Radiation Protection Dosimetry (2008), Vol. 131, No. 2, pp. 188–197
Advance Access publication 10 June 2008
doi:10.1093/rpd/ncn165

DOSE RECONSTRUCTION FOR AN OCCUPATIONAL COHORT AT THE SAVANNAH RIVER NUCLEAR FACILITY: EVALUATION OF A HYBRID METHOD

Ghassan Hamra[1], Leena A. Nylander-French[1] and David Richardson[2,]*
[1]Department of Environmental Sciences and Engineering, The University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-7400, USA
[2]Department of Epidemiology, School of Public Health, The University of North Carolina at Chapel Hill, CB #7435, McGavran-Greenberg, Chapel Hill, NC 27599-7400, USA

Received November 27 2007, revised March 25 2008, accepted April 21 2008

The Savannah River Site (SRS) is the only nuclear facility in the United States that produces tritium, a radioactive isotope of hydrogen. The purpose of the study was to derive annual tritium dose estimates for SRS employees through the development of a job-exposure matrix. The proposed method is unique in that along with qualitative information on job, area and time of employment, it utilises recorded annual whole-body dose measures, when available, in order to estimate doses from tritium intakes of the monitored workers. Using information from 75 253 dose measures for the period 1954–1978, the average proportion of the whole-body dose that was due to tritium intake was calculated; these proportions were allowed to vary by job, area and time period. This information was used to assign tritium dose levels for 43 590 employment-years. The collective estimated tritium dose was 4319 mSv compared with the total known tritium dose of 17 382 mSv. The correlation (R^2) of estimated tritium dose with known tritium dose was 0.68.

INTRODUCTION

Savannah River Site (SRS) is a 315-mile^2 nuclear fuel facility located in Aiken, SC, USA. Originally operated by E.I. duPont de Nemours & Company (DuPont), SRS has produced nuclear fuels, mainly tritium and ^{239}Pu, for >50 y. Since SRS is solely a nuclear fuels facility, radiological hazard protection is integrated into everyday operations. Although this may help reduce occupational exposures, it does not eliminate them. About 85% of the total occupational dose is characterised as external exposure, while the remaining 15% are attributable to internally deposited radionuclides(1).

One of these radionuclides is tritium, an isotope of hydrogen that emits beta radiation as it decays into helium(2). Since it acts like hydrogen, tritium gas is capable of binding to oxygen molecules to form tritiated water (HTO). HTO may enter the body via inhalation, ingestion, or absorption through the skin(3). Once absorbed, HTO will readily diffuse through cellular membranes, uniformly integrating itself into the water present in the human body(2). While tritium has a physical half-life of 12.3 y, ingested HTO has a biological half-life of about 10 d(4). In that time, tritium is capable of producing genetic mutations via beta-radiation or the energy release associated with transformation from ^{3}H to ^{3}He(2). Animal tests have shown that acute exposure to HTO can lead to malformations and death(3). However, little is known about the effects of chronic low-level exposure. One study by Joksic and Spasojevic-Tisma(5) found that low-level exposure to tritium caused chromosomal damage in human lymphocytes, but direct estimates of human cancer risk following tritium exposure are not available(6).

Savannah River Site is the only nuclear fuel facility in the US that produces tritium. Although tritium is a by-product of processes at most other nuclear facilities, the fact that SRS has the explicit task of producing tritium necessitates an examination of exposure to tritium among SRS employees. Historically, tritium dose was measured via biological monitoring at SRS. Since the late 1970s, dose measures have been maintained in an electronic format that facilitates their use for research purposes. However, dose measures for earlier time periods have only been computerised in summation with the other components of a worker's whole-body dose (i.e. summed together with penetrating dose from external irradiation).

The goal of the research was to develop a predictive model of the tritium dose component of annual recorded whole-body dose (AWBD). This research is unique in that principles of job-exposure matrix development with quantitative measures of AWBD were combined to estimate personal tritium dose for SRS employees without a known tritium dose. Often in occupational settings, a researcher has very little information with which to derive individual

---

*Corresponding author: david.richardson@unc.edu

quantitative exposure estimates. In this case, there are records of annual tritium dose measures for a large proportion of the workers in the study cohort. In addition, for those without records of annual tritium dose measures (e.g. the tritium component of the whole body dose was not available in computerised form) the records of AWBD have been computerised. The proposed model provides quantitative tritium dose estimates, which may be utilised in further research of health effects of tritium exposure among this population of workers.

METHODS

Cohort

A roster of 21 204 individuals hired by DuPont between 1950 and 1986 was enumerated. Those workers without a known (i) date of birth ($n = 57$), (ii) date of first hire ($n = 184$) or (iii) gender ($n = 10$) were excluded from the study. In addition, individuals who were employed <90 days ($n = 1355$) were also excluded since they may differ from long-term employees with respect to mortality risk and cumulative dose estimates. Finally, SRS workers previously employed at another Department of Energy facility ($n = 715$) were excluded since information on occupational radiation exposure that occurred outside of employment at SRS was not known. This left 18 883 SRS workers who met the entry criteria for inclusion in the study cohort.

Occupation and health physics area categories

A file containing work-history information was created from DuPont payroll records that contained information about dates of employment and job-title changes. Job titles were standardised and coded to 34 major occupational groups. On the basis of this information, a file was created that describes the number of days that a worker was employed during each calendar year (1951–1999). If a worker held more than one job in a calendar year, for simplicity, a single occupation for that worker was assigned based on the longest held occupation in that year.

The term ‘health physics area’ (HPA) represents a system defined by health physicists at SRS for classifying workers based on location and similarity of procedure. In each HPA, which are specific to the SRS facilities, occupational exposure to radiation among employees was under the supervision of radiation monitors or health physics staff. HPA represented a single location (such as an administrative building) or a number of work locations, which are physically separated but take part in similar processes (such as ‘100-Reactors’, which consists of five reactors at SRS, some of which are miles apart). Information on HPA was ascertained from quarterly dosimetry logbooks for the years 1958–1989. If a worker was missing information on HPA for a given employment-year, but had a known HPA for an adjacent time period during which they were employed in the same job, then, for the purposes of exposure imputations, it was assigned that HPA to the employment-year. For those employment-years for which HPA could not be assigned, there was established an ‘Unknown’ category.

Tritium dosimetry program at SRS

Tritium dose records at SRS represent the annual sum of internally deposited tritium measured via urinalysis. Calcium was added to HTO in urine samples and the evolved hydrogen from this was passed through an ionisation chamber. This practice was standard from the start of operations until 1958, and the analysis had a minimum detectable activity (MDA) level of 1 μCi/l. The reporting level was set at 1 μCi/l for a number of years, and was eventually reduced to match the current MDA of 0.1 μCi/l. Including urinalysis results, the calculation of tritium-equivalent dose (expressed in rem or Sv) took a number of factors into consideration including biological half-life, target tissue, default mass of body water, a quality factor for tritium and the mean energy of tritium beta particles(7).

When converting urinalysis results to dose estimates, the presumed patterns of exposure were taken into consideration in order to properly represent the body burden of tritium (i.e. acute exposure episodes versus chronic low-dose exposure). The details of conversion of urinalysis results are summarised by Taylor *et al.*(7) and Scalsky(8).

Annual tritium dose was recorded as a component of the annual whole-body dose and represented a fraction of the AWBD. Since tritium was measured via biological monitoring after it had been distributed in the body, tritium was referred to as a dose based on the International Society of Exposure Analysis (ISEA) definition of dose as ‘the amount of agent that enters a target after crossing an exposure surface’(9).

External dosimetry recording practices at SRS

During the beginning of operations at SRS, dosimetry services were provided by Oak Ridge National Laboratory (ORNL). ORNL processed films for SRS, and dosemeter exchange took place on a weekly basis. In 1951, personal ionisation chambers were used in addition to film dosemeters to measure exposure among SRS workers. In 1952, SRS initiated an on-site dosimetry programme. Dosemeters were the same two-element film dosemeters used by ORNL and were collected on a weekly basis. In March 1953, SRS began processing film using the ORNL film badge dosemeter. In 1957, SRS beta/photon dosemeter exchange practice was changed to occur on a biweekly basis. In 1959, SRS began using a multi-element film dosemeter. This dosemeter allowed for individual analysis of beta, gamma and X-ray exposures among personnel. In 1965, SRS implemented a 4-week exchange programme for beta/photon dosemeters, which was changed to a monthly exchange program in 1966. This monthly exchange programme remains in use today. In 1970, SRS thermoluminescent dosemeters (TLDs) replaced film as the means for recording beta/photon dose. The laboratory minimum detection limit (MDL) for this method was 0.15 mSv, as compared with 0.4 mSv for the previous method. In 1983, the use of commercial Panasonic beta/photon TLDs was implemented. This new dosimetry method reduced the MDL from 0.15 to 0.05 mSv(7).

Employment-year dosimetry records

The term ‘employment-year’ is used to describe the unit of observation contributed by a person each year he/she was employed at SRS, regardless of the number of days employed. A worker who had computerised annual dosimetry information for his/her entire employment period provided one annual dosimetry record for each employment-year.

In 1979, a computerised personal dosimetry system, referred to as the Health Protection Annual Radiation Exposure History (HPAREH) system, was implemented at SRS. The HPAREH system was developed in order to produce a file of annual radiation-exposure data for all SRS employees who were actively employed in 1979. Historical dosimetry information was entered into the HPAREH system from hardcopy personnel folders and logbooks (1951–1964), magnetic tapes of logbooks (1965–1972) and HP Master File magnetic tapes (1973–1979). Since 1979, dosimetry information has been routinely entered into the HPAREH system. The HPAREH file includes some records for years in which workers were not monitored for external radiation exposure using personal dosemeters at SRS. These records were entered into the HPAREH system in order to record information about offsite doses and internal doses from radionuclides other than tritium. If the only information for a monitoring year pertained to an estimate of offsite dose or an estimate of effective dose from an internal deposition (other than tritium), then the record was excluded from the analyses.

Dosimetry information for an additional 1058 workers was identified and computerised during the course of an epidemiological cohort study of SRS workers conducted by Oak Ridge Associated Universities, known as the SRPABST file.

Workers who terminated employment at SRS prior to 1979 were not included in the HPAREH system. An electronic file of annual radiation-dose estimates for the period of 1951–1979 was constructed for the purpose of epidemiological research conducted by the DuPont Corporation, called the Fayerweather file. In the Fayerweather file, abstraction of annual tritium-dose information was incomplete. If a non-zero tritium dose value was recorded in the Fayerweather file, it could, in most cases, be validated; however, relatively few such values were recorded.

As part of the research, dosimetry information was derived from historical dosimetry logbooks for an additional 854 workers who were employed during the period of 1964–1979. In addition, 15 752 annual dosimetry records were identified in the historical dosimetry logbooks that were not included in the HPAREH, Fayerweather or SRPABST computerised files. From these files, it is possible to abstract dosimetry information from historical logbooks for an additional 5686 employment-years. The recorded annual deep- and shallow-dose estimates were 0 rem for nearly all of the remaining 10 066 employment-years. These were dosimetry records for workers whose employment terminated after 1 January 1979 and appeared in the historical SRS logbooks but not in the HPAREH file. An estimated annual deep- and shallow-dose of 0 rem was assigned to these years. Lastly, a ‘nearby’ method was used to estimate annual whole-body dose for 13 812 employment-years for which dosimetry information was not available (i.e. 6% of the employment-years for SRS workers during the period 1954–1989). These data are described in a previous work by Richardson *et al.*(10). In the present analysis, these estimates were treated as known annual whole-body dose records.

Radiation exposure records at SRS have been maintained by a combination of manual and computer efforts following procedures to ensure data quality(7). For most of its history, SRS has used an automatic system for recording and archiving external exposure data from personnel monitoring badges in a computerised master file(11). Supplemental abstraction of data from hardcopy and magnetic tapes followed a protocol for data entry and error checking(12,13).

Modern radiation dose information is expressed in sieverts, which represents the biological equivalent dose based on Joules per kilogram multiplied by weighing factors for the exposed organism and radiological agent of interest. For the sake of consistency with contemporary nomenclature, dose estimates that were originally expressed in units of rem are discussed and reported here in sieverts, where 1 Sv = 100 rem.

Estimation of tritium dose

The objective was to estimate the tritium component of the AWBD in order to impute a value for those employment-years in which recorded tritium doses were missing. The technique applied combined an industrial hygiene approach to develop a job-area-exposure matrix (JEM) with empirical methods for exposure prediction using regression modelling.

Typically, a JEM will utilise qualitative information about the area of employment, occupation and time of employment for assignment of a level of exposure (or dose) based on expert knowledge of where and when an exposure was likely to occur(14–17). This level of exposure may be dichotomous, with an employee assigned a 'yes/no' to exposure, or ordinal, with exposure described as 'low/medium/high'(18). The proposed method of dose reconstruction differs in that this qualitative information was combined with quantitative data about estimated whole-body dose in order to provide quantitative estimates of annual tritium dose.

Previous studies of workers at SRS were focused on classifying dose level according to job and area description alone and it was shown that workers receive the highest tritium dose in one of the three processes: neutron irradiation of lithium–aluminium targets or heavy water (D_2O) and fission due to reprocessing of reactor fuels(19). However, the combinations of job-area that may have led to tritium exposure were not consistent over time. For example, there were changes over time in the type and number of reactors operating at SRS. In addition, individuals with an occupation for which tritium exposure was not expected, but who were also assigned an HPA code for working in an area where tritium exposure was expected, may not have been properly assigned a level of tritium dose, as may have been suggested in previous studies. Thus, information on occupation, HPA and calendar year has been incorporated into consideration in developing the predictive model of tritium dose.

Statistical analysis

The proportion of a worker's AWBD due to intake of tritium was estimated by fitting a linear regression model in which the dependent variable was the annual tritium dose and the independent variable was the annual whole-body dose using Statistical Analysis Software (SAS, v. 8.2, Cary, NC, USA). The model was stratified by occupational group, HPA and calendar year, thereby allowing for different estimates of the fraction of AWBD due to tritium within each stratum defined by these factors.

In addition, strata by categories of AWBD were defined. This stratification accounted for potential differences in the relationship between tritium and AWBD within subgroups defined by occupation, area and calendar year. A major concern when developing a JEM is that job titles do not provide substantive distinctions between tasks at a facility, since job titles and area codes may represent information used for administrative tasks, rather than for research purposes(16). Further dividing groups of workers who share similar occupational titles and areas into subgroups based on AWBD serves to create subgroups that have greater similarity in job activities (and therefore in their relationships between tritium dose and AWBD).

A general model was developed assuming a linear relationship between tritium dose and AWBD.

$$Y_{ijkl} = \alpha_{ijkl} + \beta_{ijkl}\mathrm{x} + \epsilon_{ijkl}$$

for $i = 1,2,\ldots, m$ year, $j = 1,2,\ldots, F$ area, $k = 1,2,\ldots, n$ occupation and $l = 1,2,\ldots, p$ AWBD group, where Y_{ijkl} represents tritium dose for the lth AWBD group in the kth occupation of the jth area in the ith year, α_{ijkl} the intercept for the lth AWBD group in the kth occupation of the jth area in the ith year, x the fixed effect for amount of AWBD exposure, β_{ijkl} amount of AWBD exposure for the lth AWBD group in the kth occupation of the jth area in the ith year and ε_{ijkl} is the random effect for the lth AWBD group in the kth occupation of the jth area in the ith year.

This model is fit using a complete data analysis; therefore, the regression coefficients are estimated for all workers who have known (i.e. computerised) tritium dose values. The parameter estimates obtained from this linear regression model were then used in conjunction with covariate patterns observed for employment-years with missing tritium-dose values in order to derive a predicted tritium dose for that year. This predictive model helped to derive estimates of an individual's tritium dose based on the known tritium dose levels of his/her coworker.

The reliability of this estimation procedure was evaluated by comparing observed tritium doses with estimated values. For these evaluations, all observed annual tritium-dosimetry records were utilised. A predicted value was derived for each annual tritium-dosimetry record using the estimation procedure described above. The correlation of observed and predicted values was calculated as a direct assessment of the model. Further evaluations of this estimation procedure were conducted in order to examine how reliably the values were estimated when observed doses were of differing magnitudes. Boxplots were created of the difference between estimated and observed by the level of the observed dose.

RESULTS

Cohort data

During the period 1951–1999, the 18 883 workers in the study cohort contributed a total of 277 735 employment-year records (Table 1). Recorded tritium doses were available for 224 357 of these

Table 1. Description of employee records for the entire SRS occupational cohort from 1951–1999.

	Number of records			
	1951–1953	1954–1978	1979–1999	Total
Total employment years	9014	155 281	113 440	277 735
Known tritium dose	2294	109 956	112 107	224 357
Missing tritium dose	6720	45 325	1333	53 378
Employment years with a AWBD > 0	1457	117 991	58 772	178 220
Known tritium dose	800	74 610	58 206	133 616
Missing tritium dose	657	43 381	566	44 604

employment-years. Thus, there were 53 378 employment-years for which tritium-dose information was unknown.

Tritium exposures were minimal for most workers during the period 1951–1953 as the first production reactor at SRS went critical in December 1953. Therefore, tritium-dose values for employment years for the period 1951–1953 were not estimated. From 1979 onwards, tritium-dose estimates were routinely computerised at SRS via the HPAREH system. As indicated in Table 1, nearly complete information on annual tritium dose estimates was obtained for workers employed during the period 1979–1999. By definition, if the AWBD was equal to 0 mSv then the annual tritium-dose component was equal to 0 mSv. Therefore, for those employment-year records in which the AWBD was equal to 0 mSv, the tritium dose was considered as known and equal to 0 mSv.

For the period 1954–1978, 155 281 employment-year records were observed and computerised tritium doses were available for 71% (109 956) of these employment-years (Table 1). Since estimation of tritium dose was not necessary for those with an AWBD of 0 mSv, computerised tritium-dose values were estimated for 43 381 employment-years.

Evaluation

There were 74 610 recorded tritium-dose values for employment-years during the period 1954–1978 on which was based the estimation of the tritium dose for the employment-years with missing tritium dose records. For the evaluation of the predictive model, the observed and estimated tritium values were compared for these employment-years. The 75th, 90th, 95th, 99th and 100th percentile of known tritium doses were 0.00, 0.65, 1.65, 3.90 and 86.45 mSv, respectively. The corresponding values for the estimated tritium dose for those individuals with a known tritium dose were 0.07, 0.73, 1.63, 3.03 and 86.45 mSv, respectively.

Figure 1 shows a box-plot of the error for the predictive model as observed tritium dose minus expected tritium dose by categories defined by observed tritium dose. Most of the estimated tritium values matched well with the observed tritium dose, since the errors for each observed dose group were near zero. However, the model over-predicted lower values and under-predicted higher values. The mean and median errors for the lowest dose category (observed dose equal to zero) were −0.06 and 0 mSv, respectively (95% of values fall in the range −0.61–0.00). For the highest observed dose category (observed dose >3.0 mSv), the mean and median of error were 1.89 and 1.36 mSv, respectively (95% of values fall in the range −0.50–9.07).

Estimation of tritium values for employment-years lacking computerised tritium records

A total of 43 381 missing tritium values with a mean of 0.10 mSv and median of 0.00 mSv were estimated. The collective sum of the estimated tritium values was 4319 mSv. When compared with the collective measured tritium dose for the period 1954–1978, the collective sum of estimated tritium values represents 20% of the collective sum of measured tritium dose. Like the distribution of known dose values, the lower 75th percentile of the estimated values is equal to zero. Tritium values for the 90th, 95th, 99th and maximum percentile were 0.121, 0.508, 2.135 and 74.533 mSv, respectively.

The mean 75th and 95th percentile of those employees with known tritium dose records are presented by area and occupation (Table 2) for comparison with the estimated tritium dose records for those without a known tritium dose record (Table 3). Data are presented in this fashion due to the skewness of predicted tritium dose values. The dose from the estimation did not match the order of the dose for the known tritium dose. For example, the estimated tritium dose was highest for the areas 100-Reactors and 232-234-H (Tritium Process/Reservoir), respectively, while the known tritium dose was highest for areas 100-Reactors and 400-D Heavy Water Plant. The fraction of tritium dose to AWBD was highest for 232-234-H (Tritium Process/Reservoir), which may explain the higher estimated tritium dose.

In addition, the upper bounds of the range distribution of the estimated tritium doses (i.e. the 97.5th percentile of the distribution) by area and occupation for employment-years without a known tritium dose were lower than the same boundary for the upper bounds of the distribution of the estimated tritium dose for area and occupation groups with known tritium-dose records. A few occupations did

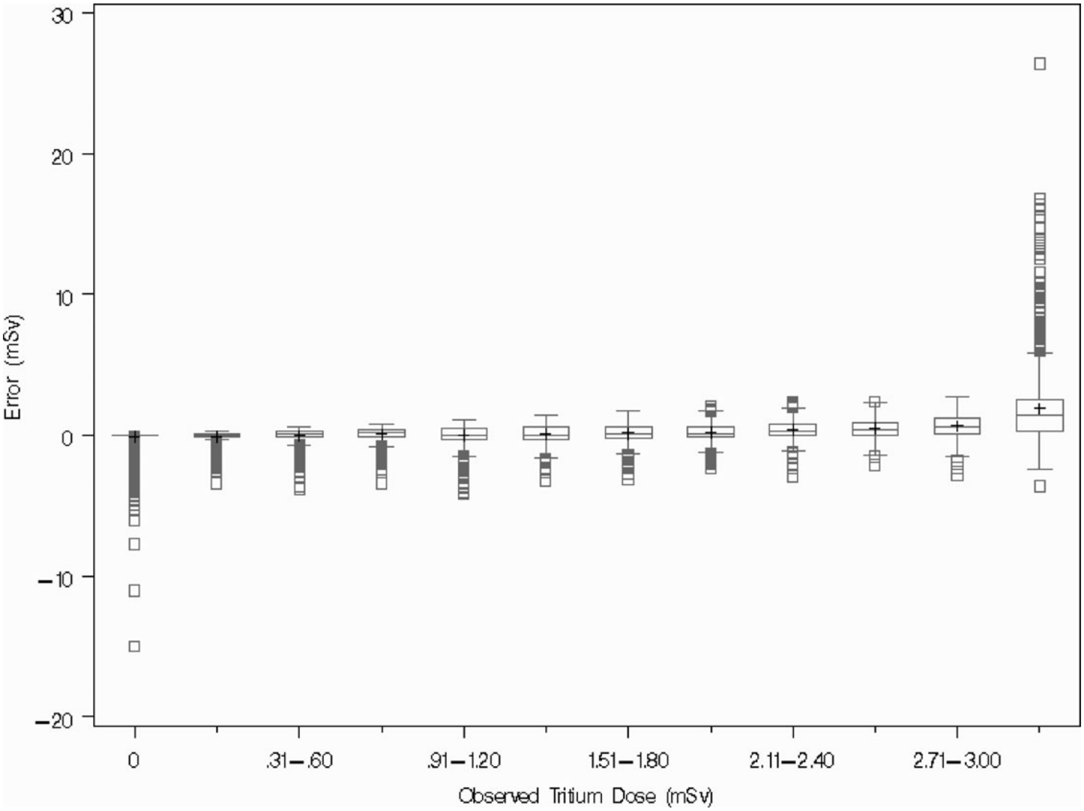

Figure 1. Box-plots of the difference between estimated tritium dose and observed tritium dose (error) by groups of observed tritium dose 1954–1978.

not follow this trend, including general service operator, engineering technician and trainee, engineer, junior physicist, chemist, raw materials operator, student, laboratory supervisor, senior/process chemist, senior/process physicist, life sciences and medical services, clerical and kindred non-manual workers and administrators and professionals (Tables 2 and 3). Some of these occupations had higher upper bound estimates than others, and may be the result of overestimation due to a few high exposure events for individuals within the same exposure category (defined in the model) as a few other workers.

DISCUSSION

This paper presents an innovative hybrid of traditional approaches to exposure assessment based upon the method of JEM in conjunction with a quantitative dose estimation approach using a stratified regression model.

A large proportion of the employment-years for which tritium dose was estimated were for workers employed in areas other than reactor operations and tritium loading/recycling. It is likely, therefore, that a large proportion of the workers with missing tritium dosimetry information had little or no occupational exposure to tritium. This is reasonably well reflected by the estimated tritium dose for workers outside the reactor and tritium areas; 79% of estimated tritium doses were 0 mSv and 90% of all estimated doses were <0.121 mSv. An important aspect of the estimation method to recognise is that small positive dose values were assigned to a large number of workers who were likely to have had little or no true exposure. If a worker's true dose was zero, the estimation approach had a tendency to assign a value that was a slight overestimate of the 'true' zero dose. Based upon evaluation of the proposed model when the true value for the annual tritium dose was zero, the mean and median estimated values derived were 0.057 and 0 mSv, respectively. The reason for this is that an estimated dose value may be greater than zero but it cannot be less than zero. In contrast, if a true dose was high relative to the other dose records (i.e. the dose was in the 99th and higher

Table 2. Mean and the 75th and 97.5th percentiles of the distribution of the annual measured tritium dose (in mSv) by health physics area and occupation 1954–1978 ($n = 74\,610$).

Area	Mean	Percentile	
		75th	97.5th
100 (Reactors)	0.702	1.050	4.050
400-D (Heavy Water Plant)	0.451	0.350	3.650
232-234-H (Tritium Process/Reservoir)	0.404	0.350	2.550
Administration	0.159	0.000	1.500
200-H (H-Main Gate and H-Trit)	0.106	0.000	1.150
773-A (experimental fuel and target fabrication)	0.088	0.000	0.250
T&T, E&I, other plant services	0.079	0.000	0.900
Unknown	0.075	0.000	0.600
200-F (F-Main Gate)	0.058	0.000	0.450
777-M (Experiment Physics Lab) and CMX	0.054	0.000	0.300
Administration and services	0.052	0.000	0.450
Physical plant	0.046	0.000	0.650
300-M (raw materials/fuel and target fabrication)	0.024	0.000	0.000
Occupation			
Reactor Operator	1.298	1.950	4.150
Heavy Water Operator	1.280	2.050	5.000
Auxiliary Operator	0.733	1.200	4.050
Radiation Monitor, Health Physicist	0.539	0.150	4.250
Rigger	0.426	0.600	2.500
Other skilled manual	0.311	0.000	3.000
Separations/Process Operator	0.263	0.000	2.750
Unknown	0.241	0.000	2.450
Technicians, analysts and assistants	0.228	0.000	1.150
Carpenter	0.198	0.000	2.150
Production/shift supervisors	0.188	0.000	2.200
Utility operator	0.186	0.000	2.050
Other operator	0.184	0.000	1.500
General service operator	0.086	0.000	0.700
Other supervisors	0.085	0.000	1.050
Production operator	0.085	0.000	0.900
Engineering technicians and trainees	0.081	0.000	1.150
Managers, specialists and associates	0.065	0.000	0.800
Engineers	0.047	0.000	0.550
Junior physicist	0.040	0.000	0.000
Chemist	0.031	0.000	0.200
Raw materials operator	0.026	0.000	0.150
Students	0.025	0.000	0.000
Crane operator	0.023	0.000	0.350
Senior engineers	0.021	0.000	0.200
Laboratory supervisors	0.018	0.000	0.050
Senior chemist, process chemist	0.018	0.000	0.000
Senior physicist, process physicist	0.016	0.000	0.250
Life scientists and medical services	0.008	0.000	0.000
Other semi-skilled workers	0.006	0.000	0.000
Clerical and kindred non-manual workers	0.005	0.000	0.000
Metallurgists	0.004	0.000	0.050
Power operator	0.003	0.000	0.000
Administrators and professionals	0.000	0.000	0.000

percentile range), then the method had a tendency to produce a positive estimate that slightly underestimated the true dose. Therefore, the model produced a small overestimate of the level for an unrecorded year for which the true dose was zero and a small underestimate of the value for an unmonitored year for which the true dose was greater than zero. If the information indicates that a worker was employed in an area in which the tritium dose rate was zero, then it is possible to assign a zero dose to that year.

Table 3. Mean and the 75th and 97.5th percentiles of the distribution of the estimated annual tritium dose (in mSv) by health physics area and occupation 1954–1978 ($n = 43\,381$).

Area	Mean	Percentile	
		75th	97.5th
100 (Reactors)	0.344	0.327	2.595
400-D (Heavy Water Plant)	0.140	0.000	1.752
232-234-H (Tritium Process/Reservoir)	0.297	0.265	2.195
Administration	0.040	0.000	0.300
200-H (H-Main Gate and H-Trit)	0.055	0.000	0.521
773-A (experimental fuel and target fabrication)	0.020	0.000	0.111
T&T, E&I, other plant services	0.101	0.000	0.651
Unknown	0.038	0.000	0.195
200-F (F-Main Gate)	0.031	0.000	0.298
777-M (Experiment Physics Lab) and CMX	0.017	0.000	0.064
Administration and services	0.016	0.000	0.088
Physical plant	0.046	0.000	0.170
300-M (Raw Materials/Fuel and Target Fabrication)	0.011	0.000	0.052
Occupation			
Reactor operator	0.733	1.050	3.170
Heavy water operator	0.716	1.192	3.450
Auxiliary operator	0.449	0.558	2.835
Radiation Monitor, Health Physicist	0.762	0.369	4.739
Rigger	0.453	0.450	4.150
Other skilled manual	0.188	0.064	1.781
Separations/process operator	0.104	0.074	0.837
Unknown	0.047	0.000	0.298
Technicians, analysts and assistants	0.095	0.000	1.250
Carpenter	0.000	0.000	0.000
Production/shift supervisors	0.130	0.025	1.422
Utility operator	0.065	0.027	0.705
Other operator	0.123	0.000	1.184
General service operator	0.028	0.000	0.096
Other supervisors	0.019	0.000	0.206
Production operator	0.000	0.000	0.000
Engineering technicians and trainees	0.019	0.000	0.075
Managers, specialists and associates	0.001	0.000	0.000
Engineers	0.010	0.000	0.080
Junior physicist	0.000	0.000	0.000
Chemists	0.001	0.000	0.000
Raw materials operator	0.053	0.000	0.537
Students	0.001	0.000	0.000
Crane operator	0.004	0.000	0.024
Senior engineers	0.001	0.000	0.000
Laboratory supervisors	0.000	0.000	0.000
Senior chemist, process chemist	0.000	0.000	0.000
Senior physicist, process physicist	0.011	0.000	0.000
Life scientists and medical services	0.000	0.000	0.000
Other semi-skilled workers	0.002	0.000	0.006
Clerical and kindred non-manual workers	0.001	0.000	0.000
Metallurgists	0.000	0.000	0.000
Power operator	0.001	0.000	0.000
Administrators and professionals	0.000	0.000	0.000

In effect, however, the proposed estimation method did just this. If the worker was employed in a occupation/area where the average recorded value was zero or near zero then the worker was assigned a zero (or near zero) value for that year. Inclusion of the annual whole body dose groups assisted with this by clustering individuals based on their known AWBD, since workers with zero (or near zero) AWBD had a propensity for similar tritium doses depending on the occupation/area combination.

The proposed method offers an approach to imputing a distribution of estimated tritium doses for employment-years with missing information using the available data from monitored workers during that year as well as information on occupation and area of employment. For the ultimate future goal of the project, which is to examine associations between tritium exposure and potential adverse health effects in workers at SRS, this predictive model provides useful information about occupational exposures to tritium.

JEMs have a number of limitations to overcome. First, utilising qualitative information to provide ordinal or dichotomous exposure classification is not always ideal for examination of exposure–disease relationship. Job and area classifications are not necessarily created for the purpose of distinguishing between tasks or exposures. Rather, they may represent distinctions created simply for administrative purposes(16). In addition, since within-job variation cannot be taken into account, JEMs suffer from non-differential misclassification of exposure(20).

The proposed model attempts to overcome these obstacles by combining an industrial hygiene approach to evaluate exposure with an empirical method of exposure prediction. This provides an understanding about exposure to tritium at SRS that may otherwise have been overlooked. First, providing quantitative estimates of tritium exposure will benefit further studies of workers exposed to this radionuclide. The estimation of tritium dose is based on known tritium and annual whole-body dose exposure. Combining estimated and known tritium doses provides a complete exposure history for employees at SRS. This level of detail about exposure is more useful than that obtained in a typical JEM. Second, the proposed method attempts to overcome the obstacle discussed by Loomis *et al.*(16) concerning codes that do not provide substantive distinctions between different jobs and areas. For example, one might assume ‘administration’ is an area of employment that would not lead to a high level of tritium exposure. However, the average tritium dose and fraction of WBDS in this area was higher than the areas of ‘experimental fuel and target fabrication’ and ‘200-H (H-Main Gate and H-Trit)’ two areas that may be expected to have a higher tritium exposure. This fact may have been overlooked, possibly leading to misclassification of the area administration as a low or no exposure area, or even 200-H (H-Main Gate and H-Trit) as a high-exposure area.

Occupation and area descriptions for SRS employees may not provide an ideal distinction between different employees’ true area and occupation. This is seen when comparing the number of known area and occupation categories compared with the ORAU Team Dose Reconstruction Project for NIOSH at SRS, which contains more specific and detailed descriptions of facilities and processes. Although the technique of dose reconstruction can help overcome this problem, the data set of the study is limited in the picture it paints of exposure scenarios for tritium at SRS.

Although there are limits to what dose reconstruction can tell us about tritium dose, it is important to estimate the exposure for employees at SRS. Increasing knowledge of tritium exposure will help to better evaluate potential relationships between exposure and disease. In addition, the estimated tritium dose records could be used to adjust available estimates of annual whole-body dose in order to take into account changes over time in tritium dose estimation methods, including International Commission on Radiological Protection models and quality factors for tritium. It is hoped that this study provides useful information for future studies at SRS, and perhaps for other facilities where worker exposure to tritium is of concern.

ACKNOWLEDGEMENTS

The authors would like to thank Drs Dana Loomis, Michael Flynn and Steve Wing for their contributions to the development of the modelling technique and comments when revising this manuscript.

FUNDING

This study was supported by the National Institute for Occupational Safety and Health (T42 OH008673).

REFERENCES

1. Cragle, D., McLain, R., Qualters, J., Hickey, J., Wilkinson, G., Tankersley, W. and Lushbaugh, C. *Mortality among workers at a nuclear fuels production facility.* Am. J. Ind. Med. **14**, 379–401 (1988).
2. Hill, R. and Johnson, J. *Metabolism and dosimetry of tritium*. Health Phys. **65**(6), 628–647 (1993).
3. Okada, S. and Momoshima, N. *Overview of tritium: characteristics, sources and problems.* Health Phys. **65**(6), 595–609 (1993).
4. Elliot, A. *Tritium dosimetry.* Nuclear Med. Commun. **26**, 481–482 (2005).
5. Joksic, G. and Spasojevic-Tisma, V. *Chromosome analysis of lymphocytes from radiation workers in tritium-applying industry.* Int. Arch. Occup. Environ. Health **71**, 213–220 (1998).
6. Straume, T. *Tritium risk assessment*. Health Phys. **65**(6), 673–682 (1993).
7. Taylor, G. A., Crase, K. W., La Bone, T. R. and Wilkie, W. H. A history of personnel radiation dosimetry at the Savannah River Site (Springfield, VA, USA: US Department of Energy) (1995).
8. Scalsky, E. D. *Technical basis document for the Savannah River Site: to be used for EEOICPA dose*

reconstructions. In: ORAU Team Dose Reconstruction Project for NIOSH. Neton, J. W., Ed. (Cincinnati: National Institute for Occupational Safety and Health) (2005).

9. Zartarian, V., Bahadori, T. and KcKone, T. *Adoption of an official ISEA glossary*. J. Expo. Anal. Environ. Epidemiol. **15**, (2005) 1–5.
10. Richardson, D., Wing, S. and Daniels, R. D. *Evaluation of external radiation dosimetry records at the Savannah River Site, 1951–1999*. J. Expo. Sci. Environ. Epidemiol. **17**, 13–24 (2007).
11. Boiter, H. P. *Radiation Exposure Records Management*. pp. 13. (Aiken, SC: Savannah River Plant) p. 13 (1975).
12. Plant, S. R. *Exposure Data Protocol*. pp. 13. (Aiken, SC: Savannah River Plant) p.13 (1984).
13. McMahan, S. R. *Exposure Data Extraction Procedures*. Fayerweather, W. E. Ed. (Aiken, SC: Savannah River Plant) (1984).
14. Hoar, S. *Job exposure matrix methodology*. J. Toxicol. Clin. Toxicol. **21**(1/2), 9–26 (1983–1984).
15. Kromhout, H., Heederik, D., Dalderup, L. and Kromhout, D. *Performance of two general job-exposure matrices in a study of lung cancer morbidity in the Zutphen cohort*. Am. J. Epidemiol. **136**, 698–711 (1992).
16. Loomis, D., Peipins, L., Browning, S., Howard, R., Kromhout, H. and Savitz, D. *Organization and classification of work history data in industry-wide studies: an application to the electric power industry*. Am. J. Ind. Med. **26**, 413–425 (1994).
17. Goldberg, M., Kromhout, H., Guenel, P., Fletcher, A., Gerin, M., Glass, D. C., Heederik, D., Kauppinen, T. and Ponti, A. *Job exposure matrices in industry*. Int. J. Epidemiol. **22**(Suppl. 2), S10–S15 (1993).
18. McGuire, V., Nelson, L., Koepsell, T., Checkoway, H. and Longstreth, W. T. *Assessment of occupational exposures in community-based case–control studies*. Annu. Rev. Public Health **19**, 35–53 (1998).
19. Hickey, J. and Cragle, D. *Occupational Exposures of Workers to Chemicals at the Savannah River Plant 1952–1984* (Oak Ridge, TN, USA: Oak Ridge Associated Universities) (1985).
20. De Vocht, F., Zock, J. P., Kromhout, H., Sunyer, J., Anto, J., Burney, P. and Kogevinas, M. *Comparison of self-reported occupational exposure with a job exposure matrix in an international community-based study on asthma*. Am. J. Ind. Med. **47**, 434–442 (2005).