# STADISTICAL CRITERIA TO ESTIMATE THE INTERNAL DOSES IN WORKERS EXPOSED TO RADIOACTIVE AIRBORNES

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Abstract.- The regulations require that monitoring of intake of radioactive material should be applied depending on radiological hazards but they do not establish precise criteria how these radiological hazards should be evaluated. Using the data from Juzbado Uranium Plant, we have made an statistical study of air sampling concentration and of the intake of a group of workers exposed to inhalation of uranium aerosols. We have found that these can be fitted to the probability distributions. Applying these distributions we have used simulation techniques to evaluate the hazards from intake. All these methods can be useful for the design and the conduct of the air control monitoring and to classify the risk for a specific workshop.

## 1. INTRODUCCIÓN

The Juzbado Fuel Fabrication Plant uranium fuel assemblies to light water reactors are made. This process requires manipulating powder of enriched uranium oxides. Hood and glove boxes are used for handling the uranium, but small amounts of radioactivity may be released into the room air as airborne. "Ceramic Area" is the working area where there is a potential radiological hazard for internal contamination The method applied in Juzbado Plant to estimate the intake is similar to those applied in other uranium facilities. The uranium radioisotopes air concentrations are periodically monitored with a Static Air Sampler" (SAS). The SAS aspirates the air from the environment using a pump. The air is led through a paper filter where the airborne is collected. Air samplers are fixed in locations $P_i$ strategically located in the workplaces. Workers are moving in the area, staying some time close every point $P_i$. The uranium air concentration is changing (Fig. 1).

The filter at point $P_i$ is collected when the workers change shift every working day $j$ and its activity $A_i(j)$ is measured. For special operations where the maximum level of airborne uranium concentration could be exceeded (i.e. while cleaning equipments, individual respirators are used), a double system to cut the flow through the filter is applied in this case. Hereafter we will not consider the concentration during these special periods of time.

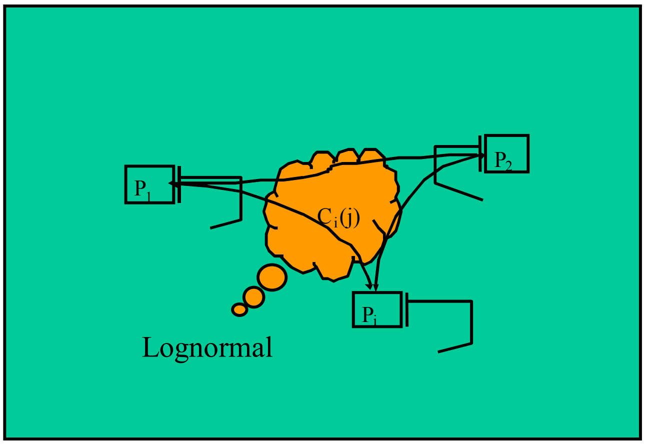


FIG. 1. *Worker moving in an area with air sampling fixed at points $P_i$. Daily concentration $C_i(j)$ at point i on day j can be fitted to a lognormal distribution*

The daily average concentration $C_i(j)$ for $j$ at point $P_i$ is given by $C_i(j)=A_i(j)/(\rho T)$, where $T$ is the time during which the air flows, $\rho$ is drawn from the filter the day $j$, usually a 8-hours shift. The worker stays every day, $j$, in $N$ different points, $i$, for a period of time $\Delta t_{ij}$. The intake for this worker during day $j$ is then $I_j \approx \nu \sum_{i=1}^{N} C_i(j)\Delta t_{ij}$ , where $\nu$ is the worker`s breathing rate. We used "≈" an not equal "=" because the concentration $C_i(j)$ is in fact the *average* concentration at $i$ for whole day $j$ and not only during period $\Delta t_{ij}$. Therefore, the intake for a worker during the day $j$ at area $i$ will be

$$I_j = \frac{\nu}{\rho T} \sum_{i=1}^{n} A_i(j)\, \Delta t_{ij} \quad (1)$$

where $\nu$ and $\rho$ will be assumed constants. Denoting $w_{ij} = \Delta t_{ij}/T$ the fraction of time the worker stays at point $P_i$ the day $j$ and $k = \nu/\rho$

$$I_j = k \sum_{i=1}^{n} w_{ij} A_i(j) \,. \quad (2)$$

in our case $\nu = \rho = 1.2$ m$^3$/h, that is $k = \nu/\rho = 1$, then

$$I_j = \sum_{i=1}^{n} w_{ij} A_i(j) \quad (3)$$

## 2. ESTIMATING THE POTENTIAL RADIOLOGICAL HAZARDS FOR INDIVIDUAL WORKERS

The standards require that monitoring of intake of radioactive material and bioassay programs should be applied depending on radiological hazards but they do not establish precise criteria how these radiological hazards should be evaluated. For instance: Monitoring of intake of radioactive material is required by 10 CFR 20.15028(b) if the intake is 'likely' to exceed 0.1 ALI (annual limit on intake), but how the hazard to exceed 0.1 is evaluated?

We have developed a statistical method to evaluate these hazards (an extension of previous author works [1,2]). We have used the data of our plants but we consider that it can be applied to others radioactive facilities.
We suppose a group of $m$ workers moving daily, during a long time, between $n$ points in an area (fig. 1). The filter activity (from SAS) $A_i(j)$ each day, $j$, at $n$ points is measured. Also, the workers register the time $\Delta t_{ij}$ staying the day, $j$, at point, $i$ (it doesn't consider the points where either the workers stay a negligible time nor the time for moving between points). Then, it can be applied eqn. (3) for obtaining the daily intakes $I_j^k$ of each worker $k$.

For $k = 1$ $\{ I_1^1, I_2^1, \ldots, I_j^1, \ldots\}$
For $k = 2$ $\{ I_1^2, I_2^2, \ldots, I_j^2, \ldots\}$
… … … … …
For $k = m$ $\{ I_1^m, I_2^m, \ldots, I_j^m, \ldots\}$

The total intake $I_D^k$ for each worker during a period of $D$ days -usually $D$ = number of working days of a year- is

$$I_D^k = \sum_{j=1}^{D} I_j^k \quad (4)$$

and the average, $\hat{I}_D$, and standard deviation, $s_D$, of $\{ I_D^1, I_D^2, \ldots, I_D^m \}$ are:

$$\hat{I}_D = \frac{\sum_{k=1}^{m} I_D^k}{m} \quad (5)$$

$$s_D = \sqrt{\frac{\sum_{k=1}^{m} \left(I_D^k - \hat{I}_D\right)^2}{m-1}} \quad (6)$$

with a confidence interval of mean given by

$$I_D = \hat{I}_D \pm t_{1-\alpha/2, m-1}\, {s_D}/{\sqrt{m}} \quad (7)$$

where $t_{1-\alpha/2,\ m-1}$ is the $t$-Student with to a given of significance $\alpha$ and $m - 1$ degrees of freedom

We are interested in evaluating the probability $p$ that any worker of these group intakes an amount $I$ lower than the limit of intake $L$ in the period [0,D]. We take into account that $\{ I_D^1, I_D^2, \ldots, I_D^m \}$ values follow a Normal distribution. In effect: $I_1^D = D\, \hat{I}_1$, $I_2^D = D\, \hat{I}_2$, …, $I_m^D = D\, \hat{I}_m$ and according to the Theorem Central of Limit the averages of a population follow a Normal Distribution. Therefore $P(I \le L) = \alpha = p$ is given by

$$\hat{I}^D + z_{1-\alpha}\, s_D = I_L \le L \quad (8)$$

where
$L$ Limit of intake, usually $L$ is a fraction f of ALI.

$z_{1-\alpha}$ z factor of a normal standard N(0,1) with one side level of signification $\alpha$ (e.g.: $\alpha$= 0.05 $z_{0.95}$ = 1.649).

## 3. ESTIMATING THE POTENTIAL RADIOLOGICAL HAZARDS IN WORKING AREAS

In many occasions we have only the daily intake $I^k(j)$ values (worker $k$ = 1, …, $m$) of a few workers and a statistical requirement to apply (8) is that $m \geq 30$. Besides the quality of $A_i(j)$ (activity measured in filter) values is better than $I^k(j)$ Therefore we are interested in evaluating the hazard of an area and not of a specific worker.

We have found that $\{A_i(j)\}$ values, in each point $i$, has a good fit to many points to the lognormal $LN(\mu_i, \sigma_i)$ distribution given by

$$LN(\mu_i,\sigma_i) \equiv \begin{cases} f_i(x) = \dfrac{1}{\sigma_i\, x\sqrt{2\pi}}\,\text{Exp}\left[-\dfrac{1}{2}\left(\dfrac{\ln x-\mu_i}{\sigma_i}\right)^2\right] \\ \text{if } x>0, \\ f_i(x) = 0, \text{ in otherwise} \end{cases} \quad (9)$$

The mean and variance of the lognormal distribution are

$$\mu_X = e^{\mu+\sigma^2/2}, \quad \sigma_X^2 = e^{2\mu+\sigma^2}\left(e^{\sigma^2}-1\right) \quad (10)$$

The following estimators derived from the transformation to the Normal distribution are widely used in practice (we have called $X_i = A_i(j)$)

$$\hat{\mu}_i = \frac{1}{N}\sum_i \ln A_i(j),$$

$$\hat{\sigma}_i^2 = \frac{1}{N}\sum_i (\ln A_i(j) - \hat{\mu}_i)^2 \quad (11)$$

where $N$ is the total number of data of the point $i$.

In some occasions $A_i(j)$ are bellow lower level detection (LLD). An improved method for normal and lognormal censured distribution [3] is utilized to take into account LLD values of $A_i(j)$.

We have considered two situations to evaluate the hazard of an area: a) Scenery A.- It is assumed that $w_{ij}$ is known being more or less the same all days for people who work in the same area, that is $w_{ij} \approx w_i$ , b ) Scenery B.- It is assumed that $w_{ij}$ changes. In both situations we want to know, for each area, the average daily intake $I$ and their uncertainties.

**Scenary A** .- They are made the assumptions that follow: a) $w_i$ takes, in each point $i$, a constant value all days, b) $A_i(j)$ values can be fitted to a lognormal distribution.

The sum of lognormal variables is not a known distribution, but there are some approximations to lognormal distributions [4]. One of the simplest is Fenton-Wilkinson's approximation (FW) [5,6]. This approximation has been proven accurate under certain conditions (see e.g.[7]) as is the case here for independent random variable (r.v.), means not too spread and similar variances. In particular, Fenton-Wilkinson's approximation for $I$ in eqn (3) provides a lognormal distribution $LN(\mu(t), \sigma^2(t))$ with mean $\mu_I$ and variance $\sigma_I^2$,

$$\mu_I = \left(\sum_i w_i\, e^{\mu_i+\sigma_i^2/2}\right),$$

$$\sigma_I^2 \approx \sum_i w_i^2\, e^{2\mu_i+\sigma_i^2}\left(e^{\sigma_i^2}-1\right) \quad (12)$$

where $\mu_I$ and $\sigma_I^2$ and are the mean and variance of the lognormal distribution of the intake of a person who usually works in the area. Then the daily intake and their uncertainties can be evaluated that follow.

$$I \approx \mu_I \pm z_{\frac{\gamma+1}{2}}\sqrt{\sum_i w_i^2\, e^{2\mu_i+\sigma_i^2}\left(e^{\sigma_i^2}-1\right)} \quad (13)$$

To evaluate the intake and their limits for a long period can be used eqn(7) and (8).

If it is not verified that means are not too spread and variances are similar, then mean $\mu_I$ and variance $\sigma_I^2$ can be estimated using simulation techniques. We can simulate the daily intake $I_j^{(k)}$ (we denote the worker by

($k$) instead of $k$ to indicate that it is a simulation) $I_j^{(k)}$ substituting in eqn.(3) $A_i(j)$ for $Random[LN(\mu_i, \sigma_i)]$ where $Random[LN(\mu_i, \sigma_i)]$ represent seudorandom elements distributed according a Lognormal distribution

$$I_j^{(k)} = \sum_{i=1}^{m} \overline{w}_i \; Random\left[LN\left(\mu_i, \sigma_i\right)\right]^{(k)} \quad (14)$$

then, mean and variance of the daily intake is evaluated as usual

$$\hat{\mu}_I = \frac{\sum_{k=1}^{n} I^{(k)}}{n} \qquad \hat{\sigma}_I^2 = \frac{\sum_{k=1}^{n}\left(I^{(k)} - \hat{I}\right)^2}{n-1} \quad (15)$$

where $n$ are the number of simulation (it should be taken $n > 1000$)

**Scenary B** .- They are made the assumptions that follow:

a) $w_{ij}$ changes, but the $\hat{w}_i$ average values is known: We have represented the daily stay of every worker in each sampling point applying the uniform distribution, $U_i(0,1)$, with a density function given by:

$$U_i(0,1) \equiv \begin{cases} 0 & \text{if} \quad x < 0, x \geq 1 \\ 1 & \text{if} \quad 0 \leq x < 1 \end{cases} \quad (16)$$

b) $A_i(j)$ values can be fitted to a lognormal distribution $LN(\mu_i, \sigma_i)$ where $\mu_i$, and $\sigma_i$ , are the average and deviation of daily (or shift) the activities, at point $i$,, $A_i(j)$ calculated with eqn (11) using experimental data.

In this case we have used a Monte Carlo simulation to estimate the daily intake $I_j^{(k)}$. We can simulate $I_j^{(k)}$ substituting in eqn.(3) $A_i(j)$ for $Random[LN(\mu_i, \sigma_i)]$ and $w_{ij}$ for $\hat{w}_i$ $Random[U_i(0,1)]$ where $Random[LN(\mu_i, \sigma_i)]$ and $Random[U_i(0,1)]$ represent seudorandom elements distributed according a Uniform and Lognormal distribution (it can be generated using standard program such as *Mathematica* or Excel). Also, every working day (shift) $j$ must be verified $\sum_{i=1}^{m} w_{ij} = 1$, them

$$I^{(k)} = \frac{1}{\sum_1^m \overline{w}_i \; Ramdom\left[U_i(0,1)\right]^{(k)}} \sum_{i=1}^{m} \overline{w}_i \; Random\left[U_i\left(0,1\right)\right]^{(k)} \; Random\left[LN\left(\mu_i, \sigma_i\right)\right]^{(k)} \quad (17)$$

Eqn (14) can be no conservative. One option too restrictive is to choose the point $i$ with the highest average concentration.

$$I^{(k)} = \max_{1 \leq i \leq m} \left\{ LN\left[\mu_i, \sigma_i\right]^{(k)} \right\} \quad (18)$$

## 4. APLICATION

Here is included an example describing how these method can be used in the real world. We have applied this procedure to a grinding workshop in Ceramic Area. The intake for workers moving in this workshop is estimated mainly by using three sampling points ($P_1$, $P_2$ ,$P_3$) near a equipment. We have also used two additional points: one represents the grinding area concentration, $P_A$, an other, $P_F$, represents the time that the worker is out of the Ceramic Area.

We have used the real $A_i$ values of a long period (>400 working days). We have found that daily activity in these points (in mBq/d) can be fitted to the following probability function: $f_1(a) = LN(5.56, 1.26)$, $f_2(a) = LN(5.83, 1.55)$, $f_3(a) = LN(5.01, 0.88)$, $f_A(a) = LN(4.43, 0.68)$, and $f_F(a) = LN(4.1, 0.71)$. The average time of staying in each point are: $w_1 = 0.20$, $w_2 = 0.30$, $w_3 = 0.25$, $w_A = 0.15$, $w_F = 0.10$. We have simulated the daily intake $I$ substituting these functions in eqn(14) making 200 simulation (the number of working days of a year), using and $m = 30$ in each simulation. The solution is shown in figure 2.

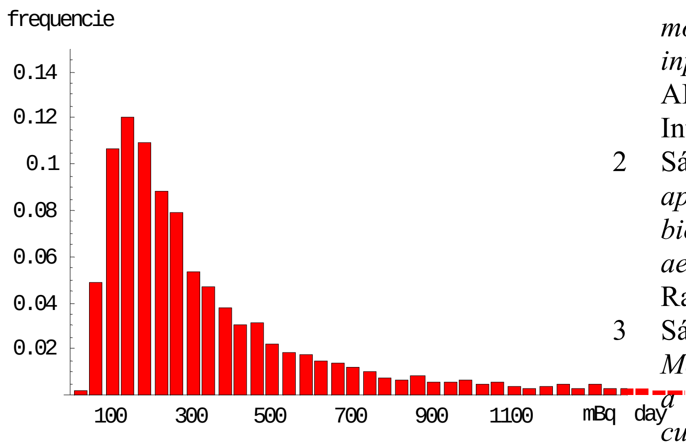


**Fig 2** *Distribution of daily intake of workers exposured to random concentration*

The average annual intake, $\hat{I}^D$, is 102.8 Bq and the standard deviation, $s_D$, 17.7 Bq. Substituting in (8) $I_L$ = 132 Bq and choosing $L$ = 150 Bq (10% ALI for uranium with low enrichment) we obtain $I_L < L$, and therefore the probability to exceed of 10% ALI in this area is <0.4%. According to 10CFR20.1502(b) neither individuals intake estimation are required..

## 5. CONCLUSIONS

The regulations require that monitoring of intake of radioactive material should be applied depending on radiological hazards but they do not establish precise criteria how these radiological hazards should be evaluated. Using the data from Juzbado Uranium Plant, we have made an statistical study of air sampling concentration and of the intake of a group of workers exposed to inhalation of uranium aerosols. We have found that these can be fitted to the probability distributions An improved method for normal and lognormal censured distribution is used to take into account lower level detection (LLD) values. Applying these distributions we have used simulation techniques to evaluate the hazards from intake. All these methods can be useful for the design and the conduct of the air control monitoring and to classify the risk for an specific workshop.

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