Practical Implications of the Bootstrap Uncertainty Analyses on Co-exposure Models

White Paper

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PURPOSE AND INTRODUCTION

The purpose of the document is to summarize how a bootstrap analysis describes the uncertainty associated with co-exposure models and explain why (1) Savannah River Site (SRS) subcontractor construction trade workers (subCTWs) are sufficiently represented in the NIOSH co-exposure models and (2) dose reconstructions are feasible.

BACKGROUND

The topics of completeness and representativeness of exposure data among the potentially exposed population at SRS has been discussed during recent SRS and Special Exposure Cohort (SEC) Issues workgroup meetings[1, 2]. In the absence of individual monitoring data, 42 C.F.R. Part 82 [DHHS 2002] allows for the use of other workers' data to complete dose reconstructions. Section 82.2 (b) states: *If individual monitoring data are not available or adequate, dose reconstructions may use monitoring results for groups of workers with comparable activities and relationships to the radiation environment.*

The groups of workers specified in §82.2(b) are generically known as coworkers. Coworkers are considered to be workers at the same site whose radiation monitoring measurements represent or bound exposures for workers not individually monitored. In this context, coworkers may represent a category of job titles, like construction trade workers (CTWs). This group of workers is considered to be a *target population,* and those with monitoring data are defined as the *study population* (Figure 1). A representative sample of the study population is called the *study sample* and NIOSH DCAS Claims Tracking System (NOCTS)[3] claimant data were used to develop a co-exposure model and reconstruct doses to unmonitored CTWs who may have been exposed and perhaps in retrospect should have been monitored [NIOSH 2016]. It is also possible that some CTWs may never have been exposed during their time on the site. For example, some may have worked only in uncontaminated environments performing new construction activities.

[1] Joint Meeting of the Savannah River Site (SRS) And Special Exposure Cohort (SEC) Issues Work Groups. November 17, 2020. *See* https://www.cdc.gov/niosh/ocas/pdfs/abrwh/2020/wgtr111720-508.pdf.
[2] Joint Meeting of the Savannah River Site (SRS) And Special Exposure Cohort (SEC) Issues Work Groups. November 20, 2020. *See* https://www.cdc.gov/niosh/ocas/pdfs/abrwh/2020/wgtr112020-508.pdf.
[3] NOCTS is an acronym for the NIOSH OCAS (Office of Compensation Analysis and Support) Claims Tracking System. NIOSH changed OCAS to the Division of Compensation Analysis and Support (DCAS) but the acronym for the tracking system, NOCTS, did not change.

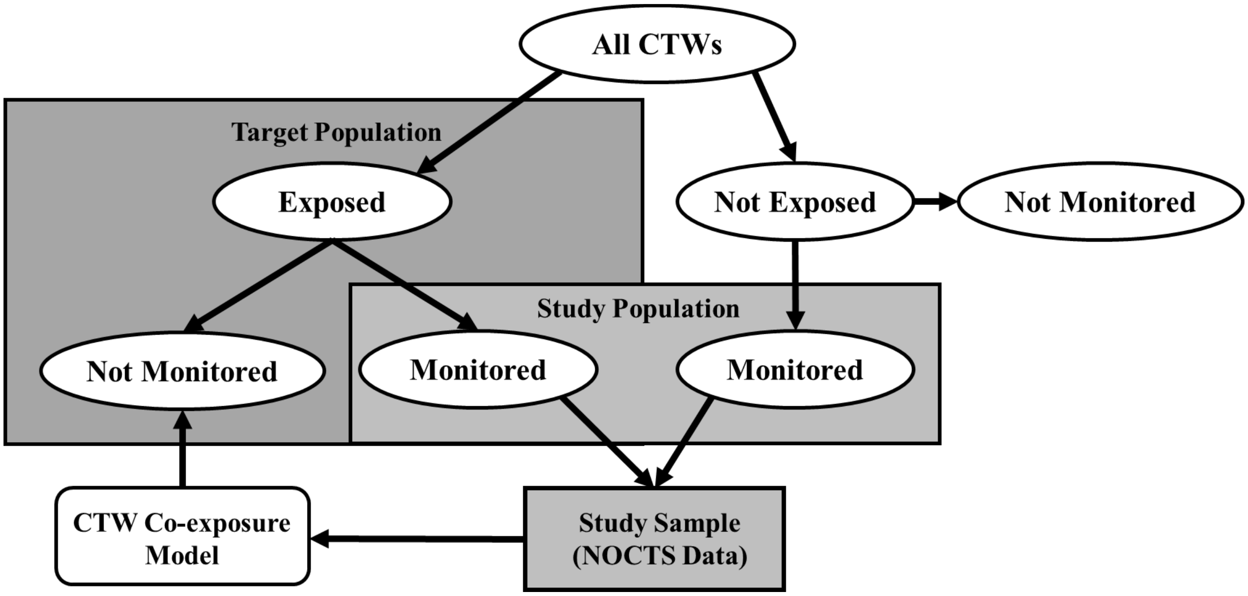

Figure 1: Derivation of a study sample used in a co-exposure model.

The current NIOSH tritium co-exposure model for CTWs combines all exposure data from subcontractor CTWs and DuPont CTWs work histories to create the Combined CTW model which estimates individual doses for workers potentially exposed and have missing or incomplete exposure records [ORAUT 2020]. Table 1 lists the numbers of NOCTS claimants and their respective strata between 1972 and 1990 that were monitored for tritium. These workers represent the study sample in the bootstrap analysis used to analyze uncertainties in the subCTWs and DuPont CTWs co-exposure models.

Table 1. Number of unique workers between 1972 and 1990 monitored for tritium *(Study Sample)*

Strata / Co-exposure Model	# tritium samples	# unique workers
subCTW	12,484	237
DuPont CTW	19,993	185
Combined CTWs	32,477	421*
nonCTW	110,602	728
TOTALS	143,079	1,079*

* Some workers changed strata between 1972-1990. One worker is in both the subCTW and DuPont CTW counts, 5 workers in both the subCTW and nonCTW counts, and 65 workers in both the DuPont CTW and nonCTW counts.

Depending on the amount and specificity of the available coworker and workplace data, the level of detail available can vary greatly for a co-exposure model. As a result, NIOSH developed, and the Advisory Board on Radiation and Worker Health approved,[4] an implementation guide that provides guidance on how to evaluate and use co-exposure models for dose reconstruction purposes [NIOSH 2020]. Two criteria considered when determining the technical adequacy of a co-exposure model are: (1) quality of data to create a co-exposure model, and (2) data completeness, defined as having sufficient number of measurements to ensure that the derived dose estimates are either bounding or represent exposure potentials to the coworkers (e.g., CTWs). Based on this guideline, NIOSH developed nine co-exposure models for key radionuclides (Americium, Tritium, Plutonium, Uranium, Fission Products, Cobalt-60, Cesium-137, Neptunium, and Thorium) at SRS [ORAUT 2020].

The SRS and SEC Issues workgroup discussions have focused on whether the current co-exposure models, which combine prime CTWs (DuPont before 1990, Westinghouse after 1990) and subcontractor CTWs (i.e., B.F. Shaw Company, Miller-Dunn Electric Company, North Brothers company, etc.), are appropriate or if this group should be separated into two co-exposure models; one for prime CTWs and the other for subcontractor CTWs. The concerns mentioned are that subcontractor CTWs exposure potentials may (1) differ from prime CTWs, (2) be under-represented in a combined co-exposure model and (3) be incomplete due to missing data associated with job-specific bioassays during the Westinghouse era (after 1990).

NIOSH has completed several documents addressing these concerns over the past several years. For example, NIOSH compared plutonium intakes between DuPont CTWs and subcontractor CTWs in the "Savannah River Site Plutonium Construction Trade Worker Stratification Refinement" document [NIOSH 2019]. "Evaluation of Bioassay Data for Subcontractor Construction Trade Workers at the Savannah River Site" [ORAUT 2019a] considered subcontractor monitoring based on job plans and Radiation Work Permits. NIOSH characterized claimant data (*study sample*) of subcontractors in "Bioassay for Subcontractor Construction Trade Workers at the Savannah Rivers Site from 1972 to 1997" [ORAUT 2019b].

Members on the Advisory Board on Radiation and Worker Health recently discussed the uncertainty in the parameter estimates associated with these co-exposure models and whether prime CTWs and subcontractor CTWs were similar.[5] A board member inquired as to whether a more rigorous statistical analysis, such as a bootstrap method, could help answer this question by providing uncertainty in the co-exposure model parameters.

ANALYSIS OF UNCERTAINTY IN CO-EXPOSURE MODELS (BOOTSTRAP METHOD)

NIOSH/ORAUT conducted this analysis using SRS tritium data to illustrate the uncertainty in model parameters and assist the discussion about whether it is warranted or not to further stratify the current co-exposure CTWs models into prime CTW and subcontractor CTW co-exposure models [ORAUT 2021]. Tritium data were selected because there was a short timeline to

[4] Joint Meeting of the Savannah River Site (SRS) And Special Exposure Cohort (SEC) Issues Work Groups. December 5, 2019. *See* https://www.cdc.gov/niosh/ocas/pdfs/abrwh/2019/wgtr120519-508.pdf.
[5] Transcript of the 137th Meeting of the Advisory Board on Radiation and Worker Health, December 9, 2020. *See* https://www.cdc.gov/niosh/ocas/pdfs/abrwh/2020/tr120920-508.pdf.

complete this work, a direct bioassay-to-dose calculation was somewhat easily computed, and uncensored data were readily available in NOCTS. Conducting this type of analysis for plutonium or other internal radionuclides is very time consuming and difficult due to the complexity of the procedure (e.g., multiple imputation for censored data, Time-Weighted One Person One Statistic (TWOPOS), and Integrated Module for Bioassay Analysis (IMBA) intake modeling) to estimate intake or dose.

The current co-exposure models in OTIB-0081, Rev. 5 are based on all CTWs combined. If these co-exposure models are further stratified and the subgroups have essentially the same dose distributions or if the stratification reduces the number of doses in each stratum, then uncertainty will likely increase in model parameters compared to the combined CTW models.

How does this impact dose reconstruction for subcontractor CTWs? If the assumption is correct that subcontractor CTWs were hired for more hazardous work than Dupont CTWs, and therefore had greater potential for internal exposure, a bootstrap analysis on separate co-exposure models could help to validate this assumption.

PRACTICAL IMPLICATIONS

There are several practical implications and key points that can be drawn from the bootstrap uncertainty analysis. These are:

1. **Although the number of prime CTWs and subcontractor CTWs varied between 1972 and 1990, subcontractor CTWs are well represented in the tritium co-exposure models.**

   When considering the composition of the tritium CTW co-exposure model using NOCTS claimant data, the number of DuPont CTWs dominate the models in the 1970s (Figure 2). This similar pattern was observed for CTWs exposed to plutonium [NIOSH 2019]. However, in the 1980s, the subcontractor CTWs comprised a greater proportion of CTW workers in the tritium co-exposure models and are therefore clearly represented in the current models in ORAUT-OTIB-0081. If subcontractor CTWs were primarily or solely monitored via "job specific" bioassay, there shouldn't be more tritium monitoring data for subcontractors in the co-exposure model than DuPont CTWs within the claimant population in the 1980s. The subcontractor claimant data should be greatly reduced if the data are significantly incomplete.

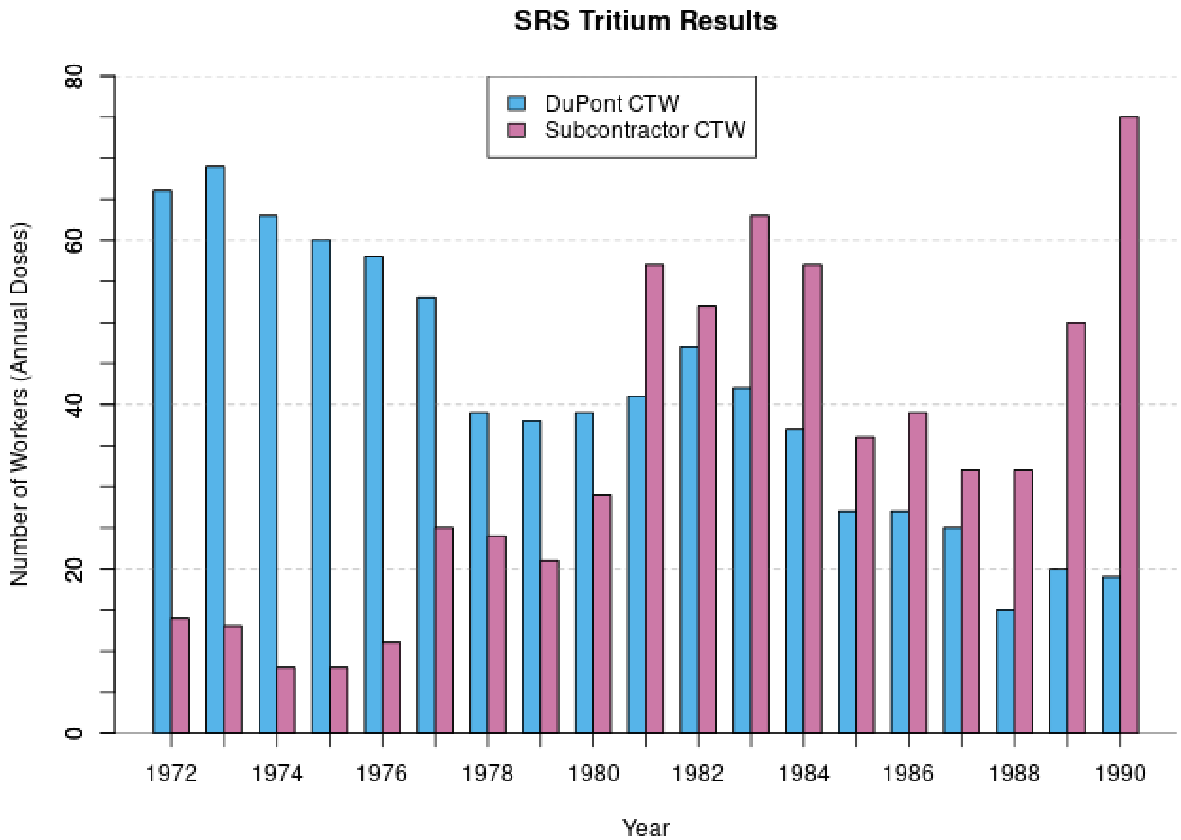

Figure 2. Number of DuPont CTWs and Subcontractor CTWs

2. **Further stratification between CTWs will increase uncertainty in the co-exposure model parameters.**

The bootstrap uncertainty analysis showed that uncertainty in the parameter estimates increased for separate tritium co-exposure models (Figure 3). This is likely to due to the smaller study sample size of the stratified data. For example, the 95% confidence intervals are much larger for subcontractor CTWs in the early 1970s because there are less CTWs available in NOCTS to develop the model with the data covering a similar range [ORAUT 2021]. The 95% confidence intervals associated with the combined CTWs model were smaller in comparison due to a larger sample size and the central tendency of combining data.

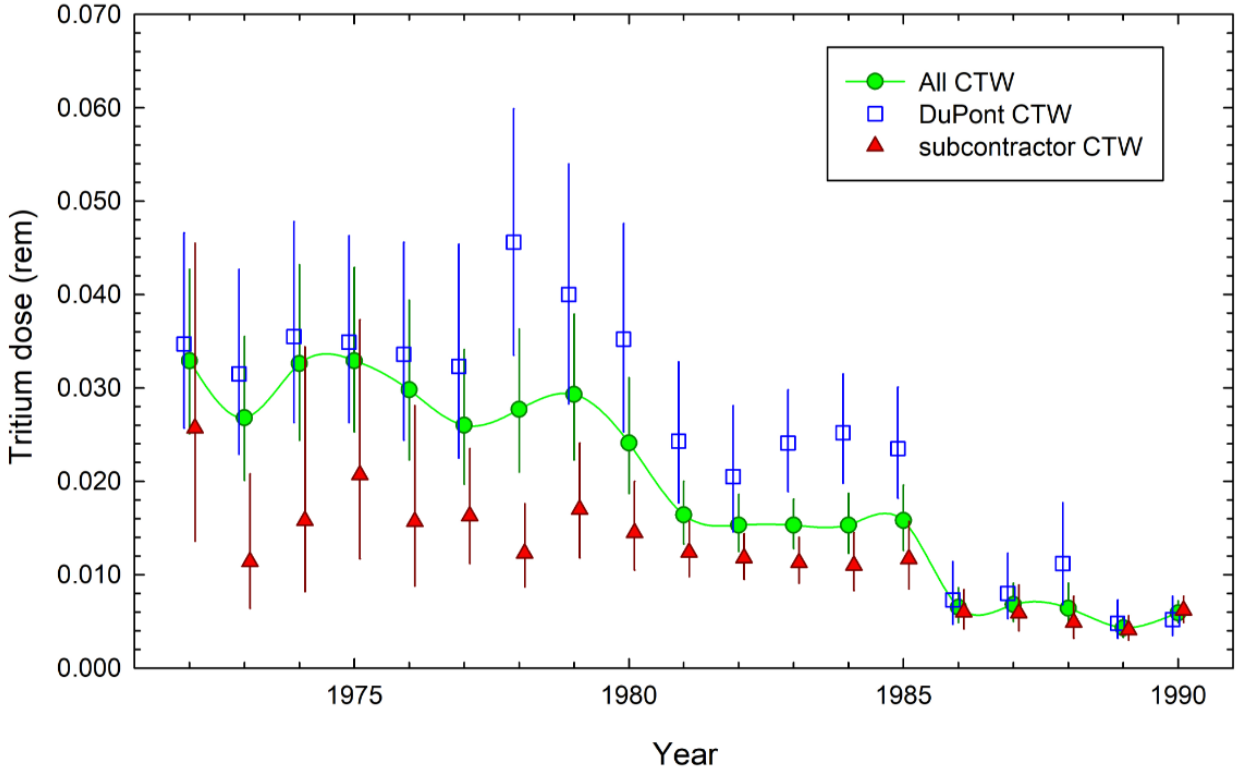

Figure 3. Geometric mean and associated 95% confidence intervals for tritium doses among CTWs between 1972 and 1990.

3. Subcontractor CTWs exposures were generally lower than prime CTWs between 1972 and 1990, however there is no practical difference between subcontractor CTWs and the current combined CTW model.

Considering the slight dominance of subcontractor data in the 1980s, if a significant exposure/dose difference exists between subcontractor CTWs and Dupont CTWs, the assumed exposure difference should be easily observed. Figure 3 illustrates that subcontractor CTWs tritium exposures (red triangular markers) were lower compared to DuPont CTWs (blue open squares) from 1972 through 1990 based on the geometric mean. The crucial time period to consider in this evaluation is from 1981 through 1990 when subcontractor CTWs outnumbered the Dupont CTWs. Subcontractor CTWs exposures were not substantially different especially after 1986 based on the overlapping confidence intervals [ORAUT 2021]. Further stratification of CTWs would result in lower dose estimates for subCTWs as compared to the combined CTW model.

For example, Table 2 lists the geometric mean (GM) and geometric standard deviation (GSD) for the year 1986. Figure 4 illustrates this same information but since GMs and GSDs are dependent parameters the confidence intervals are also dependent and presented in two dimensions (e.g., GM and GSD). This causes the confidence intervals to appear as ellipses.

Table 2. GM and GSD for three CTWs co-exposure models in 1986.

Strata / Co-exposure Model	Number	Geometric Mean (rem)	Geometric Standard Deviation
Sub CTWs	39	0.0060	2.98
DuPont CTWs	27	0.0073	3.23
Combined CTWs	66	0.0065	3.12

A couple of observations worth noting from Table 2 and Figure 4 are:

(1) There were more subcontractor CTWs (N=39) than DuPont CTWs (N=27) during this year which results in a smaller confidence interval ellipse around the subcontractor CTWs,

(2) There is no practical difference between these co-exposure models as compared to the combined CTW co-exposure model as all three strata overlap.

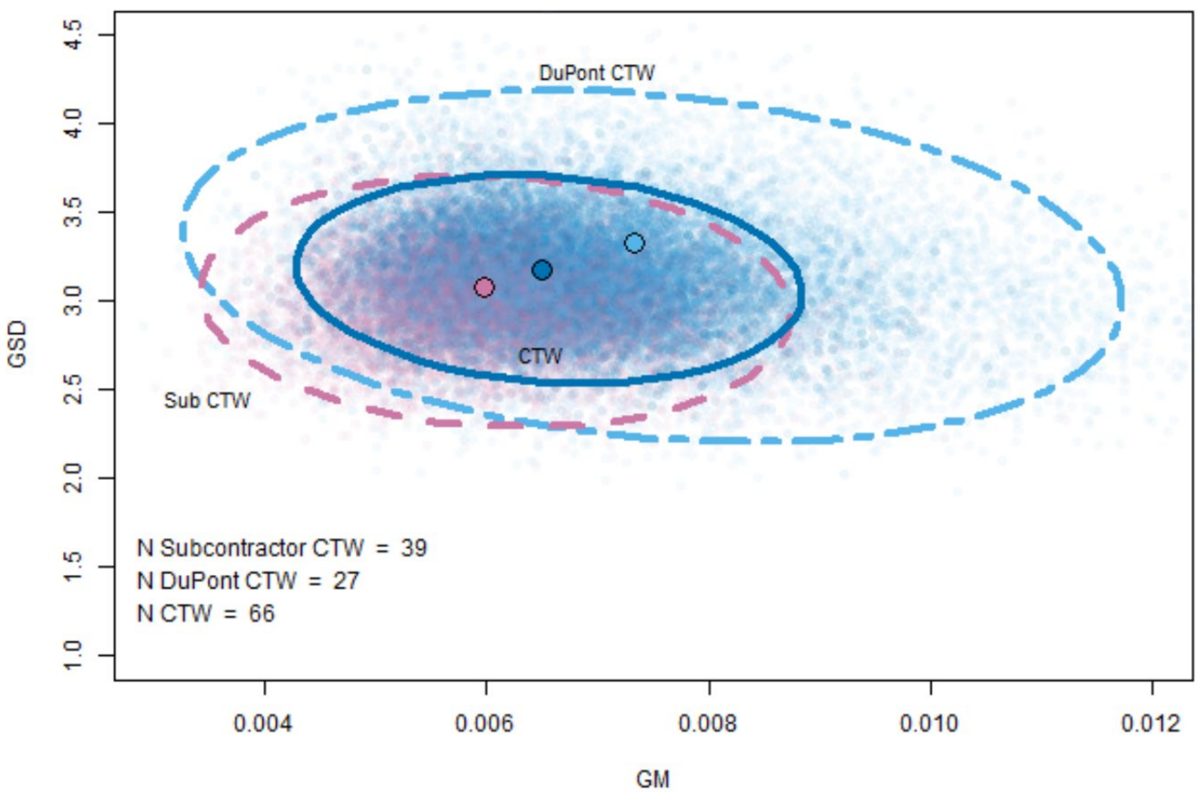

Figure 4. Plot of the 1986 tritium GM and GSD co-exposure models for subCTWs, DuPont CTWs, and combined CTWs with 95% confidence intervals

4. Downward trend in tritium doses between 1972 and 1990.

Figure 3 illustrates a downward trend in geometric mean regardless of the strata and which sub-strata dominates the combined CTW model. Figure 5 presents the 95th percentiles and the associated confidence interval of the three strata and the same downward trend is observed. This downward trend is typical of improved radiological controls and decreased exposure potential over time.

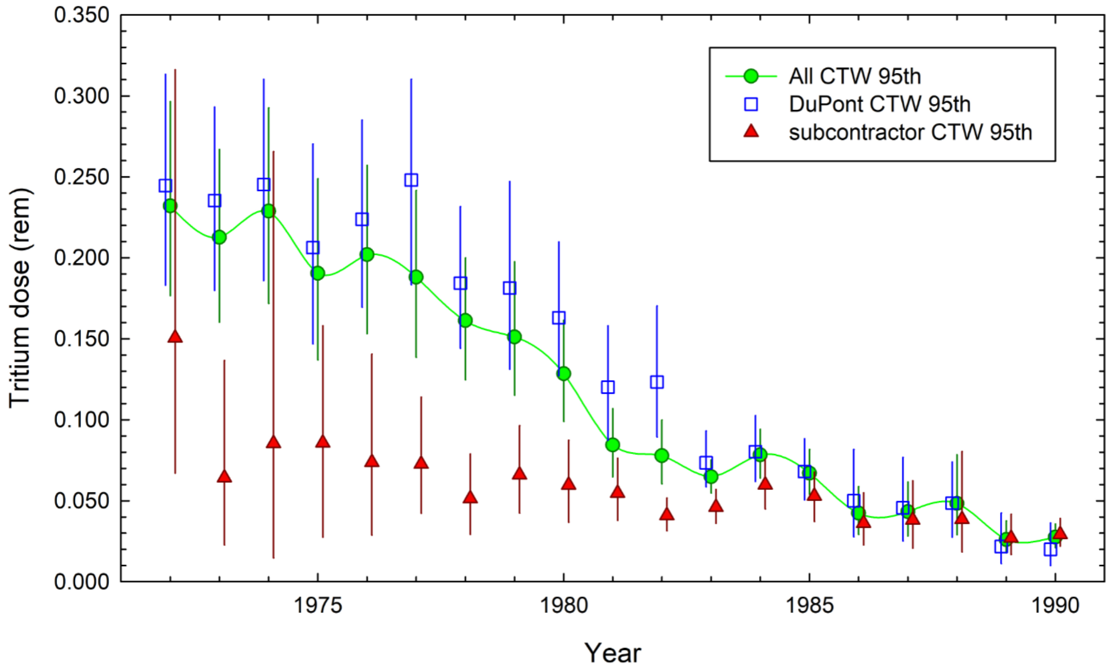

Figure 5. The 95th percentile and associated 95% confidence interval for tritium doses between 1972 and 1990.

5. The doses for CTWs can be bounded using the combined co-exposure model and the overall magnitude of the tritium doses are very low

The combined CTW co-exposure model for tritium can be used to bound dose estimates for subcontractor CTWs. Figures 3 and 5 show that the magnitude of the tritium doses for the geometric mean or 95th percentile are generally low. The 95th percentile tritium dose (Figure 5) is approximately 230 mrem per year in 1972 which was slightly less than 5% of the annual dose limit. The decreasing trend results in approximately 100 mrem (2% annual limit) by 1981 and approximately 30 mrem (<1% annual limit) in 1990. Since 1981, the 95th percentile of tritium doses were below the current monitoring threshold of 100 mrem for committed effective dose in 10 CFR 835. In other words, modern workers would not require internal personal monitoring at these dose levels.

6. **It can reasonably be assumed that the observations from this tritium bootstrap analysis are generalizable to other internal radionuclides.**

   The assumption that subcontractor CTWs were hired for more hazardous work than Dupont CTWs, and therefore had greater potential for internal exposure, is not supported based on the tritium or plutonium analyses [NIOSH 2019, ORAUT 2021]. These analyses indicate that subcontractor CTWs, in general, experienced lower doses than DuPont CTWs between 1972 and 1990. However, there is significant overlap in the uncertainties which means there is no practical difference between subcontractor and DuPont CTWs co-exposure models. The combined CTWs co-exposure models presented in OTIB-0081 are reasonable. In this uncertainty analysis, further stratification is not justified because the tritium radiological work did not appear to be different between the DuPont CTWs and the subcontractor CTWs. Further, NIOSH has not found any indication that subcontractors were only hired for non-tritium hazardous work. Therefore, one can reasonably generalize these findings to all co-exposure models at SRS and conclude that further stratification would unnecessarily increase model parameter uncertainties.

   Again, conducting this type of analysis for other internal radionuclides would be a very time consuming and difficult task due to the complexity of the procedure to convert bioassay results to dose (e.g. multiple imputation, Time-Weighted One Person One Statistic (TWOPOS), and intake modeling) especially with the added complication that these are highly-censored datasets (e.g., <limit of detection) as compared to tritium data.

CONCLUSION

NIOSH previously concluded, based on the plutonium stratification analysis, that further stratification of the SRS CTW co-exposure models is not warranted and that these combined CTW co-exposure models will produce bounding or representative dose estimates for compensation purposes [NIOSH 2019]. That conclusion remains unchanged and is further supported with this new, more statistically rigorous, uncertainty analysis using tritium data. Further, NIOSH re-affirms that the data used to generate these co-exposure models meet the completeness definition as describe in the implementation guide.

The use of the NOCTS data in Figure 2 illustrates that the tritium co-exposure models in the 1980s comprise a greater proportion of subCTWs than Dupont CTWs and are therefore considered to be sufficiently represented in the tritium co-exposure model. The similar decreasing trend in tritium doses over time give us confidence that the combined model in the 1970s is also sufficient for tritium even though the subcontractor CTWs comprise a much smaller proportion compared to the Dupont CTWs. The current co-exposure models in OTIB-0081 are based on data considered to complete, bounding and representative, thus dose reconstruction is feasible.

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