Paper

ESTIMATING ACTIVE BONE MARROW DOSE FROM OCCUPATIONAL EXPOSURE TO URANIUM AT A FORMER GASEOUS DIFFUSION PLANT

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Abstract—**Active bone marrow absorbed doses were estimated for 581 workers as part of a nested case-control study of multiple myeloma mortality at the Oak Ridge Gaseous Diffusion Plant (K-25). Uranium urinalysis results obtained by fluorometric and gross alpha measurements were available for about 20% of the 581 study subjects. These data were used to determine intakes of uranium as a result of occupational exposure during operation of the K-25 facility. Uranium solubility was inferred from the observed urinary excretion rate, job titles, and department codes. Data suggest that most study subjects were exposed to uranyl fluoride, a relatively soluble uranium compound. The median cumulative bone marrow dose determined for subjects with bioassay data was 0.06 mGy with a geometric standard deviation of 4.48. Subjects without bioassay data were assigned cumulative bone marrow dose based upon job titles and department codes. Health Phys. 93(2):113–119; 2007**

Key words: bone marrow; dose; exposure, occupational; uranium

INTRODUCTION

MULTIPLE MYELOMA, a cancer of the plasma cells, is a progressive hematologic disease in which the myeloma cells collect in bone marrow and trabecular bone, crowding out normal blood cells. The primary risk factors are age, race, and sex (SEER 2006). Based on data from 2000 to 2003, the median age at diagnosis was 70 y of age, and the median age at death was 74 y of age. Only 4% of cases were diagnosed in persons younger than 44 y. For men and women, the incidence and mortality rates are 6.9 and 4.5 per 100,000, respectively, based on the data of 17 SEER geographic locations from 2000–2003 (SEER 2006). Incidence and mortality rates for black males and females were twice as high as for whites of both sexes while Asians and Pacific Islanders have the lowest rates. Males have higher rates than females for all race/ethnicity groups except American Indians/Alaska Natives based on diagnosis years 1999–2002 (SEER 2006).

Several studies have examined the relationship between excess mortality from multiple myeloma and exposure to external ionizing radiation. A relatively recent study of cancer incidence among atomic bomb survivors, who received short term, high dose exposures, found no evidence of an excess risk for multiple myeloma (Preston et al. 1994). Studies of radiologists and veterinarians, who received relatively long term, low dose exposures, have shown evidence of excess mortality due to multiple myeloma (Lewis 1963; Matanoski et al. 1975; Blair and Hayes 1982).

Studies among workers with internal radiation exposures have included radium dial painters, Thorotrast patients, and uranium miners and millers. Radium dial painters (Polednak et al. 1978; Stebbings et al. 1984) and Thorotrast patients (Faber 1979; van Kaick et al. 1978; da Motta et al. 1979) were found to have excess mortality from multiple myeloma. Studies of uranium miners and millers have shown no excess mortality due to multiple myeloma (Wagoner et al. 1964; Archer et al. 1973).

Between 1945 and 1985, approximately 48,000 workers were involved in the construction and operation of the Oak Ridge Gaseous Diffusion Plant in eastern Tennessee. The plant, also known as K-25, produced enriched uranium for the U.S. atomic weapons program and for use in naval, research, and commercial power reactors. Workers at the K-25 facility had potential for exposure to a range of enriched, natural, and depleted uranium compounds as well as other physical and chemical agents. The National Institute for Occupational Safety and Health (NIOSH) is conducting a case control study to investigate the relationship between mortality from multiple myeloma and internal exposure to uranium at K-25. As part of this study, bone marrow doses from internal deposition of uranium were estimated for a cohort of 581 workers consisting of 98 cases of multiple

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myeloma fatality, each matched to five controls on race, sex, and attained age using incidence density sampling (Beaumont et al. 1989).

METHODS

A novel approach based upon individual median and departmental average median uranium urinalysis results and the historical bioassay monitoring practices at K-25 was developed to estimate bone marrow dose for K-25 workers. Review of historical records retrieved by NIOSH describing the objectives of the Health Division at Oak Ridge demonstrated that there was a significant emphasis placed upon monitoring the health of workers who could be exposed to potentially hazardous physical and chemical agents including radioactive materials. Health monitoring records at K-25 included results of worker medical examinations, area and personnel radiation exposure monitoring reports, and measurement results of radioactivity excreted in urine dating back to 1948. Because of the potential for internal exposure to a range of uranium enrichments, nearly all urine samples collected from workers were measured using two methods, a uranium fluorometric procedure to detect the mass of uranium being excreted and a chemical separation method to detect uranium by gross alpha counting. Fluorometric analysis results were available for 118 study subjects and uranium gross alpha analysis results were available for 115 study subjects. These monitored study subjects submitted an average of 15 urine samples during their employment. A detailed description of these data will be provided elsewhere. Estimates of uranium intake and bone marrow dose were determined directly from the urinalysis results for those study subjects who were monitored and whose individual urinalysis results could be found in the historical records.

There were 1,826 individual uranium fluorometric measurement results reported in units of mg L^{-1} and 1,764 individual gross alpha measurement results reported in units of disintegration per minute (dpm) per 100 mL. Of the 1,826 fluorometry results, 889 (49%) were reported as zero or less than a detectable level. Of the 1,764 gross alpha results, 563 (32%) were reported as zero or below a detectable level. Very little specific information could be found in the records to validate detection limits and other performance criteria for gross alpha and fluorometric methods cited in the historical records, i.e., 1940's and 1950's, so individual urinalysis data were used to impute detection levels.

During early times, fluorometric and gross alpha measurement results close or equal to background or blank values were recorded as zero or adjusted to zero by an administrative practice. Changes in the interpretation and definition for detection limit impacted the manner in which results were recorded. The value of the "detectable level" changed over time. Lubin et al. (2004) and Garland et al. (1993) have described methods for evaluating censored data using continuous distributions to glean information from the censored portion of the distribution. For this study, the fluorometric and gross alpha urinalysis measurement data were fit to a lognormal distribution using linear least squares regression and median rank plotting positions assuming data below detection were censored. The distribution of the censored results was then determined and the 50th percentile value of this distribution was substituted for all results reported as zero, or as "less than the detectable level." The geometric mean value for excretion of uranium reported by DHHS (2005) for the U.S. population was adopted as background since no data could be found to describe excretion of uranium in unexposed workers at the K-25 facility or for persons living in areas surrounding Oak Ridge, Tennessee.

Gross alpha results were normalized to 24-h excretion by scaling the activity measured in each single void urine sample to 1,400 mL, a volume representative of the urinary excretion in 1 d (ICRP 1975). Assuming that the urinalysis results for each individual were lognormally distributed (Brodsky 2000), the median excretion rate of uranium in urine was determined for each of the 115 study subjects and grouped according to department number to establish a median 24-h uranium excretion rate for each department.

Dose conversion factors (DCF_{Umix}) for low-enriched uranium (LEU) (3.5 wt. % ^{235}U), high-enriched uranium (HEU) (93.5 wt. % ^{235}U), depleted uranium (DU) (0.2 wt. % ^{235}U), and natural uranium (NU) (0.72 wt. % ^{235}U) were derived for calculating bone marrow dose for mixtures of uranium. These DCFs were used to convert equivalent bone marrow dose ($H_{234\mathrm{U}}$) from ^{234}U to absorbed bone marrow dose (D_{mix}) for any of these four uranium isotopic mixtures. The DCFs were generated using the computer software IMBA [*I*ntegrated *M*odules for *B*ioassay *A*nalysis, ACJ and Associates & National Radiological Protection Board (NRPB). Incorporating NRPB's IMBA Suite, 1997–2003. IMBA-NIOSH (Phase I), 2000–2002. IMBA Expert OCAS Edition (Task 1), 2000–2003], which calculates intake and dose using various types of bioassay data. Two versions of IMBA were used: IMBA-NIOSH (Phase I) and IMBA Expert OCAS Edition (Task 1). IMBA-NIOSH calculates equivalent dose to organs from various mixtures of uranium, but does not calculate intake. IMBA-OCAS calculates intake and equivalent dose, but does not calculate intake or dose for isotopic mixtures of uranium. However, IMBA-OCAS does provide separate contributions to

dose from alphas, betas, and gammas and allows modification of radiation weighting factors.

IMBA-NIOSH was used to calculate equivalent dose to the bone marrow (H_{mix}) for 1 y from a single acute intake of 37 mBq for each of the uranium isotopic mixtures. The contribution to equivalent dose for each of the four uranium isotopes was calculated by

$$H_i = f_i \times H_{mix}, \quad (1)$$

where H_i is the equivalent dose for each isotope of the mixture, and f_i is the fraction of activity of the ith isotope of the mixture (Table 1).

IMBA-OCAS was then used to calculate equivalent dose, H_j, for one year from an acute intake of 37 mBq for each of the j isotopes ^{234}U, ^{235}U, ^{236}U, and ^{238}U. The fraction of dose from alpha activity ($f_{\alpha,j}$) was also determined for each of the four isotopes. The absorbed bone marrow dose for the each uranium isotopic mixture, D_{mix}, was calculated by:

$$D_{mix} = \sum_{i,j} H_i(1 - f_{\alpha,j}) + H_i \frac{f_{\alpha,j}}{20}. \quad (2)$$

A radiation weighting factor equal to 20 was adopted for alpha particles. The dose conversion factor, DCF_{Umix}, for NU, LEU, HEU, and DU was calculated using:

$$DCF_{Umix} = \frac{H_{^{234}U}}{D_{mix}}. \quad (3)$$

IMBA-OCAS was used to calculate intakes and annual equivalent bone marrow doses for 33 study subjects having the highest uranium excretion determined as a sum of their gross alpha results. The annual absorbed active bone marrow dose was determined for each individual by dividing the annual equivalent bone marrow dose by the DCF_{Umix}. All activity excreted in urine was assumed to be due to ^{234}U as a result of inhaling a UF_6 aerosol with Absorption Type F and an activity median aerodynamic diameter (AMAD) of 5 μm. Otherwise, ICRP 66 default parameter values were utilized in these calculations (ICRP 1994).

IMBA-OCAS was also used to calculate the expected urinary excretion rate of activity based on an annual chronic exposure to 37 mBq d^{-1} of ^{234}U as UF_6. Annual bone marrow equivalent dose resulting from this chronic exposure was calculated for each year between 1945 and 1990 through 1998 (the study cut-off date). Cumulative equivalent bone marrow dose for an individual was determined by creating a matrix of annual bone marrow doses due to chronic exposure occurring in any year (Fig. 1). Column A of the matrix represents the annual bone marrow doses (D) resulting from an exposure received in 1945, Column B represents the annual bone marrow doses from an exposure received in 1946, etc.

The matrix was used to estimate the individual cumulative equivalent bone marrow dose, based upon annual chronic exposure of 37 mBq d^{-1} of ^{234}U as UF_6, by summing columns that coincide with the individual's work history and adjusting for the individual's actual median activity excretion rate. For example, if an individual worked at the facility from 1946 to 1948, all cells in the matrix between the B2 and D54 would be summed. The sum of the equivalent bone marrow doses was then multiplied by the ratio of the individual's actual median urinary activity excretion rate and the rate expected from exposure to 37 mBq d^{-1} of ^{234}U as UF_6. Annual equivalent bone marrow doses estimated by this method were

Table 1. Fraction of activity (f_i) contributed by uranium isotopes for the four uranium mixtures of interest.

	Uranium mixture[a]			
Isotope	NU	LEU	HEU	DU
^{234}U	0.4886	0.81836	0.96811	0.1546
^{235}U	0.0228	0.03435	0.02966	0.0107
^{236}U	0.0000	0.00000	0.00197	0.0005
^{238}U	0.4886	0.14729	0.00026	0.8342

[a] Activity fractions obtained from the IMBA-NIOSH "Edit Mixture" feature.

		A	B	C	D	E		AT
	Year	1945	1946	1947	1948	1949		1990
1	1945	D_{A1}	D_{B1}	D_{C1}	D_{D1}	D_{E1}		D_{AT1}
2	1946	D_{A2}	D_{B2}	D_{C2}	D_{D2}	D_{E2}		D_{AT2}
3	1947	D_{A3}	D_{B3}	D_{C3}	D_{D3}	D_{E3}		D_{AT3}
4	1948	D_{A4}	D_{B4}	D_{C4}	D_{D4}	D_{E4}		D_{AT4}
5	1949	D_{A5}	D_{B5}	D_{C5}	D_{D5}	D_{E5}		D_{AT5}
54	1998	D_{A54}	D_{B54}	D_{C54}	D_{D54}	D_{E54}		D_{AT54}

Fig. 1. Conceptual design of the matrix used to determine individual cumulative bone marrow equivalent dose from chronic exposure to uranium. Each cell in the matrix represents the annual bone marrow dose, D, received for that year. For example, for an exposure period that began in 1945 and ended at the end of 1948, the values, D, in all cells between and including A1 and D54 would be summed, where D_{A1} is the dose acquired in 1945 from exposure in 1945, D_{A2} is the dose acquired in 1946 from the exposure in 1945, D_{B2} is the dose acquired in 1946 from an exposure in 1946, etc.

then divided by DCF_{Umix} for the appropriate mixture to estimate the individual's annual absorbed active bone marrow dose.

This method of estimating absorbed doses from the individual *median* excretion rate was also used with the individual *mean* excretion rate for comparison. Cumulative absorbed bone marrow doses were calculated and both sets of doses were compared to the doses for these study subjects calculated directly with the IMBA program.

Uncertainty in the estimated doses was also examined. Monte Carlo simulations were used to forecast values of annual absorbed bone marrow dose incorporating uncertainties in the mean and median measured urine excretion rate, daily urinary excretion volume (24-h), in the excretion per day per chronic exposure of 37 mBq d^{-1}, and in the dose conversion factor, DCF_{Umix}. The impact of these uncertainties on annual absorbed bone marrow dose was compared to the impact of the conventional sources of uncertainty associated with routine urinalysis monitoring reported in the literature (Boecker et al. 1991; Rich et al. 1988).

Annual absorbed active bone marrow doses were imputed for study subjects who were not monitored by urinalysis. All study subjects were divided into three groups for dose estimation based on availability of urinalysis results and whether data were imputed using job titles and/or department numbers. Group I consisted only of study subjects who were monitored by urinalysis and for whom results were obtained from historical records. The average median urine excretion rate for these subjects was also assigned to their individual department number and/or job title to aid in estimating dose for unmonitored study subjects. Group II consisted of Group I study subjects plus those without urinalysis data but having a potential for exposure based on job titles and department numbers matching study subjects in Group I, adjusted for length of employment. Each non-monitored study subject in Group II was assigned the average median urine excretion rate assigned to the department number/job title. Group III study subjects included Group I and Group II study subjects as well as study subjects that had identical department numbers to Group I, but not the same job titles. Group III study subjects were also assigned the average median urine excretion rates for their department. Doses for the three groups were estimated using the method of estimating absorbed doses from the individual median excretion rate.

RESULTS AND DISCUSSION

Table 2 shows imputed detection limits for uranium in urine measured using fluorometry or gross alpha counting methods at K-25 from 1948 until 1990.

Table 2. Imputed detectable levels for the urinalysis monitoring program at K-25.

Year(s)	Fluorometry (mg L^{-1})	Alpha counting (mBq L^{-1})
1948–1957	0.01	25
1958–1977	0.001	25
1978–1979	0.001	50
1980–1990	0.001	100

Results below the imputed detectable levels for both uranium fluorometry and gross alpha counting were observed to fit a beta distribution. However, because dose to the bone marrow is directly related to alpha activity, only alpha counting results were used in the calculation of bone marrow doses. The 50th percentiles of the beta distributions for the alpha counting results were 12 mBq L^{-1} for 1948 through 1977, 23 mBq L^{-1} for 1978 through 1979, and 14 mBq L^{-1} for 1980 through 1990. These imputed values were substituted for alpha counting results reported as "zero" or "less than detection" when determining individual median and mean excretion rates.

Individual median urine excretion rates ranged from 12 to 420 mBq d^{-1} with a mean of 110 mBq d^{-1} and a median of 93 mBq d^{-1}. Individual mean urine excretion rates ranged from 12 to 3,000 mBq d^{-1} with a mean of 470 mBq d^{-1} and median of 18 mBq d^{-1}. A calculated uranium urinary excretion of 11 mBq d^{-1} is expected following chronic exposure to 37 mBq d^{-1} of uranium as a type F UF_6 aerosol.

The DCF_{Umix} for each of the four mixtures of interest are shown in Table 3. The specific activities of uranium in the urine samples for the study group were lognormally distributed. Because the value of DCF_{Umix} is dependent on the enrichment of the uranium, and the enrichment is directly related to the specific activity, it was assumed that the DCF_{Umix} also followed a lognormal distribution. The majority of the urine samples analyzed had specific activities indicating exposure to enrichments of less than 4%. Therefore, it was assumed that the DCF_{Umix} for HEU, calculated to be 19.72, could reasonably represent the upper 95th percentile. The median of the distribution was assumed to be the DCF_{Umix} for NU and the geometric standard deviation (GSD) was calculated to be 1.11.

Table 3. ^{234}U dose equivalent to U_{mix} absorbed dose conversion factors (DCF_{Umix}) for each of the four mixtures of interest.

Mixture	DCF_{Umix} (mSv mGy^{-1})
Depleted uranium (DU)	14.86
Natural uranium (NU)	16.51
Low-enriched uranium (LEU)	18.74
High-enriched uranium (HEU)	19.72

Cumulative absorbed bone marrow doses calculated using IMBA-OCAS for 33 study subjects with the highest total urinary uranium excretion ranged from 0.0016 to 0.46 mGy with an average of 0.12 mGy. Cumulative absorbed bone marrow doses calculated using the median excretion rate for these 33 study subjects ranged from 0.00094 to 0.66 mGy, with an average of 0.15 mGy. The doses ranged from 0.0012 to 4.37 mGy with an average of 0.48 mGy when the mean excretion rate was used.

The uncertainty in dose estimates was examined using Monte Carlo simulations to forecast values of cumulative absorbed bone marrow dose. When forecasting dose using the mean urinary uranium excretion rate for an individual, urinalysis results were assumed to be normally distributed with a mean and standard deviation equal to the observed mean and standard deviation for the individual. When forecasting dose using the median urinary uranium excretion rate for an individual, the urinalysis results were assumed to be lognormally distributed with a median equal to the observed median of the urinalysis results for the individual. The calculated GSDs for each subject were large, exceeding 4 in some cases. Boecker et al. (1991) estimated an overall GSD for plutonium bioassay equal to 3.4 (Table 4). Although the biokinetics, analytical methods, and monitoring practices for plutonium differ significantly from those for uranium, we have adopted the GSD suggested by Boecker et al. (1991) as a reasonable bounding value for this uncertainty analysis. Table 5 shows the assumed probability distributions and parameters used as inputs in Crystal Ball (Decisioneering, Inc., Crystal Ball Version 7.1.603.1, 1988–2005) for the Monte Carlo simulations.

The forecast cumulative bone marrow doses for the 33 study subjects with the highest mean excretion rates ranged from 0.0019 to 6.74 mGy with a mean of 0.75 mGy. The forecast doses for these subjects with the highest median excretion rates ranged from 0.0013 to 0.96 mGy with a mean of 0.23 mGy.

The predicted uranium urinary excretion rate following a chronic exposure to 37 mBq d^{-1} type F material followed a minimum extreme distribution. However, for the same chronic exposure to type M material, the predicted uranium urinary excretion rate followed a Student's *t* distribution. For simplicity, these two distributions were combined into a singular triangular distribution to create bounded uncertainty in the estimated excretion rate. Triangular distributions are typically used to represent subjective judgments about uncertainty when data are scarce, but an upper and lower bound and "most likely" value can be estimated (Frey and Cullen 1995). The minimum was assumed to be the minimum excretion rate for a type M exposure (0.164 mBq d^{-1}), the mode was assumed to be the mode excretion rate for a type F exposure (10.1 mBq d^{-1}), and the maximum was assumed to be the maximum excretion rate for a type M exposure (10.2 mBq d^{-1}). The potential for a significant exposure to type S material at the K-25 gaseous diffusion plant is quite unlikely in comparison to a highly soluble UF_6 material. Exposure to relatively insoluble materials results in less translocation and uptake in bone marrow than exposure to relatively soluble materials.

The cumulative absorbed bone marrow doses estimated using the mean excretion rate differed from doses calculated using IMBA-OCAS by 71% (range 1 to 184%). This difference was only 27% (range 1 to 85%) when the median excretion rate was used. Differences between forecasted and IMBA-calculated doses were 102% (range 18 to 189%) and 49% (range 2 to 113%) using the mean and median excretion rates, respectively. Because cumulative absorbed bone marrow doses determined using the individual median urinalysis result were similar in value to IMBA calculated doses, this method was adopted for estimating bone marrow doses for all study subjects.

Out of 115 study subjects having both alpha and fluorometric urinalysis results, one subject had only one urine sample result and was, thus, considered an unlikely candidate for exposure. The calculated cumulative bone marrow doses for the remaining 114 study subjects in Group I were lognormally distributed with a median of 0.06 mGy and a GSD of 4.48. The bone marrow doses ranged from 0.00094 mGy to 1.2 mGy.

Table 4. Contributions to the overall uncertainty in a single urinalysis result for ^{239,240}Pu (reproduced from Boecker et al. 1991).

Uncertainty	GSD
Radiochemical analysis variability	1.22
Day-to-day variability in excretion	1.88
Background interference	2.5
Distribution, retention, and dosimetry models and parameters	1.57
Combined uncertainty	3.4

Table 5. Assumed probability distributions and parameters used as inputs in Crystal Ball.

Variable	Distribution type	Parameters[a]	Parameter values
Urinalysis result (mBq L^{-1})	Lognormal	GM, GSD	Individual median, 3.4
24-h urine volume (L)	Lognormal	GM, GSD	1.4, 1.6
Excretion per unit intake of uranium (mBq d^{-1})	Triangular	Min, mode, max	0.164, 10.1, 10.2
DCF_{Umix} (mSv mGy^{-1})	Lognormal	GM, GSD	16.51, 1.11

[a] GM = geometric mean, GSD = geometric standard deviation.

The calculated and assigned bone marrow doses for the 381 study subjects in Group II (that includes 114 subjects in Group I) were lognormally distributed with a median of 0.02 mGy and a GSD of 3.95. The cumulative bone marrow doses for 403 Group III subjects (that includes 381 subjects from Group II) were also lognormally distributed with a median of 0.02 mGy and a GSD of 3.94.

The distribution of uranium in the body is primarily dependent on the chemical form and particle size distribution of the uranium compound to which the worker is exposed. In addition to these factors, the uranium enrichment also contributes to the dose (risk). Unfortunately, historical records contain little, if any, information on the relationship of uranium enrichment and work location to aid in evaluating occupational exposure at different locations in the K-25 plant.

Uranium detected in single void urine samples collected infrequently cannot be quantitatively related to any specific incident of exposure since it is highly unlikely that the initial, rapidly soluble fraction of uranium excreted soon after exposure would be detected. Rarely, if ever, can information be found in the historical records that describe the particle size distribution or material solubility to aid in evaluating an exposure. Furthermore, the frequency of urinalysis was insufficient to effectively interpret the meaning of a single elevated bioassay result since the historical records demonstrate that follow-up samples were rarely, if ever, collected. Thus, retrospective exposure assessment for K-25 workers is limited to the fraction of uranium in the body that is retained for long times post intake.

Cumulative bone marrow doses calculated for this study group were very low. For example, the average equivalent dose to the bone marrow of a non-occupationally exposed person from naturally-occurring, internally deposited radionuclides is 0.5 mSv per year (or $\sim$25 μGy assuming a radiation weighting factor of 20) (NCRP 1987). Thus, from 1946 to 1998, a non-occupationally exposed person could accumulate 26.5 mSv ($\sim$1.3 mGy), which is more than 20 times the median cumulative bone marrow dose for this study group.

CONCLUSION

Active absorbed bone marrow doses were estimated for 581 cases and controls randomly selected from former workers who were employed at the K-25 facility between 1945 and 1985. Approximately 20% of these study subjects were directly monitored for internal exposure to uranium using routine urinalysis. During employment, monitored subjects submitted an average of 15 samples that were analyzed for uranium using both fluorometric and alpha counting methods. Median excretion rates of uranium in urine recorded for 114 study subjects ranged from 12 to 420 mBq d^{-1} with an arithmetic mean of 110 mBq d^{-1} and median of 93 mBq d^{-1}.

Cumulative bone marrow dose was calculated for study subjects with the highest total summed urinalysis results using these data as input to the IMBA computer program. An alternative estimate of cumulative bone marrow dose was determined for these subjects by multiplying the median uranium excretion rate for the subject by the sum of annual bone marrow doses expected from a unit chronic exposure (37 mBq d^{-1}) to uranium. Cumulative dose estimates produced by both methods were compared. Cumulative bone marrow doses were predicted based on assumptions of uncertainty distributions for urinalysis measurement result, 24-h urine volume, excretion per unit intake of uranium, and DCF_{Umix} using Crystal Ball, a Monte Carlo simulation computer program.

Differences in cumulative bone marrow dose between the forecasted and calculated values were 49% (range 2 to 113%) using the median excretion rate. Use of the individual median urinalysis result to determine cumulative bone marrow dose yielded values similar to those provided by IMBA. Thus, individual median urinalysis results were used to estimate bone marrow doses for all study subjects.

Calculated cumulative bone marrow doses for this study group were very low in comparison to dose from naturally occurring radionuclides in non-occupationally exposed persons and especially occupationally exposed cohorts. The median bone marrow dose for 114 study subjects with bioassay data was 0.06 mGy with a GSD of 4.48. The median bone marrow dose for 403 study subjects, including the 114 study subjects with bioassay data, was 0.02 mGy with a GSD of 3.94. There were 178 study subjects for whom it was assumed that exposure was unlikely and were not assigned dose.

Disclaimer—The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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