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Military Participants at U.S. Atmospheric Nuclear Weapons Testing—Methodology for Estimating Dose and Uncertainty

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Methods were developed to calculate individual estimates of exposure and dose with associated uncertainties for a sub-cohort (1,857) of 115,329 military veterans who participated in at least one of seven series of atmospheric nuclear weapons tests or the TRINITY shot carried out by the United States. The tests were conducted at the Pacific Proving Grounds and the Nevada Test Site. Dose estimates to specific organs will be used in an epidemiological study to investigate leukemia and male breast cancer. Previous doses had been estimated for the purpose of compensation and were generally high-sided to favor the veteran's claim for compensation in accordance with public law. Recent efforts by the U.S. Department of Defense (DOD) to digitize the historical records supporting the veterans' compensation assessments make it possible to calculate doses and associated uncertainties. Our approach builds upon available film badge dosimetry and other measurement data recorded at the time of the tests and incorporates detailed scenarios of exposure for each veteran based on personal, unit, and other available historical records. Film badge results were available for approximately 25% of the individuals, and these results assisted greatly in reconstructing doses to unbadged persons and in developing distributions of dose among military units. This article presents the methodology developed to estimate doses for selected cancer cases and a 1% random sample of the total cohort of veterans under study.

INTRODUCTION

Military veterans who participated in atmospheric nuclear weapons testing conducted by the United States between 1945 and 1963 are being studied for late occurring health effects. The study cohort consists of 115,329 individuals who were present in one or more of seven test series[2]: CASTLE, CROSSROADS, GREENHOUSE, REDWING, and HARDTACK I conducted at the Bikini and Enewetak Atolls and Johnston Island in the Pacific Proving Grounds (PPG); UPSHOT-KNOTHOLE and PLUMBBOB conducted at the Nevada Test Site (NTS); and TRINITY, the first nuclear test, conducted in New Mexico (Fig. 1). We refer to our analysis of this collection of tests as the Eight Series Study.

The purpose of the study is to investigate whether low-dose radiation received by the veterans caused an increase in mortality among the exposed group. Radiation doses are being estimated for a sub-cohort of 1,857 individuals that will be used for the analysis. This article describes the methodology developed to estimate radiation doses and associated uncertainties to be used for the epidemiological analysis.

The majority of this cohort could have been exposed at either the NTS where they participated in military maneuvers, observed tests or provided support, or the PPG where personnel were aboard ships or stationed on islands in the area during and after the shots. In most instances, there was a potential for radiation exposure and resulting dose; however, individual circumstances and doses varied considerably. About 12,000 members of the study cohort also participated in test series other than those in the Eight Series Study and their additional doses are included in the dosimetry.

The largest fraction of cohort members served in the Navy, followed by the Army, Air Force and Marine Corps (Table 1). Table 2 (*1*) shows the number of individuals associated with each test series. Information about the number of detonations, types of tests, as well as ranges and total explosive yields, in millions of tons (Mt) of 2,4,6

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[2] A series consists of a number of nuclear detonations (referred to as individual shots) over a specific time period at either the Nevada Test Site or the Pacific Proving Grounds. TRINITY was a single shot in New Mexico not associated with any series.

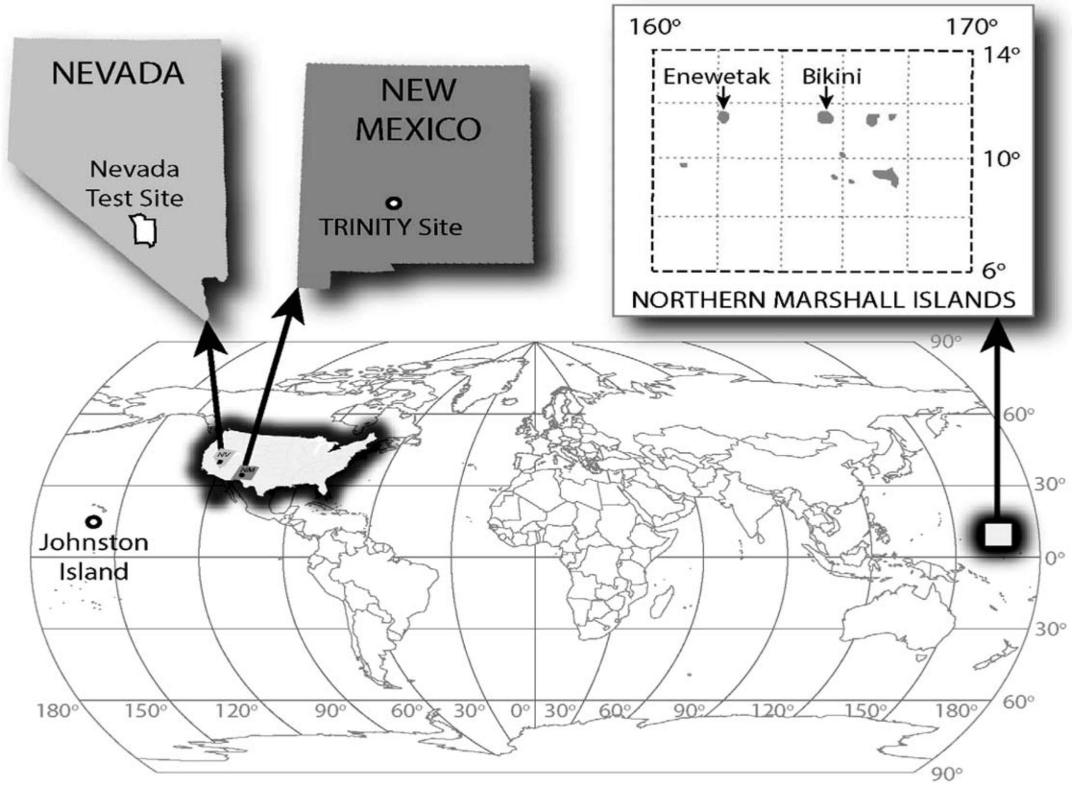

FIG. 1. Primary locations where the United States tested nuclear weapons.

trinitrotoluene (TNT) equivalent, is included for each location (e.g., the Hiroshima bomb had a yield of about 0.016 Mt). The greatest number of individuals participated in the CROSSROADS series, but many took part in other series at the PPG, including HARDTACK I, CASTLE, REDWING and GREENHOUSE. About 30% of cohort members participated in the UPSHOT-KNOTHOLE and PLUMBBOB series at the NTS.

Doses to U.S. military veterans were estimated previously under the Nuclear Test Personnel Review (NTPR) program directed by the Defense Threat Reduction Agency (DTRA)[3] within the DOD. The NTPR program was initiated in 1978 following a series of public laws that were approved by Congress and published under the Code of Federal Regulations (*2*). These laws were implemented because of concerns about radiation exposure of veterans during nuclear atmospheric testing (*3*). In 1988, legislation was passed that authorized a compensation program for veterans based on doses estimated by DOD personnel and their contractors. To estimate doses to veterans, the DOD undertook a comprehensive review of historical records and developed a dose reconstruction methodology that was designed to be high sided and favor veterans seeking compensation in accordance with the legislation.

In 2003, a committee of the National Academy of Sciences (*4*) reviewed the NTPR program to evaluate the program's effectiveness, to determine if appropriate procedures were being followed, and to make sure estimated doses were properly documented and based on sound scientific methods. The academy's report confirmed that doses being reconstructed were frequently high-sided in accordance with the objectives of the program and the enabling legislation. The report also identified a number of potential improvements to the program that have since been implemented. Those improvements included better documentation of procedures, improved quality assurance and more effective communication with veterans. Another key improvement was the digitization of thousands of historical

TABLE 1
Number of Individuals from Each Branch of the Military

Service	Eligible cohort	Case-cohort study participants
Air Force	12,888	219
Army	26,509	427
Marine Corps	5,006	83
Navy	70,892	1,128
Multiple[a]	15	0
Other	19	0
Total	115,329	1,857

[a] Some members served in more than one branch of the service.

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[3] The predecessor of DTRA was the Defense Nuclear Agency (DNA) whose legacy goes back to the Manhattan Project, which directed the development of the first atomic weapons. The DTRA program has been ongoing since the early 1980s.

TABLE 2
Number of Individuals Associated with each Atmospheric Test Series[a,b] (*1*)

Location	Test series (year)	Number in eligible cohort	Number of case-cohort study participants	Number of tests	Total yield (Mt)	Yield-range (Mt)	Type[c]
NTS	UPSHOT-KNOTHOLE (1953)	18,607	319	11	0.4	0.01–0.043	A, T
NTS	PLUMBBOB (1957)	12,251	194	23	0.34	<0.01–0.074	A, B, T
NTS	Other[d]	3,657	72	46	0.5	0.002–0.043	A, B, S, T
PPG	CROSSROADS (1946)	38,798	632	2	0.042	0.021	A, UW
PPG	GREENHOUSE (1951)	9,640	140	4	0.4	0.04–0.23	T
PPG	CASTLE (1954)	16,294	304	6	47	0.11–15	BA, S
PPG	REDWING (1956)	13,678	184	17	20	<0.1–5.0	A, BA, S, T
PPG	HARDTACK I (1958)	10,388	150	34	36	<0.01–9.3	A, B, BA, S, UW
PPG	Other[e]	7,115	136	42	58	0.1–11	A, S, UW
NM	TRINITY (1945)	726	3	1	0.021	0.021	T
Other[f]	Other[g]	1,706	24	5	0.03	<0.01-0.02	A

[a] Some individuals participated in more than one series and are included in the total count for each series in which they participated.

[b] Yields for thermonuclear tests are estimates; actual yields are still classified.

[c] T (tower), B (balloon), S (surface), A (air burst), UW (under water), BA (barge).

[d] Includes RANGER (1951), BUSTER-JANGLE (1951), TUMBLER-SNAPPER (1952), TEAPOT (1955), and HARDTACK II (1958). Also included are three 1962 PLOWSHARE tests.

[e] Includes SANDSTONE (1948), IVY (1952),WIGWAM (1955) and DOMINIC (1962).

[f] Includes the South Atlantic Ocean and Japan.

[g] Includes ARGUS (1958), occupation troops at Hiroshima or Nagasaki in 1945–1946, as well as some individuals present at test sites between test series and identified in the DTRA database as ''nonparticipants'' for that time interval.

records detailing military personnel and unit participation, radiation measurements, and other types of documents needed to perform historical dose reconstruction for specific individuals. These improvements to the NTPR program and the recent availability of these digitized records make detailed dosimetry possible using methods explained in this article. The results of the dosimetry and epidemiology will be reported in separate publications.

Previous attempts to investigate disease among nuclear test participants in the United States have yielded mixed results and these studies lacked the detailed dosimetry on individuals being studied (*5–13*). Other studies in the United Kingdom, New Zealand, and France have also investigated persons involved in atmospheric nuclear testing with similar published results, but again without dosimetry on an individual basis (*14–22*).

Watanabe *et al*. (*23*) investigated the HARDTACK I series to examine cause-specific mortality for 8,554 Navy veterans. HARDTACK I was one of the first test series where most (88%) participants wore a film badge, and those film badge readings were used for the dosimetry. Doses were reconstructed for those personnel with no or incomplete film badge data. The median radiation dose for participants was estimated to be ~0.4 mSv. Among veterans who received estimated doses >10 mSv, an increased mortality risk for all causes (RR = 1.23; 95% CI 1.04, 1.45), all cancers (RR = 1.42; 95% CI = 1.03, 1.96) and liver cancer (RR = 6.42; 95% CI = 1.17, 35.3) was observed. Watanabe *et al*. (*23*) incorporated the best available dosimetry at the time; however, dose estimates were not organ-specific and uncertainties and biases in the film badge data were not addressed.

METHODS

The fundamental approach to dose estimation is to first determine the scenario of exposure for each veteran and then to assign a dose without the high-sided bias that was often introduced in the methodology developed during the veterans' compensation program. It would be impractical (because of cost and time) to conduct dose reconstructions for all of the 115,329 military personnel in the Eight Series Study. Thus an efficient epidemiologic study design, the case-cohort approach, is used to provide dose-response information relevant for the entire cohort at reasonable cost (*24*). The sub-cohort in the current study includes 1,857 individuals, including all leukemia and male breast cancer cases and a 1% random sample of the entire cohort.

Our methodology uses film badge data collected and recorded during the testing period. Approximately 25% of the military personnel had film badge records that accounted for at least 80% of their dose. These records can be used for specific dose assignments to individuals wearing a badge and also for groups of veterans performing similar duties. Distributions of dose based on film badge readings can also be used for estimating uncertainties. One or more members of a unit performing similar duties were often issued a ''cohort'' film badge, which can help in estimating dose to the entire cohort *(3)*. While a relatively large percentage of individuals have film badge data for some series (e.g., PLUMBBOB and HARDTACK I), a relatively small percentage have film badge data for other series (e.g., CROSSROADS, GREENHOUSE and UPSHOT-KNOTHOLE). In addition, while half of the CASTLE participants have badge data in the Nuclear Test Review and Information Systems database (NuTRIS), the majority are based on a single cohort badge wearer whose dose was assigned as a badge dose to other members of the unit. For CASTLE in particular, it was identified that the cohort badge assignments were not necessarily reflective of the activities an individual may have been involved in, so these badge doses are not used for the current study. Likewise, for REDWING, although many individuals wore badges, many of the badges were damaged from high heat and humidity and do not reflect the actual exposures received (*25*).

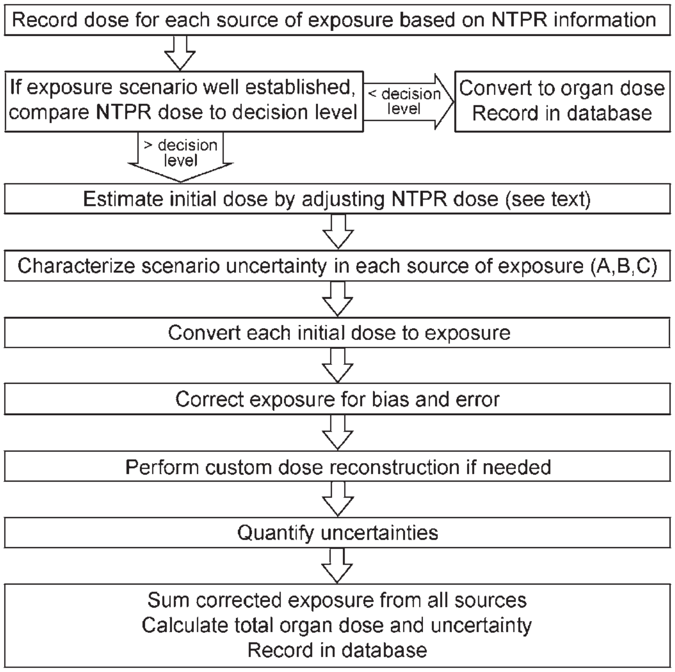

FIG. 2. Steps in the dose estimation process.

Contributing to the total body of knowledge about an individual's potential for radiation exposure are the NuTRIS documents related to military units, ships' logs, photographs of facilities, and activities at the NTS and the PPG, the NuTRIS indicator of military rate or rating (indicating an individual's job) and numerous other historical records. Individual radiation dose assessments (RDAs) were also developed for veterans who requested compensation. These RDAs were performed by DTRA using veteran-specific parameters and, in some cases, interviews with veterans or spouses. We incorporate information from these interviews into our analysis when available. Unfortunately, the number of veterans who submitted a claim for compensation within our 115,329 member cohort is small[4], and therefore these personal data, although very helpful, are limited. All of these sources of information are incorporated into our methodology.

Cancers Studied and Pathways of Exposure

Leukemia and male breast cancer were selected as the initial focus of the study. We selected leukemia because previous U.S. studies suggest a general pattern of increased leukemia risks (*3, 5–9*), but these studies did not include individual dosimetry or uncertainty. Male breast cancer was chosen because the Five Series Study of atomic veterans had reported a nonstatistically significant increased risk of 39% (*7*). The study of atomic bomb survivors reported a statistical association of male breast cancer with radiation dose but was based on small numbers (*26*), and the number of male breast cancers in our study, about 30, would be the largest study to date.

Veterans could have been exposed to both external and internal radiation. Based on conservative NTPR analyses as well as estimated doses to residents of the Marshall Islands, internal exposure to red bone marrow (organ of interest for leukemia) and male breast would almost always be no more than a few percent of the dose from external exposure (*27–29*). Other researchers have also concluded that when external and internal exposure exists from radioactive fallout of nuclear weapons, the primary exposure pathway for most organs other than thyroid is external (*30, 31*). Internal exposure may be significant as the study expands to consider cancer to other organs such as thyroid, salivary gland, liver and bone for which radionuclide intakes are important.

Criterion for Detailed Dose Reconstruction

In reviewing the historical records such as film badge data, previous dose reconstructions, and other information describing a veteran's military unit and personal activities, if it can clearly be established that the dose is below a given level that does not merit a comprehensive dose reconstruction, then the dose reported by the NTPR program is used. This approach has been taken in similar studies where a decision level (also called ''cutoff level'') is chosen for the practical reasons of cost and feasibility (*32*). Veterans with doses below the decision level are not excluded from the study and their estimated dose is still used in the analysis.

We selected a decision level of 5 mGy. We assign an uncertainty to all NTPR doses clearly less than this level characterized by a geometric standard deviation (GSD) of 1.4, consistent with NTPR estimates of uncertainty in external exposure at those levels.

Process for Dose Estimation

Figure 2 summarizes the main steps in our methodology. In the first step, we evaluate all information available in NuTRIS and NTPR literature on the veteran's potential sources of exposure along with the NTPR-estimated doses for each source. If the individual's exposure scenario is well established and the sum of all the NTPR doses is clearly less than the decision level of 5 mSv, the NTPR dose is converted to organ dose using appropriate dose coefficients and recorded in the database. If the total dose is not clearly less than the decision level, the doses recorded in NuTRIS are adjusted to provide a more realistic dose. These adjustments include:

- making use of more current information;
- correcting obvious errors in the NuTRIS entries;
- replacing suspect film badge data with reconstructed doses; and
- accounting for sources and time periods of exposure not included in NuTRIS.

The next step is to characterize the uncertainty for the occurrence of each potential source of exposure, characterized qualitatively as A, B, or C [low, medium, or high (see *Accounting for Uncertainty* section below)].

These ''initial dose'' estimates are then converted to exposure and further corrected for bias and errors in the NTPR methodology. Custom dose reconstructions are performed when the probability of occurrence of a potential scenario needs to be estimated to calculate a dose (scenario uncertainty B or C), when there is no NTPR-estimated dose for a potential exposure, or when there is no generic NTPR dose reconstruction that applies to the particular source of exposure. About two-thirds of the cases with total dose deemed not clearly less than the decision level required some custom dose reconstruction. Next, uncertainties in our final dose estimate for each source of exposure are calculated. The final step is to total the exposures from all sources, convert to annual organ dose and calculate a total uncertainty for each annual dose.

Scenarios of Exposure

The scenario of exposure accounts for the time, duration, location, duties and other factors that resulted in a veteran's exposure to radiation. Developing realistic scenarios of exposure is a key step toward estimating dose. Although individual scenario development was carried out during the NTPR program in support of claims for

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[4] There are 1,500 unique individuals within the study cohort with an RDA. Among the sub-cohort the number of RDAs is 21. When developing a scenario of exposure for our study, we also review any NTPR RDAs for individuals and military units with exposure characteristics similar to the veteran being investigated.

compensation, NTPR dose estimates for most of our cohort did not account for possible individual-specific activities and instead assumed the same generic exposure for all members of a unit.

Scenarios of exposure were divided by location, series, and type allowing for efficient consideration of the commonalities across the following broad categories:

- Ship-based scenarios at the PPG.
- Land-based scenarios at the PPG.
- Maneuvers, observers, and other activities at the NTS.

Broken down in this fashion, scenario similarities allow for transfer of knowledge gained in one situation to be applied to similar situations. This categorization is particularly important for unique pathways that may be appropriate for more than one type of individual. Exposures for the small number of case-cohort subjects at the TRINITY test are evaluated individually.

Duties for most military personnel can be generally inferred from the branch of service, the unit, and the person's rate or pay grade (enlisted) or rank (officers). The U.S. Navy employs a system of job descriptions among enlisted personnel that describes specifically what the person does while on duty. These specialties are known as ratings.[5] For example, boatswain's mates spent most of their time above deck and also operated small boats carrying crew members ashore; machinist's mates operated the ships propulsion system; electrician's mates tended to electrical systems, and so forth. The Navy rate and rating system is especially important in our analysis since approximately 60% of personnel in the cohort served in the Navy.

As discussed earlier, some veterans were interviewed by the NTPR program as part of their compensation claim, and we included this information when it was available.

Ship-Based Example

At CROSSROADS, a target ship array was situated around the surface zero location of the BAKER test, and those target ships became significantly contaminated by the base surge of water that contained high concentrations of fission products. Personnel boarded the target ships after BAKER to assess contamination and damage levels, decontaminate salvageable ships, retrieve ammunition or other equipment from those that could not be salvaged and to perform other tasks critical to maintaining the vitality of the naval fleet. A radiation monitor wearing a film badge and using monitoring equipment was typically the first person to board a contaminated ship and assess the exposure levels. For the majority of reboarded target ships, small groups of the original crew of the ship would board to complete their duties once the ship had been cleared for others to board. For a small number of target ships, large parties boarded to decontaminate and prepare the ship for re-manning after the initial inspections. Members of both of these types of boarding parties did not generally wear film badges. However, documentation for the CROSSROADS series indicates that radiation monitors played a very important role in boarding parties, limiting daily exposures from boarding party activity to 0.1 R per day[6] or whole body doses of ~0.7 mSv. At CROSSROADS, target boarding exposures represent some of the largest doses for the series. The NTPR doses contained in NuTRIS generally assign a maximum target reboarding dose to every member of the crew of a target ship for every boarding event, when we know that target boarding parties were mostly small and composed of specific subsets of crew members. It is important to determine whether crew members would have been exposed by this pathway.

This scenario example describes exposures for two members of our sub-cohort, a machinist's mate and a seaman apprentice, who served aboard the USS CATRON (APA-71). The CATRON was a target ship at CROSSROADS, which is known to have been boarded on several occasions after Shot BAKER when contamination levels were high.

Figure 3 is an excerpt from the USS CATRON (APA-71) deck log at CROSSROADS on August 16, 1946 (personal data are redacted). The log shows that a boarding party made up of two lieutenants junior grade and a variety of enlisted personnel boarded the ship and remained on board from 0730 h to 1135 h, when the tolerance limit (0.1 R or 0.7 mSv) was reached and the personnel were ordered to disembark. This is one of several boarding party listings on various days in the deck logs for this ship. Although they are removed from this figure for Privacy Act purposes, the names of the individuals in the boarding party are listed in the deck logs on every day the ship was boarded. From these logs, we are able to determine which veterans in our sub-cohort participated in boarding parties. One of the two veterans in our sub cohort, a machinist's mate first class, was listed as a member of the boarding party on August 16 and on that date only. Since we know the tolerance limit was reached, we are able to estimate the dose to this individual for this boarding event with some precision.

Unfortunately, cases where the deck logs list the names of the boarding party members are quite rare. In most cases, there is evidence that the target ship was boarded, but no indication of who boarded. In these situations, we can use the ratings of the individuals in our sub-cohort to estimate the probability that they boarded the target ship. For scenarios where target ship boarding is not known, we include the exposure pathway in our scenario and then estimate an exposure and uncertainty in that exposure based on the probability of the veteran having boarded and received a dose, using the information about the constitution of boarding parties by rating contained in limited sets of deck logs. This process is described in the Accounting for Uncertainty section.

Nevada Test Site Example

A major source of radiation exposure at the NTS was due to observing a test from trenches and then participating in maneuvers immediately following the test. These maneuvers were frequently undertaken by groups of soldiers composed of different companies, which together were known as Battalion Combat Teams (BCT). The purpose of the maneuvers was to train personnel for combat in a contaminated environment under realistic conditions. Usually, only a few personnel in each company were issued film badges. Since the radiation exposure often varied depending on location in the formation, knowledge of the relative location of a participant within a BCT is important.

This example scenario uses members of BCT B at Shot NANCY of the UPSHOT-KNOTHOLE series. Figure 4 (*33*) shows the radiation isointensity plot that was produced from the initial survey that was conducted at 0610 h following Shot NANCY. Some of the maneuver troops in BCT B moved forward into an area of high radiation intensity (~14 R h^{-1}) that was well in excess of the 2.5 R h^{-1} exposure rate guide established for the exercise. The troops withdrew from the area as soon as the error was recognized. NTPR uses different assumptions regarding the potential exposure duration and radiation intensity to reconstruct doses for the forward and rear elements of BCT B (Table 3); however, the reconstructed dose estimates for all members of BCT B recorded in NuTRIS are based on an average of the forward elements only (*34, 35*).

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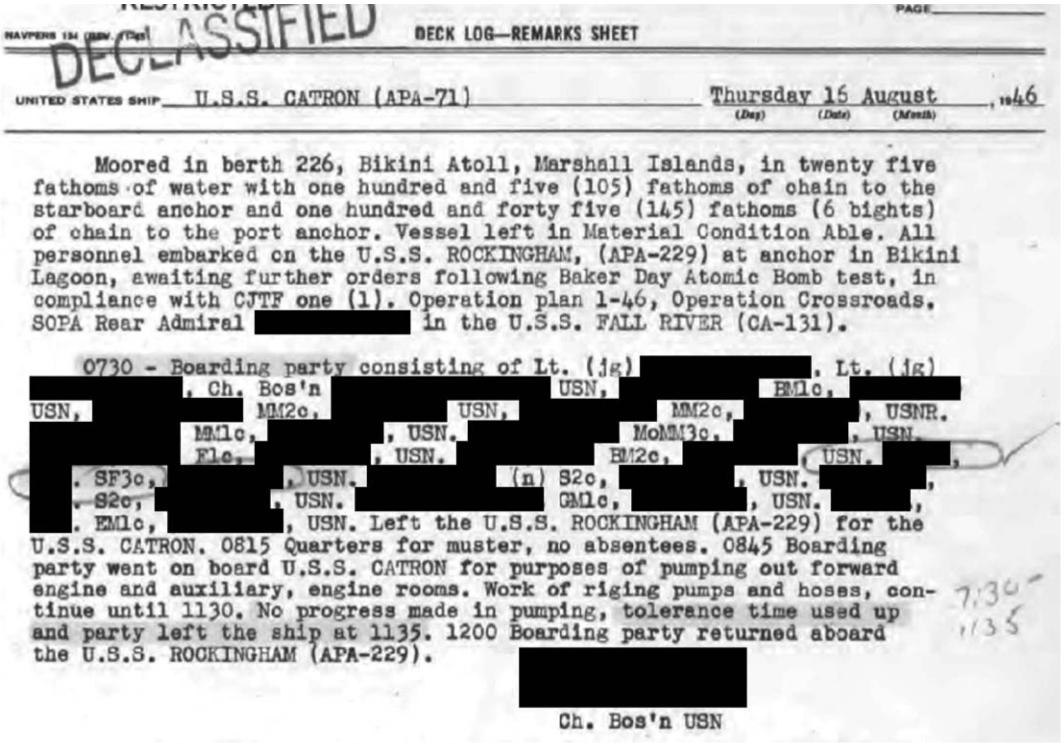
[5] The system of ratings and their abbreviations used by the U.S. Navy evolved over more than 200 years. The rating defines the job specialty of enlisted personnel and characterizes where aboard ship (or ashore) they work and what they do. For example, a radioman (RM) works with communications in the radio room; a ship fitter (SF) plans, supervises, and performs tasks necessary for fabrication, installation, and repair of metal structures; and a gunner's mate (GM) operates and maintains ship guns. Some ratings no longer exist, and new ratings have been introduced due to changes in technology with time.

[6] Historical records show that this exposure limit was generally adhered to during CROSSROADS testing.



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NAVPERS 134 DECK LOG—REMARKS SHEET PAGE

UNITED STATES SHIP U.S.S. CATRON (APA-71) Thursday 16 August, 1946
(Day) (Date) (Month)

Moored in berth 226, Bikini Atoll, Marshall Islands, in twenty five fathoms of water with one hundred and five (105) fathoms of chain to the starboard anchor and one hundred and forty five (145) fathoms (6 bights) of chain to the port anchor. Vessel left in Material Condition Able. All personnel embarked on the U.S.S. ROCKINGHAM, (APA-229) at anchor in Bikini Lagoon, awaiting further orders following Baker Day Atomic Bomb test, in compliance with CJTF one (1). Operation plan 1-46, Operation Crossroads. SOPA Rear Admiral [redacted] in the U.S.S. FALL RIVER (CA-131).

0730 - Boarding party consisting of Lt. (jg) [redacted], Lt. (jg)
[redacted], Ch. Bos'n [redacted] USN, [redacted] BM1c, [redacted]
USN, [redacted] MM2c, [redacted] USN, [redacted] MM2c, [redacted], USNR.
[redacted] MM1c, [redacted], USN. [redacted] MoMM3c, [redacted], USN.
[redacted] F1c, [redacted], USN. [redacted] BM2c, [redacted], USN. [redacted],
[redacted]. SF3c, [redacted], USN. [redacted] (n) S2c, [redacted], USN. [redacted],
[redacted]. S2c, [redacted], USN. [redacted] GM1c, [redacted], USN. [redacted],
[redacted]. EM1c, [redacted], USN. Left the U.S.S. ROCKINGHAM (APA-229) for the U.S.S. CATRON. 0815 Quarters for muster, no absentees. 0845 Boarding party went on board U.S.S. CATRON for purposes of pumping out forward engine and auxiliary, engine rooms. Work of riging pumps and hoses, continue until 1130. No progress made in pumping, tolerance time used up and party left the ship at 1135. 1200 Boarding party returned aboard the U.S.S. ROCKINGHAM (APA-229).

7:30
1135

[redacted]
Ch. Bos'n USN

FIG. 3. USS CATRON (APA-71) ship's log, August 16, 1946.

We developed a methodology to assign a dose and uncertainty based on each individual's location within the BCT using available film badge data. Two key pieces of information were used for this evaluation. First, we were able to locate 78 of the 82 badge doses reported to exist for BCT B members, and second, we were able to determine the permanent unit of each badged individual when they were sent to Camp Desert Rock to form BCT B. Historical records identified the actual units comprising BCT B and their origin and verified our assumptions. By combining this information (Table 3), we could determine that airborne infantry units comprised the forward elements, and all other infantry units comprised the intermediate elements, with field artillery and truck units comprising the rear elements. Percentile plots of the distribution of badge doses according to the permanent unit type were used to define the median dose estimate and their uncertainties (Table 3). Depending on the assigned permanent unit of each study participant, the appropriate percentile information was used to establish his initial dose estimate. If a permanent unit type was not represented by the badge data, as was the case for three participants from engineer battalion companies, then the distribution based on all badge doses was used to estimate the dose and its uncertainty.

Adjusting for Bias and Error in the NTPR Dose

There are a number of instances where the NTPR dose for a particular activity is known or believed to be systematically high-sided (biased) or where errors were made related to assumptions about exposures or model parameters. These instances are identified and adjusted to remove the effect of bias or error in the NTPR dose. Table 4 lists examples of several key instances of NTPR bias or error that required an adjustment to the NTPR dose and the approximate range of the adjustment.

The sections below explain how our methodology corrected both errors and deliberate biases associated with the examples shown in Table 4.

Correction for Cohort Badges at the CASTLE Series

For many individuals on ships at the CASTLE series, the NTPR dose was assigned based on the film badge reading of one veteran who wore a badge within a unit. This policy was implemented because it was assumed that members of units performing similar activities could be grouped into a ''cohort'' whose members would likely receive a similar dose, thus reducing the number of film badges required. However, it was discovered that a cohort was often not constituted based on similar duties and received very different exposures. Thus, a cohort member's ''true'' dose may actually have been higher or lower than the badge wearer's dose since cohort badge readings for a given unit for the same exposure interval ranged from well below the mean exposure to the entire unit to well above. Doses for members of cohorts where this disparity existed were replaced by the mean exposure of the entire crew or the mean for crew members likely to have had similar duties. This resulted in corrections that ranged from ~0.3 to ~5 times the NuTRIS dose.

Bias Correction for Film Badge Dosimetry

The NTPR program assumed the film badge reading was equivalent to the whole body dose that was recorded in NuTRIS. This assumption results in a significant overestimate of the actual dose by a factor of ~1.4 (*35*). Additional instances of bias were identified in the National Research Council report on film badge dosimetry in atmospheric nuclear tests (*25*) that recommended test-series-specific adjustments for converting film badge readings to free-in-air exposure from X or γ rays. These issues result in all NTPR doses based on film badge readings being systematically high-sided (biased) by a factor of about 1.2 to 2.0.

If the reported film badge reading was zero, and some exposure was clearly likely, a value of one-half the minimum detectable level is used as recommended in the National Research Council report.

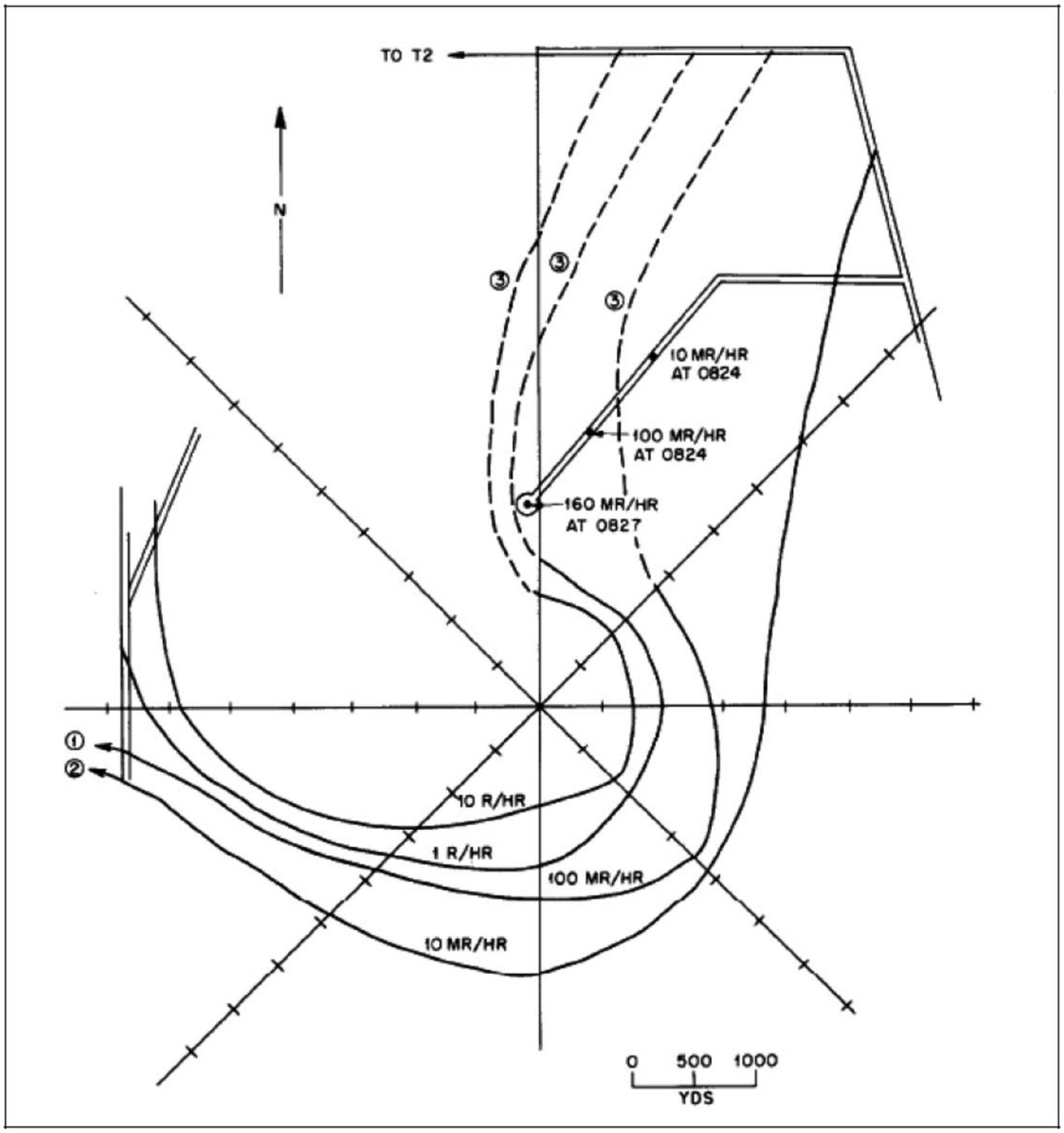

FIG. 4. Radiation exposure rate map for shot NANCY at H+1, showing lines of constant exposure.

Error Correction for Engine Room Duty

Figure 5 is a schematic diagram of a Sumner Class destroyer, similar to those present during the Pacific testing. The full-scale drawing shows various compartments of the ship where personnel worked and were berthed (i.e., slept). There are two boiler rooms (one forward and one aft) where steam is produced from freshwater and two engine rooms located just aft of the boiler rooms. These compartments are separated by watertight bulkheads, and each compartment has a separate hatch for personnel entry. The engine rooms contain a significant amount of piping where seawater is taken in and discharged. The water is used primarily for condensing steam discharged from the turbines and also for evaporating seawater to make freshwater used throughout the ship. When estimating dose, it is important to determine which personnel stood watch in the engine room since this was a primary source of exposure aboard steam-driven ships.

The NTPR mistakenly assigned some personnel to engine room duty who would not likely have served in this compartment. Furthermore, personnel assigned were assumed to be present in the

TABLE 3

Comparison of BCT B Maneuver Troop Doses (mGy) for Shot NANCY Calculated by NTPR Based on Radiation Intensity Measurements and Assumptions about Exposure Duration Compared to Actual Film Badge Dose Readings, which are Reported Based on the Unit Type. Median Dose is Shown with 90% Confidence Interval (CI)

NTPR-reconstructed doses[a] for BCT B members	Median dose in mGy (90% CI)
Forward elements	24 (17–39)
Rear elements	11 (8–16)
Film badge doses[b] for BCT B members	
Airborne infantry (n = 30)	20 (8–24)
Infantry (n = 27)	14 (8–16)
Field artillery or truck (n = 17)	9.5 (7–14)
All (n = 77)	14 (8–24)

Note. n is the number of available film badge doses.

[a] Whole body dose.

[b] Red bone marrow dose.

TABLE 4
Examples of Estimated Bias or Error[a] in NTPR Dose Assignments

Source of exposure	NTPR source of bias or error	~ Range of bias or error[b]
Cohort badges at CASTLE	NTPR assigned doses based on random cohort assignments that resulted in errors due to both overestimating and underestimating doses to particular individuals.	0.2–3.0
Film badge interpretation	NTPR assumed film badge reading equaled the whole body dose that resulted in all NTPR doses being biased high and did not correct for other known biases.	1.2–2.0
Engine room duty	NTPR assumed high-sided dose (bias) and placed unlikely rates and ratings in the engine room (error).	1.2–10
Hull and seawater contamination	NTPR assumed all personnel worked and berthed below the water level where exposure would be highest resulting in errors in individual exposures.	0.4–9.0
Bias correction for exposure to fallout on residence islands and ships	NTPR used available exposure rate measurements and model estimates of shielding that did not accurately reflect the true mean exposure. This generally biased high the mean dose to all those in a particular unit.	0.5–6.0

[a] ''Bias'' refers to the tendency to systematically either overestimate or underestimate doses for a given exposure scenario. Error refers to random errors in individual doses such as errors in assumed individual exposure scenario or errors in NTPR records. Random errors for a particular exposure scenario can be in either direction, while bias is always in the same direction.

[b] Range of ratios of NTPR to AVS doses.

engine room regardless of the specific rates and ratings who typically manned these spaces. Based on our research, including interviews with former Navy personnel, the engine room was generally manned by machinist's mates, electrician's mates, and a chief warrant officer or junior officer. For example, the engineman rating (EN) generally did not work in the engine room but worked on machinery at other locations aboard ship. Occasionally junior enlisted personnel in training for an engineering rating were also present. NTPR also assigned high-sided dose estimates for engine room personnel, assuming they were always in close proximity to highly contaminated piping, condensers and evaporators. The error in the assignment of engine room duty and the high-sided estimates of resultant doses led to overestimates of dose by factors between ~1.2 to ~10. The overestimates were generally greater for large ships.

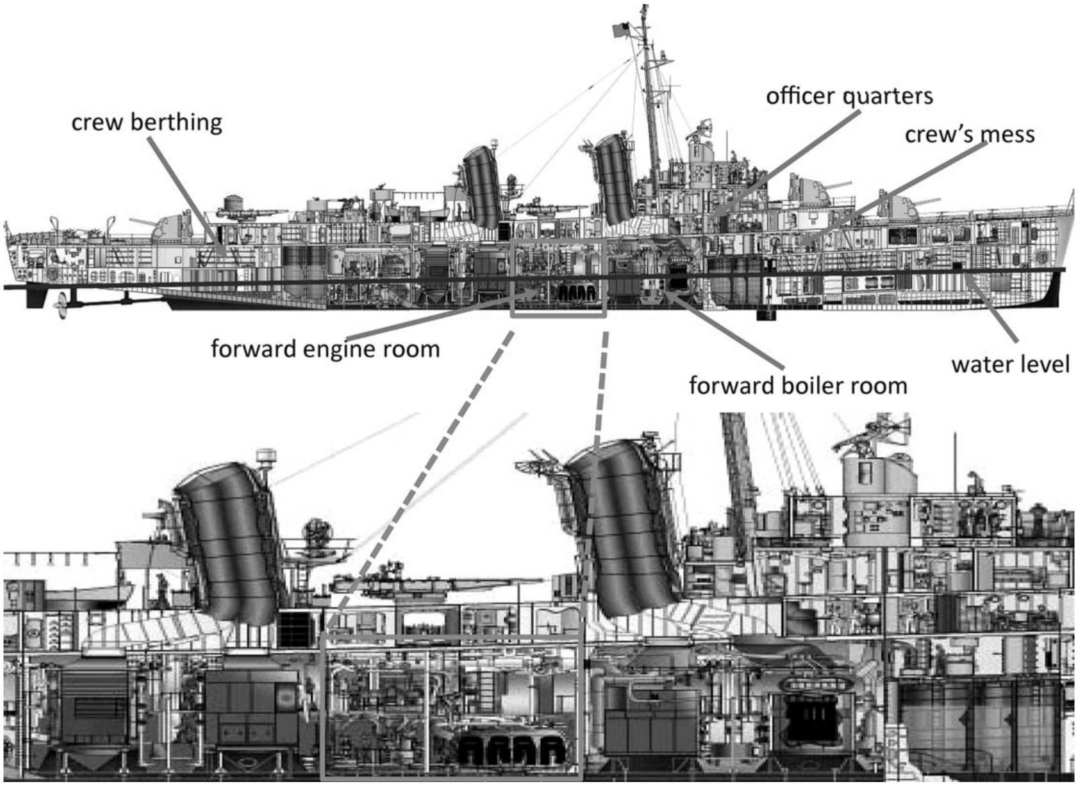

FIG. 5. Diagram of a SUMNER class destroyer illustrating various compartments aboard ship.

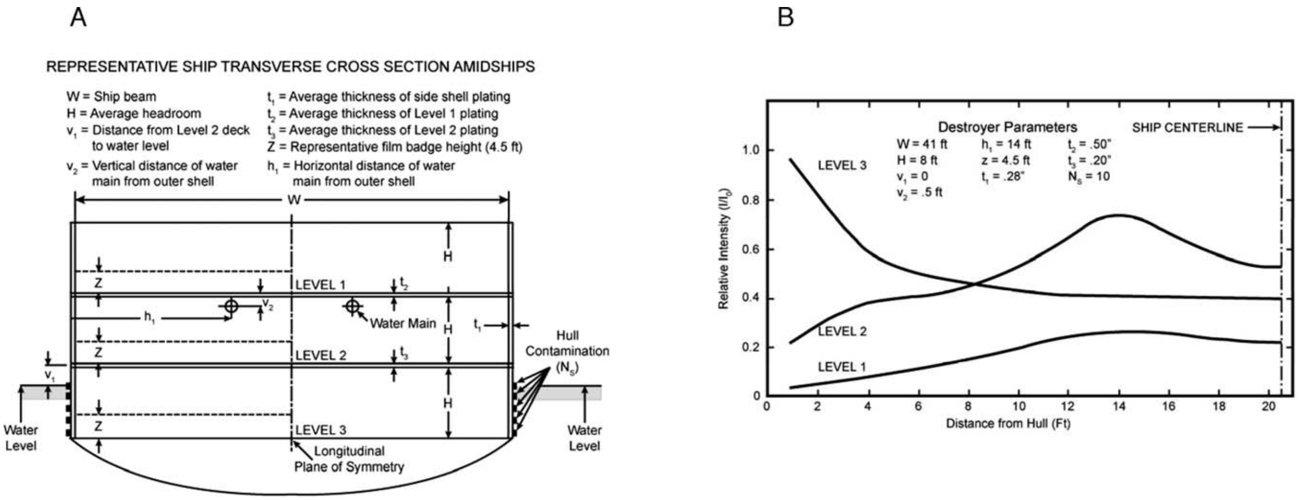

FIG. 6. Panels A and B: Apportionment factor model developed by NTPR for CROSSROADS to account for exposure below decks from piping systems aboard ship.

Corrections for Hull and Seawater System Contamination Exposure

The NTPR developed a model to estimate exposure from hull and piping contamination at various locations aboard ship (*36*). Contamination of a ship's hull generally occurred as a result of the ship traversing contaminated lagoons near the test site. The intensity of the radiation field vs. time was estimated for various deck levels and locations aboard ship and used to estimate a mean exposure to crew members when below deck relative to the degree of contamination. These ''apportionment factors,'' which varied with type and size of ship, were intended to account for differences in gamma exposure from hull contamination and from seawater in piping systems at different locations throughout the ship. NTPR apportionment factors were based on measurements aboard a variety of operational and target ships following specific tests and took into account three shipboard levels, with the highest exposure rate generally occurring at the lowest below-deck level aboard ship, which was below the waterline. Figure 6 illustrate the three levels assumed by NTPR and the change in exposure rate with distance from the hull and seawater piping[7]. The NTPR assigned all members of the crew the same mean exposure regardless of where they worked or were berthed, and it was necessary to adjust these factors based on rank, rate and rating of specific individuals. Our methodology adjusted the NTPR apportionment factors to account for the fact that there were typically more than three levels aboard ship and in some cases, such as on larger ships, personnel worked and were berthed several levels above the waterline (Fig. 5). This adjustment was made by dividing ships in the study into seven groups based on the vessel's beam (width at the widest point). Drawings were located for the different ship types to provide information about the levels above and below the waterline. The drawings also provided locations aboard ship for berthing compartments for officers, enlisted personnel, chiefs, and other military personnel stationed on transport or other specialty vessels. Once this information was known, the apportionment factor was adjusted to account for any location onboard ship depending on the ship type. This information, coupled with a person's rate, rating, or rank, gives a more realistic estimate of exposure. For example, a machinist's mate who stood watch in the engine room of a destroyer was assigned an apportionment factor of 0.5, while a signalman who worked several levels above the waterline had an apportionment factor of 0.02, meaning he received very little exposure from contaminated ship piping.

A correction was also made for gamma exposure from hull contamination in berthing quarters aboard ship. The enlisted crew, the chiefs and officers each had separate berthing. This correction can be important, especially when comparing berthing aboard a destroyer to that of a much larger ship such as a carrier or transport ship. Generally, exposure differential from seawater while sleeping on larger ships would have been small compared to that received on a destroyer; however, even within a destroyer, it is evident that the exposure while sleeping among officers, chiefs and the enlisted crew could vary significantly depending on proximity to contaminated hull and piping. On a destroyer, for example, officers and chiefs generally received only one-half as much exposure from contaminated hull and piping during berthing as did other personnel. Because NTPR also assumed all crew members were below deck for the same number of hours each day (generally 14–16 h, although it is likely many were below deck for 20 h per day or more), additional adjustments were made to reflect the actual fraction of the day spent below deck compared to topside. These adjustments for both time below deck and location ranged from ~0.4 to ~9 times the NTPR assigned dose.

Bias Correction for Exposure to Fallout on Residence Islands and Ships

The major source of exposure to most military participants at the PPG was from fallout on the various islands or ships where they were located during the test series. If valid film badge readings were available, they are used to estimate the dose for veterans for the period of time covered by the badge. If there were periods without film badge data, doses for the remaining exposure times are based on NTPR reconstructions.

The NTPR estimated exposure from fallout on residence islands and ships using measurements of exposure rate made by test personnel shortly after the fallout deposited. They estimated the mean total (integral) exposure by correcting for decay and applying an estimated shielding correction for the fraction of the day the average veteran might have spent indoors (e.g., partially shielded by tents or buildings) or outdoors. This practice generally overestimates exposure because the assumed decay rate did not account for environmental weathering (the migration of activity deeper into the soil with time) or remediation (decontamination of areas around work sites). Furthermore, the mean exposure rate for an island or ship was often very uncertain, based on only a limited number of measurements, and not necessarily

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[7] Seawater was used for firefighting and cleaning the exterior deck and was distributed through a main line running fore and aft aboard ship.

representative of the areas where veterans spent most of their time. For some islands and ships, the mean exposure rates in the hours immediately after the fallout were based on measurements at nearby islands or on ships in the lagoon rather than at the locations of interest.

Fortunately, for many tests series and some islands and ships, a significant fraction of personnel wore film badges during some or all of their exposure. The mean of the film badge data, adjusted for the times the badges were worn, provides a more accurate estimate of the actual mean total exposure and, thus, an estimate of the bias in the NTPR reported exposure. (In a few cases, as indicated in Table 4, the NTPR estimates of mean dose were actually low rather than high.) This adjustment for systematic bias in the mean exposure ranges between ~0.5 to ~6 times the NTPR assigned dose.

The variance estimated from these data provides an estimate of the total uncertainty in any individual's total exposure as discussed below in the Accounting for Uncertainty section.

Bias and Error Corrections for Exposure to Test Observers and Maneuver Participants

For most of the participants at the NTS, the main sources of radiation exposure were either from observing tests or from participating in military exercises after a test. In both cases, the NTPR dose was based on a combination of models simulating troop location as a function of time and survey measurements made immediately after the test. For observers, exposure was primarily from visiting displays of equipment placed in the vicinity of the blast in the first few hours after the detonation. Prompt radiation[8] was also a factor for some shots. In the case of the maneuver troops in BCTs, most of the exposure was from conducting the maneuvers in the fallout field immediately after the detonation and subsequently visiting equipment display areas. In some cases, troops received exposure during rehearsal maneuvers as a result of residual contamination of soil by radionuclides deposited from earlier shots.

We located film badge data for a number of units and used these data to estimate any bias as well as to improve estimates of individual variability in exposure within a particular unit. For the example scenario described earlier, we determined that the dose estimates in NuTRIS overestimate the dose to forward elements of BCT B by around 25%, and overestimate the median dose to any member of BCT B by almost a factor of 2 (Table 3). Thus, although the amount of NTPR high-siding in these doses was generally small, there were errors in individual doses due to NTPR assuming an individual's participation at tests when the probability of actual participation was low and due to biases resulting from assuming all members of a battalion combat team received the same exposure as the maximum exposed troops (generally those at the front of the column).

ACCOUNTING FOR UNCERTAINTY

A key component of dose estimation is the uncertainty. Our methodology separates uncertainty into two fundamental areas: uncertainty associated with defining the scenario of exposure and uncertainty in the dose for the given scenario. This section describes steps taken to account for uncertainty.

Scenario Uncertainty

Scenario uncertainty represents the degree to which an individual's location, responsibilities and activities at a specific time are known. This uncertainty was first addressed separately in a qualitative manner for each potential source of exposure using the following three categories:

- A: Individual's activities and duties are well known, or potential dose for the individual clearly falls below the dose reference level for the study, described above.
- B: Individual's activities and duties are less well known, but some aspects can be inferred from other information to estimate the probability of actually being exposed.
- C: Individual could possibly have been exposed, but very little to nothing is known about the individual's activities and duties and, thus, very little can be inferred about the probability of actually being exposed.

These three categories of uncertainty are quantified by assigning estimated probabilities to the likelihood that each exposure occurred. This is discussed in more detail later in this section.

Individual Variability in Exposures

The uncertainty in an individual's dose depends both on the uncertainty in the mean exposure corrected for NTPR bias, as discussed earlier, but also on uncertainty due to individual variability. Any individual's dose will vary about the assigned mean dose, for example, due to differences between an individual's time spent shielded while indoors or below deck, spatial differences in exposure rates, and differences in specific duties within the unit. In some cases, as discussed earlier for hull contamination exposure, we can remove some of this uncertainty by applying corrections based on a crew member's rating and rank. For most cases, all members of a unit are assigned the same mean dose for a given activity. In these cases, because we have no precise information on the actual location and specific duties of an individual crew member on an island or ship, it is important to include this variability as part of the total uncertainty in the veteran's exposure. The coefficient of variance based on film badge readings on ships and islands varied from as little as 20% to as much as 70–80%.

Thus, for each source of exposure, the uncertainty in the exposure, assuming such exposure actually occurred, has been estimated either from the mean and the dispersion in available film data if sufficient film data are available, from NTPR model calculations or both. Of particular help is a recent initiative by NTPR to revise its previous high-sided uncertainty estimates for many scenarios to carry out unbiased stochastic estimates of total uncertainty (*37*). These stochastic estimates of uncertainty generally confirmed that most NTPR point estimates of upper-bound doses from external radiation exposure (95% CI) were less than about a factor of 3 above the estimated ''unbiased'' mean dose.

Probability of Participating in Specific Activities

The NTPR generally assigned all individuals who could have participated in a particular activity a dose based on

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[8] Prompt radiation is composed of gamma rays and neutrons that occur immediately following detonation. This source of exposure differs from residual radiation arising from fallout, contaminated soil, or other debris following the shot.

TABLE 5
Probability of at Least One Boarding by Rank and Rating using Data from Seven Ships[a]

Rank or rating	Overall probability of boarding
CAPT (Captain)	0.67
LCDR (Lieutenant commander)	0.43
LT (Lieutenant)	0.08
LT(jg) (Lieutenant junior grade)	0.26
ENS (Ensign)	0.26
BM (Boatswain's mate)	0.29
EM (Electrician's mate)	0.32
F (Fireman)	0.08
GM (Gunner's mate)	0.29
MM (Machinist's mate)	0.30
RM (Radioman)	0.57
S (Seaman)	0.06
SF (Shipfitter)	0.53
SM (Signalman)	0.06
WT (Water tender)	0.26
CM (Carpenter's mate)	0.75
PhM (Pharmacist's mate)	1.00
FC (Firecontrolman)	0.25
QM (Quartermaster)	0.25

[a] Data were taken from the ships logs in which details of boardings provided information about specific individuals who boarded at least one time, the number of persons assigned to each ship of a particular rank and rate.

having participated, even if the probability of their participation was low. Examples are observing a particular shot at NTS, operating a small boat in contaminated water, boarding a target ship or participating in rest and recreation on an island. This often resulted in a significant overestimate in the dose to some cohort members.

As described in our example above for the PPG, some target ships were reboarded, usually by their original crews, for repairs, decontamination or the retrieval of salvageable items. This activity could result in significant exposures. In some cases, as with the USS CATRON, the ship's log (Fig. 3) notes which crew members participated in these boarding parties, along with the time a boarding party embarked and when it disembarked the target ship. In other cases, the ship's log notes a boarding party embarked but does not provide details about who participated. Knowledge about which crew members were most likely to reboard target ships is a key to estimating uncertainty.

The probability of participating in any particular reboarding can be estimated by knowing the rank and rating of veterans who participated and the total number of these rank and ratings for the target ship crew. By combining available data from several types of ships, a general pattern emerged about which crew members were most likely to have participated in boarding parties and the probability of their boarding. Table 5 summarizes data taken from the logs of seven ships for which detailed data were recorded on the rank and rating of the crew members who participated in any boarding parties. It is important to note that the crew of these ships included many more ratings among the total complement. However, the ratings shown in Table 5 were typically those that participated in target ship boarding.

A similar approach was taken for calculating the probability of other activities. Based on all available data, the probability, P, of participation in a given activity is estimated, as is an uncertainty in this probability estimate. Often, the uncertainty in P can only be crudely estimated due to lack of actual data. This estimated probability of participation, P, is combined with the uncertainty in the exposure, if the exposure actually occurred, to estimate the unconditional uncertainty in exposure. For example, if the probability of boarding a target ship on a particular day was $P = 0.5$ and the uncertainty in the exposure, E, assuming it occurred, had a coefficient of variation of $\sim$0.35–0.40, the coefficient of variation in the assigned exposure ($0.5 * E$) would be $\sim$1.1.

Shared and Unshared Uncertainties

As for any estimate of risk based on dose for an epidemiological study, both the total uncertainty as well as the type of uncertainty are important (*38*). In particular, it is important to understand how much uncertainty is shared among individuals (*39*). An example of shared uncertainty would be the uncertainty that arises if a single dose estimate is assigned to all members of a BCT, since any error in the models and measurements used to calculate the estimate would be the same for all exposed. If a model overestimates the average dose by 50%, everyone's dose would be overestimated by an average of 50%. In contrast, the uncertainty in dose to two individuals exposed to fallout at different test series is unshared (uncorrelated) since the doses are based on completely different sets of measurements. Note that shared uncertainty, when present, can coexist with unshared uncertainties. Continuing the BCT example, each member of a BCT had a certain probability of being absent from his unit's maneuver following a test detonation, and it is plausible that one person's absence was unrelated to the absence of anyone else in his unit. Similarly each person's actual dose coefficient for a given organ differs from the mean value by an unknown amount, which is independent of everyone else's dose coefficient.

Consideration of classical (measurement) error as opposed to Berkson-type error is also important since classical-type errors can result in a reduction of the slope of the dose-response curve while unshared Berkson-type errors will not *(38, 39)*. Our initial review of shared and unshared uncertainty in this study suggests there is, in the aggregate, relatively little shared uncertainty among members of the study group. This finding is based largely on the small number of study participants who served in the same unit at the same time and who were assigned a dose based on the same measurements. Most of the unshared uncertainty for members of the same unit is Berkson-type error. For example, although the same dose due to fallout is assigned to all unbadged personnel present on Enewetak

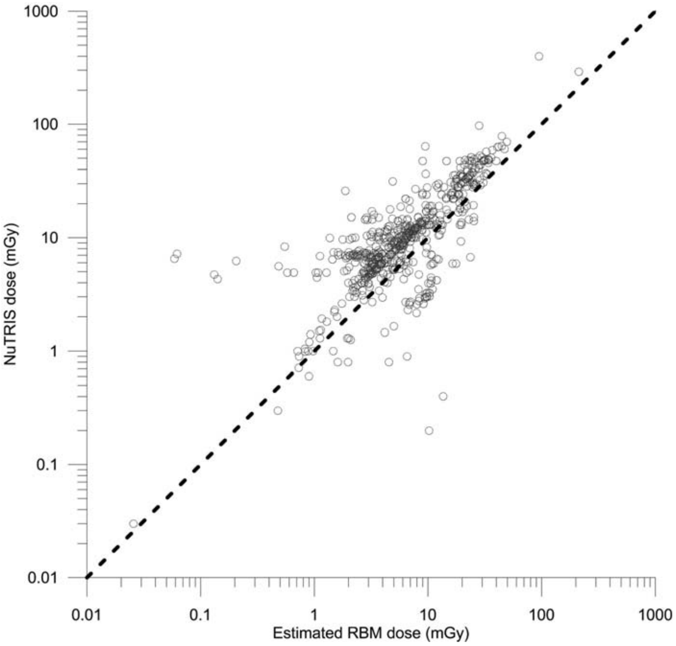

FIG. 7. Comparison of the doses reported in NuTRIS with those estimated in this study. Doses identified as clearly less than 5 mGy are not shown since the estimated dose is the same as the NuTRIS dose. The dose from external exposure to gamma radiation in this study is very close to the dose for whole body exposure in NuTRIS because of the penetrating power of the fallout gamma radiation and the fact that red bone marrow is distributed throughout the body, albeit not uniformly.

Island for a given time period, based on the mean of available film badge data for those badged, the uncertainty in any individual's ''true'' dose is due primarily to individual variations about this mean from variations in shielding (time indoors), location and specific duties. The uncertainty in the mean itself, while shared classical type uncertainty, is usually small compared to the variability about the mean. However, the actual degree of shared uncertainty will be considered in the final epidemiological analysis and discussed in the publication of that analysis.

Total Organ Dose

The total radiation exposures from all sources are combined in the dose calculation spreadsheet, and the total associated uncertainty is also computed by combining the unconditional variances for all the individual's sources of exposure. The sum of all free-in-air exposures is then multiplied by a dose coefficient that converts the estimate of total exposure to organ dose, in this case to dose to red bone marrow (6.6 mGy R^{-1}) or male breast (7.9 mGy R^{-1}). Although a rotational incidence is generally more representative than an isotropic or other angular distribution (*38*) because the angular incidence will differ depending on activity and location (ship compared to land), values between rotational and isotropic have been adopted with a bias more toward the rotational (*40–42*). The conversion factors for converting from exposure to organ dose are assumed to have an uncertainty with GSD = 1.2 which is due mainly to individual variations in actual angular incidence, in body and organ size and in energy spectra of the incident gamma radiation.

RESULTS

This article has focused on the methods being used to estimate doses and uncertainties to a sub-cohort of 1,857 veterans known to have served during the Eight Series of atmospheric nuclear tests. To date, ~80% of the 1,857 members of our sub-cohort have been reviewed, scenarios of exposure have been developed, and initial doses and scenario uncertainties assigned. Results to date provide insight into the validity of our methodology and how doses calculated with this customized methodology compare with doses used for compensation purposes.

A key finding to date is shown in Fig. 7, which compares doses reported in NuTRIS with doses estimated in this study. It is clear from Fig. 7 that the NuTRIS doses are consistently higher than our estimates, which was not unexpected considering the conservatism built into the process of assigning doses for compensation purposes. This comparison reflects not only the removal of bias from the NTPR models, but also corrections based on the methodology discussed in this paper. Some doses reported in NuTRIS were found to be incorrect for various reasons, including use of data from clearly damaged film badges, assignment of nonrepresentative cohort badge doses and mistakes during data entry[9]. The difference between the NTPR doses and those from this study is generally greatest for the lower doses since minor adjustments to already low doses can have a large relative impact. Corrections for bias and errors in NTPR-estimated doses reduced doses by as much as 90–100% for specific sources of exposure. On average NTPR dose estimates greater than 5 mGy were about 40% higher than our estimates, with about one-third of the NTPR estimates being more than a factor of 2 too high. The number of doses requiring little adjustment (i.e., doses from this study within 10% of the NTPR dose) is relatively small at about 7% of the estimated doses (56 out of 774 total doses estimated).

Approximately two-thirds of the participants whose doses have been calculated received a total dose to red bone marrow of < 5 mGy. Estimates of uncertainty generally range from a GSD of approximately 1.3–1.4 to, in some instances, more than 5. Most of the higher doses were based on film badge data, however, and the resulting uncertainties in estimated dose were generally lower, with GSDs < 1.3 (*25*).

Lack of knowledge about an individual's participation (or not) in a high-dose activity is the source of the largest uncertainty in our dose estimates. Unlike some of the NTPR

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[9] For example, a 90 mGy NuTRIS dose was due to the same 45 mGy dose being counted twice.

analyses for claims, where the individual could sometimes be interviewed and information on his scenario could be better ascertained, information about a specific individual's actual activity was seldom available. Thus, the exposure scenario had to be based solely on the activity of the veteran's unit or, in some situations, other individuals in the unit for whom specific information is available.

DISCUSSION

This article describes the detailed methodology being used to reconstruct doses to military veterans exposed during atmospheric testing of nuclear weapons by the United States. The current work takes advantage of the wealth of information produced in the NTPR program to estimate doses to specific veterans for the purpose of epidemiological analysis. Until recently, the historical records needed to undertake these detailed dose reconstructions were not available in digitized format nor made accessible to researchers.

A key contribution of this project has been the development of a methodology to characterize detailed exposure scenarios for any specific veteran. This work, with epidemiology as its endpoint, has required a detailed investigation of the likely activities of individual veterans to make estimates of their doses. The exposure scenario methodology, which comprises an essential component of the dosimetry, has provided a significant contribution to our understanding of the unique exposure circumstances encountered by these veterans and the likelihood that any individual participated in activities that resulted in their exposure. Previously, such detailed evaluations had only been completed for a small number of veterans filing a compensation claim. Thus, the extent and magnitude of conservatism of estimated doses to veterans for the purpose of compensation had not been quantified for a wide range of exposure conditions. Understanding the degree of overestimation of dose is an important finding not only to veterans themselves, but also to policy makers who may design and implement compensation programs in similar situations.

The methodology described in this article is being documented not only to explain the methods being used in this research focusing on military veterans exposed historically, but also to assist researchers and decision makers in the future who may be involved in similar types of environmental exposures.

Our final estimates of dose and uncertainty will be used with the epidemiological data to perform risk analyses for leukemia and male breast cancer mortality among our subcohort and the cohort as a whole. Because of the case-cohort design of this study, investigation of additional diseases can be carried out more efficiently using the fundamental methodology reported here. Additional publications will follow that focus on uncertainty, dosimetry results, and epidemiology.

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