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External Exposure of the United States Population from Terrestrial Sources of Radiation

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ABSTRACT

Information based on airborne gamma ray spectrometry surveys of terrestrial radioactivity in the United States and performed by the U.S. Geological Survey were reviewed and analyzed to determine the external exposure levels due to the presence of primordial radionuclide such as ^{232}Th, ^{238}U and ^{40}K in the soils. A total of 3,102 counties in 50 states were surveyed for their natural radioactivity content and about 100-million lines of data were reprocessed to determine the associated radiation hazards. The external absorbed dose rate and the corresponding annual effective dose were found to vary from 6.74 nGy h^{-1} to 93.57 nGy h^{-1} and from 40.50 μSv y^{-1} to 565 μSv y^{-1}, respectively. The population-weighted average absorbed dose rate and annual effective dose were calculated to be 38.24±12.43 nGy h^{-1} and 233±75 μSv y^{-1}, respectively. These population-weighted averages were compared to their respective values of 50 nGy h^{-1} and 280 μSv y^{-1} in the NCRP report (1987) and their worldwide averages of 55 nGy h^{-1} and 480 μSv y^{-1} in the United Nations Scientific Committee on the Effect of Atomic Radiation report (UNSCEAR 2000).

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1. INTRODUCTION

Naturally occurring radionuclide in soil or rock near the surface of the earth represent the source of a significant component of the background radiation exposure to the population. Natural sources of radiation derive from radioisotopes synthesized during the creation of the solar system and because of their long half-lives, they still exist today. Of these, potassium (^{40}K), uranium (^{238}U and its daughters), and thorium (^{232}Th and its daughters) are the only radioisotopes that produce high-energy gamma rays of sufficient intensity to be used for gamma ray mapping.

Knowledge of the natural and terrestrial radioactivity of soils is important in health physics in assessing the radiation hazard to the population, in determining changes in natural radiation background and in providing appropriate protection for human beings. In addition, natural background is used as standard in evaluating the impact of man-made radiation. The study of natural radioactivity is also important because it can serve as biochemical and geochemical tracers in the environment in case of geological events such as earthquakes and volcanic eruptions.

In the 1970s, the National Uranium Resource Evaluation (NURE) program in the U.S. took steps to stimulate uranium exploration. The NURE program initiated by the U.S. Geological Survey covered almost all of the U.S. with an airborne gamma-ray spectrometry (AGRS) survey. Data (approximately 100-million lines of data) were obtained from a series of several hundred airborne surveys, using a variety of aircraft and instrument packages (Duval et al. 2005). Data was expressed in terms of element concentrations and absorbed dose rate, providing gridded geographic maps but no statistical analysis has been evaluated.

As far as population exposure is concerned, this study is based on the evaluation of exposure of the U.S. population from terrestrial radioactivity. We have reprocessed and analyzed the complete set of data on terrestrial radioactivity of 3,102 counties in the U.S. The average value of the concentration of potassium (^{40}K), equivalent uranium (^{238}U) and equivalent thorium (^{232}Th) in each county was obtained so that the population-weighted absorbed dose rate and the corresponding annual effective dose could be calculated for each state and therefore for the country. The results were compared to data on external terrestrial radiation dose present in the National Council on Radiation Protection and Measurements (NCRP) report (1987). Data in the NCRP report were obtained from relatively few areas and have been extrapolated (even overestimated) to cover the rest of the U.S. population as the overall average absorbed dose in air.

2. EXECUTIVE SUMMARY

This summer internship research work has been supported by the DOE/FIU Science & Technology Workforce Initiative, an innovative program developed by the U.S. Department of Energy's Environmental Management (DOE-EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2008, an FIU-ARC student spent 10 weeks interning at the Pacific Northwest National Laboratory in Richland, Washington, under the supervision and guidance of Dr. Daniel Strom and Sr. Engineer Bruce Napier.

In the 1970s, the U.S. Geological Survey took steps to stimulate uranium exploration. The National Uranium Resource Evaluation (NURE) program provided coverage of almost the entire U.S. through an airborne gamma-ray spectrometry (AGRS) survey. The resulting data were reviewed and analyzed to determine the concentration and the associated radiation hazards to the population in 3,102 counties in the U.S.

3. MATERIALS AND METHODS

3.1 Basis Principles About Airborne Gamma-Ray Spectrometry

Gamma rays are electromagnetic waves of very high frequency that are spontaneously emitted by the nuclei of some radioisotopes. There are only three which are common enough within earth materials to make them useful for radiological and/or geologically purposes. Bismuth-214 (^{214}Bi) is a decay product of ^{238}U and its gamma line (1.765 MeV) therefore gives an indication of the concentration of uranium. Thallium-208 (^{208}Tl, 2.614 MeV) comes from the decay of ^{232}Th and is an indicator of thorium content. Thus, the estimation of uranium and thorium is determined indirectly. The results are reported in ppm eU (parts per million of equivalent uranium) and ppm eTh (parts per million of equivalent thorium), respectively. The term "equivalent" is a reminder that the estimate is based on the assumption of radioactive equilibrium in the ^{238}U and ^{232}Th decay series. Potassium-40 (^{40}K) is the only isotope of potassium that is radioactive. Its concentration in the soils is directly determined through its gamma line (1.460 MeV). The results are reported in % K (percent of potassium)

A gamma-ray spectrometer is designed to detect the gamma rays associated with these radioactive elements and to accurately sort the detected gamma rays by their respective energies. Airborne methods provide valuable, systematic coverage of large areas. During airborne surveys, the aircraft flew a regular grid along a pattern of parallel lines (flight lines). Most of the east-west flight lines were spaced (Figure 2) at 5-km intervals (western part of the contiguous U.S.) or at 10-km intervals (eastern part of the contiguous U.S. and Alaska). The nominal survey altitudes were 122-m above the ground with a detector volume of about 50-L of thallium-doped NaI crystal. The data were corrected for aircraft and cosmic background, altitude variations, Compton scattering, and airborne ^{214}Bi (Duval et al.. 2005), and were provided by the contractors as apparent surface concentrations of potassium, uranium, and thorium. These data were processed by the U.S. Geological Survey (USGS) to convert the count rates to concentration units. Zero and negative values were arbitrarily set to a small value close to zero. Because the count rate decreases at an exponential rate as the altitude increases, data for altitudes greater than about 180-m above the ground were set to a dummy value and were not used in the gridding process.

Figure 1. Illustration of detection system in AGRS used for the measurement of radiation from naturally occurring potassium, uranium and thorium in the soils (This experimental setup does not reflect the one used during the NURE program).

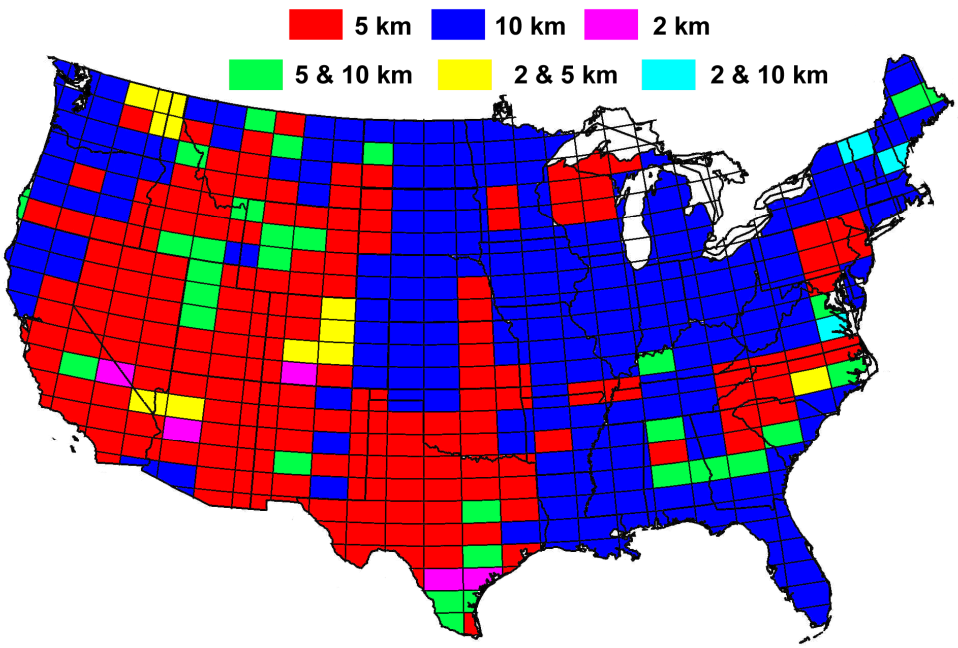

Figure 2. Flightline spacing in the contiguous U.S.

3.2 Fortran Code

FORTRAN 95 was used to process and analyze the data. The algorithm depicted in Figure 3 was translated into code. For this purpose, 13 subroutines were written and run on a personal computer with a 2.62 gigahertz (GHz) processor and 512 megabytes (MB) of random access memory (RAM). The computing time was about 10 minutes in reading and calculating the outputs for each radionuclide and for each Federal Information Processing Standard (FIPS) code.

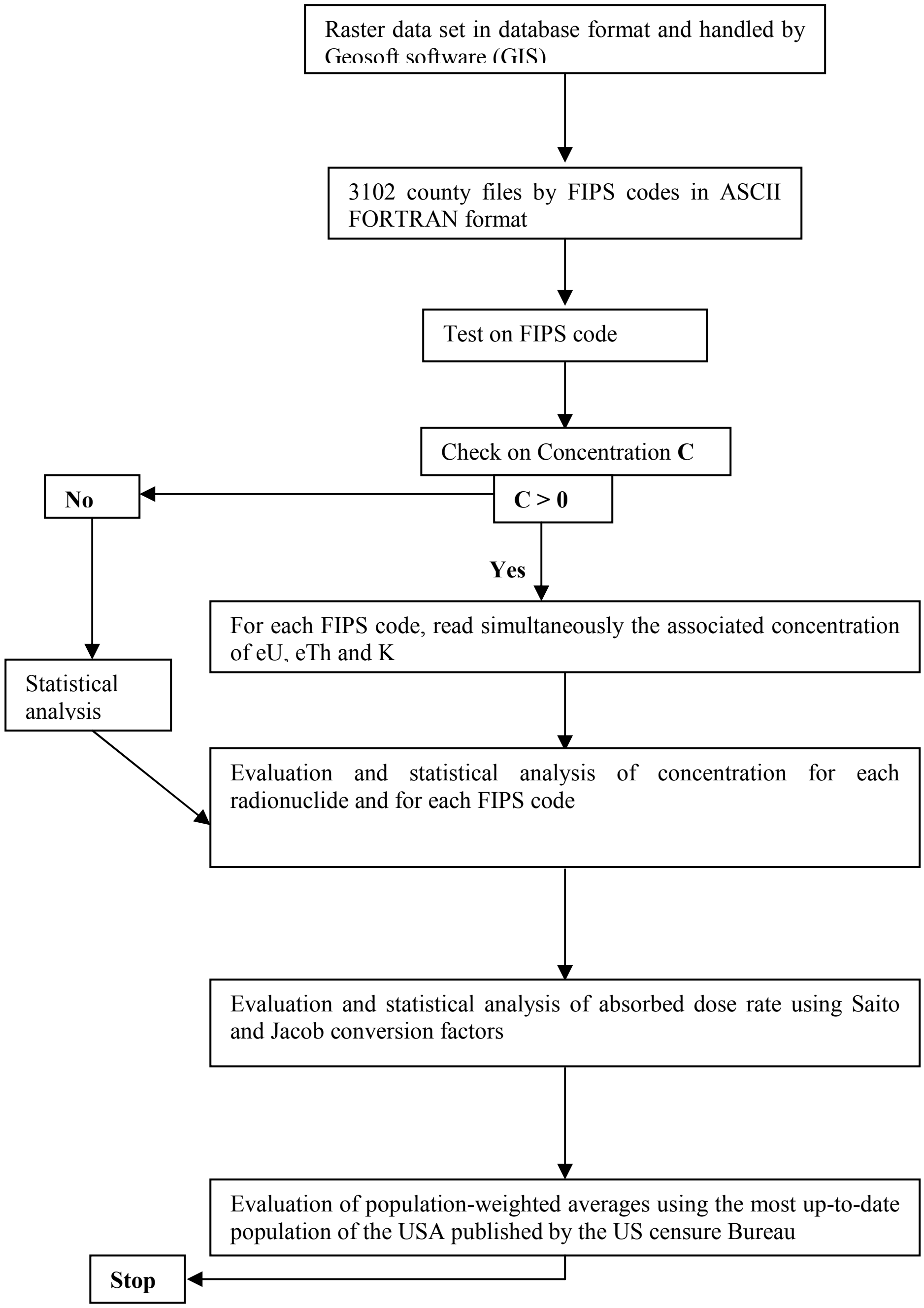

Figure 3. Algorithm used to create the 3102 ASCII files and to analyze the data.

4. RESULTS AND DISCUSSION

4.1 Activity Concentration

Table 1 provides the concentration of primordial radionuclides in the soils. As indicated, the activity of equivalent thorium ranges from 0.7 to 24 ppm (2.84 - 97.44 Bq/kg) with the highest value found in the state of Georgia (Lamar County). The equivalent uranium ranges from 0.4 to 4.5 ppm (4.94 - 56.4 Bq/kg) with the highest value in the state of New Hampshire (Carroll County) while the potassium content ranges from 0.11 to 3% (34 - 939 Bq/kg) with the highest value found in the state of Texas (Jeff Davis County). The highest observed values of equivalent ^{238}U, equivalent ^{232}Th and ^{40}K are higher than their corresponding world average values of 40 Bq/kg, 40 Bq/kg and 580 Bq/kg, respectively, as set in the UNSCEAR report (1998). Figure 4 compares the measured activity concentrations of ^{238}U, ^{232}Th and ^{40}K. Figures 5, 6 and 7 give the distribution of terrestrial radioactivity in the U.S.

4.2 Absorbed Dose Rate and Annual Effective Dose

One of the basic quantities used to quantify the energy deposition of radiation is the absorbed dose in units of J/kg, called gray (Gy). In environmental radiation measurements, for materials containing naturally occurring materials such as ^{238}U, ^{232}Th and ^{40}K, the absorbed dose rate D at 1-m above the ground can be evaluated if their concentrations are known. It can be obtained in units of nGy/h using the following equation:

$$D = \sum_x A_x \times C_x \qquad (1)$$

In the present work, the conversion factors reported by Saito and Jacob (1995), namely 0.463, 0.604, 0.0417 nGy/h per Bq/kg for ^{238}U, ^{232}Th and ^{40}K, respectively, were used.

In the field of radiation protection, the annual effective dose E (µSv/h) is used in place of absorbed dose to take into account the biological effects of different types and energies of radiation. E is obtained using the following expression:

$$E = 14.9 \times eTh + 33.6 \times eU + 81.1 \times K \qquad (2)$$

where the coefficients 14.9, 33.6, 81.1 are reported as dose conversion factors in µSv/y per unit activity. *eTh* and *eU* are equivalent thorium and equivalent uranium expressed in parts per million (ppm) and K is the potassium content expressed in percent (%). In fact, the activity concentration of a material containing 1 ppm of ^{232}Th and 1 ppm of natural uranium is 4.06 Bq/kg and 12.35 Bq/kg, respectively. For natural potassium, a concentration of 1% by weight of sample corresponds to a ^{40}K specific activity of 313 Bq/kg.

Table 2 gives the range and the mean absorbed dose in air at 1-m above the ground in the 50 states specified by their FIPS code. As indicated, the absorbed dose varies from 6.7 to 93.6 nGy/h. Colorado and Nevada show the highest state means of 60.5 and 64.2 nGy/h, respectively. Even though the means found in Arizona, Colorado and Nevada exceed the worldwide average value for soils (55 nGy/h) (Ngachin et al. 2007), all the calculated values lie within the world range (18-93 nGy/h).

The state population-weighted average values were determined using the following equation:

$$\langle X \rangle_S = \frac{\sum_j P_j \times Y_j}{\sum_j P_j} \qquad (3)$$

Where $\langle X \rangle_S$ is the weighted average value of the *S*, P_j is the population number in the county *j* and Y_j is the calculated value of the county *j*.

The country population-weighted average value *Z* was determined by taking the arithmetic mean of the state population-weighted average value:

$$\overline{Z} = \frac{\sum_S X_S}{\sum S} \qquad (4)$$

The population-weighted average absorbed dose in the U.S. has been found to be 38.2±12.4 nGy/h and lower than the worldwide average value of 55 nGy/h.

The range of values and the mean of the annual effective dose are given in Table 3. The map in Figure 9 shows that *E* varies from 40.5 to 565.1. Even though some counties present an effective dose higher that the outdoor average effective dose of 480 µSv/y (UNCEAR 2000), the population-weighted average effective dose of 234±75 µSv/y looks lower. A comparison was made with available data in the literature and published by NCRP (1987). Figure 10 depicts the distribution of the effective dose by county.

Table 1. Terrestrial Radioactivity in Soil of the United States

State Code	eTh (ppm)			eU (ppm)			K(%)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	3.6587	10.0221	5.924	1.1502	3.0254	1.9419	0.15	1.0157	0.4613
2	1.0315	3.5976	2.251	0.413	2.2021	1.0988	0.2542	0.7496	0.5209
4	4.8718	13.1845	8.416	1.7974	3.9831	2.6661	1.0269	2.592	1.8232
5	3.3158	8.2025	5.7081	1.1371	2.2444	1.7789	0.2887	1.497	0.6702
6	1.8955	13.3791	6.1185	0.7261	3.4263	1.8491	0.4411	2.2977	1.1871
8	6.4366	16.5353	9.6526	1.4127	3.3008	2.2796	1.0451	2.8215	1.8239
9	6.347	8.5148	7.4795	2.1411	2.7669	2.5135	1.0109	1.6631	1.3255
10	2.5896	6.5936	4.3817	0.9591	1.6832	1.3026	0.9476	1.0764	1.0231
12	0.691	4.4452	1.8473	0.5372	3.0828	1.1836	0.1089	0.3436	0.2136
13	1.2234	23.7831	6.5085	0.8581	4.4782	2.0139	0.1396	2.102	0.6196
16	4.4621	13.7598	8.204	1.0543	2.9518	2.1962	0.9321	2.1156	1.5191
17	3.3777	7.5765	6.4391	1.1579	2.6719	2.0041	0.9723	1.5103	1.2195
18	1.9578	7.3356	5.4745	0.9127	3.1153	2.0354	0.6693	1.5202	1.0896
19	4.7672	9.0589	6.7393	1.2675	2.3759	1.8072	0.9175	1.4601	1.1637
20	5.3097	11.352	8.8065	1.3869	2.5398	2.0137	0.6365	2.0526	1.4587
21	4.619	8.4378	6.544	1.5102	3.1221	2.1196	0.532	1.8343	1.0356
22	1.4031	7.6371	5.1713	0.5538	2.1684	1.4992	0.2229	1.3584	0.6767
23	3.9011	8.5221	5.392	1.2833	3.3747	2.0049	0.7681	1.6054	1.0994
24	2.3667	8.7554	5.4922	0.9089	2.3933	1.6949	0.3959	1.857	0.891
25	4.2692	9.0192	6.0258	1.4646	2.6747	2.0099	0.9342	1.575	1.2753
26	1.2272	4.7535	2.5069	0.4794	1.9495	0.921	0.5085	1.1624	0.8521
27	1.9796	7.3573	4.4921	0.7191	1.8236	1.2884	0.5204	1.248	0.9673
28	3.2618	7.9859	5.6501	1.0965	2.4079	1.7223	0.1586	1.2879	0.6221
29	3.4547	8.9932	6.6293	1.242	2.3295	1.8406	0.3755	1.4696	0.904
30	6.2032	9.3541	7.3593	1.6561	2.5239	1.9703	1.2891	1.9055	1.5071
31	3.7504	10.9495	7.7779	0.9399	2.8244	1.9805	1.1697	2.063	1.5427
32	6.973	13.3926	10.1879	1.9041	3.4695	2.603	1.2612	2.3566	1.8664
33	5.8522	10.6984	7.5175	2.0643	4.183	2.7077	1.1172	1.799	1.3638
34	1.8313	6.3778	4.082	0.7445	2.7753	1.7061	0.1963	1.3375	0.7124
35	3.962	10.2234	7.0638	1.4191	2.83	2.0457	0.9207	2.5233	1.5097
36	2.778	9.1611	5.9735	0.9607	2.6719	1.7749	0.5588	1.9146	1.2698
37	1.0778	14.8702	5.9482	0.4404	3.6776	1.7523	0.1261	1.9725	0.6862
38	4.6996	7.7313	5.9487	1.1723	2.2865	1.5869	0.9811	1.6487	1.2258
39	4.0253	8.1775	6.6356	1.6233	3.6707	2.502	0.7948	1.764	1.1831
40	4.6592	8.3938	6.2693	1.1876	2.1479	1.6967	0.4703	1.8058	0.9712
41	2.2188	7.6994	3.9677	0.543	2.0994	1.044	0.4435	1.7476	0.8228
42	4.8979	10.3278	6.9792	1.4019	3.5588	2.2351	0.6527	1.7619	1.0604
44	4.8979	10.3278	6.9792	2.3305	2.8951	2.5761	1.3286	1.9289	1.613
45	3.3268	10.7288	5.9204	0.9972	3.73	1.8753	0.1355	2.2142	0.607
46	5.8905	9.78	7.2507	1.4987	2.3352	1.8122	1.1871	2.0289	1.4312
47	3.3391	8.0749	5.6909	1.3929	3.1296	2.0912	0.4025	1.4834	0.7769
48	1.4884	14.0151	5.4392	0.7267	2.5297	1.583	0.1925	3.0015	0.8314
49	3.6081	10.7408	6.5425	1.6344	3.1693	2.2945	0.8515	1.8458	1.3766
50	2.3767	4.7939	3.9363	1.3169	1.9124	1.6377	0.7743	1.5448	1.1151
51	1.0684	10.7075	5.6606	0.7417	3.1551	1.7987	0.2779	2.2308	0.9603
53	1.1713	7.9444	3.9815	0.3724	2.3905	1.2033	0.3515	1.5209	0.9015
54	4.7135	8.381	6.7295	1.4553	2.5251	2.0073	0.6267	2.0342	0.9908
55	1.4096	6.483	3.7951	0.8657	1.9893	1.3359	0.517	1.5585	1.0253
56	4.1133	10.4142	8.3961	2.0331	2.8256	2.4046	1.2811	2.1808	1.6617

Table 2. Mean Absorbed Dose Rate at 1-m Above the Ground Due to Radionuclides Present in the Soil

State code	Mean	SD	Gmean	GSD	Min	Max	Rmaxmin	# of County
1	31.6278	7.5375	30.7834	1.0561	17.4925	48.9026	2.7956	67
2	18.5878	5.2798	17.8083	1.0997	8.781	26.9132	3.0649	24
4	59.6465	13.8715	58.1098	1.059	35.6054	88.889	2.4965	15
5	32.8944	7.3432	32.1071	1.0502	21.253	52.2796	2.4599	75
6	41.0483	14.3631	38.5874	1.1391	14.5484	82.348	5.6603	57
8	60.4835	9.8424	59.6993	1.027	40.0192	86.6705	2.1657	64
9	49.9833	4.5964	49.8008	1.0084	43.7294	56.7545	1.2979	8
10	31.5303	7.8591	30.8836	1.0642	24.1908	39.8222	1.6462	3
12	14.0718	4.7239	13.2369	1.1408	6.743	24.7915	3.6766	67
13	35.5376	14.5688	32.8238	1.1746	10.8472	93.5695	8.6261	159
16	52.4769	10.4969	51.4109	1.0443	29.1235	75.5865	2.5954	44
17	43.1421	2.8662	43.0392	1.0051	27.9038	48.4928	1.7379	102
18	39.2598	6.1575	38.7211	1.0306	18.7444	55.0728	2.9381	92
19	42.0266	5.2223	41.7044	1.0158	30.9935	52.9806	1.7094	99
20	52.1235	7.2104	51.6315	1.0194	36.7872	66.1031	1.7969	105
21	41.6576	5.9636	41.2276	1.0214	28.8965	55.6376	1.9254	120
22	30.0681	9.2271	28.5102	1.1254	11.5891	46.538	4.0157	64
23	39.0118	10.0659	37.9149	1.0603	26.9139	60.7883	2.2586	16
24	34.7674	11.3545	33.048	1.1116	20.0321	54.8736	2.7393	24
25	42.8905	7.2487	42.3581	1.0279	31.0189	57.9353	1.8677	10
26	22.5244	5.6573	21.8409	1.0644	13.5407	37.7722	2.7895	83
27	30.9923	6.5687	30.2252	1.0558	16.4428	43.4703	2.6437	87
28	31.8022	7.5741	30.8285	1.069	16.5078	44.2831	2.6826	82
29	38.5579	7.5136	37.7718	1.0446	22.3962	54.3283	2.4258	115
30	48.9587	3.9071	48.8109	1.0061	42.7093	62.2099	1.4566	56
31	50.5089	8.8487	49.6668	1.0366	31.6263	67.6293	2.1384	93
32	64.196	11.0791	63.2829	1.0313	45.6654	82.3705	1.8038	17
33	51.6844	9.4869	50.974	1.03	40.8742	73.5827	1.8002	10
34	29.0425	12.0247	26.499	1.2289	12.3045	46.8894	3.8108	20
35	48.6986	11.4748	47.3885	1.0587	30.363	70.127	2.3096	33
36	41.3484	7.2099	40.666	1.0368	22.0697	53.276	2.414	56
37	33.5411	14.4685	30.3111	1.2473	8.3575	70.7292	8.463	100
38	39.6408	5.3286	39.3065	1.017	32.2098	51.7117	1.6055	53
39	45.9893	6.3517	45.543	1.0204	30.4628	61.2223	2.0097	88
40	37.7306	6.4963	37.1737	1.0309	25.9142	49.4191	1.907	77
41	26.4259	8.539	25.2469	1.0946	15.2577	53.6692	3.5175	36
42	43.7078	7.3734	43.1075	1.0284	30.1435	68.6282	2.2767	67
44	54.1537	6.4338	53.8483	1.0143	45.8023	63.2416	1.3808	5
45	33.3395	11.7184	31.467	1.1242	16.2239	60.1625	3.7083	46
46	47.0238	4.9899	46.7767	1.0105	39.8132	62.6937	1.5747	66
47	36.3965	6.615	35.8017	1.0342	23.9467	53.4668	2.2327	95
48	33.4247	9.6636	32.2	1.0757	15.9752	88.6727	5.5506	251
49	48.6873	9.1305	47.8908	1.0345	32.6641	70.4792	2.1577	29
50	35.1831	5.3446	34.8006	1.0241	26.3465	45.0446	1.7097	14
51	37.3145	9.1558	36.1497	1.0692	17.4032	59.1059	3.3963	122
53	29.0873	13.806	25.7674	1.2986	10.0798	51.9471	5.1536	39
54	41.2078	6.0314	40.7584	1.0232	28.6871	57.7925	2.0146	55
55	30.8302	6.334	30.1448	1.049	15.8711	43.9941	2.772	72
56	57.2973	6.627	56.9272	1.0137	46.9794	67.901	1.4453	23

Gmean= Geometric mean; GSD= Geometric standard deviation; Rmaxmin= Max / Min

Table 3: Annual Effective Dose Due to Radionuclides in the Soil of the United States

State code	Mean	SD	Gmean	GSD	Min	Max	Rmaxmin	# of County
1	190.9262	45.6712	185.7886	1.0566	105.3263	294.8775	2.7997	67
2	112.7016	31.7936	108.0352	1.0984	53.4355	163.0224	3.0508	24
4	362.8405	84.4803	353.4606	1.0593	216.2641	540.4924	2.4992	15
5	199.171	44.8638	194.3251	1.051	128.7058	317.9774	2.4706	75
6	249.5675	87.3681	234.5977	1.1392	88.4131	500.8157	5.6645	57
8	368.3402	60.2215	363.5129	1.0273	243.0514	527.4026	2.1699	64
9	303.396	28.1589	302.2663	1.0085	264.714	344.9178	1.303	8
10	192.0249	47.4755	188.1492	1.0631	147.6612	242.0962	1.6395	3
12	84.6204	28.4077	79.5962	1.141	40.4992	147.7968	3.6494	67
13	214.8899	88.5239	198.3219	1.1765	65.3975	565.0849	8.6408	159
16	319.2336	63.8539	312.7511	1.0443	177.5031	460.4013	2.5938	44
17	262.1823	17.3725	261.5608	1.0051	170.098	294.8941	1.7337	102
18	238.3264	37.2692	235.0783	1.0304	114.1182	334.0265	2.927	92
19	255.5143	31.6392	253.5713	1.0156	188.593	322.0563	1.7077	99
20	317.1728	44.0813	314.1465	1.0196	223.2535	402.2525	1.8018	105
21	252.7091	36.5545	250.0466	1.0219	174.9314	339.0286	1.9381	120
22	182.309	56.2774	172.7891	1.1261	70.5103	283.2375	4.017	64
23	236.87	60.8724	230.2588	1.0599	163.5382	368.6302	2.2541	16
24	211.0375	69.2103	200.5283	1.1123	121.9889	333.5746	2.7345	24
25	260.7475	43.9896	257.5197	1.0279	188.5853	351.9885	1.8665	10
26	137.4051	34.3416	133.2724	1.0638	82.8341	229.5103	2.7707	83
27	188.6709	39.9665	184.0051	1.0558	100.0022	264.5733	2.6457	87
28	192.5092	46.299	186.5017	1.0704	99.4157	269.4169	2.71	82
29	233.9366	45.8991	229.099	1.0453	135.2875	330.2885	2.4414	115
30	298.0766	23.7656	297.178	1.0061	260.1333	378.7152	1.4559	56
31	307.5486	53.4808	302.5104	1.0359	193.4004	411.7305	2.1289	93
32	390.6282	67.4243	385.0699	1.0313	277.555	500.8707	1.8046	17
33	313.593	57.3963	309.3031	1.0298	248.1769	445.8539	1.7965	10
34	175.9205	73.0506	160.4226	1.2305	74.4581	284.2368	3.8174	20
35	296.4201	70.215	288.3709	1.0592	184.6369	427.6519	2.3162	33
36	251.6184	43.6387	247.5056	1.0364	134.0712	324.5522	2.4207	56
37	203.1574	87.7229	183.5597	1.2477	50.7505	430.5244	8.4832	100
38	241.3646	32.4222	239.332	1.017	196.2383	315.0292	1.6053	53
39	278.8844	38.4749	276.185	1.0203	184.7861	371.4158	2.01	88
40	229.184	40.0832	225.6968	1.0319	156.8868	301.1232	1.9194	77
41	160.9273	52.0233	153.7421	1.0946	92.9229	326.9912	3.519	36
42	265.0871	44.812	261.4313	1.0286	182.5253	416.35	2.2811	67
44	329.2156	39.2977	327.3408	1.0144	278.1929	384.6295	1.3826	5
45	201.659	71.4384	190.1694	1.126	97.8067	367.2922	3.7553	46
46	286.3525	30.4489	284.8417	1.0106	242.4244	382.1211	1.5762	66
47	220.3084	40.3361	216.6559	1.0347	144.6309	324.5847	2.2442	95
48	202.8916	59.1677	195.3457	1.0769	97.0253	541.5329	5.5814	251
49	295.8466	55.4818	291.0043	1.0345	197.971	428.0455	2.1622	29
50	214.0265	32.7954	211.6615	1.0245	160.0857	274.4637	1.7145	14
51	226.4942	55.96	219.3377	1.07	105.1106	360.7506	3.4321	122
53	177.069	83.9342	156.9109	1.2976	61.4785	315.9912	5.1399	39
54	250.015	36.6871	247.2777	1.0232	173.778	352.2812	2.0272	55
55	187.7395	38.6104	183.5527	1.0491	96.3995	267.8491	2.7785	72
56	348.5557	40.526	346.2798	1.0139	285.361	413.1539	1.4478	23

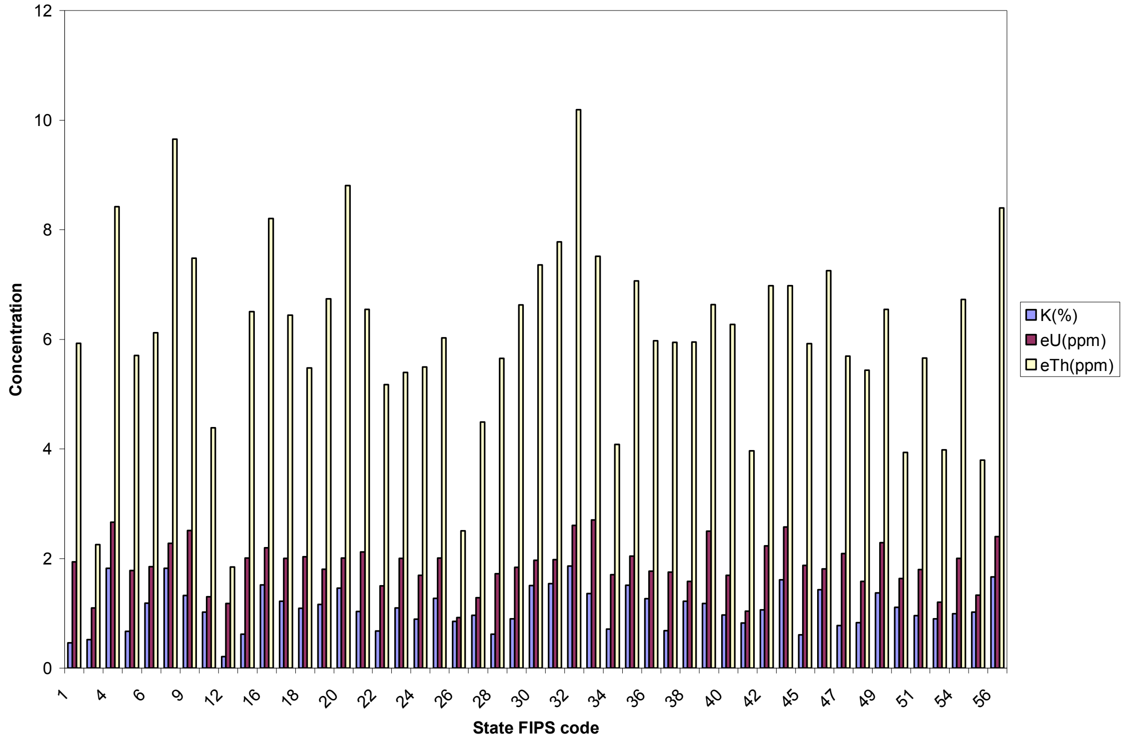

Figure 4. Natural radioactive content of the soils in the 50 states of U.S.

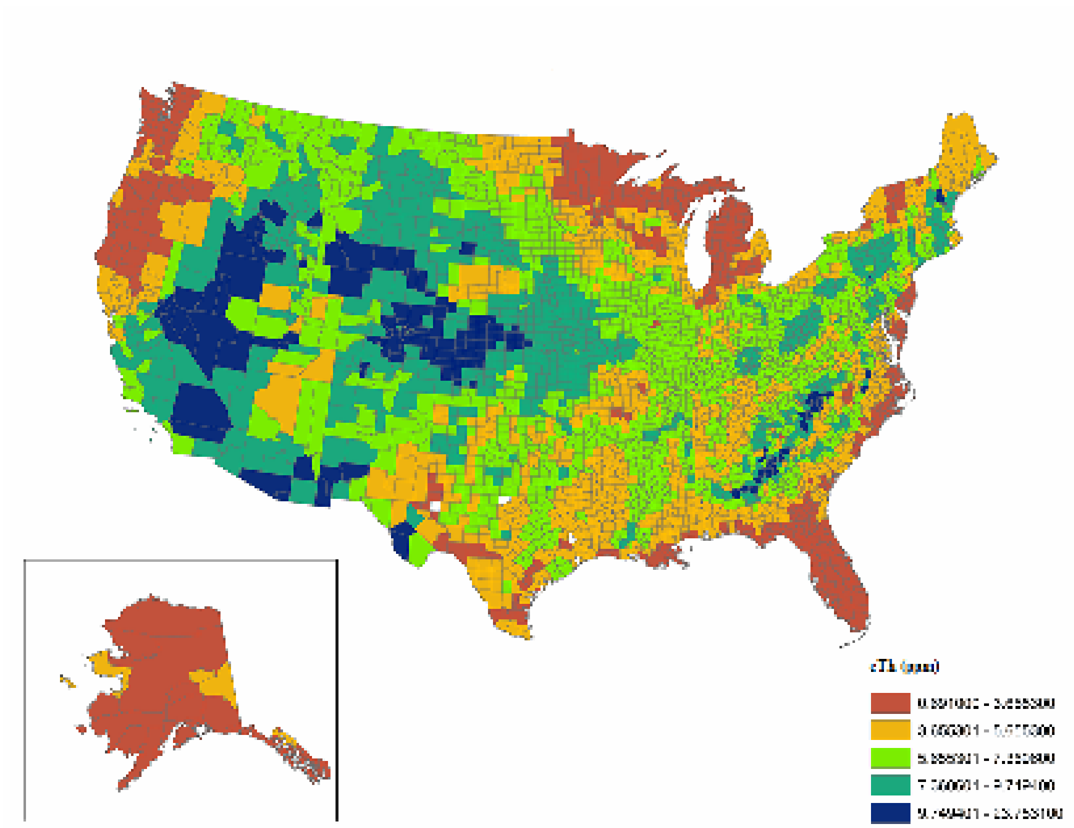

Figure 5. Thorium distribution in the soils of United States.

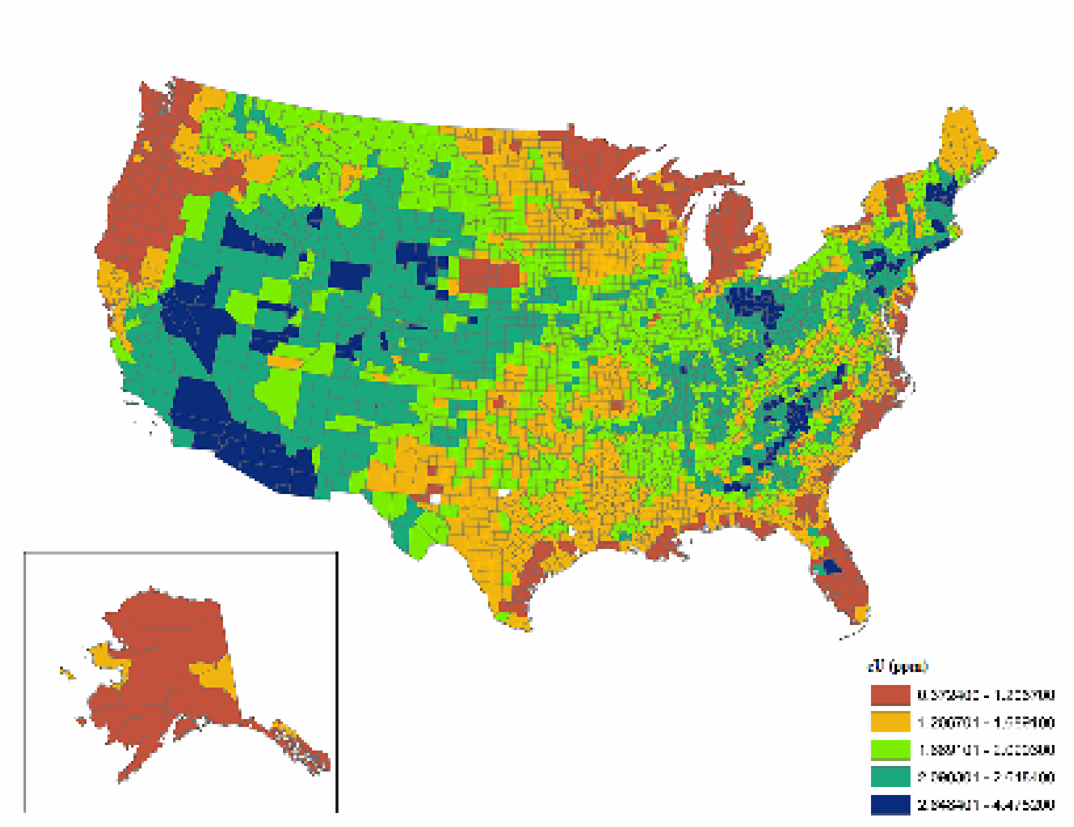

Figure 6. Uranium content in the soil of the United States.

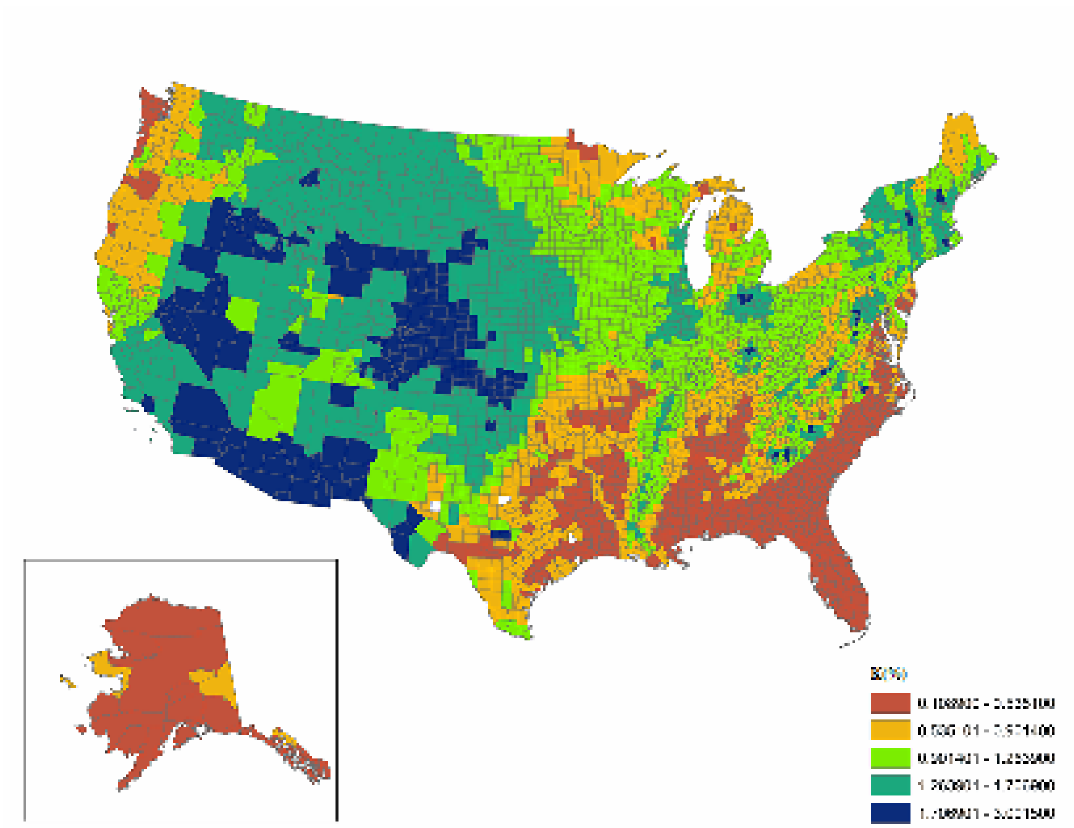

Figure 7. Potassium content in the soil of the United States.

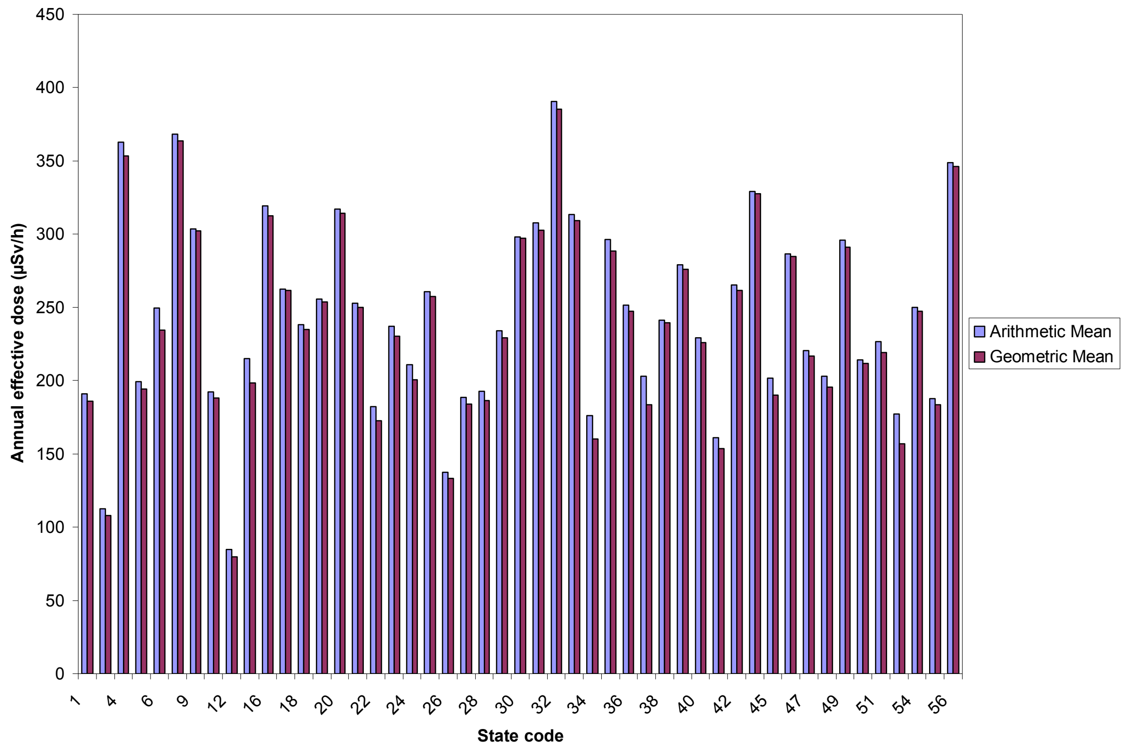

Figure 8. Mean annual effective dose in the 50 States in USA.

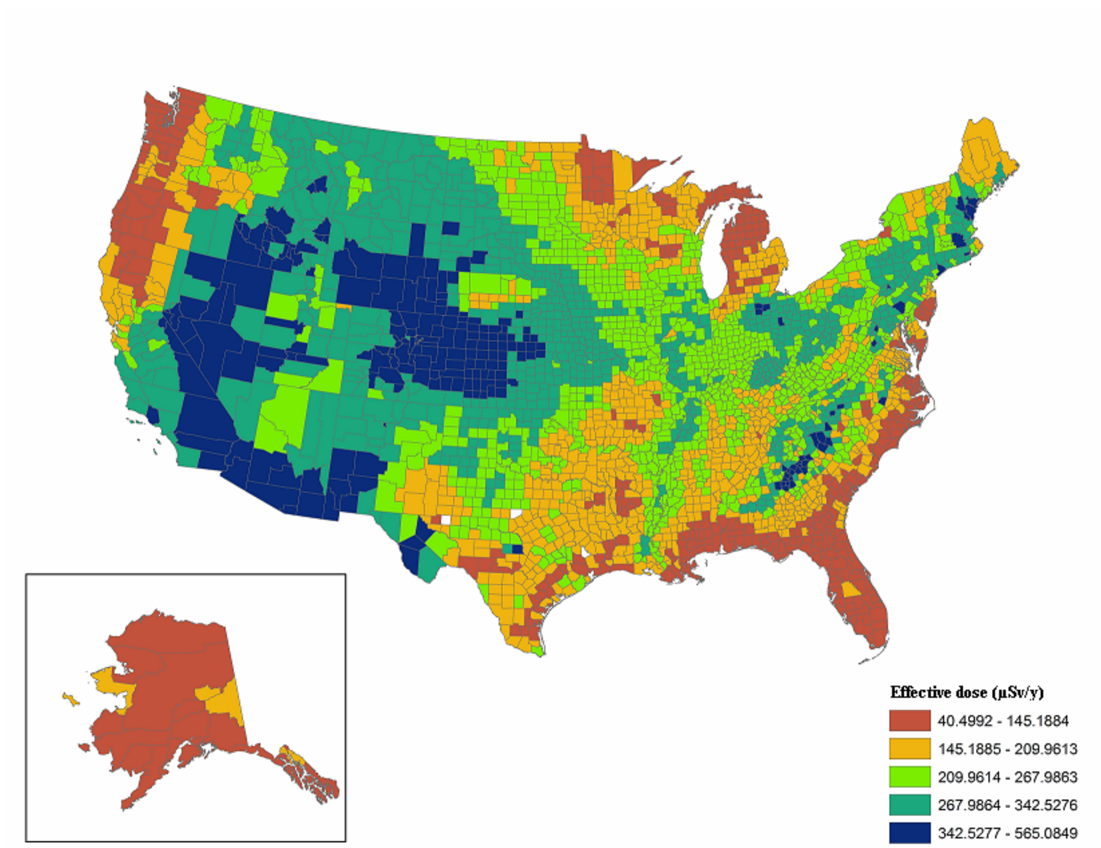

Figure 9. Map of Annual effective dose in the USA.

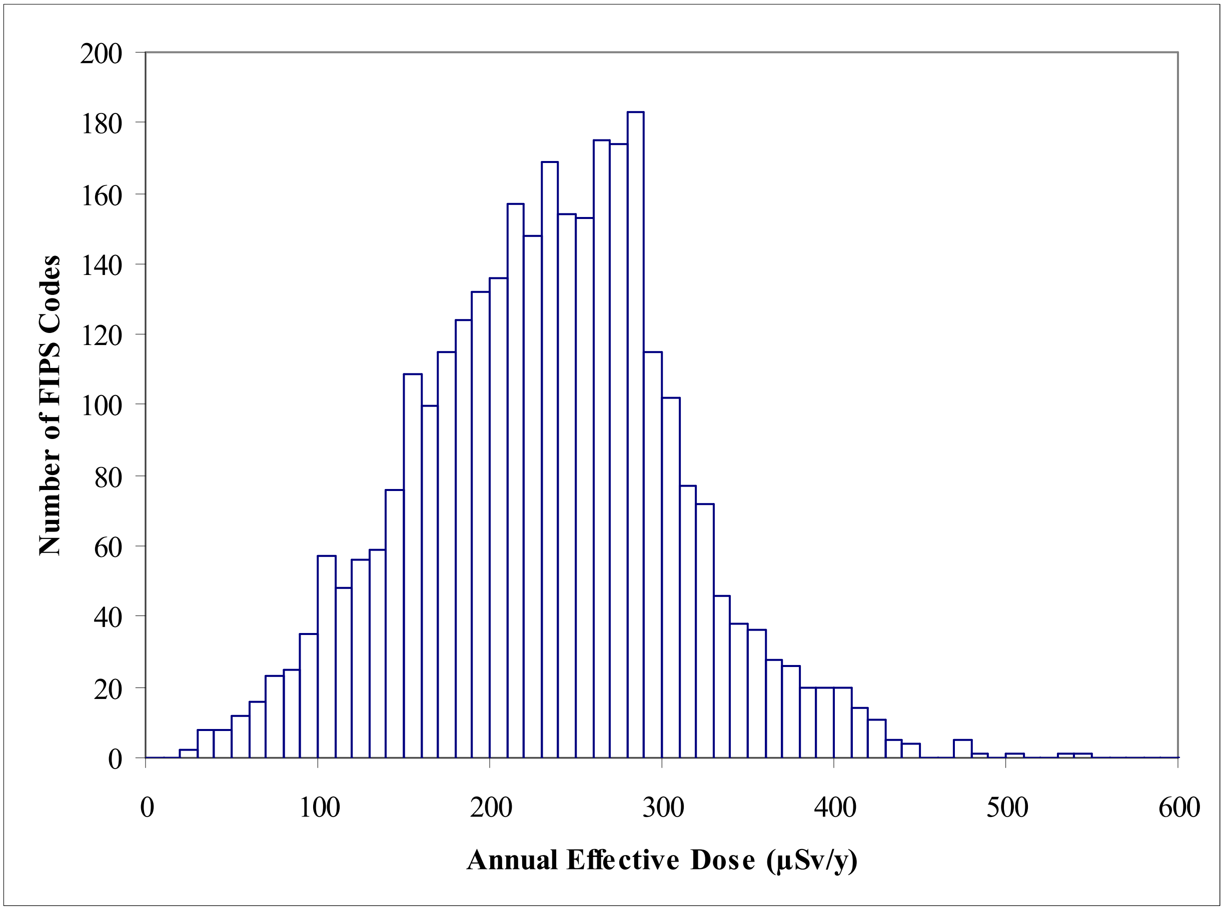

Figure 10. Distribution of annual effective dose by county, *N=3102*.

5. CONCLUSIONS AND PERSPECTIVES

Based on airborne gamma ray spectrometry surveys covering almost all the United States, it has been possible to:

- Identify the existence of some areas where the terrestrial radioactivity was about 2 times the global average.
- Determine a population-weighted average effective dose value of 234±75 µSv/y, which differs from the NCRP reported value (280 µSv/y) by 16%.
- Identify that there are large variations in annual effective dose in the United States.

In regard to the above results, except for few counties which have shown values that exceed the worldwide average value, one can conclude that, through its population-weighted average annual effective dose, the United States exposure does not exceed the worldwide average exposure of 480 µSv/y.

Table 4. Comparison of Absorbed Dose Rate with those Reported in NCRP and the Worldwide Average Value for Soils Reported by UNSCEAR

Area	Population / Year	D (nGy/h)	Reference
Coastal plain	6,756,772 / 1960	26.25	
Non-coastal plain (excluding Denver)	46,781,330	52.51	NCRP, 1987
Colorado plateau area (Denver)	1,073,624	102.74	
Population-weighted average		50	
Worldwide average	-	55	UNSCEAR, 2000
3102 Counties of 50 States in the United States	Population reported by the US Census Bureau / 2007	38.2	This work

In the future, we plan to investigate the correlation between the exposure from natural radiation and the elevation above sea level, as the higher altitude regions have higher natural background.

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IAEA-TECDOC-1363, June 2003. Guidelines for radioelement mapping using gamma ray spectrometry data.

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APPENDIX

```
!   -------------------------------------------------------------------------
!   Pacific Northwest National Laboratory, Richland, WA, USA
!   Project: Environmental Radioactivity Measurement
!   Authors: M. Ngachin, B. A Napier, D. strom
!   -------------------------------------------------------------------------
!   -------------------------------------------------------------------------
!   This subroutine evaluates xmean, xlmean, geomean, absorbed
!   dose and annual effective dose in the 3102 counties of the USA
!   -------------------------------------------------------------------------

    Program Radiation
!   Main Outer Loop Program to open files and read them
!   Number of county equivalents per state
!   Texas has the most = 254 – Texas
!   Delaware has least = 3   – Delaware
!
!   The highest county FIPS code is 840, so, if we loop to 840 on counties, that ought to do it...

    Implicit none
    Integer, parameter   :: m = 3, n = 3.
    Real, dimension(24,24) :: C
    Real, dimension(3) :: D,E
    Real,  Dimension(2000000,10):: A
!   Integer,Parameter:: nline=4050, ncol=8
    Integer,Parameter:: ncol=10, col=8
    Real, Dimension(ncol)::sumx, sumx2, sumxl, sumxl2
    integer, dimension(20000)::nzero,npos,nneg
    Real  xmean, xlmean, xsd, xlsd, geomean, geosd, &
    dummy, rmaxmin, value, xmin, xmax
    Integer i, j, k,l, istate, icnty,nline,ierr

    Character*37 Directory
```

```
Character*41 Directout
Character*35 Directin
Character*37 Direct
Character*44 Director
Character*2 State(56)
Character*3 Cnty(849)
Character*9 SSCCC
Character*9 stcty
Character*9 sscty
Character*5 ifchar
Character*5 SSFIPS
Logical Lexist

Data State/'01','02','03','04','05','06','07','08','09','10',&
     '11','12','13','14','15','16','17','18','19','20',&
     '21','22','23','24','25','26','27','28','29','30',&
     '31','32','33','34','35','36','37','38','39','40',&
     '41','42','43','44','45','46','47','48','49','50','51',&
     '52','53','54','55','56'/

Data Cnty/'001','002','003','004','005','006','007','008','009',&
     '010','011','012','013','014','015','016','017','018','019',&
     '020','021','022','023','024','025','026','027','028','029',&
     '030','031','032','033','034','035','036','037','038','039',&
     '040','041','042','043','044','045','046','047','048','049',&
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```

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'800','801','802','803','804','805','806','807','808','809',&
'810','811','812','813','814','815','816','817','818','819',&

```
            '820','821','822','823','824','825','828','827','828','829',&
            '830','831','832','833','834','835','836','838','838','839',&
            '840','841','842','843','844','845','846','847','848','849'/
      Data Directory/'N:\USGS_Aeral_Rad_Survey\CountyFiles\'/
      Data Directin/'N:\USGS_Aeral_Rad_Survey\DataFiles\'/
      Data Directout/'N:\USGS_Aeral_Rad_Survey\AbsorbeDoseFiles\'/
      Data Director/'N:\USGS_Aeral_Rad_Survey\EffectiveDoseFiles\'/
      Data Direct/'N:\USGS_Aeral_Rad_Survey\ResultFiles\'/
!     Main outer loop on the 50 states:
      Do istate = 51,51
!     Inner loop on the counties
            Do icnty = 630, 640
            ssccc = State(istate)//Cnty(icnty)//".out"
            stcty = State(istate)//Cnty(icnty)//".dat"
!           sscty = State(istate)//Cnty(icnty)//".txt"
            SSFIPS=State(istate)//cnty(icnty)
      Inquire ( File = Directory//ssccc, &
              Exist = Lexist)
      If(Lexist) then
      Open (Unit=12, File = Directory//ssccc, Status = 'OLD' )
!           Call for Subroutines
      Call  Average(A, xmean,xlmean, geomean, Directin,ssccc,stcty)
                  End if
                  Close (12)
         End do
      End do
      Close(14)
      close(20)
      close(22)
!     close(24)
!     pause
      stop
      End
```

```
!   ----------------------------------------------------------------
!   Subroutine for the calculation of average concentration of
!   eU-238, eTh-232 and K-40 in the counties of USA
!   ----------------------------------------------------------------

    Subroutine Average(A, xmean, xlmean, geomean, Directin,ssccc,stcty)

!     Variables
    Implicit none
    Integer, Parameter:: ncol=10, col=8
    Real,  Dimension(2000000,10):: A
    Real, dimension(24,24)::C,F
    Real, dimension(3)::E,D,G,H
    Real, Dimension(ncol)::sumx, sumx2, sumxl, sumxl2
    integer, dimension(20000)::npos,nneg, nzero
    Real  xmean, xlmean, xsd, xlsd, geomean, geosd, &
    dummy, rmaxmin, value, xmin, xmax
    Integer i, j, k,  l, istate, icnty, ierr, nline
    Character*35 Directin
    Real x, y, z
    Character*41 Directout
    Character*37 Direct
    Character*44 Director
    Character*9 ssccc
    Character*9 sscty
    Character*9 stcty
    Character*2 State(56)
    Character*3 Cnty(254)
    Character*5 SSFIPS
    Logical Lexist
!   Read / and Write A(nline, ncol)
    Open(Unit=14, File=Directin//ssccc, Status='replace')
    Do i=1,618752           ! This gives the number of lines of the biggest files
    Read(12,*,end=100, iostat=ierr) ((A(i,j), j=1,col))
```

```
      nline=i
      end do
      if (ierr .ne. 0) then
      write(14, *) i, j
      end if
100   continue
200 Format(3F8.4)
      sumx=0.
      sumx2=0.
      sumxl=0.
      sumxl2=0.
       Npos=0
       Nneg=0
       Nzero=0
      Do j=2,4
        xmax=A(1,j)
      xmin=A(1,j)
            Do i=1,nline
            If (xmax .LT. A(i,j) .and. A(i,j) .gt. 0 ) then
            xmax=A(i,j)
            else If (xmin.GT.A(i,j) .and. A(i,j) .gt. 0) then
                  xmin=A(i,j)
!                       endif
            endif
            rmaxmin=xmax/xmin
            if (A(i,j) .gt. 0) then
            sumx(j)=sumx(j)+A(i,j)
            sumx2(j)=sumx2(j)+(A(i,j))**2
            sumxl(j)=(sumxl(j)+log(A(i,j)))
            sumxl2(j)=sumxl2(j)+(log(A(i,j)))**2
            Npos(j) = Npos(j) +1
            else if (A(i,j) .eq. 0) then
            Nzero(j) = Nzero(j)  + 1
            else if (A(i,j) .lt. 0) then
```

```
            Nneg(j) = Nneg(j) + 1
            end if
            End do
      xmean=sumx(j)/real(npos(j))
      xlmean=sumxl(j)/real(npos(j))
      xsd=(sumx2(j)-2.*xmean*sumx(j)+npos(j)*(xmean)**2)/(npos(j)-1)
      xlsd=(sumxl2(j)-2.*xlmean*sumxl(j)+npos(j)*(xlmean)**2)/(npos(j)-1)
      geomean=Exp(xlmean)
      geosd=Exp(xlsd)
      Write(14,200)  xmean, xlmean, geomean
!     Write(14,*)  xmean, xlmean, geomean, xmin, xmax, rmaxmin,&
!      nneg(j), nzero(J), npos(j),  nline
      End do
      Call Dose(E,C,Direct,x,y,z,F,H,ssccc,Directout,Director,stcty,sscty)
      Close(14)
      Return
      End
!     ------------------------------------------------------------------
!     Subroutine of Absorbed Dose (nGy/h) and Effective Dose (microSv/y)
!     ------------------------------------------------------------------

      Subroutine Dose(E,C,Direct,x,y,z,F,H,ssccc,Directout,Director,stcty,sscty)

      Integer, parameter:: m=3, n=3,ncol=10, col=3
      Real, dimension(24,24)::C,F

      Real, dimension(3):: D,E, G,H
      Data D /0.604,0.462,0.0417/ ! Dose conversion factors for absorbed dose (Saito, 1995)
!     Data D /0.666,0.43,0.0422/ ! Dose conversion factor(nGy/h per Bq/kg) (Beck, 1972)
      Data G /14.9, 33.6, 81.1/ ! Dose conversion factors for Effective dose(saito,1995)
!     Data G /0.904,0.667,0.031/ ! Dose conversion factor(nSv/h per Bq/kg) (FGR-12 and ICRP 60)
      Integer i, j, k, ierr
      Real adose, edose, s, x, y, z
      Character*9 stcty
```

```
Character*9 ssccc
Character*9 sscty
Character*41 Directout
Character*35 Directin
Character*37 Direct
Character*44 Director

Open (Unit=20, File=ssccc, Status='new')
Open (Unit=22, File=stcty, Status='new')
Rewind(14)
Do i= 1, m
Read(14,*) (C(i,j), j=1,col)
End do
x=1.
y=1.
z=1.
Do j=1,n
x=C(1,j)*4.06
y=C(2,j)*12.35
z=C(3,j)*313
Write(20,*) x,y,z        ! x, y, z Represente the concentration converted in terms of Bq/Kg
End do
Rewind(20)
Do i=1,m
Read(20,*) (F(i,j), j=1,3)
End do
E=0.
Do i=1,1
        Do j=1,3
        E(i)=E(i)+F(i,j)*D(j)
        End do
Write(22,*) E(i)
End do
H=0.
```

```
      Do j=1,1
            Do i=1,3
            H(j)=H(j)+C(i,j)*G(i)
            End do
      Write(22,*) H(j)
      End do

      Close(20)
      Close(22)
      Close(24)
      Return
      End


!     ---------------------------------------------------------------------------
!     Pacific Northwest National Laboratory, Richland, WA, USA
!     Project: Environmental Radioactivity Measurement
!     Authors: M. Ngachin, B. A Napier, D. strom
!     ---------------------------------------------------------------------------

!     ---------------------------------------------------------------------------
!     This subroutine evaluates the concentration of eTh, eU and K in each of
!     the 3102 counties of the USA. A 3102 lines file is then created
!     ---------------------------------------------------------------------------

      Implicit none
      Integer, parameter   :: m = 3, n = 3
      Real, dimension(24,24) :: C
      Real, dimension(3) :: D,E

      Real,  Dimension(2000000,10):: A
!     Integer,Parameter:: nline=4050, ncol=8
      Integer,Parameter:: ncol=8, lic=10800
      Real, Dimension(ncol)::sumx, sumx2, sumxl, sumxl2
```

```
    Real, Dimension(lic, 3):: Mean, TMean
    Real  xmean, xlmean, xsd, xlsd, geomean, geosd, &
    dummy, rmaxmin, value, xmin, xmax
    Integer i, j, k, nzero, l, istate, icnty,nline,ierr

        Character*37 Directory
        Character*41 Directout
        Character*35 Directin
        Character*37 Direct
        Character*44 Director
    Character*2 State(56)
    Character*3 Cnty(849)
        Character*9 SSCCC
        Character*9 stcty
        Character*9 sscty
    Character*5 ifchar
    Character*6 SSFips
    Logical Lexist

    Data State/'01'…'56'/
    Data Cnty/'001' … ,'849'/

    Data Directory/'N:\USGS_Aeral_Rad_Survey\CountyFiles\'/
        Data Directin/'N:\USGS_Aeral_Rad_Survey\DataFiles\'/
        Data Directout/'N:\USGS_Aeral_Rad_Survey\AbsorbeDoseFiles\'/
        Data Director/'N:\USGS_Aeral_Rad_Survey\EffectiveDoseFiles\'/
        Data Direct/'N:\USGS_Aeral_Rad_Survey\ResultFiles\'/

!   Main outer loop on the 50 states:
    Do istate = 1,56
!   Inner loop on the counties
        Do icnty = 1,849
        ssccc = State(istate)//Cnty(icnty)//".out"
        stcty = State(istate)//Cnty(icnty)//".dat"
```

```
            sscty = State(istate)//Cnty(icnty)
            SSFips=State(istate)//".dat"
          Inquire ( File = Directin//ssccc, &
             Exist = Lexist)
            If(Lexist) then
      Open (Unit=30, File = Directin//ssccc, Status = 'old' )
      Open (Unit=40, File= 'Mean_concent.dat', Status='old')
      Do i=1,3
      Read(30,*,end=100, iostat=ierr) ((Mean(i,j), j=1,n))
      nline=i
      end do
      if (ierr .ne. 0) then
      write(14, *) i, j
      end if
   100   continue
   200        Format(A5, 3F8.4)
      Do i = 1, m
            Do j =1, n
            TMean(j,i) = Mean(i,j)
            end do
      end do
      Do k=1,1
      Write(40,200) (sscty, (TMean(k,l), l=1,n))
      end do
      End if
      Close (30)
      End do
      End do
      Close(40)
   !  pause
      stop
      End
```