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Neuherberg, October 2017

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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.

This report is dedicated to the memory of Alan Birchall, who contributed to the work presented here and made internal dose assessment widely accessible by developing IMBA software.

Content:

Abstract

Recently, several epidemiological studies were interested in identifying potential health effects of incorporated radionuclides. To achieve this work, exposure of individuals was quantified in order to be compared with health status. In order to quantify the exposure of workers, the measurement of retained or excreted activity also called bioassay, must be interpreted in terms of dose. The data available for dose reconstruction are mostly bioassay analyses (mostly urine) carried out to verify the absence (or presence) of incorporated radionuclides in the workers' body. Exposure conditions, recorded in a Job-Exposure Matrix (JEM), are known more or less precisely depending on workplace and time of exposure. However, data gathered to document workers' contaminations were collected for radiological protection purposes rather than for precise retrospective dose assessments. Therefore, a large panel of exposure scenarios could be used to reconstruct lifetime doses. Moreover, a large portion of bioassay data are recorded as below the detection limit (DL) of the measurement technique. That is why, the uncertainty on the lifetime doses is assumed to be important. The same uncertainty is expected on dose estimates for compensation claims since they are based on the same data.

In order to quantify this uncertainty, three cases of uranium exposure, all originating in the French nuclear industry, were recently distributed inside EURADOS Working Group 7 on Internal Dosimetry to a number of participants for the purposes of an intercomparison exercise aiming:

- to compare dose assessment protocols of the different participants,
- to identify sources of uncertainty, and
- to discuss the assessment of uncertainty on dose.

16 participants estimated total committed effective dose, total equivalent doses to the lungs and to the kidneys for at least one of the three workers. Worker 1 presented a large number of bioassay results and several recorded incidents; for Worker 2 only one result out of 19 was higher than the DL and this result was obtained at a time when exposure was not possible according to the JEM; the 75 bioassay results of Worker 3 were all below the detection limit.

The dispersion of the dose assessments is important, higher than the factor of three usually acknowledged for uncertainty of internal doses. From the description provided by the participants, the protocols to evaluate doses were reviewed in details and sources of uncertainty along with reasonable modelling assumptions were identified. This work will be used as a basis for defining guidelines to reconstruct lifetime doses for epidemiological studies and for compensation claims. Finally, the influence on the dose of the different uncertainty sources will be estimated by carrying a sensitivity study comparing dose assessed strictly applying the guidelines with doses calculated under alternative but reasonable modelling assumptions identified in this intercomparison.

1. Introduction

Recently, several epidemiological studies (Krewski *et al.* 2005, Darby *et al.* 2006, Cardis *et al.* 2006, Rage *et al.* 2015, Kreuzer *et al.* 2017, , Boice *et al.* 2008, Kreuzer *et al.* 2015, Gilbert *et al.* 2013, Kuznetsova *et al.* 2016, Yiin *et al.* 2017) were interested in identifying potential health effects of incorporated radionuclides. To achieve this work, exposure of individuals was quantified in order to be compared with health status. As nuclear workers' health and exposure are carefully monitored, they form a particularly interesting population to study risk induced by internal contamination. In this framework, lifetime internal dose must be assessed for all workers of the epidemiological cohort.

In order to quantify the exposure of workers, the measurement of retained or excreted activity also called bioassay, must be interpreted in terms of committed effective dose using biokinetic and dosimetric models. Practically, the dose is assessed in two steps: 1) the intake I is estimated by dividing the value of activity M observed in a bioassay t days after intake by the retention or excretion function at t, $m(t)$; 2) the committed effective dose E is calculated by multiplying the intake by the dose coefficient e_{50}:

$$I = \frac{M}{m(t)} \qquad\qquad E = I \times e_{50}.$$

If multiple measurements are available, a best estimate of intake may be obtained by applying a statistical fitting method. The excretion or retention functions m are the prediction of the biokinetic models of the bioassay (body content, organ content or daily excretion) for a unit intake. The dose coefficient is the committed effective dose received by the reference man for a unit intake. To choose the retention and excretion functions as well as the dose coefficient adapted to the situation, it is necessary to know or to assume conditions of exposure:

- radionuclide(s),
- isotopic composition,
- intake time(s),
- intake route(s): inhalation, ingestion, wound,
- physico-chemical properties of the radioactive material: absorption into blood (reference type F for soluble compounds, type M for moderately soluble and type S for insoluble materials or specific values of the absorption parameters f_r, s_r and s_s (ICRP 1994a), Activity Median Aerodynamic Diameter (AMAD) for an aerosol.

Exact values for all or some of the parameters of dose calculation are, in general, unknown and often difficult to investigate. The International Commission for Radiological Protection (ICRP) therefore recommends the use of default values for such parameters which represent the mean of published values.

In the absence of specific information, the individual is represented by the reference man of the ICRP (ICRP 1975, 2002); a worker has an occupational activity 8 hours a day, with a breathing rate of 1.2 $m^3.h^{-1}$ (ICRP 1994a); the pulmonary absorption of the material is either type F, M, or S (ICPR 1994a); the absorption from the gut is quantified by a proposed value of f_1 or f_A (ICRP 1979, 2006); the AMAD of a radioactive aerosol is 5 µm for workers with a geometric standard deviation of 2.5 and a density of 3 $g.cm^{-3}$ (ICRP 1994a); in routine monitoring, the contamination is assumed to have occurred at the middle of the monitoring interval (ICRP 1997).

The data available for dose reconstruction are mostly bioassay analyses (mostly urine) carried out to verify the absence (or presence) of incorporated radionuclides into the workers' body. Exposure conditions are known more or less precisely depending on workplace and time of exposure.

However, data gathered to document workers' contaminations were collected for radiological protection purposes and not to allow retrospective dose assessments. Therefore, a large panel of exposure scenarios could be used to reconstruct lifetime doses. Moreover, a large portion of bioassay data are recorded as below the detection limit (DL) of the measurement techniques. That is why the uncertainty on the lifetime doses is assumed to be important. The same uncertainty is expected on dose estimates for compensation claims because based on the same data. In order to quantify this uncertainty, three cases of uranium exposure, all originating in the French nuclear industry, were recently distributed to a number of participants for the purposes of an intercomparison exercise.

Many internal dose intercomparisons have been performed previously (Doerfel *et al.* 2000, Doerfel *et al.* 2007, Bingham and Bull 2013), usually focussed on a single intake event. However, this intercomparison required the participants to calculate lifetime intakes and doses, based on all of the bioassay data acquired during the workers' careers.

Many advances in internal dosimetry have taken place in recent years:

- improvements in the biokinetic models used to describe excretion and retention (ICRP, 2015);
- improvements in data treatment and assignment of uncertainties (Marsh et al. 2007, 2008);
- publication of guidance on the dose assessment process (Castellani et al. 2013);
- production of new software packages (eg AIDE, Bertelli et al. 2008; IDEA System, Doerfel 2007; IMBA, Birchall et al. 2007; IMIE, Berkosvki et al. 2007; MONDAL, Ishigure et al. 2004) which greatly facilitate intake and dose assessment.

In view of these advances, the aim of this intercomparison exercise was, in the frame of an epidemiological study (Zhivin *et al.* submitted) of occupational exposure to uranium:

- to compare dose assessment protocols of the different participants,
- to identify sources of uncertainty, and
- to discuss the assessment of uncertainty on dose.

2. Description of the intercomparison exercice

After an announcement at the EURADOS Annual Meeting 2016 held in Milano (Italy), data were provided to the members of EURADOS Working Group 7 on Internal Dosimetry on 7th March 2016 along with templates to gather answers. After being set on 30th June, the deadline for answer submission was extended to 17th July 2016 to allow data processing before the WG7 meeting on 19th September during the Radiological Protection Week held in Oxford (UK). A first discussion of the results took place at this occasion before deeper discussion in Karlsruhe (Germany) during the 2017 EURADOS Annual Meeting.

To determine if uncertainty on lifetime doses depends on the amount of available data and on the number of intakes, 3 workers were sampled "at random" in a group of workers involved in the nuclear fuel cycle (Zhivin *et al.* submitted):

- Worker 1 had 8 incidents (including 2 wounds) reported in the incident register and 188 bioassay data (77 higher than DL) including 7 faecal data.
- Worker 2 had all but one (18 out of 19) bioassay data below DL.
- Worker 3 had all (75) detection limit bioassay measurement results below DL and no known incident.

Data were anonymized to insure confidentiality. The data were provided to participants in a Microsoft Excel® file gathering (Annexe 1: Data provided to participants):

- bioassay data: date, technique and result for each bioassay measurement,
- Job Exposure Matrix (JEM): periods of potential exposure, absorption types of handled uranium compounds, semi-quantitative indication of the level of potential exposure,
- incident register: date and description of known incidents, (does not preclude other unrecorded incidents),
- all 3 workers were male.

Epidemiologists are interested in annual absorbed doses from high and low LET radiations to most organs and tissues. However, for intercomparison of results to remain manageable, EURADOS WG7.5 calculations from the available data were limited to:

- Committed effective dose (commitment period of 50 years)
- Committed equivalent dose to lung (commitment period of 50 years)
- Committed equivalent dose to kidney (commitment period of 50 years - dose to other systemic organs is expected to be strongly correlated)

The results of dose calculations were recorded in a template file 'EURADOS WG7.5 Template for U dose reconstruction.xlsx' (Annexe 2: Template provided to participants for compiling results).

The first objectives were to compare results and to identify reasons for differences because these are potential sources of uncertainty. It was proposed to answer the list of questions of the questionnaire 'EURADOS WG7.5 Questionnaire on U dose reconstruction.doc' (Annexe 3: Template provided to participants for compiling modelling) to support the discussion.

3. Results

16 participants sent 18 answers for Worker 1, 21 answers for Worker 2 and 25 answers for Worker 3. Some participants provided answers for all workers, some only to selected worker(s) and some provided different dose assessments for each worker to account for uncertainty. 1 participant did not provide committed effective doses. All participants sent back details on their calculations. Details about the assessment methods and the results of the participant are gathered in section 4.

3.1 Dose assessment interpretation

In order to quantify uncertainty on dose estimates, different parameters were calculated:

- Arithmetic mean D_{ari}, by:

$$D_{ari} = \frac{\sum_{j=1}^{n\ results} D_j}{n},$$

- Arithmetic standard deviation SD_{ari}, by:

$$SD_{ari} = \sqrt{\frac{\sum_{j=1}^{n\ results} (D_j - D_{ari})^2}{n}},$$

- Relative standard deviation SD_{rel}, by:

$$SD_{rel} = \frac{SD_{ari}}{D_{ari}},$$

- Geometric mean D_{geo}, by:

$$D_{geo} = \sqrt[n]{\prod_{j=1}^{n\ results} D_j},$$

- Geometric standard deviation SD_{geo}, by:

$$SD_{geo} = exp\left(\sqrt{\frac{\sum_{j=1}^{n\ results} (\ln(D_j) - \ln(D_{ari}))^2}{n}}\right),$$

- Robust mean D_{rob} and robust standard deviation SD_{rob} by:

  1) Sort all n values D_j
  2) Estimate the robust mean D_{rob} as the median value of n values D_j
  3) Estimate the robust standard deviation SD_{rob} as:

$$SD_{rob} = 1.483.Median(|D_{rob} - D_j|),$$

  4) Replace each value D_j by D_j^{mod} with:

$$D_j^{mod} = D_{rob} - 1.5.SD_{rob} \text{ if } D_j < D_{rob} - 1.5.SD_{rob},$$

$$D_j^{mod} = D_{rob} + 1.5.SD_{rob} \text{ if } D_j > D_{rob} + 1.5.SD_{rob},$$

$$D_j^{mod} = D_j \text{ else.}$$

  5) Estimate the new robust mean D_{rob} by:

$$D_{rob} = \frac{\sum_{j=1}^{n\ results} D_j^{mod}}{n},$$

6) Estimate the new robust standard deviation SD_{rob} by:

$$SD_{rob} = 1.134.\sqrt{\frac{\sum_{j=1}^{n\ results}\left(D_j^{mod} - D_{rob}\right)^2}{n-1}},$$

7) Repeat steps 4 to 6 until the third digits of D_{rob} and SD_{rob} are no longer modified.

where D_j is the dose j^{th} dose results among the n results provided for each worker and each dose.

The dose can be total committed effective dose, total committed equivalent lung dose or total committed equivalent kidney dose.

Arithmetic mean and arithmetic standard deviation are commonly used to derive central and dispersion estimates from a set of results. However, as in this intercomparison, results were distributed over several orders of magnitude, geometric mean and geometric standard deviation were more appropriate. Robust mean and robust standard deviation are recommended by ISO standard ISO 13528:2015 (ISO 2015a) to describe central and dispersion estimates from interlaboratory comparison results without discarding any outliers. Indeed outliers are iteratively substituted by the value:

$$D_{rob} \pm 1.5.SD_{rob},$$

in the assessment of D_{rob} and SD_{rob}.

In order to estimate the overall uncertainty factor, the ratio of the highest dose result by the lowest, $R_{max/min}$, was estimated by:

$$R_{max/min} = \frac{\max\ (D_j)}{\min\ (D_j)}.$$

All the results were checked for mistakes. Identified errors were corrected. In this way, the results dispersion is only due to different assessment methods.

3.2 Dose assessments for Worker 1

3.2.1 Description of available data

The data available for Worker 1 (Annexe 1: Data provided to participants) were:

- 5 faeces bioassay between 07/1967 and 03/1974 with:
  - 2 faeces qualified as 48h samples,
  - 2 faeces samples measured by both mass and activity techniques,
  - all faeces higher than DL.
- 156 urine bioassay between 06/1964 and 06/1980 with:
  - 5 urines qualified as 24h samples and 2 as spot urine,
  - 25 urine samples measured by both mass and activity techniques,
  - 181 urine measurements included 111 values below DL.
- exposure from Job Exposure Matrix (JEM):
  - no exposure between 1962 and mid-1966,
  - potential exposure to Type F natural U between mid-1966 and 1976,
  - potential exposure to Type F and Type M natural U between 1977 and 1980,

- 11 identified incidents (2 wounds) between 1967 and 1974 included one wound and one inhalation with U nitrate.

3.2.2 Total committed effective dose

The results obtained by the different participants are presented in Figure 1. The parameters estimated to describe central values and dispersion are gathered in Table 1.

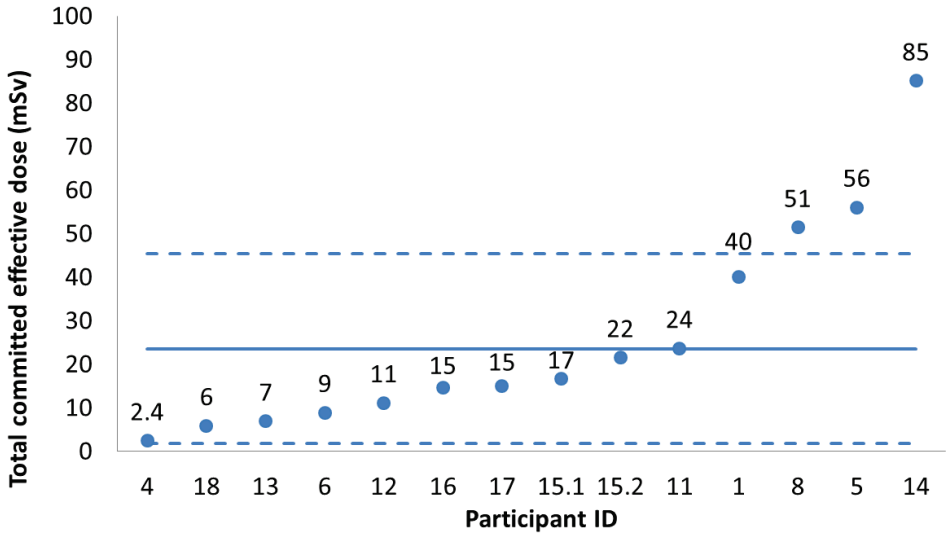

Figure 1: Total committed effective dose (mSv) assessed by the different participants for Worker 1. Blue line = robust mean D_{rob}, dashed lines = $D_{rob} \pm SD_{rob}$ with SD_{rob} the robust standard deviation. IDs 12, 13 and 14 are for the same participant assuming either mixture of absorption Types or Type F or Type M respectively. IDs 15.1 and 15.2 are minimal and maximal dose estimates from participant ID 15.

Table 1: Descriptive parameters of the total committed effective doses (mSv) assessed by the different participants for Worker 1

Min (mSv)	2.4
Max (mSv)	85
Ratio Max/Min	35
Median (mSv)	16
Arithmetic mean (mSv)	26
Arithmetic standard deviation (mSv)	24
Relative standard deviation (%)	92
Geometric mean (mSv)	17
Geometric standard deviation	2.6
Robust mean (mSv)	24
Robust standard deviation (mSv)	22

3.2.3 Total committed equivalent lung dose

The results obtained by the different participants are presented on Figure 2. The parameters estimated to describe central values and dispersion are gathered in Table 2.

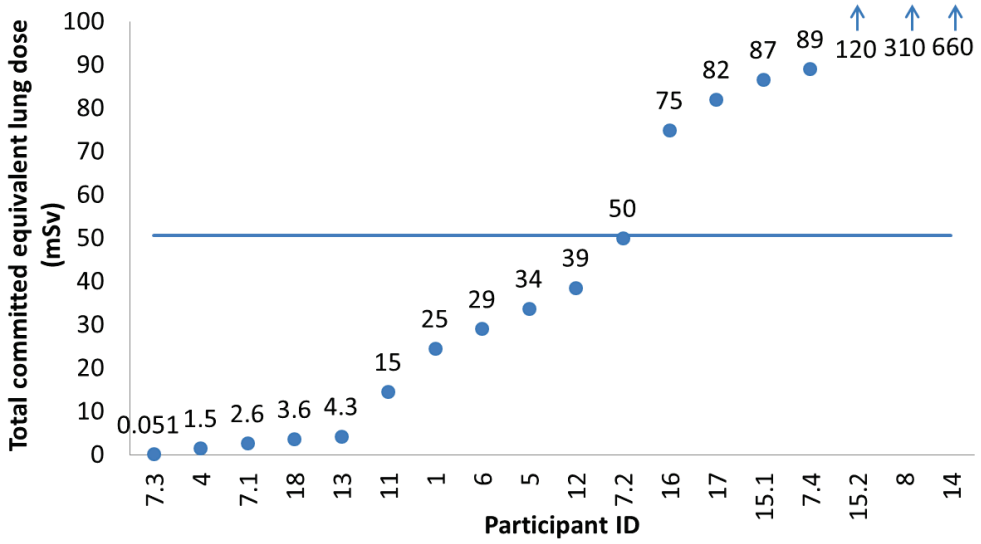

Figure 2: Total committed equivalent lung dose (mSv) assessed by the different participants for Worker 1. Blue line = robust mean D_{rob}. IDs 12, 13 and 14 are for the same participant assuming either mixture of absorption Types or Type F or Type M respectively. IDs 7.1, 7.2, 7.3 and 7.4 are respectively median, mean, 5th and 95th percentiles of dose distribution determined by participant ID 7. IDs 15.1 and 15.2 are minimal and maximal dose estimates from participant ID 15.

Table 2: Descriptive parameters of the total committed equivalent lung doses (mSv) assessed by the different participants for Worker 1

Min (mSv)	0.051
Max (mSv)	660
Ratio Max/Min	13000
Median (mSv)	36
Arithmetic mean (mSv)	90
Arithmetic standard deviation (mSv)	160
Relative standard deviation (%)	180
Geometric mean (mSv)	23
Geometric standard deviation	8.7
Robust mean (mSv)	51
Robust standard deviation (mSv)	52

3.2.4 Total committed equivalent kidney dose

The results obtained by the different participants are presented on Figure 3. The parameters estimated to describe central values and dispersion are gathered in Table 3.

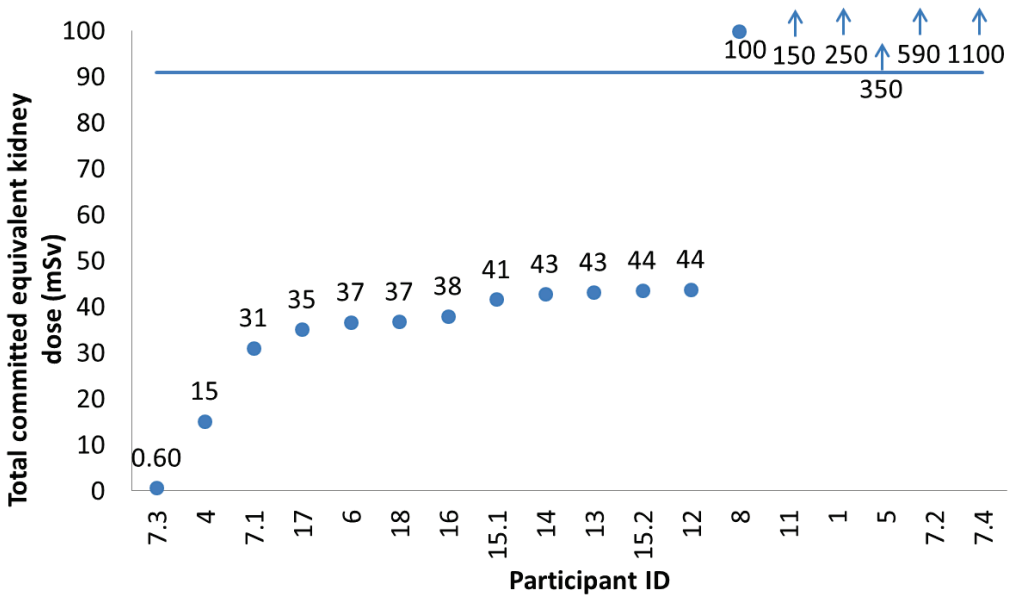

Figure 3: Total committed equivalent kidney dose (mSv) assessed by the different participants for Worker 1. Blue line = robust mean D_{rob}. IDs 12, 13 and 14 are for the same participant assuming either mixture of absorption Types or Type F or Type M respectively. IDs 7.1, 7.2, 7.3 and 7.4 are respectively median, mean, 5th and 95th percentiles of dose distribution determined by participant ID 7. IDs 15.1 and 15.2 are minimal and maximal dose estimates from participant ID 15.

Table 3: Descriptive parameters of the total committed equivalent kidney doses (mSv) assessed by the different participants for Worker 1

Min (mSv)	0.60
Max (mSv)	1100
Ratio Max/Min	1800
Median (mSv)	43
Arithmetic mean (mSv)	160
Arithmetic standard deviation (mSv)	270
Relative standard deviation (%)	170
Geometric mean (mSv)	58
Geometric standard deviation	4.8
Robust mean (mSv)	91
Robust standard deviation (mSv)	100

3.3 Dose assessments for Worker 2

3.3.1 Description of available data

The data available for Worker 2 (Annexe 1: Data provided to participants) were:

- no faeces bioassay
- 19 urine bioassay between 10/1962 and 01/1969 with:
  - 19 urine measurements included 18 values below DL,

- no indication of sampling period,
- all urine samples measured by mass,

- exposure from Job Exposure Matrix (JEM):
  - potential exposure to Types F, M and S natural U between 06/1963 and 12/1963
  - no exposure between 01/1964 and 12/1976
  - potential exposure to Type F natural U between 01/1977 and 09/1982
  - no identified incidents.

3.3.2 Total committed effective dose

The results obtained by the different participants are presented on Figure 4. The parameters estimated to describe central values and dispersion are gathered in Table 4.

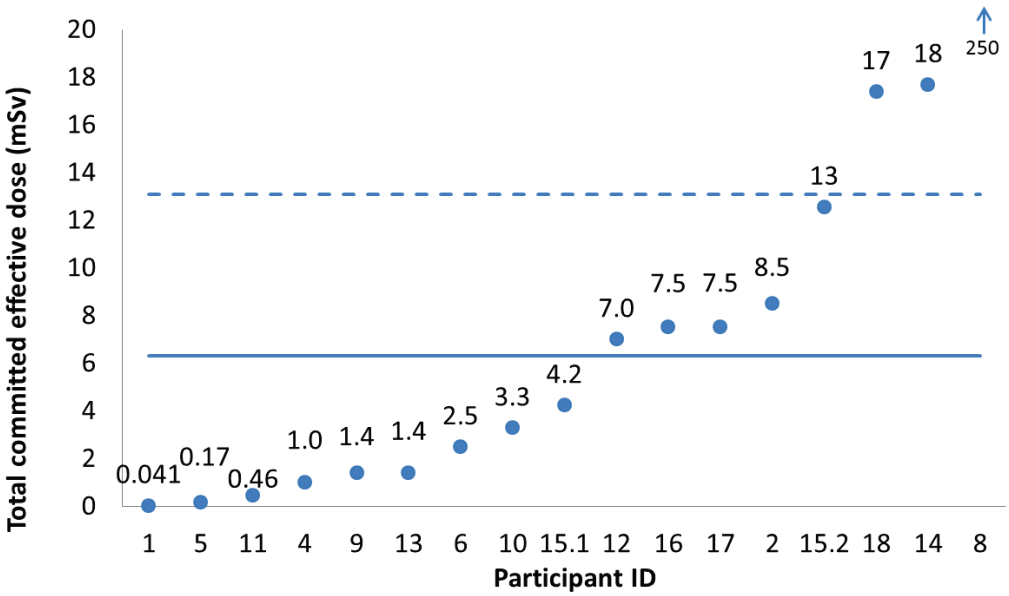

Figure 4: Total committed effective dose (mSv) assessed by the different participants for Worker 2. Blue line = robust mean D_{rob}, dashed line = $D_{rob} + SD_{rob}$ with SD_{rob} the robust standard deviation. IDs 12, 13 and 14 are for the same participant assuming either mixture of absorption Types or Type F or Type M respectively. IDs 15.1 and 15.2 are minimal and maximal dose estimates from participant ID 15.

Table 4: Descriptive parameters of the total committed effective doses (mSv) assessed by the different participants for Worker 2

Min (mSv)	0.041
Max (mSv)	250
Ratio Max/Min	6100
Median (mSv)	4.2
Arithmetic mean (mSv)	20
Arithmetic standard deviation (mSv)	60
Relative standard deviation (%)	300
Geometric mean (mSv)	3.3
Geometric standard deviation	7.0
Robust mean (mSv)	6.3
Robust standard deviation (mSv)	6.8

3.3.3 Total committed equivalent lung dose

The results obtained by the different participants are presented on Figure 5. The parameters estimated to describe central values and dispersion are gathered in Table 5.

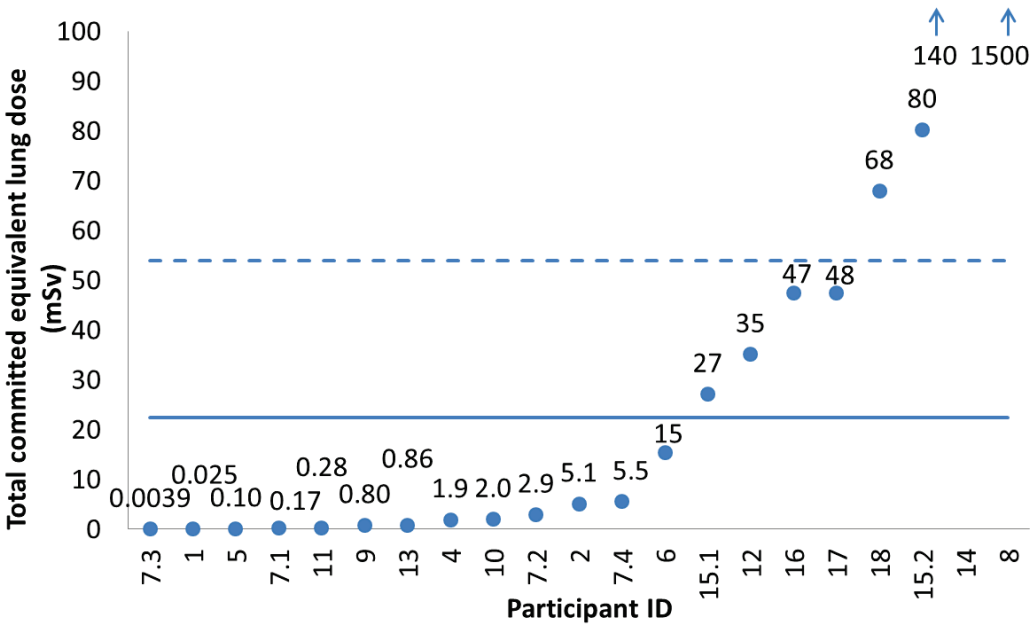

Figure 5: Total committed equivalent lung dose (mSv) assessed by the different participants for Worker 2. Blue line = robust mean D_{rob}, dashed line = $D_{rob} + SD_{rob}$ with SD_{rob} the robust standard deviation. IDs 12, 13 and 14 are for the same participant assuming either mixture of absorption Types or Type F or Type M respectively. IDs 7.1, 7.2, 7.3 and 7.4 are respectively median, mean, 5th and 95th percentiles of dose distribution determined by participant ID 7. IDs 15.1 and 15.2 are minimal and maximal dose estimates from participant ID 15.

Table 5: Descriptive parameters of the total committed equivalent lung doses (mSv) assessed by the different participants for Worker 2

Min (mSv)	0.0039
Max (mSv)	1500
Ratio Max/Min	380000
Median (mSv)	5.1
Arithmetic mean (mSv)	93
Arithmetic standard deviation (mSv)	320
Relative standard deviation (%)	340
Geometric mean (mSv)	4.0
Geometric standard deviation	21
Robust mean (mSv)	22
Robust standard deviation (mSv)	32

3.3.4 Total committed equivalent kidney dose

The results obtained by the different participants are presented on Figure 6. The parameters estimated to describe central values and dispersion are gathered in Table 6.

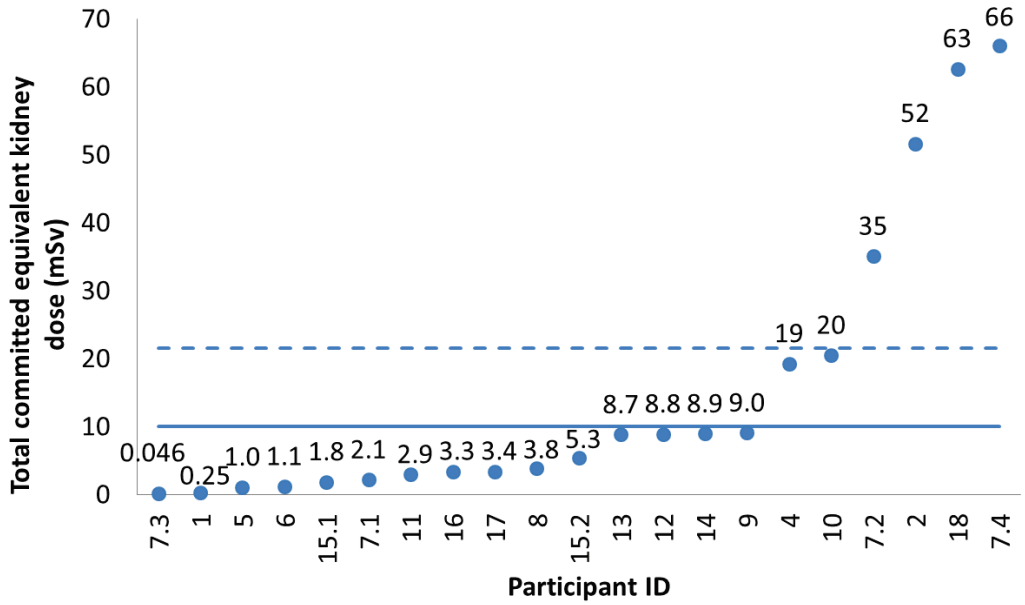

Figure 6: Total committed equivalent kidney dose (mSv) assessed by the different participants for Worker 2. Blue line = robust mean D_{rob}, dashed line = $D_{rob} + SD_{rob}$ with SD_{rob} the robust standard deviation. IDs 12, 13 and 14 are for the same participant assuming either mixture of absorption Types or Type F or Type M respectively. IDs 7.1, 7.2, 7.3 and 7.4 are respectively median, mean, 5th and 95th percentiles of dose distribution determined by participant ID 7. IDs 15.1 and 15.2 are minimal and maximal dose estimates from participant ID 15.

Table 6: Descriptive parameters of the total committed equivalent kidney doses (mSv) assessed by the different participants for Worker 2

Min (mSv)	0.046
Max (mSv)	66
Ratio Max/Min	1400
Median (mSv)	5.3
Arithmetic mean (mSv)	15
Arithmetic standard deviation (mSv)	21
Relative standard deviation (%)	140
Geometric mean (mSv)	5.1
Geometric standard deviation	5.9
Robust mean (mSv)	10
Robust standard deviation (mSv)	12

3.4 Dose assessments for Worker 3

3.4.1 Description of available data

The data available for Worker 3 (Annexe 1: Data provided to participants) were:

- no faeces bioassay
- 47 urine bioassay from 06/1968 to 12/1981
  - all values below DL,
  - no indication of sampling period,
  - 28 urine samples measured by both mass and activity techniques,
  - 15 samples measured only by activity,
  - 4 samples measured only by mass,
- Exposure from JEM
  - potential exposure to Type F natural U between 07/1965 and 12/1981
  - no identified incidents

3.4.2 Total committed effective dose

The results obtained by the different participants are presented on Figure 7. The parameters estimated to describe central values and dispersion are gathered in Table 7.

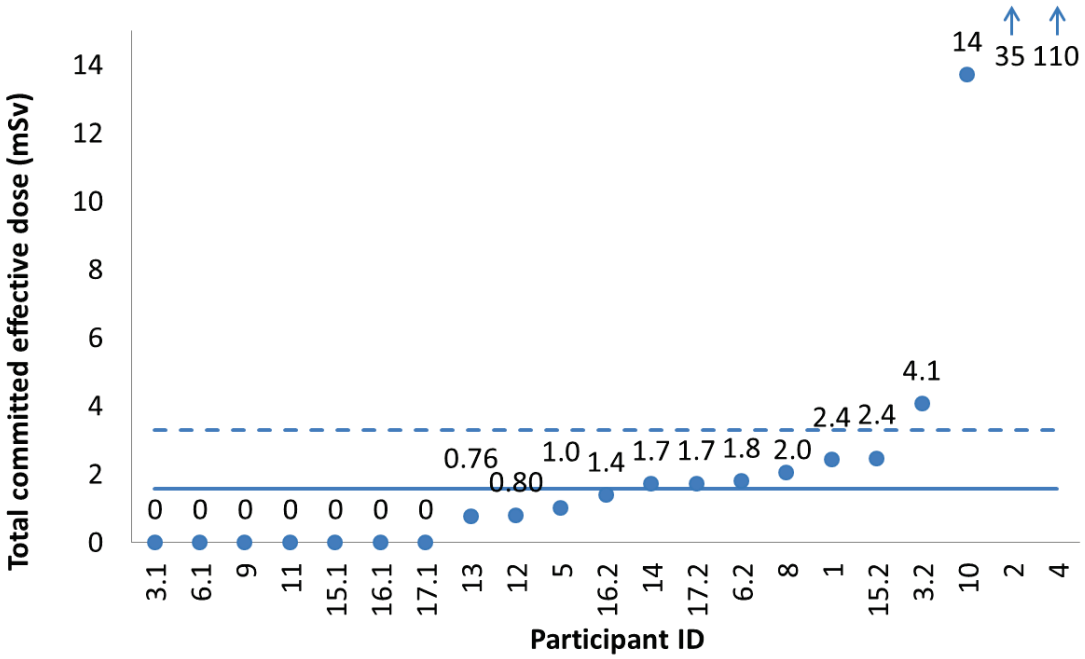

Figure 7: Total committed effective dose (mSv) assessed by the different participants for Worker 3. Blue line = robust mean D_{rob}, dashed lines = $D_{rob} \pm SD_{rob}$ with SD_{rob} the robust standard deviation. IDs 12, 13 and 14 are determined by one participant either as mean, median values of dose distribution using a Bayesian approach or using CURE protocol respectively. IDs 3.1 and 3.2, 6.1 and 6.2, 15.1 and 15.2, 16.1 and 16.2, 17.1 and 17.2 are minimal and maximal dose estimates from participants ID 3, 6, 15, 16 and 17 respectively.

Table 7: Descriptive parameters of the total committed effective doses (mSv) assessed by the different participants for Worker 3. nd: not defined

Min (mSv)	0.0
Max (mSv)	110
Ratio Max/Min	nd
Median (mSv)	1.4
Arithmetic mean (mSv)	8.5
Arithmetic standard deviation (mSv)	25
Relative standard deviation (%)	290
Geometric mean (mSv)	nd
Geometric standard deviation	nd
Robust mean (mSv)	1.6
Robust standard deviation (mSv)	1.7

3.4.3 Total committed equivalent lung dose

The results obtained by the different participants are presented on Figure 8. The parameters estimated to describe central values and dispersion are gathered in Table 8.

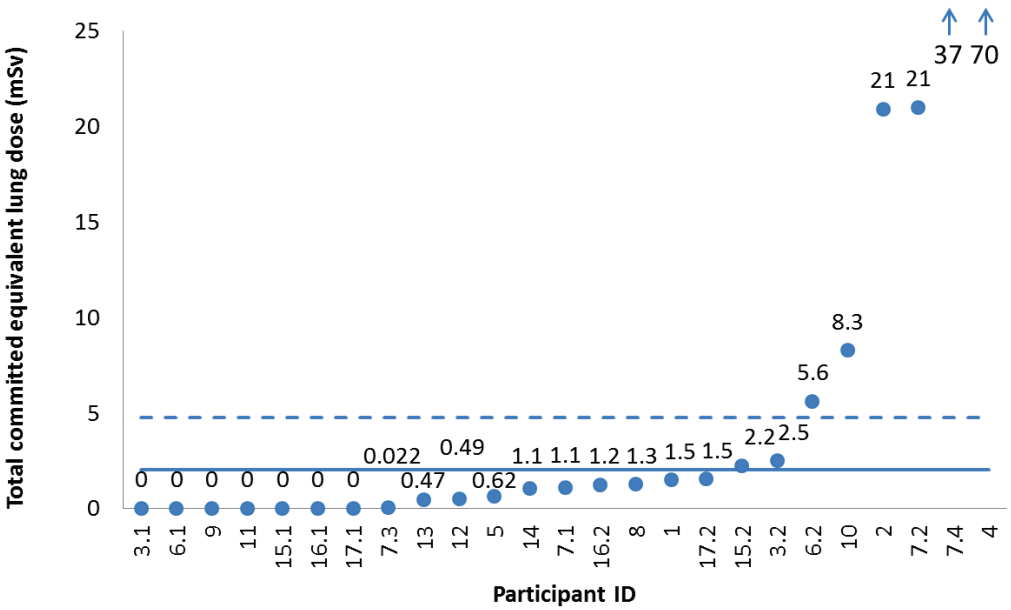

Figure 8: Total committed equivalent lung dose (mSv) assessed by the different participants for Worker 3. Blue line = robust mean D_{rob}, dashed line = $D_{rob} + SD_{rob}$ with SD_{rob} the robust standard deviation. IDs 12, 13 and 14 are determined by one participant either as mean, median values of dose distribution using a Bayesian approach or using CURE protocol respectively. IDs 7.1, 7.2, 7.3 and 7.4 are respectively median, mean, 5th and 95th percentiles of dose distribution determined by participant ID 7. IDs 3.1 and 3.2, 6.1 and 6.2, 15.1 and 15.2, 16.1 and 16.2, 17.1 and 17.2 are minimal and maximal dose estimates from participants ID 3, 6, 15, 16 and 17 respectively.

Table 8: Descriptive parameters of the total committed equivalent lung doses (mSv) assessed by the different participants for Worker 3. nd: not defined

Min (mSv)	0.0
Max (mSv)	70
Ratio Max/Min	nd
Median (mSv)	1.1
Arithmetic mean (mSv)	7.1
Arithmetic standard deviation (mSv)	16
Relative standard deviation (%)	230
Geometric mean (mSv)	nd
Geometric standard deviation	nd
Robust mean (mSv)	2.0
Robust standard deviation (mSv)	2.7

3.4.4 Total committed equivalent kidney dose

The results obtained by the different participants are presented on Figure 9. The parameters estimated to describe central values and dispersion are gathered in Table 9.

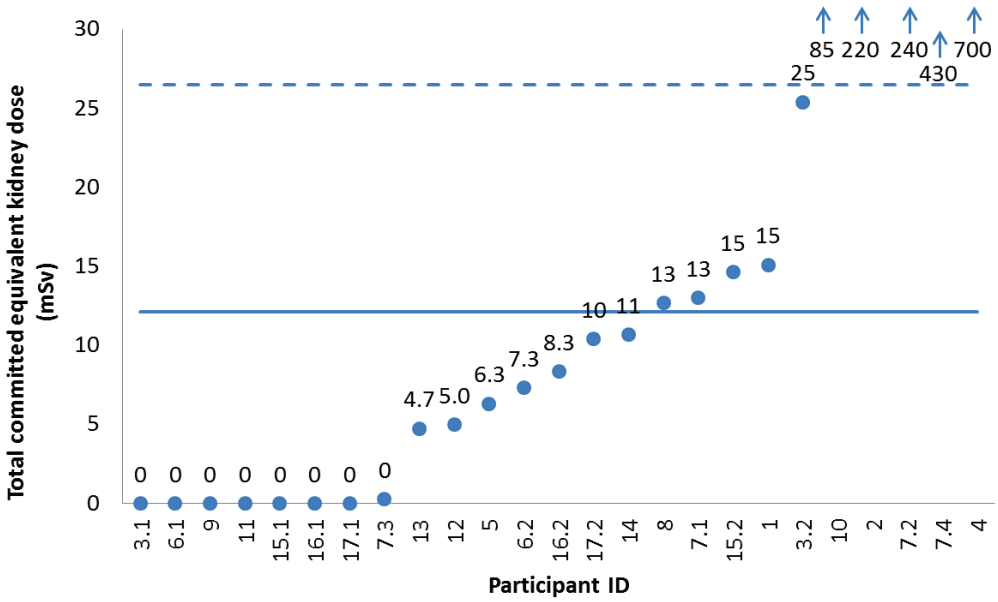

Figure 9: Total committed equivalent kidney dose (mSv) assessed by the different participants for Worker 3. Blue line = robust mean D_{rob}, dashed line = $D_{rob} + SD_{rob}$ with SD_{rob} the robust standard deviation. IDs 12, 13 and 14 are determined by one participant either as mean, median values of dose distribution using a Bayesian approach or using CURE protocol. IDs 7.1, 7.2, 7.3 and 7.4 are respectively median, mean, 5th and 95th percentiles of dose distribution determined by participant ID 7. IDs 3.1 and 3.2, 6.1 and 6.2, 15.1 and 15.2, 16.1 and 16.2, 17.1 and 17.2 are minimal and maximal dose estimates from participants ID 3, 6, 15, 16 and 17 respectively.

Table 9: Descriptive parameters of the total committed equivalent kidney doses (mSv) assessed by the different participants for Worker 3. nd: not defined

Min (mSv)	0.0
Max (mSv)	700
Ratio Max/Min	nd
Median (mSv)	8.3
Arithmetic mean (mSv)	72
Arithmetic standard deviation (mSv)	170
Relative standard deviation (%)	240
Geometric mean (mSv)	nd
Geometric standard deviation	nd
Robust mean (mSv)	12
Robust standard deviation (mSv)	14

3.5 Dose assessment procedures

The different procedures applied by the participants to assess doses for the three workers were gathered in order to identify reasonable modelling assumptions.

3.5.1 Intake regimes and exposure pathway

The numbers of intakes used to estimate doses for Worker 1, Worker 2 and Worker 3 respectively are presented on Figure 10, Figure 11 and Figure 12 respectively.

To estimate doses from routine exposure, some participants applied the procedure recommended by ICRP (ICRP 1997), by assuming acute intakes occurring at the middle interval between two bioassay whereas other applied chronic intakes. Some chronic exposures were cut into sub-periods when changes are reported in the JEM.

Most participants used information provided by the incident register to model acute intakes due to abnormal events. However, one participant used only one chronic exposure for the whole career.

When defining chronic exposures, some participants used information from bioassay, other from the JEM and other from both sources. Worker 2 was particularly interesting because bioassay data and JEM seemed to contradict each other because the only urine sample leading to a result higher than the DL was collected at a period were exposure to uranium is not possible according to the JEM.

Routine exposures were considered as inhalation by all participants. For abnormal event, inhalation was chosen by all participants when not stated otherwise in the incident register. When information was available in the register, all participants but one used this information.

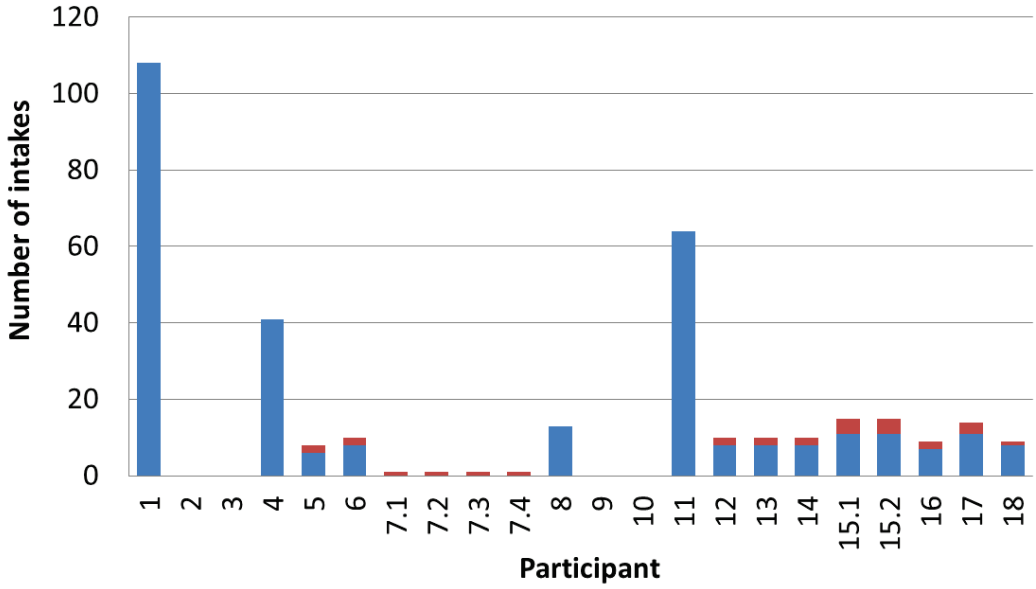

Figure 10: Number of intakes assumed by participants to estimate doses for Worker 1. Blue: acute intakes, red: chronic intakes

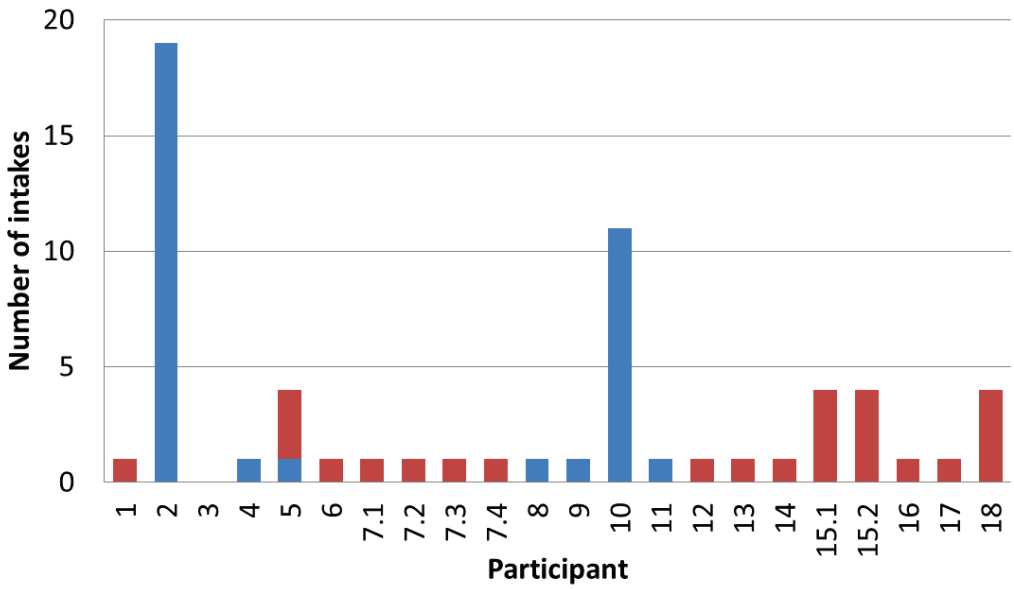

Figure 11: Number of intakes assumed by participants to estimate doses for Worker 2. Blue: acute intakes, red: chronic intakes

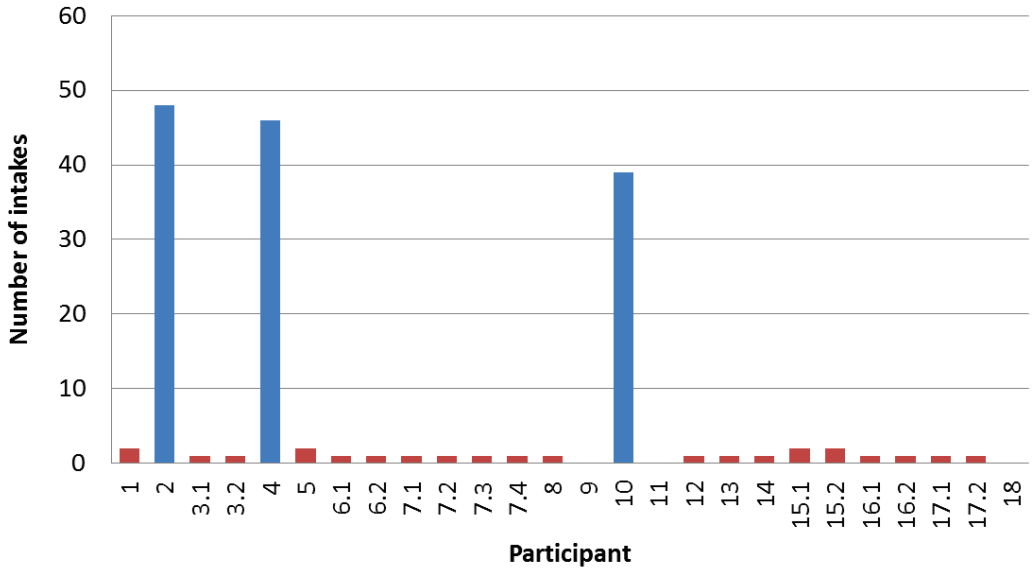

Figure 12: Number of intakes assumed by participants to estimate doses for Worker 3. Blue: acute intakes, red: chronic intakes

3.5.2 Absorption into blood

When information on absorption into blood was available in the JEM or in the incident register, most participants used the specified absorption type for dose assessment. However, when no information was provided as for Worker 2, participants assumed different absorption types (Figure 13). Most participants used the most likely absorption from the JEM. Other selected the reference Type M of ICRP as recommended by ICRP by default (ICRP 1994a, 1997). Some participants preferred to model the lack of information by a mixture of absorption types F, M and S. Finally, one participant tested all absorption types and recorded the doses obtained with the absorption best fitting the bioassay data.

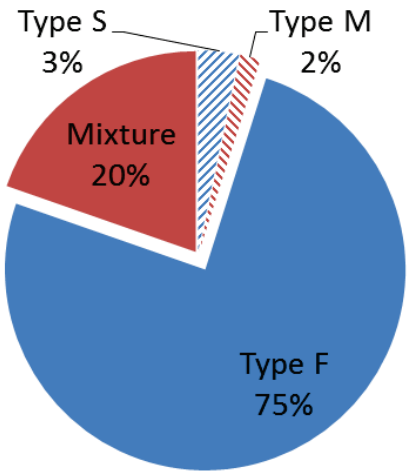

Figure 13: Absorption into blood assumed by the different participants for Worker 2. Mixture: mixture of absorption types F, M and S

3.5.3 Processing of bioassay data

All participants did not process the bioassay data in the same way. As an example, the numbers of bioassay data used for dose assessment for Worker 1 by each participant are presented on Figure 14. Some participants did not estimate intakes for data below DL for Worker 1 because they assumed that no intake had taken place during the monitoring period if the following bioassay was below DL. One participant did not integrate faeces bioassay in its intake evaluation. However, most participants used all data available.

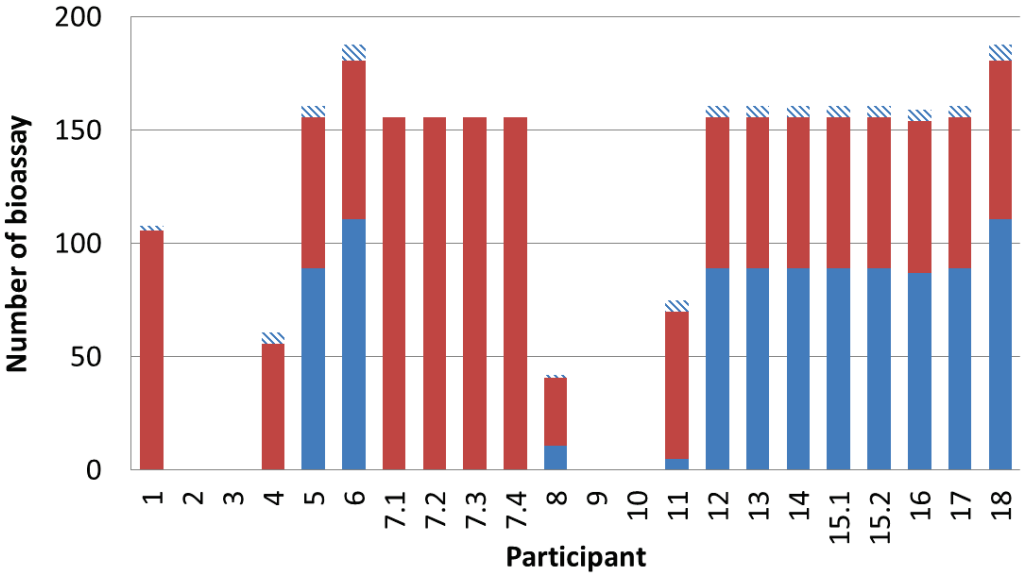

Figure 14: Bioassay data used by the participants to estimate doses for Worker 1. Red: urine results higher than DL, blue: urine data below DL, dashed: faeces results

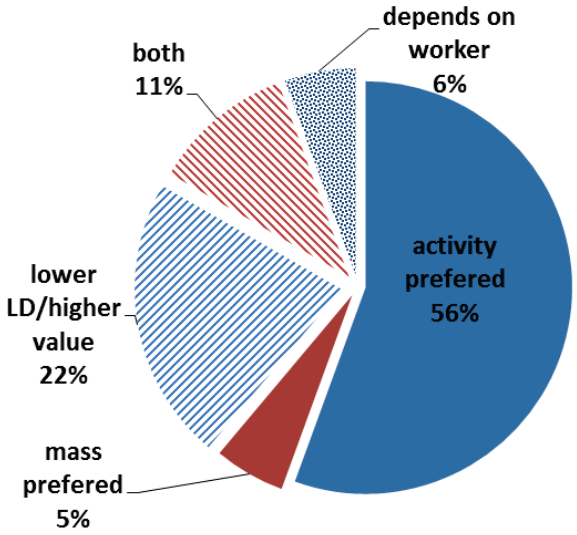

Figure 15: Results preferred by participants when bioassay were quantified in mass and in activity

When uranium content was measured in mass and in activity, most participants preferred activity to avoid assumptions on isotopic composition (Figure 15). Others estimated doses from the results with the lowest DL or the highest value in order to be conservative. One participant chose to use mass measurement and another one did not apply the same procedure to all workers. Finally, two participants decided to use all available information and therefore, integrated both activity and mass measurements in their assessments.

To convert uranium mass into activity, 88 % of the participants assumed natural uranium isotopic composition and two of them assumed ^{238}U specific activity.

To convert uranium concentration in urine into daily urinary excretion, all participants used the reference daily volume of 1.6 $l.d^{-1}$ recommended by ICRP (ICRP 2002) for male. For faeces samples, 57 % of the participants assumed that samples were daily samples, 21 % that the collection period was 48h and 22 % used a reference ash weight to estimate 24h faecal excretion.

Concerning the bioassay uncertainty, all participants used EURADOS IDEAS Guidelines (Castellani *et al.* 2013) scattering factor (SF) values:

- SF = 1.1 was used by 64 % of the participants for real 24h urine samples, 27 % chose an SF of 1.6 and one particopant used 1.6 for radiometric and 2.5 for gravimetric measurements.
- for urine excretion normalised into daily urine by volume, 92 % of the participants chose a SF of 1.6 and 8 % decided to use a SF of 2.5 for mass measurements anf 1.6 for activity in order to give more weight of activity measurement when estimating intakes.
- SF = 3 for all participants for faeces samples,
- for 48h samples, 50 % of the participants used a SF of 2.5 whereas the rest of them use the same SF as for daily samples (SF = 3).

Most participants (83 % for urine data, 94 % for faecal samples) did not subtract any dietary contribution from bioassay. The activity levels subtracted by others were from ICRP (ICRP 1975), Davesne *et al.* (2014) or from participant's experience.

3.5.4 Treatment of data below detection limit

Estimating intakes from data below DL raises several questions about the actual possibility of intakes, and if intakes are likely, on the bioassay value to be used to assess those intakes. Some participants applied the operational radiation protection approach considering that the dose is equal to zero when bioassay data are below detection limits. Other decided to assess a best estimate of intake or to give a range from minimum (= zero) to maximum intake values.

The different approaches were particularly visible when treating the data of Worker 3 because all bioassay data were below DL. From Figure 16, it appeared that some participants decided:

- to treat data below DL as such (no imputation),
- to replace below DL data with a numerical quantified result (imputation) of different values (Figure 17):
  - *zero*,
  - *DL/2*,
  - *DL/4*,
  - *DL*,
  - *DL.(1-f)* with *f* being the frequency of below DL data over the dataset.

This imputation was carried out by 47 % of the participants for all data below DL whereas 29 % of the participants imputed only for the last data below DL in each chronic period (CURE project approach (Blanchardon *et al.* 2014, Laurent *et al.* 2016) (Figure 16).

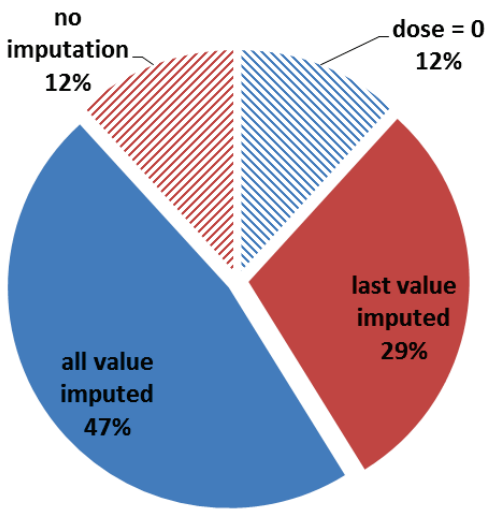

Figure 16: Treatment of data below detection limit for Worker 3

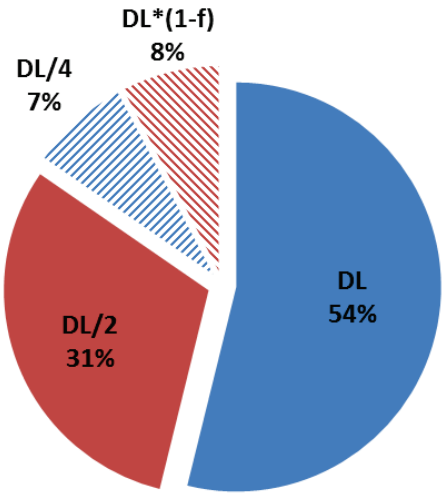

Figure 17: Value imputed when treating data below detection limit for Worker 3

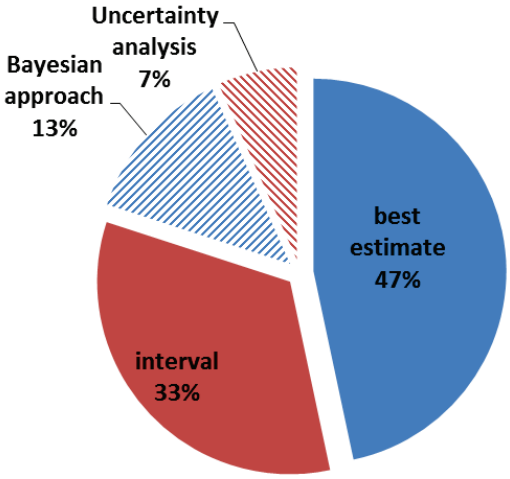

Figure 18: Recording of doses when only data below detection limit are available (Worker 3)

When reporting results for Worker 3, participants gave (Figure 18):

- best estimates of dose after imputation of DL, DL/2, DL/4, or
- median and mean doses estimated by a Bayesian approach with an uninformative prior, or
- median, mean, 5th and 95th percentiles from an uncertainty analysis, or
- dose intervals [min dose – max dose].

3.5.5 Radionuclide for dose assessment

In dose assessment from estimated intake, most of participants assumed that the incorporated material was natural uranium whereas 14 % considered only ^{234}U for sake of simplicity. 2 participants chose material containing only ^{238}U or ^{238}U and ^{235}U.

3.5.6 Biokinetic and dosimetric models

All participants used the same ICRP models: ICRP Publication 66 (ICRP 1994a), ICRP Publication 30 (ICRP 1979), ICRP Publication 69 (ICRP 1995), and ICRP Publication 60 (ICRP 1991). The only differences were for wound: some participants (64 %) used NCRP wound model (NCRP 2006) and others (36 %) injection.

3.5.7 Software and intake assessment procedures

A large panel of software was used by participants to assess doses (Figure 19). Intakes were calculated by applying different procedures:

- Maximum likelihood fit of all data and intakes simultaneously (56 %),
- Serially, maximum likelihood of one intake at a time (6 %),
- One intake per bioassay data, at the middle of time interval between data (39 %).

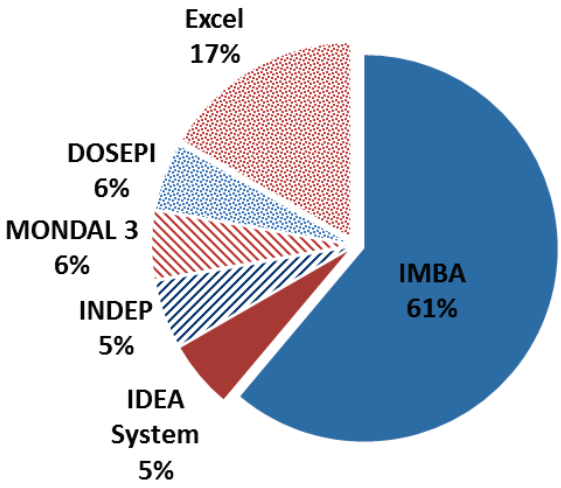

Figure 19: Software used by participants to estimate doses: Excel: Microsoft Excel®; DOSEPI, IRSN, France; MONDAL, Ishigure *et al.* 2004; INDEP: InDEP; Oak Ridge Center for Risk Analysis, Inc. Oak Ridge, TN, v. 4.2, 2016, Anderson *et al.* 2013; IDEA System, Doerfel 2007; IMBA, Birchall *et al.* 2007

4. Assessment methods of participants

In order to understand the differences between the doses estimated by the different participants, it was proposed that participants thoroughly describe their methods of assessment:

- Data processing : conversion of mass into activity, into daily excretion,
- Dietary contribution to uranium excretion,
- Biokinetic and dosimetric models,
- Intake assessement procedure,
- Radionuclide and isotopic composition
- Exposure pattern,
- Chemical form,
- Treatment of data below DL,
- Intake and dose estimates.

The purpose of this supplement to the intercomparison is not to assign blame to anyone deemed to have produces a 'faulty' assessment—there is no, universally agreed, 'correct' answer. The intention is that by examining the various assumptions and methods used by different assessors, it will be possible to identify where areas of uncertainty lie, so that guidance on dose assessment can be improved.

4.1 Participant ID 1: The ARN assessments

4.1.1 General assumptions

4.1.1.1 Processing of Data

Activity measurements in $pCi.l^{-1}$ were multiplied by 0.037 to convert to $Bq.l^{-1}$. All the exposures reported in the JEM refer to Natural uranium. Mass measurements in $\mu g.l^{-1}$ were multiplied by 0.0252 (specific activity of natural uranium) (0.02518 from EURADOS IDEAS Guidelines; Castellani *et al.* 2013) to convert to $Bq.l^{-1}$. Both were then multiplied by 1.6 to convert to $Bq.d^{-1}$. This conversion is taken from ICRP Publication 89 (2002) which gives a daily urine excretion of 1.6 l for reference man.

Faecal activity measurements in pCi were multiplied by 0.037 to convert to Bq. Faecal results were taken to represent daily output, except for samples flagged as 48 hrs. In these latter cases the activity was divided by 2 to give the excretion per day.

Where both mass and activity measurements were reported for the same day, the mass measurements were used in Worker 1. Meanwhile in the case of Worker 3 we used activity measurements where both were available. All available data, both above and below DL, have been used for the dose assessment with the exception in Worker 1, due to the criteria that a break in bioassay monitoring over more than 3 monitoring intervals would indicate the cessation of potential exposure during that break and no intake would be evaluated during that period (CURE dosimetric protocol; Blanchardon *et al.* 2014). In view of inconsistency between JEM and bioassay data, ARN has decided to model a unique constant chronic inhalation from the beginning up to the end of period 1 (1/06/1963 - 31/12/1963).

4.1.1.2 Dietary contribution to uranium excretion

The background urine excretion of uranium adopted was 0.0001 $mg.d^{-1}$ (0.00252 $Bq.d^{-1}$). Nevertheless, it was observed that the subtraction does not change significantly the provided data. In the case of faeces no subtraction was attempted.

4.1.1.3 Models

The biokinetics models used were: ICRP Publication 66 Human Respiratory Tract Model (ICRP 1994a) with Type F and AMAD of 5 µm, ICRP Publication 30 gastro-intestinal tract-model (ICRP 1979), and uranium systemic model ICRP Publication 69 (ICRP 1995). The dosimetric model (tissue weighting factors, radiation weighting factors) was that described in ICRP Publication 60 (ICRP 1991).

When the pathway intake was a wound, the assessment was based on NCRP wound model (NCRP 2006).

4.1.1.4 Intake assessment procedure

Acute intakes and doses for Worker 1 were estimated using a Microsoft Excel® spreadsheet with the excretion fractions and dose coefficients from AIDE software (Bertelli *et al.* 2008) for inhalation and from NCRP (2006) for wounds. The chronic intakes of Workers 2 and 3 were estimated using the software IMBA Professional Plus-Update (Birchall *et al.* 2007) meanwhile the doses were assessed using Microsoft Excel® spreadsheet.

4.1.2 Assessments

4.1.2.1 Worker 1

Radionuclide and isotopic composition

The job exposure matrix (JEM) for Worker 1 indicates that all potential exposures were to natural uranium.

Exposure pattern

Accordingly with the JEM there were exposures since 31/07/1966. It was assigned the date for the 1st intake at the 1st incident date (bioassay data on 13/12/1966) and it was assumed as an acute inhalation. There were identified seven incidents that have correlation with the bioassay data information. There is an eighth registered incident but this bioassay datum on 3/06/1970 (5 $pCi.l^{-1}$) corresponds to the contribution of a previous assessed intake (number 6). Therefore, we reported 7 acute intakes (Table 10) corresponding to 7 out of 8 that are shown in the incident register.

The bioassay datum on 23/5/1972, even if it is reported in the incident register, it is not a new intake due to it has been considered contribution of the previous intake.

The ARN reported 108 intakes included seven incidents (two wounds) The other 101 reported intakes were considered resulting from chronic exposures in routine monitoring periods (Type F=30 days). They were assessed as acute intakes occurred at mid-point period (these 101 were informed as chronic exposure in the *EURADOS WG7 5 Template for U dose reconstruction* setting the beginning and the ending of each monitoring period).

When there are not bioassay data, due to the criteria that a break in bioassay monitoring over more than 3 monitoring intervals would indicate the cessation of potential exposure, and so, no intake would be evaluated during that period.

Table 10: Incident exposures for Worker 1 set by participant ID 1

Intake number	*Date of incident*	*Bioassay data*	*Incident register*	*Intake - path*
1	13/12/66	Urine 24 hs / incident data 14/12/66: 15 pCi	No	Inh
2	17/03/1967	Urine 24 hs Data 18/03/67 : 10 $pCi.l^{-1}$	Yes Wound	wound
3	13/06/1967	Urine/ incident data 28/06/67 : 199 $pCi.l^{-1}$	No	wound
-	11/10/1967	-	Yes, external contamination	-
-	3/06/1970	Contribution of previous intake	Yes	-
12	30/08/1971	Urine / incident data 30/08/1971: 53.4 $pCi.l^{-1}$	Yes Inhalation	Inh
14	23/09/1971	Urine 24 hs / incident 23/09/1971:16.6 pCi	Yes Wound	wound
-	23/05/1972	Contribution of previous intake	Yes	-
42	4/03/1974	Urine 24 hs / incident 5/03/74 : 899 $pCi.l^{-1}$	Yes Inhalation	Inh
43	14/03/1974	Urine 15/03/74 : 20.04 $pCi.l^{-1}$	Yes Inhalation	Inh

Chemical form

All inhalations intakes have been assigned to type F.

Wound intakes were assigned as weakly retention category.

Treatment of data below DL

All the data reported as < DL, were replaced by DL/2.

Intake and dose estimates

The dose coefficients of Natural Uranium (NU) presented in Table 11 were taken from IMBA software (Birchall *et al.* 2007) for inhalation and from NCRP report 156 (2006) for wound to proceed with the dose assessment with an excel spreadsheet.

Table 11: Dose coefficient used for Worker 1 by participant ID 1

Natural Uranium	*e(50) (Sv.Bq^{-1})*	*H(50) Lung (Sv.Bq^{-1})*	*H(50) Kidney (Sv.Bq^{-1})*
Inhalation Type F	$6.17.10^{-7}$	$3.79.10^{-7}$	$3.85.10^{-6}$
Wound, Weak	$2.15.10^{-6}$	$1.30.10^{-6}$	$1.35.10^{-5}$

The intakes and doses assessment results for inhalation and wound are shown in Table 12.

Table 12: Intakes and doses for inhalation and wound assessed for Worker 1 by participant ID 1

	Intake (Bq)	*Effective Dose (mSv)*	*H (50) Lung (mSv)*	*H (50) Kidney (mSv)*
Inhalation	$6.13.10^{4}$	37.8	23.2	236
Wound	$1.01.10^{3}$	2.17	1.31	13.6
Total	$6.23.10^{4}$	40.0	24.5	250

The ID 1 final results are shown in Table 13.

Table 13: Dose estimates for Worker 1 for participant ID 1

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
40.0	24.5	250

4.1.2.2 Worker 2

Radionuclide and isotopic composition

The job exposure matrix (JEM) for Worker 2 indicates that all potential exposures were to natural uranium.

Exposure pattern

The JEM indicates potential exposure only in periods 1, 8, 9 & 10. Although, the JEM indicates exposure in periods 8, 9 & 10, it is also noted that there are no urine data corresponding to the last 6 exposure periods. In view of inconsistency between JEM and bioassay data, ARN has decided to model a unique constant chronic inhalation from the beginning up to the end of 1st period (1/06/1963 - 31/12/1963). It means a 180 days period of chronic exposure via inhalation.

Chemical form

All data have been assigned to absorption Type F.

Treatment of data below DL

We assigned a value of DL/2 in the case of < DL records.

Intake and dose estimates

The theoretical excretion fraction of 0.27 corresponding to 1 Bq.d^{-1} of a chronic exposure was used. It was determined from IMBA (Birchall *et al.* 2007) and ISO standard 27048 (ISO 2011).

A chronic intake of 0.36 Bq.d^{-1} is obtained using a Microsoft Excel® spreadsheet or IMBA.

Assuming 180 days of exposure period, the total intake of 66 Bq is obtained (0.36 Bq.d^{-1} x 180 d).

Dose assessment results obtained with IMBA was different from those obtained with Microsoft Excel®. So, we decided to perform doses assessment with a Microsoft Excel® spreadsheet and the doses coefficients presented in Table 14.

Table 14: Dose coefficient used for Worker 2 by participant ID 1

Natural Uranium	*e(50) (Sv.Bq^{-1})*	*H(50) Lung (Sv.Bq^{-1})*	*H(50) Kidney (Sv.Bq^{-1})*
Inhalation Type F	6.17.10^{-7}	3.79.10^{-7}	3.85.10^{-6}

The results that ARN obtained considering the intake of 66 Bq with the above doses coefficients are gathered in Table 15.

Table 15: Dose estimates for Worker 2 for participant ID 1

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
4.05.10^{-2}	2.50.10^{-2}	2.54.10^{-1}

4.1.2.3 Worker 3

Radionuclide and isotopic composition

The job exposure matrix (JEM) for Worker 3 indicates that all potential exposures were to natural uranium.

Exposure pattern

All of the urine data for this case are below DL. Accordingly with the pattern shown by IMBA (Birchall *et al.* 2007) graph of the bioassay data, ARN has decided to model the case as two constant chronic inhalations.

The definition of the two exposure periods were based on the graph of bioassay data. The 1st exposure period was set from the 1st bioassay data on 19/6/1968 to 26/12/1972 and the 2nd exposure period from 25/6/1973 to 11/12/1981.

Chemical form

The JEM indicates exposure to type F material in all exposure periods.

Treatment of data below DL

All of the data < DL was assigned as DL/2.

Intake and dose estimates

IMBA Software (Birchall *et al.* 2007) was used for intake estimation and the results presented in Table 16 were obtained.

Table 17 contains dose coefficients used to assess doses from intakes.

Table 16: Intakes assessed for chronic exposures of Worker 3 by participant ID 1

	Daily intake (Bq.d^{-1})	*Exposure duration (d)*	*Intake (Bq)*
1st chronic period	0.456	1627	$7.42.10^{2}$
2nd chronic period	1.04	3046	$3.18.10^{3}$
	Total		$3.92.10^{3}$

Table 17: Dose coefficient used for Worker 3 by participant ID 1

Natural Uranium	*e(50) (Sv.Bq^{-1})*	*H(50) Lung (Sv.Bq^{-1})*	*H(50) Kidney (Sv.Bq^{-1})*
Inhalation Type F	$6.17.10^{-7}$	$3.79.10^{-7}$	$3.85.10^{-6}$

The results of dose assessment are shown in Table 18.

Table 18: Dose estimates for Worker 3 for participant ID 1

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
2.42	1.49	15.1

4.1.3 Comments

We realized that it would have been more appropriate to apply the dosimetric protocol of the CURE project (Laurent *et al.* 2016) for assessing the 3 cases. Unfortunately, we knew about this document with no time to do it. It would contribute to diminish the variability in the setting of exposure periods. It seems that a relevant source of uncertainty is related with the lack (or inconsistency) of information between JEM and bioassay data. The definition of chronic exposure periods has been a subjective matter based on our own criteria which could be different from others assessors.

4.2 Participant ID 2: A. Pántya (MTA)

4.2.1 General assumptions

4.2.1.1 Processing of Data

Activity measurements in pCi.l^{-1} were multiplied by 0.037 to convert to Bq.l^{-1} and mass measurements in µg.l^{-1} were multiplied by 0.0127. Only specific activity of ^{235}U and ^{238}U was considered with ratios corresponding to their occurrence in nature: ^{238}U (99.27%), ^{235}U (0.72%). Both measurement values were then multiplied by 1.6 to convert to Bq.d^{-1}. This conversion factor is taken from ICRP Publication 89 (ICRP 2002) which gives a daily urine excretion of 1.6 l for reference man. Where mass and activity measurements were reported for the same day, the highest value was used, which is a conservative assumption. When the values were below DL, we selected the lower data namely the result with the highest.

4.2.1.2 Dietary contribution to uranium excretion

The dietary background of uranium intake was not taken into account. There was no information about dietary habits and the place of residence for the workers in the case scenarios.

4.2.1.3 Models

The used biokinetic models were: ICRP Publication 66 Human Respiratory Tract Model (ICRP 1994a) with Type F and AMAD of 5 µm, ICRP Publication 30 gastro-intestinal tract-model (ICRP 1979), and uranium systemic model ICRP Publication 69 (ICRP 1995). The dosimetric model (dose coefficients) values given in ICRP Publication 119 (ICRP 2012) were used in this assessment as implemented by MONDAL-3 software.

4.2.1.4 Intake assessment procedure

In routine monitoring, we assumed that the acute intake was in the mid-point. We calculated the intake activity for these dates separately for the uranium isotopes with the MONDAL- 3 after these were summed up in the excel document according to the mass ratio of the uranium isotopes.

4.2.2 Assessments

4.2.2.1 Worker 1

Not analysed.

4.2.2.2 Worker 2

Radionuclide and isotopic composition

All the measurements are for mass of uranium and according to job exposure matrix (JEM), potential exposure of Worker 2 was to natural uranium, so ^{235}U and ^{238}U was taken into consideration.

Exposure pattern

The acute intakes were considered in the middle of all measurement intervals.

Chemical form

Absorption Type F has been assigned to all data.

Treatment of data below DL

When one value was above DL while another was not, the value above the DL was used. Remaining results below DL were used to assess doses conservatively assuming the DL value as measured activity, which gives an upper (conservative) limit for the result instead of a best estimate.

Intake and dose estimates

Route of intake: inhalation.

Assuming acute intakes in the middle of all measurement intervals.

All calculations were done using MONDAL Software and Excel.

The intake and dose estimates for Worker 2 are presented in Table 19.

Table 19: Dose estimates for Worker 2 for participant ID 2

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
8.51	5.10	51.6

4.2.2.3 Worker 3

Radionuclide and isotopic composition

In the case of Worker 3, we used activity and mass measurements where both were available, and if the values were below DL, we selected the lower data, which has the higher sensitivity. According to the job exposure matrix (JEM), the potential exposure of Worker 3 was to natural uranium, so ^{235}U and ^{238}U isotopes were taken into consideration.

Exposure pattern

All of the urine results for this case were below DL. As a conservative assumption, it was decided to treat this case as an acute inhalation.

Chemical form

The JEM indicates exposure to type F material in all exposure periods.

Treatment of data below DL

In this case only data below DL was available, so for the upper estimation of the dose, we calculate with these values.

Intake and dose estimates

Route of intake: inhalation.

Assuming acute intakes in the middle of all measurement intervals.

All calculations were done using MONDAL Software and Excel.

The intake and dose estimates for Worker 3 are presented in Table 20.

Table 20: Dose estimates for Worker 3 for participant ID 2

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
35.2	20.9	220

4.2.3 Comments

Reconstruction of cases for Worker 2 and Worker 3 was difficult due to the lack of informative data. Information about uncertainties should be recorded in the future.

4.3 Participant ID 3: A.-L. Lebacq (SCK●CEN)

4.3.1 General assumptions

4.3.1.1 Processing of Data

Results expressed in mass were converted in activity by assuming a specific activity for natural uranium of 25.1 mBq.µg^{-1} from EURADOS IDEAS Guidelines (Castellani *et al.* 2013). Daily excretions were obtained by assuming a reference daily urine volume of 1.6 l.d^{-1} and a daily reference ash weight of 4 g ash.d^{-1} from ICRP Publication 89 (ICRP 2002).

Activity expressed in pCi were converted into mBq by applying 1 pCi = 37 mBq.

When results were given as activity and mass for the same sample, the result used to estimate doses is:

- the quantified result if one over two is quantified,
- the higher result if both were quantified,
- the lower detection limit if both results were below DL.

4.3.1.2 Dietary contribution to uranium excretion

No dietary contribution was subtracted from uranium excretion because no indication is given on the population monitored and as the detection limits are all are much higher (> 202 mBq.d^{-1}) than the reported data for Reference Man in ICRP Publication 23 (1.25 – 12 mBq.d^{-1}) (ICRP 1975).

4.3.1.3 Models

The biokinetic models used in these assessments are: the Human Respiratory Tract Model (ICRP 1994a), the Gastro-Intestinal Tract Model (ICRP 1979), NCRP wound model (NCRP 2006) and systemic model for uranium (ICRP 1995). Retention/excretion functions and annual absorbed doses after unit intake were evaluated with DCAL programme (Eckerman 2006) on the basis of the aforementioned biokinetic models, the radionuclide transformation data from ICRP Publication 38 (ICRP 1983) and the organ and tissue masses of the ICRP reference person (ICRP 1975).

4.3.1.4 Intake assessment procedure

IMBA software (Birchall *et al.* 2007) was used. It assessed all intakes simultaneously.

4.3.2 Assessments

4.3.2.1 Worker 1

Not analysed.

4.3.2.2 Worker 2

Not analysed.

4.3.2.3 Worker 3

Radionuclide and isotopic composition

From the job-exposure matrix, an inhalation of natural uranium was assumed.

Exposure pattern

A chronic exposure from 36/07/1965 to 31/12/1981 was defined from the job-exposure matrix.

Chemical form

From the job-exposure matrix, an inhalation of Type F compounds was assumed with the following parameters: f_r=1; s_r=100 d^{-1} (ICRP 1994a). By default, an AMAD of 5 µm was used.

Treatment of data below DL

In order to obtain a maximum dose, all data recorded as below DL were set equal to DL.

Intake and dose estimates

Intake and dose estimated for Worker 3 are presented in Table 21.

Table 21: Intake and dose estimates for Worker 1 for participant ID 3

Participant ID	*Intake (Bq)*	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
3.1	0	0	0	0
3.2	6600	4.07	2.50	25.4

4.4 Participant ID 4: Argentine-CNEA

4.4.1 General assumptions

4.4.1.1 Processing of Data

Activity measurements in $pCi.l^{-1}$ were multiplied by 0.037 to convert to $Bq.l^{-1}$ [1]and mass measurements in $\mu g.l^{-1}$ were multiplied by specific activity of natural uranium to convert to $Bq.l^{-1}$. And then $pCi.l^{-1}$ was multiplied by 0.037 to convert to $Bq.l^{-1}$ again. Both were then multiplied by 1.6 to convert to $Bq.d^{-1}$. This conversion is taken from ICRP Publication 89 (ICRP 2002) and Safety Report Series N° 37 (IAEA 2004) which gives a daily urine excretion of 1.6 l for reference man.

Faecal activity measurements in pCi were multiplied by 0.037 to convert to Bq. Besides, in the case of faecal samples we assumed that the sample type was 48h faecal samples.

The measured body content, body region content or excretion rate ($\mu g.g^{-1}$ or $pCi.g^{-1}$) is multiplied by the gram per day of faeces excreted by human reference (ICRP 1975, IAEA 2004). In order to assess the measure we did not correct the value because it is expressed in units of pCi.

Where both mass and activity measurements were reported for the same day, the activity measurements were used. This is because activity measurements are relatively unambiguous, as the excretion curves and dose factors for different uranium isotopes do not differ much. Mass measurements require some assumption about specific activity in order to convert them to activity and this conversion factor is highly nuclide dependent. Besides, it is a conservative assumption.

4.4.1.2 Dietary contribution to uranium excretion

Experience has shown that the typical background excretion of uranium varies noticeably across different sites. So, we assumed that for all bioassay measurements background level was already subtracted.

4.4.1.3 Models

The ICRP Publication 66 Human Respiratory Tract Model (ICRP 1994a) was used.

The ICRP Publication 30 (ICRP 1979) was used for the gastro-intestinal tract.

The NCRP Report No. 156 (2006) was used for the wound.

The ICRP Publication 69 (ICRP 1995) was used for systemic biokinetic model.

The ICRP Publication 78 (ICRP 1997) was used for dosimetric model.

In the absence of any evidence to the contrary, an AMAD of 5 microns was used throughout.

4.4.1.4 Intake assessment procedure

Once the time and route of intake have been determined or assumed, the intake was calculated as:

$$I = \frac{M}{m(t)}$$

where:

- *M*: is the bioassay result (Bq);
- *t*: is the time since the intake;
- *m(t)*: is the value of the bioassay prediction (retention or excretion) taken from the tables of ICRP Publication 78 (ICRP 1997).

For routine monitoring, whenever a measurement under detection limit appeared followed by a positive measurement, the time (*t*) of the intake was determined dividing the days since the first measurement by two. We suppose that the intake was in the mid-point.

However, in the case that the exact moment of the intake was known, the time (*t*) was determined as the days from the intake to the measurements.

When we had multiple bioassay results for an intake values were fitted by the unweighted least squares fit (ULSF) method (IAEA 2004):

$$I = \frac{\sum_j M_j m(t_j)}{\sum_j m(t_j)^2}.$$

Moreover, we checked on significance of new measurement and consistency with previous evaluation by applying EURADOS IDEAS Guidelines (Castellani et al. 2013). We calculated the contributions from previous intakes to *M* and assessed the uncertainty on *M* ("scattering factor" SF). Then we calculated the contributions (*P*) from previous intakes by:

$$P = \sum_j^{all\ previous} I_j . m(t - t_j),$$

where I_j are the values of intakes evaluated at previous times (t_j), and *t* is the time of measurement. So, if $M / SF^2 > P$ then we assumed a new intake has occurred and we calculated the net value ($N = M - P$) of the radionuclide and finally we obtained the result of intake from:

$$I = \frac{N}{m(t)}.$$

If $M/SF^2 < P < M.SF^2$ we assumed that there was no evidence of a new intake. These assumptions were based on section 7.3 of EURADOS IDEAS Guidelines (Castellani et al. 2013).
Faecal results were assigned a default SF of 3 (faecal 24 hr sample). Urine results were assigned a default scattering factor of 1.6 (Simulated 24-hr urine, creatinine, volume or specific gravity normalized). This information is in Table 4.10 Typical values for the scattering factor SF for various types of *in-vitro* measurements from different studies (Type B errors) (EURADOS IDEAS Guidelines; Castellani et al. 2013).

4.4.2 Assessments

4.4.2.1 Worker 1

Radionuclide and isotopic composition

The job exposure matrix (JEM) for Worker 1 indicates that all potential exposures were to natural uranium.

Exposure pattern

The JEM indicates exposure only in periods 4 to 10 (potential exposure period ID for the worker).

In periods (ID) 4 to 8, the exposure is given as natural uranium type F only, so we assumed natural uranium type F.

In ID 9 (1-1-1977 to 31-3-1979) and 10 (1-4-1979 to 30-9-1980), the frequency and quantity of exposure to the three inhalation types F, M & S are in the ratio 1:1:0. So, we assumed natural uranium type M, because it is more conservative.

Chemical form

The solubility that was used for the assessment was types F and type M.

For wounds we used NCRP Report No. 156 Wound Model (NCRP 2006). The solubility that was used for the assessment was type Weak.

Treatment of data below DL

For Worker 1, measurements under detection limit don't trigger any further assessment. We assumed that was not an intake.

Intake and dose estimates

Bioassay data were separated by year. Although each year was evaluated separately, it was considered the last measurement of the year and the influence in the following year. In the case that the values corresponded to the same intake, they were taken into account.

We made a first general observation to identify the highest values and their subsequent to confirm if their corresponded to the same incorporation event. Subsequently we calculated the intake value of each event. When we had multiple bioassay results for an intake values were fitted by the unweighted least squares fit (ULSF) method (IAEA 2004). We assumed an acute pattern, because it is more conservative.

All the intake values of each event were added by year and then we added all the year's values in a manner to have a lifetime value.

Of the eight recorded incidents, the 2/6/1970 one was no used for the calculation because their values were equal or less than DL.

Besides the recorded incidents we observed relevant values that indicated possible events no registered. We considered these events as acute ones. We assumed that all the urine bioassay measurements were urine 24h.

Dose estimated for Worker 1 are presented in Table 22.

Table 22: Dose estimates for Worker 1 for participant ID 4

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
2.42	1.49	15.1

4.4.2.2 Worker 2

Radionuclide and isotopic composition

The job exposure matrix (JEM) for Worker 2 indicates that all potential exposures were to natural uranium, so the 'natural uranium' type F was used.

Exposure pattern

The JEM indicates exposure only in periods 1 (1-6-1963 to 31-12-1963), 8 (1-1-1977 to 31-3-1979), 9 (1-4-1979 to 31-1-1982) & 10 (1-2-1982 to 30-9-1982). In period 1 the frequency and quantity of exposure to the three inhalation types F, M & S are in the ratio 3:1:1. The quantity and frequency exposure for natural uranium type F is the highest, so we assumed natural uranium type F. In periods 8, 9 and 10, the exposure is given as type F only and the dates begin at 1-1-1977 and finish at 30-9-1982, but there was no information in bioassay data for these dates. However, in contradiction to the JEM, the only non-DL urine result (4 $\mu g.l^{-1}$) occurs in 2 (day)-08 (month)-1965 (year); (albeit a value lower than the DL equal 5 $\mu g.l^{-1}$). But the JEM indicated "no possible exposure" for this date, so it was not used.

The JEM indicates that the Worker 2 had been exposure between 1-6-1963 to 31-12-1963. So, the only intake was in 6-11-1963.

Chemical form

The solubility that was used for the assessment was types F. This mixture was represented by the following parameters: f_r=1; s_r=100 d^{-1} (ICRP 1994a). No incidents were recorded for Worker 2.

Treatment of data below DL

In real practice, measurements under detection limit don't trigger any further assessment. Nevertheless, if an intake event is suspected, other monitoring data (air monitoring, contamination monitoring) is required in order to assess the case.

However, for this intercomparison exercise we based on Section 6.2 of EURADOS IDEAS Guidelines (Castellani et al. 2013) for assessing Worker 2 case:

…"Common approaches are to treat each "below DL" value as a positive value equal to the DL value, equal to DL/2 or equal to DT/2. The first approach will clearly lead to an overestimate of the

intake, but there is no simple method to quantify the degree of overestimation. The approach to replace the unknown values with DT/2 is recommended here, in the interest of harmonization with the ISO standard (ISO 2011). However it is acknowledged that this method has no strong foundation in mathematics"…

In conclusion, data below DL was treat as a positive value equal DL/2 and that it was acute intake; because it is a conservative assumption.

Intake and dose estimates

The committed effective dose (Sv) was evaluated with this equation:

$$E = I \times e_{50}.$$

where:

e_{50}= Dose coefficient per unit intake ($Sv.Bq^{-1}$) depends on:

- the radionuclide,
- the chemical form of the radionuclide
- the intake pathway
- the age at intake which is tabulated (ARN 2003).

The e_{50} for effective dose from natural uranium type F for workers = $5.8.10^{-7}$ $Sv.Bq^{-1}$ (AMAD = 5 μm)

The e_{50} for lung absorbed dose from natural uranium type F = 3.710^{-7} $Sv.Bq^{-1}$

The e_{50} for kidney absorbed dose from natural uranium type F = 3.710^{-6} $Sv.Bq^{-1}$.

Dose estimated for Worker 2 are presented in Table 23.

Table 23: Dose estimates for Worker 2 for participant ID 4

Intake date	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
6/11/1963	1.02	1.92	19.2

4.4.2.3 Worker 3

Radionuclide and isotopic composition

The job exposure matrix (JEM) for Worker 3 indicates that all potential exposures were to natural uranium.

Exposure pattern

All of the urine results for this case are below DL. It was decided to treat it as an acute inhalation because it is a conservative assumption.

Chemical form

The JEM indicates exposure to type F material in all exposure periods.

Treatment of data below DL

All the measurements values were used for the calculation. Data below DL was treat as a positive value equal DL/2.

Intake and dose estimates

Bioassay data were separated by year. The intake corresponding to each bioassay was calculated as:

$$I = \frac{DL/2}{m(t)}.$$

Then the year intake is calculated by:

$$I_t = I_1 + I_2 + \cdots.$$

For each year, the committed effective dose (Sv) was evaluated with this equation:

$$E = I_t \times e_{50}.$$

Each year intakes were summed to obtain the total intake. The sum of the dose in each year was the total dose in his entire working life.

Dose estimated for Worker 3 are presented in Table 24.

Table 24: Dose estimates for Worker 3 for participant ID 4

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
110.2	70.3	702.7

4.4.3 Comments

- The description of the sample type was insufficient. It was not clear the type of urine bioassay neither the volume of the sample: Urine, Urine 24h, and Urine Immediate. Urine samples collected over periods of less than 24 h are normalized to an equivalent 24 h value, but we do not have information about volume urine samples. In the case of faces bioassay we assumed that they were 48h faecal sample.
- In the cases of Worker 2 and Worker 3 bioassay data, there is no explanation of the reason for the change in the detection limits, e.g: Worker 2, ID sample number 9.
- It would be useful to support our assessment to had information of other monitoring data.
- It would be useful a detailed description of each incident.
- It would be important to offer intensive training courses about fitting methods (e.g: maximum likelihood method) and software application.
- When we studied the feedback of the exercise results and comments about the works, many doubts arose about the interpretation of the pattern of the intakes. It would be useful a detailed description of when we have to adopt acute o chronic intake. Different participants had different interpretations in this regard. We would like discuss about this issue to achieve a common criteria.

4.5 Participant ID 5: C.M. Castellani (ENEA)

4.5.1 General assumptions

4.5.1.1 Processing of Data

In case of unique datum available for time of measurement, the value has been accepted and the proper conversion factor to evaluate Bq $U_{nat}.d^{-1}$ has been used. When both measurement data types (mass and activity) are available for the same time of measurement, and that both are above the detection limit (DL), the value that determines the greater value of Bq Unat.d^{-1} has been used. When one value is above DL while the other is not, the value above the DL has been used. When both values are below DL the value which determines the lower values has been used. The numerical value of reported DL has been halved to calculate the value of decision threshold (DT) i.e DT= DL/2. The value has been used inside IMBA™ software (Birchall *et al.* 2007) and the indication of "<LOD" has been put on data type column, in accordance with Par. 14.2.2 of Annex 2 of Version 2 EURADOS IDEAS Guidelines (Castellani *et al.* 2013). All available data, both above and below DL, have been used for the dose assessment in Workers 1 and 2.

In case of Worker 3, when only data "below DL" are available the numerical value of DT/2=DL/4 and the indication of "Real" data inside IMBA (Birchall *et al.* 2007) have been used (par. 6.2 of EURADOS IDEAS Guidelines; Castellani *et al.* 2013).

All data have been converted in Bq of U_{nat} with the following percentages in activity: ^{234}U 48.71%, ^{235}U 2.26%, ^{238}U 49.03% (as in Annex 1 of EURADOS IDEAS Guidelines; Castellani *et al.* 2013). The used conversion factor is therefore 2.5185 x 10^{-2} Bq $U_{nat}.(\mu g\ U_{nat})^{-1}$.

The normalization factor of urinary daily excretion for male adopted in the calculation is 1.6 $l.d^{-1}$ (par. 8.3.2 of ICRP Publication 89; ICRP 2002)

The SF value for all urinary data has been put equal to 1.6. The SF_A contribution has been considered to be negligible.

The SF value for each faeces data (in Worker 1 case) has been put equal to 3 for 24h collection and equal to 2.5 for a 48 h collection (average value between 3 for 24 h and 2 for 72 h collection). Also in this case the SF_A contribution has been considered to be negligible.

4.5.1.2 Dietary contribution to uranium excretion

A constant urinary excretion rate due to dietary intake of U_{nat} = 21.7 ng $U.d^{-1}$ = 0.547 mBq U $.d^{-1}$ has been subtracted to each daily excretion measurement value.

The value of 21.7 ng $U.d^{-1}$ is the calculated 84-th percentile of the lognormal distribution of daily urinary excretion of U_{nat} for a control population in a French study (see lognormal parameters for urines in Table 1 at page 1052 of the article by Davesne *et al.* (2014)).

No subtraction for dietary intake on faeces data has been performed.

4.5.1.3 Models

The HRTM as presented in ICRP Publication 66 (ICRP 1994a) has been used with 5 μm AMAD and absorption type F (f_r = 1 , s_r = 100 d^{-1}), f_1 = 0.02. For the systemic phase the Model of ICRP Publication 69 (ICRP 1995) has been used.

To simulate wound the injection pathway has been adopted.

4.5.1.4 Intake assessment procedure

It is widely used the IMBA™ software (Birchall *et al.* 2007) to fit contemporarily all intake regimes selecting the date of intake on the basis of the JEM and, in limited number of cases, by the behaviour of data (e.g. marked increase).

Inside IMBA (Birchall *et al.* 2007), the maximum likelihood method permits to use data both below and above DL.

4.5.2 Assessments

4.5.2.1 Worker 1

Radionuclide and isotopic composition

The data are referred to Natural Uranium, the isotopic composition is assumed as indicated in par. 4.5.1.1.

Exposure pattern

The first period of constant intake has been arbitrary set from day 18/3/1964, i.e. 3 months earlier than first routine measurement. The reference beginning date of exposure has therefore been set on 18/3/1964.

The end of the exposure period has been set on the last routine measurement day, i.e. 23/6/1980.

The first chronic intake has been set via inhalation; the considered period is 19/3/1964 to 16/3/1967. The used dose coefficient is: $6.17.10^{-6}$ Sv.(Bq U_{nat})$^{-1}$

The 2nd acute intake has been set on 17/3/1967 and injection has been used to simulate wound absorption. The dose coefficient for unit uptake used in the evaluation is $2.16.10^{-6}$ Sv.(Bq U_{nat})$^{-1}$

The acute intake of 10/11/1967 (for external contamination) reported in the incident register has not been considered in the evaluation as judged not to be determining an internal contamination.

The acute intake of 3/6/1970 (inhalation) reported in the incident register has not been considered in the calculations, as preliminary evaluations permit to estimate it as negligible.

The 3rd acute intake is via inhalation on 30/8/1971 (as reported in the incident register): leakage from glove box.

The 4th acute intake (23/9/1971) is via injection (to simulate wound as for second intake).

The probable intake on 23/5/1972, even if reported in the incident register, has been considered to be negligible.

The 5th acute intake has been set inside the period between 21/1/1974 and 18/2/1974, seeing an increase in urine excretion rate and not knowing the exact day of intake.

The 6th and 7th intakes via inhalation have been set in dates reported in incident register (4 and 14 March 1974).

The last (8th) constant chronic inhalation period has been set from 15/3/1974 (one day after the acute intake of 14/3/1974) up to 23/6/1980.

Chemical form

All data have been assigned to absorption type F.

Treatment of data below DL

As detailed in 4.5.1.1, i.e. use of value of DT=DL/2 and "<LOD" setting in IMBA software (Birchall *et al.* 2007).

Intake and dose estimates

All the 8 intakes have been evaluated simultaneously with IMBA software (Birchall *et al.* 2007), fitting together both urine and faeces data.

From the estimated rate of intake (as evaluated from IMBA software; Birchall *et al.* 2007) an overall intake has been evaluated for the first and last chronic intakes.

It is acknowledged that it is not possible to reconcile the faeces data with the urine data for the different acute intakes if the absorption type F is used. A little better fit can be achieved using S absorption type. This fitting is not presented because not consistent with the declared compound absorption. Due to the number of urine data the weight of faeces data is very low. Practically the fitting has been based only on urine data. Due to the indication of a compound that is principally of F type, the discrepancy of faeces data between measured and model values remains in at least 2 orders of magnitude without explanation.

The results of the assessment for Worker 1 are reported in Table 25.

Table 25: Dose estimates for Worker 1 for participant ID 5

Intake Number	*Intake Pattern*	*Date*	*To*	*Intake (Bq)*	*Effective Dose (mSv)*	*Lung Dose (mSv)*	*Kidney dose (mSv)*
1	Chronic inhalation	19/03/1964	16/03/1967	939	$5.79.10^{-1}$	$3.56.10^{-1}$	3.62
2	Injection	17/03/1967		23660	51.1	30.7	319
3	Inhalation	30/08/1971		309	$1.90.10^{-1}$	$1.17.10^{-1}$	1.19
4	Injection	23/09/1971		967	2.09	1.25	13.1
5	Inhalation	01/02/1974		976	$6.02.10^{-1}$	$3.70.10^{-1}$	3.76
6	Inhalation	04/03/1974		117	$7.23.10^{-2}$	$4.45.10^{-2}$	$4.52.10^{-1}$
7	Inhalation	14/03/1974		2	$1.22.10^{-3}$	$7.48.10^{-4}$	$7.60.10^{-3}$
8	Chronic inhalation	15/03/1974	23/06/1980	2331	1.44	$8.84.10^{-1}$	8.99
				Total	56.0	33.7	350

4.5.2.2 Worker 2

Radionuclide and isotopic composition

The data are referred to Natural Uranium, the isotopic composition is assumed as indicated in par. 4.5.1.1. Correction for dietary intake has been used as indicated in par. 4.5.1.2

Only one real datum has been introduced at the date of 2/8/1965

Exposure pattern

Four periods are considered, each via inhalation, 5 µm AMAD, absorption type F:

- 1st period: from 2/4/1962 to 31/5/1963: chronic intake.
- 2nd period: 1/6/1963 - 31/12/1963: acute intake in date 1/6/1963
- 3rd period: 1/1/1964 – 31/12/1966: chronic intake.
- 4th Period: 1/1/1967 – 30/9/1982: chronic intake.

Chemical form

All data have been assigned to absorption type F.

Treatment of data below DL

As detailed in 4.5.1.1: Data "< DL" have been put to a value equal to DT=DL/2 and indication in IMBA (Birchall *et al.* 2007): "<LOD", as indicated for maximum likelihood method in par. 14.2 Annex 2 of EURADOS IDEAS Guidelines (Castellani *et al.* 2013).

Intake and dose estimates

The fitting determines intake rate mainly during the third period, in which is present the real value. After that, from 1st Jan 1967 a lower constant rate of intake has been fitted up to 30/9/1982. The selection of the date of separation of intake periods is due to the fact that in the following period the JEM changes with frequency and quantity of U_{nat} with absorption type F, to a value of "3", meaning greater potential intake. Actually measurements cover only the period 1/1/1967 to 12/11/1969 (the eight last measurements). The fitting implicitly distribute the rate of intake (due to the average value of fitted intake rate) during the complete JEM period (1/1/1967-30/9/1982) determining a very low rate of intake.

The results of the assessment for Worker 2 are reported in Table 26.

Table 26: Dose estimates for Worker 2 for participant ID 5

Intake Number	*Intake Pattern*	*Date*	*To*	*Intake (Bq)*	*Effective Dose (mSv)*	*Lung Dose (mSv)*	*Kidney dose (mSv)*
3	Chronic inhalation	1/1/1964	31/12/1966	263.2	$1.63.10^{-1}$	$9.99.10^{-2}$	1.01
4	Chronic inhalation	1/1/1967	30/9/1982	5.6	$3.43.10^{-3}$	$2.11.10^{-3}$	$2.13.10^{-2}$
				Total	$1.66.10^{-1}$	$1.02.10^{-1}$	1.03

The used dose coefficients for committed effective and organ doses are reported in Table 27.

Table 27: Dose coefficients for committed effective and organ doses used in assessments

Radionuclide	*Percentages (%)*	*Effective dose coefficient (Sv.Bq^{-1})*	*Lung dose coefficient (Sv.Bq^{-1})*	*Kidney dose coefficient (Sv.Bq^{-1})*
^{234}U	48.71	$3.17.10^{-7}$	$1.96.10^{-7}$	$1.99.10^{-6}$
^{235}U	2.26	$1.37.10^{-8}$	$8.42.10^{-7}$	$8.54.10^{-8}$
^{238}U	49.03	$2.86.10^{-7}$	$1.75.10^{-7}$	$1.78.10^{-6}$
U_{nat}	100.00	$6.17.10^{-7}$	$3.79.10^{-7}$	$3.85.10^{-6}$

4.5.2.3 Worker 3

Radionuclide and isotopic composition

All available data are "below DL".

Exposure pattern

Due to the JEM description and the possibility to introduce a greater quantity from 1/1/1975, only two chronic intake periods have been used for the evaluation. Period 1: 26/7/1965 (beginning of the JEM description) to 31/12/1974; period 2: 1/1/1975 to 31/1/1982 (end of JEM description). Actually the data are available up to 11/12/1981.

Chemical form

All data have been assigned to absorption type F.

Treatment of data below DL

In this case only data "below DL" are available. The numerical value of DL has been divided by 4 as the numerical value of DT/2=DL/4 has been assumed (see par. 6.2 of EURADOS IDEAS Guidelines; Castellani *et al.* 2013), the correction due to dietary intake has been performed and finally the data have been considered to be real by using the "Real" indication for the Data Type inside IMBA software (Birchall *et al.* 2007).

Intake and dose estimates

The assessment for Worker 3 is reported in Table 28.

Table 28: Dose estimates for Worker 3 for participant ID 5

Intake Number	*Intake Pattern*	*Date*	*To*	*Intake (Bq)*	*Effective Dose (mSv)*	*Lung Dose (mSv)*	*Kidney dose (mSv)*
1	Chronic inhalation	26/7/1965	31/12/1974	936.0	0.577	0.355	3.6
2	Chronic inhalation	1/1/1975	31/1/1982	706.5	0.435	0.268	2.71
				Total	1.01	0.623	6.31

From the fitting the second rate of intake of 0.2731 Bq.d^{-1} is slightly greater than that of the first (0.2717 Bq.d^{-1}) but not substantially different. Due to the total number of days (greater in the first

period in respect to the second) the intake in the 1st period is greater. So the potential increase of rate of intake has not been proved by the data.

Actually the assumption to use a real value, even of small amount as DL/4; introduces an element of conservativism in the dose assessment and can be only considered as a "conventional dose".

4.5.3 Comments

- These three cases are very challenging exercises aimed at the evaluation of the long-life committed equivalent and effective doses assessment.
- To my feeling the most difficult aspect to consider in the performance of calculations is related to the "correct" choice of the period of intake and the relative pattern (i.e. acute versus chronic). In the case of Worker 1 I have tried to use both the information present in the JEM and in one occasion (5th intake period) also the behaviour of the monitoring data. For the Worker 1 case the observed chi square evaluation and the autocorrelation coefficients are very bad, in particular I have not been able to fit adequately both faeces and urine data especially for a F type compound. With a compound of S type the result is better, but even not satisfactory (p-value always less than 0.05). Maybe a different choice of dates of intake (e.g. in the proximity of the days of faecal excretion) could improve the overall fit of the data.
- For Worker 2 I have experienced a computational error which determines the use of a wrong dose coefficient: the lesson is always to check the overall results for consistency with known correct dose coefficients at the end of the evaluation.
- For Worker 3 it was not possible, even with IMBA software (Birchall et al. 2007), to perform maximum likelihood evaluation using only "less than" data. The outcome of the fitting is dose= "zero". Therefore I have followed the suggestion of EURADOS IDEAS Guidelines (Castellani et al. 2013) to use the DT/2 value (i.e. DL/4), and considering all of them as "real" data. This can therefore be considered only as a "conventional dose".

4.6 Participant ID 6: D Bingham (AWE)

4.6.1 General assumptions

4.6.1.1 Processing of Data

The U_mass results were converted from $\mu g.l^{-1}$ to $Bq.l^{-1}$ by multiplying by 0.0256 on the basis that only exposures to natural uranium were reported in the job exposure matrix.

The U_activity results were converted from $pCi.l^{-1}$ to $Bq.l^{-1}$ by multiplying by 0.037.

The following conversions and manipulations were made to urine results:

- They were converted from $Bq.l^{-1}$ to $Bq.d^{1}$ by multiplying by 1.6 (ICRP 2002).
- The collection date was taken to be the dd/mm/yy: 12:00 + 6h for sample provision, unless a different collection period was specified.
- A higher scattering factor of 2.5 was assumed for the U_mass results compared to the U_activity (SF of 1.6) results. This was based on previous experience with measurements of uranium results by mass.

If U_mass and U_activity results were available for the same day then both were included in the analysis.

The following conversions and manipulations were made to the faecal data:

- The results were converted from g^{-1} ash to day^{-1} assuming a dry ash weight of 3.5 $g.d^{-1}$. This value was based on a study done at AWE of faecal ash weights (Bingham *et al.* 2007).
- The results for 48 hour results were converted to a day^{-1} activity. Other results were assumed to be over 24 h.
- A scattering factor of 3 was assumed for all faecal results.

4.6.1.2 Dietary contribution to uranium excretion

No allowance was made for dietary uranium excretion for either the urine or faecal samples. Normal dietary urinary excretion would be well below the reporting limits for these techniques. The faecal results were well above what would be expected from normal dietary intakes (up to about 1 $Bq.d^{-1}$).

4.6.1.3 Models

ICRP Publication 60 (ICRP 1991) radiation and tissue weighting factors, ICRP Publication 66 HRTM (ICRP 1994a), ICRP Publication 30 GIT (ICRP 1979) and ICRP Publication 69 biokinetic models for uranium (ICRP 1995) were used in this assessment as implemented by IMBA Professional Plus (Birchall *et al.* 2007). The NCRP report-156 wound model (NCRP 2006) was used as implemented in IMBA (Birchall *et al.* 2007).

4.6.1.4 Intake assessment procedure

The general approach was to set up chronic intake regimes around the periods of work in the job exposure matrix (JEM) but also taking into account the dates for the bioassay data. Acute intakes were taken from information in the incident register or as highlighted in the bioassay data. The exposure material for each intake regime was assumed to be Type F, M or S or material specific depending upon the information provided in the JEM or incident register.

All the available bioassay data was included. Fitting of observed to expected values was done in IMBA (Birchall *et al.* 2007) using the maximum likelihood method.

4.6.2 Assessments

4.6.2.1 Worker 1

Radionuclide and isotopic composition

Although the exposure material was reported as natural uranium, the assessment was made using ^{234}U as the exposure nuclide in IMBA (Birchall *et al.* 2007) rather that the natural uranium mixture. This was mainly so that the calculations would be quicker in IMBA (Birchall *et al.* 2007). Doses calculated using natural uranium appeared to be about 6% lower than those calculated using ^{234}U, based on a single comparison of assessments.

Exposure pattern

For Worker 1, although bioassay started while working at the DT_AT4 facility, all the results while working at this facility were below DL. As no intake would be calculated by IMBA (Birchall *et al.* 2007) for an exposure over this period, a chronic intake was not included for this period. Although the JEM had 7 entries for work at 77_UDG1, the type of exposure seemed to be very similar in all of

these so there were combined into a single chronic exposure. The same was done for work at 3_CME4.

Table 29: Intakes modelled in the final IMBA run for Worker 1 for participant ID 6

Intake number	*Intake pattern*	*Intake start date*	*Intake end date*	*Radionuclide*	*Pathway*	*AMAD (µm)*	*Absorption Type*
1	Chronic	01/07/66	31/12/76	^{234}U	Inhalation	5	UF_6 / U nitrate mix
2	Chronic	01/01/77	30/09/80	^{234}U	Inhalation	5	UF_6 / U nitrate mix
3	Acute	13/12/66		^{234}U	Inhalation	5	UF_6 / U nitrate mix
4	Acute	07/03/67		^{234}U	Inhalation		UF_6 / U nitrate mix
5	Acute	10/11/67		^{234}U	Wound -		soluble weak
6	Acute	10/09/68		^{234}U	Inhalation	5	UF_6
7	Acute	30/08/71		^{234}U	Inhalation	5	UF_6
8	Acute	23/09/71		^{234}U	Wound -		soluble weak
9	Acute	23/05/72		^{234}U	Inhalation		UF_6 / U nitrate mix
10	Acute	04/03/74		^{234}U	Inhalation		U nitrate

The acute intakes were added based on the dates given in the incidents register or on the bioassay data. If an acute intake was for an insignificant amount it was removed due to the restriction in IMBA (Birchall *et al.* 2007) on the number of intake regimes. The date but not the time for each acute intake was set up in IMBA (Birchall *et al.* 2007). As the time was not specified it was set at 00:00. There was a concern that the rapid urinary excretion of UF_6 and uranyl nitrate (U nitrate) would mean that the calculated intakes would be very sensitive to the time of the sample compared to the time of the incident. So when setting up the bioassay data, it was assumed that the sample date given was noon of the day when the sample was asked for, and that for the urine samples the collection period was 0.25 day unless otherwise specified. Thus there would be an 18 h gap between the time of the incident and provision of the urine sample, with a collection period of 6 hours.

There didn't seem to be any incidents linked to the faecal data so they were assumed to be part of routine monitoring.

Exposure patterns for Worker 1 are gathered in Table 29.

Chemical form

There was evidence of exposure to UF_6 and uranyl nitrate at facility UDG1. Where there was evidence of an acute exposure to one of these materials then I used the material specific absorption parameter values recommended in the draft OIR (Blanchardon *et al.* 2014). When setting up the chronic intakes or acute intakes where the material was not specified, then it was assumed the values were a composite/average of UF_6 and uranyl nitrate (Table 30). Table 29 presents how the exposure materials were assigned to intake regimes.

Table 30: Specific absorption parameters used for Worker 1 by Participant ID 6

Material	f_r	s_r (d^{-1})	s_s (d^{-1})	f_1
UF_6	1	10		0.02
Uranyl nitrate	0.9	3	0.005	0.02
UF_6/U nitrate mix	0.95	7	0.005	0.02

Treatment of data below DL

Data reported as DL was assigned the data type "<LOD" in the IMBA program (Birchall *et al.* 2007) with the result set to the reported less than value.

Intake and dose estimates

The results of dose assessments for Worker 1 are reported in Table 31.

Table 31: Dose estimates for Worker 1 for participant ID 6

Intake number	*Intake (Bq)*	*Committed effective dose (mSv)*	*Lung committed equivalent dose (mSv)*	*Kidney committed equivalent dose (mSv)*
1	15232.4	5.55	17.8	23.0
2	7920.9	2.89	9.28	12.0
3	22.2	0.0081	0.026	0.0335
4	14.5	0.0053	0.017	0.0219
5	7.6	0.0174	0.0105	0.109
6	44.1	0.0126	0.0115	0.0756
7	116.5	0.0333	0.0304	0.200
8	1.6	0.00354	0.00214	0.0223
9	122.9	0.0448	0.144	0.186
10	776.9	0.345	1.68	0.961
Total		8.91	29.0	36.6

4.6.2.2 Worker 2

Radionuclide and isotopic composition

All the measurements are for U mass, which may suggest the exposure to natural or depleted uranium rather than enriched materials. However, similar to Worker 1 above, for practical reasons ^{234}U was used instead of natural uranium in IMBA (Birchall *et al.* 2007).

Exposure pattern

Although Worker 2 worked in 3 different facilities, there was only 1 facility that Worker 2 was present at that also had a bioassay result above the detection level. With no reported incidents, a chronic intake was assumed over this period of work (Table 32).

Table 32: Intakes modelled in the final IMBA run for Worker 2 for participant ID 6

Intake number	*Intake pattern*	*Intake start date*	*Intake end date*	*Radionuclide*	*Pathway*	*AMAD (µm)*	*Absorption Type*
1	Chronic	01/01/64	31/12/66	^{234}U	Inhalation	5	Mixed OIR Type F/M/S

No intake would be calculated for the other exposure periods as there were no results above the detection level. However, the bioassay data for these periods were used in the assessment.

Chemical form

As there was no information on the exposure material at the facility the exposure occurred at, the solubility parameters were set to the average of a Type F/M/S based on the default OIR parameter values (Blanchardon *et al.* 2014, Table 33).

Table 33: Specific absorption parameters used for Worker 2 by Participant ID 6

Material	f_r	s_r (d^{-1})	s_s (d^{-1})	f_1
Mixed Type F/Type M/Type S	0.4	12	0.002	0.004

Treatment of data below DL

Data reported as DL was assigned the data type "<LOD" in the IMBA program (Birchall *et al.* 2007) with the result set to the reported less than value.

Intake and dose estimates

The results of dose assessments for Worker 2 are reported in Table 34.

Table 34: Dose estimates for Worker 2 for participant ID 6

Intake number	*Intake (Bq)*	*Committed effective dose (mSv)*	*Lung committed equivalent dose (mSv)*	*Kidney committed equivalent dose (mSv)*
1	1121.2	2.50	15.3	1.10

4.6.2.3 Worker 3

Radionuclide and isotopic composition

As with Worker 1, although the exposure material was reported as natural uranium, for convenience the exposure nuclide was set as ^{234}U in IMBA (Birchall *et al.* 2007).

Exposure pattern

The individual worked at the same plant with little change to type and frequency of exposure over this period, so a single chronic intake was assumed. As the bioassay data started before the reported start date in the JEM, the start date of the chronic intake was set to 1 monitoring period (this appeared to be 3 months) before the first bioassay result (Table 35).

Table 35: Intakes modelled in the final IMBA run for Worker 3 for participant ID 6

Intake number	*Intake pattern*	*Intake start date*	*Intake end date*	*Radionuclide*	*Pathway*	*AMAD (µm)*	*Absorption Type*
1	Chronic	19/03/68	31/12/81	^{234}U	Inhalation	5	UF_6 / U nitrate mix

Chemical form

The JEM suggested exposure to type F material. However, as this person was working in UDG1 at around the same time as Worker 3 for whom more information was available, it was assumed that Worker 1 was exposed to the same UF_6 and uranyl nitrate mix as Worker 1 (Table 35).

Treatment of data below DL

Data reported as DL was assigned the data type '<LOD' in the IMBA program (Birchall *et al.* 2007) with the result set to the reported less than value. This would mean that a zero dose would be calculated in IMBA (Birchall *et al.* 2007). In order to provide an upper estimate on the dose, the 2 final measurement results, which were on the same day with one being a U mass measurement the other a U activity measurement, were set at the reporting level.

Intake and dose estimates

The results of dose assessments for Worker 3 are reported in Table 36.

Table 36: Dose estimates for Worker 3 for participant ID 6

Participant ID		*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
6.1	Lower estimate	0	0	0
6.2	Upper estimate	1.8	5.6	7.3

4.6.3 Comments

The methodology used in these assessments regarding treatment of the bioassay data and setting up the intake regimes was similar to that used in the alpha-risk study (Bingham *et al.* 2016). Worker 1 highlights the case where when the methodology has been followed a poor fit is achieved in the end (at least according to the Chi^2 test, the autocorrelation test in IMBA (Birchall *et al.* 2007) said the fit was acceptable). It is not clear how cases with poor fits should be treated, if at all, or how this can be reflected in the final assessment.

With the small number of cases involved here it was possible to do various assessments looking at different assumptions e.g. regarding solubility and intake regimes. This did give some confidence in the final assessment, or at least some of the assumption underlying it. For example, the doses seemed pretty robust to assumptions on intake regimes, particularly when there were chronic intakes present. But as might be expected, the assumptions regarding lung solubility did seem to make quite a difference to the dose.

4.7 Participant ID 7: J. Anderson (CDC/NIOSH)

4.7.1 General assumptions

4.7.1.1 Processing of Data

Urine uranium gravimetric data reported in $\mu g.l^{-1}$ were converted to natural uranium activity concentration by multiplying by 0.025 $Bq.\mu g^{-1}$ and then converted to 24-hour excretion ($Bq.d^{-1}$) by multiplying by 1.6 $l.d^{-1}$ (ICRP 2002). Urine radioactivity concentrations (pCi and $pCi.l^{-1}$) were converted to Bq by multiplying by 0.037 $Bq.pCi^{-1}$ and then samples reported in $pCi.l^{-1}$ were converted to 24-hour excretion. Samples with activity reported as pCi were assumed to be 24-hour samples. Faecal samples were not processed.

4.7.1.2 Dietary contribution to uranium excretion

Urine concentration was not corrected for background uranium from dietary contribution as it generally is on the order of a few ng, which is negligible compared occupational exposure.

4.7.1.3 Models

The biokinetic models used were the ICRP Publication 66 Human Respiratory Tract Model (ICRP 1994a), the ICRP Publication 30 Gastrointestinal Tract Model (ICRP 1979), and the ICRP uranium systemic model found in Publication 69 (ICRP 1995). The dosimetric model used was that described in ICRP Publication 60 (ICRP 1991).

4.7.1.4 Intake assessment procedure

Intakes and doses were assessed using methods similar to that used in a pooled study of U.S. gaseous plant workers (Anderson *et al.* 2016). If both gravimetric and radiometric results were available for a urine sample, the radiometric results were used. One chronic intake was assumed for each worker, with the intake starting on the first date of employment and ending on the last date of employment. Intakes were calculated using least-squares regression assuming uniform logarithmic error with a geometric standard deviation equal to 1.6. The intake was assumed to be due to a single chronic inhalation exposure to a soluble (ICRP Publication 66 Absorption Type F; ICRP 1994a) uranium aerosol with a 5-µm activity median diameter particle size.

Urine bioassay data for all three workers were pooled based on time period and detection/administrative reporting limit (DL), i.e., gravimetric measurements 1964-1970 (DL <5 $\mu g.l^{-1}$), activity measurements 1967-1973 (DL <5 $pCi.l^{-1}$), and activity measurements 1974-1980 (DL <10 $pCi.l^{-1}$). Urine data were then imputed for samples reported as less than the DL using the formula

$$imputed\ value = DL.(1 - f)$$

where f = fraction of samples in the pooled set that were less than the DL (Anderson and Apostoaei 2017).

The Internal Dose Evaluation Program (InDEP; Oak Ridge Center for Risk Analysis, Inc. Oak Ridge, TN, v. 4.2, 2016, Anderson *et al.* 2013) was used to estimate intakes and organ doses.

4.7.2 Assessments

4.7.2.1 Worker 1

Radionuclide and isotopic composition

Because the JEM specifies natural uranium, 50-year committed equivalent doses were calculated assuming the intake activity was 49.14% ^{234}U, 2.23% ^{235}U, and 48.61% ^{238}U.

Exposure pattern

A single chronic intake was assumed to begin on the first date of employment (17/09/1962) and end on the last date of employment (30/09/1980).

Chemical form

The JEM suggests that the likeliest exposure was to a uranium compound with the behaviour of Type F absorption.

Treatment of data below DL

For gravimetric data dated 1964-1970, left-censored data were replaced with 0.46875 $\mu g.l^{-1}$. Left-censored radiometric data for 1967-1973 and 1974-1980 were replaced with 2.7 $pCi.l^{-1}$ and 3.4 $pCi.l^{-1}$, respectively.

Intake and dose estimates

The results of dose assessments for Worker 1 are reported in Table 37.

Table 37: Intakes and committed organ doses for Worker 1 for participant ID 7

Participant ID	*Statistics*	*Intake ($Bq.d^{1}$)*	*Lung (mSv)*	*Kidneys (mSv)*
7.1	Median	1.2	2.6	31
7.2	Mean	2.5	50	589
7.3	5^{th} Percentile	0.18	0.051	0.60
7.4	95^{th} Percentile	8.6	89	1058

4.7.2.2 Worker 2

Radionuclide and isotopic composition

Because the JEM specifies natural uranium, 50-year committed equivalent doses were calculated assuming the intake activity was 49.14% ^{234}U, 2.23% ^{235}U, and 48.61% ^{238}U.

Exposure pattern

A single chronic intake was assumed to begin on the first date of employment (01/06/1963) and end on the last date of employment (30/09/1982).

Chemical form

The JEM suggests that the likeliest exposure was to a uranium compound with the behaviour of Type F absorption.

Treatment of data below DL

With the exception of one urine sample, all urine data were reported to be below the detection/administrative reporting limit. These data points were replaced by an imputed value of 0.47 $\mu g.l^{-1}$.

Intake and dose estimates

The results of dose assessments for Worker 2 are reported in Table 38.

Table 38: Intakes and committed organ doses for Worker 2 for participant ID 7

Participant ID	*Statistics*	*Intake ($Bq.d^{-1}$)*	*Lung (mSv)*	*Kidneys (mSv)*
7.1	Median	0.078	0.17	2.1
7.2	Mean	0.15	2.9	35
7.3	5^{th} Percentile	0.011	0.0039	0.046
7.4	95^{th} Percentile	0.48	5.5	66

4.7.2.3 Worker 3

Radionuclide and isotopic composition

Because the JEM specifies natural uranium, 50-year committed equivalent doses were calculated assuming the intake activity was 49.14% ^{234}U, 2.23% ^{235}U, and 48.61% ^{238}U.

Exposure pattern

A single chronic intake was assumed to begin on the first date of employment (26/07/1965) and end on the last date of employment (31/01/1982).

Chemical form

The JEM suggests that the likeliest exposure was to a uranium compound with the behaviour of Type F absorption.

Treatment of data below DL

All urine data for this worker were below the detection/administrative reporting limit, so data points were replaced by imputed data: 0.47 $\mu g.\ l^{-1}$ for samples where only gravimetric measurements were attempted and 2.7 and 3.4 $pCi.l^{-1}$ for samples where radiometric analysis was performed in 1969-1973 and 1974-1981, respectively.

Intake and dose estimates

The results of dose assessments for Worker 3 are reported in

Table 39.

Table 39: Intakes and committed organ doses for Worker 3 for participant ID 0

Participant ID	*Statistics*	*Intake ($Bq.d^{-1}$)*	*Lung (mSv)*	*Kidneys (mSv)*
7.1	Median	0.58	1.1	13
7.2	Mean	1.1	21	241
7.3	5^{th} Percentile	0.080	0.022	0.26
7.4	95^{th} Percentile	3.7	37	427

4.8 Participant ID 8: K. Tani (QST-NIRS)

4.8.1 General assumptions

4.8.1.1 Processing of Data

All measured data were normalized to equivalent 24 hour values in $Bq.d^{-1}$.

Values of urinary activity measurements in $pCi.l^{-1}$ or pCi were multiplied by 0.037 to convert to $Bq.l^{-1}$ or Bq, respectively, and those of mass measurements in $\mu g.l^{-1}$ were multiplied by 0.025270 (specific activity of natural uranium, i.e. 48.86% for ^{234}U; 2.28% for ^{235}U and; and 48.86% for ^{238}U in activity) to convert to $Bq.l^{-1}$ except for the data on 18/03/1967. Because the data on that day seems to be attributed to an intake of ^{238}U occurred on the previous day, i.e. 17/03/1967, according to the given incident register, this measured value was multiplied by 0.012437 (specific activity of ^{238}U). The values converted to $Bq.l^{-1}$ were then multiplied by 1.6, a value of daily urine excretion for male in reference to ICRP Publication 89 (ICRP 2002) and EURADOS IDEAS Guidelines (Castellani *et al.* 2013), to convert to $Bq.d^{-1}$. The other values converted to Bq could be directly regarded as $Bq.d^{-1}$ because these sample type was indicated as 'Urine 24h'.

Values of faecal activity measurements in pCi were multiplied by 0.037 to convert to Bq, and those of mass measurements in $\mu g.(g\ ash)^{-1}$ were multiplied by 0.025270 (specific activity of natural uranium) to convert to $Bq.(g\ ash)^{-1}$. Some of the values converted to Bq were then divided by 2, a value of sampling days, because the sample type of these data was indicated as 'Faeces 48h'. The other values were directly regarded as $Bq.d^{-1}$ although no information on the sampling period is available. The values converted to $Bq.(g\ ash)^{-1}$ were multiplied by 4, which was assumed in EURADOS IDEAS Guidelines (Castellani *et al.* 2013) as daily faecal ash, to convert to $Bq.d^{-1}$.

Higher values were selected to use for evaluation on the safe side if both data of activity and mass measurements were available on the same day. According to the methodology introduced in EURADOS IDEAS Guidelines (Castellani *et al.* 2013), each positive data was checked, one by one, whether a value was higher than 'the critical monitoring quantity' corresponding to committed effective dose of 0.1 $mSv.y^{-1}$ under the assumption that an acute intake took place on the middle date of a previous monitoring interval. It was confirmed that all given positive data were deemed worthy of adopting for an explicit assessment.

4.8.1.2 Dietary contribution to uranium excretion

Daily excretion activity of uranium attributed to the dietary background generally has wide range among individuals and regions: 0.00125-0.0125 $Bq.d^{-1}$ in urine and 0.035-0.045 $Bq.d^{-1}$ in faeces, as reported in ICRP Publication 23 (ICRP 1975). The lowest values of the ranges, i.e. 0.00125 $Bq.d^{-1}$ in urine and 0.035 $Bq.d^{-1}$ in faeces, were assumed for the dietary background on the safe side because no information was available on blank bioassay samples obtained either from the workers before/at the beginning of their employment, from non-occupationally exposed workers in the same workplaces or from the population living in the area near their workplaces. These background values, however, were much lower than the DL, leading to no substantive effects on the results.

4.8.1.3 Models

IMBA Professional Plus version 4.0.42, a software developed by PHE, UK (Birchall *et al.* 2007), was used both to analyse retention function with biokinetic models, described in ICRP Publication 30

(ICRP 1979), ICRP Publication 66 (ICRP 1994a) and NCRP report No. 156 (NCRP 2006), and with a systemic model of uranium, described in ICRP Publication 69 (ICRP 1995), and to evaluate dose with a dosimetric model, described in ICRP Publication 60 (ICRP 1991) and Publication 68 (ICRP 1994b).

4.8.1.4 Intake assessment procedure

Although no information was available on uncertainty of measurements, typical values of the scattering factor (SF) recommended in EURADOS IDEAS Guidelines (Castellani *et al.* 2013), i.e. 1.6 for urinary data normalized to equivalent 24 hour values; 1.1 for urinary data with sample type of 'Urine 24h'; 3 for faecal data with unknown sampling period; and 2.5 for faecal data with sampling period of 48 hours, were assumed.

4.8.2 Assessments

4.8.2.1 Worker 1

Radionuclide and isotopic composition

According to the job exposure matrix (JEM), potential exposures to Worker 1 seem to be from natural uranium except the exposures due to the incidents on 17/3/1967 and 10/11/1967; ^{238}U and ^{235}U were assumed for these cases, respectively, because specific information on radionuclides were available from the given incident register.

Exposure pattern

Unless specific information on an intake due to an incident was available from the incident register, it was considered, as a default assumption, that acute intakes were occurred on the middle date of a previous monitoring interval. Although low-level chronic intake has been suspected for Worker 1, this exposure was not taken into account for the dose assessment because of following reasons: *(1)* It was difficult to obtain the goodness of fit between the measured data and the model prediction because the positive data were found rather incidentally than constantly; and *(2)* It seemed that low-level chronic intake had no substantive effects on the final result because obvious acute intakes due to accidents might have higher proportions of total dose of Worker 1.

Chemical form

Because, according to the JEM, frequency of exposure was level 3 for Type F and level 0 for Type M and S between 01/07/1966 and 31/12/1976, multiple inhalations of 5 µm AMAD aerosols with Type F were generally assumed unless information on intake pathway was available from the incident register. On the other hand, because frequency of exposure was level 1 for both Type F and M and still level 0 for Type S between 01/01/1977 and 30/09/1980, multiple inhalations of 5 µm AMAD aerosols with Type F or M, which was assigned depending on the goodness of fit between the given data and the model prediction, were assumed.

Treatment of data below DL

Data below DL were used for input data of IMBA (Birchall *et al.* 2007) as '<LOD'.

Intake and dose estimates

44 cases of acute intakes were assumed and analysed by IMBA (Birchall *et al.* 2007), and more than 0.05 of the P value, the probability of obtaining a value of chi square greater than or equal to the value calculated by random chance on the difference between the given data and the model prediction, was achieved for each fitting. As the result, committed effective doses were evaluated more than 1 mSv in 13 out of 44 cases, the bioassay data of which are shown in Table 40.

Table 40: Data on which committed dose was evaluated to be more than 1 mSv

Intake #	*Assumed pathway*	*Date*	*Type of sample*	*Bq.d^{-1}*	*Uncertainty (SF)*
1	Inhalation	17/09/1967	Urine	0.59075	1.6
		31/07/1967	Faeces	60.793	3.0
2	Inhalation	02/12/1969	Urine	1.06435	1.6
		16/12/1969	Urine	1.41955	1.6
		16/02/1970	Urine	0.29475	1.6
3	Wound	23/09/1971	Urine 24 h	0.61295	1.1
		18/10/1971	Urine	1.06435	1.6
		15/11/1971	Urine	0.70915	1.6
		20/12/1971	Urine	0.76835	1.6
		17/01/1972	Urine	< 0.29475*	1.6
		14/02/1972	Urine	< 0.29475*	1.6
		13/03/1972	Urine	0.70915	1.6
		17/04/1972	Urine	0.41315	1.6
4	Inhalation	15/05/1972	Urine	2.95875	1.6
		23/05/1972	Urine 24 h	1.99675	1.1
		19/06/1972	Urine	< 0.29475*	1.6
		03/07/1972	Urine	0.35395	1.6
		31/07/1972	Urine	< 0.29475*	1.6
5	Inhalation	21/01/1974	Urine	1.12355	1.6
		18/02/1974	Urine	0.79795	1.6
6	Inhalation	17/02/1975	Urine	4.43875	1.6
		17/03/1975	Urine	< 0.59075*	1.6
		14/04/1975	Urine	0.88675	1.6
		19/05/1975	Urine	0.82755	1.6
		16/06/1975	Urine	< 0.59075*	1.6
7	Inhalation	14/03/1977	Urine	2.48515	1.6
		18/04/1977	Urine	2.18915	1.6
		16/05/1977	Urine	< 0.59075*	1.6
8	Inhalation	13/03/1978	Urine	1.00515	1.6
		17/04/1978	Urine	< 0.59075*	1.6
9	Inhalation	16/10/1978	Urine	0.70915	1.6
		13/11/1978	Urine	< 0.59075*	1.6

Intake #	Assumed pathway	Date	Type of sample	Bq.d^{-1}	Uncertainty (SF)
10	Inhalation	19/03/1979	Urine	1.06435	1.6
		14/05/1979	Urine	0.76835	1.6
		20/05/1979	Urine	0.59075	1.6
11	Inhalation	17/09/1979	Urine	1.77475	1.6
		15/10/1979	Urine	0.70915	1.6
		12/11/1979	Urine	0.82755	1.6
12	Inhalation	19/12/1979	Urine	3.25475	1.6
		28/01/1980	Urine	< 0.59075*	1.6
13	Inhalation	21/04/1980	Urine	1.06435	1.6
		19/05/1980	Urine	< 0.59075*	1.6

* These data were below DL and used for input data of IMBA as '<LOD'

Results of intakes and doses evaluated for the 13 cases are shown in Table 41. Intake date were adjusted if the goodness of fit had not been acceptable under the first assumption of the default date, and furthermore, wound model category, e.g. Colloid, Particles or Fragment, for intake #3 and absorption types, i.e. Type F or M, for intake #7 or later were assigned depending on the goodness of fit, resulting in relative higher P values: more than 0.9 for 6 cases; and more than 0.5 for 6 cases.

Table 41: Intakes and doses evaluated by IMBA for Worker 1

Intake #	Intake date	Chemical form	P value	Intake (kBq)	Effective dose (mSv)	Lung dose (mSv)	Kidney dose (mSv)
1	30/07/1967	Type F	0.980	1.88	1.2	0.71	7.3
2	13/10/1969	Type F	0.787	4.65	2.9	1.8	18
3	23/09/1971	Fragment	0.543	25.9	2.2	1.1	18
4	01/05/1972	Type F	0.844	1.74	1.1	0.66	6.7
5	20/12/1973	Type F	0.921	2.37	1.5	0.90	9.1
6	01/02/1975	Type F	0.780	3.60	2.2	1.4	14
7	01/03/1977	Type M	0.147	5.75	11	83	5.4
8	27/02/1978	Type M	0.956	1.96	3.7	28	1.9
9	02/10/1978	Type M	0.986	1.47	2.8	21	1.4
10	05/03/1979	Type M	0.658 *	3.13	5.9	45	2.9
11	19/07/1979	Type M	0.658 *	6.66	13	97	6.3
12	30/11/1979	Type F	0.914	1.85	1.1	0.70	7.1
13	07/04/1980	Type M	0.926	1.97	3.7	29	1.9
Total	-	-	-	-	51	311	100

* Intake #10 and #11 were analysed at the same time

As particular examples, comparisons between the measured data and the model prediction on intake #1, #3 and #10-11 are shown in Figure 20, Figure 21 and Figure 22, respectively. A first

example is a case that both urinary and faecal data were available. As shown in Figure 20, the goodness of fit was acceptable for both data simultaneously although it should be noted that the number of data was quite limited. A second example is a case that the intake pathway was wound. Attempts were made for all the different wound categories, and the goodness of fit was acceptable only when the category 'Fragment' was assumed. As shown in Figure 21, the 8 data selected for intake #3 can be explained by this assumption with the adequate P value; nevertheless, it is still unknown that these data are actually associated with such assumed single intake. The last example is a case that two intakes were simultaneously evaluated as shown in Figure 22. If these intakes were evaluated separately, an overestimation may occur in assessment of intake #11 due to the retention of intake #10 because: *(1)* the absorption type of the intake #10 was assumed as Type M, resulting in the relative longer retention than Type F; and *(2)* no data soon after the intake #11 was available, which may allow to evaluate a more accurate intake independently because of the relative larger difference between the retention and such a measured value.

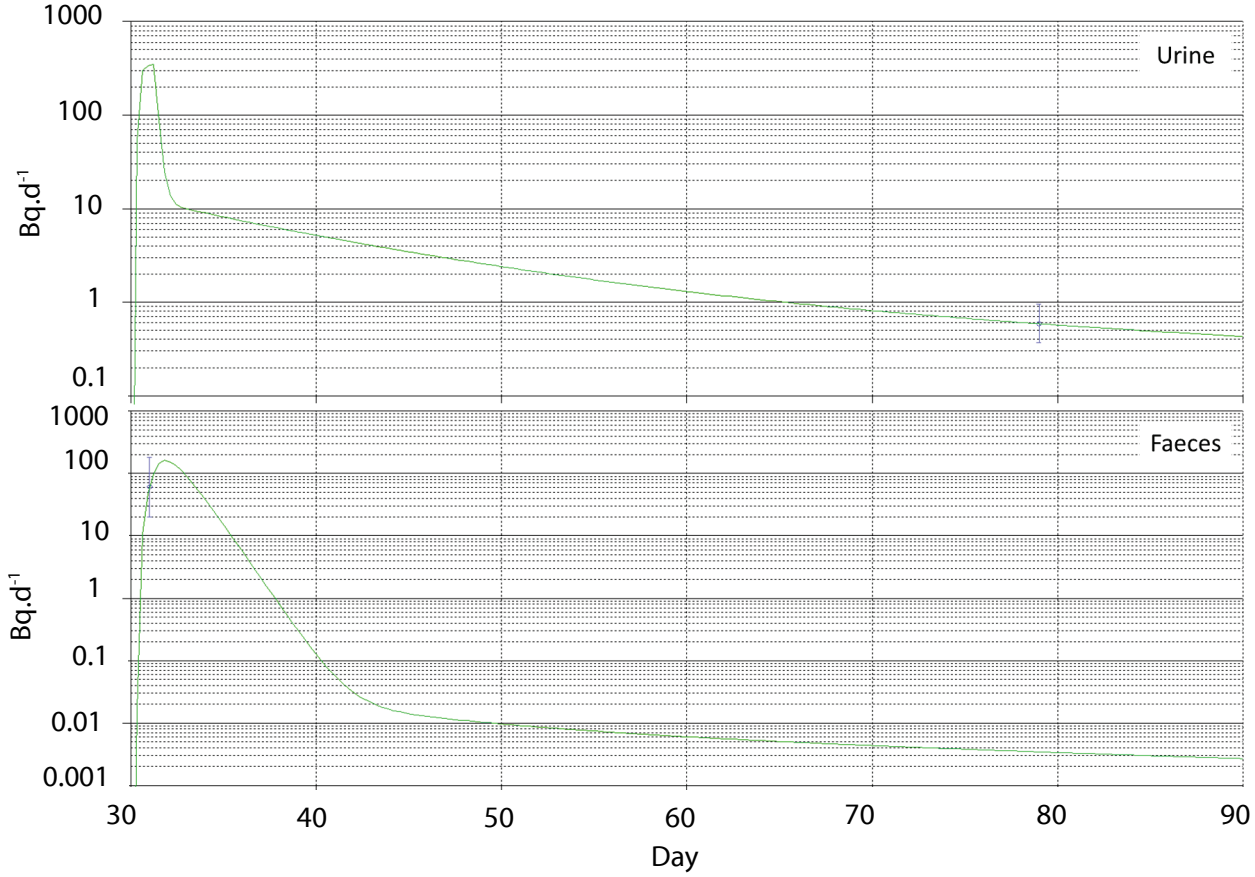

Figure 20: Comparison between the given data and the model prediction on intake #1 (Day 0 = 30/06/1967)

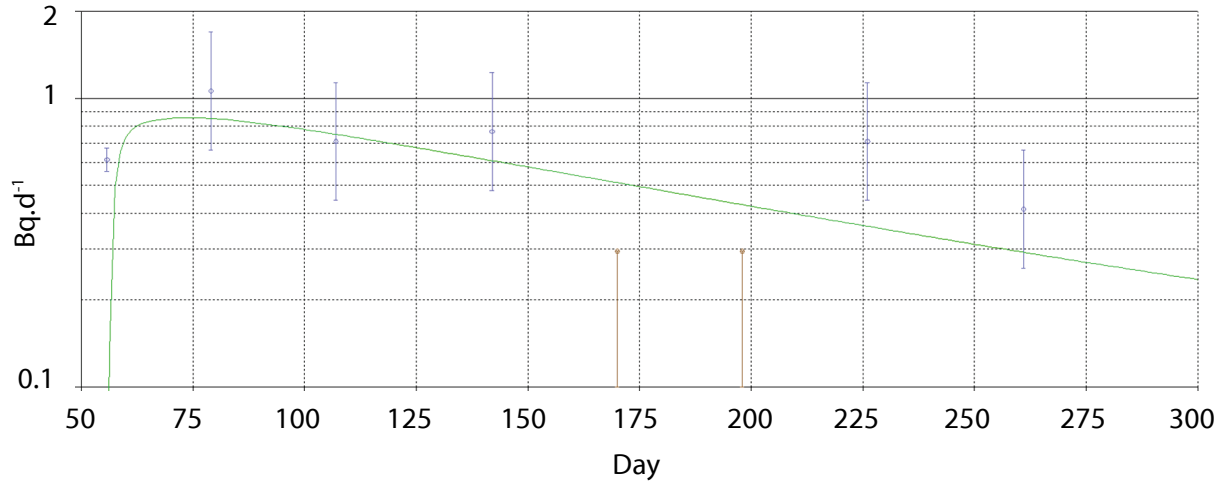

Figure 21: Comparison between the given data and the model prediction on intake #3 (Day 0 = 31/07/1971)

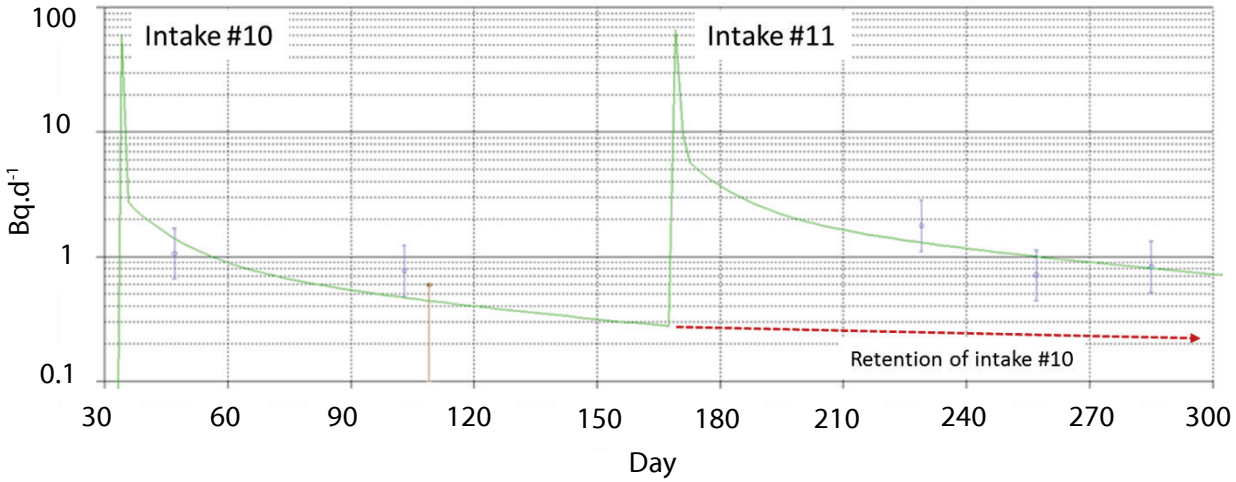

Figure 22: Comparison between the given data and the model prediction on intake #10-11 (day 0 = 31/01/1979)

4.8.2.2 Worker 2

Radionuclide and isotopic composition

According to the JEM, potential exposures to Worker 2 seem to be from natural uranium.

Exposure pattern and chemical form

A positive data was found only on 02/08/1965. However, frequency of exposure was level 0, meaning no potential exposure, at that time. According to the record of JEM before that day, showing that frequency of exposure was level 3 for Type F and level 1 for Type M and S between 01/06/1963 and 31/12/1963, the possibility of either chronic inhalation of 5 µm AMAD aerosols with Type F during the above period or acute inhalation of those with Type M/S on the middle date of the above period, i.e. 15/09/1963, was considered.

Treatment of data below DL

Data below DL were used for input data of IMBA (Birchall *et al.* 2007) as '<LOD'.

Intake and dose estimates

Data used for dose assessment for Worker 2 are shown in

Table 42. The goodness of fit was not acceptable when neither chronic intake of Type F nor acute intake of Type M was assumed but acceptable only when acute intake of Type S with P value of 0.299, as shown in Figure 23. However, the positive data is actually below DL of other data and it is quite questionable how reliable it is. Nevertheless, no strong reason to exclude the data from assessment could be found. The intake and doses evaluated for Worker 2 are shown in Table 43.

Table 42: Data used for the dose assessment for Worker 2

Date	*Type of sample*	*Bq.d^{1}*	*Uncertainty (SF)*
06/11/1963	Urine	< 0.20091*	1.6
02/04/1964	Urine	< 0.20091*	1.6
23/10/1964	Urine	< 0.20091*	1.6
08/01/1965	Urine	< 0.20091*	1.6
01/04/1965	Urine	< 0.20091*	1.6
02/08/1965	Urine	0.160478	1.6
02/11/1965	Urine	< 0.20091*	1.6

* These data were below DL and used for input data of IMBA as '<LOD'

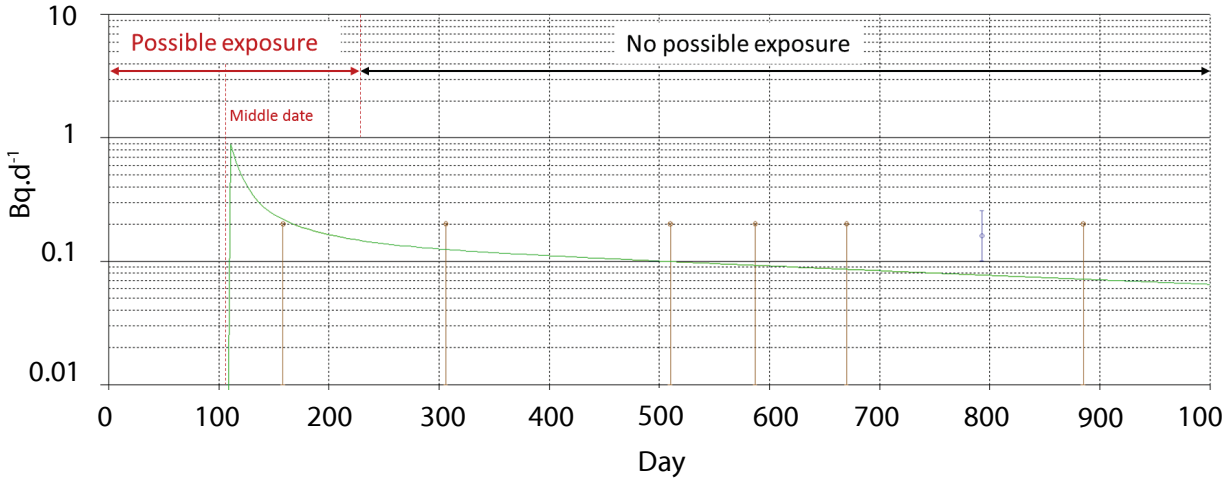

Figure 23: Comparison between the given data and the model prediction for Worker 2 (day 0 = 01/06/1963)

Table 43: Dose estimates for Worker 2 for participant ID 8

Intake (Bq)	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
39.1×10^3	250	1500	3.8

4.8.2.3 Worker 3

Radionuclide and isotopic composition

According to the JEM, potential exposures to Worker 3 seem to be from natural uranium.

Exposure pattern and chemical form

Because all given data were below DL and frequency of exposure was level 3 for Type F and level 0 for Type M and S between 26/07/1965 and 31/12/1981, chronic inhalation of 5 µm AMAD aerosols with Type F during the above period was assumed.

Treatment of data below DL

Because all given data were below DL, these values were dealt with as positive values equal to the DL/2 as recommended in EURADOS IDEAS Guidelines (Castellani *et al.* 2013), although this assumption has no strong foundation in mathematics.

Intake and dose estimates

Data used for dose assessment for Worker 3 are shown in Table 44. The goodness of fit was acceptable with the P value of 0.999, as shown in Figure 24. The intake and doses evaluated for Worker 3 are shown in Table 45.

Table 44: Data used for the dose assessment for Worker 3

Date	*Sample*	*Bq.d⁻¹ (DL/2)*	*Uncertainty (SF)*	*Date*	*Sample*	*Bq.d⁻¹ (DL/2)*	*Uncertainty (SF)*
19/06/1968	Urine	0.100455	1.6	26/10/1977	Urine	0.140887	1.6
22/09/1968	Urine	0.100455	1.6	15/12/1977	Urine	0.140887	1.6
16/12/1968	Urine	0.100455	1.6	20/02/1978	Urine	0.140887	1.6
11/03/1969	Urine	0.100455	1.6	24/04/1978	Urine	0.140887	1.6
02/06/1969	Urine	0.100455	1.6	19/06/1978	Urine	0.140887	1.6
22/09/1969	Urine	0.100455	1.6	21/08/1978	Urine	0.140887	1.6
16/12/1969	Urine	0.100455	1.6	23/10/1978	Urine	0.140887	1.6
09/03/1970	Urine	0.100455	1.6	18/12/1978	Urine	0.140887	1.6
01/06/1970	Urine	0.147375	1.6	26/02/1979	Urine	0.140887	1.6
26/10/1970	Urine	0.147375	1.6	23/04/1979	Urine	0.140887	1.6
21/06/1971	Urine	0.147375	1.6	18/06/1979	Urine	0.140887	1.6
26/06/1972	Urine	0.147375	1.6	27/08/1979	Urine	0.140887	1.6
23/10/1972	Urine	0.147375	1.6	22/10/1979	Urine	0.140887	1.6
26/12/1972	Urine	0.147375	1.6	09/03/1980	Urine	0.140887	1.6
25/06/1973	Urine	0.295375	1.6	28/04/1980	Urine	0.140887	1.6
22/10/1973	Urine	0.147375	1.6	23/06/1980	Urine	0.140887	1.6
22/04/1974	Urine	0.295375	1.6	20/10/1980	Urine	0.140887	1.6
21/06/1974	Urine	0.295375	1.6	15/12/1980	Urine	0.140887	1.6
14/10/1974	Urine	0.295375	1.6	27/02/1981	Urine	0.140887	1.6
23/12/1974	Urine	0.295375	1.6	24/04/1981	Urine	0.140887	1.6
23/06/1975	Urine	0.295375	1.6	28/08/1981	Urine	0.140887	1.6
22/12/1975	Urine	0.295375	1.6	23/10/1981	Urine	0.140887	1.6
25/10/1976	Urine	0.295375	1.6	11/12/1981	Urine	0.140887	1.6
25/04/1977	Urine	0.140887	1.6	-	-	-	-

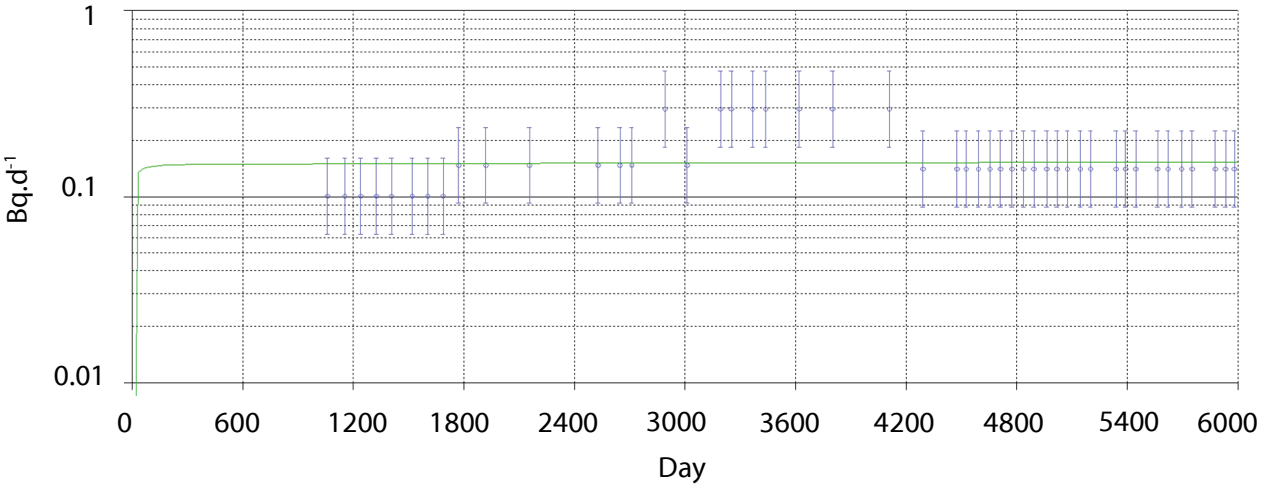

Figure 24: Comparison between the given data and the model prediction for Worker 3 (day 0 = 26/07/1965)

Table 45: Dose estimates for Worker 3 for participant ID 8

Intake (Bq.d^{-1})	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
0.549	2.0	1.3	13

4.8.3 Comments

These assessments were conducted on the basis of EURADOS IDEAS Guidelines (Castellani *et al.* 2013) as range as possible, and focused whether the goodness of fit between the given data and the model prediction was acceptable with adequate P values, i.e. more than 0.05. Nevertheless, the results still might have quite large uncertainty because, unfortunately, the assumptions leading to the best fitting is not always the same as real situations. In these assessments, it should be noted that *(1)* a limited number of data was available for fittings in the many cases, *(2)* it is still unknown if the assumed intakes and the data selected for each intake were correct because of lack of information and *(3)* amounts of evaluated intakes and doses were largely depending on each assumption of exposure pattern and chemical form, especially lung doses which could be greatly affected by absorption type.

4.9 Participant ID 10: J. Ośko (NCBJ)

4.9.1 General assumptions

4.9.1.1 Processing of Data

Activity measurements in pCi.l^{-1} were converted to Bq. l^{-1} and multiple by 1.6 to convert to Bq.d^{-1} (ICRP 2002). Mass measurements in µg.l^{-1} were multiplied by 0 0.0198 (12400/1000000.1.6) to convert to Bq.d^{-1}. The assessment of Worker 1 doses have not been done so there was no need to process the numerical values of faecal measurement.

Where both mass and activity measurements were reported for the same day, the activity measurements were used.

4.9.1.2 Dietary contribution to uranium excretion

The dietary background of uranium was not taken into account. There were no any information about dietary habits and place of workers living in case scenarios.

4.9.1.3 Models

The Human Respiratory Tract Model described at ICRP Publication 66 (ICRP 1994a), applied in used software (IDEA-System ver. MV-03.6.4, Doerfel 2007) and AMAD of 5 µm was used for both analysed cases (Worker 2 and Worker 3).

4.9.1.4 Intake assessment procedure

The software package IDEA-System ver. MV-03.6.4 (Doerfel 2007) was used for all dose assessments.

4.9.2 Assessments

4.9.2.1 Worker 1

Not analysed.

4.9.2.2 Worker 2

Radionuclide and isotopic composition

All calculations were done for ^{238}U.

Exposure pattern

The acute intakes in the middle of all measurement intervals were considered.

Chemical form

All data have been assigned to absorption type F.

Treatment of data below DL

All results below DL were used to assess doses assuming measured activity at the half value of detection limit.

Intake and dose estimates

Route of intake: inhalation.

Acute intakes in the middle of all measurement interval (in case of the result below DL, 50% of DL was taken to calculation).

All calculations were done using IDEA Software (Doerfel 2007). The intake and dose estimates for Worker 2 are presented in Table 46.

Table 46: Dose estimates for Worker 2 for participant ID 10

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
3.29	1.99	20.4

4.9.2.3 Worker 3

Radionuclide and isotopic composition

All calculations were done for ^{238}U.

Exposure pattern

All results below DL were used to assess doses assuming measured activity at the half value of detection limit.

Chemical form

All data have been assigned to absorption type F.

Treatment of data below DL

All results below DL were used to assess doses assuming measured activity at the half value of detection limit.

Intake and dose estimates

Route of intake: inhalation.

Acute intakes in the middle of all measurement interval (in case of the result below DL, 50% of DL was taken to calculation).

All calculations were done using IDEA Software (Doerfel 2007). The intake and dose estimates for Worker 3 are presented in Table 47.

Table 47: Dose estimates for Worker 3 for participant ID 10

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
13.7	8.28	85.0

4.9.3 Comments

It would be useful to know the dietary background of uranium case scenarios. NCBJ does not perform routine uranium measurements, so because of no experience in this field it was the biggest difficulty during this exercise.

4.10 Participant IDs 12, 13 and 14: R. Bull (NUVIA)

4.10.1 General assumptions

4.10.1.1 Processing of Data

Activity measurements in $pCi.l^{-1}$ were multiplied by 0.037 to convert to $Bq.l^{-1}$ and mass measurements in $\mu g.l^{-1}$ were multiplied by 0.0253 (specific activity of natural uranium) to convert to $Bq.l^{-1}$. Both were then multiplied by 1.6 to convert to $Bq.d^{-1}$. This conversion is taken from ICRP Publication 89 (ICRP 2002) which gives a daily urine excretion of 1.6 l for reference man. This differs from the ICRP Publication 23 (ICRP 1975) value of 1.4 l per day which is currently used in Harwell ADS assessments.

Faecal activity measurements in pCi were multiplied by 0.037 to convert to Bq. Faecal results were taken to represent daily output, except for samples flagged as 48 hrs. In these latter cases the activity was divided by 2 to give the excretion per day.

Where both mass and activity measurements were reported for the same day, the activity measurements were used. This is because activity measurements are relatively unambiguous, as the excretion curves and dose factors for different uranium isotopes do not differ much. Mass measurements require some assumption about specific activity in order to convert them to activity and this conversion factor is highly nuclide dependent.

4.10.1.2 Dietary contribution to uranium excretion

Experience has shown that the typical background excretion of uranium varies noticeably across the UKAEA sites (R.K. Bull. Data collected for Alpha-risk project. Unpublished). These levels vary from 1.1 $mBq.d^{-1}$ (total U activity) at Winfrith (Southern England), to 0.86 $mBq.d^{-1}$ at Dounreay (North of Scotland) and 0.26 $mBq.d^{-1}$ at Harwell (South-Central England). Given this variation within the UK, any value applied to French data would have been pure guesswork, so no subtraction was attempted.

4.10.1.3 Models

The ICRP Publication 66 Human Respiratory Tract Model (ICRP 1994a) was used. The dosimetric model (tissue weighting factors, radiation weighting factors etc) was that described in ICRP Publication 60 (ICRP 1991). The systemic model used for uranium was that contained in ICRP Publication 69 (ICRP 1995). All of these models are implemented in the code IMBA Professional Plus (Birchall *et al.* 2007).

Some of the cases used in this inter comparison involve wound incidents. No attempt was made to model the wounds as there were insufficient data to do so. These were simply treated as injection directly into the bloodstream, by using the 'injection' route in IMBA (Birchall *et al.* 2007).

In the absence of any evidence to the contrary, an AMAD of 5 microns was used throughout.

4.10.1.4 Intake assessment procedure

The software package IMBA Professional Plus-Update (Birchall *et al.* 2007) was used in all of the dose assessments. IMBA determines intake by using maximum likelihood methods.

Urine results were assigned a default scattering factor of 1.6, unless they were identified as 24 hr samples, when an SF of 1.1 was used. These values are taken from Table 4.10 of the EURADOS IDEAS Guidelines (Castellani et al. 2013). Furthermore, the value of 1.6 is consistent with a range of 1.5-2 found from a study of historical Harwell cases (R.K. Bull, unpublished).

Faecal results were assigned a default scattering factor (SF) of 3. Samples flagged as 48 hrs were given an SF of 2.5. The SF of 3 was taken from table 4.10 of the EURADOS IDEAS Guidelines (Castellani et al. 2013) for a 24-hr faecal sample. An SF of 2 is recommended for a 72-hr sample. By interpolation between these two figures an SF of 2.5 was used for 48-hr samples.

4.10.2 Assessments

4.10.2.1 Worker 1

Radionuclide and isotopic composition

The job exposure matrix (JEM) for Worker 1 indicates that all potential exposures were to natural uranium, so the 'natural uranium' mix was chosen in IMBA (Birchall *et al.* 2007) and used throughout this assessment.

Whilst it is noted that the first two incidents are recorded as ^{238}U and ^{235}U, respectively, for the purposes of calculation both were treated as natural uranium. IMBA (Birchall *et al.* 2007) requires that all intake regimes have the same isotopic composition. Therefore it would not be possible to give these two acute intakes separate isotopic compositions without breaking the calculation into two parts.

Exposure pattern

The JEM indicates no potential for exposure during the initial exposure periods from 17/09/1962 to 30/06/1966. Routine monitoring commenced on 18/06/1964, however the early results were below DL. Therefore a starting date for the first chronic inhalation period was set at 01/07/1964, the beginning of the fourth exposure period in the JEM and the first period during which the JEM states that there is a potential for exposure. The quantity and frequency of exposure remains at about the same level until the end of 1976, so this chronic intake is terminated on 31/12/1976. A second chronic inhalation regime was set to run from 01/01/1977 to 30/09/1980 to cover the last two exposure periods.

Initially 8 acute intakes were included, corresponding to the 8 incidents recorded in the incident register for Worker 1. These included both inhalation and injection (wound) intakes. However, it was noted that there were two very high faecal results, on 31/07/67 and 27/03/74. Therefore two acute intakes were inserted to account for these faecal results. Because IMBA (Birchall *et al.* 2007) has a limit of 10 intake regimes, two of the acute intakes corresponding to registered incidents had to be removed. The two chosen for removal had been assigned little activity in an initial run of IMBA (Birchall *et al.* 2007).

Chemical form

Since the JEM assigns all of the potential intakes to type F material, this default type was used for the first chronic intake regime. For the last two exposure periods equal weight is given to type F and M material. Since it is not possible, within the IMBA (Birchall *et al.* 2007) code, to fix an intake at 50% F and 50% M, a set of user-defined lung solubility parameters was used to mimic such a mixture. These were $f_r = 0.55$; s_r=100 d^{-1}; s_s=4.9.10^{-3} d^{-1}.

All of the acute intakes fall within the period when the likely exposure was to type F materials, so all of the acute inhalations have been assigned to type F.

Treatment of data below DL

Below-DL data are entered as "<LOD" in the IMBA software (Birchall *et al.* 2007), which deals with such data using the maximum likelihood method.

Intake and dose estimates

The probability of the fit to the data, based on chi-squared, was calculated by IMBA (Birchall *et al.* 2007) to be 0. Whilst this is not encouraging, it is a common feature of fits to large, complex, datasets. No doubt the situation could be improved if more than 10 intake regimes could be used.

The calculation described above provided the central estimate of the dose for this case and is given ID number 12 in the discussion of the results. Two other estimates were produced: one in which all inhalation intakes were assigned to type F and one in which all inhalation intakes were assigned to type M. (The wound incidents were still treated as injections in both cases). These provided lower and upper bounds to the dose, respectively, and were given IDs 13 and 14 in the discussion of results (Table 48).

Table 48: Dose estimates for Worker 1 for participant IDs 12, 13 and 14

ID	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
12	11.1	38.5	43.7
13	6.91	4.25	43.1
14	85.1	656	42.7

4.10.2.2 Worker 2

Radionuclide and isotopic composition

The job exposure matrix (JEM) for Worker 2 indicates that all potential exposures were to natural uranium, so the 'natural uranium' mix was chosen in IMBA (Birchall *et al.* 2007) and used throughout this assessment.

Exposure pattern

The JEM indicates exposure only in periods 1, 8, 9 & 10. In period 1 the frequency and quantity of exposure to the three inhalation types F, M & S are in the ratio 3:1:1. In periods 8, 9 and 10, the exposure is given as type F only. However, in contradiction to the JEM, the only non-DL urine result occurs in period 2 (albeit a value lower than the usual DL!). It is also noted that there are no urine data corresponding to the last 6 exposure periods. In view of the lack of structure in the urine record and the inconsistency between the presumed exposure periods and the only positive urine result, it was decided to model the intake as a single constant chronic inhalation lasting from the beginning of the first exposure period to the end of the last exposure period (1/6/63 to 30/9/82).

Chemical form

The solubility mix that was used for the assessment was 3:1:1 for types F, M and S. This mixture was represented by the following lung parameters: $f_r = 0.62$; $s_r = 100$ d^{-1}; $s_s = 7.2.10^{-4}$ d^{-1}. No incidents were recorded for Worker 2, so no acute intakes were used in the assessment. If the single positive result had been well above the DL values, it would have been tempting to insert an acute intake to account for it. However it made no sense to insert an acute to account for a lower value.

Treatment of data below DL

Below-DL data are entered as "<LOD" in the IMBA software (Birchall *et al.* 2007), which deals with such data using the maximum likelihood method.

Intake and dose estimates

The probability of fit, calculated via chi-squared, is 42.5% for this case, so the fit is adequate. The total committed effective dose, for this central estimate (ID 12), is 7.01 mSv. The lower and upper bounds to the dose were calculated using a type F chronic (ID 13) and a type M (ID 14) chronic inhalation, respectively (Table 49).

Table 49: Dose estimates for Worker 2 for participant IDs 12, 13 and 14

ID	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
12	7.01	35.1	8.84
13	1.40	0.862	8.74
14	17.7	136	8.87

4.10.2.3 Worker 3

Radionuclide and isotopic composition

The job exposure matrix (JEM) for Worker 3 indicates that all potential exposures were to natural uranium, so the 'natural uranium' mix was chosen in IMBA (Birchall *et al.* 2007) and used throughout this assessment.

Exposure pattern

All of the urine results for this case are below DL. Since there is no structure in the dataset, it was decided to treat it as a single, constant chronic inhalation over all the exposure periods (ie the chronic intake ran from 26/7/65 to 31/1/82).

Chemical form

The JEM indicates exposure to type F material in all exposure periods.

Treatment of data below DL

With this basic model structure, two different assessments were considered. As an upper bound to the intake and dose, the recommendation of the CURE protocol was used (Blanchardon *et al.* 2014, Laurent *et al.* 2016). In this case, the last urine result was set to be a 'real' result with the value of the DL.

As an alternative approach, all of the data were taken as presented (ie as DL results). When run using a maximum-likelihood method, IMBA (Birchall *et al.* 2007) fails to produce a sensible result for such a dataset. However, it is possible to obtain an estimate of intake & dose using the Bayesian module with a uniform prior. The posterior probability distribution on intake rate has no mode, but reasonable estimates of intake can be extracted from the median and mean of this distribution. No chi-squared or probability of fit is calculated for this Bayesian approach.

Intake and dose estimates

The first treatment of data below DL yields a total committed effective dose of 1.72 mSv (ID 14, Table 50). The probability of fit, calculated via chi-squared, is 4.5%, which is barely adequate. The reason for this rather poor fit seems to be that, for a chronic intake of type F, the equilibrium excretion rate is reached very quickly. The fitted excretion rate is forced to a rather low level by early data with a low DL. Consequently, the excretion curve falls well below the last pseudo-positive result.

Table 50: Dose estimates for Worker 3 for participant IDs 12, 13 and 14

ID	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
12	0.8	0.492	4.99
13	0.759	0.467	4.74
14	1.72	1.06	10.7

Applying the Bayesian approach, the mean and median total committed effective doses are 0.8 mSv (ID 12) and 0.76 mSv (ID 13), respectively (Table 50). The mean dose is regarded as the central estimate by the Harwell ADS, with the median calculated only for comparison. For an all-DL dataset, a valid lower bound for the intake and dose is 0. However, this value was not provided as a result for this intercomparison.

4.10.3 Comments

It seems that the main sources of uncertainty in these assessments arise from the assignment of intake regimes and the assignment of absorption type for the inhalation intakes.

The assignment of intake regimes is particularly important in the case of Worker 1. Because there are 8 recorded incidents, there may be a temptation to assign only acute intakes corresponding to these incidents. I believe that this would be a mistake. Urine excretion from intakes of soluble uranium decreases rapidly with time after intake. Acute intakes will fail to account for all of the excretion data. During the CURE project I created artificial uranium datasets to test out assessment procedures and found that significant underestimates of intake were possible unless chronic intakes were used to underpin the acute intakes. In the case of Worker 2 there may be a case for using an acute intake to account for the sole non-DL result. I did a trial using an acute intake, one day prior to the positive urine result, in addition to the underlying chronic intake. Almost all of the activity was assigned to the acute intake and the total committed dose equivalent dropped by a factor of about 1000! Whilst the new dose is very low, I cannot say for sure that it is wrong! In the case of a totally uninformative dataset such as that belonging to Worker 3, I can see no justification for using other than a chronic intake.

In reality, most datasets are the result of a complex set of intakes. However, assessment of artificial Pu datasets showed that these are usually adequately treated by assuming a constant chronic intake (Wilson and Bull 2007).

In the case of Worker 1, if the JEM is adhered to, the choice of lung solubility, for the inhalation intakes, is fairly clear. The early exposure periods are type F and the later ones are a mixture of type F and M. However, for simplicity, the assessor may choose to use either type F or type M for the whole assessment. The calculations I did under IDs 13 & 14 show the effect of these assumptions on the dose. The case of Worker 2 is more complicated. The only positive result occurs during exposure period 2, when the JEM does not admit any possibility of exposure, so there is no guidance on the solubility of an intake in that period. The mixture of materials for period 1 is 3:1:1 types F, M and S. For periods 8, 9 and 10 the exposure is most likely to type F material. It becomes a matter of judgement as to which of these solubilities (or a mixture of the two) that the assessor uses for this assessment. The case of Worker 3 presents no problems for solubility assignment, because all of the potential exposures are listed in the JEM as type F, so it would be perverse to make any other assumption in performing the assessment.

The cases of Worker 2 and Worker 3 illustrate the difficulties in handling 'non-informative' datasets with few or no uncensored results.

4.11 Participant ID 15: E. Davesne (IRSN)

4.11.1 General assumptions

4.11.1.1 Processing of Data

In case of bioassay uranium contents quantified using both activity and mass measurement, the result expressed in activity is preferred for dose assessment because no hypothesis on isotopic composition is needed.

Uranium masses were converted into activity by assuming an isotopic composition of natural uranium: mass in $\mu g.l^{-1}$ were multiplied by $2.5.10^{-2}$ $Bq.\mu g^{-1}$ to obtain activity in $Bq.l^{-1}$. Activities reported in pCi were converted into Bq by multiplying them by $3.7.10^{-2}$ $Bq.pCi^{-1}$.

To estimate daily excretion from urine bioassay expressed in $Bq.l^{-1}$, a reference daily excreted volume of $1.6l.d^{-1}$ (ICRP 2002) was used because all three workers were male. The activity quantified in 48h faeces sample was divided by 2 to obtain daily faecal excretion.

All bioassay date were shifted by one day to obtain date at the end of sampling instead of date of collection period beginning. This is justified because for Worker 1, an incident took place on 10/11/1967 according to the JEM but the date of the bioassay is also 10/11/1967.

4.11.1.2 Dietary contribution to uranium excretion

No contribution of diet to uranium excretion was subtracted to the data because according to the data of Davesne *et al* (2014): the 95th percentile of dietary uranium excretion is 3.7 $mBq.d^{-1}$ in urine and 228 $mBq.d^{-1}$ in faeces and these values are much lower than the daily activity quantified for the three workers.

4.11.1.3 Models

The biokinetic models used in these assessments are: the Human Respiratory Tract Model (ICRP 1994a), the Gastro-Intestinal Tract Model (ICRP 1979), NCRP wound model (NCRP 2006) and systemic model for uranium (ICRP 1995). Retention/excretion functions and annual absorbed doses after unit intake were evaluated with DCAL programme (Eckerman 2006) on the basis of the aforementioned biokinetic models, the radionuclide transformation data from ICRP Publication 38 (ICRP 1983) and the organ and tissue masses of the ICRP reference person (ICRP 1975).

4.11.1.4 Intake assessment procedure

Intakes were assessed one at a time. Firstly, for each acute intake, every bioassay following the intake time until the second below reporting level were used to assess this acute intake. Then, for each chronic period, the corresponding intake was estimated from the bioassay collected during this period and not attributed to any acute intake.

When calculating an intake, the contribution of this exposure to the following bioassay is evaluated and subtracted to bioassay activities higher than reporting level.

Intakes were estimated as the intakes maximizing the likelihood function. The likelihood function is the product of the probability to observe a given bioassay knowing the intake:

$$L(i) = \prod_i lognormal(M_i, \mu_g = i \times m(t_i), \sigma_g = SF),$$

where M_i is a bioassay attributed to this intake period, i is the intake, m is the excretion function, t_i is the delay between intake and bioassay, SF is the scattering factor. The likelihood of a measurement below reporting level was defined as the probability to observe a measurement result below the reporting level knowing exposure conditions and intake. This modelling implies the use of a cumulative distribution function for the likelihood.

For faecal sample, a SF of 3 was used. For 24-h urine, the SF was set to 1.1 and to 1.6 for other urine samples.

Intakes and doses were assessed using IRSN home-made code DOSEPI (IRSN, Fontenay-aux-Roses France).

4.11.2 Assessments

4.11.2.1 Worker 1

Radionuclide and isotopic composition

For simplicity, it was assumed that only ^{234}U was present in the contaminant material.

Exposure pattern

From the incident register and from bioassay collected in case of incident monitoring, 11 acute intakes were considered for Worker 1. However, as the urine sample collected just after the inhalation of 13/06/1967 was reported below reporting level, this incident was discarded. Moreover, the bioassay data collected after the 14/03/1974 intake were completely explained by the 04/03/1974 intake leading not to consider this last acute intake.

To summary, I assume inhalation incident on dates 13/12/1966, 07/03/1967, 10/11/1967, 03/06/1970, 30/08/1971, 23/05/1974 and 04/03/1974 and two wounds on 17/03/1967 and 23/09/1971.

Chronic exposure was assumed to start 6 months before the first bioassay and to finish the day of the last bioassay: from 19/12/1963 to 24/06/1980. According to the JEM, exposure changed on 30/06/1966, 31/12/1974, 31/12/1976. That is why, this whole period was cut in 4 subperiods: from 19/12/1963 to 30/06/1966, from 01/07/1967 to 31/12/1974, from 01/01/1975 to 31/12/1976 and from 01/01/1977 to 30/09/1980.

Chemical form

From the incident register, the aerosol inhaled on 04/03/1974 was uranium nitrate. For the other acute intakes, the chemical form stated in the JEM is used: from 01/07/1967 to 31/12/1976, absorption Type F is assumed, from 19/12/1963 to 30/06/1966 as no special absorption type is given in the matrix, a mixture of Type F, M and S is assumed, from 01/01/1977 to 30/09/1980 it is a mixture of Type F and M.
Absorption parameters used are presented in Table 51.

Table 51: Absorption parameters used by Participant ID 15

Material	f_r	s_r (d^{-1})	s_s (d^{-1})	f_1
Type F	1	10		0.02
Mixture Type F, M	0.6	6.5	5.10^{-3}	0.012
Mixture Type F, M, S	0.403	5.33	$2.55.10^{-3}$	$8.07.10^{-3}$
Uranyl nitrate	0.9	3	0.005	0.02

An AMAD of 5 µm was assumed as a default because of the lack of specific information.

For wound contamination, a weak retention is supposed.

Treatment of data below DL

For all intake estimations but one, data below reporting level are used as below reporting level by using a cumulative probability in the likelihood function. However, for the chronic period from 19/12/1963 to 30/06/1966, all bioassay are below reporting level. In this configuration, the maximum likelihood method fails to give an intake estimate because all intakes leading to bioassay below reporting levels are equally probable. To allow the estimation of the intake, the latest bioassay attached to this chronic period was set equal to the reporting level leading to an upper estimate of the dose (ID 15.2). A lower estimate is obtained by assuming that as all bioassay are below reporting level, the dose for this period is equal to 0 (ID 15.1).

Intake and dose estimates

The total dose estimates for Worker 1 are gathered in Table 52.

Table 52: Dose estimates for Worker 1 for participant ID 15

Participant ID	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
15.1	16.6	86.6	41.5
15.2	21.5	118	43.5

4.11.2.2 Worker 2

Radionuclide and isotopic composition

For simplicity, it was assumed that only ^{234}U was present in the contaminant material.

Exposure pattern

For Worker 2, no acute intake was considered because no information supports it.

Chronic exposure was assumed to start 6 months before the first bioassay and to finish the day of the last bioassay: from 03/04/1962 to 13/11/1969. According to the JEM, exposure stars on 01/06/1963 and changed on 31/12/1963, 31/12/1966, and 31/12/1976. That is why, this whole period was cut in 4 subperiods: from 03/04/1962 to 31/05/1963, from 01/06/1963 to 31/12/1963, from 01/01/1964 to 31/12/1966 and from 01/01/1967 to 13/11/1969.

Chemical form

As in the JEM, either no exposure is stated or all absorption types are possible, a mixture of absorption types F, M and S was assumed for each chronic intake (Table 51).

An AMAD of 5 µm was assumed as a default because of the lack of specific information.

Treatment of data below DL

For the third chronic exposure intake (from 01/01/1964 to 31/12/1966), data below reporting level are used as below reporting level by using a cumulative probability in the likelihood function.

For all other chronic periods, all bioassay are below reporting level. In this configuration, the maximum likelihood method fails to give an intake estimate because all intakes leading to bioassay below reporting levels are equally probable. To allow the estimation of the intake, the latest bioassay attached to this chronic period was set equal to the reporting level leading to an upper estimate of the dose (ID 15.2). A lower estimate is obtained by assuming that as all bioassay are below reporting level, the dose for this period is equal to 0 (ID 15.1).

Intake and dose estimates

The total dose estimates for Worker 2 are gathered in Table 53.

Table 53: Dose estimates for Worker 2 for participant ID 15

Participant ID	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
15.1	4.2	27.1	1.8
15.2	12.6	80.2	5.3

4.11.2.3 Worker 3

Radionuclide and isotopic composition

For simplicity, it was assumed that only ^{234}U was present in the contaminant material.

Exposure pattern

For Worker 3, no acute intake was considered because no information supports it.

Chronic exposure was assumed to start 6 months before the first bioassay and to finish the day of the last bioassay: from 20/12/1967 to 12/12/1981. According to the JEM, exposure starts on 26/07/1965 and changed on 31/12/1974, and 31/12/1981. That is why, this whole period was cut in 2 subperiods: from 20/12/1967 to 31/12/1974, and from 01/01/1975 to 12/12/1981.

Chemical form

As in the JEM, the only absorption type possible is type F, this type was used. The specific absorption parameters used were those of the ICRP Publication 130 (ICRP 2015) (Table 51).

An AMAD of 5 µm was assumed as a default because of the lack of specific information.

Treatment of data below DL

For all other chronic periods, all bioassay are below reporting level. In this configuration, the maximum likelihood method fails to give an intake estimate because all intakes leading to bioassay below reporting levels are equally probable. To allow the estimation of the intake, the latest bioassay attached to this chronic period was set equal to the reporting level leading to an upper estimate of the dose (ID 15.2). A lower estimate is obtained by assuming that as all bioassay are below reporting level, the dose for this period is equal to 0 (ID 15.1).

Intake and dose estimates

The total dose estimates for Worker 3 are gathered in Table 54.

Table 54: Dose estimates for Worker 3 for participant ID 15

Participant ID	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
15.1	0	0	0
15.2	2.4	2.2	14.6

4.11.3 Comments

The most difficult question is how to treat data below reporting levels because it can change dramatically dose estimates and risk estimates at the end. Determining exposure pattern is also tricky because of discrepancy between bioassay collection dates and exposure periods from JEM.

From intake values, it can be seen that chronic exposures are the main contributors to the total dose.

4.12 Participant ID 16: C. Challeton-de Vathaire (IRSN)

4.12.1 General assumptions

4.12.1.1 Processing of Data

All urine measurements values were converted to $Bq.d^{-1}$. Since no potential exposure to enriched or reprocessed uranium was indicated in the job exposure matrix (JEM), exposure was supposed to be all natural uranium. Values expressed in $\mu g.l^{-1}$ were multiplied by 0.025, considering a specific activity of natural uranium of $2.56.10^4$ $Bq.g^{-1}$ = 0.0256 $Bq.\mu g^{-1}$ (Table 1 of ISO standard 16638-1:2015; ISO 2015b), then by the reference daily urine volume for male, 1.6 l, as all workers were male. Values expressed in $pCi.l^{-1}$ were multiplied by 0.037 to convert pCi to Bq and then by the reference daily urine volume for male, 1.6 l.

Where both mass and activity measurements were reported for a given sample, only the activity measurement result was used.

For faecal measurements, values expressed in pCi were multiplied by 0.037 to convert to Bq and then divided by 2 to obtain $Bq.d^{-1}$ as it was considered that the collection of the faeces was performed during two days for routine faeces bioassay even when it was not specified.

The dates of sampling indicated in the data were considered as the date of the end of the excreta collection as no indication was given to consider other option.

4.12.1.2 Dietary contribution to uranium excretion

For urine measurement, the dietary background of uranium was not taken into account as the reporting limit was well above the dietary background of uranium. For faeces measurements, the dietary background were also not considered as the measured values were well above the reported mean alimentary background.

4.12.1.3 Models

The biokinetic models applied were the ICRP Publication 66 Human Respiratory Tract Model (ICRP 1994a), ICRP Publication 30 Gastro-Intestinal Tract Model (ICRP 1979), ICRP Publication 69 systemic model for uranium (ICRP 1995), NCRP wound model (NCRP 2006). AMAD was assumed to be 5 µm as the default for workers of ICRP Publication 66.

The dosimetric model was that used in the ICRP Publication 60 series of dose coefficients (ICRP 1991), with organ and tissue masses from ICRP Publication 23 (ICRP 1975), radiation emission data from ICRP Publication 38 (ICRP 1983) and weighting factors (w_R, w_T) from Publication 60 (ICRP 1991). The isotopic composition of natural uranium was used in dose calculation.

4.12.1.4 Intake assessment procedure

Periods of chronic intakes were chosen according to the potential exposure indicated in the job exposure matrix. One chronic intake was considered when the worker was exposed continuously to the same type of uranium even if the quantities slightly differ (as for intake 8 of worker 2). The dates of start and end of the chronic intake were the same as the dates of start and end indicated for the period of exposition in the JEM.

Acute intakes were considered according to the incident register and to the bioassay data. Registered incident with no "incident" bioassay performed in the same or following days were not considered as acute intake

IMBA software (Birchall *et al.* 2007) was used to calculate the intakes and the doses (maximum likelihood approach). A unique calculation was performed taking into consideration all the intakes regimes and all the bioassay data.

The uncertainties on bioassay data were represented as lognormal distributions with geometric standard deviation SF = 1.6 for generic urine data, SF = 1.1 for 24 h urine data and SF = 3.0 for faecal data (EURADOS IDEAS Guidelines, Castellani *et al.* 2013).

Effective and equivalent doses were calculated using IMBA software (Birchall *et al.* 2007). To calculate the doses for each intake regimes, as asked, calculation were performed setting the intake regimes not considered to "0".

4.12.2 Assessments

4.12.2.1 Worker 1

Radionuclide and isotopic composition

The job exposure matrix indicates possible exposure to natural uranium only, so all bioassay data and intakes are assumed to be natural uranium: 48.86% ^{234}U, 2.28% ^{235}U and 48.86% ^{238}U per activity (isotopic composition for natural uranium considered in IMBA software (Birchall *et al.* 2007)).

Exposure pattern

As a total, nine intake regimens were considered for Worker 1.

Two chronic intakes were set according to the job-exposure matrix:

- chronic 1 from 01/07/1966 to 31/12/1976 corresponding to the dates of start and end of job 77_UDG1
- chronic 2 from 01/01/1977 to 30/09/1980 corresponding to the dates of start and end of job 3_CME4

Four acute intakes with corresponding "incident" bioassay were set according to the incident register at the following dates:

- acute 3 : 17/03/1967
- acute 5: 30/08/1971
- acute 6: 23/05/1972
- acute 7: 04/03/1974

Registered incident with no "incident" bioassay performed were not considered as acute intake. The incident of 23rd September 1971 was also not considered as the urine measurement performed the day following the incident did not demonstrated result above the level routinely measurement for this worker at this time. The incident of 14th March 1974 was not considered as an intake regime either as the measured activity of the bioassay collected on 15th March was compatible with the intake due to the incident of 4th March.

Three acute intakes were added corresponding to "incident" bioassay above DL:

- acute 1: 2/12/1966
- acute 2: 06/03/1967
- acute 4: 09/09/1968

Three bioassay were performed before the dates of chronic or acute intakes considered however no intake was added as no indication of potential exposure were given the in the job exposure matrix or the incident register.

Chemical form

From the job exposure matrix, type F was assumed for the first chronic intake (from 01/07/1966 to 31/12/1976) and mixture type F + M for the second chronic exposure intake (from 01/01/1977 to 30/09/1980).

For the three acute intakes by inhalation issued from the incidence register (30/08/1971; 23/05/1972 and 04/03/1974) and the three added acute intake deduced from above LD incident bioassay measurements, type F was considered as it was the only type considered in the job

exposure matrix covering the dates of the incidents (from 01/07/1966 to 31/12/1976). For the wound contamination of 17/03/1967, a soluble weak retention is supposed.
Absorption parameters used are presented in Table 55.

Table 55: Absorption parameters used by Participant ID 16

Material	f_r	s_r (d^{-1})	s_s (d^{-1})	f_1
Type F	1	10		0.02
Mixture Type F+ M	0.6	6.5	5.10^{-3}	0.012

An AMAD of 5 µm was assumed as a default because of the lack of specific information.

Treatment of data below DL

Bioassay data below limit of detection (DL) or below reporting level (RL) were taken into account as such in the maximum likelihood fit.

Intake and dose estimates

Intakes and doses estimated for Worker 1 are gathered in Table 55 and Table 56.

Table 56: Intake estimates for Worker 1 for participant ID 16

number	*chronic 1*	*chronic 2*	*acute 1*	*acute 2*	*acute 3*
intake (Bq)	15700	6940	6.2	11.2	0.2
number	*acute 4*	*acute 5*	*acute 6*	*acute 7*	
intake (Bq)	28.2	45.9	19.8	492	

Table 57: Dose estimates for Worker 1 for participant ID 16

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
15	75	38

4.12.2.2 Worker 2

Radionuclide and isotopic composition

As for Worker 1, job exposure matrix indicate possible exposure to natural uranium only, so all bioassay data and intakes are assumed to be natural uranium: 48.86% ^{234}U, 2.28% ^{235}U and 48.86% ^{238}U per activity (isotopic composition for natural uranium considered in IMBA software (Birchall *et al.* 2007)).

Exposure pattern

For Worker 2 there was a large discrepancy between the potential exposure as stated by the job exposure matrix and the date of the bioassay measurements. Three jobs were indicated:

- 79_CEA1 from 01/06/1963 to 31/12/1963 with potential exposition to type F, M and S natural uranium. During this period, one bioassay was performed.
- 0_ADM from 01/01/1964 to 31/12/1966 with no potential exposure. However during this period, seven bioassays were performed.
- 31_DT-AT4 from 01/01/1967 to 31/01/1982 with no potential exposition from 01/01/1967 to 31/12/1976 and then potential exposition to type F natural uranium until the end of the job. Eight bioassays were performed during the period with no potential exposition and none during the period of potential exposition.

Moreover, four bioassays were performed before the first day of the first job.

As stated in 4.12.1.4, the choice of the chronic intakes was based on the potential exposure period given in the job exposure matrix. Accordingly, one chronic intake was considered from 01/06/1963 to 31/12/1963. The potential exposure included between 31/12/1976 and 31/01/1982 was not considered since no bioassay measurement was performed during this period.

No acute intake was considered as no incident was reported in the registry and no bioassay measurement was indicated as "incident".

Chemical form

From the job exposure matrix type F+M+S was assumed for the chronic intake. The frequency and quantities of type F manipulated was higher than type M or S. However the three types were considered to be potential sources of contamination so a mixture of absorption types F, M and S was assumed. Absorption parameters used are presented in Table 58. An AMAD of 5 µm was assumed as a default because of the lack of specific information.

Table 58: Absorption parameters used for Worker 2 by Participant ID 16

Material	f_r	s_r (d^{-1})	s_s (d^{-1})	f_1
Mixture Type F+M+S	0.403	5.33	$2.55.10^{-3}$	$8.07.10^{-3}$

Treatment of data below DL

Bioassay data below limit of detection (DL) or below reporting level (RL) were taken into account as such in the maximum likelihood fit.

Intake and dose estimates

Intakes and doses estimated for Worker 2 are gathered in Table 59 and Table 60.

Table 59: Intake estimates for Worker 2 for participant ID 16

number	*Chronic 1*
intake (Bq)	3540

Table 60: Dose estimates for Worker 2 for participant ID 16

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
7.5	47	3.3

4.12.2.3 Worker 3

Radionuclide and isotopic composition

As for Workers 1 and 2, job exposure matrix indicate possible exposure to natural uranium only, so all bioassay data and intakes are assumed to be natural uranium: 48.86% ^{234}U, 2.28% ^{235}U and 48.86% ^{238}U per activity (isotopic composition for natural uranium considered in IMBA software (Birchall *et al.* 2007)).

Exposure pattern

The job exposure matrix indicates only one job from 26/07/1965 to 31/12/1981 (77_UDG1) with potential exposition to uranium. This time period was considered as a chronic intake.

No acute intake was considered as no incident was reported in the registry and no bioassay measurement was indicated as "incident".

Chemical form

From the job exposure matrix type F was assumed for the chronic intake. Absorption parameters used are presented in Table 55.

Treatment of data below DL

The intake and the dose were assessed by setting the last bioassay data as "real" as proposed in the dosimetry protocol of the Concerted Uranium Research in Europe (CURE) project (Laurent *et al.* 2016). So, the dose assessed is the maximum dose which could have been received by the worker. The date of the last bioassay was 11/12/1981. The result of this analysis, as indicated in the data was <10 pCi.l^{-1} corresponding to 0.592 Bq.d^{-1}. The SF of 1.6, considered for generic urine bioassay was not modified.

Intake and dose estimates

Intakes and doses estimated for Worker 3 are gathered in Table 61 and Table 62.

Table 61: Intake estimates for Worker 3 for participant ID 16

Participant ID	*intake (Bq) for chronic 1*
16.1	0
16.2	5460

Table 62: Dose estimates for Worker 3 for participant ID 16

Participant ID	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
16.1	0	0	0
16.2	1.4	1.2	8.3

4.12.3 Comments

One source of uncertainty is the choice of the measurement to consider (mass or activity) when both are performed on the same excreta collection. For Worker 1, during the sixties, there were some incompatibilities between the results obtained by the two methods. For Worker 3, the choice to consider mass measurements may have been more accurate as the reported limit was lower than for the activity measurement but activity measurement was used in order to be in agreement with the choice for Worker 1.

Another problem is the contradiction between the potential exposure described in the job exposure matrix and the dates of the bioassays (for example considering Worker 2). This could be due to incorrect assignment of potential exposure to the different jobs and/or to missing bioassays results.

4.13 Participant ID 17: E. Blanchardon (IRSN)

4.13.1 General assumptions

4.13.1.1 Processing of Data

Measurements of activity in pCi were converted into Bq by multiplying by 0.037 $Bq.pCi^{-1}$.

Since no exposure to enriched or reprocessed uranium was indicated in the job exposure matrix (JEM), exposure is supposed to be all natural uranium. Measurements of uranium mass ($\mu g.l^{-1}$) were converted into activity ($Bq.l^{-1}$) by multiplying by the specific activity of natural uranium: $2.56.10^4$ $Bq.g^{-1}$ = 0.0256 $Bq.\mu g^{-1}$ (Table 1 of ISO standard 16638-1:2015; ISO 2015b). Where both mass and activity measurements were reported for a given sample, only the activity measurement result was used.

In the absence of indication of creatinine content or urine volume, urine measurement data expressed in $Bq.l^{-1}$ were converted to $Bq.d^{-1}$ by multiplying by the ICRP Publication 89 (ICRP 2002) reference value for adult males of 1.6 $l.d^{-1}$. Urine data in Bq flagged as "urine 24h" were taken as $Bq.d^{-1}$. Urine data flagged as "immediate urine" were arbitrarily considered to be 2 hour samples collected just after the incident.

In the absence of specific indication, faecal measurement results were assumed to correspond to daily samples and expressed as $Bq.d^{-1}$. 48 h faeces measurement results were divided by 2 in order to be expressed as $Bq.d^{-1}$.

For Worker 1, because of the overlap between dates of incidents and dates of 24h urine measurements, it was suspected that the indicated date was the time when sampling was started instead of the time of end of sampling desired for dose assessment. As a consequence, all dates were incremented by 1 day, except when "immediate urine" was indicated, for dose assessment purpose.

4.13.1.2 Dietary contribution to uranium excretion

The contribution of diet to uranium excretion in the French population may be estimated on the basis of a report by Fréry *et al.* (2011) who measured uranium in the urine of 2000 non-occupationally exposed individuals by ICP-MS. The geometric mean of the results for 756 men was 5.4 $ng.l^{-1}$ (about 0.2 $mBq.d^{-1}$) and the 95^{th} percentile was 23.4 $ng.l^{-1}$ (about 1 $mBq.d^{-1}$). This is

negligible when compared to the reporting level of 5 µg.l^{-1} and to the positive results. Dietary uranium was therefore neglected in the rest of the exercise.

4.13.1.3 Models

The biokinetic models applied were the ICRP Publication 66 human respiratory tract model (ICRP 1994a), ICRP Publication 30 gastro-intestinal tract model (ICRP 1979), ICRP Publication 69 systemic model for uranium (ICRP 1995), NCRP wound model (NCRP 2006). AMAD was assumed to be 5 µm as the default for workers of ICRP Publication 66 (ICRP 1994a).

The dosimetric model was that used in the ICRP Publication 60 series of dose coefficients (ICRP 1991), with organ and tissue masses from ICRP Publication 23 (ICRP 1975), radiation emission data from ICRP Publication 38 (ICRP 1983) and weighting factors (w_R, w_T) from Publication 60. The isotopic composition of natural uranium was used in dose calculation.

4.13.1.4 Intake assessment procedure

IRSN intake assessments were largely based on the dosimetry protocol of the Concerted Uranium Research in Europe (CURE) project (Laurent *et al.* 2016).

Intakes were estimated by a maximum likelihood fit of the biokinetic model prediction to all bioassay data with the code IMBA Professional Plus (Birchall *et al.* 2007). Consistently with the EURADOS IDEAS Guidelines (Castellani *et al.* 2013), the uncertainties on bioassay data were represented as lognormal distributions with geometric standard deviation SF = 1.6 for generic urine data, SF = 1.1 for 24 h urine data, SF = 2.0 for "immediate urine" data and SF = 3.0 for faecal data.

The definition of acute intake dates was based on the report of incidents in the incident register, plus the indication "incident" in the "monitoring" column of the bioassay data spreadsheet (in which case the incident is assumed to have taken place 24 h before the measurement date).

The definition of chronic exposure periods was adjusted to the different jobs indicated in the job exposure matrix unless there was a contradiction with the bioassay data: in the absence of any bioassay monitoring during a job, it was assumed no exposure and dose =0 ; when bioassay data were reported out of job periods or during job periods for which the JEM indicated no exposure, a potential exposure was assumed, starting about one monitoring interval before the first bioassay and ending at the last bioassay.

Table 63: Absorption parameters used by participant ID 17

Inhaled particulate materials	*Absorption parameter values*			*Absorption from the alimentary tract f_A*
	f_r	s_r (d^{-1})	s_s (d^{-1})	
Reference Type F	1	10	-	0.02
Reference Type M	0.2	3	0.005	0.004
Reference Type S	0.01	3	1.10^{-4}	2.10^{-4}
Uranyl nitrate, $UO_2(NO_3)_2$	0.9	3	0.005	0.02
F+M+S	0.403	5.33	$2.55.10^{-3}$	$8.07.10^{-3}$
F+M	0.60	6.50	$5.0.10^{-3}$	0.0120
M+S	0.105	3.0	$2.55.10^{-3}$	$2.10.10^{-3}$
F+S	0.505	6.5	$1.0.10^{-4}$	0.0101

Types of absorption and wound categories were based on indications of chemical form in the incident register and non-zero potential exposure in the JEM. Lung absorption parameter values were taken from the CURE protocol and based on ICRP Publication 130 (ICRP 2015), using mean of parameter values for mixtures of absorption types (Table 63).

For the application of the wound model, uranium compounds that would have been assigned to Type F or Type M were assigned to the soluble and weakly retained category for wound intake.

4.13.1.5 Worker 1

Radionuclide and isotopic composition

The job exposure matrix indicates possible exposure to natural uranium only, so all bioassay data and intakes are assumed to be natural uranium: 48.86% ^{234}U, 2.28% ^{235}U and 48.86% ^{238}U per activity.

Exposure pattern

Acute intakes are set according to the incident register at the following dates:

- (acute 1) 17/03/1967
- (acute 2) 10/11/1967
- (acute 3) 03/06/1970
- (acute 4) 30/08/1971
- (acute 5) 23/09/1971
- (acute 6) 23/05/1972
- (acute 7) 04/03/1974
- (acute 8) 14/03/1974

Three more acute intakes are set according to the bioassay data, when "incident" is indicated under "monitoring" and the measurement result is positive, at the following dates:

- (acute 9) 12/12/1966
- (acute 10) 06/03/1967
- (acute 11) 09/09/1968

No acute intake was assumed when the indication of incident was followed by a negative (below DL or <RL) measurement result (e.g. on 13/06/1967).

Chronic intakes were set according to the job-exposure matrix. However, bioassay monitoring started in 1964, with an apparent period of 6 months, at a time when the JEM indicated no possible exposure. So we assumed an error in the JEM and set the first period to start from 6 months before the first bioassay data (18/06/1964 – 6 months = 19/12/1963). The two other periods were set to start at the times of job changing from "31_DT-AT4" to "77_UDG1" then to "3_CME4". These were also times of change of potential exposure in terms of frequency and quantity. So:

- (chronic 1) from 19/12/1963 to 30/06/1966
- (chronic 2) from 01/07/1966 to 31/12/1976
- (chronic 3) from 01/01/1977 to 30/09/1980

14 intake regimes are identified while IMBA (Birchall *et al.* 2007) will accommodate only 10. For this practical reason, the dose assessment was done for two successive time periods from 18/06/1964 to 20/05/1972 (part 1) and from 21/05/1972 to 30/09/1980 (part 2), assuming no influence from intake in one part on the other one because exposure is to absorption type F only in 1972.

Chemical form

Chemical forms and absorption types were set according to the JEM. Possible absorption types were those with an indication of non-zero frequency and quantity at the time of intake. When only one type was possible, it was assigned. Or the corresponding wound category was assigned as explained in 4.2.1.4. When several types were possible, a mixture of them was assumed as explained in 4.2.1.4. Additionally, the incident register indicated "uranyl nitrate projection" on 04/03/1974, so the uranyl nitrate chemical form was assumed for acute intake 7. Before 01/07/1966, the JEM indicated no exposure, so in the absence of information, a mixture of types F + M + S was assumed for the first chronic exposure. In summary:

- (acute 1) 17/03/1967 – wound with soluble weak category
- (acute 2) 10/11/1967 – inhalation type F
- (acute 3) 03/06/1970 – inhalation type F
- (acute 4) 30/08/1971 – inhalation type F
- (acute 5) 23/09/1971 - wound with soluble weak category
- (acute 6) 23/05/1972 – inhalation type F
- (acute 7) 04/03/1974 – inhalation uranyl nitrate
- (acute 8) 14/03/1974 – inhalation type F
- (acute 9) 12/12/1966 – inhalation type F
- (acute 10) 06/03/1967 – inhalation type F
- (acute 11) 09/09/1968 – inhalation type F
- (chronic 1) from 19/12/1963 to 30/06/1966 – inhalation of types F+M+S mixture
- (chronic 2) from 01/07/1966 to 31/12/1976 – inhalation type F
- (chronic 3) from 01/01/1977 to 30/09/1980 – inhalation of types F+M mixture

Treatment of data below DL

Bioassay data below limit of detection (DL) or below reporting level (RL) were taken into account as such in the maximum likelihood fit (with a likelihood equal to the integral of the lognormal distribution from zero to the DL/RL).

Intake and dose estimates

Intakes and doses estimated for Worker 1 are gathered in Table 64 and Table 65.

Table 64: Intake estimates for Worker 1 for participant ID 17

number	*acute 1*	*acute 2*	*acute 3*	*acute 4*	*acute 5*	*acute 6*	*acute 7*
intake (Bq)	0.20	62	0	36	0.26	23	3700
number	*acute 8*	*acute 9*	*acute 10*	*acute 11*	*chronic 1*	*chronic 2*	*chronic 3*
intake (Bq)	0	6.4	11	29	1220	12540	8748

Table 65: Dose estimates for Worker 1 for participant ID 17

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
15	82	35

4.13.1.6 Worker 2

Radionuclide and isotopic composition

The job exposure matrix indicates possible exposure to natural uranium only, so all bioassay data and intakes are assumed to be natural uranium: 48.86% ^{234}U, 2.28% ^{235}U and 48.86% ^{238}U per activity.

Exposure pattern

Neither the incident register nor the bioassay data give any indication of an incident, so no acute intake is assumed.

The job-exposure matrix indicates two periods of potential exposure: from 01/06/1963 to 31/12/1963 and from 01/01/1977 to 30/09/1982.However, the bioassay data are in contradiction with this information from the JEM because they demonstrate that monitoring began before 1963 and stopped in 1969. Moreover, the only positive measurement data was obtained on 02/08/1965, at a time when the JEM indicates no possible exposure. As a consequence, we assume that there are errors in the JEM and we base the definition of the exposure period on the monitoring schedule, which shows a period of approximately 3 months. One chronic intake regime is set from the date of the first bioassay data (02/10/1962) minus 3 months to the date of the last bioassay data:

- (chronic 1) from 02/07/1962 to 12/11/1969

Chemical form

In the absence of more precise information, a mixture of types F + M + S is assumed.

Treatment of data below DL

Bioassay data below limit of detection (DL) or below reporting (RL) were taken into account as such in the maximum likelihood fit (with a likelihood equal to the integral of lognormal distribution from zero to the DL/RL).

Intake and dose estimates

Intakes and doses estimated for Worker 2 are gathered in Table 66 and Table 67.

Table 66: Intake estimates for Worker 2 for participant ID 17

number	*chronic 1*
intake (Bq)	4140

Table 67: Dose estimates for Worker 2 for participant ID 17

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
7.5	48	3.4

4.13.1.7 Worker 3

Radionuclide and isotopic composition

The job exposure matrix indicates possible exposure to natural uranium only, so all bioassay data and intakes are assumed to be natural uranium: 48.86% ^{234}U, 2.28% ^{235}U and 48.86% ^{238}U per activity.

Exposure pattern

Neither the incident register nor the bioassay data give any indication of an incident, so no acute intake is assumed.

The job-exposure matrix indicates a single period of potential exposure from 26/07/1965 to 31/01/1982. The bioassay data indicate monitoring over a shorter period from 1968 to 1981. But there are only less-than-DL/RL data, so a range from a minimum intake (zero) to a maximum intake will be evaluated. To evaluate the maximum intake, it makes sense to assume the longest potential exposure period indicated by the JEM. So:

- (chronic 1) from 26/07/1965 to 31/12/1981

Chemical form

The JEM indicates exposure to absorption type F only, so chronic inhalation of type F uranium is assumed.

Treatment of data below DL

Since there are only data below DL, the maximum likelihood approach is not directly applicable. Following CURE protocol, a range of intake and dose is estimated instead of a single best estimate. The minimum is zero (ID 17.1). The maximum intake is obtained by assuming that a constant chronic exposure results in the body activity increasing over time and being maximum just at the limit of detection of urine measurement at the moment of the last bioassay data: 11/12/1981. So for estimating the maximum value of intake and dose, the below DL value of 11/12/1981 is set equal to the value of DL (0.592 Bq.d^{-1}) and a maximum likelihood approach is then applied. The other data are left as less-than-DL (ID 17.2).

Intake and dose estimates

Intakes and doses estimated for Worker 3 are gathered in Table 68 and Table 69.

Table 68: Intake estimate for chronic 1 for Worker 3 for participant ID 17

Participant ID	*intake (Bq)*
17.1	0
17.2	6404

Table 69: Dose estimates for Worker 3 for participant ID 17

Participant ID	*Total committed effective dose (mSv)*	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
17.1	0	0	0
17.2	1.7	1.5	10

4.13.2 Comments

Assessing those cases gives a good opportunity to apply the dosimetric protocol of the CURE project (Laurent *et al.* 2016), which suits reasonably well the needs of the assessor. In the examples, the chronic periods of exposure are responsible for the major portion of the committed dose. The definition of their time frame and of the associated absorption type is clearly prone to large uncertainty. The numerous bioassay data below limit of detection bring additional uncertainty. The analysis of the results of the present exercise will help characterizing the influence of those factors and others and the resulting uncertainty on dose.

4.14 Participant ID 18: A. Birchall (Global Dosimetry)

4.14.1 General assumptions

4.14.1.1 Processing of Data

A reference daily urine volume of 1.6 $l.d^{-1}$ (ICRP 2002) was used to derive daily urine excretion from volumetric activity. All faecal collection periods were assumed to be 48h. All data were used to derive intakes and doses.

4.14.1.2 Dietary contribution to uranium excretion

No dietary contribution was taken into account.

4.14.1.3 Models

The biokinetic models used in these assessments are: the Human Respiratory Tract Model (ICRP 1994a), the Gastro-Intestinal Tract Model (ICRP 1979) and systemic model for uranium (ICRP 1995). Retention/excretion functions and annual absorbed doses after unit intake were evaluated on the basis of the aforementioned biokinetic models, the radionuclide transformation data from ICRP Publication 38 (ICRP 1983) and the organ and tissue masses of the ICRP reference person (ICRP 1975). Wound contaminations were treated as injection.

4.14.1.4 Intake assessment procedure

IMBA software (Birchall *et al.* 2007) was used. It assessed all intakes simultaneously.

4.14.2 Assessments

4.14.2.1 Worker 1

Radionuclide and isotopic composition

From the job-exposure matrix, an inhalation of natural uranium was assumed.

Exposure pattern

A chronic exposure from 01/06/1964 to 23/06/1990 and 8 acute intakes were defined from the job-exposure matrix.

Chemical form

A Type F compound with an AMAD of 5 µm was assumed.

Treatment of data below DL

Data recorded as below DL were treated as "<LOD" in IMBA software (Birchall *et al.* 2007).

Intake and dose estimates

The doses estimated for Worker 1 are presented in Table 70.

Table 70: Dose estimates for Worker 1 for participant ID 18

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
5.87	3.60	36.7

4.14.2.2 Worker 2

Radionuclide and isotopic composition

From the job-exposure matrix, an inhalation of natural uranium was assumed.

Exposure pattern and chemical form

4 exposure patterns were tested:

1) constant chronic intake throughout the work history
2) 4 Type F intakes defined by exposure matrix and constrained using a complex intake regime (Puncher *et al.* 2012)
3) 4 Type S intakes defined by exposure matrix and constrained using a complex intake regime (Puncher *et al.* 2012)
4) 4 intakes defined by exposure matrix and constrained using a super complex intake regime (Puncher et al. 2012) with a type S chemical form assumed for the first intake, a Type F for the 3 others.

The fourth scenario was taken as the best estimate.

Chemical form

The assumed chemical forms were Type S for the first intake and Type F for the 3 others. An AMAD of 5 µm was used for all intakes.

Treatment of data below DL

Data recorded as below DL were treated as "<LOD" in IMBA software (Birchall *et al.* 2007).

Intake and dose estimates

The doses estimated for Worker 2 are presented in Table 71.

Table 71: Dose estimates for Worker 2 for participant ID 18

Total committed effective dose (mSv)	*Total lung committed equivalent dose (mSv)*	*Total kidney committed equivalent dose (mSv)*
17.4	67.9	62.6

4.14.2.3 Worker 3

Not analysed.

5. Discussion

5.1 Central values of dose assessments

The central values presented in Table 1 to Table 9 are gathered in Table 72. Committed effective doses and committed equivalent doses to lung are highest for Worker 1 and lowest for Worker 3. Kidney equivalent doses estimated for Worker 3 are, in average, higher than for Worker 2, with the greatest values for Worker 1. This finding is consistent with the number of bioassay data, the percentage of data higher than DL and the number of recorded abnormal events.

The median and the geometric mean are really close. The largest values are obtained for the arithmetic mean and then for the robust mean. This observation can be easily explained by the presence of some 'outlier' dose assessments which have decreasing weight in calculating arithmetic mean to robust and finally to geometric mean and median.

Table 72: Central estimates of doses assessed for Worker 1, Worker 2 and Worker 3.
nd: not determined because some dose estimates are equal to 0.

Effective dose (mSv)	*Median*	*Arithmetic mean*	*Geometric mean*	*Robust mean*
Worker 1	16	26	17	24
Worker 2	4.2	20	3.3	6.3
Worker 3	1.4	8.5	nd	1.6
Lung equivalent dose (mSv)	*Median*	*Arithmetic mean*	*Geometric mean*	*Robust mean*
Worker 1	36	90	23	51
Worker 2	5.1	93	4.0	22
Worker 3	1.1	7.1	nd	2.0
Kidney equivalent dose (mSv)	*Median*	*Arithmetic mean*	*Geometric mean*	*Robust mean*
Worker 1	43	160	58	91
Worker 2	5.3	15	5.1	10
Worker 3	8.3	72	nd	12

5.2 Dispersion of dose assessments

The dispersion estimates presented in Table 1 to Table 9 are gathered in Table 73. The ratios of maximum values to minimum values are much higher than the factor of three usually acknowledged by experts for internal dose uncertainty.

Because of discrepancy between JEM and bioassay data, Worker 2 exposure was the most uncertain as compared to the other two workers. That is why the result dispersion appears to be the greatest for Worker 2 for total committed effective and lung equivalent doses.

The kidney equivalent dose seems to be the least sensitive to uncertainty because doses are estimated mostly from urine data strongly correlated to systemic doses.

Table 73: Dispersion estimates of doses assessed for Worker 1, Worker 2 and Worker 3. SD: standard deviation; nd: not determined because some dose are equal to 0.

Effective dose	*Ratio Max/Min*	*Relative SD (%)*	*Geometric SD*	*Robust SD (mSv)*
Worker 1	35	92%	2.6	22
Worker 2	6100	300%	7.0	6.8
Worker 3	nd	290%	nd	1.7
Lung equivalent dose	*Ratio Max/Min*	*Relative SD*	*Geometric SD*	*Robust SD (mSv)*
Worker 1	13000	180%	8.7	52
Worker 2	380000	340%	21	32
Worker 3	nd	230%	nd	2.7
Kidney equivalent dose	*Ratio Max/Min*	*Relative SD*	*Geometric SD*	*Robust SD (mSv)*
Worker 1	1800	170%	4.8	100
Worker 2	1400	140%	5.9	12
Worker 3	nd	240%	nd	14

5.3 Sources of uncertainty

As explained before, results were corrected for mistakes. The dispersion of results is due to uncertainty only. The sources of this uncertainty were identified by comparing the procedures used by the different participant to assess doses. All these procedures after mistake corrections were judged by the participants as reasonable. The ranges of different reasonable approaches considered as uncertainty source are:

- for the choice of intake regimes:
  - only acute intakes as recommended by ICRP Publications 78 and 130 and ISO standard 27048,
  - only chronic intakes,
  - chronic intakes to model “normal” exposure and acute intakes for “special” exposures;
- for the definition of acute intakes:
  - at the middle of a monitoring interval to assess doses for “normal” exposure,
  - only for identified events or incidents;
- for the definition of chronic intakes:
  - a single chronic intake over career,
  - based on JEM,
  - based on bioassay data,
  - based on both JEM and bioassay data;
- for the choice absorption to blood:
  - reference types F, M or S only,
  - mixtures of types,
  - specific absorption for known chemical forms,
  - when the chemical form of uranium is unknown:
    - F+M+S mixture,

        - the most likely absorption type, based on JEM for other periods,
        - type M as recommended by ICRP,
        - the absorption type with the highest goodness of fit;
- for choosing between mass and activity when both results are available:
    - activity preferred, to avoid assumptions on isotopic composition,
    - mass preferred,
    - lower DL, to be conservative,
    - higher result, to be conservative,
    - both results, to use all available data;
- for the SF values:
    - for urine concentration converted into daily urine by volume:
        - SF = 1.6,
        - SF = 2.5 for mass measurements and 1.6 for activity;
    - for 48h faecal samples:
        - SF = 2.5,
        - SF = 3;
- for the substraction of the alimentary background:
    - substraction of a reference value,
    - no subtraction;
- for the treatment of data below DL
    - treating data below DL as such,
    - replacing below DL data with a numerical quantified result value:
        - 0,
        - DL/2,
        - DL/4,
        - DL,
        - DL.(1-f) with *f* being the frequency of below DL data over the dataset;
- for the intake assessment method:
    - maximum likelihood fit of all data and intakes simultaneously,
    - serially, maximum likelihood of one intake at a time,
    - one intake per bioassay data, at the middle of time interval between data.

5.4 Assessment of uncertainty on dose

As every participant carried out his best protocol to assess doses, all protocols differ on several items and not only on a single one. Therefore, it is not directly possible, from the results of this intercomparison to identify the most critical parameters for dose assessments and to quantify their influence on doses.

In order to do so, it is planned to continue this work with a sensitivity study: doses will be assessed for the three workers according to a reference protocol which still needs to be defined. Then each reasonable modelling assumption not retained in the reference protocol will iteratively be used to estimate doses. In this way, the influence of each modelling assumption on dose estimate will be quantified.

Moreover, the reference protocol may also contribute to guidelines to estimate doses for epidemiological studies and for compensation claims.

6. Conclusion

Exposure and bioassay data of three workers occupationally exposed to uranium were distributed inside EURADOS Working Group 7 on Internal Dosimetry to provide an intercomparison of calculated lifetime doses. This exercise was particularly difficult because of the complexity of the available data, of missing information, of the proportion of below DL data and of the lack of guidelines on how to estimate lifetime doses.

16 participants estimated total committed effective dose, total equivalent doses to the lungs and to the kidneys for at least one of the three workers. Worker 1 presented a large number of bioassay and several recorded incidents; Worker 2 only one data over 19 was higher than the DL and this data was obtained at a time where exposure was not possible according to the JEM; the 75 bioassay of Worker 3 were all below detection limit.

The dispersion of the dose assessments is important, higher than the factor of three usually acknowledged for internal dose uncertainty. From the description provided by the participants, the protocols to evaluate doses were reviewed in details and sources of uncertainty along with reasonable modelling assumptions were identified. However, since all protocols were very different from each other, it was not possible to identify the most critical uncertainty sources and to quantify their influence on the dose calculation.

This work will be used as a basis for defining guidelines to reconstruct lifetime doses for epidemiological studies and for compensation claims. Finally, the influence of the different uncertainty sources on the dose will be estimated by carrying a sensitivity study comparing dose assessed by applying the guidelines with doses calculated using other reasonable modelling assumptions identified in this intercomparison.

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8. Annexe 1: Data provided to participants

8.1 Bioassay data

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 1	18/6/1964	Routine	Urine		U_mass	µg/l	<5			
Worker 1	21/12/1964	Routine	Urine		U_mass	µg/l	<5			
Worker 1	30/12/1965	Routine	Urine		U_mass	µg/l	<5			
Worker 1	16/9/1966	Routine	Urine		U_mass	µg/l	<5			
Worker 1	13/12/1966	Incident	Urine 24h		U_mass	µg/l	<5	U_activity	pCi	25
Worker 1	14/12/1966	Incident	Urine 24h		U_activity	pCi	15			
Worker 1	7/3/1967	Incident	Urine		U_mass	µg/l	<5	U_activity	pCi/l	25
Worker 1	8/3/1967	Incident	Urine		U_mass	µg/l	<5	U_activity	pCi/l	5
Worker 1	17/3/1967	Routine	Urine		U_mass	µg/l	<5			
Worker 1	18/3/1967	Incident	Urine		U_mass	µg/l	24	U_activity	pCi/l	10
Worker 1	20/3/1967	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	13/6/1967	Incident	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	28/6/1967	Routine	Urine		U_activity	pCi/l	199			
Worker 1	26/7/1967	Routine	Urine		U_mass	µg/l	<5			
Worker 1	31/7/1967	Routine	Faeces		U_activity	pCi	1644			
Worker 1	17/9/1967	Routine	Urine		U_mass	µg/l	5	U_activity	pCi/l	10

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 1	10/11/1967	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	109
Worker 1	13/11/1967	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	2/7/1968	Routine	Urine		U_activity	pCi/l	16			
Worker 1	3/7/1968	Routine	Urine		U_mass	µg/l	<5			
Worker 1	23/7/1968	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	26/8/1968	Routine	Urine		U_activity	pCi/l	5			
Worker 1	10/9/1968	Incident	Urine	UF_6 inhalation	U_mass	µg/l	<5	U_activity	pCi/l	41
Worker 1	23/9/1968	Routine	Urine		U_activity	pCi/l	17			
Worker 1	24/9/1968	Routine	Faeces		U_mass	µg/g ash	31	U_activity	pCi	662
Worker 1	26/9/1968	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	34
Worker 1	9/10/1968	Exceptionnal	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	15/10/1968	Routine	Faeces 48h		U_activity	pCi	787			
Worker 1	15/10/1968	Routine	Urine		U_mass	µg/l	6	U_activity	pCi/l	10
Worker 1	9/11/1968	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	11/11/1968	Routine	Faeces 48h		U_mass	µg/g ash	6	U_activity	pCi	261
Worker 1	17/12/1968	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	15/1/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	10/2/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	12/3/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	5
Worker 1	8/4/1969	Routine	Urine		U_mass	µg/l	<5			

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 1	6/5/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	3/6/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	2/7/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	25/8/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 1	2/12/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	18
Worker 1	16/12/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	24
Worker 1	16/2/1970	Routine	Urine		U_activity	pCi/l	5			
Worker 1	9/3/1970	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	80
Worker 1	9/4/1970	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	4/5/1970	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	1/6/1970	Routine	Urine		U_activity	pCi/l	60			
Worker 1	3/6/1970	Routine	Urine		U_activity	pCi/l	5			
Worker 1	18/6/1970	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	18/9/1970	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	26/10/1970	Routine	Urine		U_activity	pCi/l	8			
Worker 1	23/11/1970	Routine	Urine		U_activity	pCi/l	10			
Worker 1	21/12/1970	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	15/3/1971	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	12/4/1971	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	17/5/1971	Routine	Urine		U_activity	pCi/l	8			

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 1	14/6/1971	Routine	Urine		U_activity	pCi/l	9			
Worker 1	2/8/1971	Routine	Urine		U_activity	pCi/l	16			
Worker 1	30/8/1971	Incident	Urine		U_activity	pCi/l	53.4			
Worker 1	13/9/1971	Routine	Urine	Inhalation	U_activity	pCi/l	9			
Worker 1	23/9/1971	Incident	Urine 24h	Wound	U_activity	pCi	16.6			
Worker 1	18/10/1971	Routine	Urine		U_activity	pCi/l	18			
Worker 1	15/11/1971	Routine	Urine		U_activity	pCi/l	12			
Worker 1	20/12/1971	Routine	Urine		U_activity	pCi/l	13			
Worker 1	17/1/1972	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	14/2/1972	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	13/3/1972	Routine	Urine		U_activity	pCi/l	12			
Worker 1	17/4/1972	Routine	Urine		U_activity	pCi/l	7			
Worker 1	15/5/1972	Routine	Urine		U_activity	pCi/l	50			
Worker 1	23/5/1972	Incident	Urine 24h		U_activity	pCi	54			
Worker 1	19/6/1972	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	3/7/1972	Routine	Urine		U_activity	pCi/l	6			
Worker 1	31/7/1972	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	18/9/1972	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	16/10/1972	Routine	Urine		U_activity	pCi/l	14			
Worker 1	20/11/1972	Routine	Urine		U_activity	pCi/l	10			

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 1	18/12/1972	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	15/1/1973	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	11/2/1973	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	19/3/1973	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	16/4/1973	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	14/5/1973	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	18/6/1973	Routine	Urine		U_activity	pCi/l	5			
Worker 1	6/8/1973	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	17/9/1973	Routine	Urine		U_activity	pCi/l	10			
Worker 1	15/10/1973	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	19/11/1973	Routine	Urine		U_activity	pCi/l	9			
Worker 1	17/12/1973	Routine	Urine		U_activity	pCi/l	<5			
Worker 1	21/1/1974	Routine	Urine		U_activity	pCi/l	19			
Worker 1	18/2/1974	Routine	Urine		U_activity	pCi/l	13.5			
Worker 1	4/3/1974	Incident	Spot urine		U_activity	pCi/l	117			
Worker 1	5/3/1974	Incident	Urine 24h	UF_6	U_activity	pCi/l	899			
Worker 1	14/3/1974	Incident	Spot urine		U_activity	pCi/l	2.8			
Worker 1	15/3/1974	Incident	Urine 24h		U_activity	pCi/l	20.04			
Worker 1	18/3/1974	Routine	Urine		U_activity	pCi/l	7.5			
Worker 1	27/3/1974	Routine	Faeces		U_activity	pCi	940			

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 1	16/4/1974	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	20/5/1974	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	17/6/1974	Routine	Urine		U_activity	pCi/l	48			
Worker 1	16/9/1974	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	14/10/1974	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	17/11/1974	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	16/12/1974	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	17/1/1975	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	17/2/1975	Routine	Urine		U_activity	pCi/l	75			
Worker 1	17/3/1975	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	14/4/1975	Routine	Urine		U_activity	pCi/l	15			
Worker 1	19/5/1975	Routine	Urine		U_activity	pCi/l	14			
Worker 1	16/6/1975	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	18/8/1975	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	15/9/1975	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	20/10/1975	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	17/11/1975	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	15/12/1975	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	19/1/1976	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	16/2/1976	Routine	Urine		U_activity	pCi/l	<10			

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 1	15/3/1976	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	17/5/1976	Routine	Urine		U_activity	pCi/l	10			
Worker 1	14/6/1976	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	13/9/1976	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	18/10/1976	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	15/11/1976	Routine	Urine		U_activity	pCi/l	10			
Worker 1	20/12/1976	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	17/1/1977	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	16/2/1977	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	14/3/1977	Routine	Urine		U_activity	pCi/l	42			
Worker 1	18/4/1977	Routine	Urine		U_activity	pCi/l	37			
Worker 1	16/5/1977	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	13/6/1977	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	11/7/1977	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	8/8/1977	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	19/9/1977	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	17/10/1977	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	14/11/1977	Routine	Urine		U_activity	pCi/l	42			
Worker 1	12/12/1977	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	16/1/1978	Routine	Urine		U_activity	pCi/l	<10			

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 1	13/2/1978	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	13/3/1978	Routine	Urine		U_activity	pCi/l	17			
Worker 1	17/4/1978	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	15/5/1978	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	12/6/1978	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	14/8/1978	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	18/9/1978	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	16/10/1978	Routine	Urine		U_activity	pCi/l	12			
Worker 1	13/11/1978	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	11/12/1978	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	22/1/1979	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	19/2/1979	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	19/3/1979	Routine	Urine		U_activity	pCi/l	18			
Worker 1	14/5/1979	Routine	Urine		U_activity	pCi/l	13			
Worker 1	20/5/1979	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	17/9/1979	Routine	Urine		U_activity	pCi/l	30			
Worker 1	15/10/1979	Routine	Urine		U_activity	pCi/l	12			
Worker 1	12/11/1979	Routine	Urine		U_activity	pCi/l	14			
Worker 1	18/12/1979	Routine	Urine		U_activity	pCi/l	55			
Worker 1	28/1/1980	Routine	Urine		U_activity	pCi/l	<10			

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 1	25/2/1980	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	25/3/1980	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	21/4/1980	Routine	Urine		U_activity	pCi/l	18			
Worker 1	19/5/1980	Routine	Urine		U_activity	pCi/l	<10			
Worker 1	23/6/1980	Routine	Urine		U_activity	pCi/l	<10			
Worker 2	2/10/1962	Routine	Urine		U_mass	µg/l	<5			
Worker 2	4/2/1963	Routine	Urine		U_mass	µg/l	<5			
Worker 2	16/5/1963	Routine	Urine		U_mass	µg/l	<5			
Worker 2	6/11/1963	Routine	Urine		U_mass	µg/l	<5			
Worker 2	2/4/1964	Routine	Urine		U_mass	µg/l	<5			
Worker 2	23/10/1964	Routine	Urine		U_mass	µg/l	<5			
Worker 2	8/1/1965	Routine	Urine		U_mass	µg/l	<5			
Worker 2	1/4/1965	Routine	Urine		U_mass	µg/l	<5			
Worker 2	2/8/1965	Routine	Urine		U_mass	µg/l	4			
Worker 2	2/11/1965	Routine	Urine		U_mass	µg/l	<5			
Worker 2	1/2/1966	Routine	Urine		U_mass	µg/l	<5			
Worker 2	11/5/1967	Routine	Urine		U_mass	µg/l	<5			
Worker 2	10/11/1967	Routine	Urine		U_mass	µg/l	<5			
Worker 2	15/5/1968	Routine	Urine		U_mass	µg/l	<5			
Worker 2	26/6/1968	Routine	Urine		U_mass	µg/l	<5			

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 2	13/11/1968	Routine	Urine		U_mass	µg/l	<5			
Worker 2	8/1/1969	Routine	Urine		U_mass	µg/l	<5			
Worker 2	29/4/1969	Routine	Urine		U_mass	µg/l	<5			
Worker 2	12/11/1969	Routine	Urine		U_mass	µg/l	<5			
Worker 3	19/6/1968	Routine	Urine		U_mass	µg/l	<5			
Worker 3	22/9/1968	Routine	Urine		U_mass	µg/l	<5			
Worker 3	16/12/1968	Routine	Urine		U_mass	µg/l	<5			
Worker 3	11/3/1969	Routine	Urine		U_mass	µg/l	<5			
Worker 3	2/6/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 3	22/9/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 3	16/12/1969	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 3	9/3/1970	Routine	Urine		U_mass	µg/l	<5	U_activity	pCi/l	<5
Worker 3	1/6/1970	Routine	Urine		U_activity	pCi/l	<5			
Worker 3	26/10/1970	Routine	Urine		U_activity	pCi/l	<5			
Worker 3	21/6/1971	Routine	Urine		U_activity	pCi/l	<5			
Worker 3	26/6/1972	Routine	Urine		U_activity	pCi/l	<5			
Worker 3	23/10/1972	Routine	Urine		U_activity	pCi/l	<5			
Worker 3	26/12/1972	Routine	Urine		U_activity	pCi/l	<5			
Worker 3	25/6/1973	Routine	Urine		U_activity	pCi/l	<10			
Worker 3	22/10/1973	Routine	Urine		U_activity	pCi/l	<5			

identification number	Sampling date	reason for sampling = type of monitoring	type of bioassay sample		measurement technique 1	bioassay unit 1	bioassay result 1	measurement technique 2	bioassay unit 2	bioassay result 2
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 3	22/4/1974	Routine	Urine		U_activity	pCi/l	<10			
Worker 3	21/6/1974	Routine	Urine		U_activity	pCi/l	<10			
Worker 3	14/10/1974	Routine	Urine		U_activity	pCi/l	<10			
Worker 3	23/12/1974	Routine	Urine		U_activity	pCi/l	<10			
Worker 3	23/6/1975	Routine	Urine		U_activity	pCi/l	<10			
Worker 3	22/12/1975	Routine	Urine		U_activity	pCi/l	<10			
Worker 3	25/10/1976	Routine	Urine		U_activity	pCi/l	<10			
Worker 3	25/4/1977	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	26/10/1977	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	15/12/1977	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	20/2/1978	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	24/4/1978	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	19/6/1978	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	21/8/1978	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	23/10/1978	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	18/12/1978	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	26/2/1979	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	23/4/1979	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	18/6/1979	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	27/8/1979	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10

identification number	*Sampling date*	*reason for sampling = type of monitoring*	*type of bioassay sample*		*measurement technique 1*	*bioassay unit 1*	*bioassay result 1*	*measurement technique 2*	*bioassay unit 2*	*bioassay result 2*
id_worker	**sample_date**	**monitoring**	**sample_type**	**comment**	**meas1**	**unit1**	**result1**	**meas2**	**unit2**	**result2**
Worker 3	22/10/1979	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	9/3/1980	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	28/4/1980	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	23/6/1980	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	20/10/1980	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	15/12/1980	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	27/2/1981	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	24/4/1981	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	28/8/1981	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	23/10/1981	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10
Worker 3	11/12/1981	Routine	Urine		U_mass	µg/l	<7	U_activity	pCi/l	<10

8.2 Job exposure matrix (JEM)

Note : semi-quantitative indication of potential exposure level from 0 to 3 is expressed in terms of frequency (freq.) of potential exposure and quantity (quant.) of handled material. 0 means no possible exposure.
Based on job profile, occupational medicine records, interviews, experts' consensus and investigation.

uranium enrichment →		*natural uranium*						*reprocessed uranium*							
U compound absorption type →		*Type F*		*Type M*		*Type S*		*Type F*		*Type M*		*Type S*		*start of potential exposure period*	*end of potential exposure*
level of potential exposure →		*freq.*	*quant.*	*freq.*	*quant.*	*freq.*	*quant.*	*freq.*	*quant.*	*freq.*	*quant.*	*freq.*	*quant.*		
id_worker	**job**														
Worker 1	31_DT-AT4	0	0	0	0	0	0	0	0	0	0	0	0	17/9/1962	31/12/1963
Worker 1	31_DT-AT4	0	0	0	0	0	0	0	0	0	0	0	0	1/1/1964	31/12/1965
Worker 1	31_DT-AT4	0	0	0	0	0	0	0	0	0	0	0	0	1/1/1966	30/6/1966
Worker 1	77_UDG1	3	2	0	0	0	0	0	0	0	0	0	0	1/7/1966	31/12/1966
Worker 1	77_UDG1	3	2	0	0	0	0	0	0	0	0	0	0	1/1/1967	7/1/1969
Worker 1	77_UDG1	3	2	0	0	0	0	0	0	0	0	0	0	8/1/1969	31/12/1973
Worker 1	77_UDG1	3	2	0	0	0	0	0	0	0	0	0	0	1/1/1974	31/12/1974
Worker 1	77_UDG1	3	3	0	0	0	0	0	0	0	0	0	0	1/1/1975	31/12/1976
Worker 1	3_CME4	1	1	1	1	0	0	0	0	0	0	0	0	1/1/1977	31/3/1979
Worker 1	3_CME4	1	1	1	1	0	0	0	0	0	0	0	0	1/4/1979	30/9/1980
Worker 2	79_CEA1	3	3	1	1	1	1	0	0	0	0	0	0	1/6/1963	31/12/1963
Worker 2	0_ADM	0	0	0	0	0	0	0	0	0	0	0	0	1/1/1964	31/12/1966
Worker 2	31_DT-AT4	0	0	0	0	0	0	0	0	0	0	0	0	1/1/1967	7/1/1969
Worker 2	31_DT-AT4	0	0	0	0	0	0	0	0	0	0	0	0	8/1/1969	31/12/1971

uranium enrichment →		*natural uranium*						*reprocessed uranium*							
U compound absorption type →		*Type F*		*Type M*		*Type S*		*Type F*		*Type M*		*Type S*		*start of potential exposure period*	*end of potential exposure*
level of potential exposure →		*freq.*	*quant.*	*freq.*	*quant.*	*freq.*	*quant.*	*freq.*	*quant.*	*freq.*	*quant.*	*freq.*	*quant.*		
id_worker	**job**														
Worker 2	31_DT-AT4	0	0	0	0	0	0	0	0	0	0	0	0	1/1/1972	31/12/1973
Worker 2	31_DT-AT4	0	0	0	0	0	0	0	0	0	0	0	0	1/1/1974	31/12/1974
Worker 2	31_DT-AT4	0	0	0	0	0	0	0	0	0	0	0	0	1/1/1975	31/12/1976
Worker 2	31_DT-AT4	3	3	0	0	0	0	0	0	0	0	0	0	1/1/1977	31/3/1979
Worker 2	31_DT-AT4	3	3	0	0	0	0	0	0	0	0	0	0	1/4/1979	31/1/1982
Worker 2	31_DT-AT4	3	3	0	0	0	0	0	0	0	0	0	0	1/2/1982	30/9/1982
Worker 3	77_UDG1	3	2	0	0	0	0	0	0	0	0	0	0	26/7/1965	31/12/1966
Worker 3	77_UDG1	3	2	0	0	0	0	0	0	0	0	0	0	1/1/1967	7/1/1969
Worker 3	77_UDG1	3	2	0	0	0	0	0	0	0	0	0	0	8/1/1969	31/12/1973
Worker 3	77_UDG1	3	2	0	0	0	0	0	0	0	0	0	0	1/1/1974	31/12/1974
Worker 3	77_UDG1	3	3	0	0	0	0	0	0	0	0	0	0	1/1/1975	31/12/1976
Worker 3	77_UDG1	3	3	0	0	0	0	0	0	0	0	0	0	1/1/1977	31/5/1978
Worker 3	77_UDG1	3	3	0	0	0	0	0	0	0	0	0	0	1/6/1978	31/12/1981
Worker 3														1/1/1982	31/1/1982

8.3 Incident register

identification number for the worker	*time of intake*			*radionuclide or element or chemical form*	*body localisation of initial contamination*	*intake pathway*
	day/month/year	*hour:minutes*				
id_worker	**Date_Incid**	**Time_Incid**	**Description**	**Radionuclide**	**Localisation_Conta**	**Intake_path**
Worker 1	17/03/1967	15:30	Was filling a vinyl barrel; wounded his left hand when removing it from the contaminated material	U238	left hand	Wound
Worker 1	10/11/1967	08:25	floor decontamination, filter overflowing, hairs were contaminated	U235	hair	External contamination
Worker 1	03/06/1970	15:58	following MDU alarm setting off	U		Inhalation
Worker 1	30/08/1971		Probable HF leakage from glovebox	U		Inhalation
Worker 1	23/09/1971	15:05	Right side hit handle of transport device	uranyl nitrate	right side	Wound
Worker 1	23/05/1972	09:00	Probable uranium inhalation	U		Inhalation
Worker 1	04/03/1974	16:15	Uranyl nitrate projection	uranyl nitrate		Inhalation
Worker 1	14/03/1974	16:00	Probable inhalation of uranium dust from unknown source	U		Inhalation

9. Annexe 2: Template provided to participants for compiling results

Dose estimations for Worker_1

Click on column head to obtain some precisions

Parameters of dose reconstruction

Intake number	*Intake pattern*	*Intake start date*	*Intake end date*	*Radionuclide*	*Pathway*	*AMAD (µm)*	*Absorption Type*	f_r	s_r (d^{-1})	s_s (d^{-1})	f_1 or f_A

Please add lines as needed

Results of dose reconstruction

Intake number	*Intake (Bq)*	*Committed effective dose (Sv)*	*Lung committed equivalent dose (Sv)*	*Kidney committed equivalent dose (Sv)*

Please add lines as needed

Total committed effective dose (Sv)	*Total lung committed equivalent dose (Sv)*	*Total kidney committed equivalent dose (Sv)*

Bioassay used for the dose reconstruction

Urine data

Date of bioassay	*Bioassay result*	*Bioassay unit*	*Uncertainty type*	*Uncertainty value*	*Data used to calculate intake #*

Please add lines as needed

Faecal data

Date of bioassay	*Bioassay result*	*Bioassay unit*	*Uncertainty type*	*Uncertainty value*	*Data used to calculate intake #*

Please add lines as needed

10. Annexe 3: Template provided to participants for compiling modelling

EURADOS
European Radiation Dosimetry Group e.V.

- WG7 "INTERNAL DOSIMETRY" -

Exercise of dose reconstruction in the frame of epidemiological studies of uranium workers

Questionnaire on dose estimation

PLEASE SEND FILLED QUESTIONNAIRE TO ESTELLE DAVESNE (estelle.davesne@irsn.fr) OR ERIC BLANCHARDON (eric.blanchardon@irsn.fr) UP TO 30TH JUNE 2016

YOU ARE ENCOURAGED TO ANSWER AS MANY QUESTIONS AS POSSIBLE, BUT ALL ARE NOT COMPULSORY.

YOUR NAME:
INSTITUTION:
EMAIL ADDRESS:

1. Measurement results

1.1. Did you process the numerical values of urine measurement? How?

1.2. Did you process the numerical values of faecal measurement? How?

1.3. If both mass and activity measurements were available on the same day, which one did you use?

1.4. Did you take the dietary background of uranium into account? How?

2. Models and parameters

2.1. Which biokinetic model did you use for the respiratory tract?

2.2. Which biokinetic model did you use for the gastro-intestinal tract?

2.3. Which biokinetic model did you use for the wound?

2.4. Which systemic biokinetic model did you use?

2.5. Which dosimetric model did you use?

2.6. How did you define periods of chronic intake (if any)?

3. Assessment method

3.1. How did you evaluate intakes?

3.2. How did you evaluate doses?

3.3. Did you use software? Which one?

3.4. How did you assess doses for Worker 3 having only "less than detection limit" data?

3.5. When there were several intake regimes, did you fit all intakes simultaneously or each intake separately?

3.6. When a positive measurement result was not related to any known incident, did you assume that it was due to a chronic intake (over which period),to an acute intake (at which time) or did you discard it?

3.7. What did you do if a registered incident was not followed by any bioassay?

3.8. How did you associate bioassay results with incidents? (if applicable)

3.9. How did you associate bioassay results with potential chronic exposure periods? (if applicable)

4. Do you have other comments, questions, or concerns?