# RADIOACTIVE ELEMENTS IN INDIANA COALS

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**Indiana Geological Survey Open File-Study 07-03**
August 2007

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**Abstract**

Variations in uranium and thorium are described for Pennsylvanian high- volatile bituminous coals in Indiana. The average U concentration is 1.77 ppm and it ranges from 0.18 ppm to 17.0 ppm. The average Th concentration is 1.83 ppm, with a range of 0.28 ppm to 18.0 ppm. The coals have lower U and Th contents than associated clastic sediments. The contents of U and Th in fly ash generated from the Springfield and the Danville coals are about 20 ppm and 10 ppm, respectively. U and Th values in Indiana coals and their coal combustion products are low and should not cause concern of radiological risk. However, there is always the possibility of some local enrichment and, therefore, their concentrations both in coal and coal combustion products should be monitored.

***Key words***: Uranium, thorium, coal, flyash, Indiana

**Introduction**

Radioactive elements in coal, especially if occurring in high concentrations, are of concern because of the possibility of radiation following coal combustion. During coal combustion, radioactive elements are released from the coal mass and are distributed between the gas phase and solid combustion products. Whereas radionuclides in bottom ash and coarser fly ash captured in the pollution control devices are kept under control, those in the gas phase and those in finer fly ash particles are of concern because they are discharged to the atmosphere (e.g., Papp et al., 2002).

In general, radiation from industrial sources is significantly lower than that from natural sources (~18% versus 82%, respectively, NCRP, 1987), and coal-burning power plants are responsible for much less than 1% of the total dose (Fig. 1). Yet, locally released volumes could be significant and need to be monitored. Elevation in radiation doses around coal-fired power plants were reported from various locations worldwide, and dominantly from Europe (Papp et al., 2002; Androvic et al., 2004; Karangelos et al., 2004). In the United States, estimates of Gabbard (1993) suggested that in 1982 the total release of U from 154 “typical” power plants was 801 tons and the release of Th was 1971 tons. However, two principal things need to be remembered when analyzing these types of data: 1) that only a fraction of these elements is radioactive, consequently, only a fraction of the emissions is hazardous, and 2) current fly ash collection systems of coal-fired power plants are much improved, compared to the older ones, releasing less fly ash to the atmosphere (Androvic et al., 2004). But even if these emissions are not large, coals that contain large amounts of radioactive elements should be identified and carefully considered before using for combustion.

Uranium (U) and thorium (Th) and their decay products, dominantly radium (Ra) and radon (Rn), are radioactive elements in coal that cause the greatest environmental concern. In general, these elements occur in coal in low concentrations. In the majority of coals, average concentrations of U are on the order of a few parts per million (ppm, on whole coal basis) (Tadmor, 1986, and review within). Similar U concentrations occur in other rocks and soils. However, U-rich coal can occur locally, and has been reported from various regions. Some coals, commonly those of low rank, have U contents exceeding 1000 ppm (Breger and Schopf, 1955; Jurain, 1968; Jeczalik, 1970; Koester and Zieger, 1978; Valkovic, 1983; Papastefanou and Charalambous, 1984; and others).

Uranium became a major scientific interest in the 1950s because of the economic importance of this element, and specifically its increased demand related to nuclear energy needs. Various theories on its origin were presented (Bouška, 1981; Swaine, 1990). In areas having plutonic or volcanic activity, uranium was often thought to be of epigenetic origin, with water or other fluids infiltrating the coal from radioactive tuffaceous rocks (Gott et al., 1952; Gill and Zeller, 1957; Dybek, 1962) or from granitic bodies (e.g., Christoph, 1963). In other areas, U was dispersed in organic matter, suggesting the presence of urano-organic complexes (Jurain, 1968). This organic association was also suggested for Illinois coals (Gluskoter et al., 1977). A similar conclusion was reached by Breger and Schopf (1955), who documented a negative correlation between ash content and U content in the Devonian age Chattanooga carbonaceous shale. Significantly less is known about the concentration and associations of Th in coal, which are often within 1 to 4 ppm range, as compared to the average crustal abundance which is ~10 ppm. Most Th occurs in phosphate minerals, such as monazite or apatite (Zielinski and Finkelman, 1997).

This paper documents concentrations of uranium and thorium in the high volatile bituminous coals of Indiana. The coals are of Pennsylvanian age and occur in the eastern part of the Illinois Basin (Figs. 2 and 3). The purpose of the paper is to discuss distribution of these elements in Indiana coals and their implications with regard to post-coal combustion environmental concerns.

## 1. Methods

The source of the U and Th data for this study is a recently compiled coal-quality database (Mastalerz et al., 2005) that includes data acquired from 1975 to 1977 (Oman et al., 1992; Bragg et al., 1998), as well as new data generated from 1994 to the present. The latter include all the bench data as well as numerous full channel analyses. The distribution of data points used for this study is presented in Figure 2. All the radioactive element analyses were provided by the U.S. Geological Survey (Denver); these and other trace element analyses were performed using inductively coupled plasma atomic emission spectroscopy (ICP-AES) and inductively coupled plasma mass spectroscopy (ICP-MS) using acid digestion as precursors to analysis. USGS procedures for these analyses and their precision are outlined in Meier et al. (1996) and Palmer (1997).

Vertical distributions of uranium and thorium in individual coal beds were studied using bench samples that collectively covered the whole coal thickness from the top to the bottom. Proximate analyses were obtained on each sample using the standard ASTM procedures (ASTM, 2006). In addition to raw samples, float fractions obtained after washing the coal in heavy liquids (1.55g/$cm^3$ density) were also analyzed to compare element concentrations in raw versus washed coal.

Comparison of U and Th contents between coal and fly ash was made on two coal beds, the Springfield and the Danville, for which we were able to sample the coal in the mine, follow its path to the plant, and collect fly ash samples generated from the same coal that was sampled in the mine (Mastalerz et al., 2004).

## 2. Results

### 3.1 Uranium

The majority of the coal samples have U contents below 2 ppm (Fig. 4A), with the lowest and the highest values of 0.18 and 17.0 ppm, respectively (Table 1). Similar values have been recorded for the coals in Illinois (Harvey et al., 1983; Demir et al., 1998). The coal beds having the highest amounts of U content are the Houchin Creek and the Colchester Coal Members (Table 1, Fig. 5) with 3.90 ppm and 4.36 ppm, respectively. In general, the lower part of the coal-bearing sequence (the Brazil and Mansfield Formations) is characterized by lower U content than the upper part of the sequence represented by the formations of the Carbondale Group.

Comparing coal-bearing regions of the United States, Indiana places in the middle for U (Fig. 6); whereas the Western Interior Basin is characterized by the highest average U content.

With rare exceptions, variations in U content among individual coal benches, both for raw coal and washed float fractions (Figs. 7-11), follow those of ash. For the majority of samples, higher amounts of U occur in higher-ash samples (Figs. 7, 9-11). No relationship with sulfur is apparent. These observations suggest that U is associated dominantly with the inorganic fraction. A very modest to complete lack of reduction in U content in the washed float fraction compared to the unwashed raw coal further suggests an association with the very dispersed inorganic fraction that is not removed during washing. The rare exceptions where a high ash content is not associated with increased U content (Fig. 8) suggests an association with organic matter.

The suggested association of U with mineral matter may be considered unexpected. In most high-U coals, the organic matter has been indicated as the host of this element. It has been documented experimentally that organic matter can readily extract U from water solutions (Moore, 1954; Cameron and Leclair, 1975). This has been the case in nature for epigenetic enrichment of U in some coals and carbonaceous shales (e.g. Bachman et al., 1957). For Indiana coals, U contents are low with no significant epigenetic enrichment and the concentrations observed likely come from the original plant make-up of the coal. The U/Th ratio for Indiana coals ranges from 0.25 to 2.29 (Table 2), similar to, for example, ratios observed for modern tree barks in non-industrial areas of England (Bellis et al., 2001).

### 3.2 Thorium

The dominant majority of the coal samples have Th contents ranging from 1 ppm to 2 ppm (Fig. 4B). Generally, samples having low Th content also have low U contents (Fig. 12A), although the correlation between these two elements is not strong. The average Th content for the coal beds studied does not present any trend stratigraphically (Fig. 5, Table 2). However, when compared to the U content, the coals of the Carbondale Group are characterized, with few exceptions, by higher U than Th content (U/Th ratio for all the coals of this unit is 1.22), whereas those of the Brazil and Mansfield Formations have more Th than U (average U/Th ratio is 0.72). The average crustal ratio of U/Th is 0.3 (Taylor, 1964). Coals of the Carbondale Group are brighter (vitrinite-rich) than the coals of the Brazil and Mansfield Formations (that are richer in liptinite and inertinite) (Mastalerz et al., 2004), and the difference in relative proportions of the U and Th may have resulted from differences in plant assemblage proportions.

Comparing coal-bearing regions of the United States, Indiana appears in the lower content group both for Th and U (Fig. 6), with the Western Interior Basin and Gulf Coast coals having the highest contents.

Variations in Th content between individual coal benches, similar to U, follow those of ash (Figs. 7-11). This relationship with Th appears to be even stronger than for U and the ash yield; in cases where U does not follow the ash-content trend, Th still does (Fig. 8 This holds true not only for the bench samples but for the whole-seam samples as well. Th, with the exception of two samples, correlates positively with ash content (Fig. 12B), whereas for U significantly larger scatter is observed (Fig. 12C). This correlation with ash suggests an association with minerals like monazite or apatite, as mentioned by Zielinski and Finkelman (1997), rather than with organic matter. No relationship with sulfur is apparent. A very modest reduction, no reduction, or a slight enrichment in Th content in the washed float fraction suggests an association with finely dispersed minerals which are not easily removed during washing.

### 3.3 Uranium and thorium in coal versus associated clastic sediments

Comparing U and Th concentrations in the coal and associated clastic rocks (Table 3) indicates that clastic rocks have, on average, about twice as much U and Th as the coals. Ratios of U/Th for the clastic rocks associated with the coals are within a range observed for the coals (Table 2). Clastic partings within the coal beds on average contain more U and Th than the roof and floor lithologies (Table 3). Roof and floor rocks have very similar average Th contents, whereas floor rocks contain more U than the roof rocks. These observations are in agreement with the above mentioned association of U and Th with mineral matter in coal. Higher average U and Th contents in associated clastic rocks than in coal does not imply, however, that the coal next to the floor, bottom, or clastic parting will always have higher U and Th contents than coal further away. Figures 7 through 11 demonstrate that whereas in some locations U is higher in the coal next to the roof (Figs. 8), floor (Figs. 9), or clastic partings (Fig. 10; bench at depth of 450.7 to 451.8 occurs directly above 24 cm thick mudstone), in other locations this regularity does not exist (Fig. 7).

### 3.4 Uranium and thorium in coal versus fly ash

There is little information about U and Th in fly ash from Indiana coals. Our recent study comparing the properties of the low-sulfur Danville coal and high-sulfur Springfield coal to their corresponding fly ash obtained at power plants (Mastalerz et al., 2004) provided also some data on U and Th contents. Table 4 shows both U and Th contents of the fly ash samples collected from baghouses (low temperature fly ash) and rear pass hopper (higher temperature ash) (Fig. 13), together with the value of the coal before combustion.

These data demonstrate that, for the Danville coal, the content of U of the pulverized coal (on ash basis) is similar to U contents in their corresponding fly ash. There is, however, a small difference in U/Th ratio between coal (~0.49) and fly ash (~0.63), indicating small relative enrichment in U compared to Th in the latter (Table 4). This U enrichment may suggest that there is some U volatility during combustion and subsequent condensation on fly ash, in contrast to Th. This difference in ratio is, however, small and its significance and interpretation requires further testing. The concentrations of Th and U in fly ash compared to those in the coal implies that both U and Th are retained after combustion primarily in fly ash. Other studies provided similar observations (e,g., Tadmor, 1986), demonstrating that, in comparison to fly ash, significantly less Th and U is retained in bottom ash, mechanical collector ash, or ESP ash. Yet it has also been documented that fly ash alone can have large variations of both U and Th, depending on local conditions of ash collection (Lyon, 1977; Coles et al., 1978). For the fly ash studied, these variations are rather small (Table 4); there is no difference in U content between higher temperature (and coarser) fly ash represented by ash from boiler 1 rear pass hopper, and lower temperature (finer) fly ash represented by samples from the baghouses (Fig. 13B), although it was mentioned before that U concentrates in finer particles (UNSCEAR, 1982; Zielinski and Finkelman, 1997). No Th enrichment observed with decreasing fly ash particle size (and decreasing temperature) (Fig. 13), in agreement with previous observations (UNSCEAR, 1982). Additionally, there is no trend in U and Th concentrations along the gas flow in the baghouse ash collection system (Fig. 13); baghouses B1 and B2, nearest to the burner units, are not much different with regard to U and Th content from those that are most distant (B7 and B8). This absence of U and Th variations with temperature suggests that these elements are not volatilized, or volatilized only slightly, at the combustion temperature used and, consequently have no tendency to concentrate or condensate on the surface of finer grains during cooling. As such, they are in contrast with Hg or Se that, because of their volatility and subsequent condensation, have much higher concentrations in the low temperature fly ash from baghouses than in the higher temperature fly ash from rear pass hopper of this plant (Mastalerz et al., 2004).

For the high-sulfur Springfield coal, the U and Th concentration in coal (given on an ash basis in Table 5) is also very similar to the concentrations in the fly ash, indicating that these elements are retained in the fly ash. The ratio of U/Th in the pulverized coal (1.27 on average) is elevated to 1.54 in the fly ash, indicating small relative enrichment in U compared to Th in the fly ash, similar to the Danville coal. The higher U/Th ratio in the fly ash from the high-sulfur Springfield coal (Table 5) than that from the low-sulfur Danville coal (Table 4) may reflect corresponding differences of that ratio in the coal feed.

### 3.5 Implications for environmental impacts of radioactive elements associated with coal utilization

A series of studies have evaluated the radiation hazard from coal-burning plants (e.g., Lee et al., 1977; McBride et al., 1977; Jacobi, 1981; De Santis and Longo, 1984; Nakaoka et al., 1985; Gabbard, 1993; Bem et al., 2002; Adrovic et al., 2004; Kumar et al., 2005; Flues et al., 2006) and from post-combustion ash piles (Lee et al., 1977). The main concern resulting from these studies is that U concentrates in fine (<10μm) fractions of fly ash. This is a respirable fraction and, therefore, presents an inhalation hazard to man when released into the atmosphere.  Some studies demonstrate that a portion of U and radium is also released from coal combustion products in the vapor phase (Papastefanou and Charalambous, 1984).

The analysis of the literature on the release rates of radionuclides contained in fly ash indicates that coal-burning power plants equipped with modern ash-filtration devices release about an order of magnitude less radioactivity to the atmosphere than older power plants without such devices. The estimate of the release rates of $^{238}U$ vary between locations, with the most common estimates at around $1x10^9$ Bq per year, normalized to 1000 MWe (Tadmor, 1986, and reference within). Averaging the release rates from various locations, it was calculated that for coal having U contents of 1 to 2 ppm and Th contents of 3 to 5 ppm (values well representing Indiana coals), a release rate of $7.5x10^5$ to $1.5x10^6$ Bq of $^{238}U$ per MWe year is expected (US EPA, 1979; IAEA, 1982; UNSCEAR, 1982).

Radionuclides released into the atmosphere are transported and, when deposited, add their radioactivity to the deposition site. Data on reactivity around coal-fired power plants also vary; often the values are low (e.g., Nakaoka et al., 1985; Bem et al., 2002) and close to the normal background concentrations for the radionuclides (which is $\sim10^{-6}$ Bq $m^{-3}$), but in some locations enrichment in Th and U was noted around power plants (Ray and Parker, 1977; Styron et al., 1979; Papp et al., 2002; Karangelos et al., 2004; ). Although the estimates of the release rates, environmental radioactivity, as well as radiation doses caused by coal combustion do vary between investigators (UNSCEAR, 1982; US EPA, 1979; Nakaoka et al., 1985), there is a general consensus that the radiation dose, both from the air and from the ground, caused by coal combustion is insignificant and that the resultant radiological risk is small. The individual coal-combustion-related radiation dose (0.01-0.05 mSv year$^{-1}$) amounts to 1-5% of the natural background radiation, and Tadmor (1986) estimates that its radiological risk corresponds to the possibility of one lethal cancer in 25 to 50 years. For comparison, the average person in the U.S. receives an effective dose of about 3 mSv per year from naturally occurring radioactive materials and cosmic radiation from outer space (http://www.radiologyinfo.org/en/safety/index.cfm?pg=sfty_xray&bhcp=1).

On average, both uranium (1.77 ppm) and thorium (1.83 ppm) contents of Indiana coals are lower than average values of American coals (Th – 3.2 ppm; U – 2.1 ppm, Finkelman, 1994), and lower than the average crustal concentrations of these elements (average earth's crust U and Th concentrations of 2.7 and 9.6ppm, respectively, Taylor, 1964). Maximum values recorded are 17 ppm for U (Table 1) and 18 ppm for Th (Table 2). Even those values are still low considering radiation doses and should not cause concern. The concentrations of Th and U in the fly ash of Indiana coals are ~10 times those in the coal (Tables 4, 5); these are still low levels, comparable to those in common rocks and soils and the Earth's crust. The release rates of radionuclides cited above ($7.5x10^5$ to $1.5x10^6$ Bq of $^{238}U$ per MWe year) should well represent coal combustion products from Indiana coals.

Although U contents in the Indiana coals and fly ash studied are low and, the majority of which seems to be associated with mineral rather than organic matter (perhaps contributing to the low volatility of these elements), there is always the possibility of local enrichments, and therefore, concentrations should be monitored.

## 3. Conclusions

The following conclusions can be made based on this study:

1) Indiana coals are characterized by low amounts of U and Th. The average values are 1.77 ppm for U and 1.83 ppm for Th, and the ranges 0.18 ppm to 17.0 ppm and 0.21 ppm to 18.0 ppm, respectively. The Colchester Coal Member has the highest U content (4.36 ppm on average) and the Lower Block Member has highest Th content (3.36 ppm on average).
2) Uranium and, to an even greater extent, Th seem to be associated with mineral matter, as suggested by their correlation with ash content in coal, and by their frequently elevated concentrations next to roof, floor, and intra-seam clastic partings. At least some fraction of these elements must be sourced from associated clastic rocks that have higher concentrations of both U and Th than the coal.
3) After combustion, U and Th are retained in fly ash, as indicated considering ash content in coal and the comparison of U and Th contents in coal versus fly ash.
4) U and Th values in Indiana coals and their coal combustion products are low and should not cause concern of radiological risk. However, there is always the possibility of some local enrichment, therefore, their concentrations both in coal and coal combustion products should be monitored.

## Acknowledgments

Funding for this project was provided by the U. S. Geological Survey (NaQCI Program), grant 99QAG0008-5, and the Indiana Department of Commerce grant SWL-14. We would like to thank three anonymous reviewers and editor, Jim Hower, for helpful comments and suggestions. We also thank Indiana mining companies for access to coal mines and power plants for access to fly ash samples.

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**Figure captions**

Fig. 1. Contribution of natural and man-made radiation sources to the total average effective dose in the U.S. population. Source, NCRP, 1987.

Fig. 2. Map of southwestern Indiana showing distribution of U and Th data points used in this study.

Fig. 3. Stratigraphic position of coal beds in Indiana (based on the TriState Committee on Correlation of the Pennsylvanian System in the Illinois Basin, 2001).

Fig. 4. Histograms of U (A) and thorium (B) contents in Indiana coals. Values are given on a whole-coal basis.

Fig. 5. Comparison of average U and Th contents for coal seams in Indiana.

Fig. 6. Comparison of average U and Th contents for selected coal-bearing regions in the USA. Source of data: Bragg et al., 1998.

Fig. 7. Uranium and Th (A) and sulfur and ash (B) contents in coal benches in raw coal and in washed coal (float fractions) in the Danville Coal Member from Sullivan County, Indiana. Note that benches having higher ash yields (33-69 and 69-96) also have higher U and Th contents.

Fig. 8. Uranium and Th (A) and sulfur and ash (B) contents in coal benches in raw coal and in washed coal (float fractions) in the Hymera Coal Member from Sullivan County, Indiana. In this location, the bench having the highest ash yield (65-97) has relatively low U but high Th.

Fig. 9. Uranium and Th (A) and sulfur and ash (B) contents in coal benches in raw coal and in washed coal (float fractions) in the Springfield Coal Member from Gibson County, Indiana.

Fig. 10. Uranium and Th (A) and sulfur and ash (B) contents in coal benches in raw coal and in washed coal (float fractions) in the Seelyville Coal Member from Gibson County, Indiana. The bench at 450.7-451.7 having the highest U and Th occurs directly above a clastic parting.

Fig. 11. Uranium and Th (A) and sulfur and ash (B) contents in coal benches in raw coal and in washed coal (float fractions) in the Lower Block Coal Member from Clay County, Indiana. Note that benches having higher ash yields also have higher U and Th contents.

Fig. 12. (A) Relationship between U and Th contents in the whole seam samples.

(B) Relationship between ash yield and Th content in the whole seam samples. Except in two locations with the highest Th content, increase in ash yield is associated with increase in Th content.

(C) Relationship between ash yield and U content in the whole seam samples.

Fig. 13. U and Th concentrations in the fly ash collected from the rear pass hopper and baghouses. Note that there is no trend in U and Th concentrations along the gas flow path. Rear pass hopper ash was coarsest and had the highest temperatures, whereas baghouse fly ash was finer and had lower temperatures.

**Tables**

Table 1. Uranium contents in coal beds (on a whole-coal basis) in Indiana. n- number of samples. For comparison, U.S. coal average is 2.1 ppm, Earth's crust 2.7 ppm, and Earth's shales ~4 ppm (Finkelman, 1994; Zielinski and Finkelman, 1997).

Table 2. Thorium contents in coal beds (on a whole-coal basis) in Indiana. n- number of samples. For comparison, US coal average is 3.2 ppm, Earth's crust -10 ppm, and Earth's shales ~12 ppm (Finkelman, 1994; Zielinski and Finkelman, 1997).

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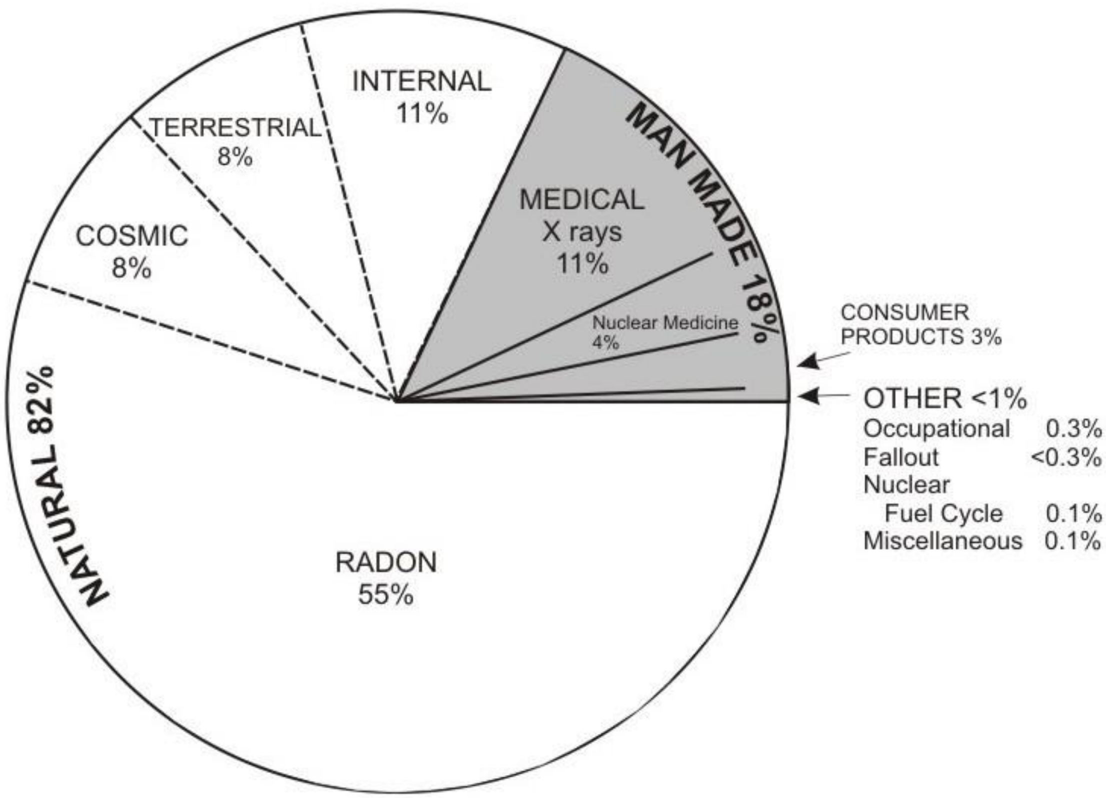



Figure1. Contribution of natural and man-made radiation sources to the total average effective dose in the U.S. population. Source, NCRP, 1987.

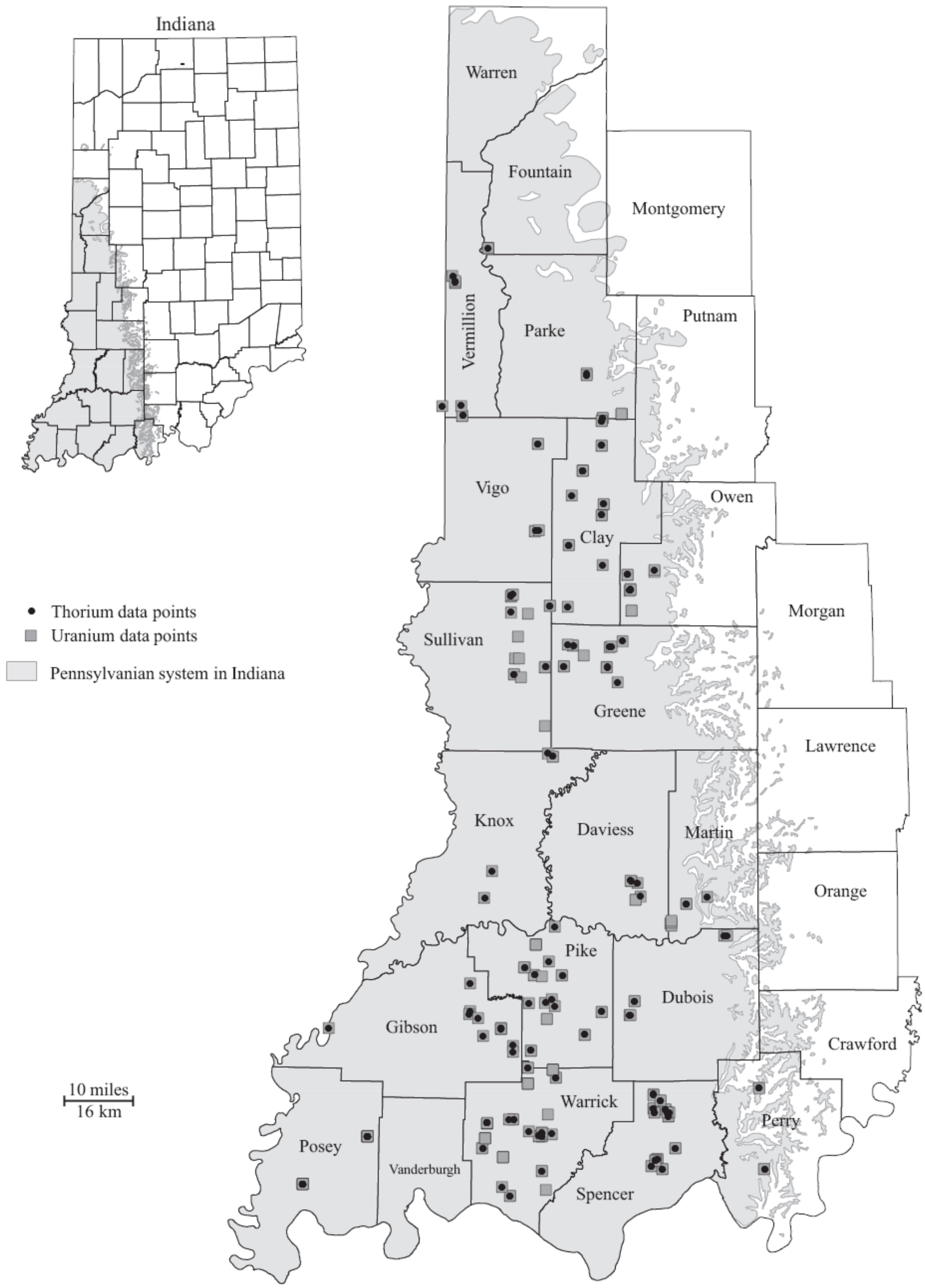



Figure 2. Map of southwestern Indiana showing distribution of U and Th data points used in this study.

**INDIANA**

| | | Coal Member |
|---|---|---|
| McLeansboro Group | Mattoon Fm. | Cohn |
| | Bond Fm. | Fairbanks |
| | Patoka Fm. | Parker<br>Raben Branch<br>Hazelton Bridge<br>Ditney |
| | Shelburn Fm. | Pirtle |
| Carbondale Group | Dugger Fm. | Danville<br>Hymera<br>Herrin<br>Bucktown |
| | Petersburg Fm. | Springfield<br>Houchin Creek |
| | Linton Fm. | Survant<br>Colchester<br>Seelyville |
| Raccoon Creek Group | Staunton Fm. | Unnamed Staunton Fm. coals |
| | Brazil Fm. | Minshall / Buffaloville<br>Upper Block<br>Lower Block |
| | Mansfield Fm. | Shady Lane<br>Mariah Hill<br>Blue Creek<br>Pinnick<br>St. Meinrad<br>French Lick |

Figure 3. Stratigraphic position of coal beds in Indiana (based on the TriState Committee on Correlation of the Pennsylvanian System in the Illinois Basin, 2001).

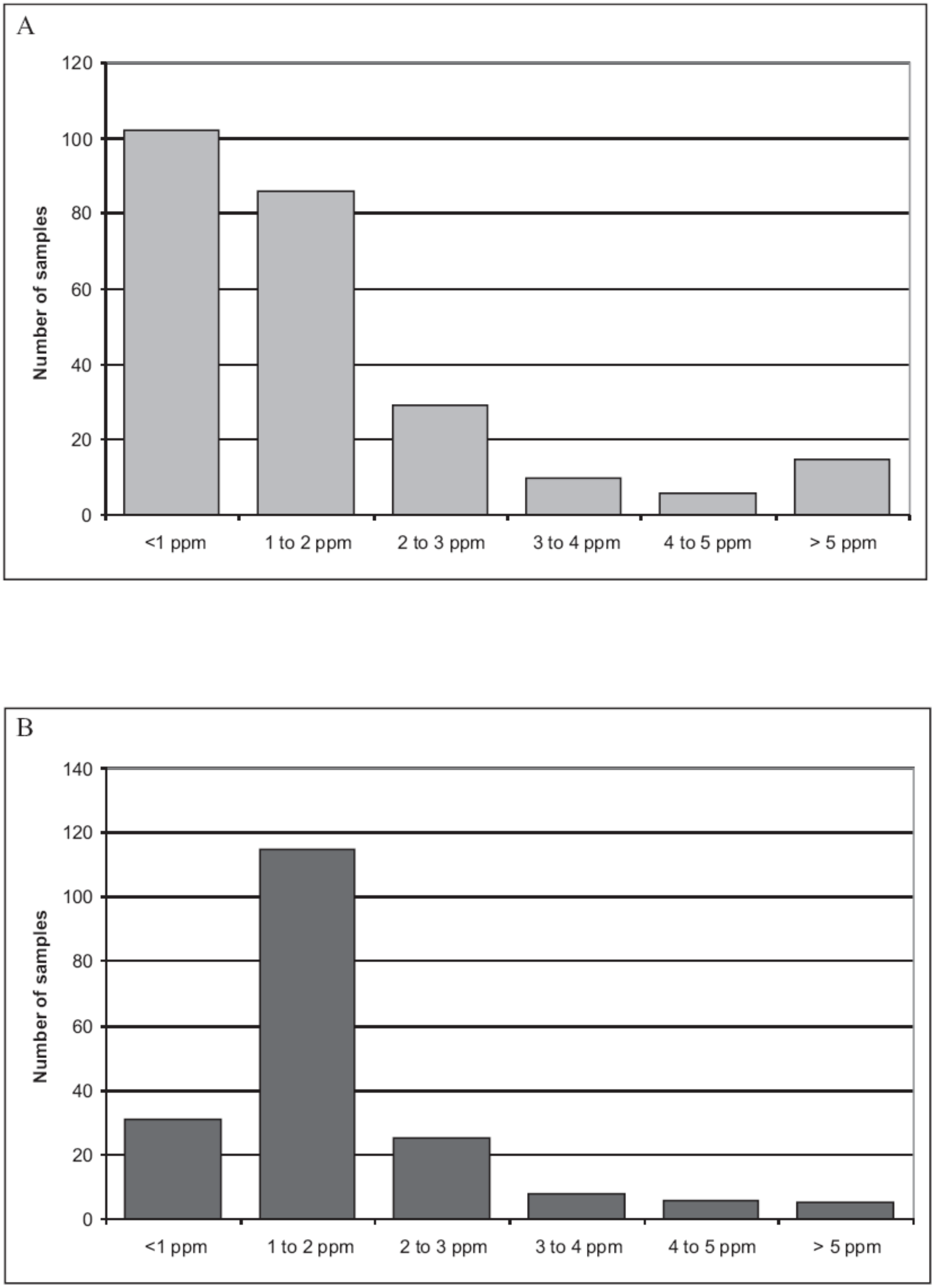



Figure 4. Histograms of U (A) and thorium (B) contents in Indiana coals. Values are given on a whole-coal basis.

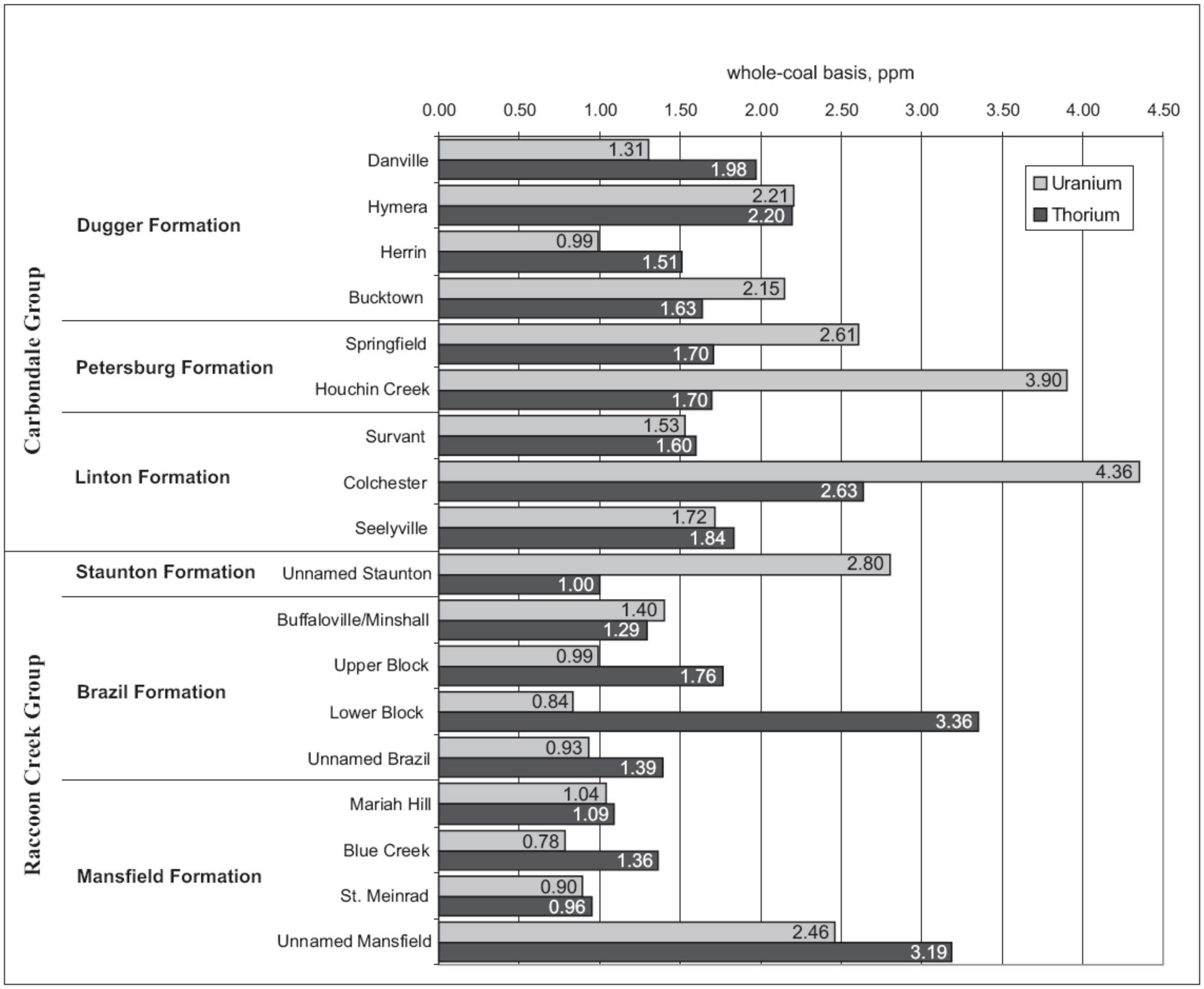



Figure 5. Comparison of average U and Th contents for coal seams in Indiana.

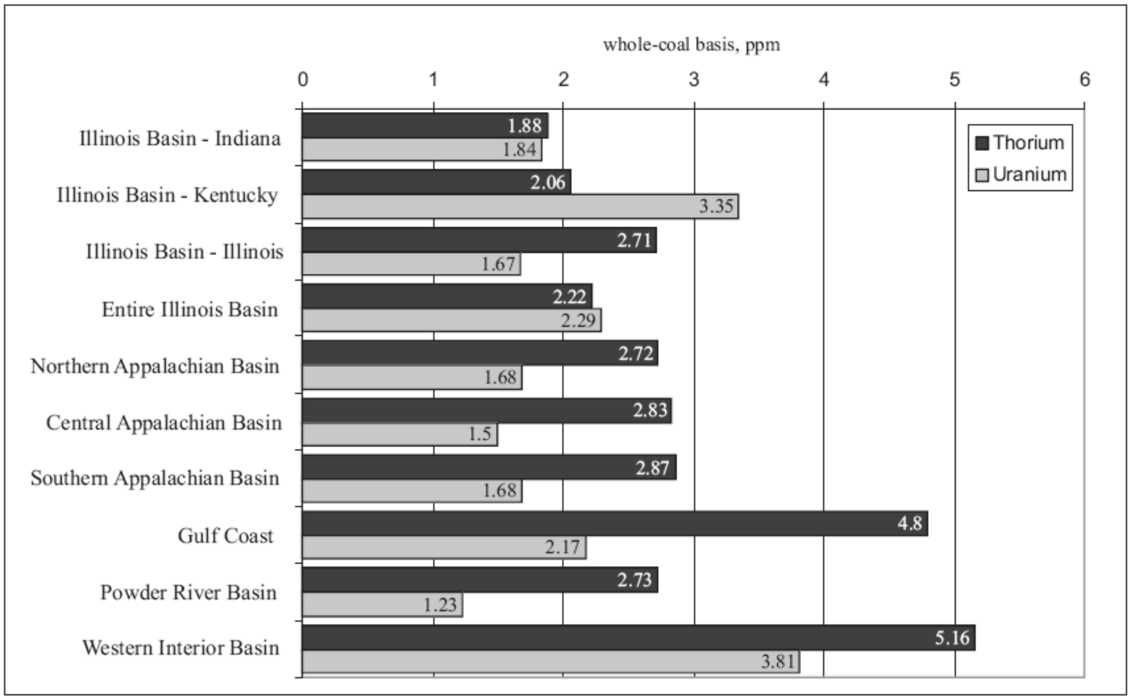
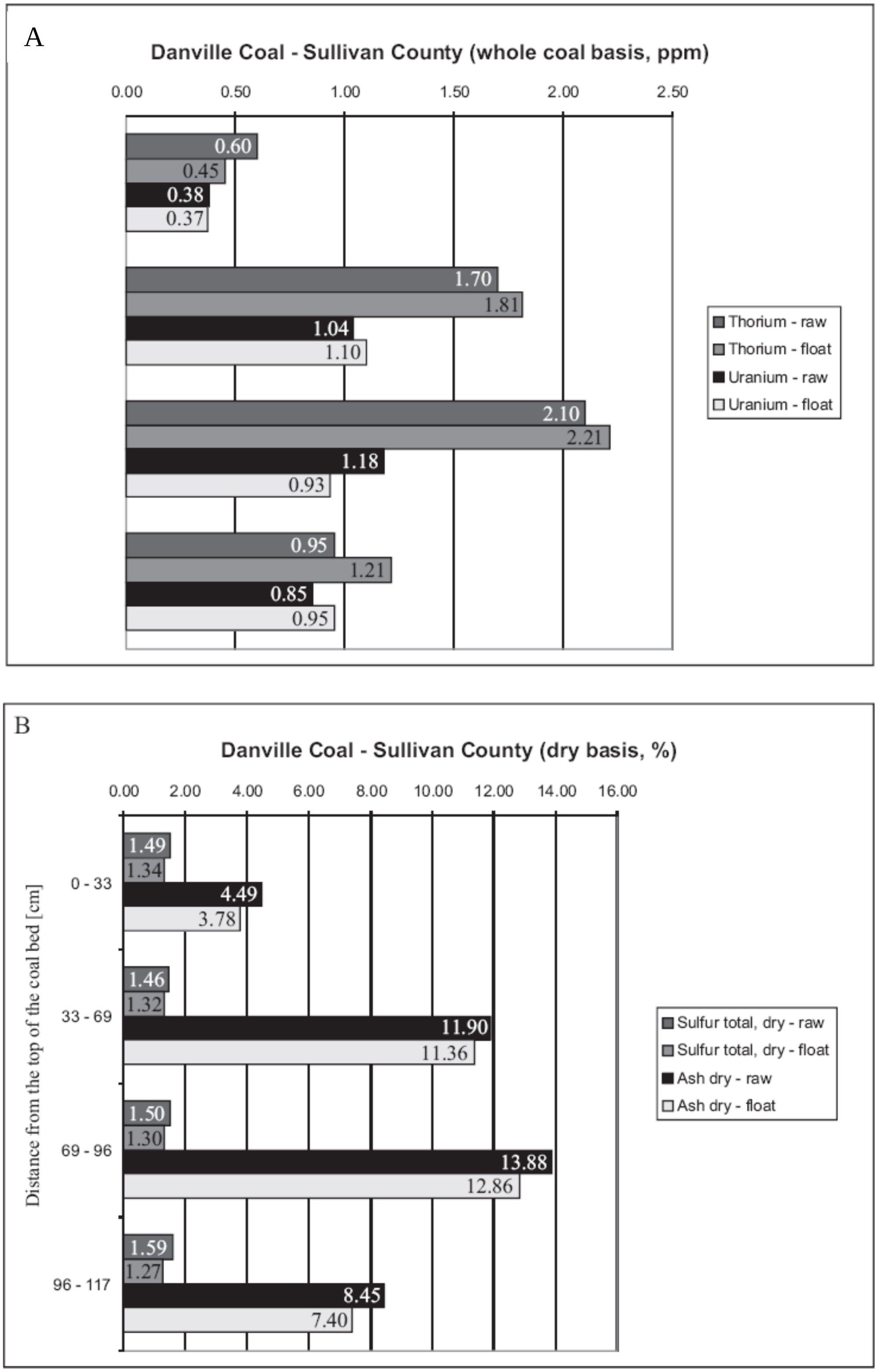



Figure 6. Comparison of average U and Th contents for selected coal-bearing regions in the USA. Source of data: Bragg et al., 1998.

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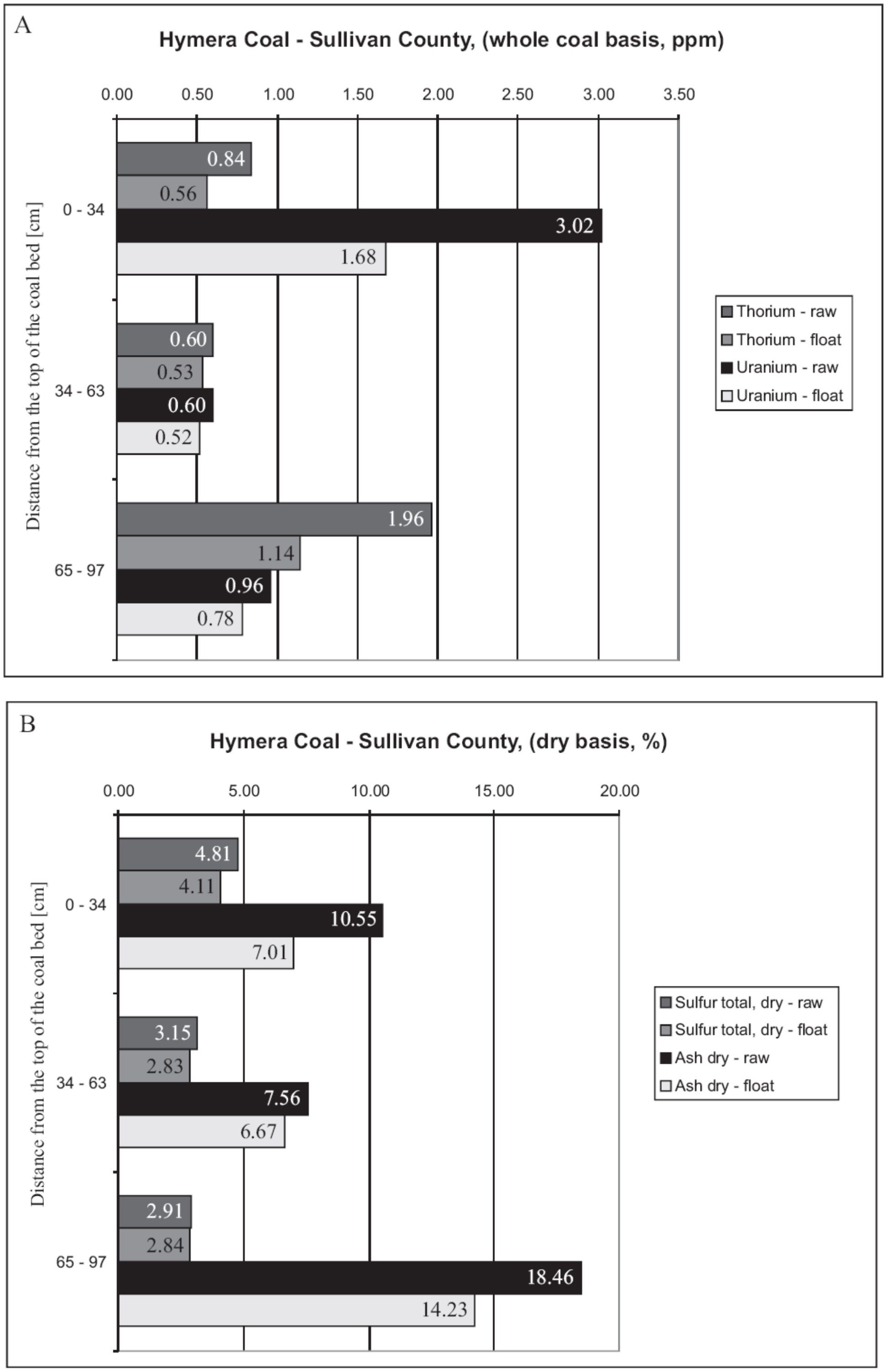


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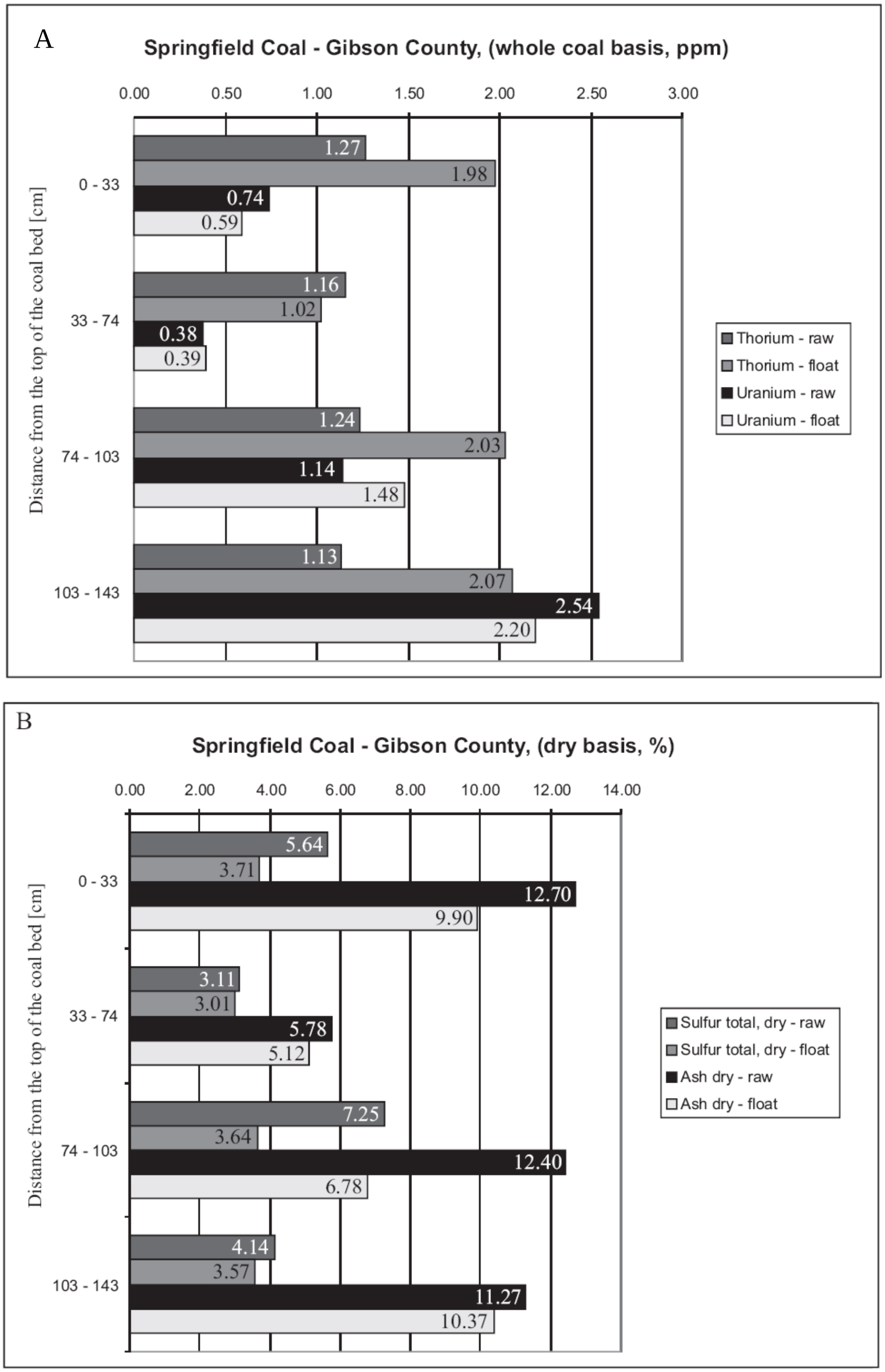


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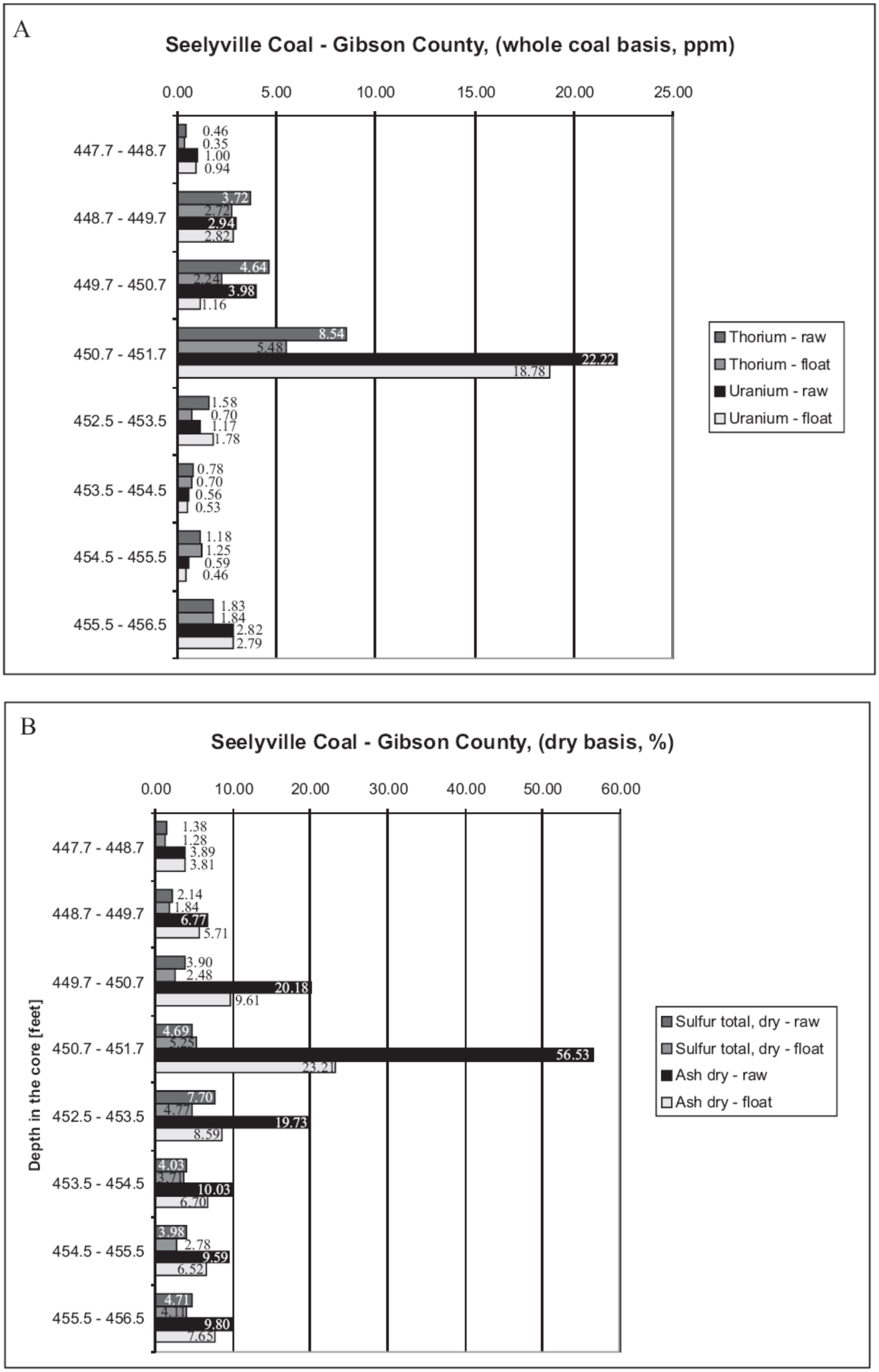
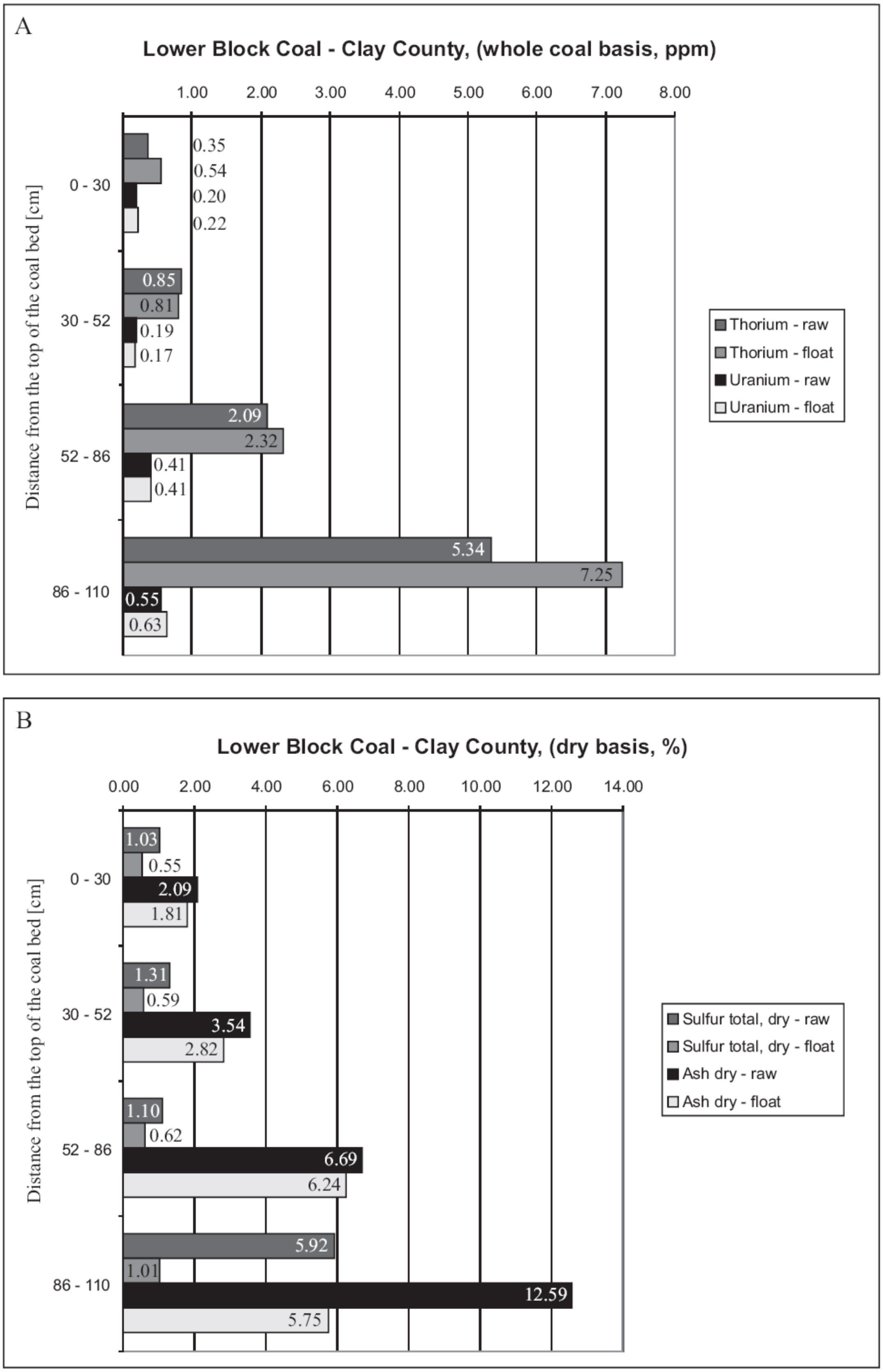



Figure 10. Uranium and Th (A) and sulfur and ash (B) contents in coal benches in raw coal and in washed coal (float fractions) in the Seelyville Coal Member from Gibson County, Indiana. The bench at 450.7-451.7 having the highest U and Th occurs directly above a clastic parting.

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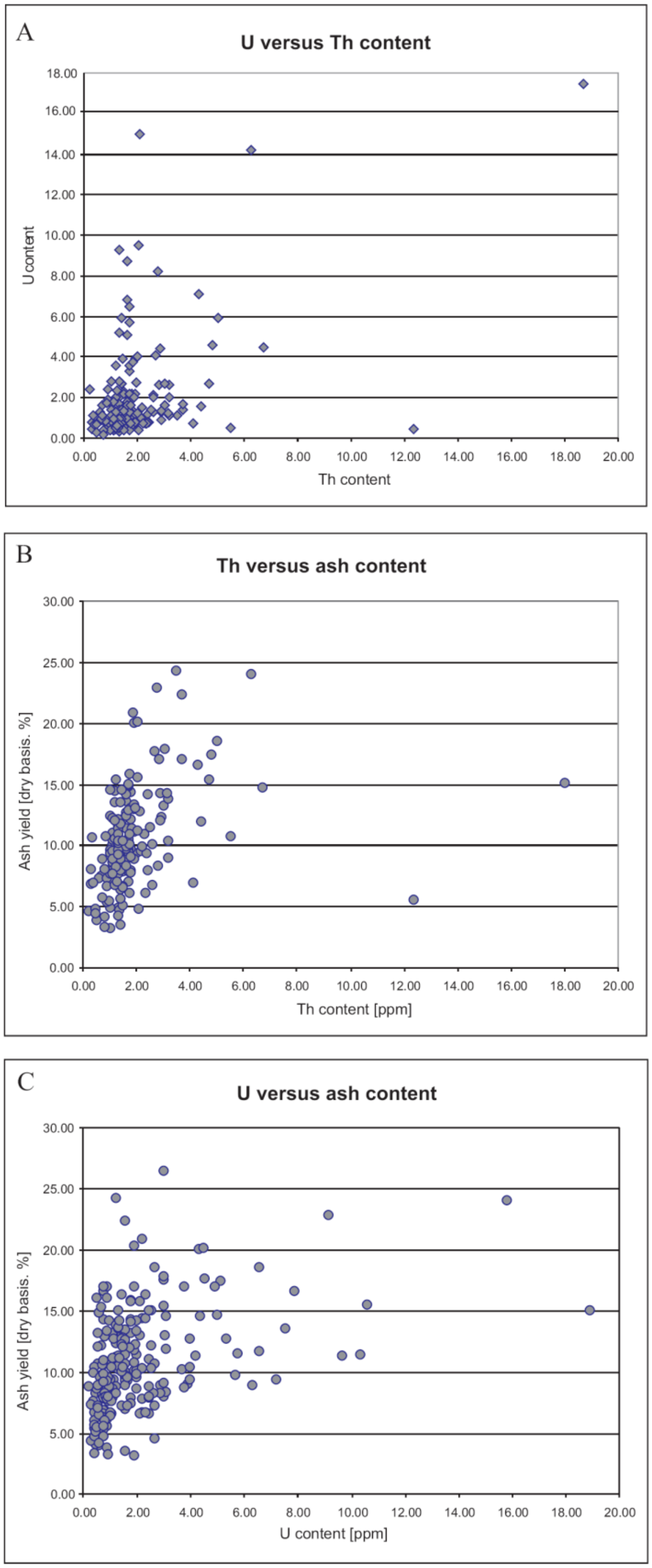


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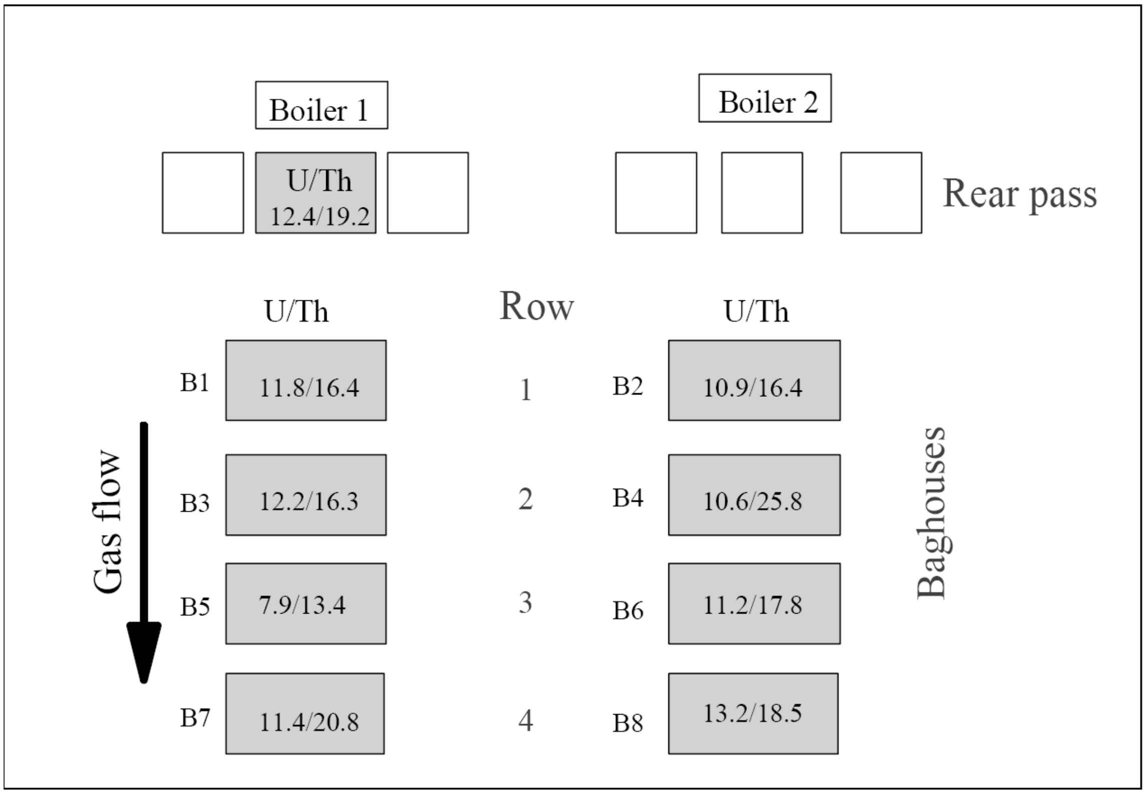


Fig. 13. U and Th concentrations in the fly ash collected from the rear pass hopper and baghouses. Note that there is no trend in U and Th concentrations along the gas flow path. Rear pass hopper ash was coarsest and had the highest temperatures, whereas baghouse fly ash was finer and had lower temperatures.

| Coal Member | Average U content [ppm] | Standard deviation | Min. | Max. | n |
|---|---|---|---|---|---|
| Danville | 1.31 | 0.83 | 0.35 | 3.76 | 28 |
| Hymera | 2.21 | 1.67 | 0.46 | 8.24 | 40 |
| Herrin | 0.99 | 0.45 | 0.67 | 1.31 | 2 |
| Bucktown | 2.15 | 2.65 | 0.53 | 5.20 | 3 |
| Springfield | 2.61 | 2.75 | 0.33 | 15.0 | 51 |
| Houchin Creek | 3.90 | 3.31 | 1.18 | 9.52 | 5 |
| Survant | 1.53 | 1.04 | 0.71 | 3.94 | 9 |
| Colchester | 4.36 | 6.58 | 0.70 | 14.22 | 4 |
| Seelyville | 1.72 | 1.28 | 0.48 | 4.41 | 12 |
| Buffaloville/Minshall | 1.40 | 0.79 | 0.18 | 2.40 | 9 |
| Upper Block | 0.99 | 0.66 | 0.37 | 2.30 | 18 |
| Lower Block | 0.84 | 0.48 | 0.38 | 1.60 | 11 |
| Unnamed Brazil | 0.93 | 0.33 | 0.40 | 1.90 | 20 |
| Mariah Hill | 1.04 | 0.54 | 0.53 | 1.80 | 4 |
| Blue Creek | 0.78 | 0.48 | 0.27 | 1.70 | 7 |
| St. Meinrad | 0.90 | 0.11 | 0.82 | 0.97 | 2 |
| Unnamed Mansfield | 2.46 | 3.96 | 0.53 | 17.0 | 17 |
| **Average** | **1.77 ppm** | | | | |

Table 1. Uranium contents in coal beds (on a whole-coal basis) in Indiana. n- number of samples. For comparison, U.S. coal average is 2.1 ppm, Earth's crust 2.7 ppm, and Earth's shales ~4 ppm (Finkelman, 1994; Zielinski and Finkelman, 1997).

| Coal Member | Average Th content [ppm] | Standard deviation | Min. | Max. | n | U/Th |
|---|---|---|---|---|---|---|
| Danville | 1.98 | 0.72 | 1.00 | 3.70 | 22 | 0.66 |
| Hymera | 2.20 | 1.61 | 0.28 | 6.72 | 19 | 1.00 |
| Herrin | 1.51 | 0.30 | 1.30 | 1.72 | 2 | 0.66 |
| Bucktown | 1.63 | 0.31 | 1.30 | 1.90 | 3 | 1.32 |
| Springfield | 1.70 | 0.88 | 0.71 | 5.50 | 39 | 1.54 |
| Houchin Creek | 1.70 | 0.64 | 1.10 | 2.66 | 5 | 2.29 |
| Survant | 1.60 | 0.56 | 1.10 | 2.90 | 9 | 0.96 |
| Colchester | 2.63 | 2.44 | 1.20 | 6.27 | 4 | 1.66 |
| Seelyville | 1.84 | 1.29 | 0.28 | 4.70 | 11 | 0.93 |
| Buffaloville/Minshall | 1.29 | 1.22 | 0.21 | 4.40 | 9 | 1.09 |
| Upper Block | 1.76 | 0.66 | 1.10 | 3.20 | 16 | 0.56 |
| Lower Block | 3.36 | 3.70 | 0.97 | 12.36 | 8 | 0.25 |
| Unnamed Brazil | 1.39 | 0.71 | 0.40 | 3.20 | 16 | 0.67 |
| Mariah Hill | 1.09 | 0.45 | 0.64 | 1.60 | 4 | 0.95 |
| Blue Creek | 1.36 | 1.57 | 0.45 | 3.70 | 4 | 0.57 |
| St. Meinrad | 0.96 | 0.21 | 0.81 | 1.10 | 2 | 0.94 |
| Unnamed Mansfield | 3.19 | 5.00 | 0.90 | 18.00 | 11 | 0.77 |
| **Average** | **1.83 ppm** | | | | | |

Table 2. Thorium contents in coal beds (on a whole-coal basis) in Indiana. n- number of samples. For comparison, US coal average is 3.2 ppm, Earth's crust -10 ppm, and Earth's shales ~12 ppm (Finkelman, 1994; Zielinski and Finkelman, 1997).

| | Th | U | n | U/Th |
|---|---|---|---|---|
| Coal | 1.83 | 1.77 | 190/248 | 0.98 |
| Roof rock | 3.69 | 2.26 | 63 | 0.61 |
| Clastic parting | 5.41 | 4.57 | 71 | 0.84 |
| Floor rock | 3.4 | 3.63 | 60 | 1.07 |

Table 3. Comparison of Th and U concentrations (averages) in coal and associated rocks in Indiana. Values are given in ppm on a whole-rock basis. Data for associated rocks come from Oman et al., 1992.

| Field number | Ash [%] | C [%] | $S_{total}$ [%] | Th [ppm] | U [ppm] | U/Th |
|---|---|---|---|---|---|---|
| Boiler 1 baghouse 1 | 73.3 | 22.71 | 0.34 | 16.4 | 11.8 | 0.72 |
| Boiler 1 baghouse 3 | 74.1 | 22.73 | 0.35 | 16.3 | 12.2 | 0.75 |
| Boiler 1 baghouse 5 | 64.4 | 17.60 | 0.30 | 13.4 | 7.9 | 0.59 |
| Boiler 1 baghouse 7 | 72.5 | 24.20 | 0.32 | 20.1 | 11.4 | 0.57 |
| Boiler 1 average | **71.08** | **21.81** | **0.33** | **16.6** | **10.8** | 0.65 |
| | | | | | | |
| Boiler 2 baghouse 2 | 77.3 | 20.71 | 0.19 | 16.4 | 10.9 | 0.66 |
| Boiler 2 baghouse 4 | 69.5 | 18.31 | 0.19 | 25.8 | 10.6 | 0.41 |
| Boiler 2 baghouse 6 | 76.5 | 19.00 | 0.23 | 17.8 | 11.2 | 0.63 |
| Boiler 2 baghouse 8 | 81.5 | 15.71 | 0.19 | 18.5 | 13.2 | 0.71 |
| Boiler 2 average | **76.2** | **18.43** | **0.20** | **19.6** | **11.5** | 0.59 |
| | | | | | | |
| Boiler 1 rear pass hopper | 98.10 | 0.84 | 0.29 | 19.2 | 12.4 | 0.65 |
| | | | | | | |
| Pulverized Coal boiler 1 | 9.94 | 69.04 | 0.48 | 20.8 | 10.5 | 0.50 |
| Pulverized Coal boiler 1 | 10.40 | 69.78 | 0.45 | 21.0 | 10.0 | 0.48 |
| | | | | | | |
| Mine Prod. - washed | 9.84 | nd | 0.508 | 21.3 | 10.5 | 0.49 |

Table 4. Uranium and Th concentrations in fly ash compared to those in the Danville coal from which the fly ash was produced. In coal, U and Th data are presented on ash basis. In addition, ash yield (in weight %), carbon content (C), and total sulfur content (in weight %) are shown.

| Field number | Ash [%] | C [%] | $S_{total}$ [%] | Th [ppm] | U [ppm] | U/Th |
|---|---|---|---|---|---|---|
| Unit 2 econ. east fly ash | 96.10 | 3.32 | 0.70 | 17.6 | 24.4 | 1.39 |
| | | | | | | |
| Unit 3 econ. east fly ash | 95.70 | 3.11 | 0.80 | 13.1 | 22.6 | 1.73 |
| Unit 3 econ. west fly ash | 95.90 | 3.28 | 0.66 | 14.4 | 21.7 | 1.51 |
| | | | | | | |
| Unit 2+3 FGD gypsum | 77.30 | 0.09 | 20.7 | 7.6 | 0.57 | 0.08 |
| | | | | | | |
| Pulverized Coal Unit 3 Mill C1 | 16.50 | | 5.35 | 17.1 | 16.7 | 0.98 |
| Pulverized Coal Unit 3 Mill B1 | 14.20 | 62.61 | 5.49 | 17.1 | 20.3 | 1.19 |
| Pulverized Coal Unit 3 Mill E | 13.30 | 65.17 | 5.16 | 14.0 | 19.0 | 1.36 |
| | | | | | | |
| Pulverized Coal Unit 2 Mill B3 | 14.30 | 64.51 | 5.52 | 14.3 | 21.1 | 1.48 |
| Pulverized Coal Unit 2 Mill A | 15.40 | 64.61 | 5.19 | 13.9 | 18.6 | 1.34 |

Table 5. Uranium and Th concentrations in fly ash compared to those in the Springfield coal from which the fly ash was produced. In coal, U and Th data are presented on ash basis. In addition, ash yield (in weight %), carbon content (C), and total sulfur content (in weight %) are shown.