NIOSH Response to Short-lived Radionuclide Issues Raised in Comment 5 of SC&A's NTS Resuspension Issues Status Report

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PURPOSE

This is the National Institute for Occupational Safety and Health's (NIOSH) response to Comment 5 of the *Status Report on Resuspension Issues at the Nevada Test Site* (Sanford Cohen and Associates [SC&A] 2015). This white paper describes the analysis method used to estimate the environmental dose from short-lived radionuclides during the period 1963 to 1972 at the Nevada Test Site (NTS). Results of the analysis method are presented to illustrate the impact of various assumptions.

SUMMARY OF RESULTS

The results show that the method used to estimate the internal dose from short-lived radionuclides is favorable to claimants. The treatment of refractory elements enhancing their activity results in higher doses is compared to not making corrections to the primary data.

Results are presented for the Small Boy and Little Feller I shots. The calculated dose values are similar to the values previously presented in the NTS Environmental Technical Basis Document (TBD) (ORAUT 2012). Some changes to the values in the TBD have occurred as a result of modifications to the evaluation and application of dose correction factors.

BACKGROUND

The NTS Environmental TBD was reviewed by SC&A and concerns were expressed in the *Status Report on Resuspension Issues at the Nevada Test Site* (SC&A 2015). The 5th comment in this report dealt with the evaluation of inhalation and ingestion dose from short-lived radionuclides.

Summary of the Issue

Comment 5 is stated as follows:

Derivation of the concentration of relatively short-lived radionuclides in soil for January 1, 1963, employed the Hicks' tables (Hicks 1982) for the Small Boy event that occurred on July 14, 1962. In fact, the contamination in soil on January 1, 1963, reflects fallout from numerous tests that resulted in surface contamination, such as the Sedan test on July 6, 1962, and Little Feller II on July 7, 1962, which occurred shortly before Small Boy, and Little Feller I that occurred after Small Boy on July 17, 1962. As such, NIOSH should address whether tests shortly before and after Small Boy on July 14, 1962, could also have contributed substantively to the fallout levels in soil derived for January 1, 1963. In a related matter, the protocol used in the TBD to account for fractionation is overly simplistic and appears to rely primarily on the Small Boy event. NIOSH will need to demonstrate that the approach used to account for fractionation does not substantively underestimate doses.

Draft responses to this issue have been submitted and reviewed by SC&A. The following is the response submitted for review.

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The evaluation report (ER) for Special Exposure Cohort (SEC)-00055 (NIOSH, 2006), which covers the time period of January 27, 1951 to December 31, 1962, specifically discusses the inability to reconstruct doses between the cessation of testing in July of 1962 and the end of that year. The last paragraph of Section 4.5 states:

> *Above-ground testing at the NTS began on January 27, 1951, and concluded on July 17, 1962. NIOSH considers reconstruction of internal doses at the NTS feasible for periods after cessation of atmospheric testing beginning on January 1, 1963. During the period of atmospheric testing, the source term to which workers were exposed changed with each detonation, due mainly to re-suspension and mixing of fallout caused by the blast waves. After the final above-ground test, NIOSH considers the radiological source term to be sufficiently stable so as to allow assumptions adequate for dose reconstruction. The extension of the SEC period through December 31, 1962, approximately six months after the last atmospheric test, allows time for the stabilization of the source term and for decay of the shorter-lived radionuclides associated with the final atmospheric tests.*

In addition, the ER for SEC-0084 (NIOSH 2007) describes a model for the reconstruction of environmental internal doses beginning on January 1, 1963. Thus, the ERs for the SECs are clear on the time period for which environmental doses can be reconstructed.

After reviewing the above response, SC&A indicated the following in an email:

We continue to believe that it is possible to derive exposures during this time period, and that these exposures (for workers not covered by the SEC) might be significant relative to the exposure post-January 1, 1963, the time period where NIOSH has developed a protocol to reconstruct these environmental exposures.

The current analysis adheres to the NIOSH position that evaluation of environmental internal dose cannot begin prior to 1963.

Summary of Analyses Performed

In response to the comment, the following analyses have been performed to investigate the impact of the assumptions:

1. Review the analysis method and assumptions in detail.
2. Perform evaluations for alternate assumptions regarding treatment of refractory elements.
3. Perform evaluations using Hicks data from Little Feller I.

The NTS Environmental TBD (ORAUT 2012) evaluates internal dose based on annual intake rates of selected radionuclides by year, starting in 1963. The intake rates are given in Table 4-7 of the NTS Environmental TBD. The intake rates were maximized based on air monitoring data. The resulting intakes include strontium-90 intakes by year. For 1966 and later years, the

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strontium-90 intake is constant at 1.55 Bq/yr. For the years 1963 to 1965, the intake rate was scaled upward to account for early resuspension at a higher rate.

The NTS Environmental TBD includes evaluation of the dose from short-lived fission and activation products starting in 1963, based on the last atmospheric shots in 1962. The shots were Small Boy (July 13, 1962) and Little Feller I (July 17, 1962). The dose results were based on the Small Boy data as that provided a higher estimate of dose. The comments from the Working Group suggested that the Little Feller I and Sedan shot results also be considered. The Sedan shot was an underground shot (635 feet) that resulted in atmospheric releases. Because of the uncertainty regarding release of activity to the surface and the relative releases of volatile and refractory materials, the analyses have not used the data for the Sedan shot.

This white paper describes the evaluation of the additional correction factors to account for the dose from short-lived fission and activation products for years 1963 to 1972. The correction factors are applied by multiplying the strontium-90 dose by the correction factor for each year to get the total dose to each organ. The resulting doses are small and are only retained for a few organs as given in Table 4-9 of the TBD, and are discussed below.

ANALYSIS METHOD FOR SHORT-LIVED RADIONUCLIDE DOSE

The following discussion provides details of the analysis method, including changes compared to the initial analysis. This is the analysis method described in the current NTS Environmental TBD text and in Attachment A (ORAUT 2012).

Overview of Data and Analysis Method

The evaluation of dose from short-lived radionuclides is based on the relative dose compared to the dose from intake of strontium-90. The intake of strontium-90 is provided in the TBD and is used as the basis for the estimation of dose from the short-lived radionuclides. The fraction of dose from strontium-90 is evaluated first for specific organs and as a function of time following the shot for full years of 1963 through 1972. Then the correction factor is evaluated for each organ by integration of the curve of dose fraction as a function of time. The inverse of the integral over one year is the correction factor for that year.

The basis for the activity of each radionuclide present as a function of time is data provided in reports by Hicks (Hicks 1981; Hicks 1982). The data presented in the Hicks papers give the relative activity of radionuclides present following several of the atmospheric test shots at NTS. The values were based on runs of the ORIGEN computer program. The following is a summary of the calculations performed to estimate the ground concentrations (Hicks 1981). The input to the ORIGEN program was the total number of fissions per kiloton. The total burst was for 1.43E17 fissions in a fuel element composed of 1 kg each of U-235, U-238, and Pu. The fission yield is not that of a nuclear device, so the values were corrected by a relative fission yield which includes the refractory fraction (RF) for each element. 152 fission products and 25 neutron-induced activation products were included. Presumably, the activity of neutron-induced

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activation products included consideration of structural materials present. There would be differences for balloon shots, tower shots, ground level shots, and underground shots.

The result is the fractionated inventory of each radionuclide at time zero. For refractory radionuclides, a refractory fraction was applied by Hicks for each radionuclide in the analysis. This was done to represent the off-site activity, allowing for enhanced on-site deposition of refractory elements (Hicks 1982). Application of the refractory fraction is the only treatment of deposition of activity as the analysis did not include any atmospheric transport or deposition calculation.

The results were decayed for times from 1 to 21 hours, 1 to 300 days, and 1 to 50 years. This gives the activity of each radionuclide as a function of time for a 1 kt fission yield. The external dose for each time was evaluated by Hicks and the ground concentrations were normalized to give a dose rate of 1mR/hr at 12 hours. Therefore, the ground concentrations values are relative values, not absolute values.

The volatile elements used in the analysis by Hicks are:

- Ge,
- As,
- Se,
- Br,
- Kr,
- Rb,
- Mo,
- Tc,
- Cd,
- In,
- Sn,
- Sb,
- Te,
- I,
- Xe,
- Cs,
- W,
- Au, and
- Pb.

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The refractory elements[1] used in the analysis by Hicks are:

- Be,
- Na,
- Mn,
- Fe,
- Co,
- Cu,
- Sr,
- Y,
- Zr,
- Nb,
- Ba,
- Rare Earths,
- Th,
- U,
- Np,
- Pu,
- Am, and
- Cm.

The actual application of volatile versus refractory assumptions was based on data provided by Hicks for the Pacific test shots and summarized in Table A-8 of the NTS Environmental TBD (ORAUT 2012), which is shown here as Table 1. Because the selection of volatile versus refractory assumptions included comparison of measured and estimated concentrations, the representations by Hicks are used in the current analyses. The table is reproduced here with the relative ratios adjusted to show the refractory fraction of 0.4 for the purely refractory radionuclides. The tests Small Boy and Little Feller I were assigned refractory fractions of 0.4 by Hicks. The refractory fractions for mass number chains 91, 140, and 141 were calculated as described below. This table includes a large number of radionuclides including many with very short half-lives that will not be present after a short period of time. The actual number of radionuclides included in the present analysis is much smaller and is based on the radionuclides included in the Hicks (1981) "days" and "years" tables.

[1] Although elemental strontium is assumed to be refractory, the isotope Sr-90 is treated as a volatile because it is a progeny of Kr-90 and Rb-90, which are volatile and were in existence while on-site deposition was occurring. Mo-99 and Tc-99 are treated as refractory by Hicks (1981) without a reason for the treatment.

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Table 1: Far-Field Refractory Enrichment Ratios Modified by the Small Boy Refractory Ratios

Radionuclide	Refractory Fraction Ratio
Be-7	0.4
Na-24	0.4
Mn-54	0.4
Fe-55	0.4
Fe-59	0.4
Cu-64	0.4
Cu-67	0.4
W-181	1.0
W-185	1.0
W-187	1.0
W-188	1.0
U-237	0.4
U-239	0.4
U-240	0.4
Np-239	0.4
Np-240m	0.4
Np-240	0.4
Am-241	0.4
Cm-242	0.4
Ge-75	1.0
Ge-77	1.0
As-77	1.0
Se-77m	1.0
Ge-78	1.0
As-78	1.0
As-79	1.0
Se-79m	1.0
Br-80	1.0
Se-81m	1.0
Se-81	1.0
Br-82	1.0
Se-83	1.0
Br-83	1.0
Kr-83m	1.0
Br-84	1.0
Kr-85m	1.0
Kr-87	1.0
Kr-88	1.0
Rb-88	1.0
Rb-89	1.0
Sr-89	1.0
Sr-90	1.0
Y-90	1.0
Sr-91	0.85
Y-91m	0.85
Y-91	0.85
Sr-92	0.4

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Radionuclide	Refractory Fraction Ratio
Y-92	0.4
Sr-93	0.4
Y-93	0.4
Y-94	0.4
Y-95	0.4
Zr-95	0.4
Nb-95	0.4
Zr-97	0.4
Nb-97m	0.4
Nb-97	0.4
Nb-98	0.4
Mo-99	0.4
Tc-99m	0.4
Mo-101	1.0
Tc-101	1.0
Mo-102	1.0
Tc-102	1.0
Tc-102	1.0
Ru-103	1.0
Ru-103m	1.0
Tc-104	1.0
Ru-105	1.0
Rh-105m	1.0
Rh-105	1.0
Ru-106	1.0
Rh-106	1.0
Rh-107	1.0
Pd-107m	1.0
Pd-109	1.0
Ag-109m	1.0
Pd-111m	1.0
Pd-111	1.0
Ag-111m	1.0
Ag-111	1.0
Pd-112	1.0
Ag-112	1.0
Ag-113	1.0
Ag-115	1.0
Cd-115m	1.0
Cd-115	1.0
In-115m	1.0
Cd-117	1.0
In-117m	1.0
In-117	1.0
Cd-118	1.0
In-118	1.0
Cd-119	1.0
In-119m	1.0
In-119	1.0

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Radionuclide	Refractory Fraction Ratio
Sn-121	1.0
Sn-123m	1.0
Sn-123	1.0
Sn-125	1.0
Sb-125	1.0
Sb-126	1.0
Sn-127	1.0
Sb-127	1.0
Te-127	1.0
Sn-128	1.0
Sb-128m	1.0
Sb-128	1.0
Sn-129m	1.0
Sn-129	1.0
Sb-129	1.0
Te-129m	1.0
Te-129	1.0
Sb-130m	1.0
Sb-130	1.0
I-130	1.0
Sb-131	1.0
Te-131m	1.0
Te-131	1.0
I-131	1.0
Te-132	1.0
I-132	1.0
Te-133m	1.0
Te-133	1.0
I-133	1.0
Xe-133m	1.0
Xe-133	1.0
Te-134	1.0
I-134	1.0
I-135	1.0
Xe-135m	1.0
Xe-135	1.0
Cs-136	1.0
Cs-137	1.0
Ba-137m	1.0
Xe-138	1.0
Cs-138	1.0
Cs-139	1.0
Ba-139	1.0
Ba-140	0.82
La-140	0.82
Ba-141	0.60
La-141	0.60
Ce-141	0.60
Ba-142	0.4

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Radionuclide	Refractory Fraction Ratio
La-142	0.4
La-143	0.4
Ce-143	0.4
Pr-143	0.4
Ce-144	0.4
Te-132	1.0
I-132	1.0
Te-133m	1.0
Te-133	1.0
I-133	1.0
Xe-133m	1.0
Xe-133	1.0
Te-134	1.0
I-134	1.0
I-135	1.0
Xe-135m	1.0
Xe-135	1.0
Cs-136	1.0
Cs-137	1.0
Ba-137m	1.0
Xe-138	1.0
Cs-138	1.0
Cs-139	1.0
Ba-139	1.0
Ba-140	0.82
La-140	0.82
Ba-141	0.60
La-141	0.60
Ce-141	0.60
Ba-142	0.4
La-142	0.4
La-143	0.4
Ce-143	0.4
Pr-143	0.4
Ce-144	0.4
Pr-144	0.4
Pr-145	0.4
Cd-146	0.4
Pr-146	0.4
Pr-147	0.4
Nd-147	0.4
Nd-149	0.4
Pm-149	0.4
Pm-150	0.4
Nd-151	0.4
Pm-151	0.4
Pm-152	0.4
Sm-153	0.4
Sm-155	0.4

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Radionuclide	Refractory Fraction Ratio
Eu-155	0.4
Eu-157	0.4
Eu-158	0.4
Eu-159	0.4
Ge-159	0.4
Tb-161	0.4

Source: ORAUT 2012, Table A-8.

The Hicks data were used to calculate the total (relative) internal dose for selected times from five days to 10 years. The fraction of internal dose to each organ for each time was evaluated. The resulting curve of fraction of dose from strontium-90 versus time was integrated for annual periods to give the total fraction of dose from strontium-90 per year. For example, for 1963 the integration started at 172 days and continued one year, considering the time of the shot on July 14, 1962. The inverse of this integral value was applied as a correction factor to the internal dose calculated using the strontium-90 intakes from Table 4-7 (ORAUT 2012), as discussed above.

The above approach is claimant favorable because it considers the activity of short-lived radionuclides to all have started in July of 1962, the date of the last above-ground shot. There were many above-ground shots from 1951 to 1962 of higher yields that also contributed to the strontium-90 activity on the ground. The assumption that all of the short-lived radionuclide activity is related to the maximum strontium-90 activity results in an overestimate of dose.

Analysis Steps

The starting point in the analysis is the data from Hicks for a specific shot, using the data for decay times of days and years. The data are corrected to represent the activity deposited near the test site. The data provided by Hicks included multiplication by the refractory fraction to represent the relative activities at off-site locations. This application was reversed by dividing by the refractory fraction for each radionuclide using the volatile/refractory designations as provided by Hicks and summarized in Table 1 above. This provides an estimate of the initial relative activities near the location of the test shot in the cloud without consideration for deposition at the test site. The activity in the deposited material near the test shot site could be different because of preferential deposition of the refractory material. Therefore, the relative values were again divided by the refractory fractions.

Hicks used effective refractory fractions for three decay chains (below). The effective refractory fractions are for chains in which some of the radionuclides are volatile and some are refractory.

RF = refractory fraction for the shot (0.4 for Small Boy and Little Feller I)

Mass chain 91:

RF_{91} = 0.75 + 0.25xRF = 0.85 for Small Boy and Little Feller I

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Mass chain 140:

$RF_{140} = 0.70 + 0.30xRF = 0.82$ for Small Boy and Little Feller I

Mass chain 141:

$RF_{141} = 0.33 + 0.67xRF = 0.60$ for Small Boy and Little Feller I

Although the reasoning for the above equations is not immediately obvious from the decay chains, the results are reported to agree generally within experimental error with measured soil concentrations (Hicks 1982).

The next step is the evaluation of the fraction of dose from strontium-90.

The adjusted data sets are used for input to the analysis that provides the fraction of the dose during each year that is from strontium-90 relative to the dose from strontium-90 plus short-lived radionuclides. The Hicks data provide the relative activity of the radionuclides, which is sufficient for the current analysis because the output desired is the relative dose from the radionuclides.

The relative activity of each radionuclide for a specific time (from five days to 10 years) is entered into a spreadsheet that evaluates the relative dose from each radionuclide using inhalation or ingestion dose factors. The list of radionuclides excludes the radionuclides included in Table 4-7 (Am-241, Pu-238, Pu-239/240, Co-60, Cs-137, Sr-90, Eu-152, Eu-154, and Eu-155), except for strontium-90, because the dose from these radionuclides is included in other parts of the dose evaluation and assignment. Including them in this analysis would be a duplication of dose. The guidance in the TBD directs the dose reconstructor to include internal dose based on the intakes of the radionuclides in Table 4-7 as part of the environmental dose.

The time period of interest starts about six months after the shot. Therefore, the activity of yttrium-90 will be in equilibrium with and equal to that of strontium-90. The ytrrium-90 activity is set to the strontium-90 activity in the relative dose analysis.

Because strontium-90 stays in the body for much more than a year, the dose factors used for strontium-90 are the dose from one year of intake, with the dose integral ending at the end of the first year. These dose factors have been evaluated using the IMBA computer program. The other radionuclides in the analysis are based on the 50-year dose commitment value although the dose for many of the short-lived radionuclides is received during the first year. This results in a smaller value for relative dose from strontium-90 which is claimant favorable in the estimation of dose from the short-lived radionuclides.

The relative dose from strontium-90 is evaluated for times from 5 days to 3650 days (10 years) for all internal organs of interest (and for which dose conversion factors are available.) The array of relative dose values is entered into a spreadsheet that evaluates the correction factors for specific organs for each year of the 10-year period. The starting time is January 1, 1963, using

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the data offset from the time of the shot to the end of 1962, as in Table 2.

Table 2: Days Offset from Time of Shot to January 1, 1963

Shot Name	Days Offset to January 1, 1963
Little Feller I	169
Small Boy	172

The curve of relative dose from strontium-90 is integrated for each annual period, using the curve fit by Excel as either linear or polynomial (quadratic). The integral value is averaged over a 365-day period. The inverse of this integral is the correction factor to be used to estimate the dose from strontium-90 and associated short-lived fission and activation products.

The correction factors are next used to estimate the internal dose from the short-lived fission and activation products. The IMBA program was used to calculate the internal dose to each organ from the intake of 1 Bq of strontium-90 type F material during a 1-year period. The dose from just the short-lived radionuclides is then calculated as shown in Equation 1.

Equation 1. Annual dose from short-lived radionuclides based on Sr-90 intake rates.

$$Dose_{sl}(year,i) = DCF_i * [CF(year,i) - 1] * Intake_{Sr\text{-}90}(year)$$

Where,

$Dose_{sl}(year,i)$ = dose to organ i from short-lived radionuclides during a given year based on intake of strontium-90, rem,

DCF_i = strontium-90 dose conversion factor for 1-year intake of 1 Bq, to organ i, rem/Bq,

$CF(year,i)$ = factor giving the dose from strontium-90 and short-lived radionuclides to organ i during a specific year, and

$Intake_{Sr90}(year)$ = intake of strontium-90 for a specific year from Table 4-7, Bq/year.

Note that the correction factor, CF(year,i) includes the dose from strontium-90 and is always greater than or equal to 1.0. The subtraction of 1 in the equation removes the strontium-90 dose. The dose from strontium-90 is included when the intakes of Table 4-7 of the NTS TBD are applied in a dose reconstruction.

This evaluation of dose is different from the method used in the previous analysis. Previously, the correction factors were applied to the dose commitment from strontium-90 in years after the first year. However, the dose factors for the short-lived radionuclides are 50-year dose

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commitments and include all possible dose from each radionuclide for the year of intake. The correction factors are developed for the year of intake.

ANALYSIS RESULTS

The dose analysis has been performed for inhalation and ingestion intake routes for the two shots indicated above. The doses have been evaluated using the method described above in which the refractory fractions have been removed (by dividing the activity by the refractory fraction) twice to represent the relative activity in soil near the test location. Additional analyses have been performed for inhalation dose for the Small Boy test. These additional analyses were performed to investigate the impact of increasing the activity of the refractory radionuclides by removing the refractory fraction. First the analysis was done without removing the refractory fractions, and then the analysis was done after removing the refractory fractions once. The first analysis represents the relative activities at an off-site location (per suggestion by Hicks) and the second analysis represents the relative activities at the source location without consideration of deposition.

The following tables provide the results of the inhalation correction factor analysis for the shots. For each analysis two tables are presented. The first is based on Table 4-8 of the NTS Environmental TBD (ORAUT 2012) and provides the correction factors for estimation of organ dose from the strontium-90 dose. The second is based on Table 4-9 in the NTS Environmental TBD and gives the calculated dose to selected organs for each year from 1963 to 1972. Only the doses greater than 0.0005 rem are included and presented to three significant figures.

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Table 3: Annual Inhalation Dose Correction Factors for Various Organs Based on Deposition from Event Small Boy

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Skin, Adrenals, Thymus, Small Intestine, Spleen, Muscle, Uterus, Pancreas, Kidneys, Breast, Testes, Esophagus, Ovaries, Brain, Stomach, Thyroid, Gall Bladder	1,500	477	231	136	79	26	14	8.8	6.2	4.5
Upper Large Intestine	784	250	120	70	46	19	12	8.8	6.6	5.1
Urinary Bladder	499	170	84	50	33	23	6.0	3.9	2.8	2.1
Lungs	54,201	16,814	7,865	4,515	2,920	2,041	482	322	232	175
Extra Thoracic Regions	1,258	428	214	151	87	57	40	29	23	18
Lower Large Intestine	439	144	70	41	27	13	8.3	5.9	4.4	3.4
Colon	525	173	85	50	33	31	18	12	8.4	6.3
Liver	13,459	6,631	4,399	3,292	2,630	1,660	626	350	228	162
Red Bone Marrow	82	23	12	7.8	5.4	3.9	3.0	2.3	1.9	1.6
Bone Surface	192	78	43	28	19	14	11	8.8	7.1	5.9

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Table 4: Annual Inhalation Dose (Rem) from Short-Lived Activity from Event Small Boy

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Liver	0.003	0.001	Negl[a]	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Bone Surface	0.003	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lower Large Intestine	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
ET[b](ET2), LN[c](ET), LN(TH[d])	0.002	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lung	0.012	0.002	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl
ET1	1.305	0.243	0.088	0.050	0.029	0.018	0.013	0.009	0.007	0.006

[a]Negl means the dose is less than 0.0005 rem and is negligible.
[b]ET=extra-thoracic region.
[c]LN=lymph node.
[d]TH=thoracic.

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Table 5: Annual Inhalation Dose Correction Factors for Various Organs Based on Deposition from Event Little Feller I

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Skin, Adrenals, Thymus, Small Intestine, Spleen, Muscle, Uterus, Pancreas, Kidneys, Breast, Testes, Esophagus, Ovaries, Brain, Stomach, Thyroid, Gall Bladder	432	159	77	45	29	20	6.5	4.8	3.7	2.9
Upper Large Intestine	165	58	30	18	12	8.7	6.6	5.1	4.1	3.4
Urinary Bladder	646	176	56	26	15	5.2	3.4	2.4	1.8	1.4
Lungs	15,794	4,801	2,175	1,223	780	171	105	71	52	39
Extra Thoracic Regions	500	160	76	44	29	13	9.5	7.1	5.5	4.4
Lower Large Intestine	108	41	22	14	9.8	7.2	5.6	4.4	3.6	3.0
Colon	105	41	22	14	9.8	7.2	5.6	4.4	3.6	3.0
Liver	3,804	1,866	1236	297	108	58	37	25	19	14
Red Bone Marrow	25	19	4.8	3.5	2.8	2.3	2.0	1.7	1.5	1.3
Bone Surface	29	13	7.8	5.4	4.1	3.2	2.6	2.2	1.9	1.6

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Table 6: Annual Inhalation Dose (Rem) from Short-Lived Activity from Event Little Feller I

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Liver	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Bone Surface/Red Bone Marrow	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lower Large Intestine	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
ET[a](ET2), LN[b](ET), LN(TH[c])	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lung	0.003	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
ET1	0.519	0.090	0.031	0.014	0.009	0.004	0.003	0.002	0.001	0.001

[a]ET=extra-thoracic region.
[b]LN=lymph node.
[c]TH=thoracic.

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The following two sets of tables provide the results of the ingestion correction factor analysis for the two shots.

Table 7: Annual Ingestion Dose Correction Factors for Various Organs Based on Deposition from Event Small Boy

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Skin, Adrenals, Thymus, Small Intestine, Spleen, Muscle, Uterus, Pancreas, Kidneys, Breast, Testes, Esophagus, Ovaries, Brain, Stomach, Thyroid, Gall Bladder	139	61	37	26	19	15	12	10	8.4	7.2
Bladder	56	18	9.1	5.6	3.8	2.7	2.1	1.6	1.3	1.1
Bone Surface	5.7	3.2	2.2	1.8	1.6	1.4	1.3	1.3	1.3	1.3
Stomach	380	131	65	39	26	18	31	17	11	7.9
Small Intestine	107	36	22	16	12	10	8.4	7.3	6.4	5.8
Upper Large Intestine	392	175	63	32	19	13	9.1	6.8	5.3	4.2
Lower Large Intestine	306	151	38	20	12	8.2	5.9	4.4	3.4	2.8
Colon	346	170	70	34	20	13	9.5	7.1	5.5	4.3

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Table 8: Annual Ingestion Dose (Rem) from Short-Lived Activity for Various Organs Based on Deposition from Event Small Boy

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Adrenals, Breast, Brain, Skin, Kidney, Muscle, Pancreas, Esophagus, Liver, Ovaries, ET[a], ET1, ET2, LN[b](TH[c]), LN(ET), Lungs, Spleen, Testes, Thymus, Thyroid, Uterus, Gall Bladder	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Bladder	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Bone Surface	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Stomach	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Small Intestine	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Upper Large Intestine	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lower Large Intestine	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Colon	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl

NOTE: All values are less than 0.0005 rem.
[a]ET=extra-thoracic region.
[b]LN=lymph node.
[c]TH=thoracic.

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Table 9: Annual Ingestion Dose Correction Factors for Various Organs Based on Deposition from Event Little Feller I

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Adrenals, Breast, Brain, Skin, Kidney, Muscle, Pancreas, Esophagus, Liver, Ovaries, ET[a], ET1, ET2, LN[b](TH[c]), LN(ET), Lungs, Spleen, Testes, Thymus, Thyroid, Uterus, Gall Bladder	91	29	14	7.7	5.0	3.5	2.6	2.0	1.5	1.3
Bladder	11	5.2	3.4	2.5	2.0	1.7	1.5	1.3	1.2	1.1
Bone Surface	3.1	1.7	1.3	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Stomach	103	34	17	10	6.6	4.7	5.4	4.5	3.8	3.3
Small Intestine	65	27	17	12	10	8.0	6.8	5.9	5.3	4.7
Upper Large Intestine	153	27	17	12	9.0	7.2	5.9	4.9	4.2	3.7
Lower Large Intestine	86	42	38	20	12	8.2	5.9	4.4	3.4	2.8
Colon	124	61	14	10	7.2	5.7	4.7	3.9	3.3	2.9

[a]ET=extra-thoracic region.
[b]LN=lymph node.
[c]TH=thoracic.

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Table 10: Annual Ingestion Dose (Rem) for Various Organs Based on Deposition from Event Little Feller I

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Adrenals, Breast, Brain, Skin, Kidney, Muscle, Pancreas, Esophagus, Liver, Ovaries, ET[a], ET1, ET2, LN[b](TH[c]), LN(ET), Lungs, Spleen, Testes, Thymus, Thyroid, Uterus, Gall Bladder	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Bladder	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Bone Surface	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Stomach	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Small Intestine	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Upper Large Intestine	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lower Large Intestine	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Colon	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl

NOTE: All values are less than 0.0005 rem.
[a]ET=extra-thoracic region.
[b]LN=lymph node.
[c]TH=thoracic.

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Table 11: Annual Inhalation Dose Correction Factors for Various Organs Based on Deposition from Event Small Boy Without Refractory Fraction Adjustments

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Skin, Adrenals, Thymus, Small Intestine, Spleen, Muscle, Uterus, Pancreas, Kidneys, Breast, Testes, Esophagus, Ovaries, Brain, Stomach, Thyroid, Gall Bladder	908	330	166	99	66	47	18	11.8	8.4	6.3
Upper Large Intestine	450	165	85	52	35	19	12	8.8	6.6	5.1
Urinary Bladder	407	150	77	46	31	22	6.0	3.9	2.8	2.1
Lungs	20,188	7,016	3,462	2,047	1349	955	181	119	84	63
Extra Thoracic Regions	453	155	78	66	32	19	12	8.8	6.6	5.2
Lower Large Intestine	291	109	57	35	24	9.8	6.8	5.0	3.9	3.1
Colon	335	120	61	36.9	25	18.5	12.3	8.8	6.6	5.1
Liver	2,742	1,351	896	671	109	58	37	25	19	14
Red Bone Marrow	30	12	7.1	4.9	3.6	2.8	2.2	1.8	1.5	1.3
Bone Surface	31	14	8.4	5.9	4.4	3.5	2.8	2.3	2.0	1.7

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Table 12: Annual Inhalation Dose (rem) for Various Organs Based on Deposition from Event Small Boy Without Refractory Fraction Correction

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Liver	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Bone Surface	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lower Large Intestine	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
ET[a](ET2), LN[b](ET), LN(TH[c]),	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lung	0.004	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
ET1	0.469	0.088	0.032	0.022	0.010	0.006	0.004	0.003	0.002	0.001

[a]ET=extra-thoracic region.
[b]LN=lymph node.
[c]TH=thoracic.

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Table 13: Annual Inhalation Dose Correction Factors for Various Organs Based on Deposition from Event Small Boy with One Refractory Fraction Adjustment

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Skin, Adrenals, Thymus, Small Intestine, Spleen, Muscle, Uterus, Pancreas, Kidneys, Breast, Testes, Esophagus, Ovaries, Brain, Stomach, Thyroid, Gall Bladder	1156	416	211	127	85	60	65	35.7	23.1	16.3
Upper Large Intestine	480	181	95	58	39	27	19	15	11	9.2
Urinary Bladder	407	150	77	46	31	22	6.0	3.9	2.8	2.1
Lungs	25,352	7,991	3,786	2,191	1,425	999	247	176	132	103
Extra Thoracic Regions	698	243	123	92	51	33	23	17	13	10
Lower Large Intestine	351	128	66	40	27	20	15	11	9.0	7.3
Colon	369	137	71	43.7	30	21	16	12	9.5	7.7
Liver	6,074	2,993	1,986	1,486	808	264	140	89	62	46
Red Bone Marrow	42	12	7.0	4.7	3.4	2.6	2.1	1.7	1.4	1.2
Bone Surface	60	26	15	10	7.2	5.5	4.3	3.5	2.9	2.4

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Table 14: Annual Inhalation Dose (rem) for Various Organs Based on Deposition from Event Small Boy with One Refractory Fraction Correction

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Liver	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Bone Surface	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lower Large Intestine	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
ET[a](ET2), LN[b](ET), LN(TH[c])	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lung	0.006	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
ET1	0.724	0.137	0.050	0.030	0.017	0.011	0.007	0.005	0.004	0.003

[a]ET=extra-thoracic region.
[b]LN=lymph node.
[c]TH=thoracic.

Table 15: Annual Inhalation Dose (rem) for Various Organs Based on Deposition from Event Small Boy – Current TBD

Organ	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Liver	0.002	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Bone Surface	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Lower Large Intestine	0.001	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
ET(ET2)[a], LN[b](ET), LN(TH[c])	0.002	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl	Negl
Lung	0.008	0.002	0.001	0.001	Negl	Negl	Negl	Negl	Negl	Negl
ET1	1.635	0.248	0.164	0.164	0.146	0.138	0.138	0.138	0.138	0.138

[a]ET=extra-thoracic region.
[b]LN=lymph node.
[c]TH=thoracic.

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GENERAL CONCLUSIONS

The purpose of application of the refractory fractions by Hicks (1981, 1982) was to estimate the relative activities of refractory and volatile radionuclides at off-site locations. The phenomenon of fractionation is described by Hicks (1982) as follows.

> *The phenomenon of fractionation is due to both chemical and physical separation of the radionuclides. Chemical separation occurs in the first few minutes. At zero time, everything in the vicinity of the device is vaporized. As the fireball cools to about 3000°C the FeO and soil components form liquid droplets in which the refractory elements dissolve (Ad60). The fireball cools to the melting point of soil and iron oxides, ~1500°C, in about 20 sec (Mi63, St58). The solidified droplets contain the refractory elements, while the volatile elements and their radioactive daughters remain in the gas phase. In 6-8 minutes, when the cloud has cooled to ambient temperature, ~50°C, the volatile elements (except for Kr and Xe) and their daughters condense on the surface.*

The volatile phase consists of those elements in the gas phase when the liquid droplets solidify. The refractory phase consists of those elements in the liquid droplets when they solidify. The volatile/refractory ratio is the ratio of the amounts of volatile phase to the refractory phase.

The solid particles in the cloud of nuclear debris fall to earth at different velocities and from different altitudes. This process has the effect of separating the debris by particle size along the path of the cloud. Thus, the refractory phase and the volatile phase are partially physically separated, a process taking hours or days.

Off-site fallout is characterized by an excess of volatile phase, because the smaller particles tend to be deposited farther from ground zero.

The application of the refractory fraction (inverse of the volatile/refractory ratio) was to account for preferential deposition as the cloud moved downwind and off-site. The selection of the value to use for refractory fractions was based on the comparison of calculated and measured soil concentrations as a function of distance from the test shot (Hicks 1982). The results of the analyses indicated that the volatile/refractory ratio increased from about one near the shot site to over three at long distances off-site. The application of refractory fractions by Hicks is summarized as follows:

- For air drops and balloon shots, no fraction was assumed by setting RF to 1.0.
- For low tower, surface, and underground shots, a refractory fraction of 0.4 was applied.
- For all other shots a refractory fraction of 0.5 was applied.
- The two shots evaluated for July of 1962 were Small Boy (low tower) and Little Feller I (surface), and have a refractory fraction of 0.4 (Hicks 1981).

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For the present analysis, the results are needed for distances closer to the shot representing on-site locations. This is the reason the Hicks data were adjusted by reversing the refractory fraction correction.

A summary of the doses in the tables in the previous section is given in the following table.

Table 16: Summary of Dose Results for ET1 from Inhalation

Event	Analysis	ET1 Dose (rem)	Ratio to Small Boy, TBD Method	Source
Small Boy	TBD Method	1.305	1.00	Table 4
Little Feller I	TBD Method	0.519	0.40	Table 6
Small Boy	No refractory adjustment	0.469	0.36	Table 12
Small Boy	One refractory adjustment	0.724	0.55	Table 14
Small Boy	Current TBD	1.635	1.25	Table 15

The results indicate the application of the refractory fraction once, to represent off-site activities, results in the lowest doses from inhalation intakes. As the refractory fraction is removed from the analysis, once and then twice, the doses increase. This indicates that the analysis method used in the NTS Environmental TBD is favorable to claimants. The same is true for the ingestion intake analyses. Consequently no change to the method used in the TBD is recommended. Minor changes to the values in the TBD have occurred as a result of modifications to the evaluation and application of dose correction factors. Specifically, removal of the radionuclides in the TBD Table 4-7 from the correction factor analysis reduced the resulting doses because it increased the fraction of the dose from strontium-90.

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