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# The 15-Country Collaborative Study of Cancer Risk among Radiation Workers in the Nuclear Industry: Study of Errors in Dosimetry

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**To provide direct estimates of cancer risk after low-dose protracted exposure to ionizing radiation, a large-scale epidemiological study of nuclear industry workers was conducted in 15 countries. As part of this study, identification and quantification of errors in historical recorded doses was conducted based on a review of dosimetric practices and technologies in participating facilities. The main sources of errors on doses from "high-energy" photons (100–3000 keV) were identified as the response of dosimeters in workplace exposure conditions and historical calibration practices. Errors related to dosimetry technology and radiation fields were quantified to derive period- and facility-specific estimates of bias and uncertainties in recorded doses. This was based on (1) an evaluation of predominant workplace radiation from measurement studies and dosimetry expert assessment and (2) an estimation of the energy and geometry response of dosimeters used historically in study facilities. Coefficients were derived to convert recorded doses to $H_p(10)$ and organ dose, taking into account different aspects of the calibration procedures. A parametric, lognormal error structure model was developed to describe errors in doses as a function of facility and time period. Doses from other radiation types, particularly neutrons and radionuclide intake, could not be adequately reconstructed in the framework of the 15-Country Study. Workers with substantial doses from these radiation types were therefore identified and excluded from analyses. Doses from "lower-energy" photons (<100 keV) and from "higher-energy" photons (>3 MeV) were estimated to be small.** 

## INTRODUCTION

Radiation protection guidelines for occupational exposure have been based mainly on risk estimates derived from studies of atomic bomb survivors in Hiroshima and Nagasaki, in conjunction with models that extrapolate the effects of acute (or short-term) exposures to the relatively low exposure rates of environmental and occupational concern, and across populations with different baseline cancer risks (*1*). To derive direct estimates of the effects of protracted (or long-term) exposures, an International Collaborative Study of Cancer Risk among Radiation Workers in the Nuclear Industry[3] was carried out in 15 countries, using a common core protocol (*2*). Details of the design and results of this study, referred to as the 15-Country Study throughout this paper, are presented in companion papers (*3, 4*). This is the largest analytical epidemiological study of nuclear workers ever conducted.

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[3] Throughout this paper, the term nuclear industry will be used to refer to facilities engaged in the production of nuclear power, the manufacture of nuclear weapons, the enrichment and processing of nuclear fuel, the production of radioisotopes or reactor or weapons research. Uranium mining is not included.

Since the accuracy and precision of recorded dose estimates have been shown to vary with time and place (*5*), and because the accuracy and the comparability of doses are essential in an epidemiological study of the effects of low-dose radiation exposure, a Study of Errors in Dosimetry was set up within the framework of the 15-Country Study. The main objectives were (1) to evaluate the comparability across facilities and time of currently available dose estimates and (2) to identify and quantify bias and uncertainties in available dose estimates (*6*). Work under this study was coordinated by a Dosimetry Subcommittee—a group of dosimetrists, epidemiologists and radiation protection experts (MM, FB, EC, JJF, ESG, CH, BH, ITC and DU).

Sources of errors were considered separately for ''high-energy'' photons (100–3000 keV)—which were judged to have been measured with sufficient accuracy and in a way comparable across facilities and time for the majority of workers (*5–10*)—and other radiation types [exposure to ''lower-energy'' (<100 keV) and ''higher-energy'' (>3000 keV) photons, neutrons and internally incorporated radionuclides]. It is noted that the equivalent doses for the majority of workers in the majority of the facilities in the study were predominantly from ''high-energy'' photons.

## MATERIAL AND METHODS

In the epidemiological study, information about both the total equivalent dose from external exposures and the high-energy (>100 keV) X- and γ-ray equivalent dose (in mSv) was collected for *each study subject,* for *each year* of monitoring and for *each facility* where a dose was received. Annual doses were obtained by summing dose estimates over a year. Annual tritium doses were also obtained for each subject and each year in the facilities where they were available. In this study, all doses are expressed in terms of equivalent dose with the units of sievert.[4]

### *Identification of Sources of Errors*

Because practices and technologies for monitoring and recording doses from different radiation types differed across countries and over time, it was necessary to obtain detailed information on dosimetric practices for each of the facilities included in the 15-Country Study. The following sources of information were used to critically evaluate the historical dose data provided and to identify the main sources of dosimetric errors:

1. A series of three complementary questionnaires (see Thierry-Chef *et al.*[5] for details) completed by all participating facilities, provided information on historical practices for monitoring individual doses, including characteristics of dosimeters used, their calibration and laboratory evaluation, dosimetric quantities estimated, and monitoring criteria and frequency of monitoring. In addition, they provided information on record-keeping practices, including criteria for recording doses that were below the threshold of the dosimeters or from missing or damaged dosimeters, predominant radiation fields, potential for exposure to neutrons and for internal contamination and practices, and criteria for monitoring doses from these radiation types.
2. Documentary information on monitoring methods in participating facilities, including any critical evaluation of monitoring practices and intercomparisons between dosimetry services.
3. Oral and written communications with health physicists and others in participating facilities, having local, particularly historical, knowledge of the facilities under study.

### *Errors in Doses*

There are several types of error in recorded doses based on dosimeter readings. The first is the intrinsic sampling variation in measurements inherent to different types of dosimeters, referred to as laboratory error. These errors are independent from person to person and are thus ''unshared''. For these errors, the ''classical error'' model applies, in which the estimated values of the input data are assumed to be distributed around the true values of the input data for each subject (*11*). Independent classical errors are known to bias dose–response relationships toward the null. Laboratory error can be an important source of error in a single dosimeter measurement. However, these errors have been shown to have very little effect on dose–response analyses in nuclear worker studies (*12*). This is because the cumulative doses used in these studies, especially the larger doses that are most influential in the dose–response analyses, are the sum of many independent measurements, and thus their relative error from laboratory sources is small. This paper does not evaluate laboratory error.

From the standpoint of epidemiology, the most important errors may be those that result from errors in the dosimetry system used to estimate individual doses from the dosimeter measurements. Because dosimeters, especially those used in early calendar year periods, are limited in their ability to respond accurately to all exposure conditions (energy and geometry), inaccuracies in taking accurate account of these conditions and their impact on dosimeter measurements can result in bias. In addition, dosimetry systems were not designed to estimate the organ doses of interest for epidemiology. A primary objective of this paper is to estimate bias factors (and their uncertainties), specific for each facility and calendar year period, that can be applied to recorded doses to produce corrected doses that are, on average, unbiased estimates of the target dose of interest (e.g. organ doses). Because the dosimetry system is common for nuclear workers in a particular facility, these errors are shared between workers and over the years when a particular dosimetry system is in use.

Within a group defined by facility and calendar year period, exposure conditions vary among workers, and thus true doses may differ from the doses obtained by applying the group bias factor (unshared errors). However, if the group bias factors are estimated without error, the group mean doses (after application of the bias factor) will be correct, and thus these errors follow a ''Berkson'' error model (*11*). Under this model, the true doses vary around the estimated doses. The presence of Berkson errors does not bias estimates of the dose–response relationship when the model is linear (*13*), although it influences the width of the confidence intervals (*14*). Unlike the laboratory errors discussed above, to the extent that workers continue to perform the same type of work in the same location, errors for different periods for the same worker are likely to be correlated.

In this work, sources of errors in doses were studied both for ''high-energy'' photons and for other types of radiation. Attempts were made to quantify the errors related to the major sources of errors in ''high-energy'' photons, as described below. Quantification of errors in doses from other radiation types is very difficult in the context of a large epidemiological cohort study, so workers with a potential for receiving sub-

[4] Throughout this paper, any reference to dose implies equivalent dose expressed in sieverts. Since workers with substantial doses from neutrons or radionuclide intake were excluded from the main study population, the predominant source of dose is photon radiation with a radiation weighting factor of 1, and, where adequately measured, doses from tritium. Equivalent doses to organs in sieverts could therefore equally well be expressed in terms of absorbed dose in grays with the same numerical values.

[5] I. Thierry-Chef, M. Marshall, J. J. Fix, E. Cardis, F. Bermann, E. S. Gilbert, C. Hacker, B. Heinmiller, W. Murray, S. Ohshima, M. S. Pearce, F. Pernicka and D. Utterback, International Collaborative Study of Cancer Risk among Radiation Workers in the Nuclear Industry—Study of Errors in Dosimetry. In preparation, International Agency for Research on Cancer, Lyon.

stantial[6] doses from these radiation types were identified and excluded from the epidemiological analyses (see the Results).

### *Quantification of Errors in Doses from ''High-Energy'' Photon Radiation*

As shown in the Results section, the major sources of errors come from the fact that dosimeters, especially those used in early years, did not always respond accurately to all the radiation energies to which workers were exposed or to all geometries of exposure. Biases resulting from these sources are strongly dependent on the energy and geometry of the radiation. Workers in many of the participating facilities have been exposed under a wide variety of energies and geometries, and the specific energy and geometry associated with any given dose record is generally not known; this therefore introduces a major source of dosimetric uncertainty. Moreover, the relationship between recorded doses and organ doses also depends on energy and geometry. Three major geometries of exposure were considered in this study: anterior-posterior (AP), workers facing radiation sources; rotational (ROT), uniform exposure in a horizontal plane; and isotropic (ISO), uniform exposure in three dimensions. Differences in calibration practices and in the dosimetric quantities measured in different countries and facilities are also sources of bias, while incomplete knowledge concerning historical procedures for measuring and recording doses are a source of uncertainty.

Quantification of the bias and uncertainties was based on an approach derived initially by the U.S. National Research Council (*15*) for film badge dosimetry during nuclear weapons testing and modified for Hanford workers (*16*). Following the NRC approach, uncertainties from individual sources are assumed to follow independent lognormal distributions. The lognormal distribution was chosen largely for convenience, since there was no strong reason to prefer alternative distributions (*16*). Note that the use of a normal distribution would lead to a significant possibility of values less than zero, which are physically impossible.

There are several identified sources of errors. The quantification of errors focused on exposure conditions in the workplace, dosimetry technology, and calibration practices. Systematic errors (i.e. biases, $B$) from each source of error were characterized and quantified, as well as the uncertainty ($K$) on these systematic errors. The interval ($B/K$, $B*K$) is the 95% confidence interval on the bias factor. Overall bias factors, $B$, are obtained by multiplying together individual bias factors:

$$B = \prod_i B_i. \tag{1}$$

If $S_i$ is the standard deviation of $\ln(B_i)$ and the $B_i$ are independent, then the standard deviation of $\ln(B)$ is estimated by $S = \sqrt{\Sigma_i S_i^2}$ and the overall uncertainty, $K$, is given by

$$K = \exp(1.96*S). \tag{2}$$

Two groups of factors were derived for each facility and calendar year period (the approach is described further in this paper):

1. Calibration factors ($B_c$ and $K_c$) to quantify the errors related to calibration practices (see below) and to convert the original doses, recorded in various quantities and units, into a common quantity that we call recorded $H_p(10)$ values.
2. Dosimetric factors ($B_d$ and $K_d$) to quantify errors related with the response of dosimeters to conditions of exposure. Dosimetric bias factors $B_d$ were first derived in terms of $H_p(10)$ to convert recorded $H_p(10)$ values into corrected $H_p(10)$ values. Dosimetric biases were also derived in terms of organ dose to convert recorded $H_p(10)$ values into organ dose (lung, colon and bone marrow), the quantities of interest in the study (see below).

An overall bias factor $B$ was then derived, in terms of $H_p(10)$ and organ dose, since the product of each bias $B_d$ and $B_c$ and the associated uncertainty on $B$ was obtained from all identified uncertainties (Eq. 2). Correction factors for converting recorded doses to $H_p(10)$ and organ doses were then derived as the mean of the lognormal distributions, i.e.

$$\text{Correction factor} = \frac{B}{\exp\left(\frac{S^2}{2}\right)}. \tag{3}$$

#### *1. Quantification of errors related to calibration practices ($B_c$, $K_c$)*

Radiation has been recorded in different quantities over the years. Recorded doses were converted to recorded $H_p(10)$—the latter, personal dose equivalent in soft tissue at 10 mm depth (*17*), having been chosen as the common quantity in this study—using conversion coefficients derived from ICRP 51 (*18*) and ICRP 74 (*19*). Since no conversion coefficient was available for radium sources, the energy spectrum of the source was estimated (63% of exposure rate from 1.5 MeV, 23% from 600 keV, 13% from 300 keV, and 1% from 80 keV) to derive appropriate conversion coefficients.

The consistency between reported calibration practices and recording quantities was discussed with the facility experts to determine bias and uncertainty. In addition to the nature of calibration sources, particular attention was paid to backscatter radiation (from the worker's body and, where relevant, from the phantom used for calibration of dosimeters). Correction was also made for the presence of other factors, which might have affected the calibration process (e.g. presence of a table). All biases ($B_{source}$, $B_{back}$, $B_{fact}$) were multiplied to provide a unique ''calibration'' bias $B_c$ using Eq. (1); uncertainties ($K_{source}$, $K_{back}$, $K_{fact}$) were combined to obtain a ''calibration'' uncertainty factor ($K_c$) using Eq. (2). These factors were derived for each facility and period when a different calibration practice was used.

#### *2. Quantification of errors related to the response of dosimeters in workplace exposure conditions ($B_d$, $K_d$)*

Our approach involved the estimation of a dosimetric bias factor ($B_d$) (ratio of measured to true dose) for each dosimeter model used in each facility, based on the energy and geometry response of the dosimeter and the main exposure conditions in that facility as follows:

$$\begin{aligned} B_d = \exp[ & f(100\text{–}300)*f(\text{AP})*\ln B_{100\text{–}300,\text{AP}} \\ & + f(100\text{–}300)*f(\text{ROT})*\ln B_{100\text{–}300,\text{ROT}} \\ & + f(100\text{–}300)*f(\text{ISO})*\ln B_{100\text{–}300,\text{ISO}} \\ & + f(300\text{–}3000)*f(\text{AP})*\ln B_{300\text{–}3000,\text{AP}} \\ & + f(300\text{–}3000)*f(\text{ROT})*\ln B_{300\text{–}3000,\text{ROT}} \\ & + f(300\text{–}3000)*f(\text{ISO})*\ln B_{300\text{–}3000,\text{ISO}}], \end{aligned} \tag{4}$$

where $f$(100–300), $f$(300–3000), $f$(AP), $f$(ROT) and $f$(ISO) represent the average fractions of dose to workers from photons in the ranges 100–300 keV and 300–3000 keV (ranges in which the response of early dosimeters may differ) and received in the three main geometries of exposure (AP, ROT and ISO), respectively. $B_{100\text{–}300,\text{AP}}$, $B_{100\text{–}300,\text{ROT}}$, $B_{100\text{–}300,\text{ISO}}$, $B_{300\text{–}3000,\text{AP}}$, $B_{300\text{–}3000,\text{ROT}}$, and $B_{300\text{–}3000,\text{ISO}}$ (i.e. $B_{\text{energy,geometry}}$) denote the estimated bias in dosimeter response for energies in the ranges 100–300 and 300–3000 keV, in AP, rotational and isotropic geometry, respectively. The $B_{\text{energy,geometry}}$ for each energy and geometry combination was derived in terms of $H_p(10)$ from the results of the experiments (*20*) described below. The uncertainties in each of the energy- and geometry-specific bias factors ($K_{\text{energy,geometry}}$) were derived from the same experiments and were combined into one uncertainty factor, $K_{response}$, following Eq. (2).

An additional uncertainty factor ($K_{exposure}$) was derived, as the ratio between the response of the dosimeter in the estimated average exposure conditions and its response in the upper and lower bounds of the esti-

[6] I.e. more than 10% of their total equivalent dose for external radiation and more than $^1/_{10}$ of the annual limit of intake (ALI) for internal contaminants.

mated range of exposure conditions (see below), to account for the estimated variation of the exposure conditions between workers.

The uncertainties in the $H_p(10)$ dosimeter response $K_{d,H_p(10)}$ were obtained by combining $K_{response}$ and $K_{exposure}$ with an additional uncertainty related to the conduct of the experiment $K_{experiment}$ (including the reproducibility of the position of dosimeters on the phantom and uncertainty in dose delivered—see Thierry-Chef *et al.*[5] for details) (Eq. 2).

Each $B_{energy,geometry}$ was also estimated in terms of organ doses (lung, colon and red bone marrow) for the purpose of assessing the risk of cancer in specific organs. The conversion coefficients from $H_p(10)$ to organ dose were derived from ICRP reports 51(*18*) and 74 (*19*). The uncertainty in the organ dose response, $K_{d,organ}$, was obtained by combining $K_{response}$, $K_{exposure}$ and $K_{experiment}$ with the uncertainty in the conversion coefficients between $H_p(10)$ and organ dose $K_{organ}$ (Eq. 2).

To simplify the assessment of predominant exposure conditions in study facilities, they were classified into nuclear power plants (NPPs) and ''mixed activities'' facilities (including research centers, fuel fabrication sites and reprocessing plants), since exposure conditions could differ between these groups. Average and extreme exposure conditions were estimated for each group based on information obtained in two steps.

In the first, facilities representatives of these two groups were chosen (Swiss NPPs and the ''mixed activities'' facility of Saclay in CEA-COGEMA, France). Experts from these facilities were asked to provide their best estimates of (1) the proportion of the average dose to a worker in their facility due to different photon energies, 0–100 keV, 100–300 keV and 300–3000 keV; and (2) the proportion of the average dose to a worker received in AP, rotational and isotropic geometries. In Switzerland, the evaluations were based both on expert judgment and on results of a study of exposure conditions and dose optimization in one NPP (*21*). The latter took into account job types, main radiation sources, average time spent in different areas, impact of shielding and physical controls on the radiation field.

Conditions of exposure in ''mixed activities'' facilities (where a great variety of sources may be present and various jobs may be performed) are in general difficult to evaluate. In Saclay, exposure conditions were assessed by experts in nine representative installations. For each installation and each job category, the experts provided their best estimate of the predominant exposure conditions. An overall weighted average was made for the site, using numbers of workers in the different sectors as weights. The energy distribution thus obtained was checked using a method in which the proportion of dose from different photons energies (0–100, 100–300 and 300–3000 keV) is assessed from responses under filters of a multi-element dosimeter (*22*).

The second step involved assessments by two groups of international experts (one for each group of facilities) who reviewed results from Switzerland and Saclay, available measurements from several UK facilities (Burgess, personal communication) and U.S. commercial NPPs (*23, 24*) and expert assessments from Hanford (*25*). The experts were asked for an expert estimate of predominant exposure conditions applicable to each group of facilities. The range of answers was used as a measure of the uncertainty of this estimate and of the variability of average exposure conditions between workers and sites.

In parallel, the energy and geometry response of all dosimeters used historically in participating facilities had to be estimated. Technical information on the different dosimeter types was compiled and reviewed critically. This was complemented by a series of experiments performed on 10 representative dosimeter types: four early film badges, three multi-element film badges, and three thermoluminescence dosimeters (TLDs). The dosimeters were irradiated on an anthropomorphic phantom in two ranges of energy (100–300 keV, specifically at effective energies of 118 and 208 keV, and 300–3000 keV, specifically at 662 keV) and three geometries (AP, rotational and isotropic) (*20*). Bias in dosimeter response was defined as the ratio between the personal dose equivalent assessed by the dosimeter [$H_p(10)_a$] and the personal dose equivalent delivered [$H_p(10)_d$]. Two sets of conversion coefficients were used: the first to convert *air kerma* at the position of the dosimeter during the experiment into $H_p(10)_d$, the second to convert the quantities in which results were provided by laboratories to $H_p(10)_a$. Results from the exposures to narrow beam filtered X-ray techniques at 118 and 208 keV were combined assuming that these energies were representative, respectively, of 25% and 75% of the typical doses received by workers in the 100–300 keV range (see Thierry-Chef *et al.*[5]). Estimates of the uncertainties in the response of the dosimeters used in the experiments included the variability of results across dosimeters at a given energy and geometry, the uncertainty in the reproducibility of the position of the dosimeters on phantom, and the uncertainty in the dose delivered (see Thierry-Chef *et al.*[5]).

The bias and uncertainty related to the energy and geometry response of all dosimeter types used over the years in participating facilities were then determined as follows:

1. For recent dosimeters: The bias was estimated as the mean of the biases in the response of the three irradiated types of dosimeters of the same category (multi-element film badge or TLD) and the uncertainty was obtained, for each category, as the combination of the uncertainties in the response of the three types of dosimeters.
2. For older dosimeters: the bias in the response under any filter used in the past was assessed from the experimental results for each film-filter combination under study at the three energies and geometries. For each energy and geometry, the film response under each filter for all films was plotted as a function of an attenuation parameter (filter thickness linear attenuation coefficient). The response of an old film dosimeter was determined from empirical fits to these plots, and the uncertainty was estimated as the standard error of this predicted response. Details are presented in Thierry-Chef *et al.*[5] Where information on filter thickness was not available, bias and uncertainty were assessed using the median response and the largest uncertainty of all dosimeters used during the same period in the country of interest. Where no information was available at the country level, the overall median (from all dosimeters used in all countries over the period of interest) and the highest overall uncertainty were used.
3. For less common dosimeters, such as pocket ionization chambers, the bias and the uncertainty in response were assessed based on documentary evidence and the knowledge and experience of the Dosimetry Subcommittee members (see Thierry-Chef *et al.*[5] for details).

## RESULTS

### *Identification of Sources of Errors*

#### *1. ''High-energy'' photon radiation*

The main sources of errors considered were (a) exposure conditions in the workplace (predominant energy and geometry of exposure); (b) dosimetry technology, including the energy and angular response of early dosimeters and laboratory practices implemented during dosimeter fabrication and processing; (c) calibration practices introduced to test dosimeters before their use and to define the necessary coefficients to express doses in terms of the required dosimetric quantity; and (d) administrative practices implemented to record doses in files. They are presented below on the basis of the information obtained from the participating facilities.

#### *a. Exposure conditions in the workplace*

NPPs represented 63% of the facilities. They represent, however, a much smaller percentage of the collective dose in the study since, in general, they started operations later than ''mixed activities'' facilities. Most of the nuclear reactors in the power plants were light water reactors (LWR), mainly pressurized water reactors (PWR) and boiling water reactors (BWR), representing 50 and 20% of the power plants, respectively. There were also heavy water reactors (HWR, 3%), gas-cooled reactors (GCR, 26%), and water-cooled graphite moderated reactors (RBMK, 1%). Responses to the questionnaires (presented in detail in Thierry-Chef *et al.*[5]) indicated that, in such facilities, the major sources of radiation were fission and activation products, and that the sources were mostly shielded. Most of the exposure (90% or more in the majority of facilities) appeared to be from photons in the range 100–3000 keV based on the questionnaires and expert judgment. The estimated proportion of exposure from lower- or higher-energy photons was generally below 10%.

Exposure conditions in ''mixed activities'' facilities were much more variable (see Thierry-Chef *et al.*[5]) since this group included fuel cycle (fuel fabrication, processing and waste treatment), research and isotope production facilities, where many different activities have been performed in the last 50 years.

Dosimeter readings can be affected by environmental factors such as humidity, temperature, light and chemicals (*26*). Responses to the questionnaires indicated that conditions in the work environment generally were not extreme in terms of temperature or humidity. In addition, protective packets were introduced very early to reduce the impact of light and humidity on dosimeter reading. Working practices were also introduced to minimize the risk of deterioration. There appears to be little likelihood of a significant bias related to environmental conditions. In rare cases, however, some dosimeters may have been under extreme conditions during transportation or storage or may have been affected incidentally. Errors related to this are expected to be small: They will affect single dosimeter readings and generally will not be correlated for the same worker (*25*).

Another source of uncertainty occurs when workers are exposed in non-uniform fields. In general, the dose would be averaged because of the movement of the worker relative to the source and multiple exposures contributing to the annual dose. Where substantial highly non-uniform exposure could have occurred, an assessment of the equivalent whole-body dose would have been made by the health physicists.

## *b. Dosimetry technology*

Supplementary Table 1 summarizes the characteristics of the dosimeters used historically to measure photon doses in all French facilities and in one U.S. ''mixed activities'' facility (facilities chosen to provide an example of the evolution over time of dosimetry technology and practices). Details of the dosimeters used in other facilities can be found in Thierry-Chef *et al.*[5] The main categories were film dosimeters and TLDs. Over time, dosimeter designs changed. In early years, bare film was used, with a substantial over-response to photon energies below 300 keV,

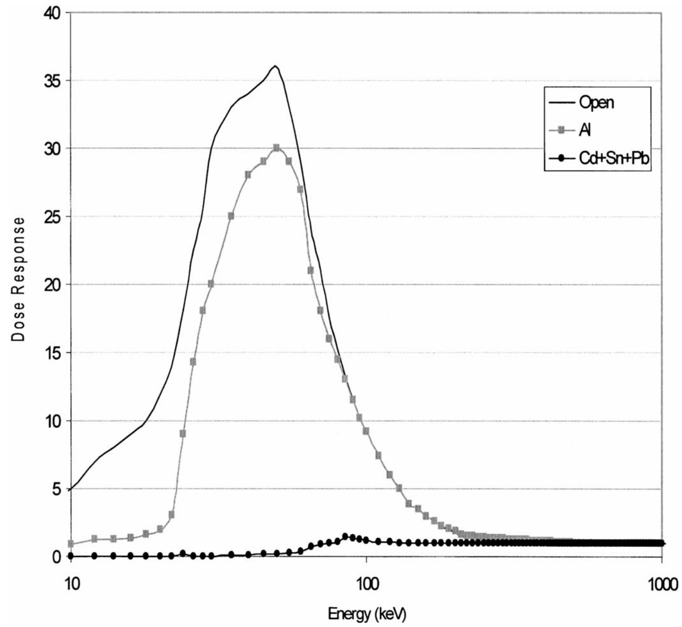


**FIG. 1.** Response of the Kodak type I dosimeter: bare film, under aluminum filter (to remove β-particle response) and under heavy filtration (to flatten the proton energy response). Adapted from ref. (*27*).

and particularly below 100 keV (Fig. 1, bare film). The amount of overestimation depended on the proportion of lower-energy photon radiation in the work environment and the type of film in use. One or two filters, made of lead, tin or cadmium, were commonly introduced to reduce this over-response and to avoid blackening of films due to β particles (Fig. 1) (*27*). Since the 1960s, the use of multi-element dosimeters, with a variety of filters made of different materials with variable atomic number and density thickness in mg/cm$^2$, became widespread to allow a better estimation of dose from lower- and higher-energy photon radiation (see for example refs. (*28, 29*)].

From the early 1970s, TLDs have been used widely to determine photon doses. The most common TLDs are lithium-based (LiF or $Li_2B_4O_7$). Calcium sulfate crystals ($Ca_2SO_4$) are also used in many facilities. Only one country used aluminum oxide ($Al_2O_3$) with plastic and aluminum filters. Based on various studies (*30–33*), the response of lithium-based TLDs is comparatively accurate in the energy range under study, while that of calcium-based TLDs is more variable and depends on the filters used.

Several other dosimeters types were also used in some facilities, including (1) pocket ionization chambers (PIC), which are very sensitive to physical shock, temperature and humidity, and tend to overestimate dose (it was common practice to assign two PICs to each person and record the lowest reading), and have large uncertainties; (2) radiophotoluminescent (RPL) dosimeters (*34–37*), whose response is independent of energy above 100 keV; the spherical form of the RPL dosimeter used in one facility is a symmetrical dosimeter and has an excellent geometry response,[7] no in-

[7] Personal communication, Moser.

formation could be found, however, on the geometry response of non-spherical RPLs; (3) mixed dosimeters (film+TLD) with response similar to that of other dosimeters used at the time (multi-element film and TLDs) (*33, 38–39*).

International intercomparison studies (*33, 38–41*), set up from the 1970s demonstrate that all recent dosimeters (multi-elements and TLD) provide reliable response to energy and geometry of irradiation.

Random errors related to the dosimeter response depend on physical characteristics of the detector, such as variations in the photographic emulsion and film processing or variations in the sensitivity of thermoluminescence detectors. Although errors are highly correlated for readings for a group of workers in the same period, it is reasonable to assume that errors would be independent for readings for the same worker over several periods, providing several dosimeters were used during a year.

Laboratory practices, which include all steps related to detector fabrication, reading process and dose determination, can also be the source of bias and uncertainties. Strict control and rules are generally implemented in laboratories (chemical reactions during fabrication and development of film, for example, should follow very strict procedures), however, and material is regularly checked to reduce errors related to these practices. Further, the cumulative dose estimates used in epidemiological studies, particularly the larger doses that are the most influential in the dose–response analyses, are the sum of many independent measurements, and thus their relative error is small. Systematic errors are therefore unlikely to be significant (*25*).

### *c. Calibration practices*

Supplementary Table 2 presents an example (from the same French and U.S. facilities) of the information obtained by questionnaire concerning calibration practices (detailed information for all facilities can be found in Thierry-Chef *et al.*[5]). As shown, dosimetric quantities have changed over time, as have dosimeter testing and calibration practices. Dosimetry systems in use in participating facilities have been calibrated in terms of Exposure, Dose in air, Dose in water, Dose in tissue, or various quantities based on these concepts, and $H_p(10)$, and the impact of this on recorded doses needs to be taken into account.

Radiation sources commonly used in participating facilities to calibrate dosimeters to photon radiation were $^{226}$Ra, $^{137}$Cs and $^{60}$Co (Supplementary Table 2). All of these radiation sources provide primary photon energies in the range of 100–3000 keV. While $^{137}$Cs and $^{60}$Co emit photons of specific energies (662 keV for $^{137}$Cs and 1173 and 1332 keV for $^{60}$Co), $^{226}$Ra actually emits a wide range of energies (80–1500 keV) including lower energies for which some over-response by bare film would be expected. Radium was used in early years because it was easily available and was considered to be representative of exposure conditions at work. A small bias is expected, therefore, especially for calibration of earlier dosimeters with no filters or insufficient filter thickness to compensate for the over-response.

It was general practice to routinely calibrate dosimeters in air (Supplementary Table 2). Calibration for type testing (before the routine use of dosimeter model, to obtain information about its energy and angular response) was performed either on-phantom (to simulate backscatter from the body) or in-air, the latter allowing the exposure of many dosimeters at the same time. These practices could result in biases in dosimeter readings that need to be quantified. In addition, information is missing from a number of facilities or periods (see Thierry-Chef *et al.*[5]).

A possible bias due to scatter from wooden tables and walls during calibration was mentioned in a few facilities; this will have led to overestimation of doses recorded during calibration and hence to underestimation of workers' doses in the workplace. These problems were greatest in earlier years (when the dosimetric quantity was Exposure), but they affect only a small proportion of the facilities and periods. Dosimeter readings were generally compensated for these effects, but if not, small corrections are needed.

Because dosimeters are also exposed to background radiation, which does not form part of the occupational exposure, it is necessary to subtract background from all readings. Correction for background has been carried out in most places. Although it was reported in the questionnaires that no adjustment for background had been carried out in some facilities and periods, the Dosimetry Subcommittee felt the question may have been misunderstood and hence that the responses were uncertain; therefore, no systematic correction was made.

### *d. Administrative practices*

Supplementary Table 3 summarizes the criteria for monitoring workers, as well as the frequency of dosimeter exchange in the same selected French and U.S. facilities (detailed results concerning all facilities can be found in Thierry-Chef *et al.*[5]). In almost all facilities and periods, only workers intervening in areas where there was a potential for exposure (controlled or designated areas) or category A and B workers (*42*) were monitored. It was, however, the practice in a number of older facilities to monitor all workers on the site. Dosimeters were worn on the front of the torso (i.e. chest) in nearly all facilities, except in a few places where it was worn on the waist. The dosimetry subcommittee judged that both positions would give an adequate estimate of $H_p(10)$.

The frequency of dosimeter exchange has tended to change over time. Monitoring frequency was greater in early years (daily in one facility, weekly in many facilities up to 1965) than more recently, with an increasing proportion of monitoring carried out quarterly.

Supplementary Table 3 also shows practices used to record doses when they were missing (lost or unreadable dosimeters) or were below the detection threshold of the dosimeter. Information is also shown on recording thresholds and increments. In most facilities most of the time, missing doses were assigned either (1) from the doses of colleagues working in the same area, sometimes supplemented with information on the worker's dose in adjacent periods and on his/her activity, or (2) from operational dosimetry (often PICs or pencil electronic dosimeters) or from a second dosimeter if the worker wore more than one. These practices are not thought to induce any major bias in recorded doses.

In some older facilities in the UK, however, either zero or a notional dose (generally the fraction of the annual permissible dose for the period covered by the dosimeter, based on occupational dose limits in force at the time) was recorded in early periods when the dosimeter was missing, resulting in systematic under- and overestimation of the dose. This problem, which was identified previously, has been resolved through the post-hoc determination of doses in these facilities (*43*).

An additional source of error, which could not be quantified systematically for such a large-scale epidemiology study, is the possibility that some workers did not wear their dosimeters. This problem may be more important in early years, when the wearing policy and controls might not have been as strict as in recent years. However, exposure of workers, particularly to higher levels, were monitored by health physics staff, who typically used portable instruments to measure workplace exposure levels and to establish workplace protection practices such as using additional types of dosimeters. Significant variance among radiation exposures measured with different dosimeters and instruments would generally be investigated to determine realistic doses for individual workers. Where there was sufficient evidence of noncompliance, doses should have been amended and disciplinary action taken for workers who did not wear assigned dosimeters properly.

Rules for recording doses below the detection threshold of dosimeter also varied across countries and over time (Supplementary Table 3). Although the majority of such doses were recorded as zero (leading to some underestimation of dose), in some facilities they were recorded as the threshold (thus overestimating dose). This is of particular concern for early periods in the UK when dosimeters were exchanged weekly or fortnightly and the detection threshold was high, and this was resolved through rereading of old dosimeters (*43, 44*). In other facilities, the problem was judged to be small because of the lower threshold values and lower frequency of dosimeter exchange.

## 2. *Other sources of radiation*

Historical practices for measuring doses from other types of radiation (''lower- and very-high-energy'' photons, neutrons and internal contamination by fission and activation products, tritium, transuranics and uranium and thorium) were less reliable than those for ''high-energy'' photons. Facilities where substantial doses from these radiation types could have been received were therefore asked to identify workers who had potential for substantial doses. Those workers were then excluded from the main epidemiological analyses.

### *a. ''Lower-energy'' photon radiation (<100 keV)*

Answers to the questionnaire (not shown) indicate that potential for exposure to ''lower-energy'' photons in NPPs was small, with much less than 10% of dose from photons with energies below 100 keV. In ''mixed activities'' facilities, the proportions varied, with the highest reported proportion being around 30%. Since the mid 1960s, workers in plutonium finishing plants have been typically irradiated with 60 keV photons resulting from the decay of $^{241}$Am. Although the response of the multi-element dosimeters in the 1960s was adequate for dose estimation at the surface of the body or at a depth of 10 mm [$H_p(10)$], the dose to deep organs was lower. In addition, a larger uncertainty was associated with measurements of dose from these photon energies than from higher energies, in particular for film dosimeters in use before the 1960s. Dosimetry experts from individual countries and facilities were therefore asked to identify facilities where substantial doses from ''lower-energy'' photons could be received (of the order of 10% or more of their annual ''high-energy'' photon dose) so that they could be flagged and excluded from the main epidemiological analyses.

### *b. ''Higher-energy'' photon radiation (>3000 keV)*

Exposure to ''higher-energy'' photons is also known to contribute to the dose of some workers, in particular some individuals in the operation of some power reactors. Experts answering the questionnaire mentioned the presence of $^{16}$N, which implies a possible exposure to 6 MeV photon radiation. The proportion of the dose from this type of photons was generally estimated to be below 5%. Dose from these ''higher-energy'' photons is known to be overestimated in film badges by 50–60%, although corrections could be made to doses obtained with multi-element dosimeters (*45*). The impact on dose estimates was thought to be small, and workers exposed to ''higher-energy'' radiation were included in the main analysis.

### *c. Neutron exposure*

Responses to the questionnaire indicated that exposure to neutrons could occur in some facilities, including reactors and facilities involved in plutonium treatment (see Thierry-Chef *et al.*[5]). In general, in these facilities a small number of workers were involved.

Measurement of neutron exposure is much more difficult than measurement of ''high-energy'' photon exposure, and doses have tended to be underestimated and, for some energies, not monitored at all, particularly in earlier periods. However, many monitoring systems were capable of estimating doses from some neutron energies, particularly thermal neutrons. The main techniques used for neutron monitoring in participating facilities were film and track dosimetry or thermoluminescence and albedo dosimetry and, more recently, track-etch detectors such as PADC (polyallyl diglycol carbonate). Rem counters have also been used, as well as environmental monitoring. None of these systems was capable of accurate dose estimation for all neutron energies to which workers were potentially exposed, however. For example, studies of some reactor workforces (*46, 47*) have shown that doses from intermediate-energy neutrons could be underestimated and could be substantial for individual workers. In the majority of participating facilities, only a small proportion of the worker population was substantially exposed to neutrons. Dosimetry experts from individual countries and facilities were asked to identify facilities where substantial doses from neutrons could be received so that workers with potential for substantial neutron equivalent doses (of the order of 10% or more of their annual ''high-energy'' photon dose) could be flagged and excluded from the main epidemiological analyses.

Criteria for flagging workers varied with country and facility. They are described in detail in Thierry-Chef *et al.*[5] In ''mixed activities'' facilities, substantial work has gone into the identification of workers based on type of activities performed and/or information on recorded neutron doses. In the U.S.-Hanford study, for example, workers who had worked in plutonium finishing facilities in the period 1950–1957 were flagged, as well as workers who had either (1) at least 2 years with an annual neutron dose ≥1 mSv and ≥5% of the total annual dose and a total annual dose ≥5 mSv in the period 1957–1971, (2) an annual neutron dose ≥50% the total annual dose and a total annual dose ≥2 mSv in the period 1972–1985, or (3) at least 1 year with an annual neutron dose ≥10 mSv. In France CEA-COGEMA, all subjects who had worked in particular installations where they could have received substantial doses were excluded. In most NPPs, criteria were based on monitoring results. In early days, total doses were not always well estimated and workers were therefore flagged if they had a neutron dose recorded before the end of 1964. After that date, estimates became more accurate and workers were flagged if they had a neutron dose greater than 0.5 mSv and greater than 5% of their photon dose in the period 1965–1974, from the mid-1970s techniques became fairly robust, and from 1975 workers were flagged if they had a neutron dose that was greater than 1 mSv and greater than 10% of their photon dose.

### *d. Intake of radionuclides*

Radionuclides involved in internal contamination are specific for different facilities and activities. Results from the questionnaire (see Thierry-Chef *et al.*[5] for details) showed that contamination with tritium was possible in some reactors and research centers, while contamination with plutonium and actinides could occur in some fuel treatment facilities or in weapon fabrication and research centers. With the exception of tritium, which uniformly irradiates the entire body of each worker, doses from radionuclide intake are usually specific to certain organs. Since organs have the tendency to concentrate chemical products, they also concentrate radionuclides with similar properties.

Doses from radionuclide intake are difficult to assess, particularly for transuranics such as plutonium, and have generally been poorly estimated. Direct monitoring of radiation from radionuclide intake is possible (by whole- or partial-body counting) only for $\gamma$- and higher-energy X-ray emitters. Monitoring is generally based of measurements of excretion (urine and/or fecal analyses) or potential intake [personal (in recent years) or static air sampling], and these techniques have improved with time. Further, estimation of organ doses requires knowledge of the mode of intake, particle size, chemical form and solubility; lung doses, for example, can vary by more than an order of magnitude as result of the variables. Doses are received over a period that depends on the retention of the radionuclide in various organs, and estimation of the dose depends on complex models that have changed over the years. The use of monitoring data for deriving estimates of internal doses to various organs would therefore require a considerable amount of work and substantial financial and human resources to review individual monitoring records and work histories and to estimate doses. Since this could not be conducted in the framework of the 15-Country Study, dosimetry experts from individual countries and facilities were asked to identify facilities where substantial doses (>10% of the annual limit of intake) from intake of radionuclides (other than tritium) could have occurred so that workers with potential for such doses could be flagged and excluded from the main epidemiological analyses. Flags were also provided if substantial tritium doses were received and dose estimates were not available.

Criteria for flagging workers varied with country and facility. They are described in detail in Thierry-Chef *et al.*[5] A few workers in commercial power plants had potential for substantial dose from intake of radionuclides. Flagging in ''mixed activities'' facilities was based on information on monitoring and/or on the workplace and activity of different workers. In Hanford, for example, workers were flagged if they had at least one confirmed deposition for plutonium, uranium or other radionuclides. In the UK-AEA, workers who appeared on a special list of ''confirmed internal deposition of plutonium'' were flagged, while for UK-Sellafield, all workers ever monitored for plutonium (irrespective of the results) were flagged.

Although tritium is recognized as contributing to internal dose, the distribution of tritium in the body is considered uniform and the residence time of tritium in the body is short; it is convenient to include tritium dose in the whole-body estimate for the purpose of the study, whether or not

**TABLE 1**
**Characteristics of Sources of Errors**

| Sources of errors | Uncertainties in estimated bias factors[a] | Uncertainties resulting from variation in the correct bias factors among workers[a] | Potential impact on the doses | Considered in the quantification of errors |
|---|---|---|---|---|
| Conditions of exposure | | | | |
| Energy | Shared | Berkson | major | yes |
| Geometry | Shared | Berkson | major | yes |
| Other environmental factors (heat, humidity, light) | Shared | Berkson | negligible | no |
| Dosimetry technology | | | | |
| Response to energy | Shared | Berkson | major | yes |
| Response to geometry | Shared | Berkson | major | yes |
| Laboratory practices (dosimeter processing and reading) | Unshared | Classical | minor | no |
| Calibration practices | | | | |
| Dosimetric quantity | Shared | Berkson | major | yes |
| Radiation source used for calibration | Shared | Berkson | major | yes |
| Backscatter factor | Shared | Berkson | major | yes |
| Factors affecting sources | Shared | Berkson | minor | yes |
| Administrative practices | | | | |
| Frequency of monitoring | Shared | Berkson | generally minor | no |
| Criteria for monitoring | Shared | Berkson | generally minor | no |
| Rules for below threshold doses and for missing doses | Shared | Berkson | generally minor | no |

[a] With the exception of laboratory practices, the errors in the estimated bias factors from each of the sources are shared among workers in the same time period and facility, while errors that result from variation in the correct bias factors among workers within a group defined by time period and facility are Berksonian.

it is included in the dose record used for regulatory purposes. Workers with substantial doses from tritium therefore were not excluded from the epidemiological analyses.

## *Quantification of Errors in Doses from ''High-Energy'' Photon Radiation*

Table 1 summarizes the sources of errors considered for doses from ''high-energy'' photons, together with their characteristic and potential impact on recorded doses. The major sources of errors identified for these were exposure conditions in the workplace, dosimetry technology and calibration practices. Errors from these sources were quantified as described below and organ-dose specific dosimetric bias factors were calculated for each model of dosimeter used and by facility type (NPPs and ''mixed activities'' facilities).

**TABLE 2**
**Conversion Coefficients between Quantities for Cesium, Cobalt and Radium Sources**

| Quantities converted | Calibration source | | |
|---|---|---|---|
| | Cesium | Cobalt | Radium |
| $H_p(10)$/Exposure ($10^{-2}$ Sv R$^{-1}$) | 1.06 | 1.00 | 1.02 |
| $H_p(10)$/Ka (Sv Gy$^{-1}$) | 1.22 | 1.15 | 1.20 |
| $H_p(10)/D_{water}$ (Sv Gy$^{-1}$) | 1.09 | 1.04 | 1.08 |
| $H_p(10)/D_{tissue}$ (Sv Gy$^{-1}$) | 1.11 | 1.05 | 1.09 |
| $H_p(10)/D_t(3)$ (Sv Gy$^{-1}$) | 1.02 | 1.00 | 1.01 |
| $H_p(10)$/EDE[a] (Sv Gy$^{-1}$) | 1.16 | 1.12 | 1.14 |
| $H_p(10)/D_{testes}$ (Sv Gy$^{-1}$) | 0.99 | 1.00 | 1.00 |

[a] EDE, effective dose equivalent.

### *1. Calibration bias and uncertainties*

Because international recommendations have been introduced and are followed by the vast majority of facilities, calibration practices are thought to provide generally comparable results between countries. Facility- and period-specific bias factors, however, were estimated so that recorded doses could be adjusted adequately.

Table 2 shows the factors used to convert recorded doses to $H_p(10)$ as a function of calibration source and recorded quantity. As indicated above, the factors were derived from ICRP (*18, 19*). The estimated uncertainty in these conversion factors was $K = 1.103$.

As discussed, the use of various sources to calibrate dosimeters ($^{137}$Cs, $^{60}$Co and $^{226}$Ra) can generate an additional variation in recorded dose. For multi-element film dosimeters and TLDs, dose algorithms are based on conversion factors that are dependent on the calibration source, and hence the source does not introduce bias. For older film dosimeters, however, the response varied with characteristics of the film and the thickness of the filter, which cannot be determined retrospectively for all such dosimeters. Based on published data (*48*), a bias factor of 1 ($K = 1.2$) was used for all early (non-multi-element) film dosimeters.

**TABLE 3**
**Estimated Bias and Uncertainties Related to Calibration Practices Implemented in Selected Facilities (in France and U.S.)**

| | | Period | | Calibration source | | Backscatter | | Other factors | | Overall | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | Facility | Start | End | $B_{source}$ | $K_{source}$ | $B_{back}$ | $K_{back}$ | $B_{fact}$ | $K_{fact}$ | $B_c$ | $K_c$ |
| France | Facility-1 | 51 | 60 | 1.00 | 1.20 | 1.06 | 1.05 | 1.00 | 1.05 | 1.06 | 1.22 |
| | | 61 | 95 | 1.00 | 1.00 | 1.06 | 1.05 | 1.00 | 1.05 | 1.06 | 1.07 |
| | Facility-2 | 68 | 77 | 1.00 | 1.20 | 1.06 | 1.05 | 1.00 | 1.05 | 1.06 | 1.22 |
| | | 78 | 78 | 1.00 | 1.20 | 1.06 | 1.05 | 1.00 | 1.05 | 1.06 | 1.22 |
| | | 79 | 83 | 1.00 | 1.00 | 1.06 | 1.05 | 1.00 | 1.05 | 1.06 | 1.07 |
| | | 84 | 95 | 1.00 | 1.00 | 1.06 | 1.05 | 1.00 | 1.05 | 1.06 | 1.07 |
| | Facility-3 | 55 | 60 | 1.00 | 1.20 | 1.06 | 1.05 | 1.00 | 1.05 | 1.06 | 1.22 |
| | | 61 | 95 | 1.00 | 1.00 | 1.06 | 1.05 | 1.00 | 1.05 | 1.06 | 1.07 |
| | Facility-4 | 63 | 97 | 1.00 | 1.00 | 0.96 | 1.04 | 1.00 | 1.05 | 0.96 | 1.07 |
| U.S. | Facility-5 | 43 | 52 | 1.00 | 1.20 | 1.06 | 1.05 | 1.00 | 1.05 | 1.06 | 1.22 |
| | | 53 | 79 | 1.00 | 1.00 | 1.06 | 1.05 | 1.00 | 1.05 | 1.06 | 1.07 |
| | | 80 | 97 | 1.00 | 1.00 | 0.96 | 1.04 | 1.00 | 1.05 | 0.96 | 1.07 |

In converting from one quantity to another, it was essential to define whether backscatter radiation should be included in the measured value or in the conversion coefficient. The approach chosen was to remove the effect of backscatter when it was included in the recorded dose and to consider it in the conversion of the various recorded quantities to $H_p(10)$. In the energy range under study, backscatter radiation contributes about 10% of the exposure at the surface of the body (*49*). A bias factor of 1.1 was therefore considered in places where backscatter radiation was included in recorded doses (and a factor of 1.05 was considered in a few places where it was not known whether backscatter was included or not). The value of 10% was derived in experimental conditions, assuming the dosimeter was situated on the surface of the body. In working conditions, however, the distance between the dosimeter and the body varies (on a loose-fitting lab coat, it may be several centimeters away) and the backscatter effect decreases with distance. To take the variation in distance into account, the backscatter factor was multiplied by a factor of 0.96 ($K = 1.04$), derived from information on the effect of distance and energy on the scattering from the body found in ref. (*49*).

In some facilities wooden tables or walls were mentioned as a possible source of additional scattering during calibration procedures. Based on measurements carried out in Australia,[8] a bias factor of 0.9 ($K = 1.05$) was defined to correct for the underestimation of doses.

Details of the biases and uncertainties related to calibration practices are shown in Table 3, together with the resulting overall calibration bias and associated uncertainty for the selected French and U.S. facilities.

### *2. Evaluation of predominant exposure conditions in participating facilities*

Results of the study of exposure conditions in Swiss NPPs, where employees were involved both in routine operations and maintenance, indicated that 60–80% of their doses were accumulated during maintenance work. About 90% of the average dose in Swiss power plants was estimated to be due to photons in the range 300–3000 keV, with 70 to 80% of the dose (depending on the facility and time spent in routine maintenance) received in AP geometry.

An evaluation of the differences between reactor types, period of construction and country-specific rules was used to provide an estimate of exposure conditions in NPPs included in the 15-Country Study. The resulting expert estimate of average exposure conditions and related uncertainties is given in Table 4. On average, 10% of the dose is thought to be due to photons in the range 100–300 keV (this can vary from 5 to 20% depending on worker's activities), with the average geometry being 50% in AP and 50% isotropic. The variability in geometry is large, however, with an estimated range of 10 to 80% AP. Estimated uncertainties on these values are 5% (2 SD) on the estimate of predominant energies of exposure (for both the average estimate and the range) and 10% (2 SD) on the estimate of predominant geometries of exposure (again on average and range). Exposures in rotational geometry were thought to be negligible.

Results of the study of exposure conditions in Saclay, representing "mixed activities" facilities, indicated that 80% of the average dose was from photon energies in the range 300–3000 keV, 18% in the range 100–300 keV, and 2% in the range 0–100 keV. On average, 40% of the dose was estimated to be from AP geometry and 60% from isotropic geometry. Saclay experts judged that, in a given site, the exposure conditions were unlikely to have changed very much over time. These results were reviewed, together with those of similar expert assessments at the U.S. Hanford site (*25*), of analyses of film badge data from Saclay (*22*), and with the results of the dosimetry questionnaire by a group of international experts familiar with "mixed activities" facilities. They noted that conditions of exposure in such fa-

[8] Personal communication, Hacker.

**TABLE 4**
**Estimated Percentage of Average Doses in Nuclear Power Plants and "Mixed Activities" Facilities from Different Photon Energies and Different Geometries of Exposure**

| Facility type | | Percentage of dose received from different energy photons (keV) | | | Percentage of dose received in different geometries | | |
|---|---|---|---|---|---|---|---|
| | | 0–100 | 100–300 | 300–3000 | AP | Isotropic | Rotational |
| NPP | Average dose | 0 | 10 | 90 | 50 | 50 | 0 |
| | Range | 0–1 | 5–20 | 80–100 | 10–80 | 20–90 | 0 |
| | Uncertainty on average and ranges | | ±5 | | | ±10 | |
| Mixed activities | Average dose | 0 | 20 | 80 | 50 | 50 | 0 |
| | Variation between installations | 0 | 15–25 | 75–85 | 40–55 | 45–60 | 0 |
| | Variation between workers | 0 | 15–25 | 75–85 | 0–60 | 40–100 | 0 |
| | Uncertainty on average and ranges | | ±5 | | | ±10 | |

cilities depend on many factors such as radiation sources, worker protection and facility-specific policies. They concluded, however, that the proportion of the dose due to low-energy photon radiation is typically higher than in NPPs since the main sources of radiation are not only fission and activation products but also can include less energetic sources (in radioisotope production sites for example). The overall estimate (Table 4) was that, on average, 20% (±5%, 2 SD) of the dose is due to photons in the range 100–300 keV. The proportion was estimated to range between 15 and 25% between workers (since all workers are thought to be exposed to all sources) and between installations.

Predominant geometry of exposure was more difficult to assess because of the variety of work activities. The overall estimate was that, 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. Again, the proportion of doses received in rotational geometry was thought to be negligible. Note that in "mixed activities" facilities, exposure conditions would vary from one installation to another because of the different activities involved; this is not the case in NPPs.

### *3. Evaluation of response of dosimeters to energy and geometry of exposure*

Evaluation of the response of dosimeters to workplace conditions of exposure was based on experiments (*20*) and extrapolations to other dosimeters used historically in participating facilities as described above. The bias and uncertainty factors derived from the experiment are shown in Supplementary Table 4 for each dosimeter-energy-geometry combination. In the experiment, dosimeters were exposed to two different low energies: 118 and 208 keV and their response for the 100–300 keV range was derived from these results as discussed above. The estimated dosimeter response in each energy-geometry combination of interest and the related uncertainties ($K_{response}$) are shown in Table 5 for each of the dosimeter types used in the selected French and U.S. facilities.

**TABLE 5**
**Dosimeter Specific Bias Factors [in $H_p(10)$] and Related Uncertainties for Dosimeter Types used in Selected Facilities (in France and U.S.)**

| Dosimeter | Facility type | Exposure conditions | | | | Dosimeter response | | | | Bias | Uncertainty: Specific | | | Uncertainty: Overall |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $B_{100–300,AP}$ | $B_{100–300,ISO}$ | $B_{300–3000,AP}$ | $B_{300–3000,ISO}$ | $f_{100–300}$ | $f_{300–3000}$ | $f_{AP}$ | $f_{ISO}$ | $B_{d,Hp(10)}$ | $K_{exposure}$ | $K_{response}$ | $K_{experiment}$ | $K_{d,Hp(10)}$ |
| Open | NPP | 3.28 | 4.83 | 0.90 | 0.99 | 0.1 | 0.9 | 0.5 | 0.5 | 1.09 | 1.41 | 1.12 | 1.10 | 1.44 |
| | MA | 3.28 | 4.83 | 0.90 | 0.99 | 0.2 | 0.8 | 0.5 | 0.5 | 1.26 | 1.34 | 1.18 | 1.10 | 1.40 |
| FR-1 | MA | 1.17 | 1.17 | 0.68 | 0.74 | 0.2 | 0.8 | 0.5 | 0.5 | 0.78 | 1.06 | 1.10 | 1.10 | 1.12 |
| FR-2 | MA | 1.82 | 1.62 | 0.90 | 0.99 | 0.2 | 0.8 | 0.5 | 0.5 | 1.06 | 1.04 | 1.12 | 1.10 | 1.12 |
| FR-3 | NPP | 1.80 | 1.61 | 0.90 | 0.99 | 0.1 | 0.9 | 0.5 | 0.5 | 1.00 | 1.06 | 1.11 | 1.10 | 1.12 |
| FR-4 | NPP | 0.73 | 0.57 | 0.90 | 0.99 | 0.1 | 0.9 | 0.5 | 0.5 | 0.91 | 1.07 | 1.10 | 1.10 | 1.12 |
| U.S.-1 | MA | 1.25 | 1.16 | 0.90 | 0.99 | 0.2 | 0.8 | 0.5 | 0.5 | 0.99 | 1.03 | 1.11 | 1.10 | 1.12 |
| FR-6 | MA | 0.63 | 0.62 | 0.82 | 0.82 | 0.2 | 0.8 | 0.5 | 0.5 | 0.77 | 1.02 | 1.11 | 1.10 | 1.11 |
| Other multi-element film | NPP | 0.87 | 0.98 | 0.81 | 0.93 | 0.1 | 0.9 | 0.5 | 0.5 | 0.87 | 1.07 | 1.15 | 1.10 | 1.17 |
| | MA | 0.87 | 0.98 | 0.81 | 0.93 | 0.2 | 0.8 | 0.5 | 0.5 | 0.88 | 1.09 | 1.15 | 1.10 | 1.19 |
| FR-9 | MA | 0.86 | 0.83 | 0.78 | 0.82 | 0.2 | 0.8 | 0.5 | 0.5 | 0.81 | 1.02 | 1.15 | 1.10 | 1.15 |
| Other TLDs | NPP | 0.91 | 0.97 | 0.89 | 0.94 | 0.1 | 0.9 | 0.5 | 0.5 | 0.92 | 1.04 | 1.20 | 1.10 | 1.20 |
| | MA | 0.91 | 0.97 | 0.89 | 0.94 | 0.2 | 0.8 | 0.5 | 0.5 | 0.92 | 1.04 | 1.18 | 1.10 | 1.19 |
| U.S.-PIC | MA | 1.50 | 1.50 | 1.50 | 1.50 | 0.2 | 0.8 | 0.5 | 0.5 | 1.50 | 1.00 | 1.29 | 1.10 | 1.29 |

**TABLE 6**
**Dosimeter Specific Bias Factors [in $H_p(10)$ and Organ Doses] and Related Uncertainties for Dosimeter Types used in Selected Facilities (in France and U.S.)**

| Dosimeter | Facility type | $H_p(10)$ | | Organ dose | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $B_{d,Hp(IO)}$ | $K_{d,Hp(10)}$ | $B_{d,lung}$ | $K_{d,lung}$ | $B_{d,RBM}$ | $K_{d,RBM}$ | $B_{d,colon}$ | $K_{d,colon}$ |
| Open | NPP | 1.09 | 1.44 | 1.31 | 1.52 | 1.57 | 1.35 | 1.40 | 1.85 |
| | MA | 1.26 | 1.40 | 1.53 | 1.43 | 1.83 | 1.22 | 1.62 | 1.85 |
| FR-1 | MA | 0.78 | 1.12 | 0.95 | 1.16 | 1.14 | 1.19 | 1.01 | 1.27 |
| FR-2 | MA | 1.06 | 1.12 | 1.29 | 1.17 | 1.55 | 1.22 | 1.37 | 1.16 |
| FR-3 | NPP | 1.00 | 1.12 | 1.21 | 1.19 | 1.44 | 1.37 | 1.28 | 1.15 |
| FR-4 | NPP | 0.91 | 1.12 | 1.09 | 1.16 | 1.31 | 1.17 | 1.16 | 1.26 |
| U.S.-1 | MA | 0.99 | 1.12 | 1.20 | 1.16 | 1.44 | 1.15 | 1.28 | 1.17 |
| FR-6 | MA | 0.77 | 1.11 | 0.94 | 1.16 | 1.12 | 1.29 | 1.00 | 1.18 |
| Other multi-element film | NPP | 0.87 | 1.17 | 1.05 | 1.20 | 1.26 | 1.19 | 1.12 | 1.30 |
| | MA | 0.88 | 1.19 | 1.07 | 1.21 | 1.28 | 1.23 | 1.13 | 1.35 |
| FR-9 | MA | 0.81 | 1.15 | 0.98 | 1.18 | 1.18 | 1.27 | 1.04 | 1.25 |
| Other TLDs | NPP | 0.92 | 1.20 | 1.10 | 1.23 | 1.32 | 1.27 | 1.17 | 1.29 |
| | MA | 0.92 | 1.19 | 1.12 | 1.21 | 1.34 | 1.30 | 1.18 | 1.31 |
| U.S.-PIC | MA | 1.50 | 1.29 | 1.65 | 1.33 | 1.37 | 1.65 | 1.55 | 1.42 |

The largest biases and uncertainties were associated with response of early dosimeters to low-energy photon radiation. Even at low energies, the response of modern dosimeters was within ±35%, i.e. consistent with the IEC (International Electrotechnique Commission) recommendation, adopted in many countries as a basis for accreditation. PICs were thought to overestimate doses by a factor if 1.5 with a large associated uncertainty ($K = 1.29$), while the spherical RPL dosimeters were considered to be unbiased with respect to energy and geometry.

*4. Dosimetric bias and uncertainties*

For each dosimeter used in participating facilities, the resulting dosimetric bias factor ($B_d$) based on the estimated energy and geometry-specific bias factors for that dosimeter and the estimated predominant conditions of exposure in the facility are shown in terms of $H_p(10)$ in Table 5. This table also shows the individual uncertainty factors $K_{exposure}$, $K_{response}$, $K_{experiment}$ and the overall uncertainty factor $K_{d,H_p(10)}$.

Despite the substantial overestimation of doses by bare film in the 100–300 keV range (3.28 and 4.83 for AP and isotropic geometries, respectively), the overall bias factor for such dosimeters in ''mixed activities'' facilities is only 1.26, because the proportion of the dose in working conditions due to photons in this energy range represents only about 20% of the dose. The uncertainty on the dosimeter response derived from the experiment is large, however ($K = 1.40$).

Bias factors and associated uncertainties were also derived in terms of organ doses (bone marrow, colon and lung) for each dosimeter used in participating facilities (see Thierry-Chef *et al.*[5]); the uncertainties also include uncertainty in conversion factors from $H_p(10)$ to organ dose ($K = 1.103$) (Table 6).

*5. Overall bias and uncertainties*

Biases and associated uncertainties from calibration practices and from dosimeter response in workplace exposure conditions were combined. They are shown in terms of $H_p(10)$ and organ dose in Table 7 for the selected French and U.S. facilities. These factors were used in the epidemiological analyses to convert individual annual recorded doses into $H_p(10)$ and organ dose following Eq. (3).

## DISCUSSION

Within the 15-Country Study, the Study of Errors in Dosimetry was carried out to assess the comparability of doses recorded in participating facilities. Identification and quantification of bias and uncertainties was based on (1) questionnaires completed by local experts, (2) experimental results using representative dosimeters, and (3) data from sample power plants and ''mixed activities'' facilities. Some facilities included in the study began operation prior to 1950, and many changes in dosimetry technology and conditions of work have occurred that could influence the adequacy of dose estimates. In some cases, it was difficult for participants to provide accurate historical information.

However, based on their knowledge of the nuclear industry activities in different countries, the Dosimetry Subcommittee members were able to expand and interpolate questionnaire data.

*Calibration Practices*

It has been very difficult for the participants to provide information on calibration practices, especially for early years, since calibration procedures were very rarely documented. Interpretation of the answers to the questionnaires was conducted with care, and the major sources of errors were quantified, based on the judgment of the Dosimetry

**TABLE 7**
**Final Estimated Biases and Uncertainties in Selected Facilities (in France and U.S.)**

| | | | | Bias | | | | | | Uncertainty | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Period | | $H_{(10)}$ | Lung | RBM | Colon | | | $H_{p(10)}$ Overall | Overall $K_{organ}$ | | |
| Country | Facility | Start | End | $B_c$ | $B_{d,Hp(10)}$ | $B_{Hp(10)}$ | $B_{lung}$ | $B_{RBM}$ | $B_{colon}$ | $K_c$ | $K_{d,Hp(10)}$ | $K_{Hp(10)}$ | $K_{lung}$ | $K_{RBM}$ | $K_{colon}$ |
| France | Facility-1 | 1950 | 1956 | 1.06 | 1.26 | 1.33 | 1.62 | 1.94 | 1.72 | 1.22 | 1.40 | 1.48 | 1.51 | 1.33 | 1.69 |
| | | 1957 | 1960 | 1.06 | 0.78 | 0.83 | 1.01 | 1.21 | 1.07 | 1.22 | 1.12 | 1.26 | 1.28 | 1.31 | 1.22 |
| | | 1961 | 1966 | 1.06 | 0.78 | 0.83 | 1.01 | 1.21 | 1.07 | 1.07 | 1.12 | 1.14 | 1.17 | 1.21 | 1.07 |
| | | 1967 | 1984 | 1.06 | 0.77 | 0.82 | 1.00 | 1.19 | 1.06 | 1.07 | 1.11 | 1.13 | 1.17 | 1.30 | 1.07 |
| | | 1985 | 1994 | 1.06 | 0.79 | 0.84 | 1.02 | 1.22 | 1.08 | 1.07 | 1.15 | 1.17 | 1.20 | 1.30 | 1.07 |
| | | 1995 | 1995 | 1.06 | 0.81 | 0.86 | 1.04 | 1.25 | 1.10 | 1.07 | 1.15 | 1.17 | 1.20 | 1.28 | 1.08 |
| | Facility-2 | 1968 | 1978 | 1.06 | 0.88 | 0.93 | 1.13 | 1.36 | 1.20 | 1.22 | 1.19 | 1.30 | 1.32 | 1.33 | 1.26 |
| | | 1979 | 1995 | 1.06 | 0.88 | 0.93 | 1.13 | 1.36 | 1.20 | 1.07 | 1.19 | 1.21 | 1.22 | 1.25 | 1.15 |
| | Facility-3 | 1955 | 1960 | 1.06 | 0.78 | 0.83 | 1.01 | 1.21 | 1.07 | 1.22 | 1.12 | 1.26 | 1.28 | 1.31 | 1.22 |
| | | 1961 | 1964 | 1.06 | 0.78 | 0.83 | 1.01 | 1.21 | 1.07 | 1.07 | 1.12 | 1.14 | 1.17 | 1.21 | 1.07 |
| | | 1965 | 1995 | 1.06 | 0.88 | 0.93 | 1.13 | 1.36 | 1.20 | 1.07 | 1.19 | 1.21 | 1.22 | 1.25 | 1.15 |
| | Facility-4 | 1968 | 1982 | 0.96 | 1.00 | 0.96 | 1.16 | 1.38 | 1.23 | 1.07 | 1.12 | 1.14 | 1.21 | 1.38 | 1.29 |
| | | 1982 | 1982 | 0.96 | 0.97 | 0.93 | 1.11 | 1.33 | 1.18 | 1.07 | 1.12 | 1.14 | 1.18 | 1.20 | 1.28 |
| | | 1983 | 1997 | 0.96 | 0.91 | 0.87 | 1.05 | 1.26 | 1.11 | 1.07 | 1.12 | 1.14 | 1.17 | 1.19 | 1.18 |
| U.S. | Facility-5 | 1943 | 1952 | 1.06 | 1.50 | 1.59 | 1.93 | 2.31 | 2.05 | 1.22 | 1.29 | 1.38 | 1.41 | 1.72 | 1.99 |
| | | 1953 | 1979 | 1.06 | 0.88 | 0.93 | 1.13 | 1.36 | 1.20 | 1.07 | 1.19 | 1.21 | 1.22 | 1.25 | 1.15 |
| | | 1980 | 1997 | 0.96 | 0.92 | 0.88 | 1.08 | 1.29 | 1.13 | 1.07 | 1.19 | 1.21 | 1.23 | 1.31 | 1.20 |

Subcommittee on these answers. In the vast majority of facilities, international recommendations were followed and calibration procedures were comparable. Before strict rules were implemented, quantities used to measure doses were easily measurable, and it is estimated that conditions were generally good. The factors derived to correct for backscatter radiation, calibration sources and factors affecting sources are close to 1.

Because dosimeters are also exposed to background radiation, which does not form part of the occupational exposure, it is necessary to subtract background from all readings. In a small number of facilities, it was reported in the questionnaires that no adjustment for background had been carried out in some facilities and periods. No adjustment was made for this because the Dosimetry Subcommittee felt the question may have been misunderstood. However, sensitivity analyses were conducted in the epidemiological studies by subtracting a factor of 0.9 mSv from the individual annual doses in these facilities and periods to assess the impact of adjustment for background in these facilities.

*Response of Dosimeters to Conditions of Exposure*

The study was carried out in almost 100 facilities from 15 countries. Therefore, it was not possible to assess conditions of exposure in each participating facility. Experts from eight countries were involved in the various meetings held to evaluate predominant conditions of exposure. Their estimates were based mainly on the results of pilot studies carried out in a small number of specific facilities and on results of measurements and exposure assessments in a limited number of other facilities. The diversity of sources to which workers are exposed in ''mixed activities'' facilities is reflected by the relatively high proportion of dose due to photon radiation in the range 100–300 keV compared with the dose received by workers in NPPs, where the most likely exposure is due to photon radiation from activation and fission products (20% of the dose instead of 10%). In NPPs, the main source of low-energy photons is from secondary photon radiation due to interaction between $^{137}Cs$ or $^{60}Co$ incident photon radiation and shielding.

Predominant geometries of exposure are highly related to job type and depend on activities and procedures implemented in various countries. In both NPPs and ''mixed activities'' facilities, uncertainties on estimates of predominant geometry are large since variations depending on activities and conditions are important. Additional studies would be helpful to better characterize geometry of exposures.

Response of the dosimeters used in participating facilities is generally reliable in workplace exposure circumstances and adjustments made using the coefficients derived in this study do not introduce major changes in recorded doses. Indeed, the vast majority of dosimeters used in participating facilities were multi-element film or thermoluminescence dosimeters, with reliable response characteristics over the whole energy range (100–3000 keV). Even older dosimeters with bare film, which substantially overestimated doses in the 100–300 keV range, have a relatively small overall bias factor, because of the small proportion of the dose from these photon energies.

*Bias and Uncertainties on ''High-Energy'' Photon Radiation*

Overall bias and uncertainties were derived for each facility and each period corresponding to the use of a particular type of dosimeter, and calibration practices. In the epidemiological analyses (*4*), annual doses recorded for each worker were adjusted to take the bias and related uncertainties into account. Because no major bias was identified as the result of the use of any specific dosimeter or the calibration practice, the final bias factors are generally close to 1, although the magnitude of the uncertainties varies. Although these bias factors are less than what was thought at the beginning of the study, the impact is not negligible. The biases and uncertainties are largest in the early years of operations of the older facilities (i.e. pre-1960), when the highest doses tended to be received by workers. The Study of Errors in Dosimetry has ensured that the dose estimates available in the facilities participating in the 15-Country Study were made comparable between countries and facilities and has provided time- and facility-specific estimates of dosimetric uncertainties. For the purpose of the dose–response analyses presented in refs. (*2–4*), doses to the colon, lung and active bone marrow were obtained by dividing the recorded doses by the appropriate organ dose bias factor; analyses did not, however, fully account for uncertainties in dose estimates described here. Such analyses, using a method described by Stayner *et al.* (manuscript submitted for publication), are under way and will be presented in detail in a separate manuscript.

### *Other Sources of Radiation*

Since photon radiation in the energy range between 100 and 3000 keV is predominant in the types of facilities under study, dosimetry research has concentrated, from the beginning of the industry, on the detection of photon radiation in this energy range and doses have been measured historically with sufficient accuracy to be used in an epidemiological study.

The adequacy of practices and technology to measure and record doses from other radiation types (in particular lower-energy photons and neutrons) and doses from intakes of various radionuclides was in contrast subjected to substantial variability, particularly in the earlier years. Workers with potential for substantial doses (10% or more of their whole-body dose) from these radiation types were therefore flagged and excluded from the main epidemiological analyses. Indeed, it was not feasible to adequately address effects of these radiation types in the 15-Country Study because of the enormous amount of work needed to reconstruct doses and associated uncertainty. A multinational nested case-control study is currently being started (http://www.alpha-risk.org) to assess the effects of plutonium and uranium exposures on the risk of lung cancer and leukemia.

## CONCLUSION

The Study of Errors in Dosimetry presented here was carried out within the framework of the International Collaborative Study of Cancer Risk among Radiation Workers. Methods have been developed to enable the comparison of recorded doses through time and among different facilities and to quantify identified bias and uncertainties in historical recorded worker dose. Doses from photon radiation in the energy range 100–3000 keV have been measured with adequate precision and accuracy to be used in an epidemiological study, since the beginning of the industry in participating facilities. To allow comparability of dosimetric data across facilities and time, the main sources of errors have been identified and quantified and used to adjust annual recorded doses for epidemiological analyses and the assessment of risk.

## SUPPLEMENTARY INFORMATION

Supplementary Tables 1–4: http://10.1667/RR0552.1.s1.

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