Published in final edited form as:
Radiat Res. 2015 June ; 183(6): 632–642. doi:10.1667/RR14006.1.

Dose Estimation for a Study of Nuclear Workers in France, the United Kingdom and the United States of America: Methods for the International Nuclear Workers Study (INWORKS)

I. Thierry-Chef[a,1], **D. B. Richardson**[b], **R. D. Daniels**[c], **M. Gillies**[d], **G. B. Hamra**[e], **R. Haylock**[f], **A. Kesminiene**[a], **D. Laurier**[g], **K. Leuraud**[g], **M. Moissonnier**[a], **J. O'Hagan**[f], **M. K. Schubauer-Berigan**[c], **E. Cardis**[h,i,j], and **INWORKS Consortium**

[a] International Agency for Research on Cancer, Lyon, France

[b] Department of Epidemiology, University of North Carolina, Chapel Hill, North Carolina

[c] National Institute for Occupational Safety and Health, Cincinnati, Ohio

[d] Public Health England, Centre for Radiation, Chemical and Environmental Hazards (PHE-CRCE), Chilton, Didcot, Oxon, United Kingdom

[e] Department of Environmental and Occupational Health, Drexel University School of Public Health, Philadelphia, Pennsylvania

[f] Public Health England, Centre for Radiation, Chemical and Environmental Hazards (PHE-CRCE), Moor Row, Cumbria, United Kingdom

[g] Institut de Radioprotection et de Sûreté Nucléaire (IRSN), PRP-HOM/SRBE/LEPID, Fontenay aux Roses, France

[h] Center for Research in Environmental Epidemiology (CREAL), Barcelona, Spain

[i] Universitat Pompeu Fabra (UPF), Barcelona, Spain

[j] CIBER Epidemiología y Salud Pública (CIBERESP), Madrid, Spain

Abstract

In the framework of the International Nuclear Workers Study conducted in France, the UK and the U.S. (INWORKS), updated and expanded methods were developed to convert recorded doses of ionizing radiation to estimates of organ doses or individual personal dose equivalent [$H_p(10)$] for a total number of 308,297 workers, including 40,035 women. This approach accounts for differences in dosimeter response to predominant workplace energy and geometry of exposure and for the recently published ICRP report on dose coefficients for men and women separately. The overall mean annual individual personal dose equivalent, including zero doses, is 1.73 mSv [median = 0.42; interquartile range (IQR): 0.07, 1.59]. Associated individual organ doses were estimated. INWORKS includes workers who had potential for exposure to neutrons. Therefore, we analyzed neutron dosimetry data to identify workers potentially exposed to neutrons. We created a

---

[1] Address for correspondence: 150 Cours Albert Thomas, 69372 Lyon cedex 08, France; thierrychefi@iarc.fr.

Editor's note. The online version of this article (DOI: 10.1667/RR14006.1) contains supplementary information that is available to all authorized users.

time-varying indicator for each worker, classifying them according to whether they had a positive recorded neutron dose and if so, whether their neutron dose ever exceeded 10% of their total external penetrating radiation dose. The number of workers flagged as being exposed to neutrons was 13% for the full cohort, with 15% of the cohort in France, 12% of the cohort in the UK and 14% in the U.S. We also used available information on *in vivo* and bioassay monitoring to identify workers with known depositions or suspected internal contaminations. As a result of this work, information is now available that will allow various types of sensitivity analyses.

INTRODUCTION

As part of the International Collaborative Study of Cancer among Radiation Workers (1–5), methods were developed to derive estimates of organ doses and measures of uncertainty in these dose estimates, from historical records of annual external doses for nuclear industry workers in 15 countries (6, 7). Development of these methods, based on previously published work (8–11), commenced with a systematic review of historical monitoring practices and dosimeters used in participating facilities to identify potential biases and uncertainties. Based on this a number of representative dosimeters were selected from those used historically in facilities in France, the United Kingdom and the United States. Controlled experiments were conducted on phantoms to determine their response to different geometries and energies of exposure found in the facilities participating in the study. Next, panels of experts were convened to characterize typical exposures of workers at nuclear facilities in terms of photon energies and geometries (12). A database of correction factors was created to convert historical recorded dose values to estimates of organ doses for workers in each facility, adjusting for variations in dosimeter response to predominant energy and geometry of exposure (conditions of exposure), as well as yielding estimates of uncertainty (6, 7). The same methodology was further extended to the U.S. cohort (13).

Building upon prior work, an international consortium of investigators, led by the International Agency for Research on Cancer (IARC), has undertaken an updated study of cohorts of nuclear workers in France, the UK and U.S., referred to as the International Nuclear Workers Study (INWORKS). While including fewer countries than the prior 15-country study, INWORKS encompasses more than twice the number of cancer deaths due to cancer of the parent study, reflecting updated follow-up of these cohorts and expanded cohort definitions (14–21).

The current article summarizes the methods implemented in the parent study (7) and applied in INWORKS to convert nuclear workers' recorded doses to estimates of the mean absorbed dose to an organ of interest (i.e., D_T) or personal dose equivalent in soft tissue at a depth of 10 mm [i.e., $H_p(10)$] (22, 23). Correction factors accounting for differences in dosimeter response to conditions of exposure have been modified from previous work (7) in accordance with recent recommendations from the International Commission on Radiological Protection (ICRP). These factors were derived from existing and newly gathered information acquired over the expanded period of observation in all three countries. Taken together, the information in this article allows for estimation of organ dose estimates, or $H_p(10)$ dose, from historical and contemporary radiation dose records from the nuclear industry in each country. This article focuses on external exposure to ionizing radiation from photons, while also addressing neutron dosimetry for nuclear workers in France, the UK and U.S.

MATERIALS AND METHODS

Collection of External Dosimetry Records

The INWORKS cohort is comprised of 308,297 workers (including 40,035 female workers) for whom individual external radiation dose estimates were recorded in participating nuclear facilities and calculated for each year of monitoring. Major efforts were made to obtain complete information regarding recorded doses for every individual. Details on the collection and abstraction of individual dosimetry records are described elsewhere.[2] Briefly, exposure information was abstracted from facility dosimetry records by researchers in each country who were blinded to the workers' disease and mortality status. These records were used in conjunction with other standard dose reconstruction practices (24) to estimate annual occupational doses accrued by each participating worker prior to and during the study observation period. The INWORKS study was approved by the IARC Ethics Committee.

Recruitment of study participants focused on a select list of nuclear facilities, within each of the three countries, where accrued dose primarily originated from external irradiation by low-linear energy transfer (low-LET) penetrating radiation, and had been reasonably well-measured since the beginning of the nuclear industry. Although the majority of occupational dose was attributed to exposures at these facilities, workers may have also been exposed during employment elsewhere. For this study, researchers made use of an array of exposure information (e.g., national dose registries, previous study information) to obtain more complete exposure histories for each study subject.

Types of Dosimeters Used, Conditions of Exposure and Dosimeter Response

Information on dosimeter types used to measure photon radiation was updated to include, when available, dosimeters used in the facilities participating in the study in recent years of follow-up (see Table 1). If no information was provided regarding implementation of new dosimeter types, we assumed that the latest type in use in a given facility remained unchanged.

Previously collected information about conditions of exposure was reviewed for INWORKS to encompass conditions of exposure in recent years. We had no indication of major changes in the exposure conditions of the facilities and therefore, our assessment of exposure conditions remained unchanged (12). It should be emphasized that our initial assessment already accounted for large variations in exposure conditions (7). As concluded previously (7, 25), we assume workers in the participating facilities were predominantly exposed to photon radiation in the range between 100 and 3,000 keV. The response of dosimeters in this energy range and for predominant geometries of exposure was therefore the primary concern in our evaluation of the dosimeters used in the participating facilities.

---

[2] Richardson DB, Thierry-Chef I, Kesminiene A, Cardis E. Combined analyses of mortality among nuclear workers - procedures document. Lyon, France, 2011.

Revised Bias and Uncertainty Factors (Correction Factors)

Response of dosimeters to energy and geometry of exposure combined with estimates of conditions of exposure in the workplace (taking into account calibration practices) were the basic data used to derive bias and uncertainty factors, expressed in terms of $H_p(10)$ values, for each period of time when a specific dosimeter type was used in a participating facility.

Conversion coefficients between $H_p(10)$ values and organ doses were updated to follow the recent ICRP publication 116 (23). These contemporary conversion coefficients were used to derive estimates of colon, lung and red bone marrow doses as well as female breast; the quantities of interest for the epidemiological analyses conducted in INWORKS.

Bias and uncertainty factors, specific for each facility and calendar period, were applied to recorded doses to generate corrected doses, which are on average, unbiased estimates of the organ dose of interest. The corrected doses were derived to ensure that time- and facility-specific corrections of systematic over- and underestimation of doses as well as associated uncertainties were performed. The dose-response analyses are therefore based on data comparable between countries and facilities.

As in prior work, errors related to laboratory practices (dosimeter processing and readings) were considered to have a minor impact on cumulative doses, since these are the sum of independent measurements. Administrative practices such as frequency of monitoring, criteria to monitor workers and rules to record missing or below-threshold doses were also evaluated as having minor impact on recorded doses, since these tend to have been remediated through rereading of old dosimeters and post hoc evaluations of doses for the facilities and time periods where practices might have led to systematic over- or underestimation of the doses (7).

Exposure to Neutrons

INWORKS includes workers who had potential for exposure to neutrons. In most facilities and time periods, if neutron doses were estimated for a worker then the neutron component of dose was recorded separately from photon dose. However, some facilities did not always distinguish between the sources of exposure in the worker's dose of record, and existing records were inadequate to determine the neutron contribution to the reported dose (25). In such situations we were not able to separate the component of dose due to photon exposure. The INWORKS analysis proceeds under the assumption that the vast majority of external recorded dose was due to photon radiation. Therefore, the photon component of the organ-absorbed doses is likely to be slightly overestimated for those individuals with contributions from neutrons included in recorded values.

One challenge encountered when estimating neutron doses was a lack of documented recording practices, which made it difficult to identify the neutron component of measured dose. Another important challenge remains in the design of neutron dosimeters suitable for detecting neutrons with energy ranging from about 1 meV to around 20 MeV (26). In the early 1950s multi-element film dosimeters were introduced for photon radiation monitoring. These film dosimeters typically included Cd, Ag or Rh filters dedicated to the estimation of doses from thermal neutrons. However, the technology was inadequate for measuring the full energy range, and neutrons in the range of 0.05 eV to 500 keV could not be measured at all. Neutron monitoring evolved over the years with increased capacity to measure neutrons from various energy ranges. NTA film dosimeters (nuclear emulsion) were introduced in the three participating countries in the 1950s and 1960s and were used for fast neutron detection. Albedo dosimeters were developed in parallel, with the main objective of measuring neutrons in a much wider energy range including intermediate neutrons (with energy between about 0.4 eV and 100 keV). However, albedo dosimeters must be calibrated specifically for conditions of each workplace, which should remain stable with time. Also, while they do detect neutrons with energies up to 100 keV with little energy dependence in terms of fluence, their dose equivalent response above 10 keV is very much lower. Etched track dosimeters were introduced in the 1980s and are mainly used to detect fast neutrons, although many systems are able to measure thermal neutrons as well. However, they are less likely to measure intermediate energy neutrons with acceptable efficiency, and they have poor angle dependence of response.

Only sparse information on the period of use of specific neutron dosimeter types in each participating facility was available from the questionnaires of the parent study, and it was not feasible to conduct detailed surveys on dosimeter types and conditions of exposure (i.e., energy and geometry of neutron fields in specific workplaces). Unrecorded neutron doses may arise from exposures outside the detection range of the dosimeter (e.g., neutrons of energies below the threshold for NTA film) or when the exposed worker was not monitored. Widespread personal neutron monitoring was rare in earlier years because dosimetry processing was difficult and expensive. Typically, groups of workers considered to have a low potential for substantial neutron exposures were not issued neutron dosimeters. In those cases, radiation exposure was controlled by limiting the duration of exposure and doses were not recorded. In addition, in some facilities where a potential for neutron exposures existed, only a fraction of the issued dosimetry was processed in each monitoring cycle.[3]

An additional issue for the recording of neutron doses arises from the reporting level employed by dosimetry services. In this study, the average annual $H_p(10)$ was only 1.73 mSv, so most positive photon dosimeter readings would have been only just above the reporting level. The neutron dose could be a significant fraction of the photon dose but still below the reporting threshold.

To evaluate possible unrecorded neutron doses, the distribution of neutron dose by time periods and facility was analyzed, together with the available information on neutron dosimetry technology in participating facilities. In principle, it should be possible to detect underestimation of neutron doses if, at the time when a new dosimeter was introduced, both the number of workers with positive neutron doses increased and neutron doses themselves increased (i.e., mean neutron dose increased). Distributions of neutron doses were therefore drawn for the facilities with a large number of workers monitored for neutrons (at least 1,000 workers in a given year). For each facility and each year of monitoring, we assessed: 1. the number of workers monitored for X rays and gamma rays; 2. the number of workers

---

[3] Personal communication. Summary of discussions between Drs. François Trompier (France, IRSN), Guenther Dietze (Germany), David Bartlett (UK), Timothy Taulbee (U.S., NIOSH) and Rick Tanner (UK, HPA). Meeting held in Lyon, France, February 2013.

monitored for neutrons; 3. the mean individual neutron dose (zero doses included); 4. the mean individual neutron dose (positive values only); and 5. the number of workers with positive values.

In addition, for analyses in INWORKS we used the available records of estimated neutron doses to construct categories of neutron exposure potential for the purposes of addressing concerns about confounding of associations between estimated external dose from photon exposure and mortality by neutron exposure.

RESULTS

Response of Dosimeters to Conditions of Exposure to Photon Radiation

Since the early 1990s [the period covered by a prior report (7)], thermoluminescent dosimeters have been widely used in France, the UK and the U.S. (Fig. 1), with reduced use of multi-element film dosimeters. Table 1 provides the characteristics of the dosimeters used in a selection of facilities [one nuclear power plant (NPP) and one “mixed activities” facility per country]. Updated estimated bias and uncertainty factors for $H_p(10)$ and several organ-specific doses are also provided for these in Table 1. A table is available from the authors upon request that provides information about the types of historical practices used over the range of employment settings, facilities and countries included in INWORKS. As mentioned previously, if no information was provided to us regarding implementation of new dosimeter types, we assumed that the latest type in use in a given facility remained unchanged.

Descriptive Analyses of Dose Estimates in $H_p(10)$

Doses were recorded in various dosimetric quantities, evolving with time periods and countries. The study of errors in dosimetry was conducted to ensure that photon doses, used for risk analyses, were comparable. Distributions of doses converted into $H_p(10)$ were analyzed to identify major trends in the evolution of doses. Figure 1 provides the 50th, 75th and 95th percentile of individual annual $H_p(10)$ values in mSv by country, as well as the number of workers employed in each country and each year, together with the main dosimeter types by period of use. While improvement in dosimetry technology cannot be considered as the only factor affecting dose distribution, since activities as well as radiation monitoring practices may have also changed, it can reflect evolution of the dosimetry practices in general.

Figure 1 shows that the workforce increased in the 1950s and 1960s in the UK and the U.S., reflecting increased nuclear activities for both military applications and development of nuclear electricity production. This workforce increase is associated with increasing individual annual doses. In France, the increase in the workforce is seen in the late 1960s until the early 1970s, the period when a general trend is the decrease of individual annual doses in the 1960s and 1970s. This decrease might be related to improved technologies, introduction of international rules and radiation protection regulations or decrease in production for some activities. Around the same time period, multi-element dosimeters were largely introduced together with international dosimetry inter-comparison studies.

A summary of individual annual doses and individual cumulative doses are provided in terms of $H_p(10)$, colon, lung, red bone marrow (RBM) and breast in Tables 2 and 3, respectively. Individual annual personal dose equivalent is, on average, 1.73 mSv [median = 0.42; interquartile range (IQR): 0.07, 1.59]. The mean individual annual personal dose equivalent varies from 0.93 in France to 2.26 in the UK, with a much larger dispersion in the latter country. The individual mean cumulative personal dose equivalent is 25.2 mSv (median = 3.4; IQR: 0.4, 18.4), being again higher in the UK and lower in France. In terms of organ doses, individual annual doses are on average lower (due to the depth of the organs considered), of the order of 1 mGy, except individual breast doses, in women, which are below 0.5 mGy. The mean annual personal dose equivalent for women of 0.53 mSv (median = 0.13; IQR: 0, 0.48) was much lower than the mean annual personal dose equivalent for men of 1.91 mSv (median = 0.50; IQR: 0.09, 1.82).

Exposure to Neutrons

With the introduction of new neutron dosimeters, there was neither a clear increase in mean annual doses (Appendix Fig. A1) nor a clear increase in the number of workers with positive recorded neutron doses. Changes in neutron dosimetry practices were often made in periods when activities also changed. Consequently, it was difficult to separate the impact of an increase in the number of workers with positive neutron dose from an increase in the workforce. Therefore, it was not feasible to quantify an underestimation of neutron doses in earlier historical periods compared to later historical periods.

Consequently, we created a time-varying indicator for each worker, classifying them according to whether they had a positive recorded neutron dose (flag 2), and if so, whether their neutron dose ever exceeded 10% of their total external penetrating radiation dose (flag 3). We looked more specifically at the ratio between neutron and photon doses for workers with annual photon dose greater than 1 mSv, and both neutron and photon doses recorded. The median, 5th and 95th percentiles of the neutron to photon dose ratio are 0.12, 0.007 and 1.42, respectively, reflecting the fact that, for the majority of workers with a positive recorded neutron dose, the magnitude of the annual neutron dose is small relative to the magnitude of the annual photon dose.

Table 4 shows the number of workers flagged for neutron exposure (flags 2 and 3) in each country. Thirteen percent of the full cohort was flagged for neutron exposure, with 15%, 12% and 14% flagged for France, the UK and the U.S., respectively.

DISCUSSION

Cohorts of nuclear industry workers have been followed for decades with the main objective being to assess for the risk of adverse health effects from protracted exposure to low doses of ionizing radiation. Combined analyses of these cohorts offer the potential to improve statistical precision of risk estimates. However, valid estimates of disease risk per unit exposure rely on valid and consistent dose estimates. Practices to measure and record radiation doses have evolved together with technology. Understanding the evolution of these practices is important in characterizing the main sources of errors in dose estimates, when doses in different countries and different time periods are measured to evaluate radiation risks. The method to quantify bias and uncertainty in photon dose estimates has been previously reported (7).

The French, UK and U.S. cohorts were followed until the end of 2004, 2001 and 2005, respectively. It should be noted that no major modification on photon dosimetry technology was undertaken in recent years in the participating facilities. Thermoluminescent dosimeters are now widely used in all three countries. The introduction of electronic dosimetry capable of real-time exposure monitoring is a key improvement in dosimetry technology, however, electronic dosimeters have yet to see widespread use as a primary dosimeter. This might change in the future, in which case quantification of the impact on doses will be required if further follow-up of the cohorts is undertaken. While major changes in exposure conditions might be due to decommissioning activities, our estimation of the variability in exposure conditions is wide enough to account for the introduction of these activities.

The resulting estimates of organ doses are somewhat different than those used in the 15-country study (7), since conversion coefficients between $H_p(10)$ dose values and specific organ doses have been updated using the new ICRP publication (ICRP 116) and coefficients were provided for men and women separately (23). Dose to the breast was estimated for women since they represent 13% of the INWORKS cohort, i.e., 40,035 workers.

We analyzed available neutron data and assessed the possibility of including reported neutron doses in the radiation burden of exposed workers. We also conducted analyses to identify periods with unrecorded/underestimated neutron doses due to the weakness of the early technology, to detect neutrons in wide energy ranges. From this analysis, it seemed unrealistic to correct doses without having clear information on work place allocation and work place estimation of conditions of exposure. In addition, the record of neutron dosimetry practice, especially indications of radiation weighting factors applied, were incomplete for some facilities. We therefore used neutron dosimetry data to construct a time-varying flag for workers in different categories of neutron exposure. Workers with a positive recorded neutron dose were flagged (flag 2) and among them, workers with a neutron dose ever exceeding 10% of the total external penetrating radiation dose were identified separately (flag 3). We recognize that there are several limitations to this approach. First, this approach does not overcome the problem of unrecorded neutron doses that arise either when workers were not monitored for neutrons (but were exposed to them) or when neutron doses were below the reporting threshold. Second, it does not address the problem of unidentified neutron doses that arise when workers were monitored for neutrons but data are only available for neutron dose summed with X-ray and gamma-ray doses (with no indication in the neutron dose field of the neutron component). In France and the U.S., neutron dose was recorded and computerized separately. However, in the UK NRRW records, for some sites/periods, the recorded external dose reflects measured photon and neutron doses, and we have not been able to separate out the photon component. The estimate of external dose was assumed to primarily reflect photon doses and the resulting organ absorbed doses are potentially overestimated for those individuals also exposed to neutrons.

Addressing these limitations would require an assessment of neutrons independent of available computerized neutron dosimetry data (e.g., exposure potential based on work location and activity). However, detailed job history data are not available for all workers (e.g., UK NRRW cohort members) and resources are not available for a systematic collection and classification of neutron exposure potential across INWORKS. To avoid exclusion of workers, sensitivity analyses will be conducted under different scenarios of dose distribution to assess the potential bias due to neutron exposure misclassification.

Some workers in the nuclear industry also received radiation dose from internal depositions of radionuclides including tritium. In France and the UK recorded doses, when available, were used together with information on exposure conditions to identify workers contaminated with tritium. In some periods, the tritium contribution to the dose might have been included in the recorded whole-body dose. In some U.S. facilities, tritium doses were recorded separately and used to identify workers exposed to tritium. Among the cohorts included in INWORKS, the vast majority had a relatively small tritium dose contribution, although tritium doses were an important part of the total dose at the Savannah River Site in the U.S. (27).

In general, reconstructing doses to individual organs from internal contamination requires knowledge of the characteristics of the contaminant and understanding of conditions of exposure to make use of the results of individual biological samples that are available in the dosimetry records of the participating facilities (25). Estimation of doses from intakes of radionuclides requires knowledge of the mode of intake, particle size, chemical form and solubility. Doses are received over a period that depends on retention of the nuclide in specific organs and complex models have been developed for dose estimation based on measurements of excretion (28, 29). Efforts are currently underway in participating countries to assess organ doses for contaminated workers, individually, but these are currently available only for a subset of contaminated workers (30). Therefore, this information could not be used in the current study to provide overall organ doses that integrate both internal and external exposures. In a future follow-up study of the cohorts, we might be able to do so, if organ doses from internal contamination could be evaluated for all contaminated workers. Major efforts were made, however, to identify and flag workers with potential for substantial doses from intake (>10% of the annual limit of intake). Criteria for flagging the workers varied between countries and facilities, they were all based on monitoring and/or workplace activities. Major efforts were made in the participating countries to refine flags for workers with known depositions or suspected contaminations. In INWORKS, workers who were flagged for internal contamination were not excluded from the analyses. In INWORKS, workers were grouped into two categories: those with known (or suspected) deposition and those with no contamination. The numbers of workers who were flagged for known deposition (France, UK and U.S.) and suspected deposition (UK) are provided per country in the Appendix. Sensitivity analyses will be conducted, using a variety of realistic scenarios that address the distribution of internal exposures in relevant participating facilities.

CONCLUSIONS

Within INWORKS, we conducted an analysis of the dosimetric data to: 1. Estimate organ doses for workers exposed to photon radiation with appropriate quantification of errors in doses; 2. Analyze neutron dose data to assess the possibility to include the neutron component of exposure in the dose estimation; and 3. Explore possibilities for also integrating organ doses from internal contamination.

Analysis of photon radiation was based on the work previously implemented in the 15-Country Study (7) and was updated to include additional years of monitoring in participating facilities and account for newly published ICRP dose coefficients for men and women separately. The mean annual individual dose in $H_p(10)$ is 1.73 mSv (median = 0.42; IQR: 0.07, 1.59). Individual doses were estimated for various organs of interest for cancer and noncancer risk evaluations. Neutron dose data, however, could be used only to flag workers with potential, mostly inadequately measured exposure to neutrons. Information on workers internally contaminated was used for flagging, however, estimation of organ doses due to internal contamination, if available, could not be integrated into the overall radiation burden. Future sensitivity analyses will be performed to evaluate the potential impact of missing doses from neutrons and internal contamination.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGMENTS

The authors would like to thank the participants at the February 2013 meeting held in Lyon, France: François Trompier (France, IRSN); Guenther Dietze (Germany); David Bartlett (UK), Timothy Taulbee (U.S., NIOSH) and Rick Tanner (UK, PHE) for the very fruitful discussion on neutron monitoring and associated impact on dose estimates. The authors are also very grateful to Drs. Mike Marshall, Ethel S. Gilbert, Celia Hacker and Francis Bermann for their support and careful reading of the manuscript. This work was funded by the National Institute for Occupational Safety and Health, U.S. Department of Energy through an agreement with the U.S. Department of Health and Human Services, and through a grant received by the University of North Carolina from the National Institute for Occupational Safety and Health (R03.OH-010056) and by the Ministry of Health, Labour and Welfare of Japan (GA No 2012-02-21-01). The construction of the French cohort was realized by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), with partial funding from AREVA Nuclear Cycle (AREVA NC) and Electricité de France (EDF). The construction of the UK cohort was undertaken by Public Health England (PHE), who operates the UK National Registry for Radiation Workers (NRRW). PHE thanks all organizations and individuals participating in the NRRW for their cooperation, as well as the NRRW Steering Group for their continued support.

APPENDIX

Exposure to Neutrons and Internal Contamination

Since workers exposed to neutrons are included in the INWORKS cohort, analysis of neutron data was performed to assess the feasibility for both quantifying possible unrecorded neutron doses and including the neutron component of exposure in the dose estimation.

We conducted an analysis of the recorded neutron data to detect possible underestimation of neutron doses resulting from the inability of earlier dosimeters to measure neutrons from various energy ranges. If, at the time a new dosimeter was introduced, the number of workers with positive neutron doses increased and neutron doses themselves increased (i.e., mean neutron dose increased), we could assume that before the introduction of the new dosimeter type, doses were underestimated. However, in our examination of the available data, there was no clear indication of either a change in the number of workers with positive neutron dose or a change in the mean recorded neutron dose subsequent to changes in technology (see Fig. A1). This may be because the number of workers with positive neutron doses is very low or because there is no clear trend in the dose distribution, other than a general decrease over calendar time in positive neutron doses. Figure A1 shows the annual mean of the positive individual neutron doses together with the number of workers with positive neutron doses for a representative facility from each country. Information, as provided in the questionnaires from the parent study, on the dosimetry technology is shown in parallel.

For the purposes of assessing potential confounding by neutron exposure of estimated associations between recorded photon dose and mortality, we constructed a time-varying flag for categories of neutron exposure potential. Similarly, we constructed flags for workers with known (France, UK and U.S.) or suspected (UK) internal contamination by radionuclides. Table A1 shows a summary of the number of workers flagged for neutron exposure combined with the number of workers flagged with internal contamination.

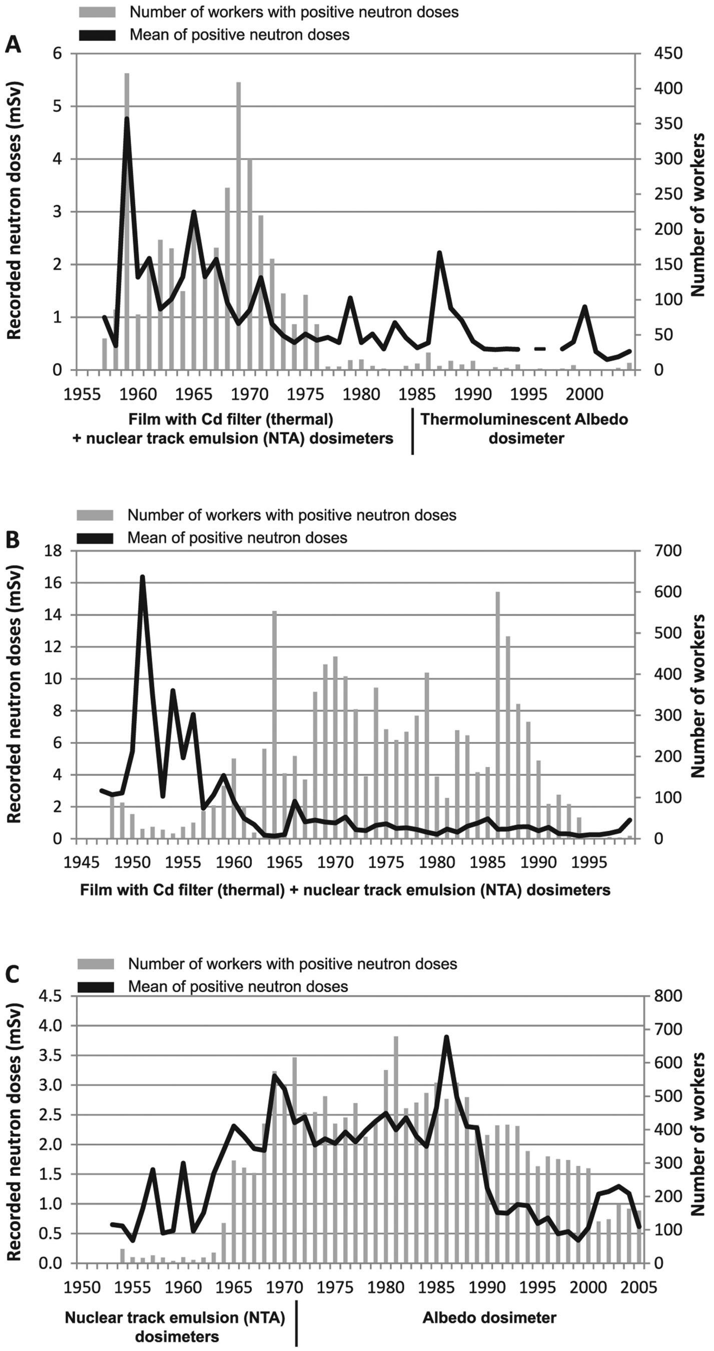

FIG. A1.

Distribution of mean individual neutron doses (positive values) and number of workers with positive neutron doses in a selected facility in France (panel A), the UK (panel B), and the U.S. (panel c).

APPENDIX TABLE A1

Number of Workers Flagged for Neutrons[a] and Internal Contamination[b]

Country	Total number of workers	No internal contamination, no neutrons	Neutrons only		Internal contamination only	Internal contamination and any neutrons	Total flagged
		Flag 1	Flag 2	Flag 3	Flag 2		
France	59,003	48,220	5,793	2,486	2,197	307	10,783
UK	147,866	98,140	5,383	2,933	32,502	8,908	49,726
U.S.	101,428	83,157	6,997	3,663	4,307	3,304	18,271
Total	308,297	229,517	18,173	9,082	39,006	12,519	78,780

[a] Workers were grouped into three categories. Flag 1: Workers with no monitoring or zero doses. Flag 2: Workers with recorded cumulative neutron doses not exceeding 10% of the total equivalent dose for external radiation. Flag 3: Workers with recorded cumulative neutron doses exceeding 10% of the total equivalent dose for external radiation.

[b] Workers were grouped into two categories. Flag 1: Workers with no deposition. Flag 2: Workers with known (France, UK and U.S.) or suspected (UK) deposition.

REFERENCES

1. Cardis E, Vrijheid M, Blettner M, Gilbert E, Hakama M, Hill C, et al. Risk of cancer after low doses of ionising radiation: retrospective cohort study in 15 countries. BMJ. 2005; 331:77. [PubMed: 15987704]
2. Cardis E, Vrijheid M, Blettner M, Gilbert E, Hakama M, Hill C, et al. The 15-country collaborative study of cancer risk among radiation workers in the nuclear industry: estimates of radiation related cancer risks. Radiat Res. 2007; 167:396–416. [PubMed: 17388693]
3. Vrijheid M, Cardis E, Blettner M, Gilbert E, Hakama M, Hill C, et al. The 15-country collaborative study of cancer risk among radiation workers in the nuclear industry: design, epidemiological methods and descriptive results. Radiat Res. 2007; 167:361–79. [PubMed: 17388694]
4. Vrijheid M, Cardis E, Ashmore P, Auvinen A, Bae JM, Engels H, et al. Mortality from diseases other than cancer following low doses of ionizing radiation: results from the 15-Country Study of nuclear industry workers. Int J Epidemiol. 2007; 36:1126–35. [PubMed: 17666424]
5. Vrijheid M, Cardis E, Ashmore P, Auvinen A, Gilbert E, Habib RR, et al. Ionizing radiation and risk of chronic lymphocytic leukemia in the 15-country study of nuclear industry workers. Radiat Res. 2008; 170:661–5. [PubMed: 18959468]
6. Thierry-Chef I, Pernicka F, Marshall M, Cardis E, Andreo P. Study of a selection of 10 historical types of dosemeter: variation of the response to $H_p(10)$ with photon energy and geometry of exposure. Radiat Prot Dosimetry. 2002; 102:101–13. [PubMed: 12408486]
7. Thierry-Chef I, Marshall M, Fix JJ, Bermann F, Gilbert ES, Hacker C, et al. The 15-country collaborative study of cancer risk among radiation workers in the nuclear industry: study of errors in dosimetry. Radiat Res. 2007; 167:380–95. [PubMed: 17388692]
8. US NRC Report. National Research Council, National Academy Press; Washington, D.C.: 1989. Film badge dosimetry in atmospheric nuclear tests..
9. Gilbert ES, Fix JJ. Accounting for bias in dose estimates in analyses of data from nuclear worker mortality studies. Health Phys. 1995; 68:650–60. [PubMed: 7730061]
10. Gilbert ES, Fix JJ, Baumgartner WV. An approach to evaluating bias and uncertainty in estimates of external dose obtained from personal dosimeters. Health Phys. 1996; 70:336–45. [PubMed: 8609025]
11. Gilbert ES. Accounting for errors in dose estimates used in studies of workers exposed to external radiation. Health Phys. 1998; 74:22–9. [PubMed: 9415578]

12. Thierry-Chef I, Cardis E, Ciampi A, Delacroix D, Marshall M, Amoros E, et al. A method to assess predominant energies of exposure in a nuclear research centre–Saclay (France). Radiat Prot Dosimetry. 2001; 94:215–25. [PubMed: 11487804]
13. Schubauer-Berigan MK, Daniels RD, Bertke SJ, Tseng C-Y, Richardson DB. Cancer mortality through 2005 among a pooled cohort of U.S. nuclear workers exposed to external ionizing radiation. Radiat Res. 2015:183.
14. Daniels RD, Bertke S, Waters KM, Schubauer-Berigan MK. Risk of leukaemia mortality from exposure to ionising radiation in US nuclear workers: a pooled case-control study. Occup Environ Med. 2013; 70:41–8. [PubMed: 23000827]
15. Metz-Flamant C, Samson E, Caer-Lorho S, Acker A, Laurier D. Solid cancer mortality associated with chronic external radiation exposure at the French atomic energy commission and nuclear fuel company. Radiat Res. 2011; 176:115–27. [PubMed: 21476856]
16. Metz-Flamant C, Samson E, Caer-Lorho S, Acker A, Laurier D. Leukemia risk associated with chronic external exposure to ionizing radiation in a French cohort of nuclear workers. Radiat Res. 2012; 178:489–98. [PubMed: 23050984]
17. Metz-Flamant C, Laurent O, Samson E, Caer-Lorho S, Acker A, Hubert D, et al. Mortality associated with chronic external radiation exposure in the French combined cohort of nuclear workers. Occup Environ Med. 2013; 70:630–8. [PubMed: 23716722]
18. Laurent O, Metz-Flamant C, Rogel A, Hubert D, Riedel A, Garcier Y, et al. Relationship between occupational exposure to ionizing radiation and mortality at the French electricity company, period 1961–2003. Int Arch Occup Environ Health 2010. 83:935–44.
19. Muirhead CR, O'Hagan JA, Haylock RG, Phillipson MA, Willcock T, Berridge GL, et al. Mortality and cancer incidence following occupational radiation exposure: third analysis of the National Registry for Radiation Workers. Br J Cancer. 2009; 100:206–12. [PubMed: 19127272]
20. Muirhead CR, O'Hagan JA, Haylock RGE, Phillipson MA, Willcock T, Berridge GLC, et al. Third analysis of the National Registry for Radiation Workers: occupational exposure to ionising radiation in relation to mortality and cancer incidence. Report No. HPA-RPD-062. Chilton, Didcot, Oxfordshire. :2009.
21. Leuraud K, Laurent O, Samson E, Caer-Lorho S, Acker A, Laroche P, et al. 0266 Mortality in the French cohort of nuclear workers monitored for external radiation exposure. Occup Environ Med. 2014; 71(Suppl 1):A34–5.
22. ICRU Report No. 39. International Commission on Radiation Units and Measurements; Bethesda: 1985. Determination of dose equivalents resulting from external radiation sources..
23. Petoussi-Henss N, Bolch WE, Eckerman KF, Endo A, Hertel N, Hunt J, et al. Conversion coefficients for radiological protection quantities for external radiation exposures. ICRP Publication 116. Ann ICRP. 2010; 40:1–257. [PubMed: 22386603]
24. NCRP Report No. 163. National Council on Radiation Protection and Measurements; Bethesda: 2009. Radiation dose reconstruction: principles and practices..
25. Fix JJ, Salmon L. A retrospective evaluation of the dosimetry employed in an international combined epidemiological study. Radiat Prot Dosim. 1997; 74:39–53.
26. Tanner, RJ.; Thomas, DJ.; Bartlett, DT.; Hager, LG.; Horwood, N.; Taylor, GC. Effect of the energy dependence of response of neutron personal dosemeters routinely used in the UK on the accuracy of dose estimation. Report NRPB-W25. National Radiological Protection Board; Chilton, UK: 2002.
27. Hamra G, Nylander-French LA, Richardson D. Dose reconstruction for an occupational cohort at the Savannah River nuclear facility: evaluation of a hybrid method. Radiat Prot Dosimetry. 2008; 131:188–97. [PubMed: 18550516]
28. Human respiratory tract model for radiological protection. A report of a Task Group of the International Commission on Radiological Protection. ICRP Publication 66. Ann ICRP. 1994; 24:1–482.
29. Human alimentary tract model for radiological protection. A report of the International Commission on Radiological Protection. ICRP Publication 100. Ann ICRP. 2006; 36:25–327. [PubMed: 17188183]

30. Riddell AE, Battersby WP, Peace MS, Strong R. The assessment of organ doses from plutonium for an epidemiological study of the Sellafield workforce. J Radiol Prot. 2000; 20:275–86. [PubMed: 11008932]

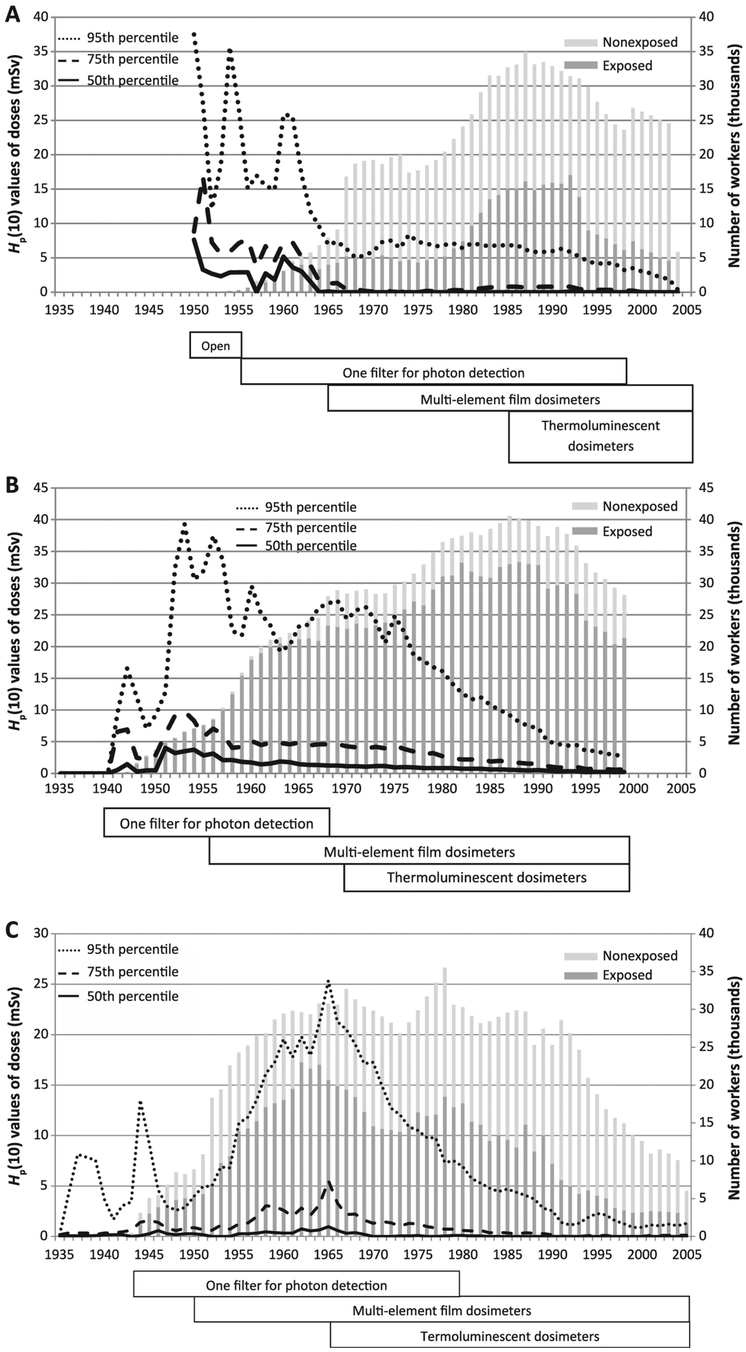

FIG. 1.

Panel A: Individual annual dose distribution in France, expressed in $H_p(10)$ (mSv), with associated workforce and dosimeters used over time. Panel B: Individual annual dose distribution in the UK, expressed in $H_p(10)$ (mSv), with associated workforce and dosimeters used over time (based on latest information available in 1999). Panel C: Individual annual dose distributions in the U.S., expressed in $H_p(10)$ (mSv), with associated workforce and dosimeters used over time.

TABLE 1

Final Bias and Uncertainty Factors to Convert Recorded Photon Doses in Terms of $H_p(10)$ (in mSv) and Organ Doses (in mGy) for One Nuclear Power Plant (NPP) and One “Mixed Activities” Facility per Country Based on Time Period and Dosimeter Use

Country, facility type Period (start–end)	Dosimeter				Male						Female							
			$H_p(10)$[a]		Colon[a]		Lung[a]		RBM[a]		Colon[a]		Lung[a]		RBM[a]		Breast[a]	
	Type	Filters	$B_{Hp(10)}$	$K_{Hp(10)}$	B_{colon}	K_{colon}	B_{lung}	B_{lung}	B_{RBM}	K_{RBM}	B_{colon}	K_{colon}	B_{lung}	B_{lung}	B_{RBM}	K_{RBM}	B_{Breast}	K_{Breast}
France, nuclear power plant[b]																		
1968–1982	Multi-element	Sn PVC	0.961	1.200	1.457	2.036	1.429	1.841	1.550	1.737	1.396	2.059	1.419	1.684	1.491	1.700	1.205	1.738
1982–1999	Multi-element	PVC Pb	0.872	1.150	1.322	1.645	1.296	1.504	1.406	1.453	1.267	1.666	1.287	1.407	1.353	1.439	1.093	1.468
1999–2003	TLD	Open window Cu Cu Pb + cu	0.839	1.270	1.272	1.835	1.247	1.694	1.352	1.615	1.218	1.854	1.238	1.581	1.301	1.590	1.052	1.628
France, mixed activities facility[c]																		
1950–1954	Open window		1.334	1.596	2.053	3.991	2.020	3.305	2.179	3.024	1.965	4.078	2.004	2.824	2.094	2.910	1.698	2.969
1955–1964	Multi-element	Open window Sn Cd	0.828	1.152	1.274	1.84	1.253	1.659	1.352	1.561	1.219	1.875	1.243	1.521	1.299	1.537	1.053	1.600
France, mixed activities facility																		
1965–2003	Multi-element	Open window Plastic A1 Cu + A1 Cu Cd + Sn + Pb Sn + Pb	0.932	1.324	1.435	2.131	1.412	1.902	1.523	1.785	1.373	2.173	1.401	1.733	1.464	1.754	1.187	1.822
2004–2014	Other TLD		0.975	1.298	1.501	1.982	1.477	1.774	1.593	1.658	1.436	2.027	1.465	1.621	1.531	1.635	1.241	1.718

Country, facility type Period (start–end)	Dosimeter				Male						Female							
			$H_p(10)^a$		Colon[a]		Lung[a]		RBM[a]		Colon[a]		Lung[a]		RBM[a]		Breast[a]	
	Type	Filters	$B_{Hp(10)}$	$K_{Hp(10)}$	B_{colon}	K_{colon}	B_{lung}	B_{lung}	B_{RBM}	K_{RBM}	B_{colon}	K_{colon}	B_{lung}	B_{lung}	B_{RBM}	K_{RBM}	B_{Breast}	K_{Breast}
UK nuclear power plant																		
1961–1963	Other multi-element		0.883	1.289	1.338	1.847	1.312	1.706	1.423	1.628	1.282	1.865	1.303	1.594	1.369	1.603	1.106	1.640
1964–1999	Multi-element	Open window	0.964	1.165	1.462	1.771	1.433	1.624	1.555	1.537	1.401	1.792	1.424	1.504	1.496	1.512	1.209	1.559
		Plastic																
		Dural																
		Sn + Pb																
		Cd + Pb																
		Pb edge shielding																
		Indium (4g)																
UK mixed activities facility																		
1950–1950	One element	Open	1.064	1.279	1.637	2.141	1.610	1.886	1.738	1.747	1.566	2.194	1.598	1.698	1.669	1.717	1.354	1.812
		Cd																
1951–1952	One element	Open	1.105	1.281	1.700	2.118	1.673	1.849	1.805	1.739	1.627	2.169	1.660	1.670	1.734	1.714	1.406	1.789
		Pb																
1953–1959	Multi-element	Open	1.000	1.265	1.539	1.907	1.514	1.705	1.634	1.589	1.473	1.953	1.503	1.557	1.570	1.569	1.273	1.659
		Fe + Pb + A1																
UK mixed activities facility																		
1960–1963	Other multi-element		0.932	1.324	1.435	2.131	1.412	1.902	1.523	1.785	1.373	2.173	1.401	1.733	1.464	1.754	1.187	1.822
1964–1999	Multi-element	Open window	0.872	1.169	1.342	2.027	1.320	1.794	1.424	1.669	1.284	2.072	1.310	1.619	1.368	1.639	1.110	1.717
		Plastic																
		Dural																
		Sn + Pb																
		Cd + Pb																
		Pb edge shielding																
		Indium (4g)																
U.S., nuclear power plant																		
1970–1985	Other multi-element		0.926	1.272	1.404	1.837	1.377	1.696	1.493	1.616	1.345	1.855	1.367	1.583	1.437	1.592	1.161	1.629

Country, facility type Period (start–end)	Dosimeter		$H_p(10)^a$		Male						Female							
					Colon[a]		Lung[a]		RBM[a]		Colon[a]		Lung[a]		RBM[a]		Breast[a]	
	Type	**Filters**	$B_{Hp(10)}$	$K_{Hp(10)}$	B_{colon}	K_{colon}	B_{lung}	B_{lung}	B_{RBM}	K_{RBM}	B_{colon}	K_{colon}	B_{lung}	B_{lung}	B_{RBM}	K_{RBM}	B_{Breast}	K_{Breast}
1986–2005	Other TLD		0.972	1.301	1.474	1.766	1.445	1.638	1.568	1.559	1.412	1.788	1.435	1.536	1.508	1.540	1.219	1.590
U.S., mixed activities facility																		
1951–1956	One element	Open	1.050	1.276	1.616	2.104	1.590	1.858	1.716	1.724	1.547	2.156	1.578	1.677	1.648	1.695	1.337	1.788
		Cd																
1957–1965	Other multi-element		0.932	1.324	1.435	2.131	1.412	1.902	1.523	1.785	1.373	2.173	1.401	1.733	1.464	1.754	1.187	1.822
1966–2005	Other TLD		0.975	1.298	1.501	1.982	1.477	1.774	1.593	1.658	1.436	2.027	1.465	1.621	1.531	1.635	1.241	1.718

TLD = thermoluminescent dosimeter.

[a] The successive steps to derive final bias and uncertainty factors are described in detail in Thierry-Chef *et al.*(7).

[b] Based on the work conducted in the 15-country study (7), we assumed that, in NPPs 10% of the dose, on average, is due to photons in the range of 100–300 keV (this can vary from 5 to 20%, depending on the worker's activities), with the average geometry being 50% in anterior-posterior (AP) and 50% isotropic. The variability in geometry is large, however, with an estimated range of 10–80% AP.

[c] Based on the same work, we assumed that in mixed activities facilities, on average, 20% (±5%, 2 SD) of the dose is due to photons in the range of 100–300 keV (this can vary between 15 and 25% between workers and between installations) and on average, 50% (±10%, 2 SD) of the dose was due to exposure in AP geometry and 50% in isotropic geometry, although for individual workers the proportion of isotropic exposure could vary from 40 to 100% isotropic.

TABLE 2

Distribution of Individual Annual Doses among Cohort Participants[a]

	Total number of workers	$H_p(10)$ (mSv)	Colon (mGy)	Lung (mGy)	RBM (mGy)	Breast (mGy) (women only)
Cohort	**(percentage of exposed workers)**	**Mean (median; IQR)**	**Mean (median; IQR)**	**Mean (median; IQR)**	**Mean (median; IQR)**	**Mean (median; IQR)**
France	59,003 (72%)	0.93 (0.14; 0.00,0.96)	0.64 (0.10; 0.00,0.66)	0.64 (0.10; 0.00,0.66)	0.59 (0.09; 0.00,0.61)	0.21 (0.00; 0.00,0.08)
UK	147,866 (88%)	2.26 (0.64; 0.17,2.08)	1.56 (0.44; 0.12,1.44)	1.55 (0.44; 0.12,1.43)	1.43 (0.41; 0.11,1.32)	0.75 (0.31; 0.12,0.70)
U.S.	101,428 (83%)	1.42 (0.32; 0.05,1.24)	0.99 (0.22; 0.03,0.86)	0.98 (0.22; 0.03,0.85)	0.9 (0.20; 0.03,0.79)	0.31 (0.06; 0,0.27)
Total	308,297 (83%)	1.73 (0.42; 0.07,1.59)	1.20 (0.29; 0.05,1.10)	1.19 (0.29; 0.05,1.09)	1.09 (0.27; 0.04,1.01)	0.43 (0.10; 0,0.39)

Notes. Values include doses recorded as zero. RBM = red bone marrow. IQR = interquartile range (25th percentile, 75th percentile).

[a] The cohort includes 268,262 men and 40,035 women.

TABLE 3

Distribution of Individual Cumulative Doses among Cohort Participants[a]

Cohort	Total number of workers (percentage of exposed workers)	$H_p(10)$ (mSv) Mean (median; IQR)	Colon (mGy) Mean (median; IQR)	Lung (mGy) Mean (median; IQR)	RBM (mGy) Mean (median; IQR)	Breast (mGy) (women only) Mean (median; IQR)
France	59,003 (72%)	18.4 (2.1; 0.0,17.0)	12.6 (1.4; 0.0,11.6)	12.6 (1.4; 0.0,11.7)	11.6 (1.3; 0.0,10.7)	2.8 (0; 0.0,0.93)
UK	147,866 (88%)	28.7 (4.2; 0.6,2.4)	19.9 (2.9; 0.4,14.1)	19.8 (2.9; 0.4,14.1)	18.2 (2.6; 0.4,12.9)	5.1 (1.4; 0.4,4.3)
U.S.	101,428 (83%)	24.0 (2.9; 0.3,16.7)	16.7 (2.1; 0.2,11.6)	16.6 (2.0; 0.2,11.5)	15.2 (1.9; 0.2,10.6)	3.7 (0.4; 0.0,2.3)
Total	308,297 (83%)	25.2 (3.4; 0.4,18.4)	17.4 (2.3; 0.3,12.8)	17.4 (2.3; 0.3,12.7)	15.9 (2.1; 0.3,11.7)	4 (0.6; 0.0,2.8)

Notes. Values include doses recorded as zero. RBM = red bone marrow. IQR = interquartile range (25th percentile, 75th percentile).

[a] The cohort includes 268,262 men and 40,035 women.

TABLE 4

Number of Workers Flagged for Neutrons

Country	Total number of workers	No neutrons Flag 1	Neutrons	
			Flag 2	Flag 3
France	59,003	50,417	6,018	2,568
UK	147,866	130,642	12,435	4,789
U.S.	101,428	87,464	9,179	4,785
Total	308,297	268,523	27,632	12,142

Notes. Workers were grouped into three categories. Flag 1: Workers with no monitoring or zero doses. Flag 2: Workers with recorded cumulative neutron doses not exceeding 10% of the total equivalent dose for external radiation. Flag 3: Workers with recorded cumulative neutron doses exceeding 10% of the total equivalent dose for external radiation.