

RADIATION EXPOSURE ASSESSMENT FOR PORTSMOUTH NAVAL SHIPYARD HEALTH STUDIES

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Occupational radiation exposures of 13,475 civilian nuclear shipyard workers were investigated as part of a retrospective mortality study. Estimates of annual, cumulative and collective doses were tabulated for future dose–response analysis. Record sets were assembled and amended through range checks, examination of distributions and inspection. Methods were developed to adjust for administrative overestimates and dose from previous employment. Uncertainties from doses below the recording threshold were estimated. Low-dose protracted radiation exposures from submarine overhaul and repair predominated. Cumulative doses are best approximated by a hybrid log–normal distribution with arithmetic mean and median values of 20.59 and 3.24 mSv, respectively. The distribution is highly skewed with more than half the workers having cumulative doses <10 mSv and >95% having doses <100 mSv. The maximum cumulative dose is estimated at 649.39 mSv from 15 person-years of exposure. The collective dose was 277.42 person-Sv with 96.8% attributed to employment at Portsmouth Naval Shipyard.

INTRODUCTION

A detailed radiological exposure assessment has been completed for 13,475 monitored civilian workers employed at the Portsmouth Naval Shipyard (PNS) located in Kittery, Maine between 1 January 1952 and 31 December 1996. The exposure assessment supports an ongoing retrospective mortality study and provides estimates of annual whole-body doses for each shipyard worker potentially exposed to penetrating radiation as a result of employment⁽¹⁾. The mortality study includes civilian workers first employed between 1 January 1952 and 31 December 1992. Vital status ascertainment and exposure assessment information was obtained through 1996.

PNS is a large industrial complex employing workers from a variety of trades, including welding, insulating, electrical, pipefitting, painting, engineering, rigging, steel fabrication and machining. The shipyard was established in 1800 and has been involved in the design, construction and repair of all types of warships, from sailing ships to nuclear-powered submarines. The number of civilian workers increased dramatically during times of war, such as in 1918, when civilian employment was 5500; in 1943, when civilian employment was 20,466; and in 1952, when civilian employment reached 10,559. As of 2002, there were 4083 civilian workers employed at PNS.

In 1955, the shipyard began training employees to construct and overhaul nuclear-powered submarines. Of the 134 submarines commissioned at the shipyard, 10 were nuclear powered, beginning with

the USS Swordfish (SSN 579) in September 1958 and ending with the USS Sand Lance (SSN 660) on 25 September 1971. From 1959 through 2002, the shipyard completed 234 overhauls or other scheduled maintenance activities on nuclear-powered submarines.

Radiation exposures were primarily the result of nuclear submarine overhaul and repair beginning in 1958. However, a small group of shipyard workers (i.e. <200) were potentially exposed while performing duties as industrial radiographers, instrument technicians or medical X-ray technicians. Some radiation exposures occurred prior to issuance of personal dosimetry at the shipyard beginning in 1950.

RADIATION CHARACTERISTICS

Nearly all the PNS collective dose is attributed to work within the shielded reactor compartment on-board nuclear-powered submarines. Access to the reactor compartment was allowed only while the reactor was shutdown. The predominant exposure was external whole-body penetrating gamma radiation emitted by activation products deposited in reactor systems and components, principally ⁶⁰Co (half-life 5.27 y). ⁶⁰Co results from neutron activation of ⁵⁹Co and emits two high-energy photons (1.17 and 1.33 MeV) during beta decay transformation to stable ⁶⁰Ni.

Fission products were not a significant source of radiation exposure at PNS. The submarine nuclear fuel assemblies are designed to retain virtually all of the fission products including gaseous radioisotopes, such as ⁸⁵Kr, ¹³³Xe and ¹³¹I. Only minute amounts

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of fission products are present in the primary coolant from the fission of naturally occurring uranium impurities that exist in fuel core structural materials.

The majority of photon radiation from shipyard sources has energies between 100 and 3000 keV. Lower energy photons (<100 keV) from scattered radiation and X-rays contribute <5% to the total photon radiation dose for most exposed workers⁽²⁾.

Except for limited exposures involving X-ray generating equipment and sealed sources, exposure profiles do not vary greatly for shipyard workers due to the similar nature of work. The shipyard reported that ~65% of the radiation field was anterior to posterior (AP), 25% was rotational (ROT) and the remaining 10% was isotropic (ISO). As noted previously, the energy distribution results from predominantly higher energy photons with some scattering, for which directional dependence is less critical for most tissues and for dosimeter response⁽³⁾.

DOSIMETRY

Gamma dosimetry

In the summer of 1950, PNS instituted a personal dosimetry programme. The first dosimeters were film badges incorporating Type K industrial X-ray film manufactured by the Eastman Kodak Company with a 0.05 cm (0.02 in.) thick lead shield in the shape of a cross. In 1952, the Type K film packet was replaced by the Eastman DF-7. The badges were worn on the trunk of the body and were issued to industrial radiographers and medical staff during periods of potential exposures. The dosimeter was sensitive to gamma radiation with an exposure-in-air range of 5.16×10^{-6} to 5.16×10^{-4} C kg⁻¹ (0.02–2 R)⁽⁴⁾. For this and succeeding gamma dosimetry, exposure values were converted to dose equivalent assuming a radiation weighting factor of one for all photons⁽⁵⁾. The detection threshold for this dosimeter was reported to be 0.2 mSv per monitoring period⁽²⁾.

In 1957, several dosimeter design improvements were made to meet the monitoring needs of nuclear-powered submarine work. The two-component film badge (SX-233) demonstrated an improved range (5.16×10^{-6} to 2.58×10^{-3} C kg⁻¹ of air) by using a less sensitive film (Dupont 510) and a sensitive film (Dupont 555) in tandem. The SX-233 also included a cadmium shield that allowed incident photon energy discrimination. The dosimeter's lower energy component (unshielded, less sensitive Dupont 510) responded to photons generated by X-ray equipment operating at a tube voltage of 80 kVp, but provided only slight response to incident gamma rays emitted by ⁶⁰Co⁽⁴⁾. The film under the shield essentially did not respond to X-rays generated at 80 kVp, allowing

for higher energy discrimination using the shielded area of the more sensitive Dupont 555 film. This dosimeter design remained essentially unchanged until July of 1969. At this time, the Dupont film packet was replaced by the two-component Kodak Type 3 Film Radiac Pack, improving the range of sensitivity (2.58×10^{-6} to 2.58×10^{-2} C kg⁻¹ of air). The detection threshold for this dosimeter is reported as 0.1 mSv per monitoring period⁽²⁾.

The DT-526/PD calcium fluoride thermoluminescence dosimeter (TLD) became the standard for personnel gamma exposure monitoring on 1 October 1974. The manufacturer reports an exposure range of 1.29×10^{-6} to 1.29 C kg⁻¹ of air for gamma energies of 80 keV to 1.3 MeV with an accuracy of $\pm 10\%$ or 1.29×10^{-6} C kg⁻¹ of air, whichever is greater⁽⁴⁾. The detection threshold for this dosimeter is reported to be 0.01 mSv per monitoring period⁽²⁾. The DT-526/PD continues to be the primary personal dosimeter for shipyard employees.

Personal radiation monitoring was conducted for all employees and visitors entering radiological areas or handling radioactive materials. Film badge monitoring was conducted bi-weekly through 1959 and was extended to monthly beginning in 1960. The DT-526/PDs are processed each day of exposure and the results summed monthly for reporting. In instances of increased routine exposures, incidents or potential over-exposures, personal dosimeters were processed before the monitoring cycle end date to ensure that workers remained compliant with administrative control limits.

Neutron dosimetry

Neutron exposure monitoring began in 1958 for personnel who were on-board submarines during power operations or handled neutron calibration sources⁽⁴⁾. Early neutron monitoring was conducted using nuclear track analysis (NTA) of Kodak-NTA film. Calibrations were conducted using a plutonium-beryllium (Pu-Be) source. A conversion coefficient of 5.05×10^2 pSv cm² was used for calibration purposes based on neutron energies of 1–10 MeV⁽⁶⁾. The reported detection threshold for the NTA method was 0.3 mSv⁽²⁾. The NTA film dosimeter was replaced by the two-element lithium fluoride (LiF) TLD (DT-586/PD) in 1978 with a reported minimum sensitivity of 0.13 mSv⁽²⁾. As of 1989, the shipyard used a four-element LiF TLD (DT-648/PD) with a reported detection threshold of 0.03 mSv⁽²⁾.

Internal monitoring

A urinalysis bioassay monitoring programme for determining internal deposition of ⁶⁰Co was instituted in December 1959 for those personnel requiring decontamination of the skin. *In vivo*

measurements for internal radioactivity in the upper and lower respiratory tract was started in 1960 and continues as a standard practice today. Internal exposure assessments were initially reserved for those workers involved in contamination incidents. Beginning in 1968, routine internal monitoring was conducted for certain radiation workers based on their exposure potential. Routine monitoring was expanded in 1971 to include all radiation workers at separation and also during their tri-annual medical examination.

The shipyard reports' early *in vivo* measurements (1959–1966) were performed using a thin-window Geiger tube detector system with a detection capability of 2.78 kBq ^{60}Co at the 90% upper confidence level (UCL). By 1971, significant improvements lowered the detection level to ~ 0.15 kBq for a chest survey. Continued improvements have now reduced the detection level to < 37 Bq.

Records keeping

The results for each monitoring interval and for each exposed worker were recorded on individual exposure record cards. The information from the cards was then transcribed to form DD 1141, Record of Occupational Exposure to Ionizing Radiation (currently NAVMED Form 6470/10), which became the official dose of record for the monitored individual. Annual reports of personal exposures for each worker from the DD 1141 forms were sent to the US Navy Bureau of Medicine and Surgery. An electronic copy of the annual doses was obtained from the shipyard and provided the vast majority of data used for this exposure assessment.

METHODS

The shipyard annual exposure data had previously been found to reasonably approximate occupational doses for use in an epidemiological study⁽⁷⁾. The reported annual doses are actually the sum of the doses estimated from the X-ray (film dosimetry only), gamma and neutron dosimetry components for each individual over all monitoring periods conducted within the assigned year. 'Dose' refers to the personal dose equivalent at a depth of 1 cm in (soft) tissue from an external field⁽⁸⁾. Annual doses were summed to determine cumulative dose for each exposed worker and collective doses for the cohort and sub-cohorts. The estimates of collective and cumulative doses illustrate exposure patterns and provide for comparison with other similar cohorts outside of PNS.

For verification of records-keeping practices, the reported annual doses were compared with a previously coded and validated dosimetry database for 204 civilian radiation workers selected from the PNS

cohort for participation in a future nested case-control study. The database was constructed from detailed dose information abstracted from DD 1141 forms for each exposed worker. The collective dose reported from the DD 1141 forms differed by $< 0.09\%$ from the value determined by annual reports. Only seven individuals had differences in cumulative dose of 0.1 mSv or greater, the largest being 2.64 mSv.

Prior exposure estimation

To ensure complete accounting of lifetime doses and to prevent worker overexposure, shipyard radiological staff identified personnel with radiation exposures outside of PNS employment or PNS exposures before to the onset of the dosimetry programme in 1950. Dose assignments for these exposures were identified as 'prior dose'. Exposure history questionnaires were completed during new radiation worker orientation to identify any previous potential radiological exposures. If additional exposures were indicated, the shipyard radiological support staff would contact former places of employment to obtain, if available, the individual's dose of record.

Prior dose was identified by an exposure year assignment of 'XX' in the electronic dose records and 836 individuals had at least one prior dose value assigned. A subset of 632 workers with prior dose ≥ 1 mSv was further evaluated. Individual radiological exposure records maintained at PNS were copied and assessed to determine the source and time period of the prior dose. These records included exposure histories from other facilities, work histories, bases of dose assignment, among others. Based on available information, each worker's final dose estimate included applicable changes to the reported prior dose value, location, exposure source and year of exposure. The dosimetry assignments for persons with prior dose values < 1 mSv were not changed except for assigning an exposure year equal to the year prior to first hire.

Because sufficient offsite records could not be obtained by the shipyard in all cases, 143 persons were administratively assigned prior dose estimates at the onset of shipyard employment. In these cases, the radiological support staff conservatively overestimated and assigned radiation doses to insure radiation exposure standards would not be exceeded with additional shipyard exposures. The shipyard practice, termed in this analysis as 'administrative dose', was to record the maximum allowable dose for each quarter that an individual worked in a radiation environment outside of PNS. In most cases, administrative doses were estimates much greater than the actual dose likely to be received by the worker.

Table 1. Sources of dosimetry data used for prior dose estimation.

Radiography	Weapons Testing	Medical staff	Commercial Power	Department of Defense	Department of Energy
Eheman <i>et al.</i> ⁽¹⁷⁾ Kumazawa <i>et al.</i> ⁽¹⁸⁾ NCRP 101 ⁽¹⁹⁾	Berkhouse <i>et al.</i> ⁽²⁰⁾ Eheman <i>et al.</i> ⁽¹⁷⁾ Johnson <i>et al.</i> ⁽²¹⁾ Martin ⁽²²⁾ NCRP 101 ⁽¹⁹⁾ Ponton <i>et al.</i> ⁽²³⁾ Ponton <i>et al.</i> ⁽²⁴⁾ Ponton <i>et al.</i> ⁽²⁵⁾ Ponton <i>et al.</i> ⁽²⁶⁾ Ponton <i>et al.</i> ⁽²⁷⁾	Eheman <i>et al.</i> ⁽¹⁷⁾ NCRP 101 ⁽¹⁹⁾ Clark <i>et al.</i> ⁽²⁸⁾ Cowing ⁽²⁹⁾ Fuller ⁽³⁰⁾ Jamieson <i>et al.</i> ⁽³¹⁾ Kumazawa <i>et al.</i> ⁽¹⁸⁾ Spalding <i>et al.</i> ⁽³²⁾ Spalding <i>et al.</i> ⁽³³⁾ Specht <i>et al.</i> ⁽³⁴⁾	Eheman <i>et al.</i> ⁽¹⁷⁾ Kumazawa <i>et al.</i> ⁽¹⁸⁾ NCRP 101 ⁽¹⁹⁾ Thomas <i>et al.</i> ⁽³⁵⁾	Eheman <i>et al.</i> ⁽¹⁷⁾ Mangeno <i>et al.</i> ⁽³⁶⁾ NCRP 101 ⁽¹⁹⁾	Eheman <i>et al.</i> ⁽¹⁷⁾ NCRP 101 ⁽¹⁹⁾

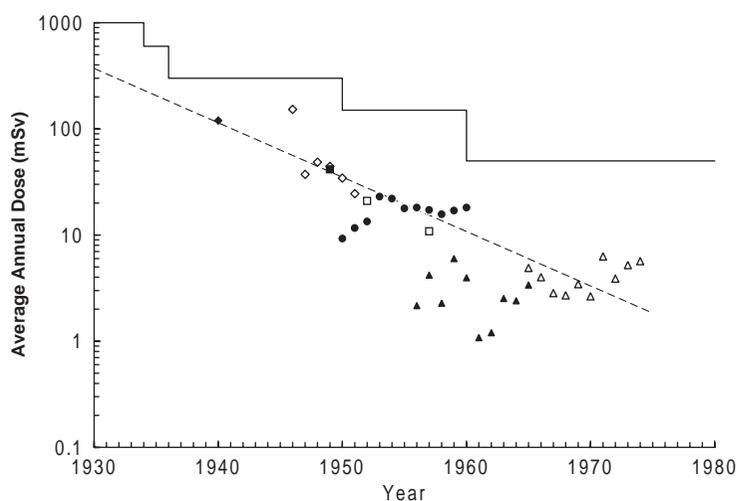


Figure 1. Derivation of Average Annual Dose, \bar{D}_y , for medical X-ray technicians by log-linear regression (dashed line). Administrative Control Levels (solid line). Data sources: Clark and Jones⁽²⁸⁾ (filled diamonds), Cowing⁽²⁹⁾ (open squares), Fuller⁽³⁰⁾ (filled triangles), Jamieson⁽³¹⁾ (open diamonds), Spaulding *et al.*⁽³²⁾ (filled squares), Spaulding and Cowing⁽³³⁾ (filled circles) and Sprech and Brodsky⁽³⁴⁾ (open triangles).

The assignment of administrative dose is a large potential error in estimating individual cumulative exposure, which could lead to significant misclassification of workers in the epidemiological analysis. Further exposure modelling was conducted for these individuals to provide better estimates of their annual and cumulative doses. The relationship used to estimate annual dose (D_y) is:

$$D_y = \bar{H}_{i,k} f, \quad (1)$$

where: $\bar{H}_{i,k}$ is the average dose equivalent determined for employment sector ' i ' during year ' k ' for individuals based on a full work year 2000 h; and f is the number of hours worked by the study subject in year ' k ' divided by 2000 h.

Prior reports (Table 1) were searched to gather exposure data for these employment sectors

identified in shipyard records of administrative dose: (1) Radiography, (2) Weapons Testing, (3) Medical Staff, (4) Commercial Power, (5) Department of Defense and (6) Department of Energy. Fitted exposure curves were derived based on the arithmetic means of the available dosimetry data (weighted by dataset size) extracted from the sources shown in Table 1. The term $\bar{H}_{i,k}$ was derived for each exposure year and sector of worker employment based on these distributions.

Figure 1 is an example of dose estimates for X-ray technicians within the medical staff sector. In this instance, arithmetic mean annual doses were extracted from the literature and were fit to a curve for estimation purposes. The annual dose data were log-transformed given the appearance of an

exponential decrease in annual doses with time. Linear regression was used to estimate the function for the log-transformed average annual doses versus year of exposure. The plot also illustrates the administrative control levels in place at PNS that were assigned *in lieu* of actual data. Although the overall trend of the annual average dose is consistent with the administrative controls, the expected dose values are reduced from the administratively assigned values ~ 10 -fold.

As another example, Figure 2 shows average weekly dose values for PNS industrial radiographers derived from the distribution of recorded doses for these workers during the years 1950–1961. Linear regression using multiple ranges of existing data was used to extrapolate weekly dose values for unmonitored PNS radiographers working prior to 1950. The primary regression dataset consisted of the arithmetic mean values for weekly doses reported for shipyard radiographers between 1950 and 1961. Given reductions in the allowable dose in 1954 and again in 1958, the regression using data for all these years may introduce bias for early dose estimates. Additional regression analyses were performed using data from 1950 to 1955 and between 1950 and 1957 to provide a range of dose estimates. Although differences are apparent, these differences were small compared with the overall dose reduction and not considered further. Annual doses were estimated for each individual by multiplying the number of weeks exposed by the average weekly dose extrapolated from data between 1950 and 1961.

RESULTS

The final radiological exposure assessment encompasses 13,475 monitored workers with 88,747 person-years of dosimetry information from all known sources of occupational radiation exposure occurring during or prior to PNS employment. A total of 11,848 (87.9%) individuals were assigned a cumulative dose of at least 0.01 mSv. The remaining individuals [1627 (12.1%)] were qualified radiation workers who received dosimetry with all monitoring results below the detection threshold. The collective dose for the cohort was 277.42 person-Sv with 268.67 person-Sv (96.8%) attributed to exposures while employed by PNS. Exposures resulting from other employment contributed 8.76 person-Sv (3.2%) to the collective dose. Descriptive statistics for external doses were determined for three exposure conditions (Table 2). The first (condition A) consists of 13,475 individuals with unmodified dose values from original shipyard assignments for both PNS and other employment sources. The second (condition B) consists of the same 13,475 individuals with adjusted prior doses included. The third (condition C) consists of 13,468 individuals with dose estimates from PNS exposures only.

The cumulative dose distribution for PNS was compared with those of radiation worker cohorts employed in the USA, UK and Canada who were previously assessed for an epidemiological study⁽⁹⁾. In Table 3, detailed external dose estimates were summarised for: US employees at the Hanford Site, Oak Ridge National Laboratory (ORNL) and the

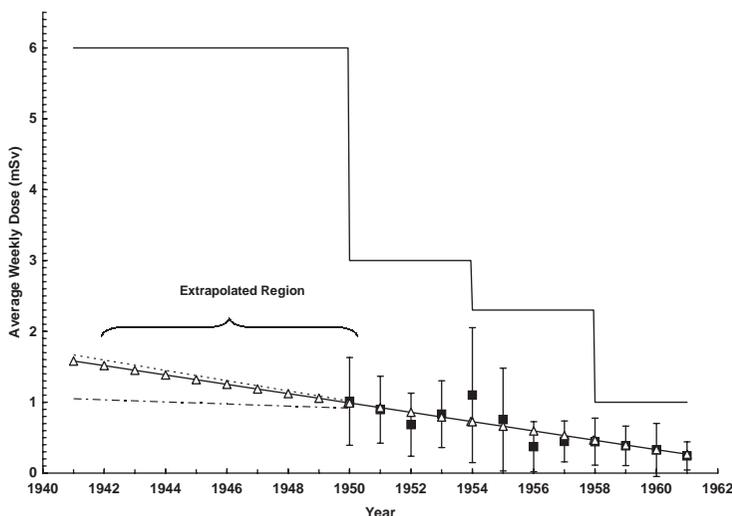


Figure 2. Linear regression of existing dosimetry to extrapolate weekly average doses for PNS industrial radiographers prior to 1950. Administrative control levels (solid line), Recorded data arithmetic mean (filled squares), 1950–1961 data regression (open triangles), 1950–1957 data regression (short dashed), 1950–1955 data regression (long dash).

Table 2. Summary statistics for cumulative doses estimated for PNS workers.

Cumulative dose statistic	Populations of workers		
	A*	B**	C***
Total number of workers	13,475	13,475	13,468
Collective dose (person-Sv)	285	277	269
Average dose (mSv)	21.1	20.6	19.9
Median dose (mSv)	3.27	3.24	2.90
Standard deviation (mSv)	46.8	45.1	44.7
Coefficient of variation	2.21	2.19	2.24
Maximum (mSv)	910	649	649
Lower quartile (mSv)	0.27	0.27	0.23
Upper quartile (mSv)	19.8	19.5	18.3
Standard skewness	219	202	206
Standard kurtosis	774	570	593
Standard skewness for log doses****	-18.4	-18.4	-17.5
Standard kurtosis for log of doses****	-10.8	-10.8	-11.7
Number of values equal to 0	1626	1627	1677
Number of workers in dose (<i>H</i>) category:			
<i>H</i> = 0	1626 (12.1%)	1627 (12.1%)	1677 (12.5%)
0 < <i>H</i> < 1 mSv	3332 (24.7%)	3343 (24.8%)	3464 (25.7%)
1 mSv ≤ <i>H</i> < 10 mSv	3810 (28.3%)	3836 (28.5%)	3813 (28.3%)
10 mSv ≤ <i>H</i> < 50 mSv	3132 (23.2%)	3128 (23.2%)	3032 (22.5%)
<i>H</i> ≥ 50 mSv	1575 (11.7%)	1541 (11.4%)	1482 (11.0%)

*A: unmodified exposure dataset provided by PNS

**B: modified exposure data with onsite, prior and administrative dose adjustments included

***C: modified exposure data with offsite exposures removed

****The natural log of cumulative dose values excluding zero.

Table 3. Radiation worker comparison.

Statistic	United States				United Kingdom		Canada
	PNS	Hanford site	Rocky Flats	ORNL	Sellafield	AEA and AWE	AECL
Monitored workers	13,475	36,925	7495	8318	10,014	30,591	11,976
Person-years	88,747	912,895	114,455	217,097	260,000	737,052	216,249
No. (%) by dose (mSv):							
0 < <i>H</i> < 10	8807 (65.4)	25,278 (68.5)	4153 (55.4)	6042 (72.7)	1986 (19.8)	17158 (56.1)	8630 (72.1)
10 ≤ <i>H</i> < 20	1374 (75.6)	4131 (79.6)	1046 (69.4)	884 (83.3)	1072 (30.5)	4225 (69.9)	1096 (81.2)
20 ≤ <i>H</i> < 50	1754 (88.6)	3587 (89.4)	997 (82.7)	751 (92.3)	1916 (49.7)	4544 (84.8)	921 (88.9)
50 ≤ <i>H</i> < 100	871 (95.0)	1684 (93.9)	627 (91.0)	316 (96.2)	1438 (64.0)	2336 (92.4)	489 (93.0)
100 ≤ <i>H</i> < 200	443 (98.3)	1112 (96.9)	417 (96.6)	187 (98.4)	1420 (78.2)	1321 (96.7)	401 (96.3)
200 ≤ <i>H</i> < 400	219 (99.9)	845 (99.2)	205 (99.3)	95 (99.5)	1244 (90.6)	736 (99.1)	272 (98.6)
<i>H</i> ≥ 400	7 (100.0)	288 (100.0)	50 (100.0)	38 (100.0)	938 (100.0)	271 (100.0)	167 (100.0)
Mean dose (mSv)	20.6	23.9	32.4	17.1	130.9	31.3	26.4
Collective dose (person-Sv)	277.4	884.1	242.5	142.4	1311.1	957.3	316.1

Values for cohorts other than PNS were extracted from Appendix B, table B.1.a of IARC Technical Report No. 25⁽⁹⁾. All doses are cumulative doses resulting from photon and neutron exposures and exposure to tritium where applicable. Percentages of monitored workers by cumulative dose are expressed in cumulative percentages.

Rocky Flats Nuclear Weapons plant; UK employees at the Atomic Energy Authority (AEA), the Atomic Weapons Establishment (AWE) and the British Nuclear Fuels (BNFL) plant of Sellafield; and

Canadian Atomic Energy of Canada (AECL) workers from the Chalk River plant⁽⁹⁾. Except for workers at Sellafield, the cumulative dose distributions share similarities typically associated with low-dose

protracted occupational radiation exposure. The distributions are highly skewed with more than half the workers from each cohort (55.4–72.7%) having cumulative doses <10 mSv and >95% having doses <100 mSv.

Nearly all the collective dose (264.23 person-Sv) resulted from the overhaul, repair and refuelling of nuclear-powered submarines after 1958. Prior to 1958, shipyard radiation exposures occurred among fewer than 200 industrial radiographers, instrument technicians or X-ray technicians. Radiographers received the majority of the 4.44 person-Sv accumulated between 1936 and 1958 (3.84 person-Sv), while instrument technicians and medical staff contributed 0.58 and 0.02 person-Sv, respectively.

There were 822 shipyard workers who received radiation exposures during employment outside of PNS. Of this group, seven had cumulative doses exclusively from other employment. The collective offsite dose was estimated at 8.7 person-Sv (3.6%). The assigned collective dose by sources of exposure is shown in Table 4.

Cardis *et al.*⁽⁹⁾ provided methods to characterise typical photon energies encountered. This information is needed for future analysis of dosimetric bias and organ-specific dose conversion anticipated for follow-on nested case-control studies of leukaemia and lung cancer mortality. Photon exposures were separated into higher and lower average photon energies by a threshold of 100 keV⁽⁹⁾. Approximately 95% of the collective dose resulted from photon radiation within the higher energy range⁽²⁾. To better define the photon energy spectra encountered, an evaluation of the lower energy component was conducted using dosimetry data for 1398 PNS radiation workers selected for a nested case-control study. Separate values assigned for 'X ray' and 'gamma' dose contributions were obtained from the DD 1141 forms and/or exposure record cards for these

individuals exposed from 1960 to 1969. The evaluation revealed a collective dose contribution from exposures to higher energy photons (100–3000 keV) of nearly 31.09 person-Sv, while lower energy photons resulted in ~1.07 person-Sv (3.4%).

An evaluation of the neutron monitoring data for shipyard workers between the years 1959 and 1975 found that neutron exposures contributed ~0.03% of the collective shipyard dose⁽⁷⁾. Only 111 workers were monitored for neutron exposures with a collective dose of 0.042 person-Sv. Nearly this entire dose (0.039 person-Sv) occurred while working near an operating submarine reactor during 1968 and 1969⁽⁷⁾. Each neutron monitoring result appears in the dosimetry records for each exposed employee. However, the annual dose records do not distinguish between neutron and gamma sources of exposure. Given the small number of affected personnel and the low doses encountered, neutron exposures were not separated from other external radiation.

An evaluation of shipyard *in vivo* and *in vitro* monitoring data revealed a total of 31 workers with an estimated internal deposition of ⁶⁰Co. Estimates of the maximum effective dose and lung committed equivalent dose were 17 and 102 mSv, respectively. These estimates were based on available details of the exposure incidents and default assumptions for the uptake of insoluble (Type S) ⁶⁰Co compounds as described by the International Commission on Radiological Protection^(10,11). Given the small likelihood and magnitude of internal exposures, further evaluation was not warranted for the cohort exposure assessment.

A plot of the collective dose by year and the number of monitored workers over time is shown in Figure 3. A significant increase in radiation monitoring and collective dose is achieved with the onset of overhaul and refuelling activities in 1959. This upward trend in collective dose continues through 1965, except for 1961, when there were no nuclear overhaul activities, and 1963, when only the USS Thresher (SSN 593) was in a limited maintenance 'shakedown' following its commissioning at PNS. Since 1965, there has been a general decline in the annual collective dose, even though the number of radiation workers remained high. The reduction in the overall average dose to individual workers can be attributed to improvement in submarine design and the implementation of more stringent institutional worker safety and training programmes.

DISCUSSION

The effect of administrative dose assignment

Adjustments to dose estimates from the shipyard records for prior dose and administrative dose assignments result in a reduction in collective dose

Table 4. Collective dose (person-Sv) from sources other than PNS.

Person-years of exposure	Assigned dose (person-Sv)	Exposure category
1496	2.70	US Navy vessels
693	1.94	Other Naval shipyards
226	0.49	Training
177	0.79	Industry
162	1.18	Medical
123	0.22	Department of Defense
119	1.01	Commercial nuclear power generation
52	0.02	Universities
33	0.32	Weapons testing
28	0.02	Department of Energy
203	0.06	Not determined

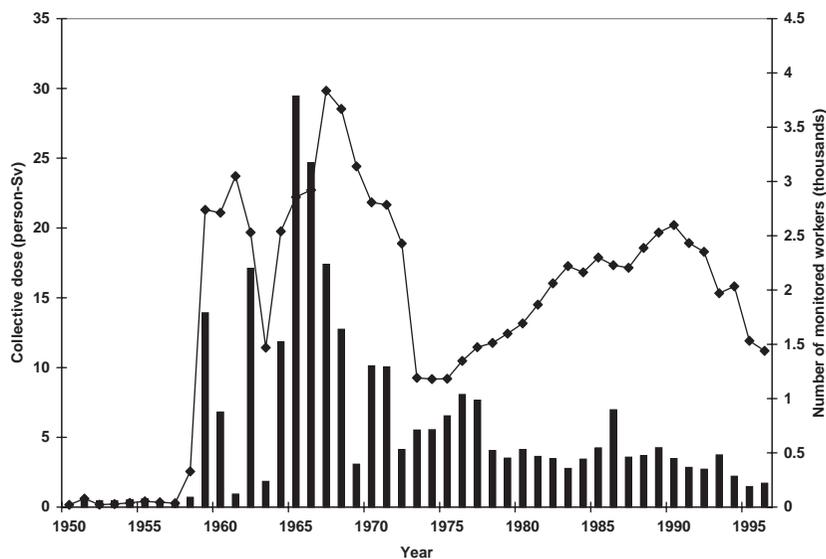


Figure 3. Annual collective dose (bar) and the number of monitored workers (filled squares) between 1950 and 1996.

of 7.35 person-Sv. More than 95% of the change is attributable to only 81 individuals. The magnitude of the adjustments to five cumulative dose categories for 13,468 workers with PNS exposure only was evaluated (Table 5). Overall, the adjustments result in shifting a small fraction of individuals from higher dose categories to the lower dose categories. The adjusted doses have little effect on the dose patterns of the cohort. However, large differences exist in the reported and adjusted doses of at least 81 individuals eligible for selection to nested case-control studies involving much smaller sample populations.

'Missed dose' from dosimetry sensitivity

The cumulative dose distribution at PNS is best approximated by the hybrid-log-normal model described by Kumazawa *et al.*⁽¹²⁾. Figure 4 shows cumulative dose data fit to a log-normal distribution with geometric mean and geometric standard deviation values of 3.86 and 10.18 mSv, respectively. All non-zero values were used in the analysis. The distribution deviates from the log-normal distribution in the high-dose range due to administrative control limits (ACLs) imposed by the shipyard. Workers with radiation exposures approaching or surpassing time-dependent exposure limits had their access rights to radiation areas removed. These limits were assigned based on the accepted protection standards of the day. Some examples of ACLs used at the shipyard were 3 mSv per week (1958–1963), 10 mSv per month (1963–1967) and 10 mSv per quarter (1974–1977)⁽⁴⁾.

The deviation from log-normality in the low-dose region becomes evident at dose values just below the measurement sensitivity of the early film badges (0.2 mSv). All non-detect monitoring results were normally reported as 'zero' dose. Therefore, radiation exposures below dosimetry recording thresholds were not included in a worker's dose of record, resulting in a potential for 'missed dose' determined by the detection limit and monitoring frequency. TLDs replaced film badge monitoring in October 1974, reducing the recording threshold by ≈ 10 -fold. Given this difference and the fact that most of the radiation work occurred before 1975, the missed dose from monitoring with TLDs is small when compared to that during the film badge monitoring period.

Log probability regression of annual dose values recorded before 1974 was used to estimate the collective missed dose. The independent variable is the standard normal deviate (z -score) and the dependent variable is the natural log of annual dose. Coefficients were determined using least squares linear regression. The data are censored to include only those dose values between a minimum of 2.40 mSv and a maximum 10.0 mSv, since that portion of the distribution may be approximated by the log-normal distribution. The results are shown in Figure 5. The final estimate is determined by subtracting the sum of recorded doses < 2.40 mSv from the sum of estimated doses obtained by regression. The missed dose contribution was estimated to be 2.73 person-Sv ($< 1\%$ of the collective dose) using this method.

Thus far, the missed dose estimate considers only those individuals with annual doses < 2.40 mSv.

Table 5. Cumulative dose category assignments before and after adjustments.

		Workers prior to dose adjustments					Category		
		1	2	3	4	5	←	Workers	↓
Category	Definition ¹	1626	3329	3806	3132	1575	←	Workers	↓
1	$H = 0$	1626	17	19	8	7		1677	1
2	$0 < H < 1$	0	<i>3311</i>	86	52	15		3464	2
3	$1 \leq H < 10$	0	1	<i>3701</i>	88	23		3813	3
4	$10 \leq H < 50$	0	0	0	<i>2983</i>	49		3032	4
5	$H \geq 50$	0	0	0	1	<i>1481</i>		1482	5

Workers following dose adjustments

¹Where cumulative dose (H) is the sum of the annual dose equivalent (mSv) from external sources of ionising radiation above background.

²The Comparison Matrix illustrates the impact from changes in dose assignments resulting from improved estimates and excluding dose from sources other than PNS. Values in italics represent workers without changes in dose category assignment. Values above and to the right of the line of italicised values represent workers with a dose reduction. Values below and to the left of the line of italicised values represent workers with an increase in cumulative dose.

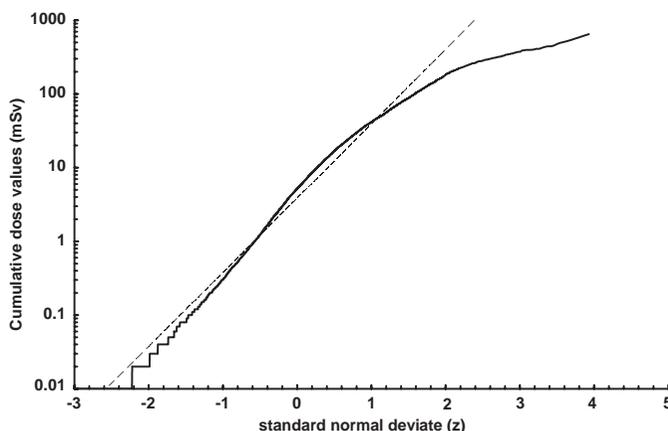


Figure 4. Fitted log-normal probability plot of cumulative doses as a result of PNS employment. Log-normal fit (dashed), actual data (solid). Fit includes cumulative doses ≥ 0.01 mSv.

A strong negative bias in the missed dose may exist since annual doses may include a number of monitoring intervals below the detection level. For example, a reported annual dose of 2.40 mSv may

have resulted from one monthly interval. The remaining 11 months may have had less than detectable results. In this instance, the actual dose received during any or all the 11 remaining months could

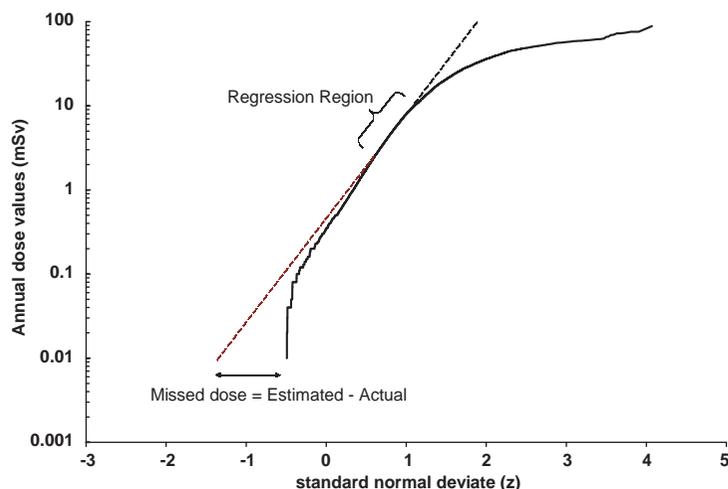


Figure 5. Plot of missed dose estimation from log probability regression of annual dose values between 2.40 and 10 mSv prior to 1974. Fit by regression (dashed line), actual data (solid line). Fit includes annual doses ≥ 0.01 mSv.

range from no dose to just below the detection threshold (0.20 mSv) for each month exposed, potentially resulting in a maximum missed dose of 2.2 mSv for the year.

Monitoring intervals per year varied among workers and cannot be derived from the annual exposure information that comprises the exposure assessment. To examine the potential bias, the same regression technique was applied using monthly monitoring data extracted from the 204 radiation workers discussed previously. The sample size is $\sim 1.5\%$ of the cohort. The sample collective dose is 4.93 person-Sv, which is $\sim 1.8\%$ of the cohort total. Based on a standard missed dose contribution of $\sim 1\%$ as taken from the cohort regression, the missed dose for the 204 workers was predicted to be < 0.050 person-Sv. However, the regression using interval dose data (data not shown) results in a missed dose estimate of 0.073 person-Sv (1.5% of the sample collective dose).

Although large uncertainties are anticipated when estimating missed doses for individuals using annual exposure data, it is unlikely that the missed dose is great when compared to recorded doses because (1) film badges were designed to provide a slight over-response to typical exposures⁽⁴⁾; (2) personal monitoring was performed mostly at monthly intervals and only when entering radiation areas, resulting in fewer instances of recorded 'zero' values, (3) the predominant exposure pathway is external radiation from gamma emitters in which the dosimetry has demonstrated a relatively good limit of detection and (4) there are several instances of recording values below the reported minimum sensitivity. For example, a recording threshold of ~ 0.1 mSv is most typical during the time period when missed dose is most likely, although the reported sensitivity of early

film dosimetry is 0.2 mSv. The practice of recording dose values below measurement sensitivities indicates that discernable changes in film densities, as determined by the shipyard dosimetrist, would prompt an assignment of some dose value > 0 .

Additional sources of error

The exposure assessment was comprised mostly of annual dose estimates by shipyard staff and is subject to potential biases inherent to the shipyard radiological protection programme⁽⁷⁾. Shipyard dosimetry procedures typically overestimate exposures to ensure that regulatory limits were not exceeded⁽⁴⁾. Likewise, variability of dosimetry practices, exposure conditions, and other factors such as the sex, age and anatomy of the exposed worker all result in uncertainty in the annual doses^(13–15).

Shipyard employees were also exposed to penetrating radiation from work-related medical X-ray examinations performed at PNS. Employee medical records indicate pre-employment and periodic chest X-ray examinations were performed throughout the time period addressed by this study. Early routine chest examinations were conducted frequently and used photofluorographic equipment, which resulted in significantly higher exposures than the direct radiographic techniques employed to date⁽¹⁶⁾. The dose from these examinations could comprise a substantial portion of a worker's total cumulative dose since many workers have relatively low doses from other occupational sources. Additionally, shipyard radiation workers were required to participate in routine chest examinations at higher frequencies than non-radiation workers, resulting in a potential association between the level of dose from

work-related X-ray examinations and the level of occupational dose.

Record keeping by shipyard staff over the years assured that sufficient data sources were available to researchers constructing detailed exposure histories for all radiation workers assigned to PNS between the years 1950 and 1997. Reviews of the dosimetry records following 1958 have uncovered only minor errors or omissions, supporting the conclusion that adequate quality controls for the records have been implemented. However, a slight reduction in both the quality and quantity of the records is observed for exposures prior to 1958, at which time recording practices were revised to meet the new demands associated with submarine overhaul and repair. Additionally, a small complement of PNS radiographers, instrument technicians, toolmakers and medical staff do not have recorded monitoring results prior to the onset of a formal monitoring programme in 1950.

CONCLUSION

Occupational radiation exposure at PNS is attributed almost exclusively to external radiation resulting from the overhaul and repair of nuclear-powered submarines. The primary radiation source was ^{60}Co distributed throughout piping and components within the reactor compartment where most radiation work was performed. Exposures to neutrons, scattered X-rays and internal emitters were found to be small fractions of external exposures to higher energy photons. The consistency of radiation sources, exposure pathways and work environments provide a rather unique cohort to study risks from low-dose protracted occupational photon radiation exposures.

The similar exposure potentials also required fewer changes in dosimetry programmes over time. Interpretation of monitoring data with fewer changes reduce uncertainties in dose estimates compared with mixed radiation fields, varying exposure geometries and changing programme missions akin to that experienced by cohorts from the national laboratories⁽⁹⁾.

Apparent discrepancies in exposure monitoring data were identified by range checks, examination of distributions and inspection of individual records. Inspection of exposure records for the upper range of cumulative doses located the discrepancy from administrative dose assignments for missing offsite exposure data. Replacement values for this type of discrepancy were derived from monitoring data for a range of industrial and service sectors available in previous exposure assessment articles and reports. Multiple datasets were available for each of the time periods and sectors except for six individuals where the mean of all sectors was used. Regression

analysis of log-transformed or non-transformed exposure data was used to calculate the measure of central tendency for each year needed. Reports with greater amounts of monitoring results were weighted more. Doses were extrapolated, as needed, for years prior to when data were available. The net change in collective dose following these imputations was a reduction in 7.35 person-Sv (2.6%). As a result of this small change in collective dose, the degree of misclassification without the correction could be determined. These changes reduce uncertainties in estimating risks for radiation-related disease in subsequent analysis.

Because of the large number of monitored workers in this exposure assessment, it was not feasible to collect period monitoring data that could be used to estimate missed dose due to dosimeter limits of detection and its interaction with period length. Alternatively, some general assumptions about the distributions of exposure data above the limit of detection allowed estimation of the missed dose for the population as a whole. Log-probability plots of dosimetry data were used to estimate a missed dose of ~ 2.73 person-Sv ($<1\%$). This value may be used in sensitivity analysis of dose-response estimation in the epidemiological study.

Given the size of the cohort, analysis of additional sources of uncertainty was extremely limited. A potential bias in the dose estimates may result from the omission of doses below measurement sensitivities and doses attributable to routine medical monitoring. Likewise, appropriate estimates cannot be achieved for certain PNS occupations, such as radium dial painters, without a detailed review of individual work histories; a difficult task to achieve for a cohort exposure assessment. To reduce these uncertainties, dose estimates for individuals participating in the follow-on nested case-control studies will include data extracted from work history information, individual dosimetry results and medical records.

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