Paper

HISTORY OF DOSE, RISK, AND COMPENSATION ASSESSMENTS FOR US VETERANS OF THE 1966 PLUTONIUM CLEANUP IN PALOMARES, SPAIN

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Abstract—In 1966, about 1,600 US military men—mostly Air Force—participated in a cleanup of plutonium dispersed from two nuclear bombs in Palomares, Spain. As a base for future analyses, we provide a history of the Palomares incident, including the dosimetry and risk analyses carried out to date and the compensation assessments made for veterans. By law, compensation for illnesses attributed to ionizing radiation is based on maximum estimated doses and standard risk coefficients, with considerable benefit of the doubt given to claimants when there is uncertainty. In the Palomares case, alpha activity in urine fell far faster than predicted by plutonium biokinetic excretion models used at the time. Most of the measurements were taken on-site but were disqualified on the grounds that they were "unreasonably high" and because there was a possibility of environmental contamination. Until the end of 2013, the Air Force used low dose estimates derived from environmental measurements carried out well after the cleanup. After these estimates were questioned by Congress, the Air Force adopted higher dose estimates based on plutonium concentration measurements in urine samples collected from 26 veterans after they left Palomares. The Air Force assumed that all other cleanup veterans received lower doses and therefore assigned to them maximum organ doses based on the individual among the 26 with the lowest urine measurements. These resulting maximum organ doses appear to be sufficient to justify compensation to all Palomares veterans with lung and bone cancer and early-onset liver cancer and leukemia but not other radiogenic cancers. Health Phys. 117(6):625–636; 2019

INTRODUCTION

ON 17 January 1966, a US bomber on airborne alert collided with its refueling tanker and three US thermonuclear bombs fell in the Mediterranean village of Palomares, Spain. In two of the bombs, the chemical explosives detonated and dispersed plutonium in a fine dust containing plutonium oxides.

About 1,600 US military personnel—mostly Air Force but including 107 Army, 37 Navy, and 38 other individuals—participated in the Palomares cleanup over a period of almost 3 mo (17 January to 11 April 1966). Most were assigned to work for a period of 2 wk, but some stayed for up to the entire 85 d duration of the cleanup.

These servicemen (we believe they were all men) were exposed via inhalation of airborne plutonium. In this paper, a history is provided of the Palomares incident, including the bioassays, dosimetry, and risk assessments carried out to date. Also covered are the compensation assessments made for veterans. Our intent is to provide a base on which future policy and scientific analyses can build. A natural next step would be to see if modifications to any conclusions would arise after a full uncertainty analysis and the use of the most recent International Commission on Radiological Protection (ICRP) biokinetic models, now being finalized for plutonium to appear in part 4 of the ICRP publication series on occupational intakes of radionuclides (OIR).[3]

Plutonium was inhaled as a result of "activities such as vehicle movement, handling debris during recovery, plowing fields to mix the contaminant into the soil, and vehicle movement. Persistent winds also contributed to the resuspension of contaminated soils from the ground or contaminated dusts

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from the surfaces of accident debris, local buildings, or agricultural crops" (Labat-Anderson 2001d).

Reportedly, 4,810 barrels were filled with contaminated soil and crops and shipped to the United States (Labat-Anderson 2001d).

The young men worked without protection against inhalation or ingestion of plutonium-contaminated particles. Wright Langham, the Los Alamos National Laboratory expert who advised on the protection of the men during the operation, later told his colleagues, "the manual says you will dress up in coveralls, booties, cover your hair, wear a respirator, wear gloves." He explained that none of that was done, however, because of concerns about alarming the local population (US DOE 1967). Further comments by Langham on this decision are reproduced in the supplemental digital content (SDC), Text S-1, http://links.lww.com/HP/A162.

A similar event occurred 2 y later in 1968 when another B-52 loaded with thermonuclear bombs crashed on the ice off of Thule, Greenland. This time, however, in the absence of a local population, a serious effort was made to protect personnel involved in the cleanup from plutonium inhalation and contamination (US SAC 1969). After this second accident, the US abandoned its policy of keeping nuclear-armed bombers in the air at all times (US DOD undated).

Upon departure from the Palomares cleanup, each of the men provided a urine sample that was shipped for analysis to the Air Force's Radiological Health Laboratory at the Wright-Patterson Air Force Base in Ohio (Odland et al. 1968). Virtually all of the assays of these samples collected on-site were done on the basis of gross alpha counts. Questions were raised about possible contamination, however, and these assays were later dismissed (Labat-Anderson 2001d).

After the cleanup personnel had left the site, additional urine samples were obtained from some of them, and measurements of their ^{239}Pu urine excretion rates were obtained using alpha spectrometry for 422 of them. Of these, 26 were selected as the highest exposed in this group and were requested to provide at least three additional urine samples over a period of almost 2 y after the accident (Odland et al. 1968). "Alpha spectrometry methods for detecting ^{239}Pu were very much at the developmental stage for most of 1966," however, and a later review questioned the quality of the measurements obtained for most of the 422 (Labat-Anderson 2001d).

A question considered was what to do with the results. The Air Force established a Plutonium Deposition Registry Board (PDRB) with representatives from all military branches to advise it on follow-up. That group met once, in October 1966, and opinion was split by service branch as to whether or not estimates of plutonium body burdens should be entered into the medical records of the veterans. It was decided to send the data "to the appropriate [service] Surgeon General for deposition and recording, as he saw fit" (PDRB 1966).

A key part of assessing risk from radiation exposure is to make a best estimate of the doses, but doing so is an uncertain business. Compensation of veterans, therefore, has evolved to include giving them the benefit of the doubt. Uncertainty analysis becomes critical. As will be seen, however, no uncertainty analysis has been provided for the estimated exposures of the Palomares veterans.

Some of the veterans of the cleanup have developed cancers and other conditions they attribute to their plutonium exposure and some have applied for benefits. A June 2016 *New York Times* article 50 y after the event described the frustrations of a group of Palomares Air Force veterans in their efforts to obtain Department of Veterans Affairs (VA) assistance for health problems they attributed to their participation in the cleanup 50 y earlier (Philipps 2016).

Basis for determining veterans' compensation

From the start of the effort to assess the doses the servicemen had received, there was recognition of the possibility of future requests for compensation: "Considerable discussion centered around the possibility of inciting undue concern in these individuals, perhaps to the point of legal action for compensation. However, this was realized, and a certain probability of risk had to be accepted if any follow-up program was to be pursued" (PDRB 1966, p. 24).

Today, a US veteran can go directly to the Department of Veterans Affairs to seek compensation.

Establishing whether or not veterans or their survivors are entitled to benefits is a two-step process laid out in Title 38 of the Code of Federal Regulations (CFR), §3.311, Claims based on exposure to ionizing radiation (US Dept of VA 2018):

1. The veteran's disease must be "radiogenic," i.e., have been shown by epidemiologic data to be caused by ionizing radiation; and
2. Since the probability of ionizing radiation causing a radiogenic disease increases with dose, the veteran must have received a large enough dose so that "it is at least as likely as not the veteran's disease resulted from exposure to radiation in service."

The dependence of risk on dose (D) is usually measured by relative risk $RR(D)$, the factor by which the risk of a radiogenic disease is increased over the baseline in the absence of radiation exposure beyond that received by a comparable unexposed population. An alternative measure is excess relative risk, $RR - 1$. For compensation purposes, the likelihood criterion in 38 CFR 3.311 is interpreted as

$$\frac{[RR(D)-1]}{RR(D)} \geq 0.5. \tag{1}$$

Because the left-hand side of the equation is a valid probability only for a simple cancer model (Beyea and Greenland 1999), it is today formally called an assigned share (AS) with

the historical designation, probability of causation (PC), kept for continuity with earlier literature (US DHHS 2003).

Calculations of the assigned share/probability of causation. The National Institute for Occupational Safety and Health (NIOSH) has established a website where the AS/PC can be calculated using the interactive radioepidemiological program (IREP) (Kocher et al. 2008; ORCRA 2018). Excess risk for 19 cancers known to be radiogenic can be calculated as a function of estimated organ dose and converted into the AS/PC using the IREP program's online calculator. Specific inputs include claimant's ages at exposure and diagnosis, and smoking status. Risk coefficients have been determined as a function of these covariates from multivariate regression analyses of epidemiological data, primarily data from the atomic bomb survivors in Japan.

It is the VA that uses the NIOSH IREP when a veteran makes a claim. In principle, however, on appeal, a veteran can submit an expert report with calculations made with different assumptions.

Handling uncertainty in the relationship between a dose and disease is a key element of IREP. Under VA rules, the 50% criterion need be met only in the upper 99% credibility interval of the overall uncertainty (ORCRA 2005). The range of uncertainty of the AS/PCs calculated by IREP can be performed for a single (e.g., maximum) dose or for a range of doses if the uncertainty in dose can be expressed in terms of a standard statistical distribution.

Establishing the organ doses a veteran received and their uncertainty ranges is therefore critical to the determination of eligibility for benefits. When the dose is uncertain, 38 CFR 3.311 again gives the veteran the benefit of the doubt: "When dose estimates provided pursuant to paragraph (a)(2) of this section are reported as a range of doses to which a veteran may have been exposed, exposure at the highest level of the dose range reported will be presumed" (US Dept of VA 2018).

The VA sets the dose range. On appeal, however, claimants can introduce their own expert opinion for both dose and uncertainty. As will be seen below, the dose estimates that have been provided by the Air Force to the VA for the Palomares veterans are extremely uncertain and, in many cases, the maximum end of the uncertain range appears to have been seriously underestimated.

MATERIALS AND METHODS

Documentation

Air Force and VA documents relating to the Palomares dosimetry and compensation decisions include PDRB 1966; USDOE 1967; AFLC 1968; Odland et al. 1968; Place et al. 1975; Maydew and Bush 1997; Labat-Anderson 2001b and d; Ashworth 2013; USAF 2014; and BVA 2017.

Software calculations

Estimates of assigned share (probability of causation) for a sample of veterans were made using the NIOSH online IREP (Kocher et al. 2008; ORCRA 2018).

Units

To facilitate comparison with the historical literature, curie units are included in parenthesis in the text and on certain figure axes. All doses are organ doses, unless otherwise indicated.

RESULTS AND DISCUSSION

Initial estimates of systemic body burdens

Langham formula. The original estimates for intake of plutonium for each of the 1,600 participants in the Palomares cleanup were based on the on-site, urine excretion data and a formula devised by Wright Langham to relate excretion rates of plutonium in urine samples with systemic body burden, not including lung burden (Langham 1956; Odland et al. 1968).[4]

$$A_L = 435 \times M(t) \times t^{0.78}. \qquad (2)$$

Here A_L is the initial body burden (i.e., activity [A] using the Langham [L] equation). A_L was often listed for veterans as a fraction of a "maximum permissible body burden" (MPBB), which at the time was an intake of 1.6 kBq (44 nCi) (Labat-Anderson 2001d). $M(t)$ is the amount excreted daily in urine at time t, with t measured in days. A_L and $M(t)$ have consistent units, so that if $M(t)$ is given in terms of Bq d^{-1}, A_L has units of Bq (Langham 1963).

The formula applies if the exposure happens during a short period around $t = 0$. The data was obtained from human injection experiments coordinated by Langham (McCally et al. 1994; Moss and Eckhardt 1995). Intramuscular and intravenous injections were used to establish resulting tissue distribution patterns (Langham 1963). The Langham formula does not account for the addition to the circulatory system of inhaled plutonium from the lungs, so that a cleanup worker's body burden estimated by eqn (2) could be much less than the total intake that would be estimated by modern biokinetic models, especially for inhalation of insoluble particles. Some inhalation data on plutonium workers existed at the time, but this data was considered inconsistent by Langham (Langham 1963). Only eqn (2) was used to assess burden at Palomares, although at times Langham multiplied his results by a factor of 10 to estimate lung burdens, based on animal experiments (Eakins and Morgan 1964).

Use of the Langham formula

In the dosimetry estimates for the Palomares cleanup veterans, inhalation was assumed to be the dominant route of intake, based on the fact that the absorption fraction from the gut is very low (Langham 1963; Harrison 1991). Using

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[4]The t exponent is sometimes given as 0.76 or 0.77.

the Langham formula, the Air Force's Radiological Health Laboratory concluded that of 1,586 urine samples taken on-site, 20 indicated body burdens larger than the then-specified MPBB, and 422 indicated between 9% and 99% of the MPBB (Odland et al. 1968). Later, off-site urine samples were sought from those whose on-site samples indicated 10% of the MPBB or more. The off-site measurements resulted in much lower estimates, however. Of the 422 cleanup veterans whose off-site samples were remeasured, only 6 were classified as having inhaled more than 10% of the MPBB (Odland et al. 1968).

Of the 422 individuals, 26 of them (the "High 26") were asked to provide three additional urine samples over a period of about 18 mo. Of these, the highest plutonium excretion rate in the first follow-on measurements corresponded to 34% of the MPBB, implying a maximum intake of 550 Bq (15 nCi) using the Langham formula. The highest of the second follow-on measurements corresponded to 10% of the MPBB, and by the time the third follow-on measurements were taken, the plutonium excretion levels had fallen, with a few exceptions, below the Air Force's assigned but not published limit of detectability for alpha spectrometry (Odland et al. 1968).

Thus, the urinary excretion rates of the High 26 dropped much more rapidly than predicted by Langham's formula, raising questions about the validity of the formula and/or the urine data. The same inconsistency arises with biokinetic excretion models in use in 2001, the last year that anyone has published fits to Palomares data (Fig. 1).

Fig. 1, which is reprinted from the Labat-Anderson report (Labat-Anderson 2001d), shows the excretion measurements for the High 26 along with four model excretion rate curves for the inhalation of various quantities of soluble and insoluble forms of [239]Pu, as calculated by Labat-Anderson using the CINDY biokinetic model, which would be considered outdated today. The lowest excretion curve corresponds to inhalation of 560 Bq (15 nCi) of insoluble plutonium (type S). The two highest curves correspond to inhaling 560 Bq (15 nCi) of soluble [239]Pu (type M) with and without the addition of 185 Bq (5 nCi) of the insoluble form. The middle curve is for 185 Bq (5 nCi) of insoluble plutonium plus 185 Bq (5 nCi) of soluble plutonium. None of the curves are consistent with the time course of the grouped excretion measurements.

The question of contamination of the on-site urine samples. Most of the urine samples obtained from the cleanup workers were collected on-site just before the men left the cleanup project (Odland et al. 1968). Most of the samples obtained thereafter were collected at the men's subsequent locations.

In the first recorded discussion of the samples, it was asserted that the on-site samples were contaminated and that plutonium body burdens calculated from them were therefore suspect. This provided the initial justification for collection of follow-on off-site samples (PDRB 1966). In the first published analysis (Odland et al. 1968), it was reported that "opportunities for sample contamination were numerous. Strong winds spread dust over a wide area, including the base camp, troops did not always follow decontamination procedures, initial samples were collected in makeshift containers, and when more acceptable ones became
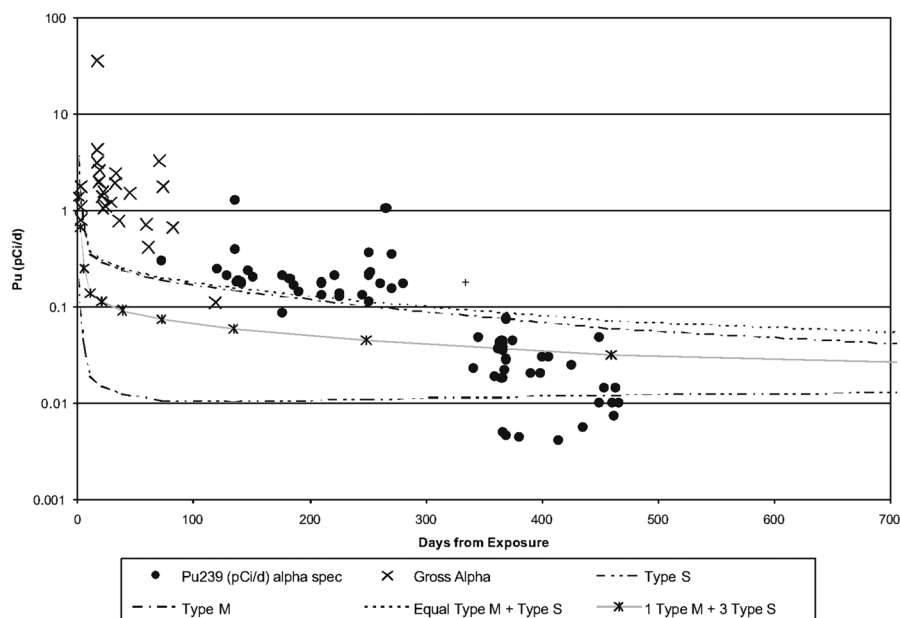
Fig. 1. Measured excretion rates for the High 26, reproduced from Fig. E-2 of Labat-Anderson (2001d). The X symbols indicate gross alpha measurements for urine samples collected on-site. The solid circles correspond to alpha spectrometry measurements for samples mostly collected off-site. They are grouped roughly according to the first and second samples taken. Nondetects are included in SDC Fig. S-1, http://links.lww.com/HP/A162.

available, their storage in a dust-free environment was not always possible."

There are no reports, however, of attempts to estimate the magnitude of the contamination, its variance, or the contribution it might have made to the body burdens.

Contamination by naturally occurring alpha emitters in the decay chains of uranium and thorium also is possible. Typical values of background alpha activity in urine have been reported by Perkin Elmer as 1.3–23 mBq L^{-1} (0.053 to 0.93 pCi d^{-1}), assuming 1.5 L of urine per day (Eikenberg et al. 2011). The analysts apparently considered this possibility at the time (Labat-Anderson 2001d). A few tens of the on-site samples were remeasured for ^{239}Pu using alpha spectrometry (Labat-Anderson 2001d). Although apparently looked for, no alpha emitters other than plutonium were reported (Labat-Anderson 2001d). The ^{239}Pu alpha measurements of the samples taken on-site were generally lower than the gross alpha results, however (Labat-Anderson 2001d).

Dose estimates by Labat-Anderson

Perhaps in response to claims for benefits, the Air Force contracted with the firm Labat-Anderson, Inc., to estimate the doses received by the Palomares veterans. Labat-Anderson was described in media reports as specialized in risk assessment (Bloomberg 2019) and in "litigation support and information services" (Hubler 2009).

The Labat-Anderson analysis published by the Air Force in April 2001 is labeled "revised" (Labat-Anderson 2001d). Neither its authors nor its reviewers are listed. It is indicated in an appendix (Labat-Anderson 2001d) that one of the unnamed authors had been director of radioanalysis at the US Air Force Radiological Health Laboratory from 1969 to 1976.

It has not been possible to seek additional information from Labat-Anderson because the company no longer exists. It was bought in 2009 by US Investigation Services (USIS), which went bankrupt in 2015 after a massive data breach and settlement of a claim of fraud by the US government (Associated Press 2014; HSN 2015).

As discussed below, Labat-Anderson carried out detailed analyses of the urine excretion data. Its report concluded, however, that the results were "unrealistically high when compared with estimates prepared for other plutonium exposure cases—persons residing in the Palomares vicinity and Manhattan Project workers" (Labat-Anderson 2001d).

No explanation was given for why the exposures of Manhattan Project workers should have been comparable to those of the veterans of the Palomares cleanup, but Labat-Anderson did develop alternative dose estimates based on environmental measurements of airborne plutonium around Palomares *after* the cleanup. The environmental estimate takes up less than two pages in the massive Labat-Anderson report.

Until late 2013, however, the Air Force based its benefit recommendations for Palomares cleanup veterans on Labat-Anderson's environmental dose estimate.

Environmental dose estimate. Labat-Anderson's environmental dose estimate was based on data taken by air-sampling stations set up after the cleanup at four locations around and in Palomares to make certain that the resident population was not being exposed to dangerous levels of wind-blown plutonium. The nearest station was about 0.5 km from the impact site of one of the bombs. The three other stations were about 1 km away from the nearest impact site. Measurements were taken starting in June 1966, 2 mo after the cleanup ended (Iranzo et al. 1987).

Labat-Anderson estimated maximum plutonium inhalation of a hypothetical cleanup veteran who had worked 12 h d^{-1}, 6 d wk^{-1} for 11 wk in postcleanup Palomares. It assumed that during that period, the veteran would have been exposed to the highest 10 d value of the *postcleanup* plutonium resuspension factor (10^{-7} m^{-1}) for an area contaminated with ^{239}Pu at a concentration of 1.18 MBq m^{-2} (Labat-Anderson 2001d). The resuspension factor is the ratio of the concentration of plutonium in the air above the ground, measured in Bq m^{-3}, to the contamination level of the ground, measured in Bq m^{-2}.

The maximum organ-weighted committed effective dose equivalent (CEDE) calculated in this way was 0.0031 Sv.

There are a number of reasons to question this estimate, however.

1. Dust generated by shoveling contaminated soil and vegetation into barrels, by deep-plowing fields, and by movement of trucks and other machinery across fields during the cleanup could have caused much more resuspension of particles than the wind.

2. It is well known that resuspension factors decline rapidly with time (Maxwell and Anspaugh 2011). The maximum resuspension coefficient of 10^{-7} quoted by Labat-Anderson for Palomares was measured 6 mo after the accident (Iranzo et al. 1994). This is consistent with measurements made 6 mo after the Chernobyl release, but measurements of resuspension coefficients immediately after the Chernobyl accident were 2 orders of magnitude higher (Garger et al. 1997).

3. The cleanup effort deliberately attempted to reduce the wind resuspension factor by deep-plowing fields that had been contaminated. The purpose was to redistribute surface plutonium through the top 30 cm of the soil and thereby make most of it inaccessible to the wind.

4. The land contamination level of 1.18 MBq m^{-2} assumed by Labat-Anderson was the level below which cleanup was deemed unnecessary—much less than the contamination levels in the areas where the cleanup took place (Iranzo et al. 1987).

Labat-Anderson recommendations for further analysis. The authors of the Labat-Anderson report were aware of the weaknesses of both the "unrealistically high" dose estimates based on plutonium levels in the servicemen's urine and the very uncertain estimate based on a hypothetical exposure to wind-blown plutonium. They acknowledged their inability to explain the great difference between these estimates. They therefore recommended that "additional effort is needed to reconcile the estimated intakes and doses derived from the urinary bioassay data with the estimates from environmental measurements. A targeted effort that includes participant activities, participant interviews, urine and other appropriate plutonium analyses using current techniques, medical records review, and modeling should be considered…" (Labat-Anderson 2001d).

Another factor Labat-Anderson could have mentioned for consideration was day-to-day variability in urine excretion, the so-called (urine bioassay) scattering factor (Castellani et al. 2013).

Initial Air Force guidance on doses, 2002

The Air Force did not, however, commission additional studies and opted to use the lower environmental dose estimate. The Air Force surgeon general issued a press release stating that "re-evaluations, using modern modeling methods, confirmed original conclusions that the exposures were not significant. …The Palomares report found that the ability to reconstruct doses from urinalysis was confounded by poor data quality, mostly as a result of sample contamination and limited analytical sensitivity. However, environmental (air) sampling data suggests that exposures were less than 500 mrem [0.005 Sv], 1/10 the current [annual] limit for radiation workers…" (AFMS 2002).

A maximum CEDE of 0.0031 Sv is also comparable to the estimated average annual global dose of 0.0024 Sv from natural background radiation, including from indoor radon (UNSCEAR 2000). Such a dose estimate, even accounting for somewhat higher individual organ doses, is too low to support a conclusion that a radiogenic illness was more likely than not due to plutonium inhaled during the Palomares cleanup.

Revised Air Force guidance, 2013

A decade later, Congress asked why the Air Force had not implemented the Labat-Anderson recommendations for additional studies (US Congress 2013). In response, the then Air Force surgeon general decided to change the recommended maximum dose estimates from the environmental estimate to doses obtained for the High 26 from the Labat-Anderson analyses of the urine data. He argued that "the follow-up biomonitoring [urine excretion] results obtained in 1967 provide a reasonable, yet conservative (worst case) exposure estimate for response personnel. Modeling methods currently available to perform dose reconstruction would not change the fundamental conclusions reached in

1968 that adverse acute health effects were neither expected or observed, and long-term risks for increased incidence of cancer to the bone, liver and lung were low. Biomonitoring today, though technically feasible, is not expected to confirm a correlation between health outcome and exposure due to the low exposure level. The Air Force is able to establish an upper bound on possible exposures for response personnel, based on the 'High 26' cohort (considered the highest exposed 26 individuals) using actual bio-monitoring results from a time close to the actual exposures and will apply this conservative approach in addressing requests from Veterans Affairs for exposure assessments. This revised conservative approach will afford the veteran with the benefit of the doubt as to level of exposure. Hence, we do not recommend additional, broad-scale, follow-up biomonitoring" (USAF 2013).

A simultaneous (6 December 2013) memo from the Air Force to the VA (Ashworth 2013) recommended the following procedure for assigning doses:

a. "Establish the veteran's presence at the incident site.
b. "Perform a review of duties based on historical records and statements provided by the veteran.
c. "Review available bioassay data for the veteran and assign an intake value.
   "(1) If the veteran is a member of the cohort with the highest exposure potential (designated as the 'High 26'), use their established intake estimates. The established intakes range from 34,000 to 570,000 picocuries (pCi) [1,260–21,000 Bq].
   "(2) For the remaining responders, define intake as 'does not exceed the intake calculated for the least exposed member of the High-26 group.' The intake range for this group will be conservatively set at 1,100 to 34,000 pCi [41–1,260 Bq].
d. "Estimate committed doses for the organ(s) of concern. The primary organs of concern from plutonium exposure are the lung, liver, and bone surface, based on International Commission on Radiological Protection (ICRP) Publication 30 (used by the Nuclear Regulatory Commission and Environmental Protection Agency) and ICRP Publication 68 (used by the Department of Energy and the Defense Threat Reduction Agency). We will provide both ICRP model results in responses to the VA.
e. "If the member does not have a valid urine sample, reconstruct the dose based on similar exposures using their specific duties, if possible. If that is not possible, consider having the member provide a urine sample for analysis using the latest analytical procedures that claim to eliminate or greatly reduce confounding factors such as radioactivity from natural or background sources."

Thus, unless measurements on new urine samples are carried out—an option raised as a possibility by Labat-Anderson

Table 1. Maximum organ dose estimates (Sv) recommended by the Air Force (USAF 2014) for compensation decisions for non-High 26 Palomares cleanup veterans, when based on a urine-excretion estimate of 1,300 Bq (34 nCi) of plutonium inhaled by the lowest exposed of the High 26 (Labat-Anderson 2001d).[a]

Organ	Dose estimates (Sv)			
	Labat-Anderson (2001d)	Air Force (2014) (using ICRP 30)[b]	Air Force (2014) (using ICRP 71)[c]	Recommendation in Air Force memo (2014)[d]
Lung	0.380	0.406	0.109	0.406
Bone surface	1.060	1.030	0.214	1.030
Liver	0.192	0.038	0.049	0.049
Red marrow[e]	0.081	0.083	0.011	NA[e]
Gonads/testes[e]	0.015	0.015	0.003	NA[e]
Committed effective dose equivalent	0.100	0.105	0.020	0.105[f]

[a]Labat-Anderson 2001d; USAF 2014. Intake of 1,300 Bq (34 nCi) using CINDY program was the lowest intake for the High 26, which serves as the maximum intake, and hence the intake for compensation purposes, for all Palomares veterans other than the High 26 (Ashworth 2013; USAF 2014).

[b]Based on ICRP Reports 26, 30, and 48, as indicated in the Air Force memo (USAF 2014). CINDY estimate was based on ICRP 30.

[c]Warning: uses dose coefficients from a biokinetic model that was developed later than the model (CINDY) used to generate the 1,300 Bq (34 nCi) plutonium intake, leading to an inconsistent dose estimate.

[d]The higher of the two Air Force columns.

[e]Not explicitly discussed in the memo text.

[f]Upper limit of range of Labat-Anderson's 0.0031 CEDE environmental estimate and the 0.105 CEDE from the second dose column.

and mentioned as a possibility in point (e) of the Air Force's advice above—the revised dose estimates are to be based on Labat-Anderson's 2001 estimates of the doses received by the High 26 group of veterans. The 98% of the Palomares cleanup veterans not in the High 26 are to be assigned a maximum dose equal to the lowest of the doses estimated for the High 26. Table 1 shows the Air Force's recommended estimates of the organ doses received by this individual.

Implications of the Air Force's 2013 guidance

As indicated in Table 2, basing plutonium inhalation estimates on maximum postcleanup environmental air measurements—as the Air Force recommended from 2002 through most of 2013—produces AS/PCs that are all well below 50% even at the 99% credibility level. On the other hand, lung and bone cancers among the Palomares survivors would be declared service related (AS/PC > 50%, at the 99th percentile) if the Labat-Anderson inhalation biokinetic dose estimates for the lowest of the High 26 are used, as recommended by the Air Force after 2013. Liver cancer reaches 50% for early diagnoses (before 1990) and comes close even for a late diagnosis at the 99+% credibility level. Although leukemia is not explicitly covered in the 2014 memo, based on the dose estimate given there for red marrow, the AS/PC for leukemias diagnosed in 1980 and earlier would also exceed 50% at the 99+% credibility level (ORCRA 2005). Additional details about the calculations

Table 2. Assigned share/probability of causation (AS/PC) obtained using the NIOSH IREP (ORCRA 2005) at the 99th percentile credibility level for maximum doses allowed for non-High 26 Palomares veterans, assumed to be male, born in 1946 and former smokers.[a]

Cancer type	Cancer onset by	Dose estimate before 2014, based on Labat-Anderson's maximum "environmental" exposure (Sv)[b]	AS/PC at 99+% credibility (%)	Dose estimate after 2013, based on Labat-Anderson's lowest Pu intake for High 26 (Sv)[c]	AS/PC at 99+% credibility (%)
Lung	2017	0.012	1.9	0.406	61
Bone	2017	0.030	11	1.03	80
Liver	1989[d]	0.0015	3.1	0.049	51
Liver	2017	0.0015	2.4	0.049	45
Leukemia	1980[d]	0.0024	2.3	0.081[e]	59
Leukemia	2017	0.0024	0.07	0.081[e]	2.4

[a]Exposure in 1966.

[b]Basis for guidance prior to 2014, based on estimates of resuspension intake. Values in Table 1 scaled by 0.31/10.5, the ratio of committed effective dose equivalents (USAF 2014).

[c]From Table 1.

[d]Only early onset cases will rise above 50% at 99th percentile credibility with an assigned dose of 0.049 Sv for liver and 0.081 Sv for leukemia.

[e]Not explicitly mentioned as an accepted maximum dose in Air Force memo (USAF 2014).

of assigned shares can be found in SDC Text S-2, http://links.lww.com/HP/A162.

Dose estimate uncertainties

The Air Force's maximum recommended dose estimates for all but 26 of the approximately 1,600 veterans are based on central values for three data urine measurements obtained off-site from a single veteran, including one nondetect that was assigned an ad hoc value of 0.11 mBq d^{-1} (0.003 pCi d^{-1}) (SDC Table S-1, http://links.lww.com/HP/A162). There is no recorded measurement of an on-site sample for this serviceman. A least-squares procedure was used to obtain the central value. No uncertainty range for intake or corresponding dose was assigned. Thus, no uncertainty in maximum dose can be included in compensation assessments using the NIOSH IREP. The uncertainty distribution for assigned share/probability of causation is therefore entirely due to uncertainties in the dose-cancer coefficient.

In addition to the data for the High 26, there are more than 1,000 other measurements, including at least one each for most of the 1,600 veterans. Most of these measurements were made on samples taken on-site, and the possibility of contamination has been raised. But, aside from noting that plutonium was detected on the outsides of some of the sample bottles, none of the analyses have attempted to establish how much the estimated doses could have been affected by contamination. In other cases, Labat-Anderson raised the possibility that laboratory errors could have affected the results. These observations support a conclusion that the measured doses are uncertain. Labat-Anderson's assessment of these doses is therefore reviewed below.

Labat-Anderson's assessment of dose using excretion measurements. Labat-Anderson reviewed and organized the available records of the 1,600 cleanup personnel. This information was then preserved in a massive Appendix C to its report (Labat-Anderson 2001a, b, c) that was only released in May 2018 with personal identifying information redacted as a result of a Freedom of Information Act request from a Yale Law School clinic working on an appeal on behalf of one of the cleanup veterans (YLC 2018). As discussed above, most of the urine samples collected within 100 d of the accident were taken in the field, and all but a few tens of those were measured only for gross alpha emissions. As noted above, concern was expressed about the accuracy of the on-site measurements due to detected contamination of the outsides of some of the sample bottles by wind-blown plutonium-contaminated dust.

Also, as already noted, 422 of the cleanup personnel had a repeat analysis recorded, a urine sample taken offsite and measured using alpha spectrometry (Odland et al. 1968). Labat-Anderson concluded, however, that, beyond the High 26 who were asked to provide additional samples, the measurement of off-site urine samples for only 31 additional veterans among the 422 (7%) produced "usable results" (Labat-Anderson 2001d)

"Other samples submitted did not produce usable results for several reasons. These reasons included laboratory errors during processing and chemical recoveries that were unreported, too low to be measured or below 40%.[5] This project established a minimum requirement for chemical recovery at 40% for alpha-spectrometry samples as a reasonable lower limit for credible results" (Labat-Anderson 2001d).

Chemical recovery percentages were determined by spiking the urine samples with 66 mBq of ^{236}Pu in an unreported chemical form (Odland et al. 1968b).

The problems that Labat-Anderson identified with the plutonium measurements were consistent with a contemporaneous evaluation: "It seems clear that in the field of low-level plutonium analysis the techniques are so exacting and the evaluation so difficult that it is common for the chemist to be unable to duplicate the work of others" (Nielsen and Beasley 1964).

On the other hand, the Air Force's Radiation Health Laboratory, which did the measurements, stated that "by use of split-sample techniques with other laboratories, we learned that our results compared favorably with theirs" (AFLC 1968).

No indication was given, however, as to the plutonium concentrations or the ^{236}Pu/^{239}Pu ratios in the split samples.

Reliability problems with plutonium were found at sites other than Palomares. Retrospective analysis of worker plutonium measurements from Britain's Sellafield plutonium separation center, carried out for epidemiology studies, found reliability problems for plutonium bioassays prior to the 1970s (Riddell 2011; Riddell et al. 2000). Assessments of dose made using early excretion measurements were thought to be high compared to assessments made with later excretion measurements. This expectation was based on the idea that plutonium exposures should follow contamination levels, which were building up over time. Apparently, the possibility that protection management was weaker in the early years was not considered an important contributing factor.

For the most recent Sellafield studies, in order to get robust estimates, dose assessments were produced only for individuals with five or more usable samples (Riddell 2011). This sample-size threshold matches the 2013 recommendation of a European consensus group (Castellani et al. 2013). Based on our extraction of data from Appendix C of the Labat-Anderson report, when nondetects were included in the totals, 19 of the High 26 had as many as five data points (SDC Table S-1, http://links.lww.com/HP/A162). When nondetects were excluded from the totals, only one of the 26 had five or more data points.

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[5] For the record, we note that contemporaneous documents indicated that all recoveries for the 422 were greater than 40%, with a range of 43–113% (Odland et al. 1968). On the other hand, Labat-Anderson did have access to the original lab cards and file notes for each veteran.

Contamination problems considered at Sellafield were of a different sort than those considered at Palomares: for instance, plating out of plutonium on the walls of the sample bottles and funnels occurred, "which was not removed by washing in water but which did re-dissolve in urine when these items were re-used."(Riddell 2011). Of course, the identification of potential problems does not mean the Palomares data are unusable; only that the uncertainties are larger than occur from alpha counting variations alone.

Assessment by groups of veterans. Given the different numbers of urine samples per serviceman and the different qualities of the measurements made on them, Labat-Anderson placed the veterans in four groups: High 26, repeat analysis, contamination cutoff, and remaining cases.

High 26 group. These were the primary focus of analysis because all had at least three off-site urine samples measured (Labat-Anderson 2001d). The on-site measurements were discarded and individual intake estimates were obtained by obtaining a best fit to theoretical excretion curves of the off-site urine excretion data points.

The on-site measurements were discarded both because they were "unreasonably high" and because there was a possibility of contamination (Labat-Anderson 2001d). Also, the fit to the predictions of the biokinetic models "tended to produce better fits for samples with lower values and taken at longer time following the exposure" (Labat-Anderson 2001d). This last rationale simply reflects that the theoretical excretion curve used by Labat-Anderson for inhaled plutonium oxide was almost flat starting 10 d after exposure (Fig. 1) while the excretion measurements fell by about an order of magnitude between the on-site urine samples and those taken off-site about 200 d after exposure, by another order of magnitude by about 400 d, and by another order of magnitude to below the limit of Labat-Anderson's assumed detectability by about 600 d (SDC Fig. S-1, http://links.lww.com/HP/A162). It is not surprising that a fit to a nearly flat theoretical curve gets better if early high data points are discarded. The fit would also have improved if the nondetects or other lower groups of late readings were removed.

After the on-site measurements were discarded, the estimated High 26 intakes ranged from 1,260 to 21,000 Bq (34 to 560 nCi) (Labat-Anderson 2001d). In its revised 2013 guidance, the Air Force chose the low end of this range

as the upper bound of the dose range for all the other cleanup veterans.

A historical note: Labat-Anderson's estimate of the highest intake for the High 26, assuming inhalation of insoluble particles, is some 37 times the 560 Bq (15 nCi) value estimated using the Langham formula for systemic body burden, which was largely based on lung-bypassing injections of plutonium. Those unfamiliar with these experiments carried out on hospital patients thought to have less than a 10 y life expectancy, in the days before informed consent was a requirement, can consult the references (McCally et al. 1994; Moss and Eckhardt 1995).

Repeat analysis group. This second group comprised 54 individuals not among the High 26 who had urine assays that passed the Labat-Anderson quality tests. Measurements of on-site samples were excluded unless they reported as no detectable activity (NDA), in which case they were assumed to be at the detection threshold. Also, "some alpha-spectrometry results that did not fit the expected urinary excretion pattern were excluded" (Labat-Anderson 2001d). The remaining measurements translated into estimated intakes ranging from 107 to 48,000 Bq (2.9–1,300 nCi). More than three-quarters of the estimated intakes (42) were higher than the lowest estimated intake for the High 26 (Labat-Anderson 2001d).

Contamination cutoff group. This group contained 313 individuals whose on-site measurements corresponded to plutonium excretion rates of less than 0. 0037 Bq d^{-1} (0.1 pCi d^{-1}). According to Labat-Anderson, this was approximately the lowest level that could be detected by the gross alpha counting techniques of the time (Labat-Anderson 2001d). Thirty individuals had more than one measurement. In these cases, Labat-Anderson discarded the higher measurement without explanation (Labat-Anderson 2001d). The resulting estimated intakes ranged from 56 to 5,600 Bq (1.5 to 150 nCi). A tally of the entries in the relevant table shows that almost half (143) were greater than the lowest estimated intake for the High 26 (Labat-Anderson 2001d).

Remaining cases group. This group contained 1,063 individuals, i.e., 73% of the 1,456 veterans who were assigned doses. All or virtually all their samples were taken on-site and Labat-Anderson concluded that "the possibility of contamination prevents useful evaluation of these data." It did report, however, that measured excretion data corresponded to intakes

Table 3. Labat-Anderson estimates of exposure range for different groups of veterans.

Group	Number of Palomares cleanup vets in group	Labat-Anderson plutonium inhalation estimate based on urinary excretion (Bq)	Ratio of inhalation estimate to lowest of the High 26
High 26	26	1,260 to 21,000	1 to 16
Repeat analysis	54	107 to 48,000	0.003 to 1.4
Contamination cutoff	313	56 to 5,600	0.0016 to 4.4
Remaining cases	1,063	2,800 to 740,000	2.2 to 590

ranging from 2,800 to 740,000 Bq (75 to 20,000 nCi) of ^{239}Pu (Labat-Anderson 2001d).

It will be seen from Table 3 that the lowest intake calculated for the remaining cases group is higher than the lowest intake calculated for the High 26, which, after 2013, the Air Force decided to use as the upper bound for the doses that would be assumed to have been received by the remainder of the 1,600 cleanup veterans. There are two potential explanations for this result. First, the estimated intake for a High 26 veteran is reduced by the existence of multiple data points used in the fits to urine excretion curves that are fairly flat over time. The later data points tend to be lower than the first alpha spectrometry measurements, thus bringing down the estimated intake. Second, there appears to be a contributing artifact due to the fact that the threshold measurement limit used for the gross alpha measurements of the on-site excretion rates were about 3 times higher than the threshold measurement limit assumed for the alpha spectrometry used for virtually all the samples taken off-site—0.009 pCi d^{-1} vs. 0.003 pCi d^{-1} (Labat-Anderson 2001d). These levels are much lower than plutonium detection thresholds reported elsewhere, however. The Air Force reported a detection limit of 19 mBq d^{-1} (0.5 pCi d^{-1}) for alpha spectrometry in connection with the similar accident that occurred near Greenland (Labat-Anderson 2001e). Other statements of detection limits associated with the Palomares accident include 0.37 mBq d^{-1} (0.01 pCi d^{-1}) (Iranzo and Richmond 1987) and 0.74 mBq d^{-1} (0.02 pCi d^{-1}) (Espinosa et al. 1998). Unstated was the extent to which any of these limits included process uncertainty as opposed to count rate uncertainty alone.

The High 26 group was thought to have had the highest plutonium excretion rates of 422 participants in the resampling program. As discussed above, this is debatable. The High 26 certainly did not have the highest measured excretion rates among the urine measurements collected on site. Based on our review of a spreadsheet printout of the on-site results (SDC Fig. S-2, http://links.lww.com/HP/A162), many readings of other veterans showed higher on-site plutonium excretion rates than many of the High 26 and some were higher than the highest of the High 26. Of the High 26, 18 had on-site readings above 1 pCi d^{-1} and 4 above 3 pCi d^{-1} (37 and 110 mBq d^{-1}, respectively). For the entire cohort, the spreadsheet printout shows 288 readings above 1 pCi d^{-1} (37 mBq d^{-1}) and 91 above 3 pCi d^{-1} (110 mBq d^{-1}), with a highest value of 124 pCi d^{-1} (4. 6 Bq d^{-1}). This is 3.5 times greater than the highest value of 35 shown for the High 26 on Fig. 1. The geometric mean for the 288 readings is 2.6 pCi d^{-1} (96 mBq d^{-1}), with an arithmetic mean of 5.4 pCi d^{-1} (200 mBq d^{-1}), while the geometric mean of the High 26 gross alpha readings is 3 pCi d^{-1} (110 mBq d^{-1}).

The fact that the High 26 did not have the highest among the on-site measurements is significant because as already noted, the Air Force has assigned to all veterans not among the High 26 the organ doses estimated for the lowest of the High 26. If, instead, estimates of inhaled plutonium based on the on-site measurements were used with the biokinetic models of the day to calculate the high ends of the uncertainty ranges for the veteran's doses, the high-end doses received by many would be much higher than their Air Force-assigned maximum doses.

CONCLUSION

About 1,600 US military men—mostly Air Force—participated in a cleanup of plutonium contamination in the Spanish village of Palomares in 1966. They worked without protection against inhalation of plutonium-contaminated particles because their supervisors did not wish to alarm Spanish citizens and officials observing the cleanup. In this paper, a history is provided of the Palomares incident, the bioassay and dosimetry that has been carried out to date, and its use in compensation decisions.

One reason that dosimetry was carried out in a 2001 report was that under 38 CFR 3.311, US veterans are entitled to compensation if they develop a radiogenic disease after their service and if they received a radiation dose to the diseased organ large enough so that the "evidence supports the conclusion it is at least as likely as not the veteran's disease resulted from exposure to radiation in service" (US Dept of VA 2018). Since such dose estimates have an uncertainty range, the veteran is given, under the law, the benefit of assuming the highest credible dose. With regard to uncertainty in cancer risk coefficients, the threshold for compensation is assessed at the 99+% credibility as determined, for example, by the NIOSH IREP calculator.

Between 2001 and 2013 (35 to 47 y after the accident), the Air Force based its estimates of the veterans' doses on measurements of airborne plutonium 6 mo *after* the cleanup. These theoretical exposures had no relationship to the actual amount of plutonium taken in by the veterans during the cleanup, when the concentration of airborne plutonium is likely to have been orders of magnitude higher.

In 2013 (47 y after the cleanup), the Air Force changed to the assumption that 26 veterans in a "high-dose" group, for which multiple off-site measurements of urine activity were available, had inhaled the amount of plutonium estimated in a 2001 reanalysis of that data and that the remainder of the group of about 1,600 had received lower doses. It was decided that the remainder, i.e., non-High 26 veterans, would be assigned the lowest inhalation estimate among the High 26 as a basis for estimating organ doses for determining compensation for a radiogenic illness. Based on the NIOSH IREP calculator, these post-2013 allowed doses are sufficiently high to justify a Palomares service connection for lung and bone cancer, as well as liver cancer diagnosed before 1990 and leukemia diagnosed before 1982.

The dose estimation process for the High 26 was limited, however, by the fact that high early urine measurements were excluded, on the grounds of potential sample contamination evidenced by the order-of-magnitude lower plutonium excretion results obtained in the first set of off-site measurements. This drop was inconsistent with the biokinetic model for excretion after exposure to plutonium oxide that was being used at the time. Discarding the early data is questionable, however, because the excretion rates calculated from off-site samples continued to drop by an order of magnitude each 200 d in contradiction to the relatively flat prediction of the biokinetic model for either soluble or insoluble plutonium. Several hundred veterans might have had higher readings than the lowest of the High 26 had their measurements not been dismissed because of laboratory failures such as low plutonium-recovery rates from the samples as evidenced by low recovery rates of a ^{236}Pu tracer. Even for the measurements that were accepted, many of the readings recorded for the veterans not among the non-High 26 were higher than some of those for the High 26, putting into question the designation of the High 26.

Virtually all the non-High 26 had either an on-site or a single off-site urine sample collected, with its plutonium content measured and fitted to a standard biokinetic model of the period to estimate the quantities of plutonium inhaled. These estimates indicate that a significant fraction could have inhaled much larger quantities of plutonium than the lowest of the High 26 currently proposed by the Air Force as a surrogate basis for calculating their doses.

It therefore appears, based on the present record, that as a result of inattention to uncertainty in urine measurements, uncertainty in biokinetic modeling, and the Air Force's exclusion of the on-site urine samples, the uncertainty ranges in the dose estimates currently being used to determine the veterans' benefits have been seriously underestimated.

Whether or not this and other conclusions would change using the most recent ICRP biokinetic models and a full uncertainty analysis is not known. The history presented here, however, can provide a base on which future policy and dosimetric analyses can build.

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