/g) OF COALS AND POWER PLANT RESIDUES

Power Plant	Coal(C)	Bottom Ash(BA)	Fly Ash(FA)	Scrubber Output(SO)	Scrubber Input	Scrubber Reactants	BA/C	FA/C	SO/C	FA/BA
M-1	1.4	7.5	*	3.0	1.2	1.0	5.4	-	2.1	-
M-2	0.4	2.9	4.7	*	*	*	7.2	11.8	-	1.6
M-3	0.6	2.2	4.4	*	*	*	3.7	7.3	-	2.0
M-4	0.7	3.5	7.5	*	*	*	5.0	10.7	-	2.1
M-5	0.8	ND	5.9	3.3	**	1.7	-	7.4	4.1	-
M-6	0.9	3.0	4.4	0.9	ND	0.3	3.3	4.9	1.0	1.5
A	**	3.7	4.4	3.1	**	**	-	-	-	1.2
Mean	0.8	3.8	5.2	2.6	-	-	4.7†	6.5†	3.2†	1.4†
Std. Dev.	0.3	1.9	1.3	1.1						
Range	0.4-1.4	2.2-7.5	4.4-7.5	0.9-3.3	-	0.3-1.7	3.3-7.2	4.9-11.8	1.0-4.1	1.2-2.1

* This waste material not produced at this power plant
** No Sample collected
† Ratio of the means
ND No data

TABLE B-3

^{214}Bi CONTENT (pCi/g) OF COALS AND POWER PLANT RESIDUES

Power Plant	Coal(C)	Bottom Ash(BA)	Fly Ash(FA)	Scrubber Output(SO)	Scrubber Input	Scrubber Reactants	BA/C	FA/C	SO/C	FA/BA
M-1	1.7	6.6	*	2.8	0.8	1.1	3.9	-	1.7	-
M-2	0.5	4.3	5.6	*	*	*	8.6	11.2	-	1.3
M-3	0.7	1.9	4.6	*	*	*	2.7	6.6	-	2.4
M-4	0.9	5.9	7.7	*	*	*	6.6	8.6	-	1.3
M-5	0.9	5.8	6.3	2.4	**	2.5	6.4	7.0	2.7	1.1
M-6	0.5	2.4	2.3	0.9	0.1	0.1	4.8	4.6	1.8	1.0
A	**	4.8	4.6	2.3	**	**	-	-	-	1.0
Mean	0.9	4.5	5.2	2.1	-	-	5.0†	5.8†	2.3†	1.2†
Std. Dev.	0.5	1.8	1.8	0.8						
Range	0.5-1.7	1.9-6.6	2.3-7.7	0.9-2.8	0.1-0.8	0.1-2.5	2.7-8.6	4.6-11.2	1.7-2.7	1.0-2.4

* This waste material not produced at this power plant
** No Sample collected
† Ratio of the means
ND No data

TABLE B-4

^{210}Pb CONTENT (pCi/g) OF COALS AND POWER PLANT RESIDUES

Power Plant	Coal(C)	Bottom Ash(BA)	Fly Ash(FA)	Scrubber Output(SO)	Scrubber Input	Scrubber Reactants	BA/C	FA/C	SO/C	FA/BA
M-1	2.1	ND	*	6.4	0.6	2.7	-	-	3.1	-
M-2	0.3	0.6	12.8	*	*	*	2.0	42.7	-	21.3
M-3	0.4	0.8	6.6	*	*	*	2.0	16.5	-	8.3
M-4	0.8	1.3	30.4	*	*	*	1.6	38.0	-	23.4
M-5	0.5	1.6	7.3	3.4	**	3.0	3.2	14.6	6.8	4.6
M-6	ND	2.0	1.7	1.0	0.3	<0.1	-	-	-	0.9
A	**	1.9	6.6	2.5	**	**	-	-	-	3.5
Mean	0.8	1.4	10.9	3.3	-	-	1.7†	13.6†	4.1†	7.8†
Std. Dev.	0.7	0.6	10.2	2.3						
Range	0.3-2.1	0.6-2.0	1.7-30.4	1.0-6.4	0.3-0.6	<0.1-3.0	1.6-3.2	14.6-42.7	3.1-6.8	0.9-23.4

* This waste material not produced at this power plant
** No Sample collected
† Ratio of the means
ND No data

TABLE B-5

^{210}Po CONTENT (pCi/g) OF COALS AND POWER PLANT RESIDUES

Power Plant	Coal(C)	Bottom Ash(BA)	Fly Ash(FA)	Scrubber Output(SO)	Scrubber Input	Scrubber Reactants	BA/C	FA/C	SO/C	FA/BA
M-1	1.5	0.7	*	8.4	0.5	1.0	0.5	-	5.6	-
M-2	0.3	<0.1	6.5	*	*	*	<0.3	21.7	-	65
M-3	0.4	0.3	3.0	*	*	*	0.7	7.5	-	10
M-4	0.6	0.3	12.1	*	*	*	0.5	20.2	-	40
M-5	0.6	0.7	3.4	1.7	**	1.3	1.2	5.7	2.8	5.7
M-6	0.3	0.7	ND	0.5	0.1	<0.1	2.3	-	1.7	-
A	**	1.0	3.0	1.5	**	**	-	-	-	3.0
Mean	0.6	0.5	5.6	3.0	-	-	0.8†	9.3†	5.0†	11.2†
Std. Dev.	0.5	0.3	3.9	3.6						
Range	0.3-1.5	<0.1-1.0	3.0-12.1	0.5-8.4	0.1-0.5	<0.1-1.3	<0.3-2.3	5.7-21.7	1.7-5.6	3.0-65

* This waste material not produced at this power plant
** No Sample collected
† Ratio of the means
ND No data

TABLE B-6

^{232}Th CONTENT (pCi/g) OF COALS AND POWER PLANT RESIDUES

Power Plant	Coal(C)	Bottom Ash(BA)	Fly Ash(FA)	Scrubber Output(SO)	Scrubber Input	Scrubber Reactants	BA/C	FA/C	SO/C	FA/BA
M-1	0.4	1.2	*	0.4	0.2	0.1	3.0	-	1.0	-
M-2	0.1	1.4	1.8	*	*	*	14.0	18.0	-	1.3
M-3	0.6	1.8	2.8	*	*	*	3.0	4.7	-	1.6
M-4	0.5	2.5	4.6	*	*	*	5.0	9.2	-	1.8
M-5	0.2	1.2	1.1	0.8	**	0.4	6.0	5.5	4.0	0.9
M-6	0.3	1.9	1.7	1.2	<0.2	<0.1	6.3	5.7	4.0	0.9
A	**	2.6	2.3	1.4	**	**	-	-	-	0.9
Mean	0.4	1.8	2.4	1.0	-	-	4.5†	6.0†	2.5†	1.3†
Std. Dev.	0.2	0.6	1.2	0.4						
Range	0.1-0.6	1.2-2.6	1.1-4.6	0.4-1.4	<0.2-0.2	<0.1-0.4	3.0-14.0	5.5-18.0	1.0-4.0	0.9-1.8

* This waste material not produced at this power plant
** No Sample collected
† Ratio of the means
ND No data

TABLE B-7

^{208}Tl CONTENT (pCi/g) OF COALS AND POWER PLANT RESIDUES

Power Plant	Coal(C)	Bottom Ash(BA)	Fly Ash(FA)	Scrubber Output(SO)	Scrubber Input	Scrubber Reactants	BA/C	FA/C	SO/C	FA/BA
M-1	0.3	1.3	*	0.3	0.2	0.1	4.3	-	1.0	-
M-2	0.2	ND	2.0	*	*	*	-	10	-	-
M-3	0.5	1.4	2.6	*	*	*	2.8	5.2	-	1.9
M-4	0.5	3.5	4.8	*	*	*	7.0	9.6	-	1.4
M-5	0.2	1.3	1.5	0.4	**	0.5	6.5	7.5	2.0	1.2
M-6	0.3	1.9	ND	1.2	0.3	0.1	6.3	-	4.0	-
A	**	1.9	2.6	1.0	**	**	-	-	-	1.4
Mean	0.3	1.9	3.0	0.7	-	-	6.3†	10.0†	2.3†	1.6†
std. Dev.	0.1	0.9	1.7	0.4						
Range	0.2-0.5	1.3-3.5	1.5-4.8	0.3-1.2	0.2-0.3	0.1-0.5	2.8-7.0	5.2-10.0	1.0-4.0	1.2-1.9

* This waste material not produced at this power plant
** No Sample collected
† Ratio of the means
ND No data

TABLE B-8

CONCENTRATION RATIO OF FLY ASH VERSUS COAL
FOR MAJOR ELEMENTS AND RADIONUCLIDES

Power plant	Al	Ti	Fe	Mean of Major Elements	^{238}U	^{226}Ra	^{214}Bi	^{210}Pb	^{210}Po	^{232}Th	^{208}Tl
M-2	5.9	8.0	7.2	7.0	11.4	11.8	11.2	42.7	21.7	18.0	10.0
M-3	6.8	7.4	4.8	6.3	6.0	7.3	6.6	16.5	7.5	4.7	5.2
M-4	6.4	6.1	3.1	5.2	12.9	10.7	8.6	38.0	20.2	9.2	9.6
M-5	5.9	5.3	3.8	5.0	5.8	7.4	7.0	14.6	5.7	5.5	7.5
M-6	5.0	3.6	7.9	5.5	4.4	4.9	4.6	-	-	5.7	-

TABLE B-9

CONCENTRATION RATIO OF BOTTOM ASH VERSUS COAL
FOR MAJOR ELEMENTS AND RADIONUCLIDES

Power plant	Al	Ti	Fe	Mean of Major Elements	^{238}U	^{226}Ra	^{214}Bi	^{210}Pb	^{210}Po	^{232}Th	^{208}Tl
M-1	3.5	3.0	3.4	3.3	3.8	5.4	3.9	-	0.5	3.0	4.3
M-2	6.1	6.4	6.9	6.5	5.8	7.2	8.6	2.0	<0.3	14.0	-
M-3	3.3	3.9	5.2	4.1	3.0	3.7	2.7	2.0	0.7	3.0	2.8
M-4	7.1	6.7	3.4	5.7	4.3	5.0	6.6	1.6	0.5	5.0	7.0
M-5	5.6	5.0	5.4	5.3	6.6	-	6.4	3.2	1.2	6.0	6.5
M-6	5.5	4.3	6.6	5.5	5.0	3.3	4.8	-	2.3	6.3	6.3

TABLE B-10

SUMMARY TABLE

MEAN (1 STD. DEV.) RADIONUCLIDE CONTENT IN COALS AND WASTES

	Activity (pCi/g)			
Radionuclide	Coal	Bottom Ash	Fly Ash	Scrubber output
^{238}U	0.9 (0.5)	4.3 (2.1)	5.4 (2.7)	2.3 (0.9)
^{226}Ra	0.8 (0.3)	3.8 (1.9)	5.2 (1.3)	2.6 (1.1)
^{214}Bi	0.9 (0.5)	4.5 (1.8)	5.2 (1.8)	2.1 (0.8)
^{210}Pb	0.8 (0.7)	1.4 (0.6)	10.9 (10.2)	3.3 (2.3)
^{210}Po	0.6 (0.5)	0.5 (0.3)	5.6 (3.9)	3.0 (3.6)
^{232}Th	0.4 (0.2)	1.8 (0.6)	2.4 (1.2)	1.0 (0.4)
^{208}Tl	0.3 (0.1)	1.9 (0.9)	3.0 (1.7)	0.7 (0.4)

TABLE B-11

COAL STATIC LEACHATES

Power Plant	pH	EC (μmhos)	TDS (ppm)	^{226}Ra (pCi/ℓ)	%total ^{226}Ra	^{210}Pb (pCi/ℓ)	%Total ^{210}Pb	^{210}Po (pCi/ℓ)	%Total ^{210}Po
M-1	7.8	2300	3000	<Blank	-	<0.1	<0.02	0.2	0.07
M-2	3.8	3000	3600	<Blank	-	<0.1	<0.17	0.2	0.33
M-3	2.9	1600	1700	<Blank	-	8.1	10.7	0.3	0.41
M-4	8.3	1100	1300	<Blank	-	0.2	0.13	0.3	0.25
M-5	7.9	1800	2300	<Blank	-	<0.1	<0.10	0.3	0.25
M-6	2.7	3500	5900	0.5	0.28	3.2	-	0.6	1.0

TABLE B-12

BOTTOM ASH STATIC LEACHATES

Power Plant	pH	EC (μmhos)	TDS (ppm)	^{226}Ra (pCi/ℓ)	%total ^{226}Ra	^{210}Pb (pCi/ℓ)	%Total ^{210}Pb	^{210}Po (pCi/ℓ)	%Total ^{210}Po
M-1	7.3	280	200	0.1	0.01	0.5	0.04	0.2	0.14
M-2	7.2	790	200	0.2	0.03	2.2	1.7	0.3	-
M-3	6.4	1300	1700	<Blank	-	0.2	0.13	0.1	0.19
M-4	10.8	460	400	<Blank	-	1.7	0.63	0.2	0.30
M-5	9.2	2000	2900	1.3	0.82	<0.1	<0.03	0.1	0.07
A	7.6	740	800	0.7	0.09	1.1	0.29	0.2	0.10
A*	11.3	2100	600	0.4	0.05	<0.1	<0.02	0.2	0.06

* Economizer ash

TABLE B-13

FLY ASH STATIC LEACHATES

Power Plant	pH	EC (μmhos)	TDS (ppm)	^{226}Ra (pCi/ℓ)	%total ^{226}Ra	^{210}Pb (pCi/ℓ)	%Total ^{210}Pb	^{210}Po (pCi/ℓ)	%Total ^{210}Po
M-2	3.9	6000	900	<Blank	-	4.7	0.18	0.8	0.06
M-3	7.2	1340	1600	<Blank	-	0.3	0.02	0.2	0.03
M-4	8.4	1600	2100	0.6	0.04	0.2	<0.01	0.3	0.01
M-5	11.5	2100	-	3.4	0.29	<0.1	<0.01	<0.1	<0.02
M-6	11.2	1900	600	<Blank	-	0.1	0.05	0.1	0.07
A	11.1	1240	400	0.7	0.08	0.4	0.03	0.2	0.03

TABLE B-14

MAXIMUM PERMISSIBLE SOLUBLE CONCENTRATIONS IN WATER

Radionuclide	Unrestricted Areas (pCi/ℓ)
^{238}U	40,000
^{232}Th	2,000
^{226}Ra	30
^{210}Pb	100
^{210}Po	700

* Code of Federal Regulations 10, Part 20, Appendix B. Revised Jan 1, 1980.

TABLE B-15

RADIONUCLIDES IN COAL GOB

Preparation Plant	Activity (pCi/g)				
	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th
G	1.4	1.2	2.0	0.7	1.7
M	0.9	0.4	0.3	0.3	1.0
C	3.6	1.6	4.4	1.7	1.4
C*	3.3				1.5
B	0.9	0.4	1.4	0.7	1.4
B*	0.9				1.2

*Value from LA-7360-PR

TABLE B-16
COAL PREPARATION PLANT WASTE STATIC LEACHATES

Preparation Plant	pH	EC (μmhos)	TDS (ppm)	^{226}Ra (pCi/ℓ)	%total ^{226}Ra	^{210}Pb (pCi/ℓ)	%Total ^{210}Pb	^{210}Po (pCi/ℓ)	%Total ^{210}Po
C	3.9	4000	5700	<Blank	-	9.9	1.1	0.2	0.06
M	7.8	2000	3200	<Blank	-	<0.1	<0.2	0.2	0.3
B	2.1	11000	16400	<Blank	-	6.9	2.5	1.0	0.7
G	3.7	1500	1500	<Blank	-	0.7	0.2	0.1	0.07